GEOTECHNICAL ASSESSMENT OF COASTAL POLDERS AGAINST CYCLONES IN BANGLADESH

A thesis Submitted by

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DEDICATION

I dedicate this thesis to my beloved parents, without inspiration of them I would not be what I am now. I also want to thank my wife for her continuous support and inspiration.

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I would like to express my sincere gratitude to my respected supervisor Dr. Mehedi Ahmed Ansary, Professor, Department of Civil Engineering, BUET for his continuous support, sincere supervision, valuable suggestions, comprehensive discussions, stimulating working enthusiasm throughout the research work. Apart from academic purpose, he has been always behind me during adversity of my life and supported me for my endeavor.

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Abstract

The stability of coastal embankments is a major concern for Geotechnical Engineers. Bangladesh is one of the countries where a majority number of people live near the coast. Every year severe tropical cyclones, sometimes with storm surges, hit the coastal area where earthen embankments work as the first line of defense. Since the 1960s, the government of Bangladesh has invested millions of dollars in the improvement of the coastal embankment of Polders to save lives and livelihoods. However, each year embankments breach at different locations of Polders. Recently, the government invested thousands of millions of taka in Coastal Embankment Improvement Project. The objective of the thesis is to test some of the newly improved Polder embankments to identify the geotechnical characteristics of the Polder embankments (existing geometry, types of embankment soil, and their geotechnical parameters), and to assess the safety status of the Polder embankments at different locations if the Polders were faced cyclonic storm surges of the same intensity the region experienced during the previous few decades. For the study purpose, the coastal area has been divided into seven regions. One Polder embankment from each region, a total of seven in seven regions, has been selected for this study. Standard Penetration tests were performed, and soil samples were collected from each selected Polders. Geotechnical parameters such as soil type, liquid limit test, and direct shear test, tri-axial test, unconfined compression tests were performed in the laboratory. The embankments have been numerically modeled in PLAXIS 3D, a finite element software, and GEO5, a limit equilibrium software. The model has been validated for a newly constructed superdyke at Chittagong. The safety status and settlement values of the superdyke model are compared with field observation values. The effect of mesh size and soil models are analyzed for the validation model. For this study, the Mohr-Coulomb model is used for Silty Sand and Fine Sand, and the Soft Soil model is used for Soft clay, Silty Clay. The PLAXIS model of the selected Polder embankments is analyzed for normal consolidation, rapid drawdown, slow drawdown, and very slow change in water level. Additionally, the coastal embankments of Polders are analyzed against surge height and thrust forces for two severe Cyclones: 1991 Cyclone and 2007 Cyclone SIDR. The safety factor of the Polder embankments ranges from 0.68 to 2.5 for different cases. In some analysis cases, some Polder embankments collapsed, and the factor of safety could not be calculated. Based on numerical study results, safety maps for Polder regions have been prepared for the above two cyclones. From the field test, laboratory investigations, and numerical study, it is evident that although the government has invested thousands of millions of takas for coastal embankment improvement projects, the coastal embankments of Polders are still unsafe against storm surges and need further improvement.

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NOTATIONS

c	Cohesion
φ	Angle of friction
ψ	Dilatancy angle
γ	Unit weight of soil
υ	Poisson’s ratio
τ	Shear stress
e_0	Initial void ratio
E	Young’s modulus
E_{oed}	Oedometer modulus
E_{50}	Secant elastic modulus at 50% peak strength
E_{ur}	Unloading/reloading modulus
V_s	Shear Wave velocity
G_{mas}	Shear Modulus

ABBREVIATIONS

SPT	Standard Penetration Test
CEP	Coastal Embankment Project
CER	Contingent Emergency Response
CEPP	Coastal Embankment Protection Project
CERP	Coastal Embankment Rehabilitation Project
CEIP	Coastal Embankment Improvement Project
WAPDA	Water and Power Development Authority
BWDB	Bangladesh Water Development Board

Chapter 1

INTRODUCTION

1.1 General

Coastal regions are geographically prone to disasters such as Cyclone, Storm surge, Tsunami, Earthquake and many more. However, throughout the world, coastal areas are most densely populated. About 50 percent of the world's population lives within 100km of the coastline and it is expected to grow in the next half centuries (World Bank, 2009). Jessore, Narail, Gopalganj, Shariatpur, Chandpur, Satkhira, Khulna, Bagerhat, Pirozpur, Jhalakati, Barguna, Barisal, Patuakhali, Bhola, Lakshmipur, Noakhali, Feni, Chittagong, and Cox's Bazar are among the 19 coastal districts of Bangladesh encompasses an area of 47,201 km2, or 32% of the nation (Figure 1.4). The coastline region is home to 35 million people which is 29% of the total population. (Ahmad, 2019).

The coastal region of Bangladesh is especially vulnerable to storm surges due to its geographical location and topography. The region is frequently effected by natural disasters like cyclones, storm surges, and floods every now and then. Especially, cyclones occur in early summer (April-May) or late rainy season (October-November) (Khalil, 1992). Recent Cyclones such as Katrina (2005, Sidr(2007), Aila (2009), Irma (2017), Maria(2017), Mora(2017), Mitchel (2018), Fani (2019), Bulbul (2019), Amphan (2020) and many more give a clear indication of an increasing trend of natural disasters in Bangladesh and all over the world. Hossain and Mullick (2020) summarized the major cyclones happened in Bangladesh from 1582 to 2020. Table A1 in Appendix A presents the major cyclones in Bangladesh.

The coastal zone is subjected to inundation by high tides, salinity intrusion, cyclonic storms and associated tidal surges etc. During 1960's and early 1970's the government decided to construct polders surrounded by embankments along the entire coastal belt to protect the people and agriculture of the coastal zone and crops from tidal inundation and saline water intrusion and release a large extent of land for permanent agriculture. In this regard the first major project taken up was the Coastal Embankment Project (CEP).

Schmidt (1969) noted the comprehensive study of "United Nations Technical Mission (the Kruger Mission)" for water resources development in East Pakistan (now

Bangladesh got independent from Pakistan in 1971). A major recommendation of the study was that “low-lying agricultural lands along the delta front, which extends 330 miles from the Indian to the Burmese border, be protected from periodic inundation of saline tidewater from the Bay of Bengal by a system of dikes.” Before the study, local farmers already built bunds (an embankment against inundation) for their cultivation purpose, but those locally constructed bunds “were poorly constructed and were often breached by tides and storms.” Although the construction started in 1958, the concept accelerated after the East Pakistan Water and Power Development Authority (EP-WAPDA) was given the responsibility. Figure 1.1 shows the project taken by EP-WAPDA in 1960.

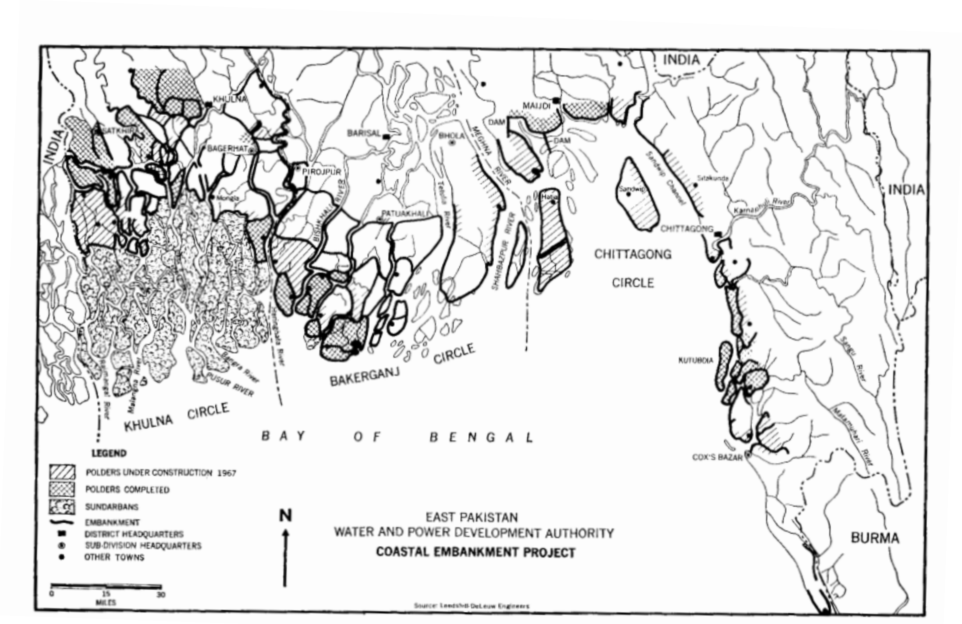


Figure 1.1: Coastal embankment project taken by EP-WAPDA in 1960 (Schmidt, 1969)

The project’s scope was set based on a feasibility report performed in 1961. Based on detailed studies and observations of erosion and sedimentation of some of the offshore islands, the project’s scope was modified. The salinity line was discovered to be south of its initially anticipated location. The embankment wide and height was increased to safeguard 3.4 million acres of fertile agricultural land in the Khulna, Bakerganj, Noakhali, and Chittagong districts of East Pakistan (now Bangladesh) from the destructive flooding of the saline coastal waters. The main aim was to enhance agricultural production and to improve communication in the area. Polders, thousands of acres of individual areas, were formed to protect the farmlands by constructing broad-based earth embankments with 14 to 24 feet in height along rivers, drainage channels, tidal estuaries, and the Bay of Bengal. Slice gates were constructed to drain the excess rainwater from the interior of the Polders and to prevent intrusion of water from outside the Polders during high tide and monsoon floods. Within the 1666-1967 fiscal year, half of the project was completed, which included the relatively stable areas in the saline zone, consisting of approximately 2600 miles of embankment in 92 polders, protecting 2.7 million acres programmed for completion in 1970-1971.

In the 1960s and 1970s, 123 polders were built, 49 of which front the sea, to protect Bangladesh's low-lying coastal districts from tidal floods and saline intrusion (Dasgupta et. al., 2014). Table A2 in Appendix A presents the list of Polders in coastal different locations in Bangladesh.

Within 1967, the productivity of 1,300,000 acres of land was increased as the area became protected by the embankments. However, the embankments did not protect the Polder areas from the devastating tropical cyclones; they reduced the havoc a little bit. Between June and October 1963, tropical cyclones submerged 260,000 acres of land and killed 11,500 people. On May 11-12, 1965, a tropical cyclone took the lives of nearly 20,000 people.

The Bangladesh Coastal Embankment Rehabilitation Project (CERP) was initiated in response to the devastating cyclone of 1987, and approved in 1995. The project closed in 2003. Between 1970 and 1998, 171 large-scale water-related hazards such as cyclones, storm-surges, droughts, floods, and river erosion disasters killed an estimated half million people and affected more than 400 million. The poor are hit hardest because they live at greater density in the most poorly constructed housing in settlements on lands prone to hazards-particularly along the 700 kilometers of coast affected by storm surges. The World Bank involved in coastal area protection through the Coastal Area Rehabilitation Project following the devastating cyclone of November 1970 whose winds and tidal surge of seven meters killed more than 200,000 people and inundated 8,100 square kilometers. The government of Bangladesh requested World Bank for assistance in June 1985 after a further 10,000 were killed by the May cyclone and this initiated preparation of the Coastal Embankment Protection Project in 1995 (World Bank, 2005).

The most difficult of which were that land for embankments had to be acquired two years in advance of construction and that all project-affected people had to be equably compensated- thus pushing back appraisal and Board presentation by a further two years. In the meantime a huge cyclone in April 1991caused 140,000 deaths and refocused attention on coastal polders.

Recognizing that the initial project objective to save lives and reduce property damage had been made redundant by the long delays, the project name was changed to the Coastal Embankment Rehabilitation Project (CERP). Table 1.1 presents the project area of CERP.

The overall objective was to improve security of life, property, crops, and livestock along the cyclone-prone coastal are. The specific objectives of the project were to: (1) provide cyclone protection, including improving the security of persons living in the protected areas, reducing damage to houses and other buildings and infrastructure and minimizing the loss of crops and livestock; (2) improve agricultural production, though preventing saline inundation during normal weather and improved cropping patterns due to reduced cyclone risks; and (3) introduce improved technology in the design and construction of protection works, and improved methods of embankment maintenance.

The line agency of Ministry of Water Resources, the Bangladesh Water Development Board (BWDB), managed the project through a special Project Implementation Unit established in Chittagong and sub offices in Cox’s Bazaar, Noakhali, and Barisal. The BWDB Project Director was assisted by three deputy directors responsible for construction, OandM, and resettlement. The Forest Department (FD) maintained its own PIU in Chittagong and was responsible for foreshore afforestation, technical assistance, and funding NGOs to establish nurseries and assist BWDB in its embankment forestry activities.

At the end of the CERP project in 2003, only 14 of the 21 polders targeted for rehabilitation were protected completely by new or renovated embankments that filled critical gaps in the sea defenses, leaving 7 polders at risk of rapid inundation from cyclones.

Table 1.1: Project area for Coastal Embankment Rehabilitation Project (CERP) (After World Bank, 2005).

Project area	**Status of Work**
Sharakhola	Incomplete
Patherghatha	Complete
Kuakata	Complete
Ramghati	Incomplete
Sudharam	Complete
Companiganj	Complete
Sonagazi	Complete
Sitakunda	Incomplete
Patenga	Complete
Anowara	Complete
Baskhali	Complete
Chanua	Complete
Chakoria	Complete
Kuruskhali	Complete
Cox's Bazaar	Complete
Teknaf	Incomplete
Moheskhali	Complete
Matherbari	Complete
Kutobdia	Incomplete
Sandwip	Incomplete
Hatiya	Incomplete

On November 15, 2007, a category IV storm named Cyclone Sidr made landfall in Bangladesh's southwest on the night of, killing 3,406 people and wreaking damage of roughly US$ 1.7 billion (Paul, 2009). On May 25, 2009, Aila made landfall on Bangladesh’s southwest coast. 11 coastal regions and more than 3.9 million people were impacted by tidal surges of high to 6.5 meters (UN, 2010). 7,100 people were injured, 1,743 kilometers of embankments were destroyed, and 190 individuals lost their lives as a result of the flooding. Aila also resulted in the deaths of around 150,000 animals, the whole or partial destruction of almost 325,000 acres of cropland, and significant losses to infrastructure (Mallick, 2011).

After cyclones SIDR and AILA struck the coastal zone causing severe damage to the infrastructure, life and property, the Government of Bangladesh (GOB) has taken Coastal Embankment Improvement Project Phase-1 (CEIP–1)(BWDB, 2013).

The First Phase of the Coastal Embankment Improvement Project for Bangladesh aims to: (a) increase the area protected in specific polders from tidal flooding and frequent storm surges, which are expected to get worse due to climate change; (b) increase agricultural production by reducing saline water intrusion in specific polders; and (c) increase the capacity of the Government of Bangladesh to respond quickly and effectively to a crisis or emergency that qualifies. There are five sections to the project. (1) The rehabilitation and enhancement of polders component will provide funding for initiatives aimed at boosting community resistance to tidal floods and storm surges. (2) Consultation with and assistance for polder stakeholders and beneficiaries will be provided via the implementation of the social and environmental management frameworks and plans component. (3) Consulting services for I surveys, designs of remaining polders to be included in the project, (ii) construction supervision of rehabilitation and improvement of coastal embankments, (iii) continuous monitoring of project activities, and (iv) providing feedback to the government and the implementing agency on the project's performance will be covered. (4) The Bangladesh Water Development Board will be assisted in executing the project through the project management, technical assistance, training, and strategic studies component. The following requirements must be met in order for the contingent emergency response component to function: (i) the Bank and the Government of Bangladesh have agreed that an eligible crisis or emergency has occurred; (ii) the Ministry of Finance has prepared and adopted the Contingent Emergency Response (CER) Implementation Plan; and (iii) Bangladesh Water Development Board has prepared, adopted, and disclosed safeguards instruments necessary as per Bank guidelines for all activities from the CER Implementation Plan (World Bank, 2022).

For Phase I, 17 priority polders have been chosen in the South West region’s five districts of Khulna, Bagerhat, Pirojpur, Barguna, Patuakhali, and Satkhira. Table 1.2 presents the locations, gross area, length of embankment, and people living in the areas for the selected priority Polders in South West Coastal regions in Bangladesh. Figure 1.2 presents the locations of priority polders for CEIP Phase I. Also, the picture shows the current construction state of the selected Polders.

Table 1.2: Selected Priority Polders for CEIP Project (Phase-I) (after BWDB, 2013).

S/No.	Polder No.	Location Name of Thana	Gross Protected Area (ha)	Length of Embankment (Km)	Polder Population (No.)
1	32	Dacope	8,097	49.5	38,397
2	33	Dacope	8,600	52.5	62,305
3	35/1	Sharankhola	13,058	63	99,182
4	35/3	Bagerhat	6,790	40	31,075
5	39/2C	Matbaria	10,748	55	43,077
6	14/1	Koyara	2,933	25	20,578
7	15	Shymnagar	3,441	27	31,788
8	16	Paikgacha,	10,445	45	31,788
9	17/1	Dumuria	5,020	45.8	118,616
10	17/2	Dumuria	3,400	11	23,919
11	23	Paikgacha	5,910	37	34,070
12	34/3	Bagerhat	3,656	17	23,888
13	40/2	Pathargatha	4,453	35.53	65,399
14	41/1	Barguna	4,048	33.81	41,317
15	43/2C	Galachipa	2,753	25.7	41,051
16	47/2	Kalapara	2,065	17.5	5,411
17	48	Kalapara	5,400	38	26,260

1.2 Geology of Bangladesh and the Research Area

Bangladesh, is a country of South Asia, is the eighth-most populous country in the world, having more than 163 million people in an area of 147,570 square kilometers (56,980 sq. mi), making it one of the most densely populated countries in the world. Bangladesh is bounded on the west, north, and east by India, on the southeast by Myanmar, and on the south by the Bay of Bengal. Bangladesh is a deltaic floodplain, consisting of flat or nearly flat land adjacent to a stream or river that occasionally or periodically floods, country formed by the deposits of the Ganges, Brahmaputra-Jamuna, and Meghna Rivers (Sultana and Thompson, 2017).

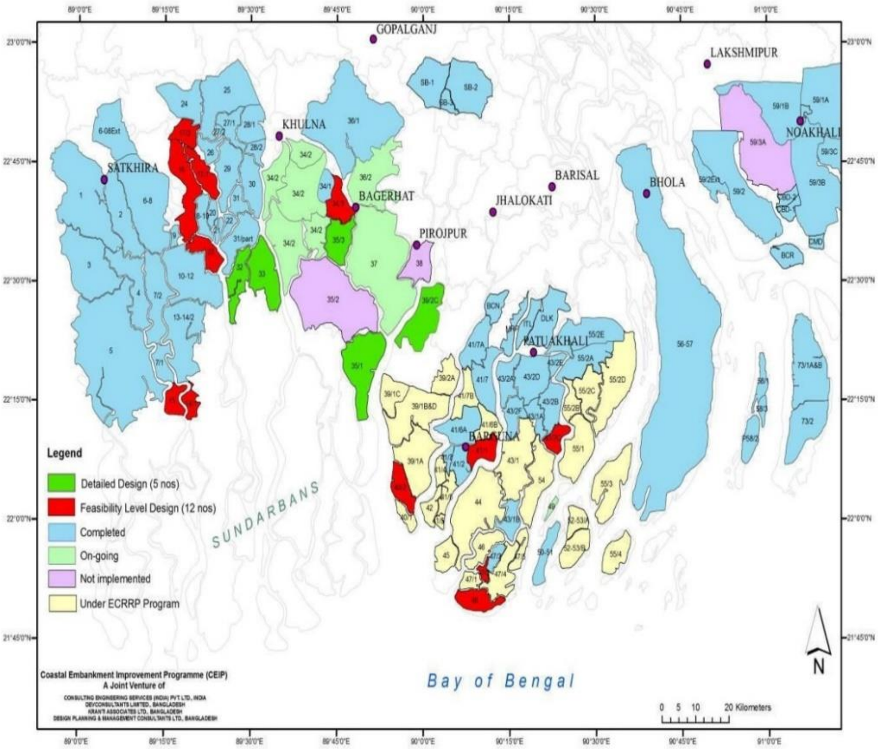


Figure 1.2: Selected Priority Polders for Coastal Embankment Improvement Project Phase-1 (CEIP–1) (BWDB, 2013)

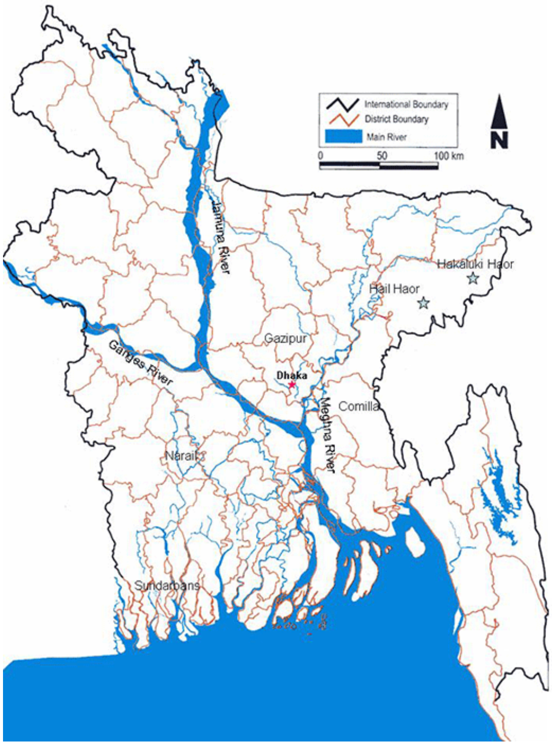


Figure 1.3: Map of Bangladesh showing significant floodplain locations and place names (Sultana and Thompson, 2017).

Bangladesh is one of the world's most floodplain-dominated countries and also one of the densely populated, with a population density of over 1,100 people per km^2. Bangladesh has approximately 700 rivers totaling 24,140 kilometers in length, thousands of smaller channels, floodplain depressions, and extensive seasonally flooded lands that collectively form the floodplain ecosystems (Akonda, 1989).

A coastal zone is the interface between the land and water. Bangladesh is a tropical country that is primarily comprised of the deltas of huge rivers that originated in the Himalayas, meeting at the Bay of Bengal in the south. According to Coastal Zone Policy, 2005 (CZPo, 2005) the length of the coastline is about 710 km long. 19 out of 64 districts of Bangladesh are identified as coastal zone, comprising 147 upazillas; and 12 of those districts are cities and towns situating right to the sea. Jessore, Narail, Gopalganj, Shariatpur, Chandpur, Satkhira, Khulna, Bagerhat, Pirozpur, Jhalakati, Barguna, Barisal, Patuakhali, Bhola, Lakshmipur, Noakhali, Feni, Chittagong, and Cox's Bazar are the coastal districts of Bangladesh (Uddin and Kaudstaal, 2003).

According to the land's position, the zone is separated into exposed and interior coasts. The exposed coastal zone is defined as upazillas that front the seashore or a river estuary. The total number of upazillas in 12 districts within the exposed coastline zone is 48. Another 99 upazillas located behind the exposed shore are referred to as the Interior coast (Sarwar, 2005).

Bangladesh's coastal zone is divided into three sections based on geographical features: (a) the eastern zone, (b) the central zone, and (c) the western zone. The western section, dubbed the Ganges tidal plain, is a semi-active delta crisscrossed by numerous canals and creeks. The central region is characterized by the most active and continuous accretion and erosion processes. This zone contains the Meghna river estuary. The eastern part is covered by a hilly, more stable terrain (Ahmed, Drake, Nawaz and Woulds, 2018).

Although the government of Bangladesh has invested millions of dollars for embankments (both coastal and river bank protection embankment), every year there are numerous cases where floods, cyclones and storm surges cause failure of embankment. Especially, for coastal regions the Polder breaches amplify the effect of coastal flooding, cyclones and storm surges.

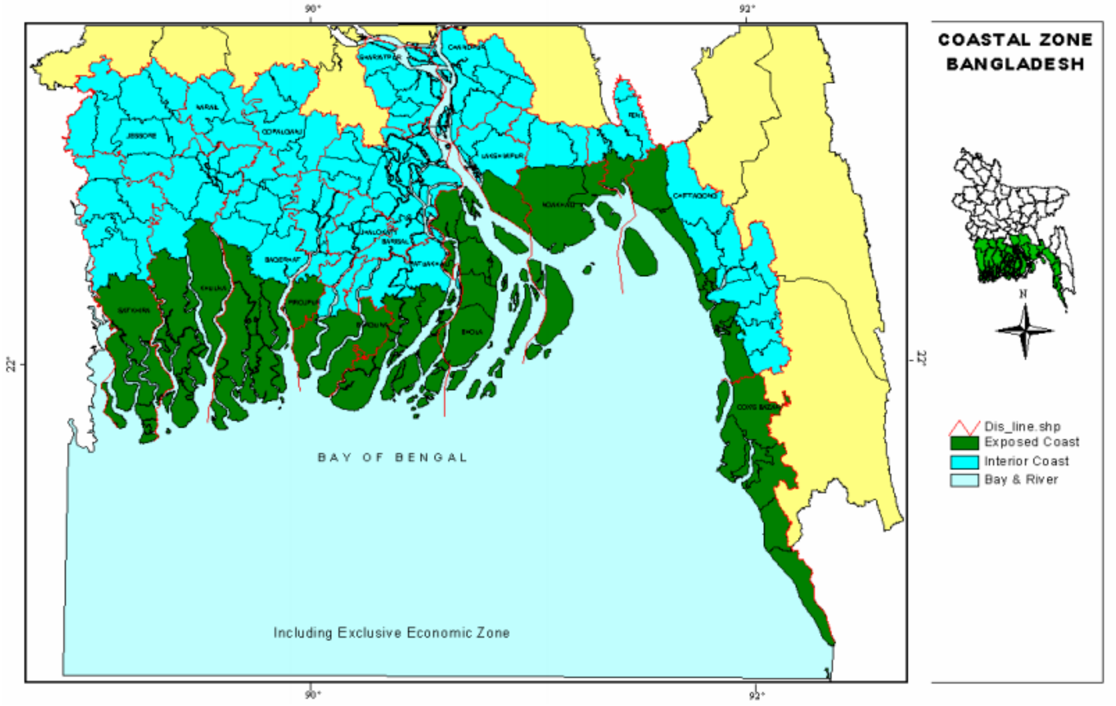
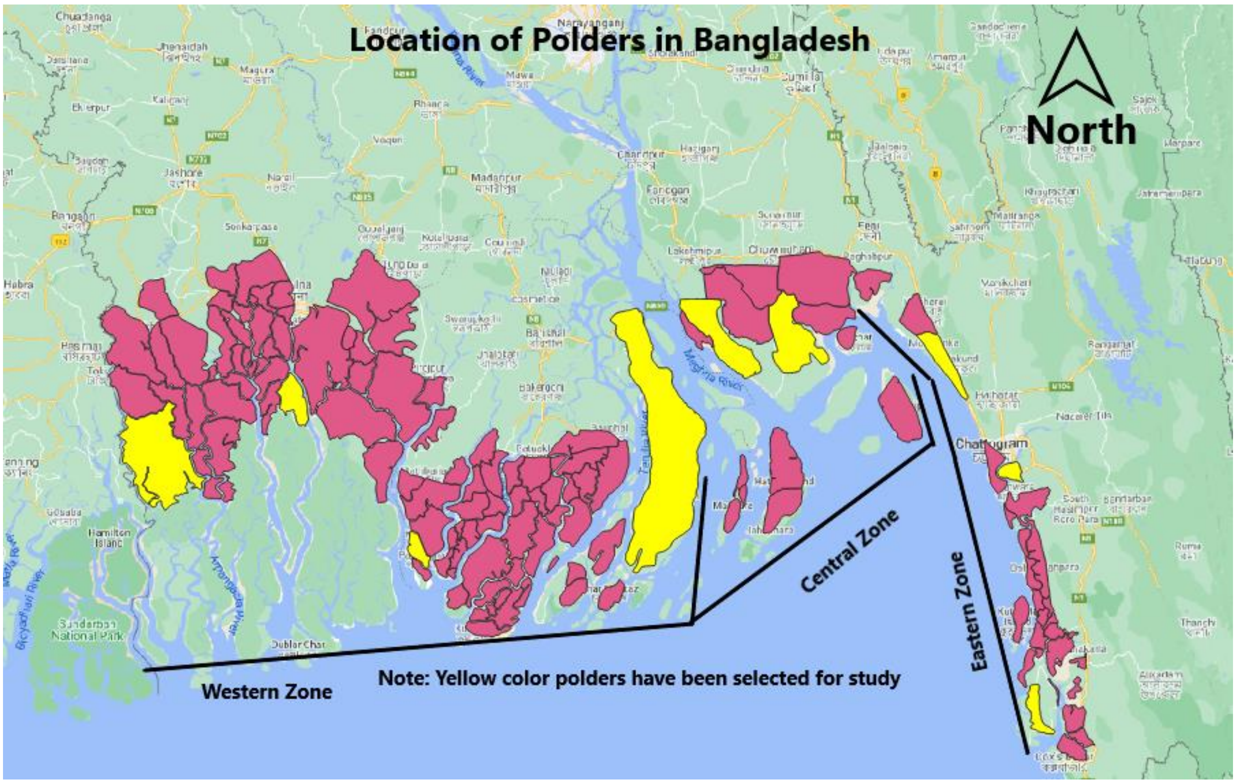


Figure 1.4: Coastal zone of Bangladesh (Islam, 2004)

Karim and Mimura (2008), Dasgupta et al. (2010), Alam and Collins (2010), Dasgupta et al. (2014), Rahman and Rahman (2015), Adnan et al. (2019) studied the vulnerability of cyclones in the coastal regions, adaptation cost and practices, effect of climate changes on severity and frequency of cyclones. However, study on geotechnical aspect of Polders in coastal regions of Bangladesh is very rare. In 1993, Ansary studied the soil properties in Coastal region of Bangladesh. Hossain (2013) investigated the causes of failure of Polder no. 14/1 in Koyra Upazilla under Khulna district. Mahin (2014) and Islam (2015) studied the effects of cyclonic storm surge and wave action on selected coastal embankments and calculated thrust forces due to storm surges on Ploders for different cyclones. However, none of the previous study focuses on the impact of surge depth and thrust forces on the geotechnical stability of the coastal Polders in Bangladesh.

The purpose of the thesis is to assess the geotechnical stability of the improved Polders through Coastal Embankment Rehabilitation Project (CERP) and Coastal Embankment Improvement Project Phase-1 (CEIP–1). Based on local geology the coastal Polders are divided into seven regions (discussed later in Chapter 3) and some of the Polders are selected for detailed analysis. The locations of the selected Polders for study is shown in Figure 1.5.

After primary classification of the coastal regions, detailed geotechnical investigations (both field test and laboratory tests) have been performed. Later, the soil strength parameters have been estimated by laboratory test results and empirical correlations. Then, the Polders have been modeled in PLAXIS 3D software (the detailed are discussed in Chapter 4) to evaluate their geotechnical safety status against pseudo cyclonic storm surges that the regions faced and severely damaged. The result assess the status of the improved Polders if they encountered those severe cyclones again. At last, safety maps have been prepared for Polders against different cyclones. Figure 1.6 presents different steps involved in the research work.


Location of Polders in Bangladesh

Note: Yellow color polders have been selected for study

Figure 1.5: Selected Coastal Polders for Geotechnical assessment.

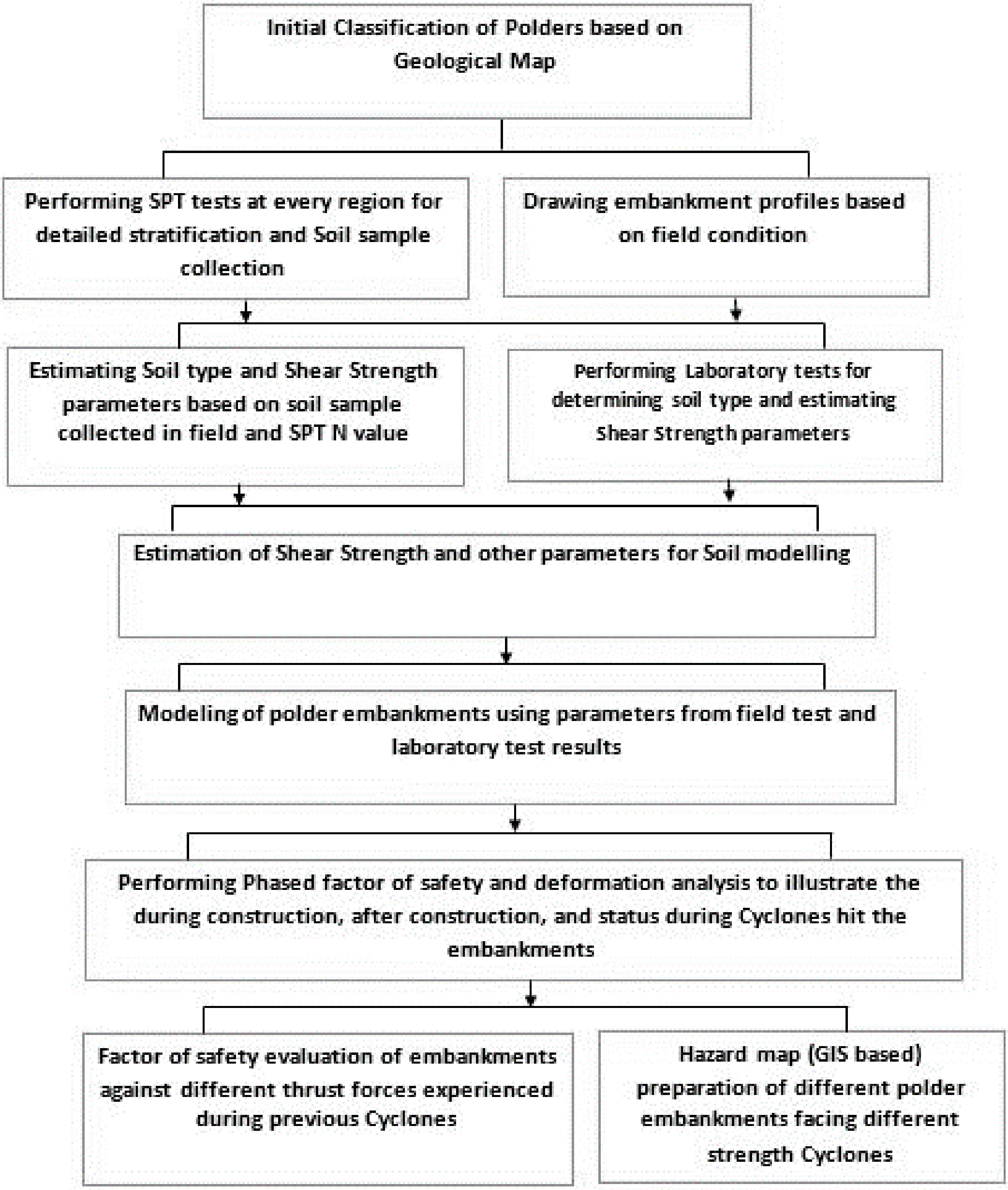


Figure 1.6: Flowchart of the study.

1.3 Objectives

The present study is aimed to evaluate the geotechnical assessment of coastal polders against cyclones in Bangladesh to meet the following objectives.

The followings are the main objectives of the research:

(i) To estimate geotechnical parameters of coastal embankments from field and laboratory tests.

(ii) To estimate the factor of safety of coastal embankments against thrust forces during cyclones.

(iii) To create maps of safety status for coastal embankments against cyclones.

1.4 Outline of the Thesis

Following the introductory chapter, chapter 2 presents the causes of slope failures, different methods of slope stability analysis, factor of safety of slopes, softwares used for slope stability, Cyclone and Storm Surges in Bangladesh, Surge depth and Thrust force for different major cyclones. Chapter 3 presents the locations and methods of geotechnical investigations, summary of soil types and geotechnical properties of Polders in the project area. Chapter 4 discusses the steps of numerical modeling of earth embankment, effect of meshes and soil models for stability analysis, validation of the embankment model, settlement and factor of safety analysis of the coastal polders for different combination of surge depth and thrust force analysis.

Chapter 5 presents a summary of research, main conclusions, and scope for future Studies.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

Assessing the stability of slopes for earth embankment is an essential, intriguing, and challenging task for civil engineers. Some of the most significant advancements in our understanding of the complicated behavior of soils have been prompted by concerns with slope stability. Extensive engineering and scientific investigations conducted over the past eighty years have yielded better understanding of soil mechanics concepts which has led to deal real problems of slope stability.

In this chapter, the basics of slope stability, factor of safety, different conditions for slope stability analysis have been discussed. In addition, different theories of slope stability analysis, both limit equilibrium and finite element method, have been discussed.

2.2 Slope Failure

It is critical to comprehend the causes of slope instability for two reasons. For the purposes of planning and building new slopes, it is essential to be able to foresee the changes in soil qualities that may emerge over time and the different loading and seepage conditions against which the slope will be exposed during its lifetime. In order to prevent a recurrence of slope failures, it is vital, for the sake of mending slopes that have collapsed, to comprehend the crucial circumstances that led to the failure.

2.2.1 Modes of slope failure

Cruden and Varnes (1996) categorized the failure of slopes into five major categories.

Fall: This refers to the separation of soil and/or rock particles that occur during the descent of a slope (Figure 2.1).

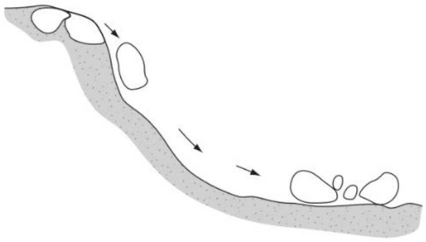


Figure 2.1: “Fall” type slope failure (Das, 2010).

Topple: This refers to forward rotating of a mass of soil and/or rock about an axis that is located below the mass's center of gravity when it is moved (Figure 2.2).

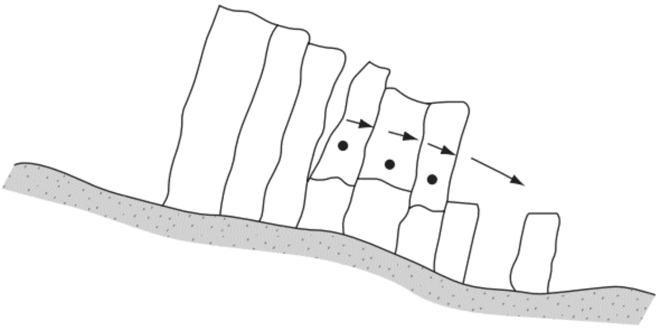


Figure 2.2: “Topple” type slope failure (Das, 2010).

Slide: This refers to the downing of a mass of soil that takes place on a surface that has been ruptured (Figure 2.3).

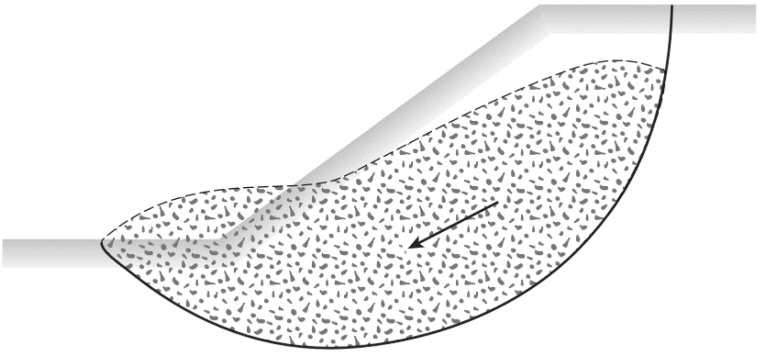


Figure 2.3: “Slide” type slope failure (Das, 2010).

Spread: This is an example of the slide-by-translation method. This phenomenon occurs due to sudden migration of water-bearing layers of sands or silts sediments deposited by clays or burdened by fills (Figure 2.4)

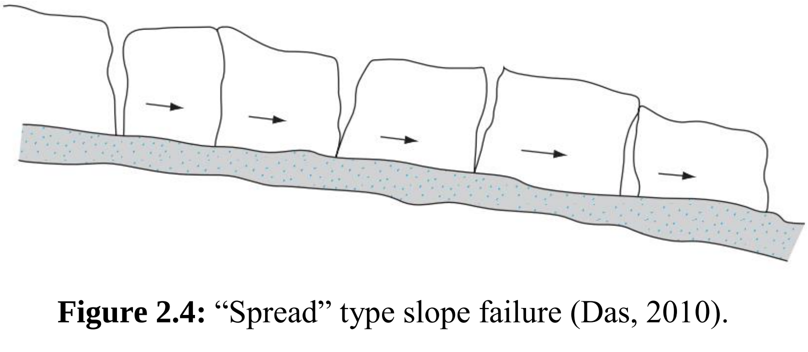


Figure 2.4: “Spread” type slope failure (Das, 2010).

Flow: Comparable to a viscous liquid, this is a downward flow of soil material **(**Figure 2.5**)**.

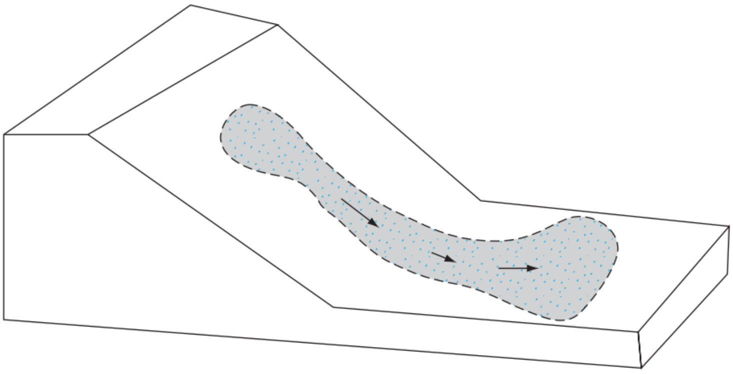


Figure 2.5: “Topple” type slope failure (Das, 2010).

2.3 Stability of Slopes for Different Conditions

Changes in the load cases on slopes and also in shear strengths of soil over time result in alterations to the safety factors of slopes. As a result, it is frequently important to conduct stability evaluations for a variety of circumstances that correspond to the various stages of a slope's life. The factor of safety against slope instability may grow or decrease as circumstances alter.

2.3.1 Stability at the end of construction

Before and after construction, based on the permeability of the soil, slope stability is evaluated using either drained or undrained strengths. Fine-grained soils are relatively impervious and the construction drainage is minimal. This is especially true for clays. For these fine-grained soils, undrained shear strengths are utilized, and the shear strength is defined by total stresses. Whereas, stability assessments employ drained strengths for freely draining soils. The correlations between drained shear strengths and effective stresses are represented, and pore water pressures are determined depending on the water table level or seepage conditions (Figure 2.6). In the same study, undrained strengths for some soils and drained strengths for others can be utilized. The most crucial condition for many embankment slopes is just after the completion of construction. However, there could occasionally be intermediary circumstances during construction which are more important. The fill may be put with a slope geometry in various fill placement procedures, including some waste fills, making the stability conditions worse during construction than they are at completion.

If an embankment is built in phases and there is considerable consolidation between them, each stage of construction needs to be examined.

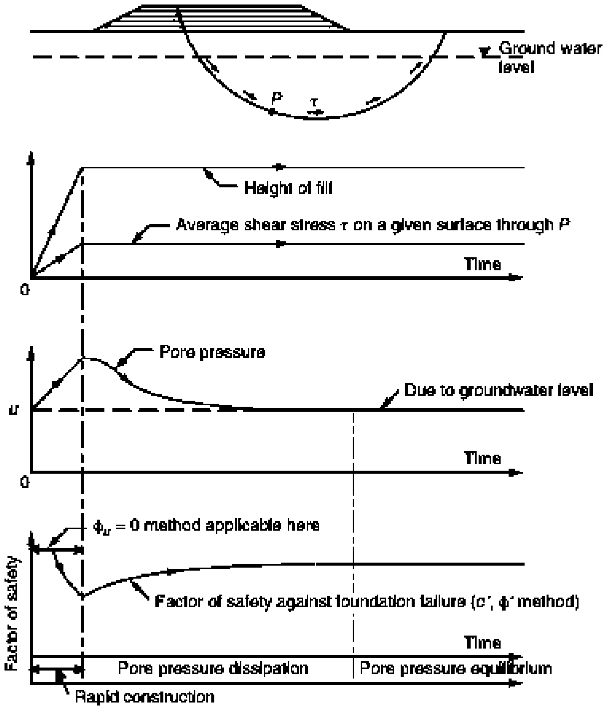


Figure 2.6: Typical variation of shear stress, pore water pressure, factor of safety of an embankment built on saturated clay (after Bishop and Bjerrum, 1960).

2.3.2 Staged construction safety

In situations where a clay foundation is so weak that it cannot support the loads imposed by an embankment of the planned final height, the stability of the embankment can be improved by placing only a portion of the planned fill and allowing the foundation clay to consolidate and gain strength prior to placing additional fill. In such instances, consolidation assessments are required to quantify the increase in effective stresses resulting from the consolidation of the foundation beneath the weight of the fill. The estimated values of effective stress are used to determine the undrained shear strengths for use in total stress (undrained strength) assessments or directly in effective stress analyses.

2.3.3 Long-term stability

The soil on slopes may either swell (with an increase in water content) or consolidate (with a decrease in water content) over time following construction. The conditions after these modifications are reflected in long-term stability evaluations. Effective stresses represent shear strengths, and pore water pressures are evaluated using the worst groundwater and seepage scenarios projected during the slope's lifespan. Depending on the complexity of the cross-section, seepage assessments can be carried out using either graphical methods (flow nets) or numerical methods (finite element, finite difference).

2.3.4 Rapid Drawdown

Rapid drawdown results when the water level next to a slope is reduced so abruptly that the soil does not have time to drain.

All materials other than the coarsest free-draining materials (k > 10^{-1} cm/sec) are considered to have undrained shear strengths. The undrained shear strength utilized in the drawdown analysis is the same as the undrained shear strength that applies to the end-of-construction condition if drawdown occurs during or soon after construction. However, the undrained strengths utilized in the drawdown study are different from those used in the end-of-construction assessments if drawdown occurs after steady seepage conditions have evolved.

2.3.5 Analysis cases for earth embankments

In Engineering Manual EM 1110-2-1902, Slope Stability, the U.S. Army Corps of Engineers (2003) gave recommendations (Table 2.1) for stability evaluations to be carried on earth dams. Some of the above-described loading conditions are applied to the upstream slope, some to the downstream slope, and others to both.

Table 2.1: Analysis Cases for Earth Embankment (After U.S. Army Corps of Engineers, EM 1110-2-1902, 2003).

Analysis case	Slope
End of construction (including staged construction)	Upstream and downstream
Long term	Downstream
Rapid drawdown	Upstream

2.4 Limit Equilibrium Procedures

In limit equilibrium analysis, two ways are employed to fulfill static equilibrium conditions. A few approaches take into account equilibrium for the total amount of soil confined underneath by an estimated slip surface and over by the slope's surface. Mathematical expressions for a single free body are developed and solved in these techniques. Such single-free-body approaches include the Infinite Slope process and the Swedish slip circle methodology. Other approaches split the soil mass into vertical and lateral slices, and equilibrium equations are created and solved for each slice. These processes, known as slices methods. Some of the slice methods are: the Simplified Bishop procedure, the Spencer's procedure, Ordinary Method of Slices, etc. It's important to note that somehow this process is based on the following assumptions: The location and the shape of the failure plane is not determined, rather it is assumed. Plain-strain deformation is assumed instead of taking into account the three-dimensional effects of slope failure. The safety results obtained from this assumption are conservative.

The Shear stresses are assumed to be distributed evenly along the whole length of the failure surface and the progressive failure is not considered.

The sliding mass is supposed to move entirely along the failure surface as a rigid block.

2.4.1 Factor of safety

After establishing the proper shear strength properties, slope geometry, pore water pressures, stability calculations must be done to assure that the resisting forces are considerably stronger than the forces causing a slope to collapse. Typical calculations include calculating a factor of safety using one of numerous limit equilibrium analysis methods. Every method of analysis utilize the same definition of factor of safety to calculate the safety status of the slope.

Factor of safety:

The factor of safety (F) is defined as the ratio of available shear strength (S) and equilibrium shear stress (τ) (Figure 2.7).

$$F = \frac{S}{\tau} \tag{2.1}$$

The equilibrium shear stress is the amount of shear force needed to keep a slope just stable. From Eqn. (2.1), this can be written as,

$$\tau = \frac{S}{F} \tag{2.2}$$

According to Mohr-Coulomb equation, the shear strength of soil can be expressed as (in terms of total stresses),

$$\tau = \frac{c + \sigma \tan \varphi}{F} \tag{2.3}$$

Or,

$$\tau = \frac{c}{F} + \frac{\sigma \tan \varphi}{F} \tag{2.4}$$

Here, φ and c are the angle of friction and cohesion.

The equation () can be written as,

$$\tau = c_d + \sigma \tan \varphi_d \tag{2.5}$$

If the shear stress is expressed in terms of effective stress,

$$\tau = \frac{c' + (\sigma - u) \tan \varphi'}{F} \tag{2.6}$$

Here, c' and φ' represent the shear strength parameters in terms of effective stress.

A slip surface is considered to compute the factor of safety, and the static equilibrium equations are employed to determine factor of safety of the plane considered. The factor of safety is considered to remain constant along the slip surface. As a result, the safety value is an average or overall value for the estimated slip surface. To identify the slip surface with the lowest factor of safety, a series of slip surfaces must be assumed. The critical failure surface is the surface having the lowest factor of safety.

Limit equilibrium, force equilibrium, and moment equilibrium are three main approaches to identify the FOS (Abramson et al. 2002).

2.4.2 Single free body procedures

The equilibrium of a single free body is taken into account for the infinite slope, Swedish Circle, and Logarithmic Spiral, methods. Although these processes are generally easy to implement, and beneficial within their scope of application.

2.4.2.1 Stability of infinite slopes

In the Infinite Slope method, the slope is supposed to have an extent that is infinite, and sliding is considered to take place along a plane that is parallel to the face of the slope (Taylor, 1948). Due to the fact that the slope is infinite, the stresses that are placed on any two planes that are orthogonal to the slope would be the same.

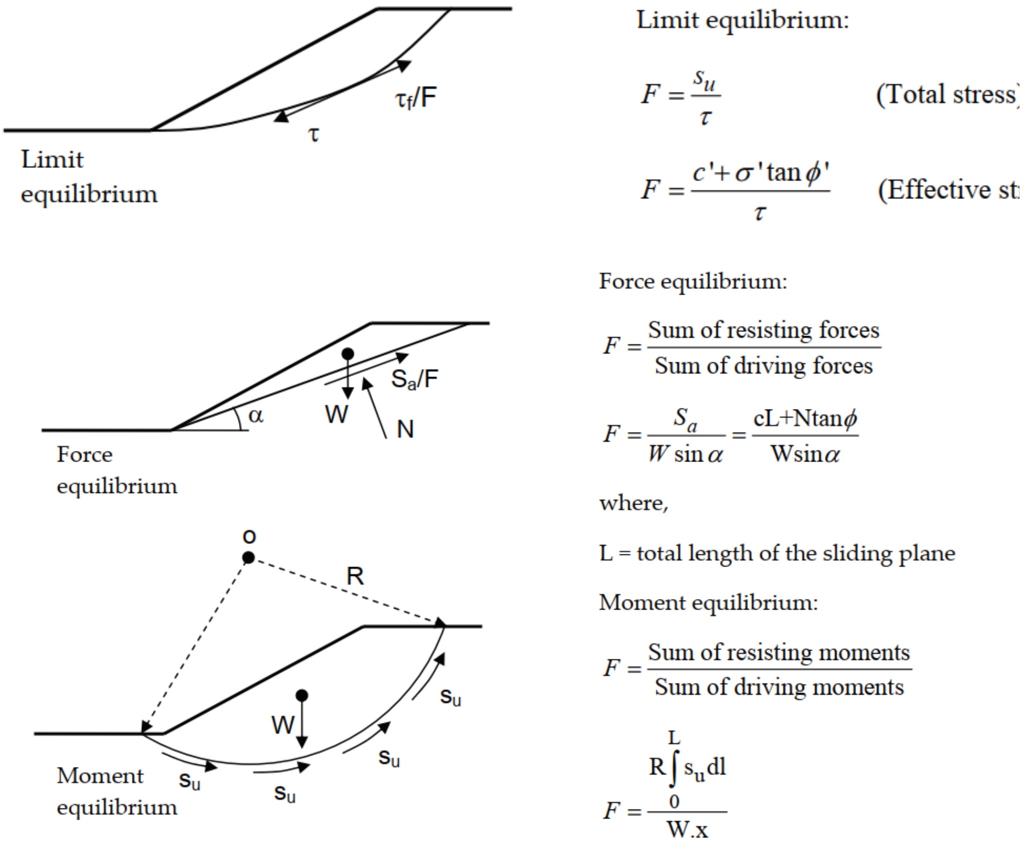


Figure 2.7: Different definitions of factor of safety of slope (Abramson et al. 2002).

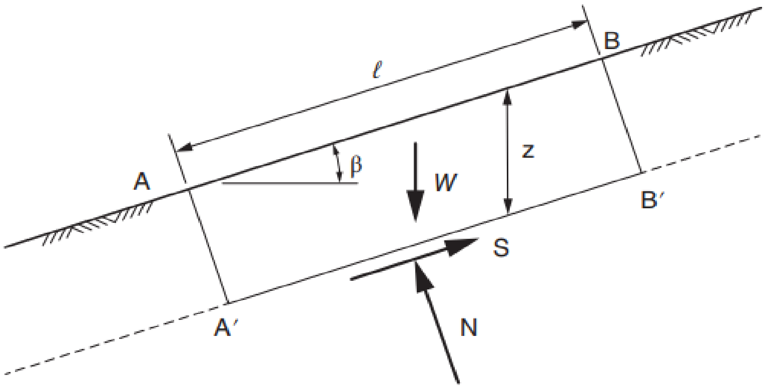


Figure 2.8: Infinite slope with slip surface (Duncan et al., 2014).

Here, shear force,

$$S = W \sin \beta \tag{2.7}$$

Normal force,

$$N = W \cos \beta . \tag{2.8}$$

Where, β is the inclination of the slip plane and slope with horizontal.

As shown in Figure 2.8, the weight of a block with unit thickness perpendicular to the plane is:

$$W = \gamma \mathrm{lz} \cos \beta \qquad (2.9)$$

Here, $\gamma, \mathrm{l}, \mathrm{z}$ are the unit weight of the soil, distance among two ends of the block and depth of shear plane.

Substituting Eq. (2.9) into Eqns. (2.7) and (2.8) gives,

$$S = \gamma \ell \mathrm{z} \cos \beta \sin \beta \qquad (2.10)$$

$$N = \gamma \ell \mathrm{z} \cos_2 \beta \qquad (2.11)$$

Dividing the Eqn. (2.10) and (2.11) by the plane area ($\ell \cdot 1$) the normal and shear stresses on the shear plane are,

Shear stress,

$$\tau = \gamma \mathrm{z} \cos \beta \sin \beta \qquad (2.12)$$

$$\sigma = \gamma \mathrm{z} \cos^2 \beta \qquad (2.13)$$

For the total stress factor of safety, after replacing these terms for the stresses into Eqn. (2.3),

$$F = \frac{c + \gamma z \cos^2 \beta \tan \phi}{\gamma z \cos \beta \sin \beta} \qquad (2.14)$$

For effective stresses, the factor of safety becomes

$$F = \frac{c' + (\gamma z \cos 2\beta - u) \tan \phi'}{\gamma z \cos \beta in \beta} \qquad (2.15)$$

2.4.2.2 Logarithmic Spiral Procedure

The Logarithmic Spiral technique assumes that the slip surface (Figure 2.9) as a Logarithmic Spiral (Frohlich, 1953). The spiral is defined by a center point, a beginning radius,r_0, and a value for φ_d. According to the equation, the spiral's radius changes with its angle of rotation,θ, around its center. The radius of the spiral,

$$r = r_{0\, e^{\tan \phi_d}} \qquad (2.16)$$

The normal stress (σ), and shear stress (τ) works along the plane of the slip surface. According to Eqn. (2.4), the shear stress can be expressed as below:

In terms of total stress, the shear stress,

$$\tau = \frac{c}{F} + \frac{\sigma \tan \varphi}{F} \tag{2.17}$$

Here, F is the factor of safety along the slip surface, c and φ are the shear strength parameters of soil. In terms of developed stress,

$$\tau = c_d + \sigma \tan \varphi_d \tag{2.18}$$

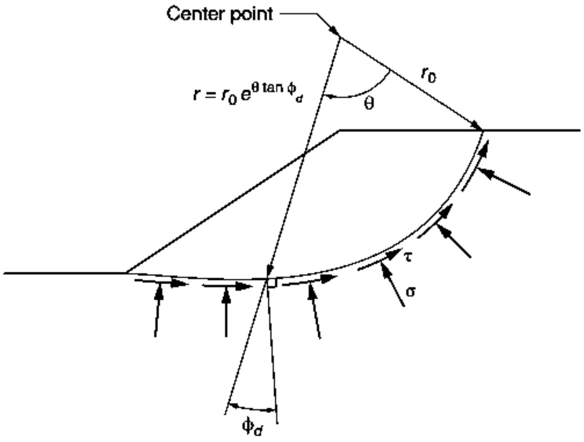


Figure 2.9: Logarithm spiral slip surface in slope (after Frohlich, 1953).

2.4.3 Some limit equilibrium (LE) methods

For the purpose of analyzing slope stability, a number of limit equilibrium (LE) theories have been developed. Fellenius (1936) was the first person to develop a technique for calculating a circular slip surface. This approach is known as the Ordinary method or the Swedish method. Bishop (1955) made a significant contribution to the field by advancing the initial technique and presenting a new relationship for the base normal force. As a result, the equation representing the FOS became non-linear. Janbu (1954a) proposed a simpler approach for non-circular failure surfaces at the same time. This method included separating a potential sliding mass into many vertical slices. Simultaneously with the construction of an improved version of the simple approach, the generalized process of slices, or GPS, was conceived of and implemented (Janbu 1973). In later years, Morgenstern-Price (1965), Spencer (1967), Sarma (1973), and a number of other researchers made further contributions using a variety of underlying assumptions for the interslice forces. Chugh (1986) came up with an approach called general limit equilibrium (GLE), which was an extension of the Spencer and Morgenstern-Price methods that satisfied both moment and force equilibrium requirements (Krahn 2004, Abramson et al. 2002). The following section provides an overview of these recent advancements and seeks to identify the primary distinctions that exist between the many methods that may be used to determine FOS.

2.4.3.1 Ordinary method

When applied to a circular slip surface, the Ordinary Method (OM) achieves moment equilibrium, but fails to account for the interslice normal and shear forces (Figure 2.10). Since iteration is not required to solve the FOS, this technique has the benefit of being simple. The moment equilibrium equation used to calculate the FOS (Abramson et al. 2002, Nash 1987).

$$F_m = \frac{\sum(C'l + N' \tan \varphi')}{\sum W \ \sin \alpha} \quad (2.19)$$

$$N' = (\mathrm{W} \ \cos \alpha - ul) \quad (2.20)$$

Here, u is the pore water pressure, l is the slice length and α slope of the slip surface.

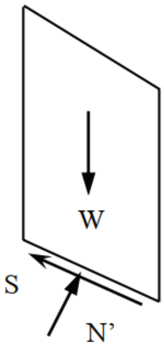


Figure 2.10: Slice of ordinary method (Aryal, 2006).

2.4.3.2 Bishop's simplified method

The Bishop's simplified method is widely used for circular shear surface analysis. In addition to interslice normal forces (E) (Figure 2.11), this technique takes into account the interslice normal forces (T) (Abramson et al. 2002). In addition, it fulfills vertical force equilibrium in order to compute the effective base normal force (N'), which is provided by the expression:

$$N' = \frac{1}{m_\alpha}\sum(W - \frac{c'l\sin\alpha}{F} - ul\cos\alpha) \tag{2.21}$$

$$m_\alpha = \cos\alpha\,(1 + \tan\alpha\frac{\tan\varphi'}{F}) \tag{2.22}$$

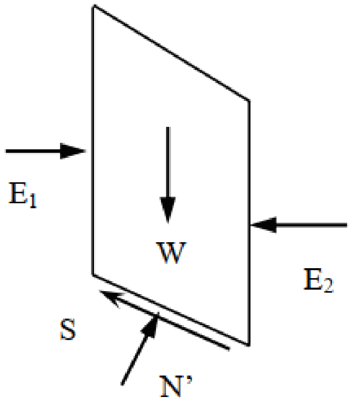


Figure 2.11: Slice of Bishop's and Janbu's simplified method (Aryal, 2006).

The procedures of calculation of force and moment equilibrium is discussed by Aryal (2006). The steps and equations of force equilibrium and moment equilibrium is discussed below (Figure 2.12 and Figure 2.13).

Force equilibrium

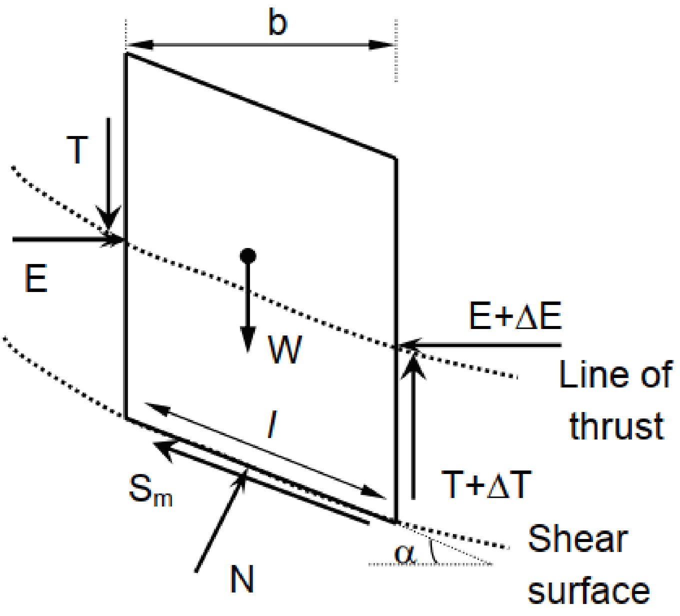


Figure 2.12: Internal forces acting on a slice (Aryal, 2006).

$$\sum F_h = 0 : S_m \cos\alpha - N\sin\alpha + \Delta E = 0 \tag{2.23}$$

Similarly,

$$\sum F_v = 0\ gives, W - \Delta T - S_m \sin\alpha - N\cos\alpha = 0 \tag{2.24}$$

Eliminating N from Eqns. (2.21) and (2.22),

$$S_m = (W - \Delta T)\sin\alpha + \Delta E\cos\alpha \tag{2.25}$$

Replacing $S_m = \frac{S_a}{F} = \frac{\tau_f l}{F}$ in Eqn. (2.23), the factor of safety for force equilibrium,

$$F = \frac{\sum \frac{\tau_f . l}{\cos\alpha}}{\sum (W - \Delta T).\tan\alpha + \sum \Delta E} \tag{2.26}$$

Where,

$$W = p.b, N = \sigma.l, \Delta T = t.b, b = l\cos\alpha \tag{2.27}$$

Putting the stress term in Eqn. (2.22), the normal stress,

Total normal stress, $\sigma = p - t\frac{\tau_f}{F}\tan\alpha$ (2.28)

Effective normal stress, $\sigma' = (p - u) - t\frac{\tau_f}{F}\tan\alpha = p' - t\text{-}\frac{\tau_f}{F}\tan\alpha$ (2.29)

Here, p is the total vertical stress, t is the interslice shear stress.

According to Mohr-Coulomb equation:

$$\tau_f = c' + \sigma'\tan\varphi' \tag{2.30}$$

Inserting the value of σ' from Eqn. (A.7) into Eqn. (2.28), the shear strength (τ_f):

$$\tau_f = \frac{(c' + (p - t - u)\tan\varphi')}{(1 + \tan\alpha\frac{\tan\varphi'}{F})} \tag{2.31}$$

Inserting τ_f from Eqn. (A.9) into Eqn. (A.4)) the factor of safety for force equilibrium becomes,

$$F = \frac{\sum\left\{\frac{b(c' + (p - t - u)\tan\varphi')}{n_\alpha}\right\}}{\sum\{b(p - t)\tan\alpha + \Delta E\}} \tag{2.32}$$

Where, $n_\alpha = cos^2\alpha(1 + \tan\alpha\frac{\tan\varphi'}{F})$ (2.33)

Similiarly, inserting τ_f from Eqn. (2.28) into Eqn. (2.24), in general terms, the factor of safety,

$$F_f = \frac{\sum[\{c'l + (N - ul)\tan\varphi'\}\sec\alpha]}{\sum\{W - (T_2 - T_1)\tan\alpha - \sum(E_2 - E_1)\}} \qquad (2.34)$$

Where, $N = \frac{1}{m_\alpha}\sum\left\{W - (T_2 - T_1) - \frac{1}{F}(c'l - ul)\tan\varphi' \sin\alpha\right\}$ (2.35)

Moment Equilibrium

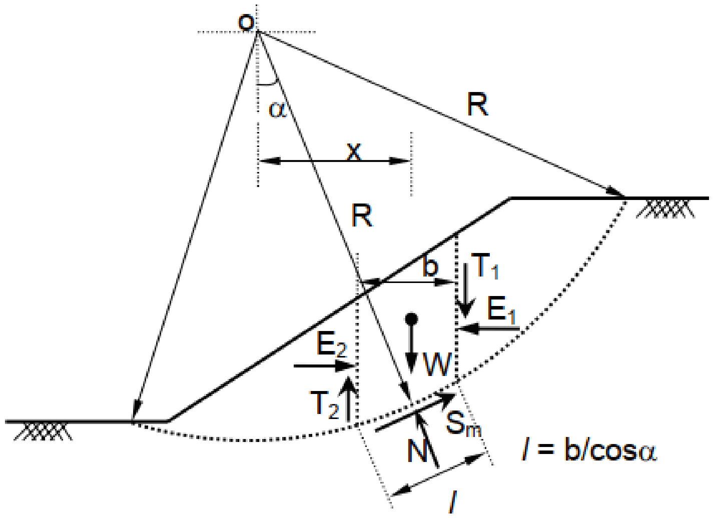


Figure 2.13: Analysis of circular slope for moment equilibrium (Aryal, 2006).

Considering the width of the slice very small, the interslice moments cancel each other.

$$\sum M_0 = 0: \ \sum R.S_m = \sum W.x \qquad (2.36)$$

By inserting

$S_m = \frac{S_a}{F} = \frac{l.\tau_f}{F}$, τ_f from Eqn. (2.29),$W = p.b \ and \ l = \frac{b}{\cos\alpha}$, the factor of safety (FOS) as:

$$F_m = \frac{R.\sum(\frac{b(c'(p-u)\tan\varphi')}{m_\alpha})}{\sum p.b.x} \qquad (2.37)$$

Where,

$$m_\alpha = \cos\alpha\ (1 + \tan\alpha\frac{\tan\varphi'}{F}) \qquad (2.38)$$

Here, u is the pore water pressure, P= W/b = total vertical stress, and α is the slope angle at the midpoint of the slice base.

Similarly, in terms of forces, the factor of safety equation can be written as:

$$F_m = \frac{\sum(c'l + (N - ul)\tan\varphi')}{\sum W \sin\alpha} \tag{2.39}$$

2.4.3.3 Janbu's methods

One of the most often used methods in stability analysis is the Janbu (1954, 1968) direct technique and the simplified method (GPS). The key distinctions between these two approaches are briefly discussed in the following paragraphs.

Janbu's simplified method

In this method, the factor of safety is calculated by horizontal force equilibrium and is based on a non-circular approach. Similar to Bishop's Simplified Method **(**Figure 2.11**)**, the approach only takes into account interslice normal forces (E) and ignores shear forces (T). In the same manner, the base normal force (N) is calculated. The FOS is calculated by,

$$F_f = \frac{\sum(c'l + (N - ul)\tan\varphi')\sec\alpha}{\sum W \tan\alpha + \sum \Delta E} \tag{2.40}$$

Where, $\sum \Delta E = E_2 - E_1$=net interslice normal forces.

The procedures of calculation of force and moment equilibrium is discussed in section 2.4.3.2.

Originally Janbu (1954) presented the factor of safety equations as below:

$$F_0 = \frac{\sum \frac{(b(c' + (p - u)\tan\varphi')}{n_\alpha}}{\sum p.b\tan\alpha} \tag{2.41}$$

$$n_\alpha = cos^2\alpha\ (\ 1 + \tan\alpha\frac{\tan\varphi'}{F}) \tag{2.42}$$

Where, b is the width of the slice, and W/b is the total vertical stress.

Janbu's Generalized Method

In order to establish a connection for interslice forces, Janbu's generalized method (JGM) (Janbu 1973) or Janbu's generalized process of slices takes into account both interslice forces and a line of thrust. Due to the interslice pressures, the FOS becomes a complicated function (Nash 1987):

$$F_f = \frac{\sum[\{c'l + (N - ul)\tan\varphi'\}\sec\alpha]}{\sum\{W - (T_2 - T_1)\tan\alpha - \sum(E_2 - E_1)\}} \tag{2.43}$$

The normal base force becomes a function of interslice forces (T):

$$N=\frac{1}{m_\alpha}\sum\left\{W-(T_2-T_1)-\frac{1}{F}(c'l-ul)\tan\varphi'\sin\alpha\right\} \tag{2.44}$$

The relationship between interslice forces (E and T) is:

$$T=\tan\alpha_t R-\frac{dE}{dx}h_t \tag{2.45}$$

Here, $\tan\alpha_t$ is the gradient of the thrust line, and the height from the midpoint of the slice base dE is h_t.

The procedures of calculation of force and moment equilibrium is discussed in section 2.4.3.2.

Janbu's direct method

The Janbu direct method (also known as JDM) relies on dimensionless parameters and a charting series to determine stability (Janbu 1954a). These charts provide a useful tool for doing slope stability analysis, which takes into account a variety of load circumstances including groundwater, surcharge, and tension fractures.The interslice forces are shown in Figure 2.14.

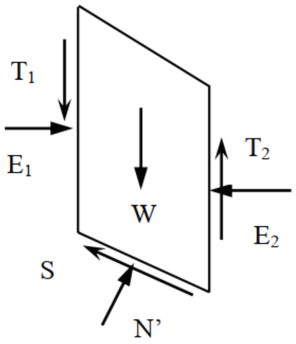


Figure 2.14: Slice of Janbu's generalized method (Aryal, 2006).

In addition to this, the approach may be used for evaluations of total as well as effective stress. It is possible to calculate the FOS for cohesive and frictional soils using the following formula (Janbu, 1954a, 1996):

$$F=N_{cf}\frac{c}{p_d},\ \lambda_{c\phi}=\frac{p_e\tan\phi}{c}\text{ and }p_e=(1-r_u)p_d \tag{2.46}$$

Where, $p_d=\gamma H$ =total stress, $p_e=$ effective stress, $N_{cf}=$ stability number, which depends on dimensionless factor $\lambda_{c\phi}$ and $r_u=\frac{u}{\gamma z}$ = pore pressure ratio.

First the center of the critical circle is identified which is also the moment equilibrium point (Figure 2.15). The center is the function of the slope angle β and a dimensionless factor ($\lambda_{c\phi}$). Using Janbu's chart the factor of safety of a circular geometry can be calculated within short time.

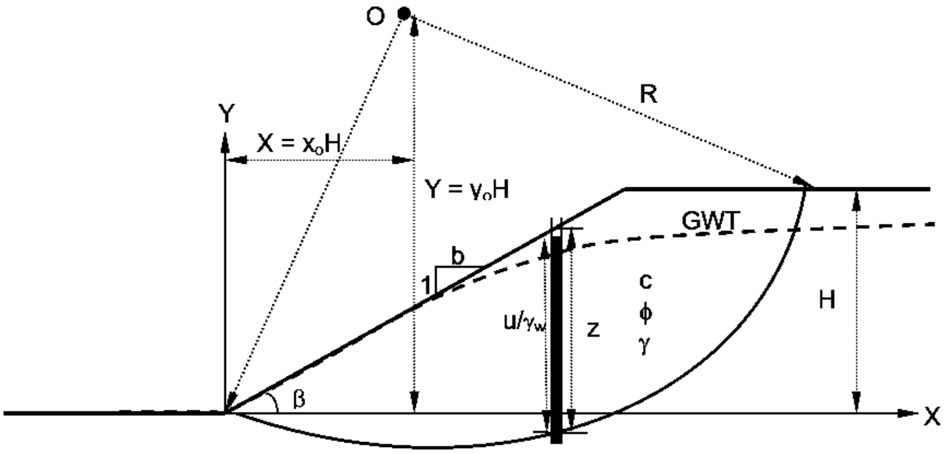


Figure 2.15: Slope geometry for Janbu's direct method (Aryal, 2006).

2.4.3.4 Sarma's method

Sarma (1973) presented a technique for a slice that is not vertical, as well as a method for universal blocks. It takes into account both the normal and shear forces that act between the slices, ensures that moment and force equilibrium are maintained, and establishes a relationship between the interslice forces using a quasi-shear strength equation.

$$T = ch + E\tan\phi \qquad (2.47)$$

Where, c, ϕ are shear strength parameters, and the slice height is h .In this method, the interslice forces are attuned until the factor of safety (FOS) for force and moment equilibrium is contented. The procedures of calculation of force and moment equilibrium is discussed in section 2.4.3.2.

The procedures of calculation of force and moment equilibrium is discussed in section 2.4.3.2.

2.4.3.5 Morgenstern-Price method

In addition to satisfying both force and moment equilibriums, the Morgenstern Price method (MPM) also considers the interslice force function. The method assumes any kind of force function, like half-sine, trapezoidal, or one that the user makes up. The relations for normal force (N) and the interslice forces (E, T) are same as Janbu's generalized method. As per MPM (1965), the angle of the interslice force may change with an arbitrary function (f(x)) as:

$$T = f(x).\lambda.E$$

F(x) is the arbitrary force function which varies along the slip surface.

$\lambda =$ Scale factor for assumed function.

$$F_f = \frac{\sum[\{c'l + (N - ul)\tan\varphi'\}\sec\alpha]}{\sum\{W - (T_2 - T_1)\tan\alpha - \sum(E_2 - E_1)\}} \quad (2.48)$$

$$\mathrm{N}=\frac{1}{m_\alpha}\sum\left\{W - (T_2 - T_1) - \frac{1}{F}(c'l - ul)\tan\varphi'\sin\alpha\right\} \quad (2.49)$$

2.4.3.6 Spenser's method

The only difference between MPM and Spencer's method (SM) is the assumption that is made about the interslice pressures. This technique takes into account both of the interslice forces, assumes that the interslice force function is constant, ensures that force and moment equilibrium are maintained, and calculates FOS in order to ensure that force and moment equilibrium are maintained. The interslice shear force is:

$$T = E\tan\theta \quad (2.50)$$

2.4.3.7 General limit equilibrium procedure

The global limit equilibrium (GLE) approach is an extension of Spencer and Morgenstern-Price techniques. In GLE, $tan\phi = \lambda.f(x)$ is used to calculate the interslice forces (Krahn 2004, Abramson et al. 2002). The GLE method is useful for comparing the most prevalent approaches in a FOS vs λ diagram, as seen in **Figure 2.16**, particularly for circular slip surface analysis.

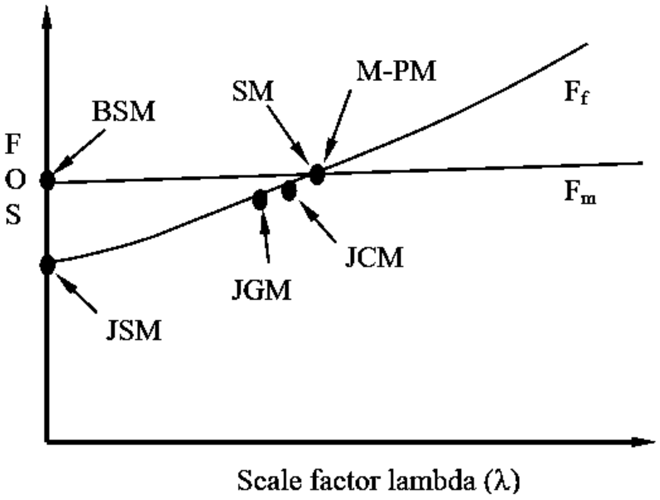


Figure 2.16: Comparison of most common limit equilibrium methods (Fredlund and Krahn 1977).

2.4.4 Summary of limit equilibrium methods

The fundamental distinction between the various LE techniques is in the manner in which the interslice normal (E) and shear (T) forces are calculated or assumed to exist. This is because all LE methods are predicated on particular assumptions for these forces. In addition to this, additional factors that go into the computation of the FOS include the form of the anticipated slip surface as well as the equilibrium circumstances. **Table 2.2** provides a synopsis of a selection of LE approaches together with the assumptions that underlie them.

2.5 Numerical Modeling Used for Stability Analysis

With the invention of computers, the computation facility has been improved in recent decades which had led to solve repetitive and complex engineering calculations within short time. Utilizing different computer-based geotechnical applications, slope stability assessments are done nowadays. For many years, software using LE formulations has been used. Similarly, interest in finite element (FE) software, which is based on different constitutive soil models, has increased among both scholars and professionals. Nowadays, in geotechnical calculations, both LE and FE-based tools are extensively used. The following sections provide a short introduction to the software utilized in this research, as well as its operating principles.

GeoStudio, Slope/W, Slide 2, Slide 3 PLAXIS LE, Geo5 are some of common limit equilibrium software commonly used for slope stability analysis. PLAXIS 2D, PLAXIS 3D, Abacus, RS 2, RS 3, are some common finite element based software used for slope stability analysis.

2.5.1 PLAXIS software

For the study of deformation, stability, and groundwater flow in geotechnical engineering, the finite element software PLAXIS was created. It is suite a finite element based program used globally for geotechnical engineering and design. The development of PLAXIS was initiated in 1987 at Delft University of Technology. Further the development was initiated to upgrade the software as a comprehensive three-dimensional finite element software that combines a user-friendly interface with comprehensive 3D modeling capabilities. In 2010 PLAXIS 3D was released with capabilities of three dimensional modeling (Brinkgreve, et al., 2016).

Table 2.2: Summary of LE methods (Abramson et al. 2002, Nash 1987)

Methods	**Circular**	**Non-circular**	**∑M = 0**	**∑F = 0**	**Conditions of for E and T**
Ordinary	✓	(*)	√	(**)	Neglects both T and E
Simplified Bishop method		-	√	-	Neglects T, but considers E
simplified Janbu method	(*)	√	-	√	neglects T but considers E
Janbu's generalized procedure of slices	√	√	(***)	√	Considers both T and E
Lowe-Karafiath	-	√	-	√	Resultant gradients at, θ = ½(α + β)
Corps of Engineers	-	√	-	√	Resultant gradients at, θ = ½(α*1* + α_2)
Sarma's method	√	√	✓ √	√	Interslice shear, T ch E = + tan*φ*
Spencer's method	√	(*)	✓ √	√	Constant inclination, T =tanθ E
Morgenst.-Price method	√	√	✓ √	√	Defined by f(x), T = f(x).λ .E

(*) Can be used to failure surfaces that are circular as well as those that aren't circular,

(**) fulfills the requirements of vertical force equilibrium for base normal force, and

(***)meets the condition of moment equilibrium for intermediate thin slices (Janbu 1957, Grande 1997)

2.5.2 GEO5 software

GEO5 software includes a number of applications for evaluating soil and rock slopes, dams, and freshly constructed embankments. This software's Slope Stability application is used to do slope stability analysis (embankments, earth cuts, anchored retaining structures, MSE walls, etc.). The slip surface is classified as circular (Bishop, Fellenius/Petterson, Janbu, Morgenstern-Price, or Spencer techniques) or polygonal (Bishop, Fellenius/Petterson, Janbu, Morgenstern-Price, or Spencer methods) (Sarma, Janbu, Morgenstern-Price or Spencer methods (GEO5 Software, n.d.).

2.5.3 GeoStudio software

GEO-SLOPE International, Canada, has developed GEOSLOPE based on the idea of limit equilibrium, which integrates a finite element approach created specifically for the deformation and stability of embankment constructions. It includes stability modeling with (SLOPE/W), seepage modeling with (SEEP/W), stress and deformation modeling with (SIGMA/W), dynamic modeling with (QUAKE/W), thermal modeling with (TEMP/W), containment modeling with (CTRAN/W), and vadose zone modeling with (VADOSE/W). The "Morgenstern technique" was used to SLOPE/W and SEEP/W to conduct the stability analysis. It is built and developed as a generic software tool for analyzing the stability of earth constructions (Devi and Anbalagan, 2017).

2.6 Constitutive Soil Models in PLAXIS

PLAXIS is a geotechnical tool for simulating soil properties. Different soil models and model parameters are used in PLAXIS to quantify the soil properties. There are seven different soil models in PLAXIS. These models include Linear Elastic (LE), Mohr-Coulomb (MC), Hardening Soil (HS), Hardening Soil with Small-Strain Stiffness (HS small), Soft Soil (SS), Soft Soil Creep (SSC), Modified Cam-Clay (MCC), and NGI ADP. Summary of applicability of soil models for different purposes are presented in Table 2.3.

Table 2.3: Applicability of soil models for different types of soil (PLAXIS, 2020)

Model	**Concrete**	**Rock**	**Gravel**	**Sand**	**Silt**	**OC clay**	**NC clay**	**Peat(org)**
Linear Elastic	C	C						
Mohr Coulomb	B	B	C	C	C	C	C	C
Hardening soil model			B	B	B	B		
HS small model			A	A	A	A	B	
UBC3D PLM			B*	B*	B*			
Soft Soil creep							A*	A*
Soft soil model							A*	A*
Jointed rock		A**						
Modified Cam-Clay							C	C
NGI-ADP model						A*	A*	A*
UDCAM-S model						A*	A*	A*
Hoek Brown		A**						
Concrete model	A							

A : The best standard model in PLAXIS for this application

B : Reasonable modelling

B : Reasonable modelling

* : Soft Soil Creep model in case time-dependent behavior is important; UBC3D-PLM model for dynamic analysis of sandy soils involving liquefaction

* : NGI-ADP model for short-term analysis and UDCAM-S model for cyclic analysis, in case only undrained strength is known

** : Jointed Rock model in case of anisotropy and stratification; Hoek-Brown model for rock in general

2.6.1 Mohr Coulomb (MC) model

The MC model combines Hooke's equation of linear isotropic elasticity with the extended Coulomb's failure criteria to create an elastic perfectly-plastic model. The soil is supposed to act as a linear elastic-perfectly plastic material in the Mohr-Coulomb yield surface. Figure 2.17 and Figure 2.18 present the fundamental concept of an elastic perfectly plastic model and Table 2.4 presents the Mohr-Coulomb yield surface in principal stress space.

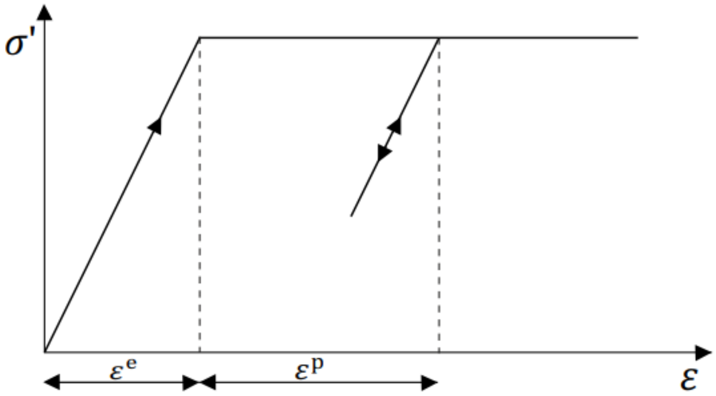


Figure 2.17: The fundamental concept of an elastic perfectly plastic model (PLAXIS, 2020).

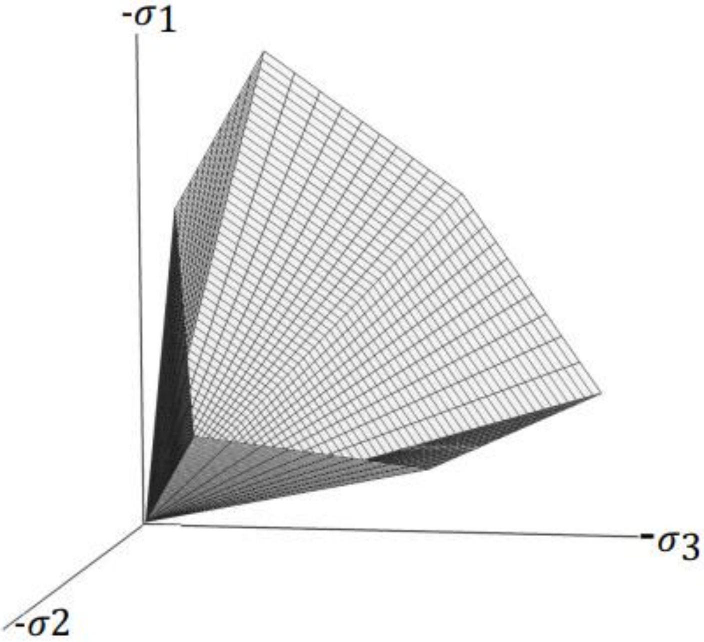


Figure 2.18: The Mohr-Coulomb yield surface in principal stress space (c = 0) (PLAXIS, 2020).

Table 2.4: Basic parameters of the Mohr-Coulomb model (after PLAXIS, 2020).

Symbol	Name of the parameter	Unit
E	Young's modulus	[kN/m^2]
ϑ	Poisson's ratio	[-]
C	Cohesion	[kN/m^2]
φ	Friction angle	[°]
ψ	Dilatancy angle	[°]
σ_t	Tension cut-off and tensile strength	[kN/m^2]
G	Shear modulus	[kN/m^2]
E_{oed}	Oedometer modulus	[kN/m^2]
V_p	Compression wave velocity	[m/s]
V_s	Shear wave velocity	[m/s]

2.6.2 Hardening Soil (HS) model

Hardening Soil Model is a real second-order soil model that can be used for any kind of soil application. The model involves shear hardening to model the irreversible plastic shear strain in deviatoric loading, and compression hardening to model the irreversible volumetric strain in primary compression in oedometer loading and isotropic loading. Failure is defined by means of the Mohr-Coulomb failure criterion. In the model, the total strains are calculated using a power-law formulation stress-dependent stiffness similar to what is used in the Duncan-Chang hyperbolic model. For loading, unloading and reloading, different stiffness moduli are used. It is assumed that hardening is isotropic, and this depends on the plastic shear and volumetric strains. When it comes to frictional hardening, a non-associated flow rule is used. When it comes to cap hardening, an associated flow rule is used. The HS Model is better than the hyperbolic model because it uses the theory of plasticity instead of the theory of elasticity. Figure 2.19 presents the relationship of Stiffness parameters of the Hardening Soil model with small-strain stiffness, and Table 2.5 presents the required parameters for the HS Model.

Table 2.5: Basic parameters for the HS Model (after PLAXIS, 2020).

Symbol	Name of the parameter	Unit
ϑ_{ur}	Unloading/ reloading poisson's ratio	[-]
c'	Cohesion	[kN/m^2]
φ'	Internal friction angle	[°]
ψ	Dilatancy angle	[°]
E_{50}^{ref}	Reference secant stiffness from drained triaxial test	[kN/m^2]
E_{oed}^{ref}	Reference tangent stiffness for oedometer	[kN/m^2]
E_{ur}^{ref}	Reference unloading/reloading stiffness	[kN/m^2]
R_f	Failure ratio	[-]
K_0^{nc}	Coefficient of earth pressure at rest (NC state)	[-]

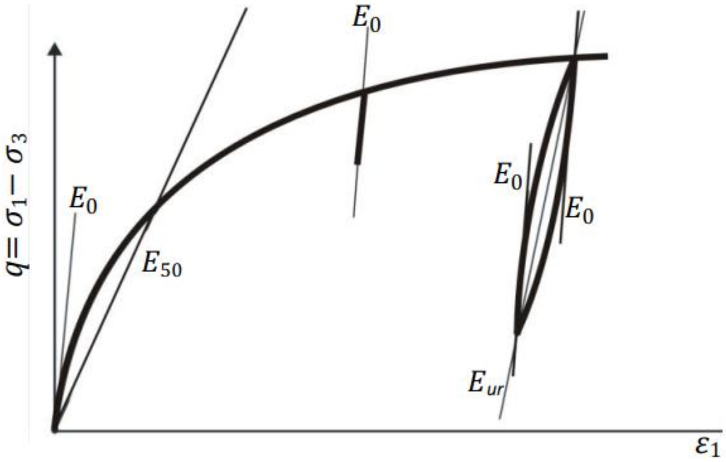


Figure 2.19: Stiffness parameters of the Hardening Soil model with small-strain stiffness in a triaxial test stiffness in a triaxial test (PLAXIS, 2020).

2.6.3 Soft Soil model

The Soft Soil model is a Cam-Clay type model especially meant for primary compression of near normally consolidated clay-type soils. Most soft soil problems can be analyzed using The Hardening Soil (HS) model, but the Hardening Soil model is not suitable the soil is very soft, with a high compressibility ($E_{oed}^{ref}/E_{50}^{ref} < 0.5$). For such soils, the Soft Soil model may be used. Figure 2.20 presents the total yield contour of Soft Soil model in principal stress space and Table 2.6 presents the parameters of the Soft Soil model.

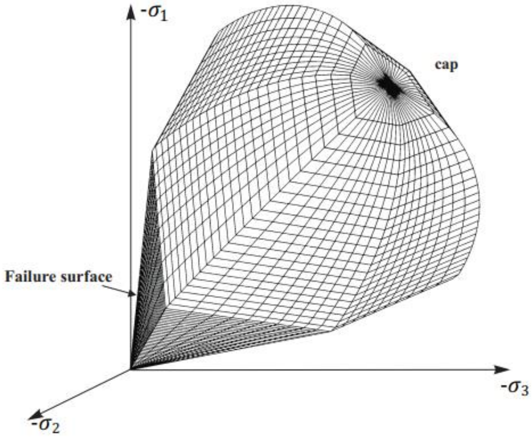


Figure 2.20: Soft Soil model total yield contour representation in major stress space (PLAXIS, 2020).

Table 2.6: Basic parameters for Soft Soil Model (PLAXIS, 2020).

Symbol	**Name of the parameter**	**Unit**
C	Cohesion	[kN/m^2]
φ	Friction angle	[°]
c_c	Compression Index	[-]
c_s	Swell Index	[-]
ψ	Dilatancy angle	[°]

2.7 Estimation of Soil Parameters for PLAXIS Modeling

The most important step of numerical modeling is to define the soil strength parameters. When laboratory investigation results are available, geotechnical characteristics of soil are estimated from the laboratory results; however, if the results are not available for some parameters for some locations, the strength parameters can be estimated from empirical correlations.

2.7.1 Young’s Modulus (E)

Young's modulus is a fundamental stiffness modulus that correlates soil stress and strain. It is designed to withstand uniaxial loading. In general, the secant modulus at 50% strength, abbreviated as E_{50}, is appropriate for soil loading circumstances. In bi-linear stress-strain relationships, it is a constant (Figure 2.21).

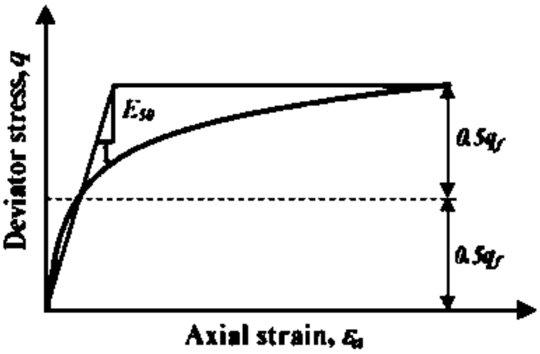


Figure 2.21: Definition of E_{50}.

2.7.2 Poisson's ratio($\boldsymbol{v}$)

In the loading situation, the drained Poisson's ratio of soils varies from 0.3 to 0.4. (Bowles 1988). The values for unloading are between 0.15 and 0.25. The undrained Poisson's ratio is 0.5 for an undrained state. The suggested Poisson's ratio for different types of soil is presented in Das (2017), it is presented in Table 2.7.

Table 2.7: Representative Values of Poisson's Ratio (after Das, 2017).

Type of soil	**Poisson's ratio ($\boldsymbol{v}$)**
Loose sand	0.2-0.4
Medium sand	0.25-0.4
Dense sand	0.3-0.45
Silty sand	0.2-0.4
Soft clay	0.15-0.25
Medium clay	0.2-0.5

According to Bishop and Hight (1977), one of the main issues connected with measuring Poisson's ratio is the high degree of precision with which measurements of strain and/or the calibration relationship must be made. In this case study, the suggestions in the PLAXIS Material Model handbook are followed in order to be consistent with the PLAXIS formulation.

2.7.3 Shear strength parameters

Shear strength parameters, cohesion(c) and angle of friction (φ), can be determined in laboratory by tri-axial test, unconfined compression test and direct shear test, depending on the soil type and purpose.

Wolff (1989) approximated the friction angle (φ') as below:

$$\varphi' = 27.1+0.3\mathrm{N}_{60} - 0.00054\ \mathrm{N}_{60}{}^{2} \qquad (2.51)$$

Hatanaka and Uchida (1996) suggested correlation between SPT N_{60} and angle of friction (φ') as below,

$$\varphi' = \sqrt{20\ \mathrm{C_N N_{60}}} + 20 \qquad (2.52)$$

Das, et al. (2017) suggested correlation between SPT N_{60} and angle of friction (φ') as below,

$$\varphi' = 0.7\ \mathrm{N}_{60} + 18.0 \qquad (2.53)$$

The unconfined compression of cohesive soil,

$$c_u = \frac{q_u}{2} \qquad (2.54)$$

Table 2.8 presents the correlations between Consistency, N-value and Unconfined Compressive Strength of Cohesive Soils.

Table 2.8: Correlations between Consistency, N-value and Unconfined Compressive Strength of Cohesive Soils (after Terzaghi and Peck (1967) and Das et al. (2017))

N value	**Consistency**	**Unconfined Compressive Strength, q_u (kPa)**
0-2	Very Soft	<25
2-4	Soft	25-50
4-8	Medium Stiff	50-100
8-15	Stiff	100-200
15-30	Very Stiff	200-400
>30	Hard	>400

Hettiarachchi and Brown (2009) suggested correlation between $\mathrm{C_u}$ and N_{60} as below,

$$\mathrm{C_u/P_a}) = \alpha' \mathrm{N}_{60} \qquad (2.55)$$

Where, $P_a = 100$ kN/m^2; average $\alpha' = 0.041$Kpa

Kulhawy and Mayne (1990) suggested correlation between $\mathrm{C_u}$ and N_{60} as below,

$$(\mathrm{C_u/P_a}) = 0.06\mathrm{N}_{60} \qquad (2.56)$$

Urmi and Ansary (2017) suggested correlation between $\mathrm{C_u}$ and $\mathrm{N_{60}}$ for cohesive soil in Bangladesh as below,

$$\mathrm{C_u} = 9.1912\ \mathrm{N_{60}} - 12.637 \qquad (2.57)$$

After estimating the shear strength parameters of soil, the parameters are selected based on the local geology and experience.

2.7.4 Shear Wave Velocity (V_s) and Shear Modulus (G_{max})

Numerous research have been conducted that demonstrate the connection between soil geotechnical characteristics like standard penetration resistance and V_s. There have been studies that have taken into account soil types (gravel, sand, silt, or clay), as well as depth, fine soil content, and corrected or uncorrected standard penetration resistance. In almost all relationships have used the functional form as presents in equation 2.41 for shear wave velocity and equation 2.42 for shear modulus.

$$V_s = A * N^B \qquad (2.58)$$

$$G_{max} = \rho * V_s^2 \qquad (2.59)$$

Here V_s is shear wave velocity (m/s); N is SPT value; A and B are constant parameters accompanied by correlation coefficient R, G_{max} is shear modulus; ρ is soil mass density.

Anbazhagan, Kumar and Sitharam (2013) suggested correlation between $\mathrm{V_s}$ and N as below,

$$\mathrm{V_s} = 106.63 * \mathrm{N}^{0.39}\ \text{(m/sec) (Clayey Soil)} \qquad (2.60)$$

$$\mathrm{V_s} = 60.17 * \mathrm{N}^{0.56}\ \text{(m/sec) (Sandy Soil)} \qquad (2.61)$$

$$\mathrm{V_s} = 68.96 * \mathrm{N}^{0.51}\ \text{(m/sec) (All type Soil)} \qquad (2.62)$$

Rahman, Kamal and Siddiqua (2018) suggested correlation between $\mathrm{V_s}$ and N as below,

$$\mathrm{V_s} = 100.58 * \mathrm{N}^{0.341}\ \text{(m/sec) (Clayey Soil)} \qquad (2.63)$$

$$\mathrm{V_s} = 82.01 * \mathrm{N}^{0.3829}\ \text{(m/sec) (Sandy Soil)} \qquad (2.64)$$

$$\mathrm{V_s} = 97.3062 * \mathrm{N}^{0.3393}\ \text{(m/sec) (All type Soil)} \qquad (2.65)$$

Chatterjee, Choudhury (2013) suggested correlation between $\mathrm{V_s}$ and N as below,

$$V_s = 77.11 * N^{0.392}\ \textit{(m/sec) (Clay Soil)} \qquad (2.66)$$

$$V_s = 54.81 * \ N^{0.525} \textit{ (m/sec) (Silty Sandy)} \qquad (2.67)$$

$$V_s = 78.21 * \ N^{0.376} \textit{ (m/sec) (All type Soil)} \qquad (2.68)$$

Hossain and Ansary (2015) suggested correlation between $\mathrm{V_s}$ and N for Bangladesh soils as below,

$$V_s = 168 * \ 0.308 * N^{0.2638} * D^{0.2396} \text{ (m/sec)} \qquad (2.69)$$

(All type Soil)

Kramer (1996) suggested correlation between G_{max} and N_{60} as below,

$$\mathrm{G_{max}} = 15.56\mathrm{N_{60}}^{0.68} \text{ (Mpa)} \qquad (2.70)$$

Anbazhagan et al. (2012) suggested correlation between G_{max} and N_{60} as below,

$$\mathrm{G_{max}} = 15.09\ \mathrm{N_{1_{60}}}^{0.74} \text{ (Mpa)} \qquad (2.71)$$

(All soil excluding fine content)

$$\mathrm{G_{max}} = 6.02\ \mathrm{N_{1_{60}}}^{0.95} \text{ (Mpa)} \qquad (2.72)$$

All soil including fine content

Imami and Tonouchi (1982) suggested correlation between G_{max} and N_{60} as below,

$$\mathrm{G_{max}} = 17.26\mathrm{N_{60}}^{0.607}\text{(Mpa) (Aluvial Clay)} \qquad (2.73)$$

$$\mathrm{G_{max}} = 12.26\mathrm{N_{60}}^{0.611}\text{(Mpa) (Aluvial Sand)} \qquad (2.74)$$

$$\mathrm{G_{max}} = 14.126\mathrm{N_{60}}^{0.68}\text{(Mpa) (All type of Soil)} \qquad (2.75)$$

Ohsaki and Iwasaki (1973) suggested correlation between G_{max} and N_{60} as below,

$$\mathrm{G_{max}} = 14.946\mathrm{N_{60}}^{0.78}\text{(Mpa) (All type of Soil)} \qquad (2.76)$$

$$\mathrm{G_{max}} = 6.374\mathrm{N_{60}}^{0.94}\text{(Mpa) (Sandy Soil)} \qquad (2.77)$$

$$\mathrm{G_{max}} = 11.59\mathrm{N_{60}}^{0.76}\text{ (Mpa) (Intermediate Soil)} \qquad (2.78)$$

$$\mathrm{G_{max}} = 13.734\mathrm{N_{60}}^{0.71}\text{ (Mpa) (Cohesive Soil)} \qquad (2.79)$$

After estimating the mechanical characteristics of soil, the parameters are selected based on the local geology and experience.

2.7.5 Void ration and unit weight

Void ratio and unit weight of soil depend on looseness and types of soils. From 1-D consolidation test void ratio of soil can be estimated, and from specific gravity test and moisture content test unit weight of soil can be appraised. However, where such results are not available, those values can be anticipated based on available research works. Typical Void Ratio, Moisture Content, and Dry Unit Weight for Some types of Soils in a Natural State are presents in Table 2.9**.**

Table 2.9: Typical Void Ratio, Moisture Content, and Dry Unit Weight for Some types of Soils (after Das et al., 2017).

Type of Soil	**Void ration (e)**	**Moisture content (W %)**	**Dry Unit weight γ_d(kN/m^3)**
Loose angular-grained silty sand	0.65	25	16
Soft clay	0.9-1.4	30-50	11.5-14.5
Dense uniform sand	0.45	16	18
Stiff clay	0.6	21	17

2.7.6 Permeability of Soil

Permeability coefficient (k) can be determined in laboratory. Determination of permeability is sensitive and prone to error because of collected sample quality. In this research the permeability values for different types of soils have been selected from standard values available in PLAXIS 3D.

2.8 Drainage Conditions for PLAXIS Modeling

There are two methods for analyzing the short-term undrained behavior of cohesive soils: total stress analysis and effective stress analysis. In the effective stress analysis, pore water pressure and soil are considered independently, but in the total stress analysis, they are regarded as a unified unit. The total stress technique has the benefit of omitting the laborious necessity to anticipate the extra pore pressure for short-term undrained conditions in clay. If the extra pore pressure is known or can be reliably predicted, the short-term behavior of undrained soils can be expressed in terms of effective stress parameters.

Effective stresses are the main thing that determine how soils behave, regardless of how they drain (Brinch-Hansen and Gibson 1949; Schmertmann 1975). Janbu (1977) came to the conclusion that the effective stresses control how saturated clays behave when they don't drain for a short amount of time. Since effective stress, not total stress, controls how soil behaves, the parameters for total stress models should take into account how pore water pressure changes over time and how stress history affects the soil. In other words, the principle of effective stress should be fully defined in the parameters.

In PLAXIS 3D, there are four ways to model how an undrained soil behaves: Undrained Method A, B, C, and D. Combination MC model uses Methods A, B, and C that are not drained. The HS model uses Method D that hasn't been drained.
Methods A, B, and D use effective stiffness parameters to model how water behaves when it is not being drained. Method C uses total stress undrained stress stiffness parameters. Methods A and D use effective strength parameters, and Methods B and C use total stress undrained strength parameters. Table 2.10 presents summary of material behavior for different soil models.

Table 2.10: Summary of model analyses (after Rahman, 2019).

Undrained Method	**Material Behavior**	**Material model**	**Computed stresses**
A	Undrained (MC)	Mohr	Effective stress
B	Undrained (MC)	Mohr	Effective stress
C	Non-porous/ Drained (MC)	Mohr Coulomb	Total stress
D	Undrained (HS)	Hardening Soil	Effective stress and pore pressure
A	Undrained (SS)	Soft Soil	Effective stress

2.9 Cyclones and Storm Surges in Bangladesh

The storm surge associated with a major tropical cyclone is the greatest coastal catastrophe in the world due to the substantial loss of life and property. Bangladesh is a global hotspot for tropical cyclones (UNDP, 2004) In Bangladesh, cyclones and storm surges are a common occurrence. In pre-monsoon (April-May) or post- monsoon (October-November), practically all cyclones strike the coastal districts of Bangladesh. (Hoque, 1991; Khan, 1995; Debsharma, 2009; Dasgupta, 2011). According to estimates, Bangladesh accounts for 80–90% of global damages and 53% of all cyclone-related fatalities globally (Ali 1999; GoB, 2008).

In Bangladesh, the coastal zone of is the mostly suffered area for cyclone and storm surge. According to a report “Bangladesh Delta Plan 2100”, prepared by Bangladesh planning commission in 2014, from 1961 to 2013, the southern and western coastal zones were each damaged by 16.4 percent and 27.9 percent of the total damage. The Noakhali and Chittagong, including the eastern part of the Meghna estuary, receive about 26.2 percent of the cyclones of Bangladesh, while the southeastern coast of Cox's Bazar, Teknaf and neighboring areas, was hit by 18 percent. Among most 61 cyclones occurred between 1960 and 2009, including those in 1960, 1970, and 1991, the severe cyclones traveled through the Meghna estuary, the East Central Coast (Eastern Bhola, Noakhali and Chittagong). The result is reported in Table 2.11. Due to strong cyclonic wave action during this storm surge, water overtopped the coastal polders, broke, and undermined the embankment. Figure 2.22 illustrates the landfall direction of major cyclones in Bangladeshi coast during 1960-2009.

2.9.1 Major cyclones in Bangladesh with surge height

Bangladesh Meteorological Department (BMD) has kept the record of major cyclone and storm surges hit Bangladesh coastal region from 1960 to 2017. Table 2.12 presents the list of major cyclones Bangladesh faced during this time period.

Table 2.11: Distribution of Land-falling Cyclones in the Coast of Bangladesh (after Bangladesh Planning Commission, 2014).

SL No.	Coastal Region	Number of Tropical Cyclones hit the Coast	% of the Total Number of Tropical Cyclones
1	Sundarban coast (Satkhira, Khulna and Bagerhat) Central coast (Borguna, Potuakhali, Pirozpur, Barisal, Bhola	17	27.9%
2	Central coast (Borguna, Potuakhali, Pirozpur, Barisal, Bhola	10	16.4%
3	Meghna estuary, east central coast (Eastern Bhola, Noakhali and Chittagong)	16	26.2%
4	Southeastern coast (Southern Chittagong, Cox‘s Bazar and Teknaf)	18	29.5%
	Total	61	100.0%

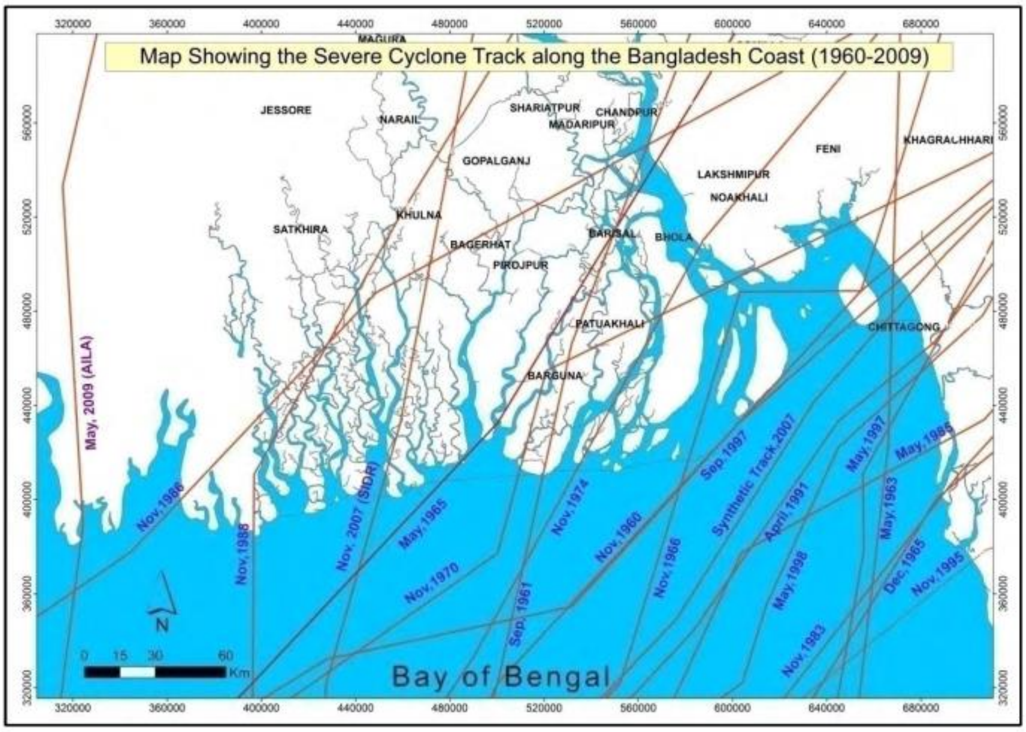


Figure 2.22: Landfall direction of major cyclones in Bangladeshi coast during1960-2009 (Source: IWM, 2013)

2.10 Surge depth and Thrust force for cyclones (Cyclone SIDR, Cyclone 1991)

Storm surges, in addition to claiming human lives, do serious damage to coastal infrastructures. Storm surges are caused by cyclonic winds and the related air pressure reduction. The main contributor is wind, which exerts a stress on the water surface that is proportional to the square of wind velocity. The resulting force exerted on the structures is an important measure in assessing the damage to coastal infrastructure. To estimate the thrust force and surge depth Akter, M. (2016), under the supervision of Dr. Anisul Haque, created an analytical model called Dynamic Force Model (DFM) by using the Variational Iteration Method to calculate the distributive thrust force produced by cyclonic wind and moving surge. They employed the Saint-Venant equations as governing equations, which are effectively 1D shallow water equations derived from the Navier-Stokes equations. The Flow field of DFM was validated by comparing the surge velocity that DFM calculated to the surge velocity that a numerical model, Delft3D.

After validation, the DFM was applied for the coastal zone of Bangladesh to compute thrust forces in the entire coastal zone for the following events: (1) Cyclone SIDR (2) 1991 cyclone (3) Hypothetical SIDR-like cyclone. Table A3 and Table A4 in Appendix A present the effect of Cyclone 1991 and Cyclone SIDR in different locations in coastal regions of Bangladesh.

Table 2.12: List of major cyclones in Bangladesh (1960 to 2017) (BMD, n.d.).

Date of Occurrence	Nature of Phenomenon	Landfall Area	Maximum Wind Speed in km/hr.	Direction of the Max. Wind Speed	Tidal Surge Height in ft.
11.10.60	Severe Cyclonic Storm	Chittagong	160	South-East	15
31.10.60	Severe Cyclonic Storm	Chittagong	193	South-East	20
09.05.61	Severe Cyclonic Storm	Chittagong	160	South-East	8-10
30.05.61	Severe Cyclonic Storm	Chittagong (Near Feni)	160	South-South-East	6-15
28.05.63	Severe Cyclonic Storm	Chittagong- Cox's Bazar	209	South-East	8-12
11.05.65	Severe Cyclonic Storm	Chittagong-Barisal Coast	160	South-South-East	12
05.11.65	Severe Cyclonic Storm	Chittagong	160	South-East	8-12
15.12.65	Severe Cyclonic Storm	Cox's Bazar	210	South-East	8-10
01.11.66	Severe Cyclonic Storm	Chittagong	120	South-East	20-22
23.10.70	Severe Cyclonic Storm of Hurricane intensity	Khulna-Barisal	163	South-West	-
12.11.70	Severe Cyclonic Storm with a core of hurricane wind	Chittagong	224	South-East	10-33
28.11.74	Severe Cyclonic Storm	Cox's Bazar	163	South-East	9-17
10.12.81	Cyclonic Storm	Khulna	120	South-West	7-15
15.10.83	Cyclonic Storm	Chittagong	93	South-East	-
09.11.83	Severe Cyclonic Storm	Cox’s Bazar	136	South-East	5
24.05.85	Severe Cyclonic Storm	Chittagong	154	South-East	15

Table 2.12 (contd.): List of major cyclones in Bangladesh (1960 to 2017) (BMD, n.d.).

Date of Occurrence	Nature of Phenomenon	Landfall Area	Maximum Wind Speed in km/hr.	Direction of the Max. Wind Speed	Tidal Surge Height in ft.
29.11.88	Severe Cyclonic Storm with a core of hurricane wind	Khulna	160	South-West	2-14.5
18.12.90	Cyclonic Storm	Cox's Bazar Coast	115	South-East	5-7
29.04.91	Severe Cyclonic Storm with a core of hurricane wind	Chittagong	225	South-East	12-22
02.05.94	Severe Cyclonic Storm with a core of hurricane wind	Cox's Bazar-Teknaf Coast	220	South-East	5-6
25.11.95	Severe Cyclonic Storm	Cox's Bazar	140	South-East	10
19.05.97	Severe Cyclonic Storm with a core of hurricane wind	Sitakunda	232	South-East	15
27.09.97	Severe Cyclonic Storm with a core of hurricane wind	Sitakunda	150	South-South-East	10-15
20.05.98	Severe Cyclonic Storm with a core of hurricane winds	Chittagong Coast near Sitakunda	173	South-South-East	3
28.10.00	Cyclonic Storm	Sundarban Coast near Mongla	83	South-South-West	-
12.11.02	Cyclonic Storm	Sundarban Coast near Raimangal River	65-85	South-South-West	5-7

Table 2.12(contd.): List of major cyclones in Bangladesh (1960 to 2017) (BMD, n.d.).

Date of Occurrence	**Nature of Phenomenon**	**Landfall Area**	**Maximum Wind Speed in km/hr.**	**Direction of the Max. Wind Speed**	**Tidal Surge Height in ft.**
19.05.04	Cyclonic Storm	Teknaf-Akyab Coast	65-90	South-East	2-4
15.11.07	Severe Cyclonic Storm with core of hurricane winds **(SIDR)**	Khulna-Barisal Coast near Baleshwar river	223	South-West	15-20
25.05.09	Cyclonic Storm **(AILA)**	West Bengal-Khulna Coast near Sagar Island	70-90	South-South-West	4-6
16.05.13	Cyclonic Storm **(MAHASEN)**	Noakhali-Chittagong Coast	100	South-South-East	-
30.07.15	Cyclonic Storm **(KOMEN)**	Chittagong-Cox's Bazar Coast	65	South-East	5-7
21.05.16	Cyclonic Storm **(ROANU)**	Barisal-Chittagong Coast near Patenga	128	West-South-West	4-5
30.05.17	Severe Cyclonic Storm**(MORA)**	Chittagong-Cox's Bazar	146	South-East	-

Chapter 3

DATA COLLECTION AND LABORATORY INVESTIGATION

3.1 Introduction

The first step to assessing any project's geotechnical stability is to identify the soil stratification in that particular region. In particular, the slope stability analysis of coastal embankments highly depend on the field factors such as the geometry of the slopes, soil characteristics of the earthen Polder embankments, and types and geotechnical characteristics of the underneath soil on which the Polders are built. In this chapter field and test programs performed for the study purpose are discusses. The geotechnical investigation results for different Polder embankments are summarized for numerical study for stability analysis.

3.2 Test Programs and Collection of Data

Several site visits were performed at Coastal regions of Bangladesh to cover the whole area where Polders have been built to protect the locality from the effect of storm surges during cyclones. The purpose of the visits was to carry out Standard Penetration Test (SPT) at different Polder locations in different areas. Soil samples (disturbed and undisturbed) were collected during geotechnical investigations. The geometry of the Polder embankments, based on field scenario, were drawn to model the Polders for stability analysis purposes. Meanwhile, from 2015 to 2018, Research Project on Disaster Prevention/Mitigation Measures against Floods and Storm Surges in Bangladesh, a joined collaboration research project between Kyoto University of Japan and Bangladesh University of Engineering and Technology (BUET), was done at Institute of Water and Flood Management (IWFM), BUET. The purpose of the project was to assess the geotechnical characteristics of Polder embankments in southern coastal region of Bangladesh. For the research purpose the Standard Penetration Test (SPT) was performed on the Polder embankments. The tests were performed at the center line of the embankment from top level. Relevent geotechnical parameters, necessary for embankment numerical modeling, are collected from Urmi (2019). Geotechnical characteristics of the Polder embankments are discussed later in this chapter.

3.2.1 Zonation of polders based on local geology

Ansary (1993) studied the geological characteristics of Bangladesh giving especial care to the coastal region. Bangladesh is a very flat delta region formed by the sediments of multiple rivers and the tributaries that feed into it. A multitude of overlapping sub-deltas of recent flood plain deposits make up the terrain. Ansary noted that the only exceptions are the Garo hills in the northern section of Mymensingh district, the Sylhet hills and hillocks, and the Chittagong Hill Tracts. Additionally, Comilla has a little section of hill called as Lalmai hill. Ansary noted the Coastal region comprising Barisal, Chittagong, Cox’s Bazar, Khulna, Noakhali and Patuakhali are underlain by floodplain and meandering deposits laid down by the rivers and their tributaries.

Based on Geological map (Figure 3.1) prepared by United States Geological Survey (USGS) (Persits, et al. 2001). It is clear that the geology of coastal Polders can be classified in several area. For the study purpose, based on surface geology the coastal region has been divided into seven regions. Region 1 comprises of Jessore, Satkhira, and Khulna district. The surface geology consist of tidal Deltaic deposits (dt), Deltaic silt (dsl), Mangrove swamp deposit (dsw), Marsh clay and peat (ppc). However, Deltaic silt deposit is prominent in this region. Region 2 includes Khulna, Bagherhat, Patuakhali, Pirojpur, Gopalganj, Barishal, and Barguna district. The surface geology of this region consist of tidal deltaic deposits (dt), Estuarine deposits (de), Deltaic silt (dsl), Mangrove swamp deposit (dsw), Marsh clay and peat (ppc). The most conspicuous deposit type of this region is tidal Deltaic deposits (dt). Region 3 is comprised of Bhola and Noakhali districts. The soil type of this region consist of Estuarine deposits (de), and Tidal mud (dm). Laxmipur and Noakhalui are included in Region 4. Deltaic deposits (dt), Chandina alluvium(ac), and Alluvial silt and clay (asc) are the constituents of this region. Particularly Feni district and Sitakunda, Patharghata, Mirsharai, and Sandwip of Chittagong district are included in Region 5. Beach and dune sand (csd), Boka Bil Formation (Tbb), Dupi Tila formation (QTdt), tipam Sandstone, Valley alluvium and colluvium (ava) are the deposits of this region. However the main deposit type is Beach and dune sand (csd). Chittagong port, Patiya, Anowara, patenga, Halishahar, Khulshi, Double Mooring of Chittagong district makes the Region 6. Beach and dune sand (csd), Boka Bil Formation (Tbb), Dihing and Dupi Tilaf (QTdd), Tipam Sandstone (Tt), Valley alluvium and colluvium (ava) are the deposits of this region. Region 7 is comprised of Pekua, Maheshkhali, Kutubdia , Cox'S Bazar Sadar, Chakaria Ramu, Ukhia Teknaf of Cox's Bazar district. Beach and dune sand (csd), The region consist of Boka Bil Formation (Tbb), Dihing and Dupi Tilaf (QTdd), Dupi Tila formation (QTdt), Tipam Sandstone (Tt), Valley alluvium and colluvium (ava), Estuarine deposits (de), and Tidal mud (dm) deposit. Table 3.1 to 3.7 present the zones and soil types of seven coastal regions.

3.2.2 Locations of the SPT tests

For this study purpose, the whole coastal region of Bangladesh has been divided into seven regions. From every region, one upgraded Polder, either by CERP or CEIP project, has been selected for the geotechnical assessment. Bhola, Barguna, Satkhira, Noakhali, Anwara (Chittagong), Laxmipur, Sitakunda (Chittagong), and Moheshkhali, previously severely affected Coastal districts of Bangladesh have been selected to assess the current conditions of the Polders after improvement. A brief description of the locations of study areas and the number of geotechnical investigations are presented below.

3.2.2.1 Location 1-Bhola

Bhola district is surrounded on the north by Lakshmipur and Barisal districts, on the south by Lakshmipur and Noakhali districts, on the east by the (lower) Meghna river and Shahbazpur Channel, and on the west by Patuakhali District and the Tetulia river. Three points have been selected for SPT tests in Bhola Polder. The points have been taken at interval of 0.50 km (500 m). The points are given in Table 3.8. While performing the tests the cross section of the Bhola Polder was approximated as Figure 3.2.

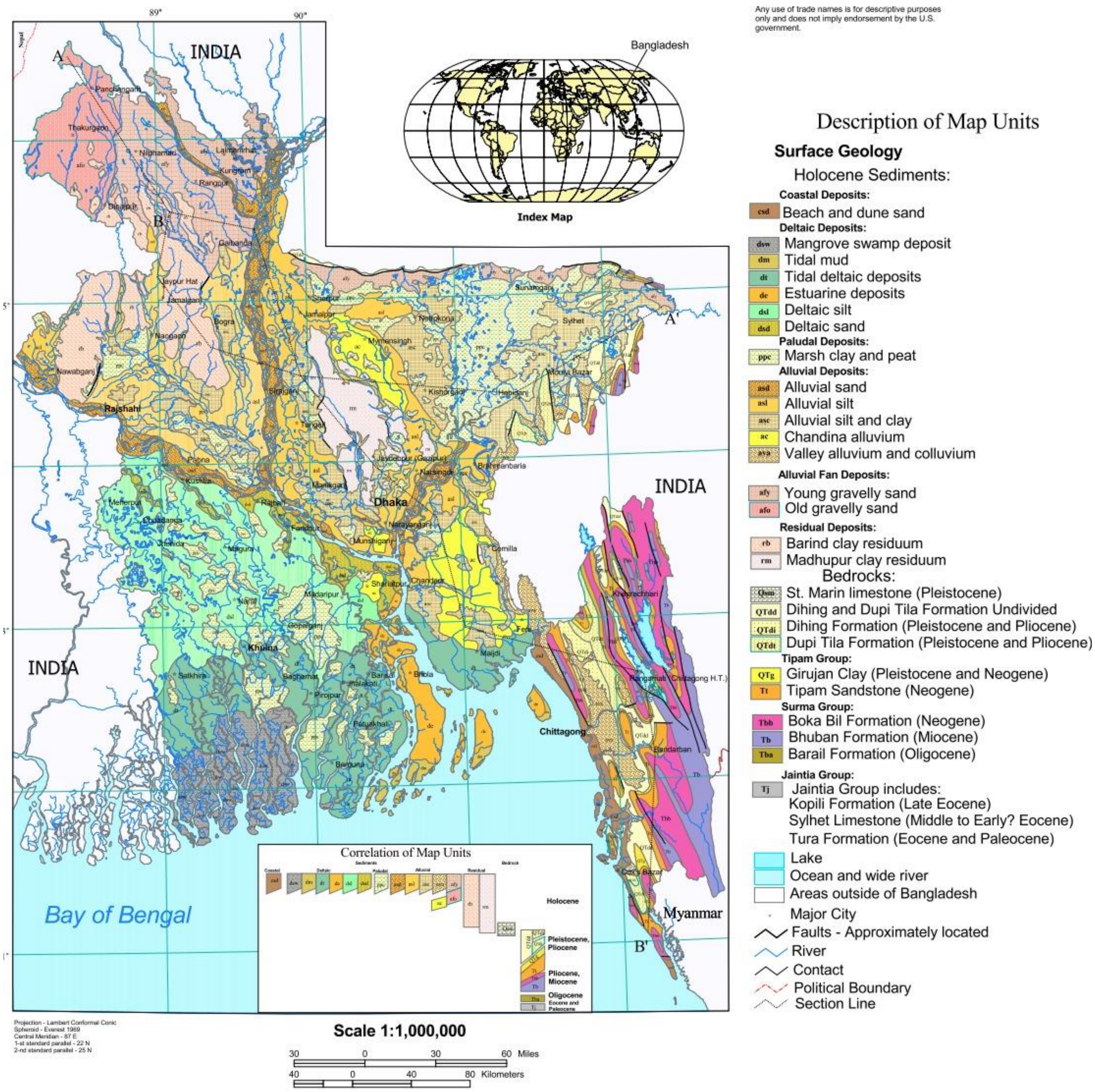


Figure 3.1: Geological map of Bangladesh (Persits, F.M., et al. 2001)

Table 3.1: Region 1 of the coastal Polder area

		Region 1				dsl Deltaic silt
District Name	**Name of Upozilla**	**Polder Number**				**Geology (Figure 3.1)**
Jossore	Keshabpur	24				dsl-ppc
Satkhira	Tala	6-08 Ext	6-8	16	25	dt
Satkhira	Satkhira Sadar	6-08 Ext	1	2	6-8	dt
Satkhira	Kalaroa	6-08 Ext				dsl
Satkhira	Debhata	1	3			dt
Satkhira	Assasuni	2	4	6-8	7/2	dt
Satkhira	Kaliganj	3	4	5		dt
Satkhira	Shyamnagar	5	7/1	15		dsl-dsw
khulna	Koyra	14/1	13-14/2	10-12		dsw-dt
khulna	Paikgachha	10-12	9	23	18/19	dt-ppc
		20	20/1	21	22	
khulna	Dumuria	17/1	17/2	26	29	dt-ppc
		27/1	27/2	25		
khulna	Batiaghata	29	28/1	28/2	30	ppc
		31	34/2			
khulna	Phultala	25				ppc-dsl
khulna	Khan Jahan Ali	25				dsl-dsd
khulna	Daulatpur	25	28/1			dsl-dsd
khulna	Khalishpur	28/1				dt-ppc
khulna	Dacope	31 (part)	32	33		dt-ppc

Table 3.2: Region 2 of the coastal Polder area

Region 2						dt Tidal deltaic deposits
District Name	**Name of Upozilla**	**Polder Number**				**Geology (Figure 3.1)**
Bagerhat	Mollahat	36/1				dt-dsl
Bagerhat	Chitalmari	36/1	36/2			dt-ppc
khulna	Rupsa	36/1	34/2			dt-ppc
Bagerhat	Fakirhat	36/1	34/1	34/2		
Bagerhat	Bagerhat Sadar	36/1	36/2	34/1	34/2	dt
		34/3	35/3	37		
Bagerhat	Kachua	36/2	37			dt-ppc
Bagerhat	Rampal	34/2	35/3	35/2		ppc
Bagerhat	Mongla	35/2				ppc-dsw
Bagerhat	Morrelganj	35/2	35/1	37		dt
Bagerhat	Sarankhola	35/1				dt-dsw
Pirojpur	Zianagar	37	38			dt-dsl
Pirojpur	Pirojpur Sadar	38				dt
Pirojpur	Bhandaria	39/2C				ppc-dt
Gopalganj	Kotali Para	SB-1				ppc
Barisal	Agailjhara	SB-2				dsl
Barisal	Wazirpur	SB-2	SB-3			dsl
Barguna	Patharghata	40/1	40/2	39/1A		dt
Barguna	Bamna	39/1 BandD	39/2A			dt-ppc
Pirojpur	Mathbaria	39/1 BandD	39/2A			dt-ppc
Barguna	Betagi	BCN	41/7A	41/7B		dt-ppc
Patuakhali	Mirzaganj	MRP	41/7			dt-ppc

Table 3.2(contd.): Region 2 of the coastal Polder area

District Name	Name of Upozilla	Polder Number				Geology (Figure 3.1)
Patuakhali	Dumki	ITL	DLK			dt-ppc
Patuakhali	Patuakhali Sadar	ITL	DLK	43/2A	43/2D	ppc-dt
		43/2E	55/2A			
Barguna	Barguna Sadar	41/6A	41/6B	41/1	41/2	dt
		41/3	41/4	41/5	42	
Barguna	Amtali	45	44	43/1	43/2F	ppc-dt
		43/1A				
Barguna	Kala Para	44	43/1B	46	47/3	dt
		47/4	47/5	47/1	48	
Patuakhali	Galachipa	43/2B	43/2C	55/1	55/2B	ppc-dt
		55/2C	55/2A	49	50-51	
Patuakhali	Dashmina	55/2C	55/2A	55/2D		ppc-dt
Patuakhali	Bauphal	55/2A	55/2E	55/2E	55/2D	dt-de

Table 3.3: Region 3 of the coastal Polder area

Region 3						de Estuarine deposits
District Name	**Name of Upozilla**	**Polder Number**				**Geology (Figure 3.1)**
Bhola	Char Fasson	56/57				de
Bhola	Lalmohan	56/57				de
Bhola	Manpura	58/1	58/2	58/3		de-dm
Bhola	Tazumuddin	56/57				de
Bhola	Burhanuddin	56/57				de
Bhola	Daulathkan	56/57				de
Bhola	Bhola Sadar	56/57				de
Noakhali	Hatiya	73/1A and 73/1B	73/2			de-dm

Table 3.4: Region 4 of the coastal Polder area

Region 4						dt Tidal deltaic deposits
District Name	**Name of Upozilla**	**Polder Number**				**Geology (Figure 3.1)**
Lakshmipur	Kamalnagar	59/2E	59/2	59/3A		dt
Lakshmipur	Ramgati	59/2E	59/3	59/3A		dt
Noakhali	Subarnachar	59/4	59/3A	59/3B		dt-ac
Lakshmipur	Lakshmipur Sadar	59/3A	59/1B			asc-ac
Noakhali	Noakhali Sadar (Sudharam)	59/3A	59/1B	59/3B	59/1A	asc-ac
		59/3C				
Noakhali	Begumganj	59/1B	59/1A			ac-asc
Noakhali	Kabirhat	59/3B	59/1A	59/3C		asc-ac
Noakhali	Companigonj	59/3B	59/1A	59/3C		ac-asc
Noakhali	Senbagh	59/1A				asc-ac

Table 3.5: Region 5 of the coastal Polder area

Region 5						csd Beach and dune sand
District Name	**Name of Upozilla**	**Polder Number**				**Geology (Figure 3.1)**
Feni	Daganbhuiyan		59/1A			ac-asc
Feni	Sonagazi		60			dt-ac
Chittagong	Sitakunda		61/1			Tbb-ava
Chittagong	Pahartali		62			csd-Tbb
Chittagong	Mirsharai		61/2			ava-Tbb
Chittagong	Sandwip		72			de-dm

Table 3.6: Region 6 of the coastal Polder area

Region 6						csd Beach and dune sand
District Name	**Name of Upozilla**	**Polder Number**				**Geology (Figure 3.1)**
Chittagong	Halishahar	62				csd-Tbb
Chittagong	Double Mooring	62				ava-Tt
Chittagong	Chittagong Port	62				csd-ava
Chittagong	Patenga	62				csd
Chittagong	Khulshi	62				ava-QTdt
Chittagong	Patiya	63/2				ava-Tt
Chittagong	Anowara	63/1A	63/1B			csd-ava
Chittagong	Banshkhali	64/1A	4/2A	4/1C	64/1B	csd-QTdd

Table 3.7: Region 7 of the coastal Polder area

Region 7						Tbb Boka Bil Formation (Neogene)
District Name	**Name of Upozilla**	**Polder Number**				**Geology (Figure 3.1)**
Cox's Bazar	Pekua	4/2A	64/2B			csd
Cox's Bazar	Maheshkhali	70	69			csd-QTdd
Cox's Bazar	Kutubdia	71	66/4			de-dm
Cox's Bazar	Chakaria	65	65/A-3	65/A	65/A-1	ava-QTdd
		66/4				
Cox's Bazar	Cox'S Bazar Sadar	66/3	66/2	66/1		Tbb-QTdt
Cox's Bazar	Ramu	66/2	66/2			Tbb-QTdt
Cox's Bazar	Ukhia	67/A				Tt-Tbb
Cox's Bazar	Teknaf	67	67/B			Tbb-csd

Table 3.8: Test points at Bhola

Sl. No.	**Test Points**	**Test Name**	**Latitude**	**Longitude**
01	Bhola -01	SPT	22^0 09’ 44” N	90^0 48’ 33.2” E
02	Bhola -02	SPT	$22^0$09’53.7” N	90^0 48’ 45.5” E
03	Bhola -03	SPT	$22^0$09’30.3” N	90^0 48’ 25.6” E

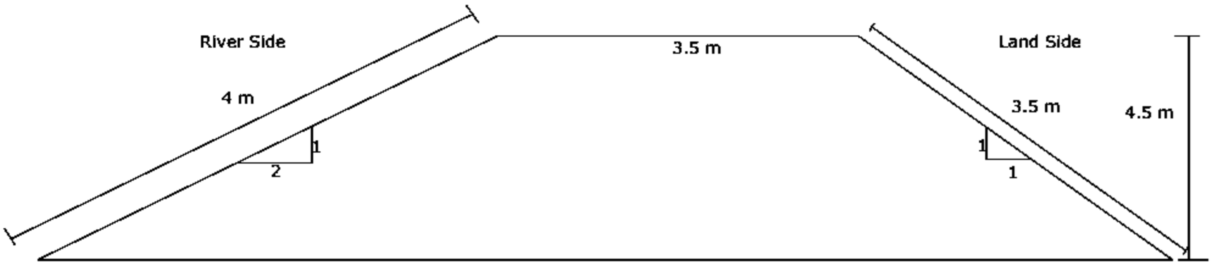


Figure 3.2: Geometry of the Bhola Polder

3.2.2.2 Location 2-Noakhali

Noakhali is bordered on the north by Comilla district, south by the Meghna River and the Bay of Bengal, east by Feni and Chittagong districts, and west by the west Lakshmipur and Bhola districts. Three points have been selected for SPT tests in Noakhali Polder. The points have been taken at interval of 0.50 km (500 m). The points are given in Table 3.9. While performing the tests the cross section of the Noakhali Polder was approximated as Figure 3.3.

Table 3.9: Test points at Noakhali

Sl. No.	Test Points	Test Name	Latitude	Longitude
01	Noakhali -01	SPT	$22^0$34’53.6” N	91^0 00’ 0.8” E
02	Noakhali -02	SPT	$22^0$35’2.8” N	91^0 00’ 13.5” E
03	Noakhali -03	SPT	$22^0$31’52.9” N	91^0 04’ 15.2” E

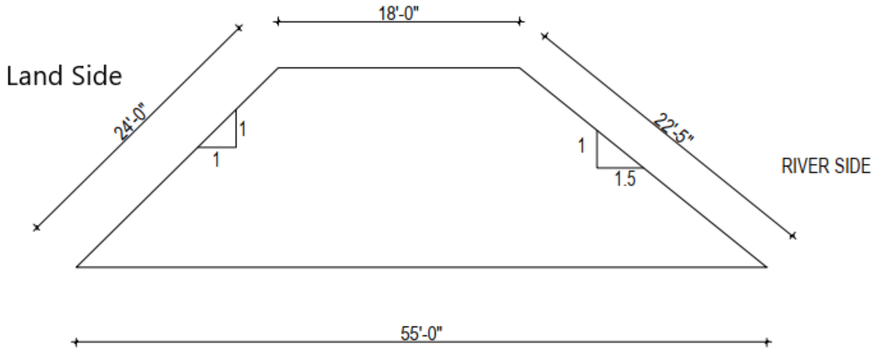


Figure 3.3: Geometry of the Noakhali Polder

3.2.2.3 Location 3-Barguna

Barguna is located on the south by Patuakhali and the Bay of Bengal. It borders Pirojpur and Bagerhat districts on the western side. The Paira River, Bishkhali River, Khakdon River, and Baleshwar River are all significant rivers in Barguna district. Three points have been selected for SPT tests in Barguna Polder. The points have been taken at interval of 0.50 km (500 m). The points are given in Table 3.10. While performing the tests the cross section of the Barguna Polder was estimated as Figure 3.4.

Table 3.10: Test points at Barguna

Sl. No.	Test Points	Test Name	Latitude	Longitude
01	Barguna-01	SPT	22.042910	90.074140
02	Barguna-02	SPT	22.047571	90.076729
03	Barguna-03	SPT	22.056064	90.107513

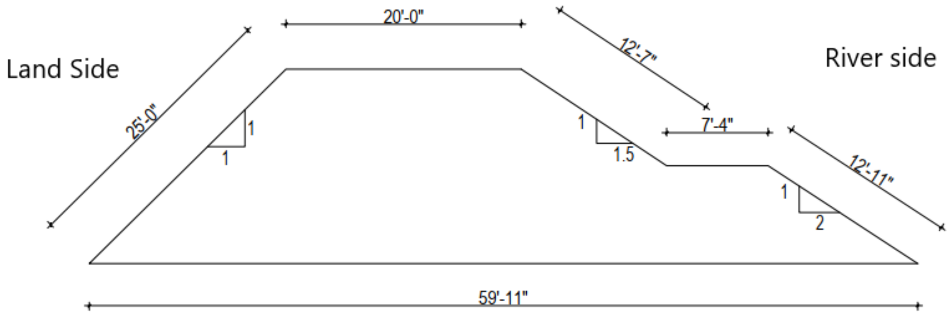


Figure 3.4: Geometry of the Barguna Polder

3.2.2.4 Location 4-Moheshkhali

Moheshkhali is the only hilly Island in Bangladesh. There is an ocean on one side and a mountain on another side. Three points have been selected for SPT tests in Moheshkhali Polder. The points have been taken at interval of 0.50 km (500 m). The points are given in Table 3.11. While performing the tests the cross section of the Moheshkhali Polder was approximated as Figure 3.5.

Table 3.11: Test points at Moheshkhali Polder

Sl. No.	Test Points	Test Name	Latitude	Longitude
01	Moheshkhali-01	SPT	21.508248	91.949500
02	Moheshkhali-02	SPT	21.508351	91.959400
03	Moheshkhali-03	SPT	21.723160	91.878071

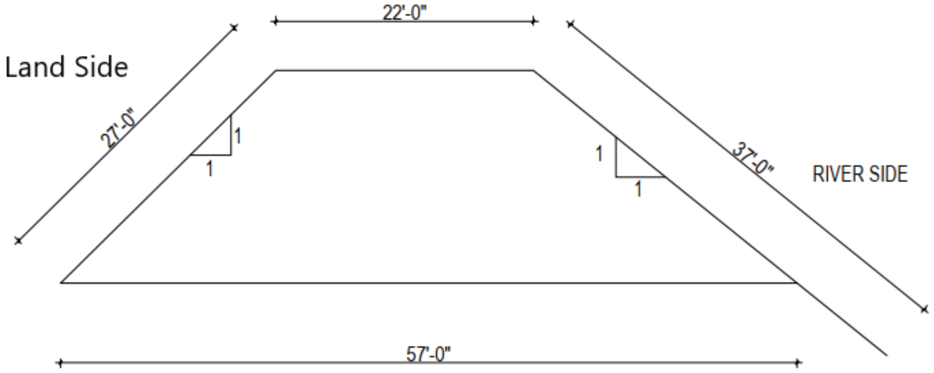


Figure 3.5: Geometry of the Moheskhali Polder

3.2.2.5 Location 5-Parki Beach, Anwara, Chittagong:

The Beach in Anwara Thana under southern Chittagong region is known as Parki Beach. It's about 28 km from Chittagong city and lies in the Karnafuli river channel. The main beach is about 15 km long. Two points have been selected for SPT tests in Anwara Polder. The points have been taken at interval of 0.50 km (500 m). The points are given in Table 3.12. While performing the tests the cross section of the Anwara Polder was approximated as Figure 3.6.

Table 3. 12: Test points at Parki Beach, Anwara, Chittagong

Sl. No.	Test Points	Test Name	Latitude	Longitude
01	Parki Beach, Anwara, Chittagong -01	SPT	22.164123	91.823521
02	Parki Beach, Anwara, Chittagong -02	SPT	22.159039	91.815539

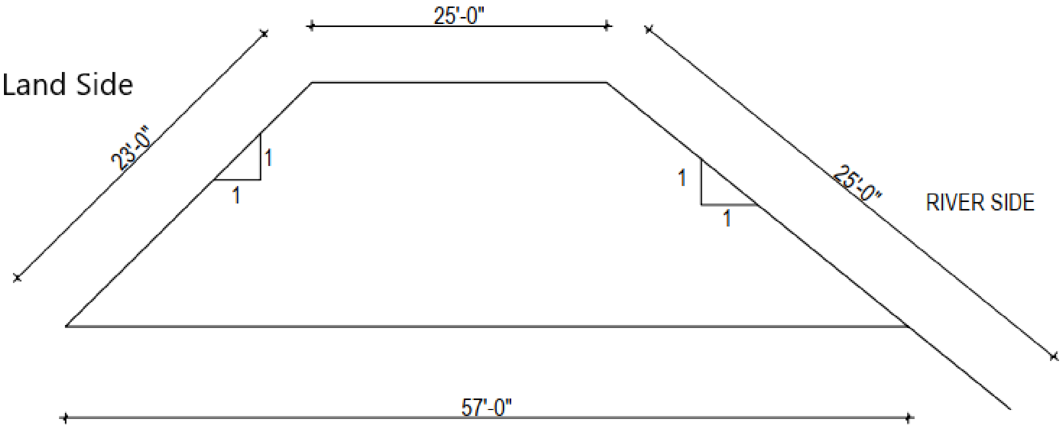


Figure 3.6: Geometry of the Anwara Polder

3.2.2.6 Location 6-Sitakunda, Chittagong

Sitakunda Upazila is located in the district of Chittagong. It is bordered on the north by mirsharai and fatikchhari upazilas, on the south by pahartali thana, on the east by Fatikchhari, hathazari upazilas, and panchlaish thana, and on the west by sandwip upazila and Sandwip channel. Two points have been selected for SPT tests in Sitakunda Polder. The points have been taken at interval of 0.50 km (500 m). The points are given in Table 3.13. While performing the tests the cross section of the Sitakunda Polder was approximated as Figure 3.7.

Table 3.13: Test points at Sitakunda Chittagong

Sl. No.	Test Points	Test Name	Latitude	Longitude
01	Sitakunda, Ctg-01	SPT	22.514576	91.684370
02	Sitakunda, Ctg-02	SPT	22.514454	91.687730

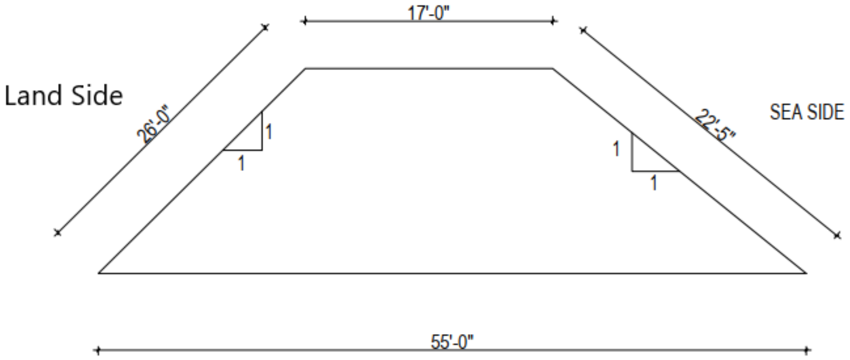


Figure 3.7: Geometry of the Sitakunda Polder

3.2.2.7 Location 7-Satkhira

It is bordered to the north by Jessore District, on the south by the Bay of Bengal, to the east by Khulna District. The main rivers are the Kopotakhi River across Dorgapur union of Assasuni Upazila, Morichap River, Kholpetua River, Betna River, Raimangal River, Hariabhanga river, Ichamati River, Betrabati River and Kalindi-Jamuna River. Three points have been selected for SPT tests in Satkhira Polder. The points have been taken at interval of 0.50 km (500 m). The points are given in Table 3.14. While performing the tests the cross section of the Satkhira Polder was approximated as Figure 3.8.

Table 3.14: Test points at Satkhira Polder

Sl. No.	Test Points	Test Name	Latitude	Longitude
01	Satkhira-01	SPT	22.153650	89.113440
02	Satkhira-02	SPT	22.152140	89.112520
03	Satkhira-03	SPT	22.4750430	88.9984910

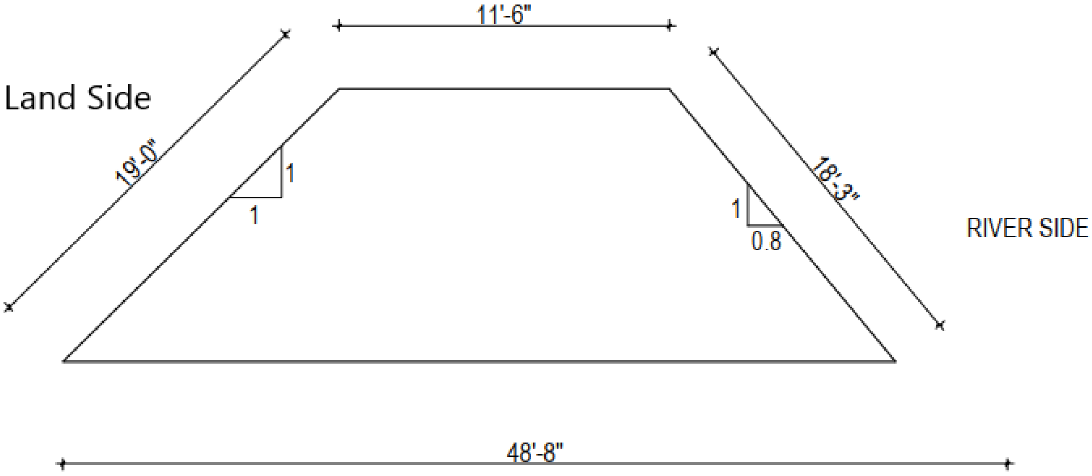


Figure 3.8: Geometry of the Satkhira Polder

3.2.3 Summary of Geotechnical Parameters of Coastal Embankments of Selected Polders

At each coastal region of Bangladesh SPT tests were performed. All the borelog reports of selected coastal embankments are presented in Appendix C. From all the selected coastal embankment of Polders soil samples, both disturbed and undisturbed, are collected for geotechnical investigations. Atterberg Limit tests, Consolidation test, Direct Shear test, Tri-axial Test, Grain Size analysis and other relevant studies in Geotechnical Engineering Laboratory of Bangladesh University of Engineering and Technology (BUET). The relevant geotechnical parameters for this study are summarized in Table 3.15(Urmi, 2019).

Table 3.15: Summary of Geotechnical Parameters of Coastal Polders (after Urmi, 2019)

Location	Depth (m)	Soil type	SPT N value (Average)	Liquid Limit (LL) (ω %)	Shear strength parameters from Consolidated Drained Direct Shear test		Shear strength parameters from Tri-axial Test		Compression Index and Swell Index from Consolidation test	
					Cohesion c′(kPa)	Angle of friction	Cohesion c′(kPa)	Angle of friction	C_c	C_s
Charfashion, Bhola (BH-01)	0m-4.5m	Clayey	5	37			20	5		
	4.5m-	Fine	6		6.8	31.2				
	10.5m-	Clayey	6							
Charfashion, Bhola (BH-	0m-	Silty	5	36			25	5	0.199	0.044
	10.5m-	Clayey	8		1.5	30.2				
Charfashion, Bhola (BH-	0m-4.5m	Clayey	4	33			22	5	0.206	0.003
	4.5m-	Fine	10		7.3	31.2				
	9m-	Clayey	5							
	16.5m-	Fine	10							
Charfashion, Bhola (BH-04)	0m-4.5m	Silty	5	32						
	4.5m-	Clayey	7							
	9m-21m	Fine	10		8	34.1				

Table 3.15 (contd.): Summary of Geotechnical Parameters of Coastal Polders (after Urmi, 2019)

Location	**Depth (m)**	**Soil type**	**SPT N value (Average)**	**Liquid Limit (LL) (ω %)**	**Shear strength parameters from Consolidated Drained Direct Shear test**		**Shear strength parameters from Tri-axial Test**		**Compression Index and Swell Index from Consolidation**	
Puraton Bad, Barguna (BH-01)	0m-7.5m	Silty	4	42			36	23.3		
	7.5m-	Fine	10		2.5	28.5				
	21m-30m	Fine	12							
Natun Bad, Barguna (BH-	0m-6m	Silty	4	39			28.5	27	0.182	0.028
	6m-10m	Fine	14		0	35				
	10m-30m	Fine	10							
Patharghata, Barguna (BH-03)	0m-10m	Silty	5	32			30	23	0.193	0.025
	10m-	Silty	2							
	19.5m-	Fine	12		4.5	36				
Patharghata, Barguna (BH-04)	0m-4.5m	Silty	5	41			46	34	0.202	0.016
	4.5m-	Silty	3							
	19.5m-	Fine	24		4	27.8				
	6m-10m	Fine	14							
	10m-30m	Fine	10							

Table 3.15 (contd.): Summary of Geotechnical Parameters of Coastal Polders (after Urmi, 2019)

Location	**Depth (m)**	**Soil type**	**SPT N value (Average)**	**Liquid Limit (LL) (*ω* %)**	**Shear strength parameters from Consolidated Drained Direct Shear test**		**Shear strength parameters from Tri-axial Test**		**Compression Index and Swell Index from Consolidation**	
Shaymnagar, Munshigang, Satkhira (BH-	0m-13.5m	Silty Clay	2	34			10	24	0.157	0.029
	13.5m-	Fine	8		8.1	23.9				
	16.5m-	Fine	25							
Shaymnagar, Munshigang, Satkhira	0m-4.5m	Silty	3				32	25	0.200	0.009
	4.5m-	Fine	5		6	23.6				
	16.5m-	Fine	25							
Kaliganj, Satkhira (BH-03)	0m-7.5m	Silty	1				12	23	0.157	0.029
	7.5m-18m	Fine	15							
	18m-30m	Fine	30							
Anowara,Chittagong (BH-01)	0m-3m	Silty	9	34			70	24.8		
	3m-9m	Silty	15		4.6	28.5				

Table 3.15(contd.): Summary of Geotechnical Parameters of Coastal Polders (after Urmi, 2019)

Location	**Depth (m)**	**Soil type**	**SPT N value (Average)**	**Liquid Limit (LL) (*ω* %)**	**Shear strength parameters from Consolidated Drained Direct**		**Shear strength parameters from Tri-axial Test**		**Compression Index and Swell Index from**	
Anowara,Chittagong (BH-01)	9m-12m	Silty	3							
	12m-	Silty	6							
	16.5m-	Fine	14				10	28.3		
Anowara,Chittagong (BH-02)	0m-3m	Silty	3	42						
	3m-9m	Silty	2		0	29.5			0.259	0.016
	9m-12m	Silty	2							
	12m-18m	Silty	3							
	18m-24m	Fine	20							
Ramgati, Laxmipur (BH-01)	0m-	Silty	4	33			25	36	0.186	0.016
	13.5m-	Fine	18		0.16	32.9				
	15m-18m	Clayey	8							
	18m-30m	Fine	25							
Ramgati, Laxmipur	0m-7.5m	Silty	5	37			45	26	0.188	0.032

Table 3.15(contd.): Summary of Geotechnical Parameters of Coastal Polders (after Urmi, 2019)

Location	**Depth (m)**	**Soil type**	**SPT N value (Average)**	**Liquid Limit (LL) (ω %)**	**Shear strength parameters from Consolidated Drained Direct**		**Shear strength parameters from Tri-axial Test**		**Compression Index and Swell Index from**	
	7.5m-18m	Fine	16		5.1	27.6				
	18m-30m	Fine	20							
Tanki Bazar, Laxmipur, Noakhali	0m-6m	Clayey	5							
	6m-15m	Clayey	20						0.17	0.004
	15m-30m	Fine	35		2.4	33.7				
Tanki Bazar, Laxmipur, Noakhali	0m-6m	Clayey	5	43						
	6m-12m	Fine	12		0	29.6				
	12m-25m	Fine	25							
Sitakunda (BH-01)	0m-3m	Sandy	9							
	3m-9m	Silty	5						0.186	0.016
	9m-25m	Fine	20							
Sitakunda (BH-02)	0m-3m	Clayey	14							
	3m-19.5m	Silty	4							
	19.5m-	Fine	20							

Table 3.15(contd.): Summary of Geotechnical Parameters of Coastal Polders (after Urmi, 2019)

Location	**Depth (m)**	**Soil type**	**SPT N value (Average)**	**Liquid Limit (LL) (*ω* %)**	**Shear strength parameters from Consolidated Drained Direct Shear test**		**Shear strength parameters from Tri-axial Test**		**Compression Index and Swell Index from Consolidation**	
Moheskhali Sadar (BH-01)	0m-4.5m	Silty	5	29			40	23	0.239	0.013
	4.5m-9m	Fine	10		0.64	28.9				
	9m-10.5m	Dense	50							
Moheskhali Sadar (BH-02)	0m-3m	Clayey	7	32			78	32	0.188	0.144
	3m-6m	Fine	10		2.6	29.7				
	6m-9m	Fine	25							
	9m-10.5m	Dense	50							

Some mechanical properties of soils are necessary for the PLAXIS model of Polders. Determination of those properties are out of scope of the geotechnical investigation programs. For this reasons, necessary parameters for modeling purpose are determined based on empirical correlations based on SPT N value. The correlations are discussed in Chapter 2. Necessary model parameters for the study area are summarized in **APPENDIX B**.

Chapter 4

NUMERICAL MODELING AND ANALYSIS

4.1 Introduction

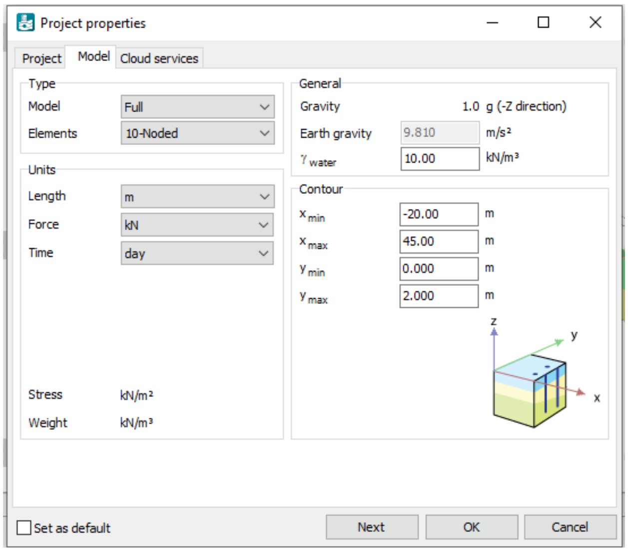
In this chapter, the different steps of PLAXIS 3D numerical modeling, basics of different constitute soil models, reason of selecting soil models for earth embankment stability and deformation analysis, parametric study, and validation of numerical embankment method are discussed. In the first part of this chapter the embankment model is validated with a real project and then all the coastal Polder embankment projects are analyzed for deformation and safety status calculation for different conditions the Polders face during cyclonic storm surges.

4.2 Steps of numerical modeling of earth embankment in PLAXIS

Plaxis3D is a finite element based software which enabled the graphical input processes for the rapid production of complicated finite element models, while the expanded output capabilities allow for the full display of computational findings. To analyze the safety and deformation of embankments, the model has to be generated and analyzed following some steps. In this section, the steps for creating model and analysis for the Bhola Polder embankment is presented.

4.2.1 Creating new project

In this step, the units, dimensions of the project (length and width) is specified

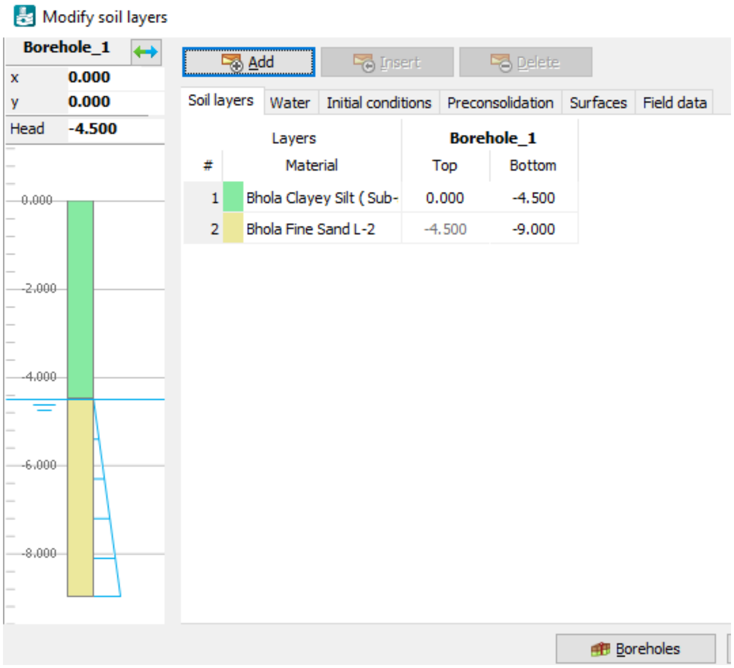


Model: Full
Elements: 10-Noded
Length: m
Force: kN
Time: day
Stress: kN/m²
Weight: kN/m³
Gravity: 1.0 g (-Z direction)
Earth gravity: 9.810 m/s²
γ_{water}: 10.00 kN/m³
x_{min}: -20.00 m
x_{max}: 45.00 m
y_{min}: 0.000 m
y_{max}: 2.000 m
☐ Set as default

Figure 4.1: Creation of Bhola Polder embankment.

4.2.2 Defining the soil stratigraphy

In this step the subsurface soil stratigraphy and borehole water level are defined based on field observation.



Borehole_1

x 0.000

y 0.000

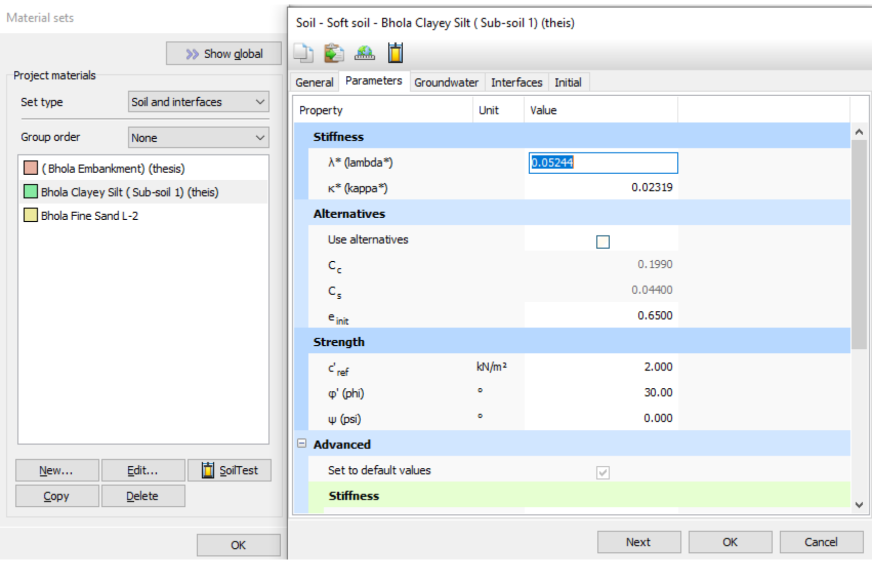
Head -4.500

	Layers	Borehole_1	
#	Material	Top	Bottom
1	🟩 Bhola Clayey Silt (Sub-	0.000	-4.500
2	🟨 Bhola Fine Sand L-2	-4.500	-9.000

Figure 4.2: Defining Soil stratigraphy for Bhola Polder embankment.

4.2.3 Creating and assigning the material data sets

In this step materials are defined based on field and laboratory test results. The basis for selecting material models for different types of soil is discussed in later part of this chapter.



Project materials

Set type: Soil and interfaces

Group order: None

🟥 (Bhola Embankment) (thesis)
🟩 Bhola Clayey Silt (Sub-soil 1) (theis)
🟨 Bhola Fine Sand L-2

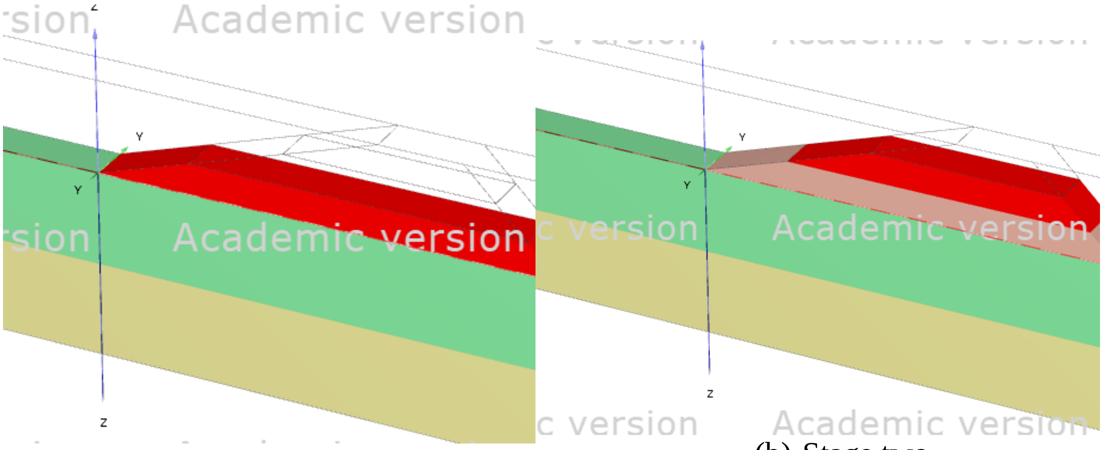
Soil - Soft soil - Bhola Clayey Silt (Sub-soil 1) (theis)

Property	Unit	Value
Stiffness		
λ* (lambda*)		0.05244
κ* (kappa*)		0.02319
Alternatives		
Use alternatives		☐
C_c		0.1990
C_s		0.04400
e_{init}		0.6500
Strength		
c'_{ref}	kN/m²	2.000
φ' (phi)	°	30.00
ψ (psi)	°	0.000
Advanced		
Set to default values		☑
Stiffness		

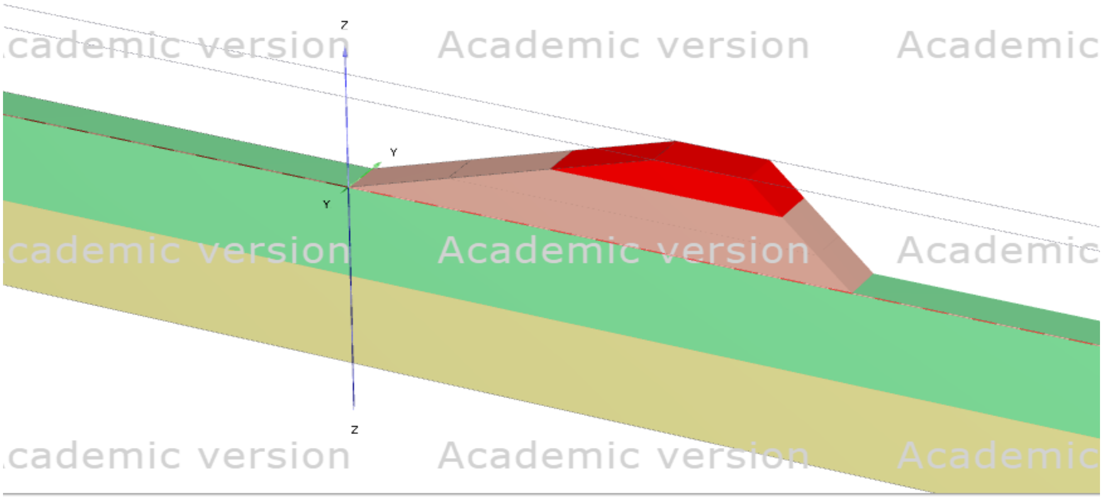
Figure 4.3: Defining material for Bhola Polder embankment.

4.2.4 Defining Embankment in different stages

In this step, embankment is defined and extruded in different stages.



(a) Stage one (b) Stage two



(c) Stage three

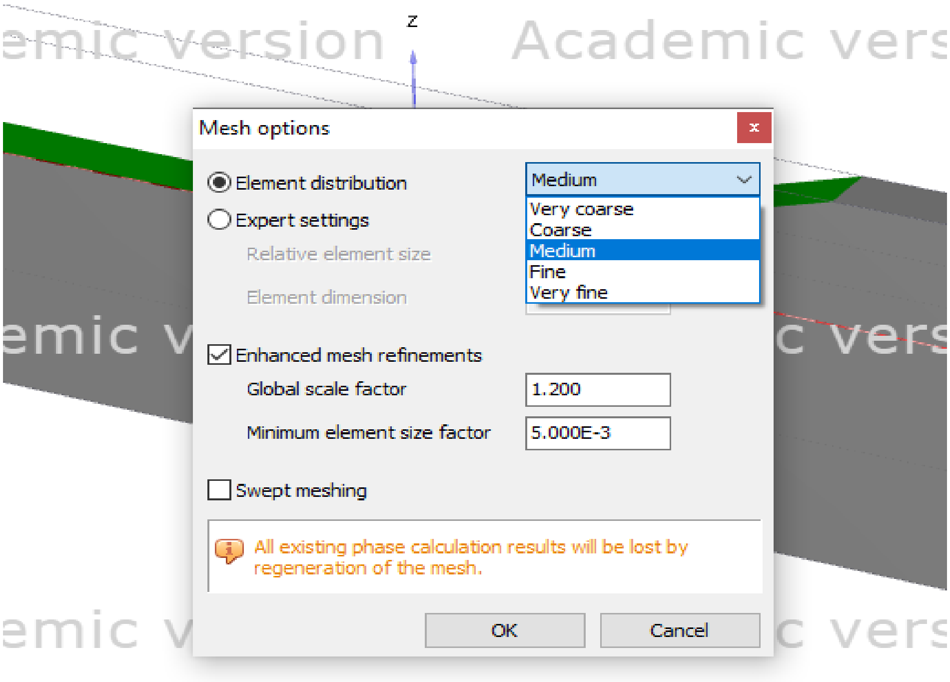
Figure 4.4: Construction of Bhola Polder embankment in different stages ((a) stage one, (b) stage two, (c) stage three)

4.2.5 Generation of mesh

Meshing is the process of dividing the embankment model in small components for finite element analysis. There are five mesh option available in PLAXIS 3D, depending on the coarseness of the elements. The effect of meshing process is discussed in later part of this chapter.

4.2.6 Defining flow condition

In this step, the water level (the embankment is facing) is defined.



Mesh options

● Element distribution: Medium

○ Expert settings

Relative element size

Element dimension

☑ Enhanced mesh refinements

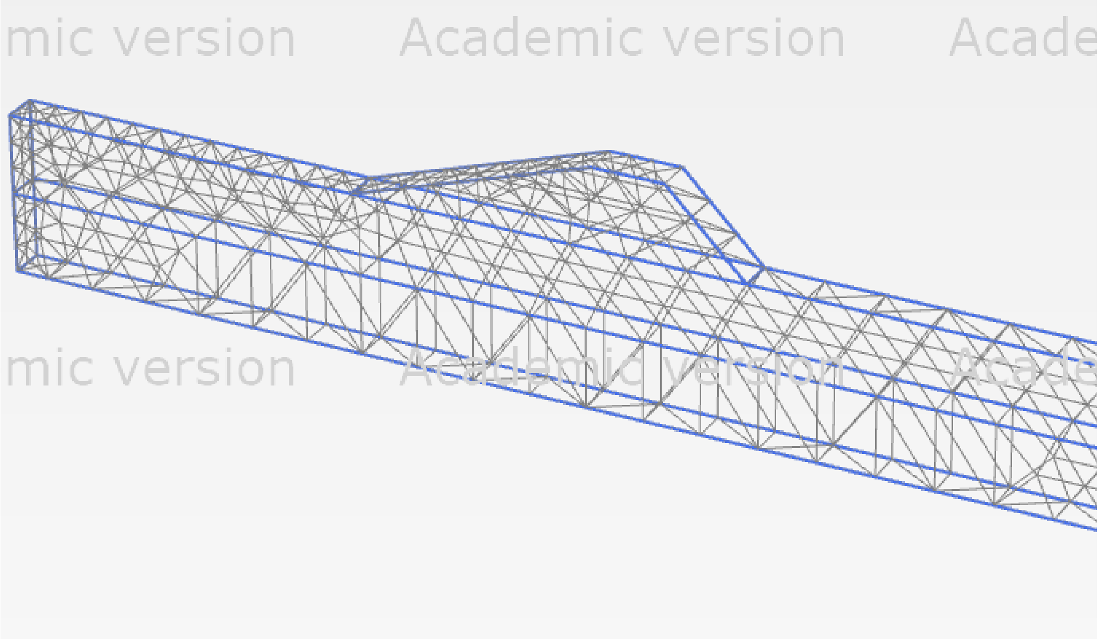
Global scale factor: 1.200

Minimum element size factor: 5.000E-3

☐ Swept meshing

All existing phase calculation results will be lost by regeneration of the mesh.

(a) Selection of meshing method



(b) Completion of mesh

Figure 4.5: Meshing of Bhola Polder Embankment (Medium mesh) ((a) Selection of meshing method, (b) Completion of mesh)

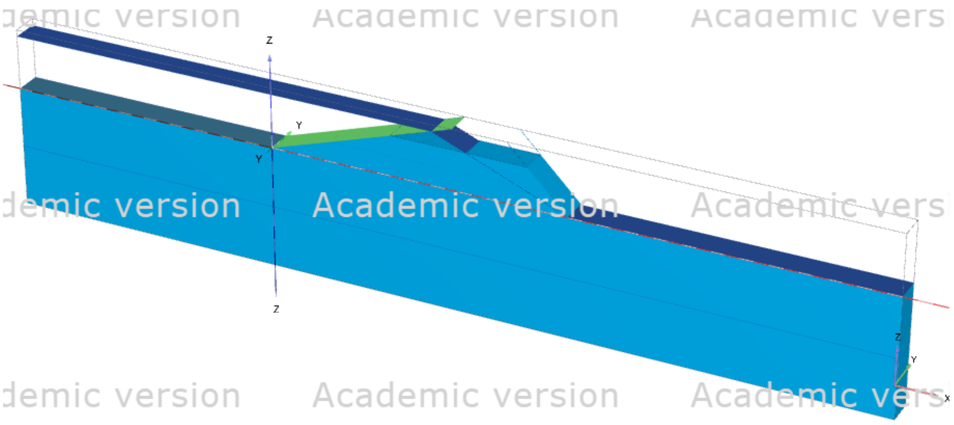


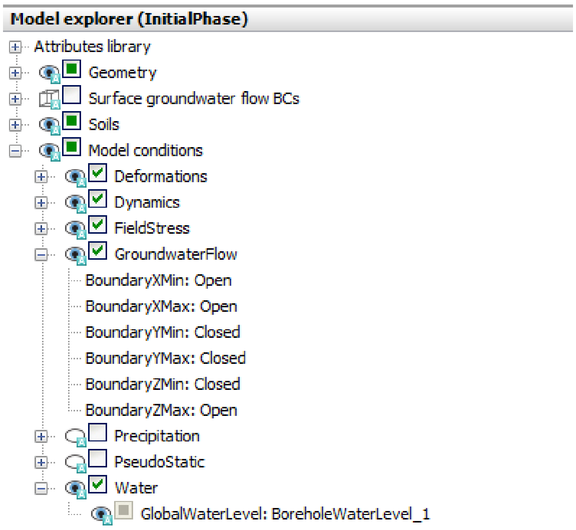
Figure 4.6: Defining water level for the Bhola Polder Embankment.

4.2.7 Definition of calculation

In this step, the stages of embankment construction and analysis type is defined.

4.2.7.1 Initial phase

In the initial phase the embankment is not present. Hence, the embankment soil volumes are deactivated. For the Initial phase, the phreatic option is selected for the pore pressure calculation type and the Global water level is set to borehole water level corresponding to the water level defined by the heads specified for the boreholes. The boundary conditions for flow is specified in the Model conditions subtree in the Model explorer.



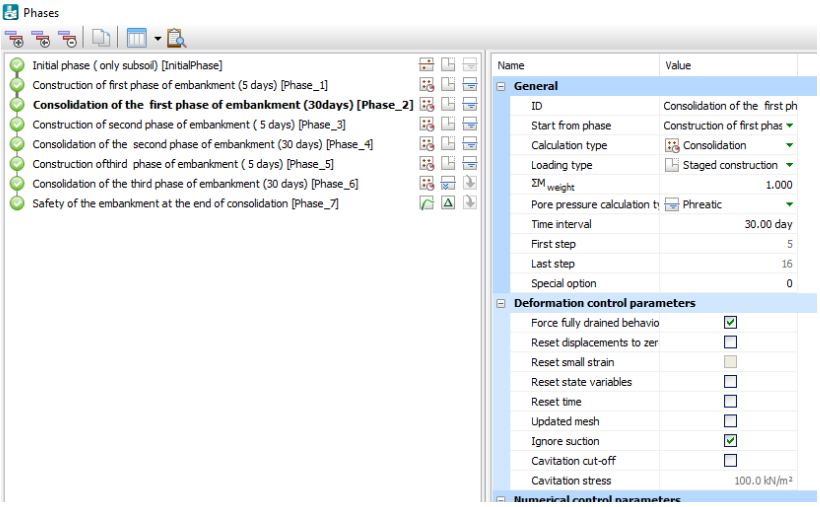
Model explorer (InitialPhase)

- Attributes library
- 🟩 Geometry
- ☐ Surface groundwater flow BCs
- 🟩 Soils
- 🟩 Model conditions
  - ☑ Deformations
  - ☑ Dynamics
  - ☑ FieldStress
  - ☑ GroundwaterFlow
    - BoundaryXMin: Open
    - BoundaryXMax: Open
    - BoundaryYMin: Closed
    - BoundaryYMax: Closed
    - BoundaryZMin: Closed
    - BoundaryZMax: Open
  - ☐ Precipitation
  - ☐ PseudoStatic
  - ☑ Water
    - ▪ GlobalWaterLevel: BoreholeWaterLevel_1

Figure 4.7: Boundary conditions for groundwater flow for Bhola Polder Embankment

4.2.7.2 Consolidation analysis

In the following stages of Initial phase, the construction time and calculation type is specified.



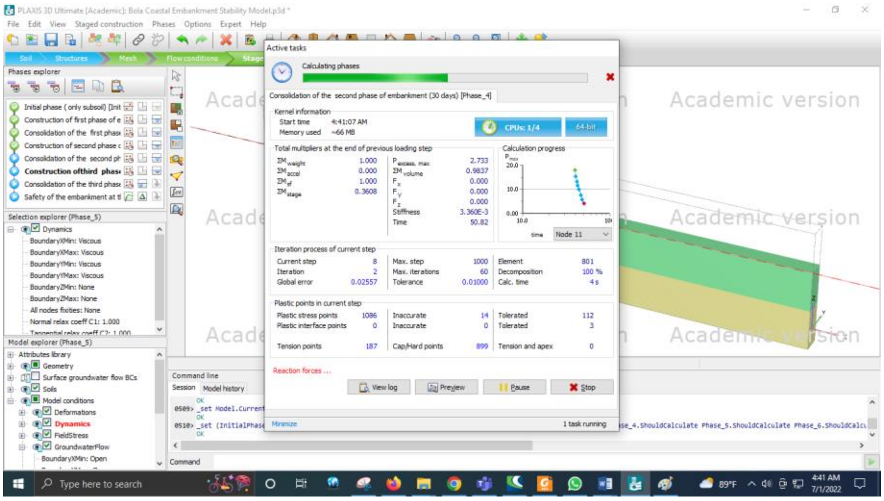
Initial phase (only subsoil) [InitialPhase]
Construction of first phase of embankment (5 days) [Phase_1]
Consolidation of the first phase of embankment (30days) [Phase_2]
Construction of second phase of embankment (5 days) [Phase_3]
Consolidation of the second phase of embankment (30 days) [Phase_4]
Construction ofthird phase of embankment (5 days) [Phase_5]
Consolidation of the third phase of embankment (30 days) [Phase_6]
Safety of the embankment at the end of consolidation [Phase_7]

Name	Value
General	
ID	Consolidation of the first ph
Start from phase	Construction of first phas
Calculation type	Consolidation
Loading type	Staged construction
ΣM_{weight}	1.000
Pore pressure calculation t	Phreatic
Time interval	30.00 day
First step	5
Last step	16
Special option	0
Deformation control parameters	
Force fully drained behavio	☑
Reset displacements to zer	☐
Reset small strain	☐
Reset state variables	☐
Reset time	☐
Updated mesh	☐
Ignore suction	☑
Cavitation cut-off	☐
Cavitation stress	100.0 kN/m²
Numerical control parameters	

Figure 4.8: Definition of stages for Bhola Polder Embankment analysis.

4.2.8 Execution of the calculation

Before starting the calculation, some node or stress points are selected for close observation of deformation and safety status.



Consolidation of the second phase of embankment (30 days) [Phase_4]

Kernel information
Start time 4:41:07 AM
Memory used ~66 MB

Total multipliers at the end of previous loading step

ΣM_{weight}	1.000	$P_{excess, max}$	2.733
ΣM_{accel}	0.000	ΣM_{volume}	0.9837
ΣM_{sf}	1.000	F_x	0.000
ΣM_{stage}	0.3608	F_y	0.000
		F_z	0.000
		Stiffness	3.360E-3
		Time	50.82

Calculation progress: Node 11

Iteration process of current step

Current step	8	Max. step	1000	Element	801
Iteration	2	Max. iterations	60	Decomposition	100 %
Global error	0.02557	Tolerance	0.01000	Calc. time	4 s

Plastic points in current step

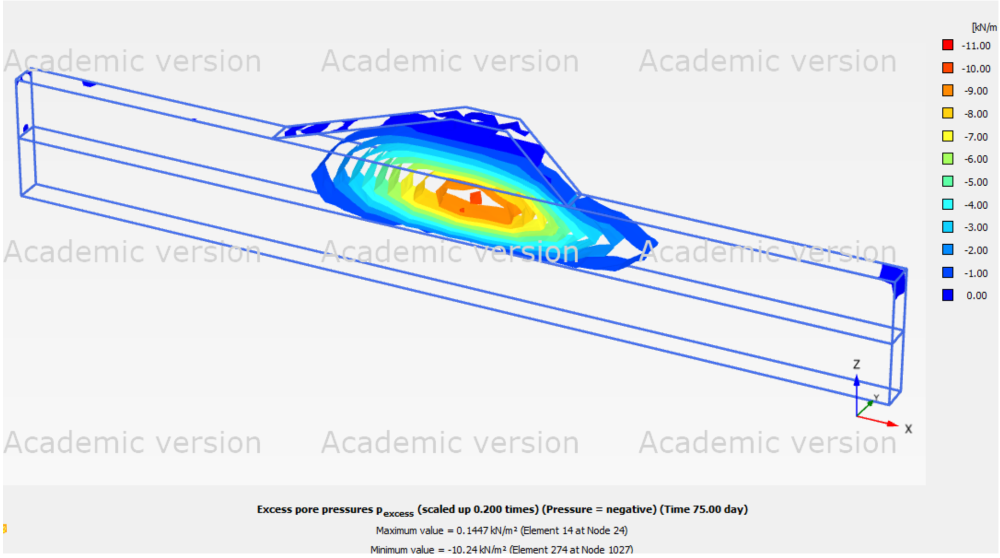
Plastic stress points	1086	Inaccurate	14	Tolerated	112
Plastic interface points	0	Inaccurate	0	Tolerated	3
Tension points	187	Cap/Hard points	899	Tension and apex	0

Reaction forces ...

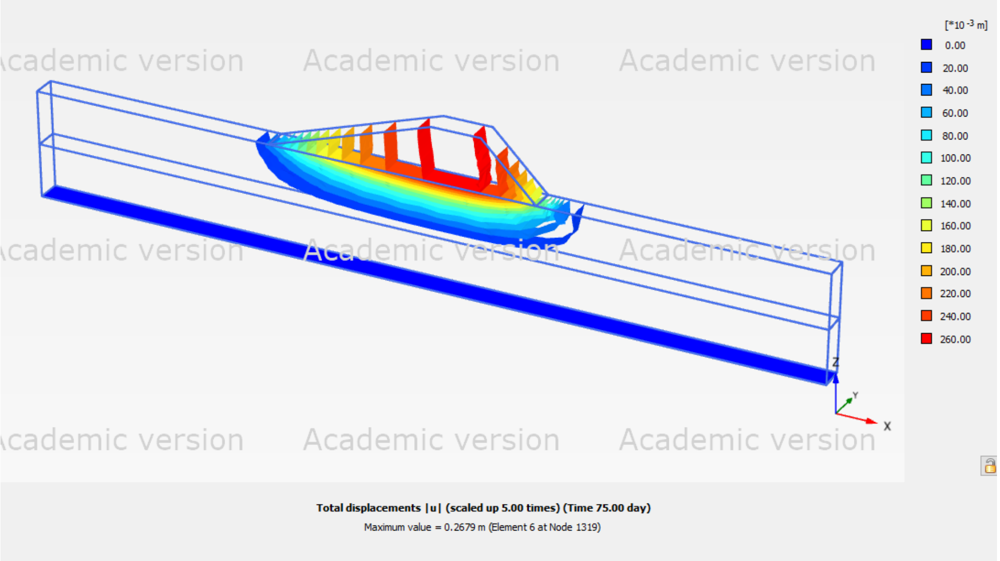
Figure 4.9: Calculation progress of Bhola Polder Embankment analysis.

4.2.9 Results

After the end of calculation, pore water pressure, deformation, strains etc. of the embankment at different stages can be shown in output window.



(a) Excess pore water pressure of Bhola Polder at the end of consolidation



(b) Deformation of Bhola Polder at the end of consolidation

Figure 4.10: (a) Excess pore water pressure, (b) Deformation of Bhola Polder Embankment at the end of consolidation.

4.2.10 Safety analysis

For purely frictional soil,

$$Safety\ factor = \frac{S_{maximum\ available}}{S_{needed\ for\ equilibrium}}$$

Where S represents the shear strength.

$$Safety\ factor = \frac{c - \sigma_n \tan\varphi}{c_r - \sigma_n \tan\varphi_r}$$

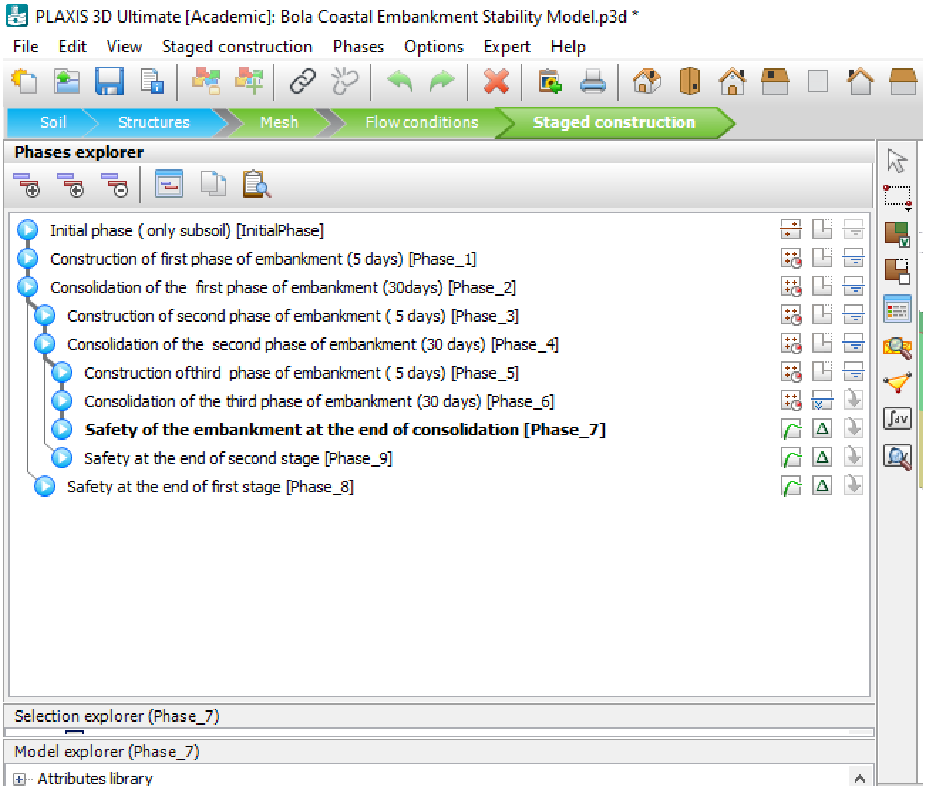
Here, c and φ are the input strength parameters and σ_n is the actual normal stress component, c_r and φ_r are the reduced strength parameters which are just large enough to maintain equilibrium. In this approach the cohesion and the tangent of the friction angle are reduced in the same proportion:

$$\frac{c}{c_r} = \frac{\tan\varphi}{\tan\varphi_r} = \sum M_{sf}$$

The reduction of strength parameters is controlled by the total multiplier $\sum M_{sf}$. This parameter is increased in a step-by-step procedure until failure occurs. The safety factor is then defined as the value of $\sum M_{sf}$ at failure.

4.2.10.1 Defining the safety calculation

For the case of design and construction of embankment, it is critical to consider not just ultimate stability, but also stability in different stages. PLAXIS 3D facilitates to calculate factor of safety at different stages of construction.



Initial phase (only subsoil) [InitialPhase]
Construction of first phase of embankment (5 days) [Phase_1]
Consolidation of the first phase of embankment (30days) [Phase_2]
Construction of second phase of embankment (5 days) [Phase_3]
Consolidation of the second phase of embankment (30 days) [Phase_4]
Construction ofthird phase of embankment (5 days) [Phase_5]
Consolidation of the third phase of embankment (30 days) [Phase_6]
Safety of the embankment at the end of consolidation [Phase_7]
Safety at the end of second stage [Phase_9]
Safety at the end of first stage [Phase_8]

Figure 4.11: Definition of factor of safety for Bhola Polder Embankment at different stages.

4.2.11 Evaluation of the safety results

Although the overall displacements after safety computation have no physical relevance, the incremental displacements in indicate the probable failure mode.

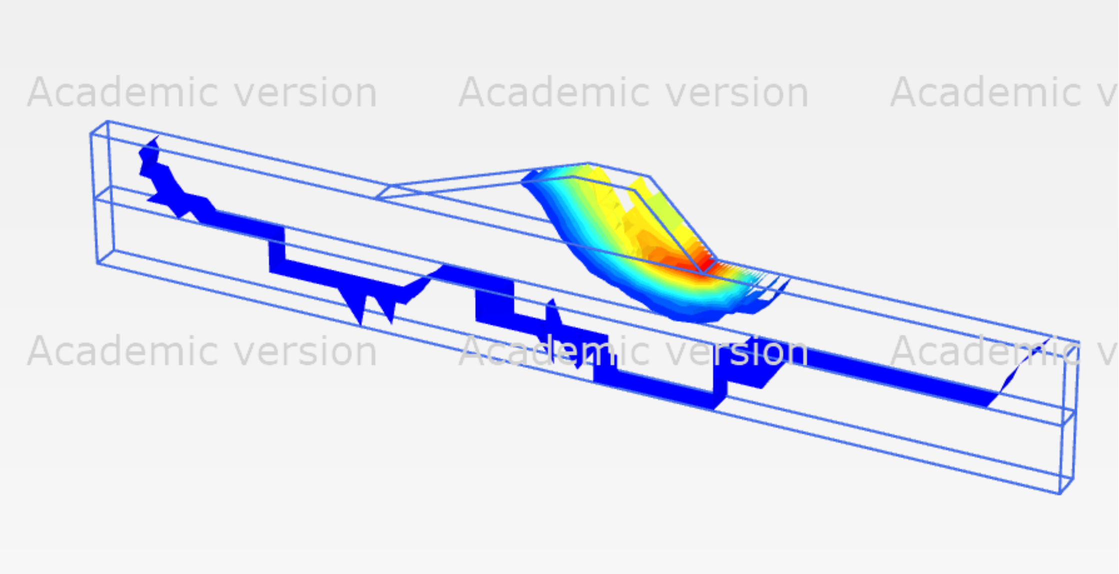
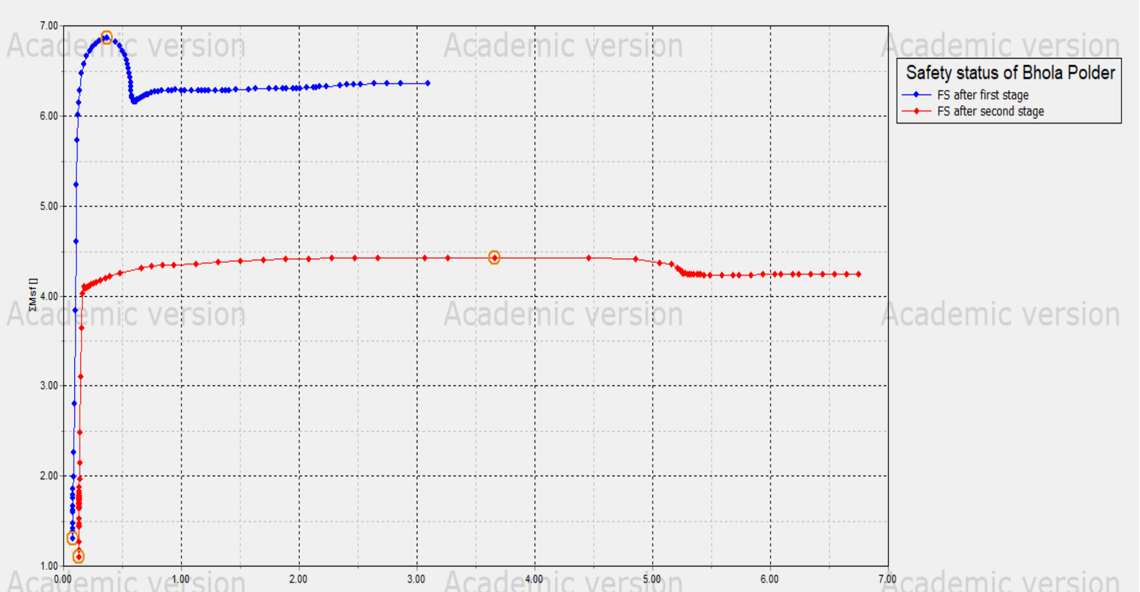
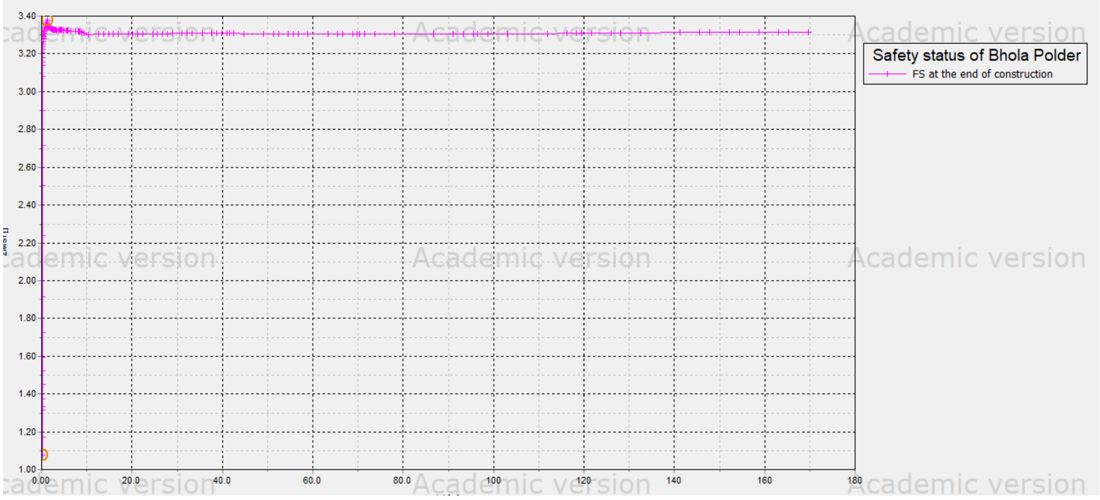


Figure 4.12: Failure Mechanism of the Bhola Polder embankment at the end of consolidation.

Safety factor of the embankments can be plotted for different nodes selected for analysis. Factor of safety can be plotted as total displacement (IuI) in x axis and $\sum M_{sf}$ in y axis.



(a) Factor of safety of the Bhola Polder at the end of 1st and 2nd stage of construction.



(b) Factor of safety of the Bhola Polder at the end of the construction

Figure 4.13: Factor of safety of the Bhola Polder (a) at the end of 1st and 2nd stage of construction, (b) at the end of the construction

4.3 Validation of the Recently Constructed Superdyke at Bangabandhu Sheikh Mujib Shilpa Nagar (BSMSN) Project

Before selecting any numerical model, validation of the model to real data is very important for geotechnical engineering projects. For the thesis purpose, a newly constructed superdyke constructed near Feni River for the purpose of Bangabandhu Sheikh Mujib Shilpa Nagar (BSMSN) was selected. In this project the construction process of the embankment and its potential settlement and factor of safety were calculated and the performance of the embankment was monitored with time.

For this research case, the embankment was modeled in PLAXIS 3D in differ stages to mimic the real project work. The settlements of the embankment at the landside, riverside and middle of the embankment, at different locations, from the PLAXIS 3D model were compared with observed settlement values. Later, the safety status of the embankment at different locations are compared between PLAXIS 3D model result and theoretical calculation.

4.3.1 Description of the case study project

Bangladesh is a developing country, and the connectivity is the most important part of development. As a result the need of new road construction on rise. In some cases some sections of the embankment has to be built on soft soil. In addition, for construction of economic zones, which is generally take place on the bank of rivers, most of the cases earth embankment is built to protect the project area from flood, cyclone and storm surges. Recently, some research on soil improvement with vertical drains have been conducted. Sudipta et al. (2017) studied the ground improvement by preloading with vertical sand drain (VSD) for the road project at the Rampal Coal Based Power plant. Ripon et al. (2020) studied the construction of embankment of a newly constructed railway track at Kashiani–Gopalganj section. In this project prefabricated vertical drain (PVD) was used with preloading and staged construction techniques. Hore and Ansary (2020) studied different soil improvement techniques used for Dhaka Mass Rapid Transit Project for improving soil bearing capacity. Sand Compaction Pile (SCP) and Dynamic Compaction (DC) methods are used in Tongi to Uttara soil improvement project. Reang et al. (2021) studied some sections of railway embankment (connecting between Agartala and Dhaka) constructed over soft soils project. In this project prefabricated vertical drains were installed in triangular pattern. In every cases, soil improvement techniques resulted in soil improvement of soil strength properties. In these previous studies all the consolidation and settlement calculations are done based on theoretical approach, but no numerical study is done for the evaluation of ground improvement with prefabricated vertical drain. In this study, seven embankment section of the Mirasarai, Chittagong have been modeled with PLAXIS 3D, a finite element software. Later, the settlement of the embankment sections at different locations are compared to study the effectiveness of PVD for soil improvement. The factor of safety of the embankments are also analyzed from the model result and compared with Low’s method ((1989).

The total area of the project is 3000 acres of contiguous land (12.14 sq. km), adjoining three sub-districts (Mirasarai, Sitakunda, Sonagazi). The project consist of 25 kilometers of coast lines of Sandeep channel of the Bay of Bengal. The length of the superdyke is 2.992 km long (chainage K2+325 to K5+317). Alignment of the coastal embankment is shown in Figure 4.15.

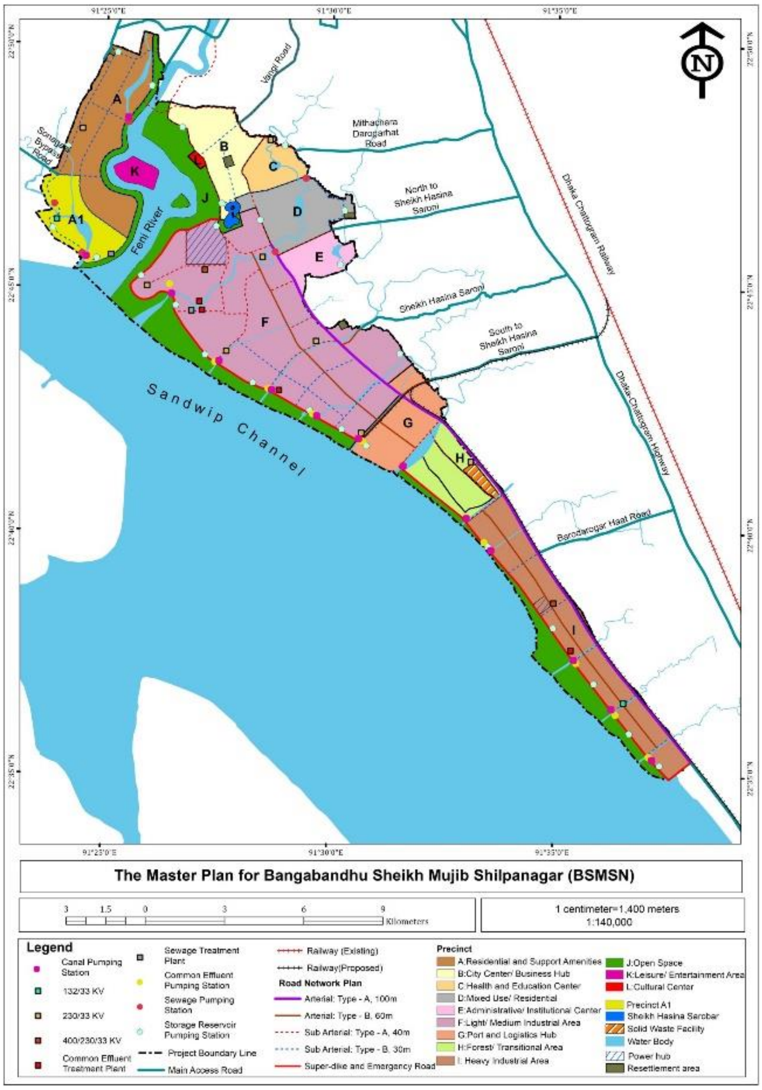


Figure 4.14 : Master Plan of Bangabandhu Sheikh Mujib Shilpa Nagar (BEPZA, 2022)

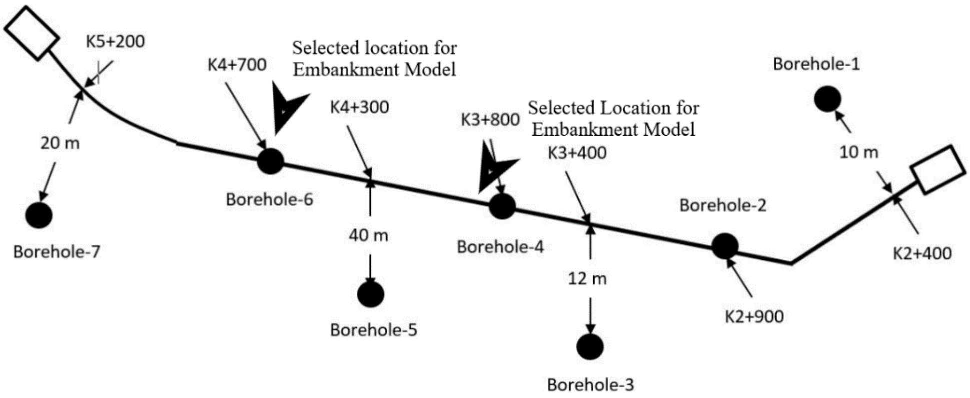


Figure 4.15: Layout and location of soil exploration of embankment for Bangabandhu Sheikh Mujib Shilpa Nagar.

4.3.2 Geotechnical Investigation of the Project

Seven borehole locations are selected for Standard Penetration Tests in the embankment project. The generalized soil profile and geotechnical properties of soils at different locations are presented in the following sections.

4.3.2.1 Generalized soil profile of the project area at Mirasarai, Chittagong.

Geotechnical investigations were carried out in two phases, before and after the construction of the superdyke. In both phases, seven boreholes were drilled between chainage 2+400 km and 5+200 km. At the first phase, seven boreholes were drilled between chainage 2+400 km and 5+200 km. The height of the existing embankment was about 3 m above the original ground level. The boreholes were drilled to a depth of 30 m below the Existing Ground Level (EGL).

In the second phase, another seven boreholes were drilled along the centerline of the embankment to a depth of 36m below the embankment top, between chainage 2+400 km and 5+200 km. At this stage, the height of the embankment was about 6 m above original ground level. The summary of the soil investigations are presented in Table 4.1 to Table 4.6.

4.3.2.2 Laboratory Investigations

Soil samples collected during soil explorations were investigated in the laboratory according to the ASTM (2006) standard. Moisture content (ASTM D2216), liquid limit (ASTM D4318), plastic limit test (ASTM D4318), specific gravity (ASTM D854) and grain size analysis (ASTM D422), Unconfined compression test (ASTM D2166), Consolidated drained direct shear test (ASTM D3080), and One dimensional incremental loading consolidation tests (ASTM D2435) were performed to identify the geotechnical characteristics of the project.

Table 4.1: Sub-soil profile from 1st and 2nd phase of geotechnical investigations of the Mirasarai, Chittagong superdyke project.

Bore hole No.	**Reduced Level (m) in 1st Phase**	**Soil type along depth (m) in 1st Phase**	**SPT in 1st Phase**	**Reduced Level (m) in 2nd Phase**	**Soil type along depth (m) in 2nd Phase**	**SPT in 2nd Phase**
01.	+3.10	Silty clay, grey, very soft (3m)	1-2	+9.16	Silty fine sand, grey medium to loose sand (9 m)	7-22
		Silty fine sand grey loose to silty clay very soft (3-10.5m)	2-9		Silty clay medium stiff to silty fine sand, grey medium dense and clayey silt with fine sand (9-21 m)	11-22
		Clayey silt with fine sand, grey, stiff to silty fine sand, grey, medium dense to dense (10.5-30)	4-48		Silty fine sand, grey, medium dense to dense (21-30)	13-47
02.	+6.01	Silty fine sand, grey loose to medium dense to medium stiff (6 m)	5-14	+9.18	Silty fine sand, grey loose to medium dense to silty clay grey medium stiff (10.5 m)	4-13
		Silty clay, grey soft with silty fine sand, grey medium dense (6-12 m)	2-21		Silty fine sand, grey medium dense to silty clay grey medium stiff to stiff (10.5-21 m)	6-22
		Silty clay grey medium stiff to stiff to silty fine sand, grey, medium dense to dense (12-30 m)	6-41		Silty fine sand, grey, medium dense to dense (21-30 m)	13-43
03	+2.80	Silty clay grey soft to silty fine sand grey loose (7.5 m)	2-7	+9.31	Silty fine sand, grey loose to dense and clayey silt fine sand, grey medium stiff to soft (10.50 m)	2-38
		Silty clay grey soft to medium stiff to clayey silt with fine sand grey medium stiff (7.5-19.5 m)	3-11		Silty fine sand, grey, medium dense to silty clay, grey, medium stiff to stiff (10.5-22.5 m)	4-23
		Silty fine sand, grey, dense (19.5-30)	13-50		Silty fine sand, grey, medium dense to dense (22.5-30)	25-46

Table 4.1(contd.): Sub-soil profile from 1st and 2nd phase of geotechnical investigations of the Mirasarai, Chittagong superdyke project.

Bore hole No.	**Reduced Level (m) in 1st Phase**	**Soil type along depth (m) in 1st Phase**	**SPT in 1st Phase**	**Reduced Level (m) in 2nd Phase**	**Soil type along depth (m) in 2nd Phase**	**SPT in 2nd Phase**
04.	+6.27	Silty fine sand, grey very loose to loose to silty clay, grey, soft to stiff (9 m)	2-5	+9.44	Silty fine sand, grey loose to dense to silty clay, grey, medium stiff (10.5 m)	6-36
		Clayey silt, grey medium stiff to silty clay medium stiff (9-24 m)	2-10		Silty fine sand, grey, medium dense and silty clayey silt with fine sand, grey stiff to medium to silty clay grey, medium stiff to stiff (10.5-24 m)	6-21
		Silty fine sand, grey, medium dense to very dense (24-30 m)	7-50		Silty fine sand, grey, medium dense to very dense (24-30 m)	22-50
05.	+2.90	Silty clay, grey, very soft to silty fine sand grey loose (10.5 m)	1-9	+9.24	Silty fine sand, grey, medium dense to silty clay, grey, medium stiff (10.5 m)	4-28
		Clayey silt with fine sand, grey, stiff to silty fine sand, grey medium dense (10.5-18 m)	5-23		Silty fine sand, grey, medium dense to loose with silty fine sand, grey, medium dense to silty clay, grey, medium stiff (10.5-22.5)	5-28
		Silty clay, grey, medium stiff to Silty fine sand, grey, medium dense to very dense (18-30 m)	5-50		Silty fine sand, grey, dense to very dense (22.5-30)	32-50
06.	+7.171	Silty fine sand, grey loose to silty clay, grey soft (7.50 m)	2-11	+9.19	Silty fine sand, grey, medium dense to silty clay, grey, soft stiff (7.5 m)	4-18

Table 4.1 (contd.): Sub-soil profile from 1st and 2nd phase of geotechnical investigations of the Mirasarai, Chittagong superdyke project.

Bore hole No.	**Reduced Level (m) in 1st Phase**	**Soil type along depth (m) in 1st Phase**	**SPT in 1st Phase**	**Reduced Level (m) in 2nd Phase**	**Soil type along depth (m) in 2nd Phase**	**SPT in 2nd Phase**
		Silty fine sand, grey, dense to silty clay, medium stiff (7.50- 15 m)	8-20		Silty fine sand, grey, medium dense with silty clay, grey, medium stiff to stiff (7.5-22. m5)	4-17
		Silty clay, grey, medium stiff to silty fine sand, grey medium dense to dense (15-30 m)	7-42		Clayey silt with fine sand, grey, stiff to silty fine sand, grey, medium dense to very dense (22.5-30 m)	12-50
07.	+3.50	Silty clay, grey soft (4.5 m)	2	+9.21	Silty fine sand, grey, loose to medium dense (4.5 m)	7-14
		Silty fine sand, grey dense to Silty clay, grey medium stiff to stiff (4.5-21 m)	5-22		Silty clay, grey soft to stiff (4.5-21 m)	3-32
		Silty fine sand, grey dense to very dense (21-30 m)	34-50		Silty fine sand, grey, medium dense to very dense (21-30 m)	33-50

Table 4.2: Sub-soil profile from 1st and 2nd phase of geotechnical investigations of the Mirasarai, Chittagong superdyke project.

1st phase of geotechnical investigations					
Borehole No.	**Sample No.**	**Depth (m)**	**Water Content (%)**	**Bulk Unit Weight (kN/m^3)**	**Dry Unit Weight (kN/m^3)**
BH-1	UD-3	5.18-5.64	29-35.2	17.6-18.6	13-14.4
BH-2	UD-1	6.71-7.16	32-48.6	16.5-17.6	11.1-13.3
BH-4	UD-1	6.71-7.32	55.8-66.7	16.2-16.8	9.9-10.3
BH-4	UD-2	8.23-8.69	38.4	17.9	12.9
BH-5	UD-1	2.13-2.59	55.1	15.8	10.2
BH-5	UD-2	3.66-4.12	43.5	7.6	12.3
BH-6	UD-1	5.18-5.64	37.7	17.4	12.5
BH-6	UD-2	6.71-7.16	41.1-41.2	16.8-17.1	11.9-12.1
BH-7	UD-1	2.13-2.59	38.7-39.1	17.5	12.6
BH-7	UD-2	3.66-4.12	56.5-60	15.4-15.5	9.6-9.9
2nd phase of geotechnical investigations					
BH-1	UD-1	10.05-10.50	331.1-41.0	17.7-18.9	12.5-14.3
BH-1	UD-2	11.55-12.0	45.2	17.1	11.8
BH-2	UD-1	8.55-9.00	38.7-46.5	17.1-17.6	11.7-12.7
BH-2	UD-2	10.05-10.50	40.3-49.8	16.8-17.7	11.2-12.6
BH-3	UD-1	7.05-7.50	18.5	18.6	15.7
BH-3	UD-2	8.55-9.00	33.8-34.0	18.0-18.3	13.4-13.7
BH-4	UD-1	7.05-7.50	18.8	17.8	16.4
BH-4	UD-2	8.55-9.00	35.8-36.1	18.4-18.5	13.5
BH-4	UD-3	10.5-10.05	38.9-42.3	16.7-17.7	11.7-12.6
BH-5	UD-1	7.05-7.50	40.0	17.5	12.5
BH-5	UD-2	8.55-9.00	44.2-44.4	17.6-17.7	12.2-12.3
BH-6	UD-1	7.05-7.50	36.0-40.01	16.9-18.1	11.7-13.3
BH-6	UD-2	8.55-9.00	41.3-56.1	16.6-17.6	10.6-12.2
BH-7	UD-1	7.05-7.50	36.1-42.5	17.5-17.9	12.0-13.2
BH-7	UD-2	10.05-10.50	30.7-32.7	18.5-18.9	14.0-14.5

Table 4.3: Summary of grain size distribution of selected silty clay samples of the Mirasarai, Chittagong superdyke project.

2nd phase of geotechnical investigations							
Chainage (km)	Borehole and Sample No.	Depth (m)	Specific gravity, G_s	% fine No. 200 sieve (0.075 mm)	Grain Size Distribution		
					% Sand Size (> 0.075 mm)	% Silt Size (0.005 to 0.075)	% Clay Size (<0.005 mm)
K2+900	BH-2, UD-2	10.05-10.50	2.75	99.4	0.6	43.6	55.8
K4+300	BH-5, UD-1	7.05-7.50	2.75	99.7	0.3	53.8	45.9
K5+300	BH-7, UD-1	7.05-7.50	2.69	99.9	0.1	47.1	52.8

Table 4.4: Summary of Unconfined Compression test results of the Mirasarai, Chittagong superdyke project.

1st phase of geotechnical investigations								
Chainage (km)	**Borehole and Sample No.**	**Depth (m)**	**Specific Gravity (G_s)**	**Water Content (%)**	**Dry Density (kN/m^3)**	**Unconfined compressive strength, q_u (kN/m^2)**	**Axial strain at failure, ε_f (%)**	**Consistency**
K2+400	BH-1 andUD-3	5.55-6.00	2.66	29-35.2	13-14.4	18-29	3-8	Very soft
K2+900	BH-2 and UD-1	7.05-7.50	2.88	55.1	11.1-13.3	18-23	8-15	Very soft
K4+300	BH-5 and UD-1	2.55-3.00	2.79	41.2	10.2	12-27	2.5-5	Very soft
K4+700	BH-6 andUD-1	7.05-7.50	2.79	38.7-39.1	11.9-12.1	21-40	15	Very soft
K5+200	BH-7 and UD-1	2.55-3.00	2.73	32-48.6	12.6	43-55	10-13	Soft
K5+200	BH-7 andUD-2	4.05-4.50	2.84	56.5-60	9.6-9.9	10-11	14	Very soft
1st phase of geotechnical investigations								
K2+400	BH-1 and UD-2	11.5-12.0	2.78	45.2	11.8	26	11	Very soft
K2+900	BH-2 and UD-1	8.55-9.00	2.75	38.7-46.5	11.7-12.7	43-44	11-12	Soft

Table 4.4(contd.): Summary of Unconfined Compression test results of the Mirasarai, Chittagong superdyke project.

Chainage (km)	Borehole and Sample No.	Depth (m)	Specific Gravity (G_s)	Water Content (%)	Dry Density (kN/m^3)	Unconfined compressive strength, q_u (kN/m^2)	Axial strain at failure, ε_f (%)	Consistency
K2+900	BH-2 andUD-2	10.05-10.50	2.75	40.3-49.8	11.2-12.6	30-36	8-10	Very soft
K3+400	BH-3 and UD-1	7.05-7.50	2.72	33.8-34	13.4-13.7	44-49	16-17	Soft
K3+400	BH-3 and UD-2	8.55-9.00	2.73	35.7	13.4	47	12	Soft
K3+800	BH-4 andUD-1	7.05-7.50	2.75	34.7	13.5	112	11	Firm
K3+800	BH-4 and UD-2	7.05-7.50	2.73	35.8-36.1	13.5	46-59	12-17	Soft
K3+800	BH-2 and UD-3	10.05-10.50	2.74	38.9-42.4	11.7-12.4	25-32	15	Very soft
K4+300	BH-5 andUD-2	8.55-9.00	2.75	40	12.5	41	15	Soft
K4+300	BH-5 and UD-1	7.05-7.50	2.77	44.2-44.4	12.2-12.3	14	14-15	Very soft
K4+700	BH-6 andUD-3	7.05-7.50	2.75	36	13.3	70	12	Soft
K5+200	BH-7 and UD-1	10.05-10.50	2.69	42-42.5	12-12.3	45-64	10-15	Soft
K5+200	BH-7 and UD-2	10.05-10.50	2.74	30.7-32.5	14.0-14.5	63-81	6	Soft

Table 4.5: Summary of One-Dimensional consolidation test results of the Mirasarai, Chittagong superdyke project.

Chainage (km)	Borehole and Sample No.	Depth (m)	Sample Orientation	Moisture content w_0 (%)	Dry Unit Weight(γ_d) (kN/m^3)	Specific gravity (G_s)	Void ratio(e_0)	Compression Index C_c	Swell Index C_s	Co-efficient of consolidation for vertical flow c_v (m^2/year)	Co-efficient of permeability for horizontal flow c_h (m^2/year)	Co-efficient of permeability for vertical flow k_v m/s	Co-efficient of permeability in vertical flow (k_h m/s) (x 10^{-9})
1st Phase Geotechnical Investigations													
K2+900	BH-2,UD-2	8.55-9.00	V	49	11.6	2.89	1.45	0.41	0.09	4.5-14.3	-	6.8×10^{-10} to 2.6×10^{-9}	-
K3+800	BH-4,UD-2	8.55-9.00	H	38.4	12.9	2.70	1.05	0.26	0.05	-	10.2 - 35.4	-	1.2-5.9
K4+300	BH-5,UD-2	4.05-4.50	H	43.5	12.3	2.79	1.22	0.31	0.05	-	21.3 - 38.9	-	1.3-1.5
K4+700	BH-6, UD-1	5.55-6.00	V	39.3	12.5	2.80	1.19	0.39	0.10	4.7-7.8	-	2.3×10^{-10} to 2.0×10^{-9}	-
2nd Phase Geotechnical Investigations													
K3+400	BH-3, UD-2	10.05 - 10.50	V	40.6	12.8	2.73	1.10	0.27	0.06	8.2-23.5	-	8.4×10^{-10} to 6.0×10^{-9}	-

Table 4.5(contd.): Summary of One-Dimensional consolidation test results of the Mirasarai, Chittagong superdyke project.

Chainage (km)	Borehole and Sample No.	Depth (m)	Sample Orientation	Moisture content w_0 (%)	Dry Unit Weight(γ_d) (kN/m^3)	Specific gravity (G_s)	Void ratio(e_0)	Compression Index C_c	Swell Index C_s	Co-efficient of consolidation for vertical flow c_v (m^2/year)	Co-efficient of permeability for horizontal flow c_h (m^2/year)	Co-efficient of permeability for vertical flow k_v m/s	Co-efficient of permeability in vertical flow (k_h m/s) (x 10^{-9})
K3+800	BH-4, UD-3	10.05 - 10.50	H	40.6	12.6	2.74	1.13	0.32	0.06	-	7.6-11.4	-	5-5.3
K4+300	BH-5, UD-2	8.55-10.05	V	41	12.5	2.77	1.17	0.32	0.06	10.7 - 17.5	-	7.4×10^{-10} to 1.1×10^{-9}	-
K4+700	BH-6, UD-1	7.05-7.50	V	44.3	11.7	2.74	1.29	0.37	0.06	4.7-11.4	-	4.9×10^{-10} to 7.3×10^{-9}	-
K4+700	BH-6, UD-2	8.55-9.00	V	41.3	12.2	2.75	1.21	0.40	0.08	5.9-26.4	-	1.1×10^{-10} to 5.8×10^{-9}	-
K5+200	BH-7, UD-1	7.05-7.50	H	36.1	13.2	2.69	1.00	0.27	0.08	-	21.6 - 36.4	-	1.3-8.1

Table 4.6: Summary of consolidated drained direct shear test results on Undisturbed Samples (2nd phase) of the Mirasarai, Chittagong superdyke project.

Chainage	**Borehole and sample**	**Depth (m)**	**Specific gravity, G_s**	**Initial void ratio, e_0**	**Water content (%)**	**Dry Density (kN/m^3)**	**Effective Normal stress, σ_n' (kN/m^2)**	**Effective cohesion, c' (kN/m^2)**	**Effective angle of internal friction, Φ' (Deg.)**
K2+400	BH-1 andUD-1	10.05-10.50	2.69	0.85-0.99	33.1-36.5	13.25-14.25	124, 248 and 372	0	31.0
K4+700	BH-6 and UD-2	8.55-9.00	274	1.25-1.53	47.3-56.1	10.62-11.94	124, 248 and 372	0	25.0
Laboratory reconstituted Non-cohesive sample									
K3+800	BH-2 and D-23, D-24	34.5-36.0	2.75	0.82-0.84	23.1-24.8	14.67-14.85	155, 248 and 372	0	36.9
K4+300	BH-5 and D-16, D-17	24.0-25.5	2.79	0.95-1.02	25.7-30.3	13.56-14.03	136, 238 and 372	0	35.4
K5+200	BH-7 and D-21, D-22	31.5-33.0	2.79	0.72-0.75	21.1-22.7	15.65-15.87	155, 248 and 372	0	36.9

4.3.3 Method of construction

Based on geotechnical investigations, it was clear that there exists a thick clay layer (very soft to soft) below the existing ground level. The thickness of the soft soil varies from 1.5m to 5m, depending on the different locations. As a ground improvement method, vertical drains were designed to the depth of approximately 10 m below the ground level to cover the full depth of the soft clay layer. The consultants initially examined different options of vertical drains. Approximate cost and required times are summarized in (Table 4.7). Based on the comparison, due to the lowest consolidation time, PVDs (width = 100 mm, t = 3.8 mm) at 1.0 m c/c in a triangular pattern was chosen for implementation. The layout of the selected PVD layout is shown in Figure 4.16.

Table 4.7: Approximate cost and consolidation time for three options of soil improvement of the Mirasarai, Chittagong superdyke project.

Options	Consolidation Time	Material Cost (USD/m^2)	Construction Cost (USD/m)
200 mm diameter sand drain @ 1.0 m c/c in a triangular pattern	80-145	2.8	1.3
200 mm diameter sand drain @ 1.5 m c/c in a triangular pattern	90-170	2.0	1.0
250 mm diameter sand drain @ 1.0 m c/c in a triangular pattern	75-140	3.0	1.5
250 mm diameter sand drain @ 1.5 m c/c in a triangular pattern	80-150	2.5	1.2
PVDs (width = 100 mm, t= 3.8 mm) @ 1.0 m c/c in a triangular pattern	40-100	5.5	4.5
PVDs (width = 100 mm, t= 3.8 mm) @ 1.0 m c/c in a triangular pattern	90-135	4.0	4.0
PVDs (width = 100 mm, t= 3.8 mm) @ 1.0 m c/ci n a triangular pattern	170-270	3.0	4.0

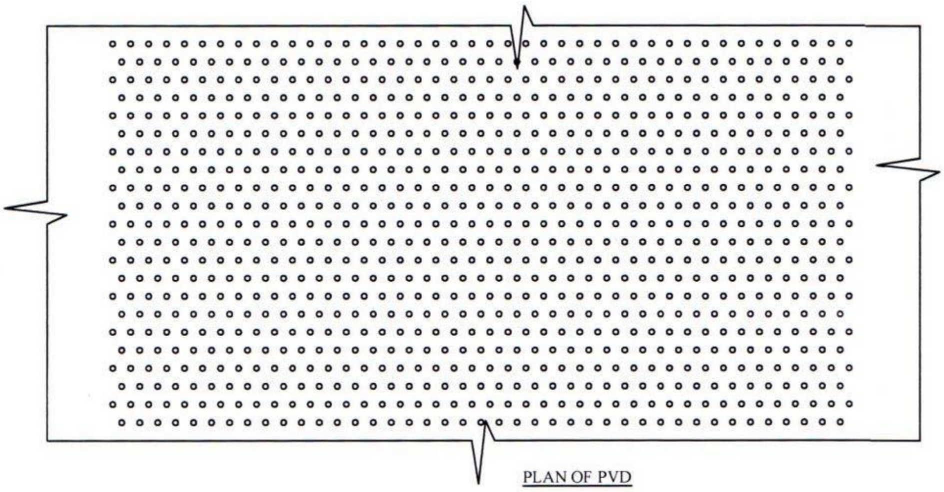


Figure 4.16: PVD layout for ground improvement of the Mirasarai, Chittagong superdyke project.

Before the installation of PVD, a 0.5m sand layer was spread over the fill material. A geotextile was laid over the sand blanket and 0.3m sand layer was spread over the geotextile. The top of the PVDs were penetrated at least 1m into the sand layer.Typical cross section of the superdyke is shown in Figure 4.17.

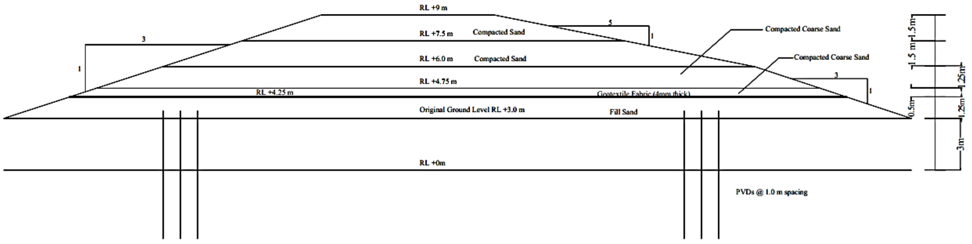


Figure 4.17: Typical Section of an embankment section of the Mirasarai, Chittagong superdyke project.

4.3.4 Stability analysis of the embankment by theoretical approach

Analyses for stability against foundation failure for embankment loading on the soft unimproved ground were carried out using the method proposed by **Low (1989)**. The method is a convenient and straightforward semi-analytical procedure to calculate the safety factor of embankments constructed on soft clay (Figure 4.18). Stability numbers N1 and N2 are developed for the normalized foundation strength and normalized embankment strength, respectively (Figure 4.19).

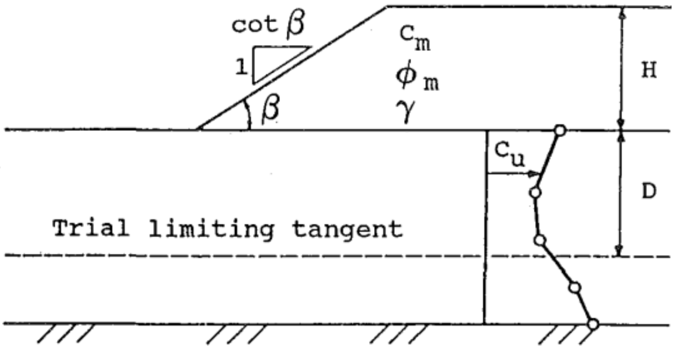


Figure 4.18: Embankment on weak soil (Low, 1989).

According to **Low (1989)**, the minimum F_s corresponding to a trial limiting tangent at depth D is given by the equation,

$$(F_s)_D = N_1 \frac{C_A}{\gamma H} + N_2 (\frac{C_m}{\gamma H} + \gamma \tan \varphi_m) \tag{4.1}$$

The value of $(F_s)_D$ may be expresses as,

$$(F_s)_D = N_1 \frac{C_A}{\gamma H} + N_2 (\frac{C_m}{\gamma H} + \lambda \tan \varphi_m) \tag{4.2}$$

Where, $N_1 = N_1(\frac{D}{H}, \cot \varphi)$; $N_2 = N_2(\frac{D}{H}, \cot \varphi)$; $\lambda = \lambda(\frac{D}{H}, \cot \varphi)$

C_A =Average undrained shear strength within the depth D

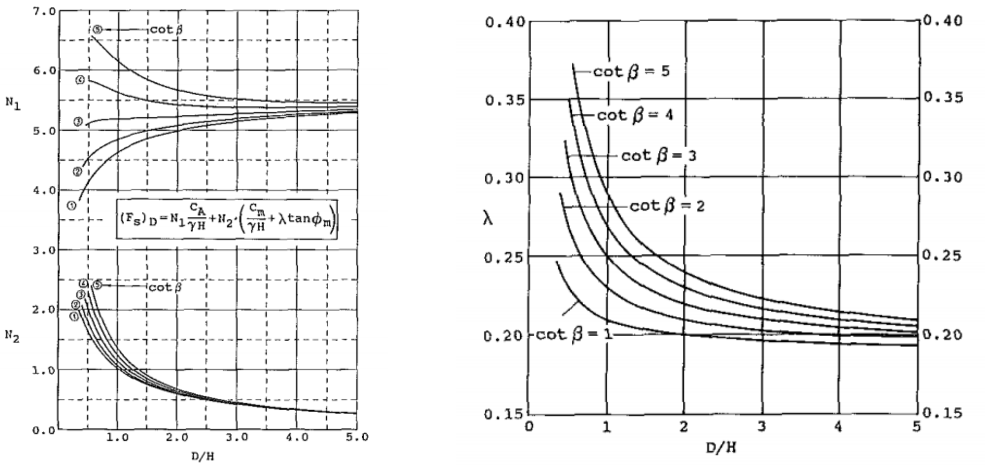


Figure 4.19: Stability Factors N_1, N_2 , and coefficient λ for Embankments on Weak Foundations (Low, 1989)

4.3.5 Settlement calculation by theoretical approach

Terzaghi's (1943) one-dimensional consolidation theory are considered for calculation of the consolidation settlements of the embankment for full design load (60 kPa) and the time required for the consolidation.

Consolidation settlement,

$$S_c = \frac{C_c}{1+e_0} H \log \frac{p_0{}' + \Delta p}{p_0{}'} \tag{4.3}$$

Time for consolidation settlement,

$$t = \frac{T_V}{C_v} H^2 \tag{4.4}$$

Estimated settlement, time for consolidation, and factor of safety of the embankment are calculated for two cases: (i) without soil improvement, (ii) for improvement of subsoil using Prefabricated Vertical Drain (PVD). Those results are presented in Table 4.8 and 4.9.

For the observation of performance of PVD based soil improvement, settlement plates were installed at eight sections to measure the actual field settlements under the embankment loading. At each section, three settlement plates were installed, one at the centerline, one at the land side toe and one at the sea side toe. The field observed results are discussed in section 4.3.7.1.

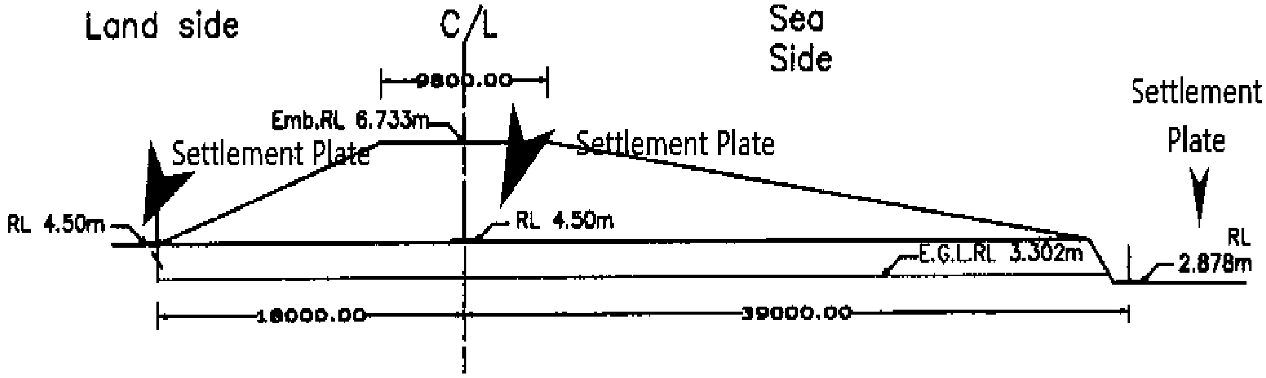


Figure 4.20: Location of settlement plates for field observations.

Table 4.8: Summary of the results of settlement analysis, time for settlement and stability analysis with initial soil parameters for full embankment height of the Mirasarai, Chittagong superdyke project.

1st phase of Geotechnical Investigations (calculated)											
Chainage (km)	**Thickness of soft clay layer (m)**	**e_0**	**C_c**	**c_v (m^2/year)**	**c_h (m^2/year)**	**Settlement at center line (mm)**	**Settlement at sea side toe (mm)**	**Settlement at land side toe (mm)**	**Time for 95% consolidation at center line with PVD (day)**	**Minimum factor of safety**	
										Land side	**Sea side**
K2+900	3.0	1.45	0.41	6	9	565	49	31	37	1.28	1.77
K3+900	4.5	1.05	0.26	10	15	557	55	35	24	1.15	1.48
K4+300	4.5	1.22	0.31	15	22	613	61	38	17	1.15	1.48
K4+700	4.5	1.19	0.39	6	9	782	77	49	41	1.15	1.48

e_0 - Initial void ratio, Cc - Compression Index, cv - Co-efficient of consolidation for vertical flow, ch - Co-efficient of consolidation for horizontal flow

Table 4.9: Factor of Safety against sub-soil failure of the compacted embankment of the Mirasarai, Chittagong superdyke project.

1st phase of Geotechnical Investigations							
Chainage (km)	**Th_{SCL}**	**e_0**	**C_c**	**c_v**	**c_h**	**FS_{min}**	
						Land side	**Sea side**
K3+400	3.0	1.10	0.27	10	15	1.78	2.42
K3+900	4.5	1.13	0.32	6	9	2.17	2.73
K4+300	4.5	1.17	0.32	10	15	2.17	2.73
K4+700	1.5	1.25	0.39	7	11	1.88	2.98
K5+200	12.0	1.00	0.27	15	22	1.78	1.94

Th_{SCL} - Thickness of soft clay layer (m), **e_0-** Initial void ratio, **C_c**-Compression Index, **c_v-** Co-efficient of consolidation for vertical flow (m^2/year), **c_h- Co-**efficient of consolidation for horizontal flow(m^2/year)

4.3.6 Numerical modeling of the embankment

The geometry and the soil profile of any embankment project vary significantly along with the layout. Therefore, estimation of the factor of safety and settlement potential of the embankment sections at various locations with traditional methods is time-consuming and repetitive. In this regard, numerical modeling of geotechnical problems is becoming popular, especially with the improvement of the calculation efficiency of computers. Modeling of embankment not only facilities the easiness of the calculation, but it also helps to model projects having complex geometry. In addition, the results of the calculation can be presented in graphics which makes the evaluation more understandable. Even the model can be adjusted easily with the change in geometry, soil parameters in design, or any stage of the project.

As the subsoil profile vary along the layout of the embankment, it is not possible to identify global factor of safety for the whole embankment. That is why we have selected two borehole points at two different chainages to model the embankment section. The sections are selected at locations where settlement plates were installed to monitor the real settlements (Figure 4.15). Another reason for selecting the locations (k3+900, Borehole-4; and K4+700, Borehole-6) is the variability of existence of soft clay layers in the project. For Borehole-4, the soft clay layer is about 4.5m thick below the existing ground level, whereas the thickness of the soft clay layer is about 12m for Borehole-6. The soil profiles at Borehole-4 and Borehole-6 are shown in Figure 4.21 and Figure 4.22.

4.3.6.1 Defining the soil stratigraphy

The selected two sections of the superdyke are modeled in PLAXIS 3D for assessing geotechnical stability. Figure 4.23 and Figure 4.23 presents the subsoil geometry of the embankment sections in model. Figure 4.25 presents the structure of the embankment with PVD. Material modeling, construction stages, analysis results are presented in subsequent sections.

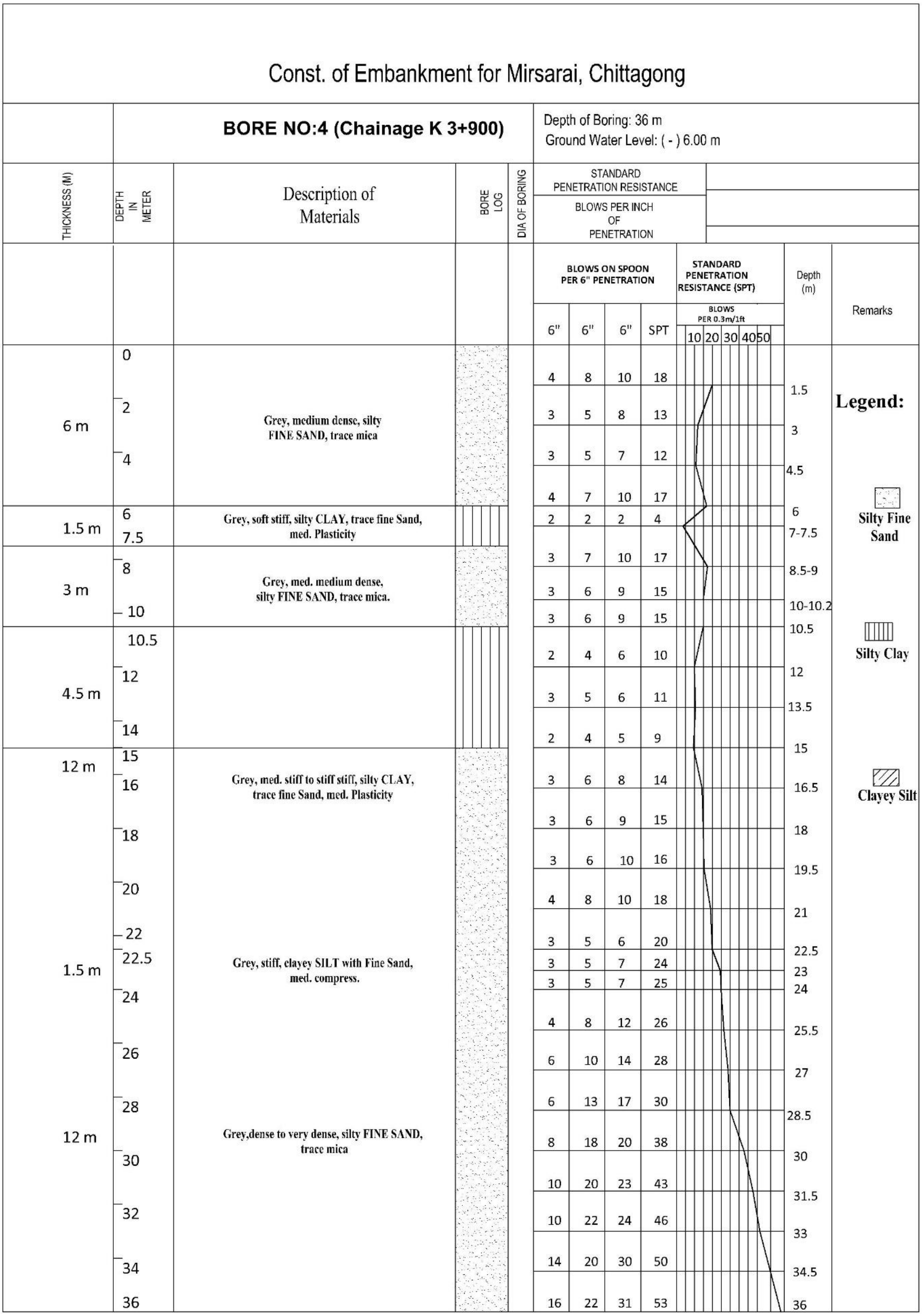
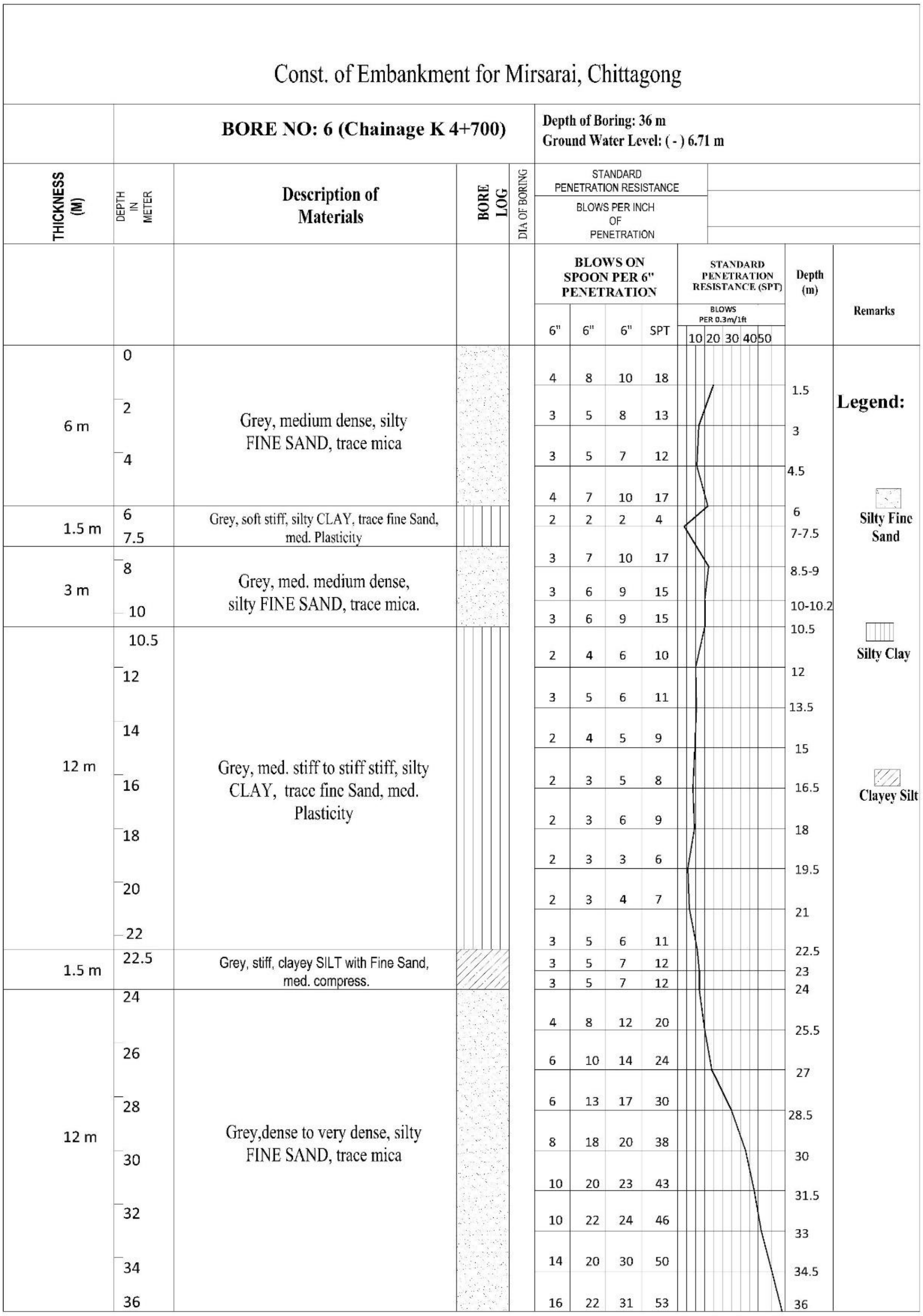


Figure 4.21: Soil profile at Chainage K 3+900 (Borehole No.4)



Const. of Embankment for Mirsarai, Chittagong

BORE NO: 6 (Chainage K 4+700)

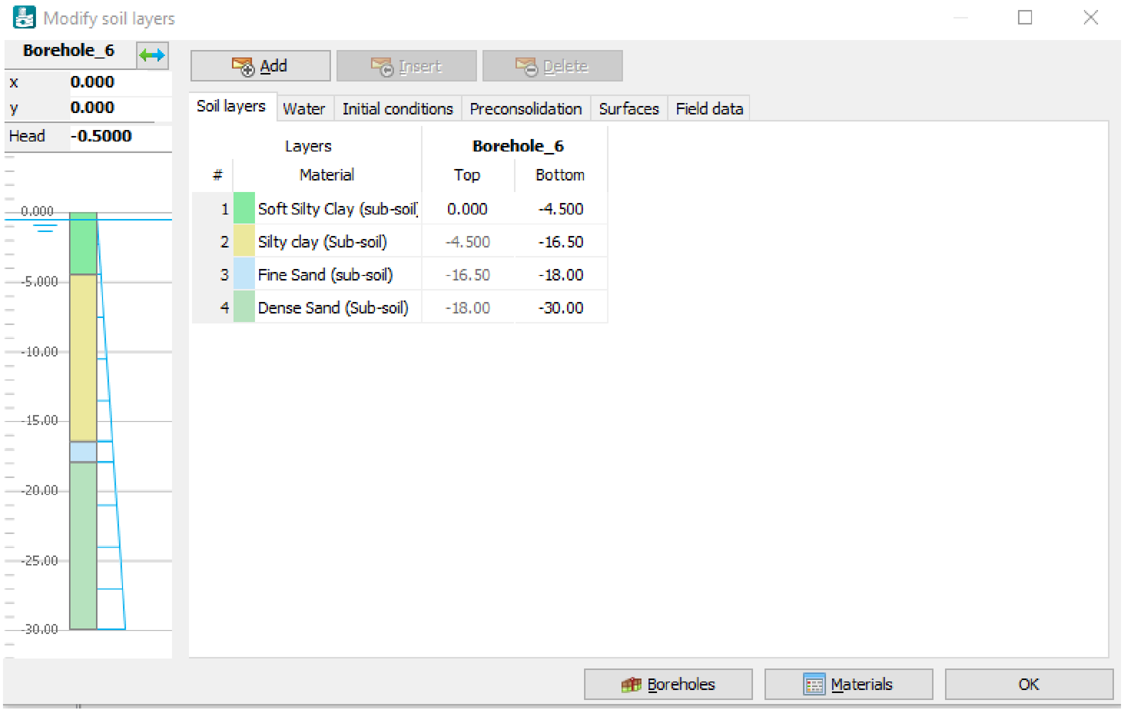
Depth of Boring: 36 m
Ground Water Level: (-) 6.71 m

THICKNESS (M)	DEPTH IN METER	Description of Materials	BORE LOG
6 m	0, 2, 4	Grey, medium dense, silty FINE SAND, trace mica	Silty Fine Sand
1.5 m	6, 7.5	Grey, soft stiff, silty CLAY, trace fine Sand, med. Plasticity	Silty Clay
3 m	8, 10	Grey, med. medium dense, silty FINE SAND, trace mica.	Silty Fine Sand
12 m	10.5, 12, 14, 16, 18, 20, 22	Grey, med. stiff to stiff stiff, silty CLAY, trace fine Sand, med. Plasticity	Silty Clay
1.5 m	22.5	Grey, stiff, clayey SILT with Fine Sand, med. compress.	Clayey Silt
12 m	24, 26, 28, 30, 32, 34, 36	Grey,dense to very dense, silty FINE SAND, trace mica	Silty Fine Sand

STANDARD PENETRATION RESISTANCE
BLOWS PER INCH OF PENETRATION

BLOWS ON SPOON PER 6" PENETRATION				Depth (m)
6"	6"	6"	SPT	
4	8	10	18	1.5
3	5	8	13	3
3	5	7	12	4.5
4	7	10	17	6
2	2	2	4	7-7.5
3	7	10	17	8.5-9
3	6	9	15	10-10.2
3	6	9	15	10.5
2	4	6	10	12
3	5	6	11	13.5
2	4	5	9	15
2	3	5	8	16.5
2	3	6	9	18
2	3	3	6	19.5
2	3	4	7	21
3	5	6	11	22.5
3	5	7	12	23
3	5	7	12	24
4	8	12	20	25.5
6	10	14	24	27
6	13	17	30	28.5
8	18	20	38	30
10	20	23	43	31.5
10	22	24	46	33
14	20	30	50	34.5
16	22	31	53	36

Figure 4.22: Soil profile at Chainage K 4+700 (Borehole No.6)



Borehole_6

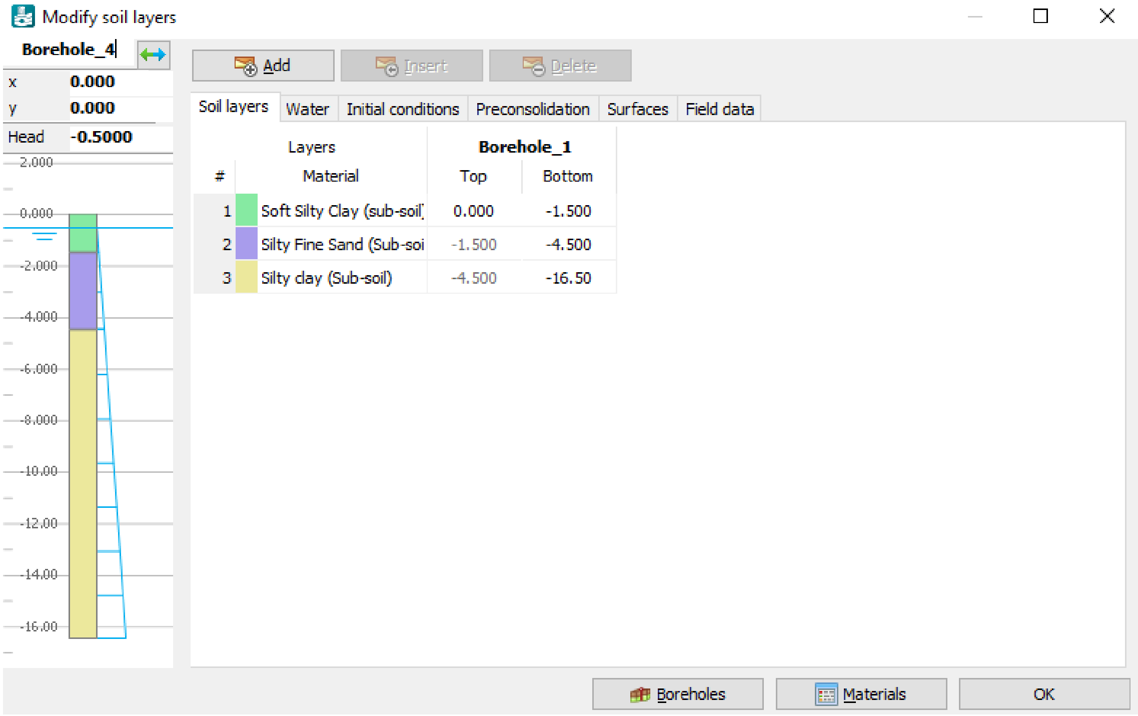
x 0.000

y 0.000

Head -0.5000

Layers			Borehole_6	
#		Material	Top	Bottom
1	🟩	Soft Silty Clay (sub-soil	0.000	-4.500
2	🟨	Silty clay (Sub-soil)	-4.500	-16.50
3	🟦	Fine Sand (sub-soil)	-16.50	-18.00
4	🟩	Dense Sand (Sub-soil)	-18.00	-30.00

Figure 4.23: Subsoil profile for embankment at Borehole -4 (Chainage K3+900)



Borehole_4

x 0.000

y 0.000

Head -0.5000

Layers			Borehole_1	
#		Material	Top	Bottom
1	🟩	Soft Silty Clay (sub-soil	0.000	-1.500
2	🟪	Silty Fine Sand (Sub-soi	-1.500	-4.500
3	🟨	Silty clay (Sub-soil)	-4.500	-16.50

Figure 4.24: Subsoil profile for embankment at Borehole -6 (Chainage K4+700)

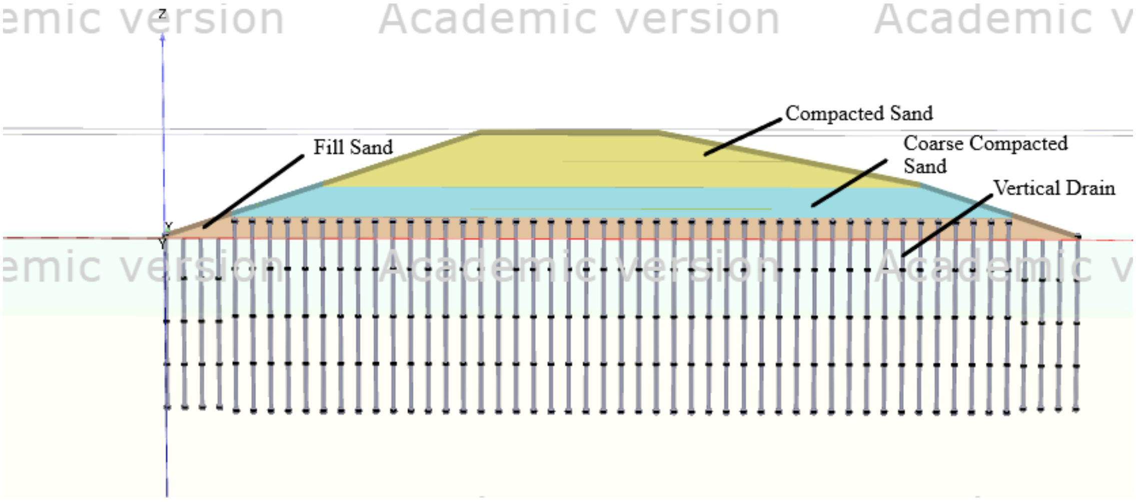


Figure 4.25: Modeling of embankment section (Refer to **Figure: 4.17**)

4.3.6.2 Material modelling

A material model is a set of equations that describe the stress-strain relationship of a particular material. In Plaxis, there are several material models to model the characteristics of materials; all material models in Plaxis are based on a relationship between the effective stress rates (σ'), and the strain rates$(\in')$. Mohr-Coulomb model, the Hardening Soil model, the Hardening Soil model with small-strain stiffness, the Soft soil model, Soft Soil Creep model, etc., are important models for different types of soil and interfaces. Geotextile used in embankment is modelled as elastic material. Engineering properties for Geotextile, sub-soil and embankment materials for the superdyke model are presented in Table 4.10.

4.3.6.3 Staging on embankment model

Construction of the embankment in the project is done in different phases to allow the soil layers to consolidate. Plaxis 3D facilitates the model of the embankment in different stages and allows time to consolidate. We have used this option to represent the real project condition in both embankment model cases. **Table 4.11** represents the activation of different parts of the embankment in various stages and times allowed for consolidation.

Table 4.10: Engineering properties for Geotextile, sub-soil and embankment materials.

Properties of Geotextile		
Material name	Material model	Tensile Strength (kN/m)
Geotextile	Elastic	2500

Properties for sub-soil and embankment materials.						
Parameter	**Name**	**Compacted Clay**	**Compacted Sand**	**Compacted Coarse- Sand**	**Fill Sand**	**Unit**
Material model	Model	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	
Typeof material behaviour	Type	Undrained (A)	Undrained (A)	Drained	Undrained (A)	
Soil unit weight above phreatic level	$\gamma unsat$	11	16	17	16	kN/m^3
Soil unit weight below phreatic level	γsat	18	19	20	19	kN/m^3
Initial void ratio	e_{init}	0.9	1.19	1	1.25	
Shear wave velocity	V_s	100	120	130	150	m/s

Table 4.10 (contd.): Engineering properties for Geotextile, sub-soil and embankment materials.

Parameter	**Name**	**Compacted Clay**	**Compacted Sand**	**Compacted Coarse- Sand**	**Fill Sand**	**Unit**
Young's modulus (constant)	E'	$22.5 * 10^3$	$63.4 * 10^3$	$58.5 * 10^3$	$73.39 * 10^3$	kN/m^2
Poisson's ratio	ν'	0.3	0.3	0.3	0.3	
Cohesion (constant)	c_{ref}'	20	2	1	1	kN/m^2
Friction angle	φ'	2	25	35	25	Degree(°)
Dilatancy angle	ψ	0	0	1	0	Degree(°)
Groundwater						
Data set		USDA	Hypres	USDA	Hypres	
Model	-	Van Genuchten	From data set	Van Genuchten	From data set	
Soil type	-	Silty Clay	Medium Sand	Sand	Medium fine	
> 2μm	-	48	19	4	19	%
2μm - 50μm	-	45	74	4	74	%

Table 4.10 (contd.): Engineering properties for Geotextile, sub-soil and embankment materials.

Parameter	**Name**	**Compacted Clay**	**Compacted Sand**	**Compacted Coarse- Sand**	**Fill Sand**	**Unit**
50µm - 2mm	-	7	7	92	7	%
Use defaults	-					
Horizontal permeability (x-direction)	k_x	$4.75 * 10^{-3}$	0.02272	7.128	0.02272	m/day
Horizontal permeability (y-direction)	k_y	$4.75 * 10^{-3}$	0.02272	7.128	0.02272	m/day
Vertical permeability	k_z	$4.75 * 10^{-3}$	0.02272	7.128	0.02272	m/day
Change in permeability	k	$1 * 10^{15}$	$1 * 10^{15}$	$1 * 10^{15}$	$1 * 10^{15}$	-
Initial						
K_0	-	Automatic	Automatic	Automatic	Automatic	
Lateral earth pressure coefficient	K_0	0.5000	0.5000	0.5000	0.5000	

Table 4.10 (contd.): Engineering properties for Geotextile, sub-soil and embankment materials.

Parameter	**Name**	**Compacted Clay**	**Compacted Sand**	**Compacted Coarse- Sand**	**Fill Sand**
Parameter	Name	Very soft silty clay	Soft silty clay	Medium stiff clay	Unit
Material model	Model	Soft soil	Soft soil	Mohr-Coulomb	
Type of material behaviour	Type	Undrained (A)	Undrained (A)	Drained	
Soil unit weight above phreatic level	$\gamma unsat$	15	13.5	15.5	kN/m^3
Soil unit weight below phreatic level	γsat	18	15	18	kN/m^3
Initial void ratio	e_{init}	1.19	1.21	1	
Shear wave velocity	V_s	-	-	120	m/s
Compression Index	C_c	0.39	0.4	-	
Swell Index	C_s	0.1	0.08	-	

Table 4.10 (contd.): Engineering properties for Geotextile, sub-soil and embankment materials.

Parameter	**Name**	**Compacted Clay**	**Compacted Sand**	**Compacted Coarse- Sand**	**Fill Sand**
Young's modulus (constant)	E'	-	-	$45.5 * 10^3$	kN/m^2
Poisson's ratio	ν'	-	-	0.3	
Cohesion (constant)	c_{ref}'	12	20	2	kN/m^2
Friction angle	φ'	1	1	25	Degree(°)
Dilatancy angle	ψ	0	0	1	Degree(°)
Data set		USDA	Hypres	Hypres	
Model	-	Van Genuchten	Van Genuchten	Van Genuchten	Van Genuchten
Soil type	-	Silty Clay			
> 2µm	-	48	19	19	%
2µm - 50µm	-	45	74	74	%
50µm - 2mm	-	7	7	7	%

Table 4.10 (contd.): Engineering properties for Geotextile, sub-soil and embankment materials.

Parameter	**Name**	**Compacted Clay**	**Compacted Sand**	**Compacted Coarse- Sand**	**Fill Sand**
Use defaults	-				
Horizontal permeability (x-direction)	k_x	$4.75 * 10^{-3}$	$4.75 * 10^{-3}$	0.04	m/day
Horizontal permeability (y-direction)	k_y	$4.75 * 10^{-3}$	$4.75 * 10^{-3}$	0.04	m/day
Vertical permeability	k_z	$4.75 * 10^{-3}$	$4.75 * 10^{-3}$	0.04	m/day
Change in permeability	c_k	$1 * 10^{15}$	$1 * 10^{15}$	$1 * 10^{15}$	-
K_0	-	Automatic	Automatic	Automatic	
Lateral earth pressure coefficient	K_0	0.5000	0.5000	0.5000	

Table 4.11: Stage construction phases for embankment

Phase	**Analysis type**	**Elements**	**Activate**	**Allowed time (Days)**
Initial Phase	K_o	Sub-soil	✓	-
		Fill Sand	X	
		Vertical Drain	X	
		Compacted Coarse Sand (Part-1)	X	
		Geotextile	X	
		Compacted Coarse Sand (Part-1)	X	
		Compacted Sand (Part-1)	X	
		Compacted Sand (Part-2)	X	
Phase 1	Consolidation	Sub-soil	✓	7 (Construction)
		Fill Sand	✓	
		Vertical Drain	X	
		Compacted Coarse Sand (Part-1)	X	
		Geotextile	X	
		Compacted Coarse Sand (Part-1)	X	
		Compacted Sand (Part-1)	X	
		Compacted Sand (Part-2)	X	
Phase 2	Plastic	Sub-soil	✓	30 (Consolidation)
		Fill Sand	✓	
		Vertical Drain	✓	
		Compacted Coarse Sand (Part-1)	X	
		Geotextile	X	
		Compacted Coarse Sand (Part-1)	X	
		Compacted Sand (Part-1)	X	
		Compacted Sand (Part-2)	X	

Table 4.11 (contd.): Stage construction phases for embankment

Phase	**Analysis type**	**Elements**	**Activate**	**Allowed time (Days)**
Phase 3	Consolidation	Sub-soil	✓	3 (Construction)
		Fill Sand	✓	
		Vertical Drain	✓	
		Compacted Coarse Sand (Part-1)	✓	
		Geotextile	X	
		Compacted Coarse Sand (Part-1)	X	
		Compacted Sand (Part-1)	X	
		Compacted Sand (Part-2)	X	
Phase 4	Plastic	Sub-soil	✓	15 (Consolidation)
		Fill Sand	✓	
		Vertical Drain	✓	
		Compacted Coarse Sand (Part-1)	✓	
		Geotextile	✓	
		Compacted Coarse Sand (Part-1)	X	
		Compacted Sand (Part-1)	X	
		Compacted Sand (Part-2)	X	
Phase 5	Consolidation	Sub-soil	✓	7 (Construction)
		Fill Sand	✓	
		Vertical Drain	✓	
		Compacted Coarse Sand (Part-1)	✓	
		Geotextile	✓	
		Compacted Coarse Sand (Part-2)	✓	
		Compacted Sand (Part-1)	X	
		Compacted Sand	X	
Phase 6	Plastic	Sub-soil	✓	15 (Consolidation)
		Fill Sand	✓	
		Vertical Drain	✓	

Table 4.11 (contd.): Stage construction phases for embankment

Phase	Analysis type	Elements	Activate	Allowed time (Days)
		Compacted Coarse Sand (Part-1)	✓	
		Geotextile	✓	
		Compacted Coarse Sand (Part-2)	✓	
		Compacted Sand (Part-1)	✓	
		Compacted Sand (Part-2)	✓	
Phase 7	Consolidation	Sub-soil	✓	5 (Construction)
		Fill Sand	✓	
		Vertical Drain	✓	
		Compacted Coarse Sand (Part-1)	✓	
		Geotextile	✓	
		Compacted Coarse Sand (Part-2)	✓	
		Compacted Sand (Part-1)	✓	
		Compacted Sand (Part-2)	X	
Phase 8	Plastic	Sub-soil	✓	15 (Consolidation)
		Fill Sand	✓	
		Vertical Drain	✓	
		Compacted Coarse Sand (Part-1)	✓	
		Geotextile	✓	
		Compacted Coarse Sand (Part-2)	✓	
		Compacted Sand (Part-1)	✓	
		Compacted Sand (Part-2)	X	
Phase 9	Consolidation	Sub-soil	✓	7 (Construction)
		Fill Sand	✓	
		Vertical Drain	✓	
		Compacted Coarse Sand (Part-1)	✓	
		Geotextile	✓	

Table 4.11 (contd.): Stage construction phases for embankment

Phase	Analysis type	Elements	Activate	Allowed time (Days)
		Compacted Coarse Sand (Part-2)	✓	
		Compacted Sand (Part-1)	✓	
		Compacted Sand	✓	
Phase 10	Plastic	Sub-soil	✓	15 (Consolidation)
		Fill Sand	✓	
		Vertical Drain	✓	
		Compacted Coarse Sand (Part-1)	✓	
		Geotextile	✓	
		Compacted Coarse Sand (Part-2)	✓	
		Compacted Sand (Part-1)	✓	
		Compacted Sand	✓	
Phase 11	Safety	Sub-soil	✓	-
		Fill Sand	✓	
		Vertical Drain	✓	
		Compacted Coarse Sand (Part-1)	✓	
		Geotextile	✓	
		Compacted Coarse Sand (Part-2)	✓	
		Compacted Sand (Part-1)	✓	
		Compacted Sand	✓	

4.3.6.4 Results of embankment models

The embankment are modeled in phases and analyzed for consolidation settlement. Here is the final settlement profile of the embankment sections. From the model results (Figure 4.26 and Figure 4.27), the settlement values at section K3+900 and K4+700 are found 214mm and 490 mm. The factor of safety of the embankment sections (K3+900 and K4+700) are found as 2.05 and 1.96(Figure 4.28 and Figure 4.29).

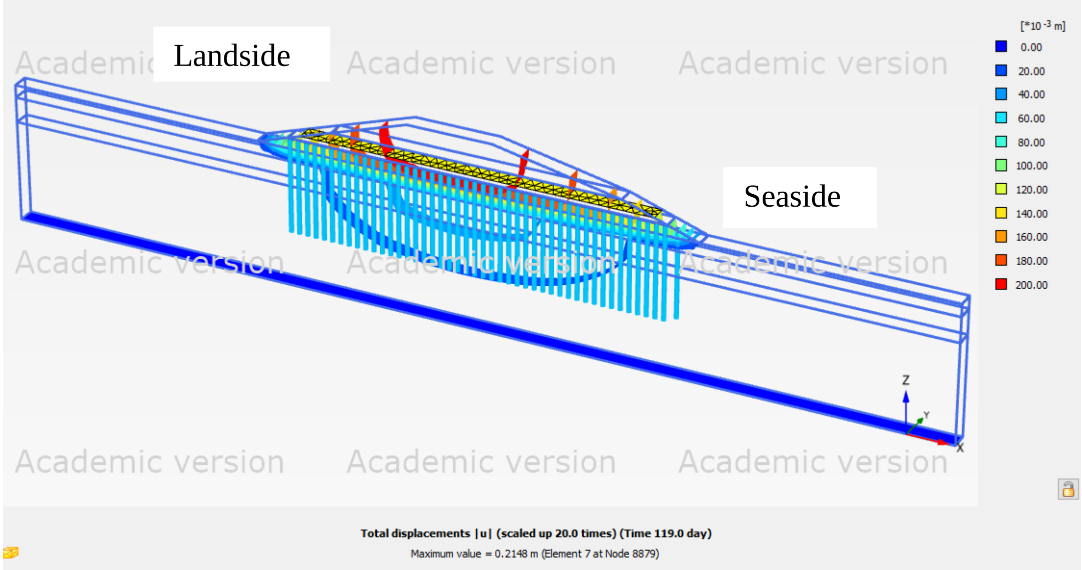


Figure 4.26: Settlement of embankment located at K3+900 (Borehole 04)

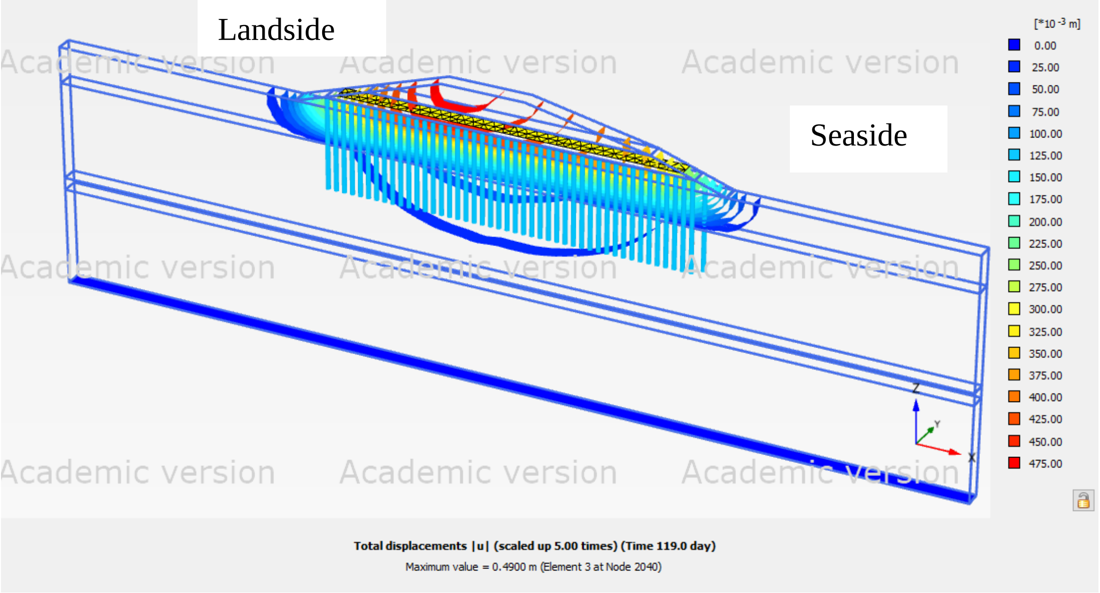


Figure 4.27: Settlement of embankment located at K4+700 (Borehole 06)

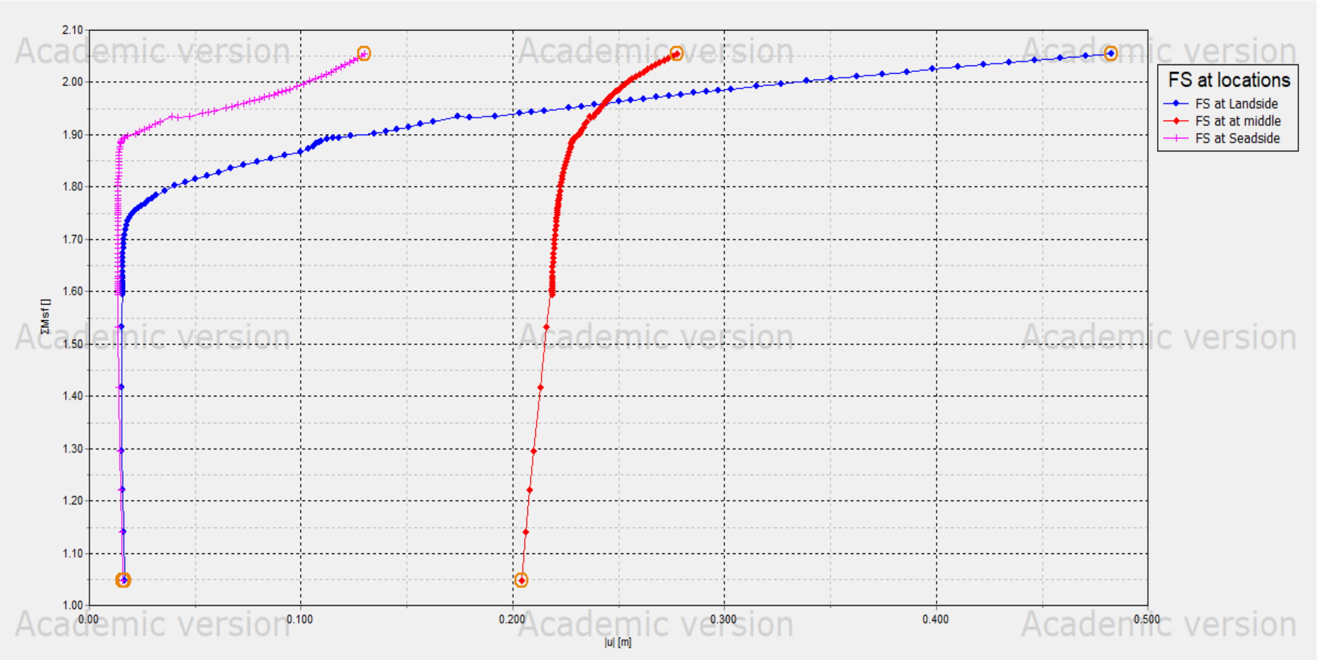


Figure 4.28: Factor of safety of embankment located at K3+900 (Borehole 04)

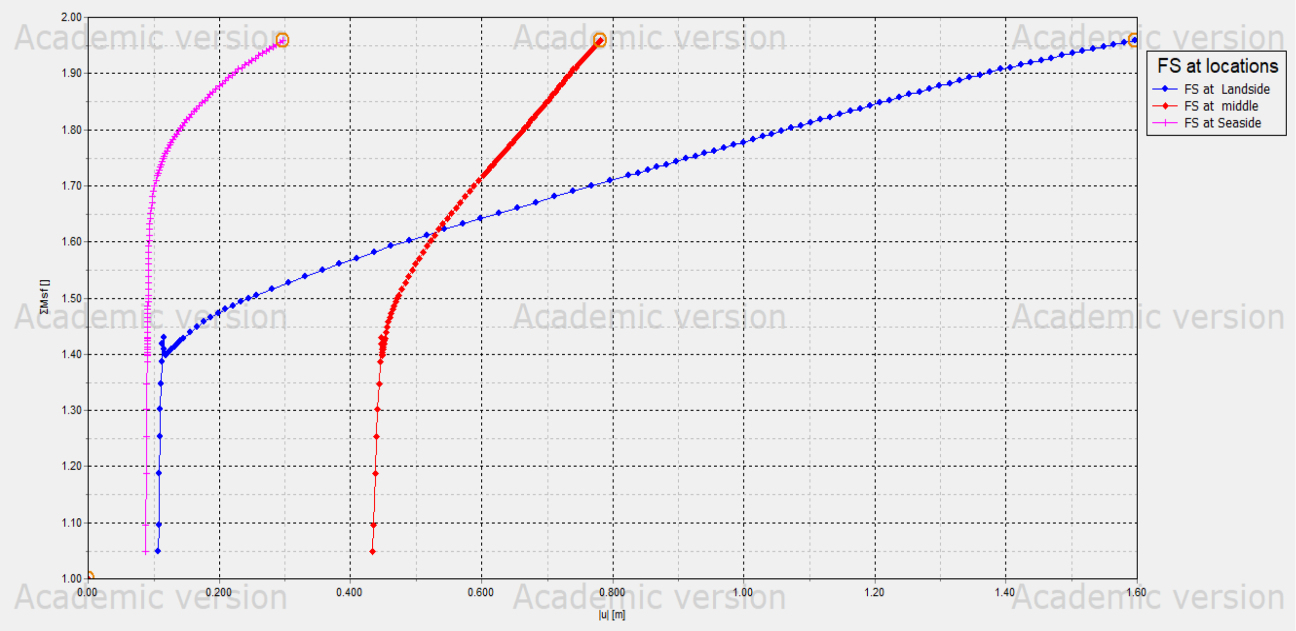


Figure 4.29: Factor of safety of embankment located at K4+700 (Borehole 06)

4.3.6.5 Effect of Meshing

A fully defined geometry is divided into finite elements for performing finite element calculation. These combinations of the finite element are called mesh. Mesh coarseness is considered to have a significant effect on calculated results. Fine meshing is vital to get accurate results in any analysis, but it takes longer to calculate. The mesh generation process includes soil stratigraphy, structure, loads, and boundary. The element distribution depends on the relative element size factor (r_e); there are five global levels in PLAXIS, as shown in Table 4.12.

Table 4.12: Types of mesh in PLAXIS 3D.

Element Distribution	r_e
Very Coarse	2
Coarse	1.5
Medium	1.0
Fine	0.7
Very Fine	0.5

To study the sensitivity of mesh sizes on results obtained in the analysis four types of four mesh sizes have been used for same embankment model. Figure 4.30, 4.31, 4.32, and 4.33 show the mesh element connectivity plot for coarse, medium, fine and very fine mesh.

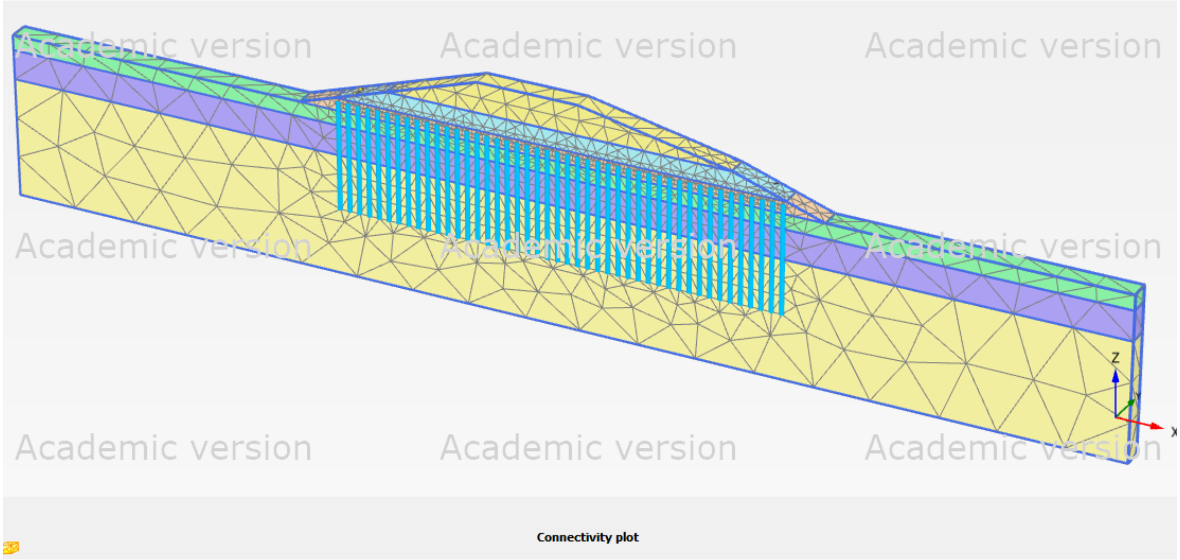


Figure 4.30: Mesh Connectivity plot of embankment model for Coarse Mesh

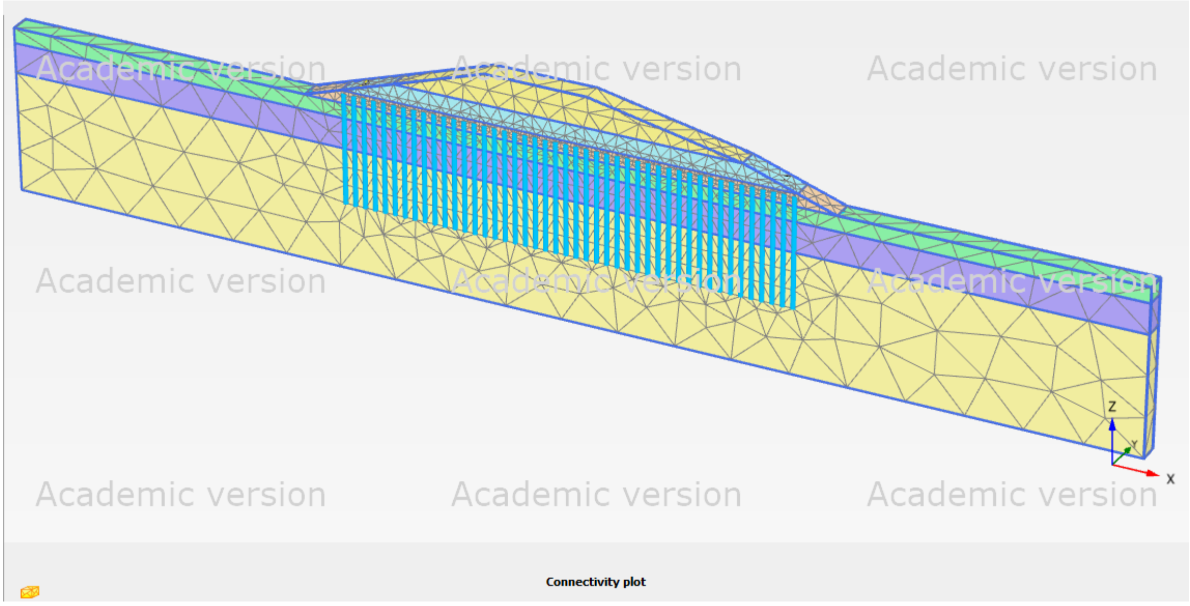


Figure 4.31: Mesh Connectivity plot of embankment model for Medium Mesh

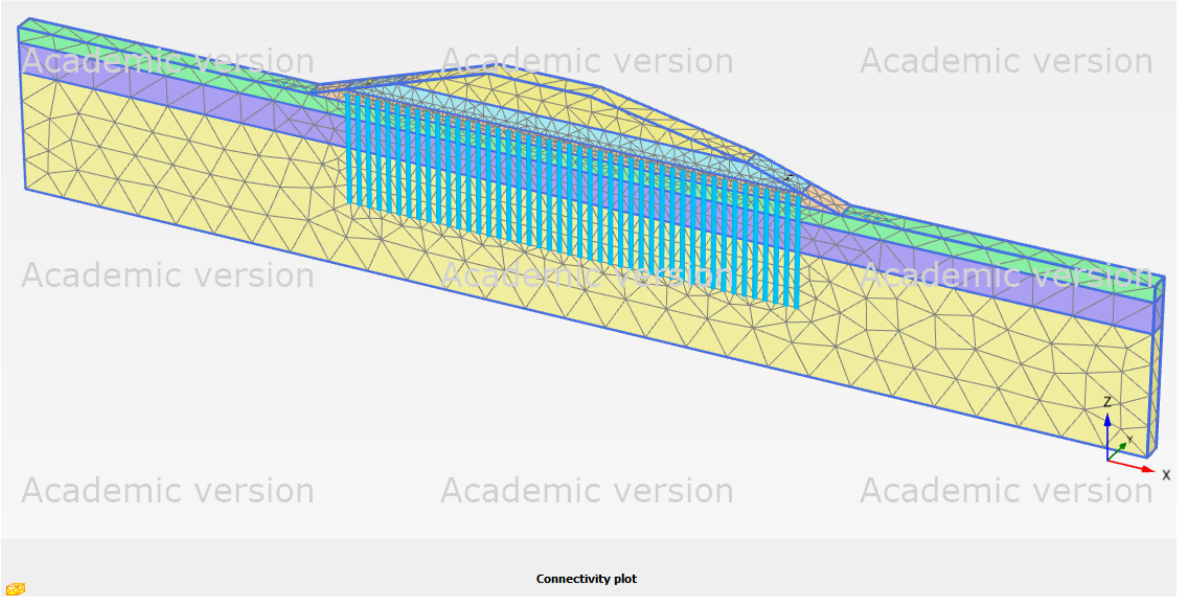


Figure 4.32: Mesh Connectivity plot of embankment model for Fine Mesh

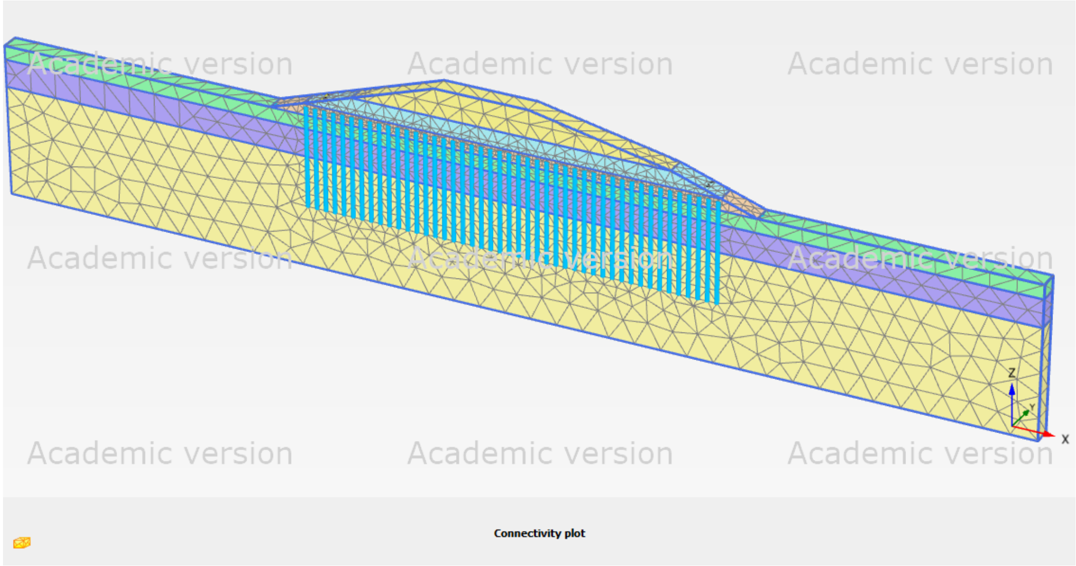


Figure 4.33: Mesh Connectivity plot of embankment model for Very Fine Mesh

4.3.6.6 Effect of Mesh on safety and settlement estimation

To observe the effect of mesh, the settlement of the embankment model are observed for coarse, medium coarse, fine and very fine mesh. Figure 4.34, 4.35, 4.36, 4.37 show the settlement profile of the embankment for the four mesh cases.

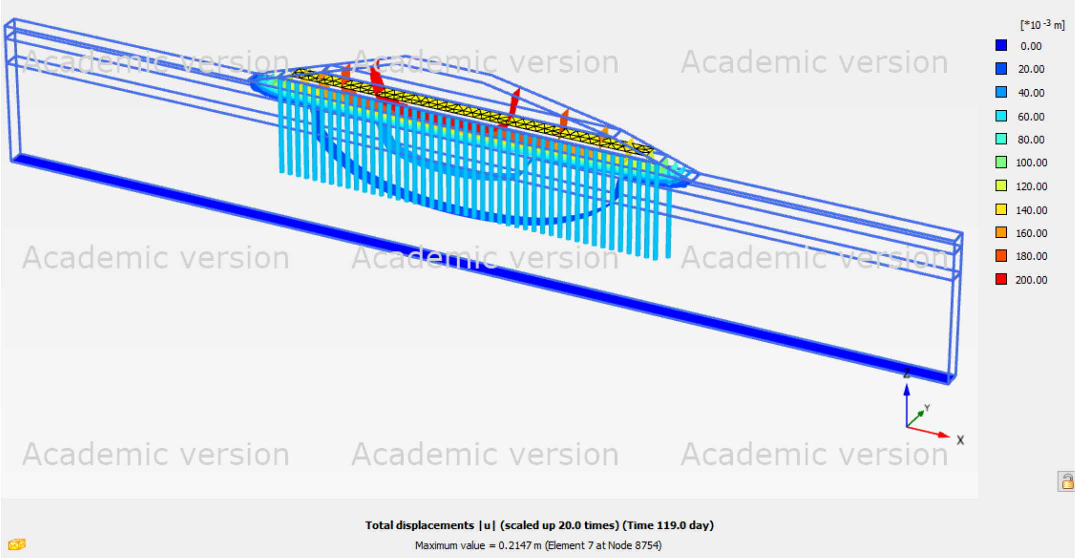
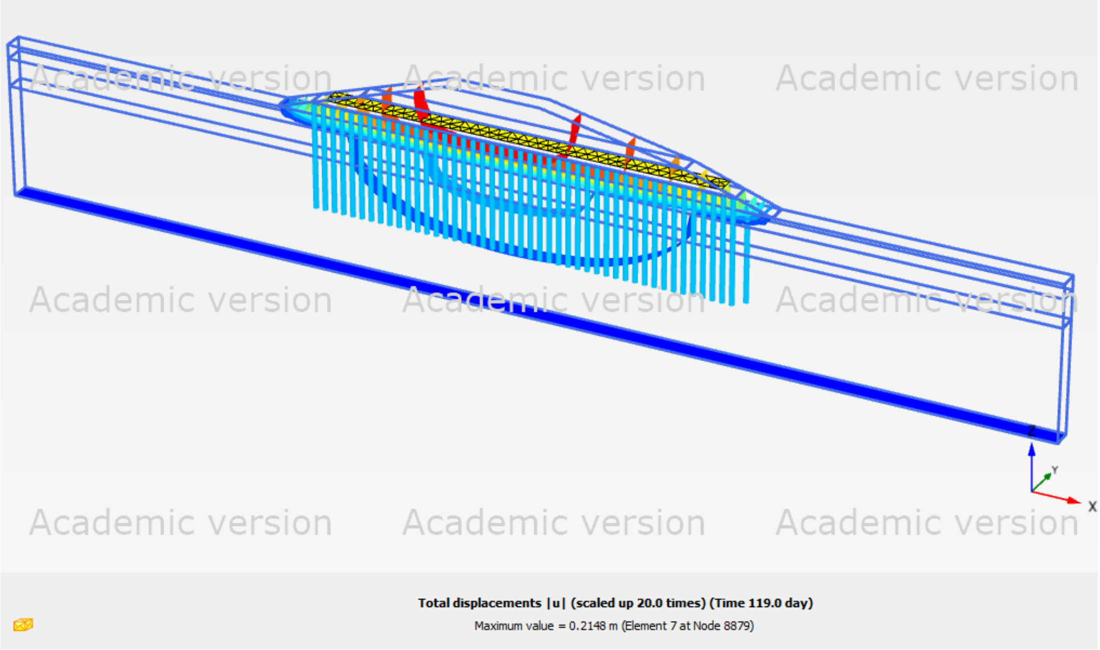
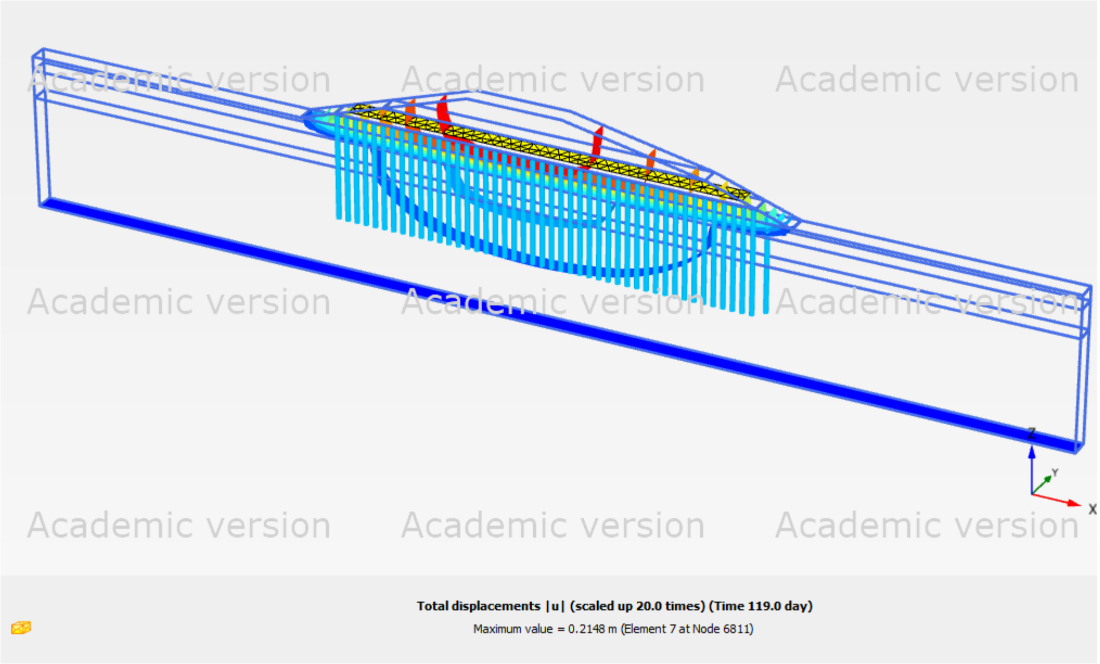


Figure 4.34: Settlement profile of embankment for coarse mesh



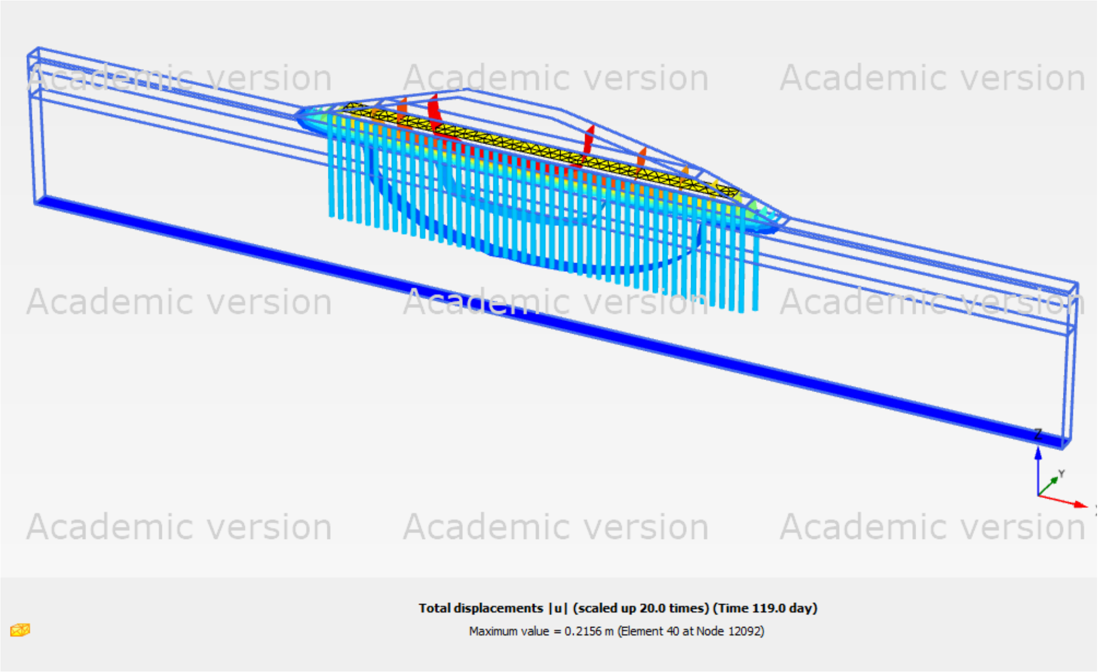
Total displacements |u| (scaled up 20.0 times) (Time 119.0 day)
Maximum value = 0.2148 m (Element 7 at Node 8879)

Figure 4.35: Settlement profile of embankment for medium coarse mesh



Total displacements |u| (scaled up 20.0 times) (Time 119.0 day)
Maximum value = 0.2148 m (Element 7 at Node 6811)

Figure 4.36: Settlement profile of embankment for fine mesh



Total displacements |u| (scaled up 20.0 times) (Time 119.0 day)

Maximum value = 0.2156 m (Element 40 at Node 12092)

Figure 4.37: Settlement profile of embankment for very fine mesh

From the results of total settlement of the embankment models for different mesh sizes, it is observed that for coarse mesh maximum settlement value is 214.7 mm, for medium mesh the settlement value is 214.8 mm, for fine mesh settlement value is 214.8 mm, and for very fine mesh settlement value is 215.6 mm.

A predetermined point at the middle of the embankment is selected for every mesh size analysis to observe the effect of the mesh size closely. The consolidation settlement of that point is analyzed for the project time and shown in Figure 4.38.

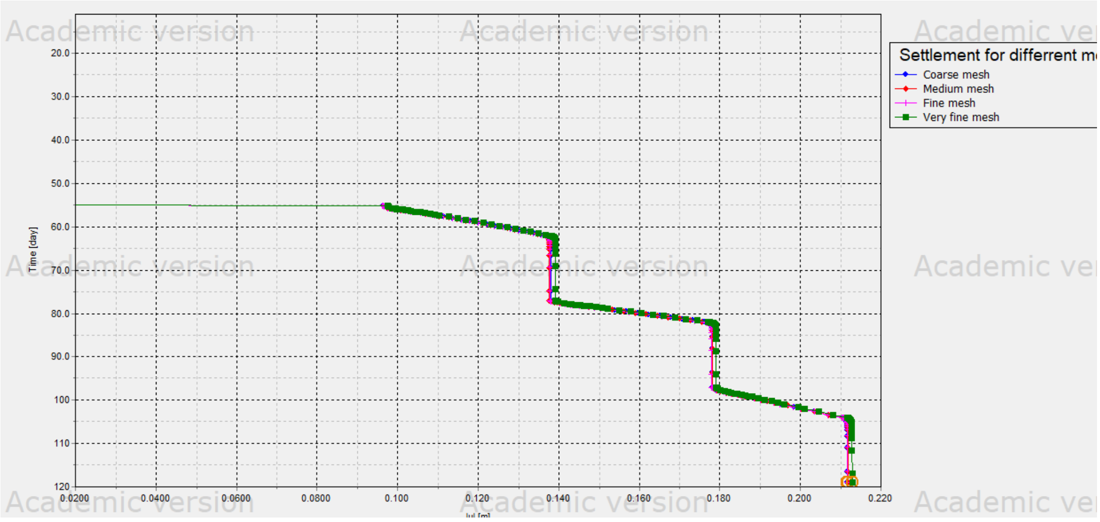


Figure 4.38: Settlement of embankment at middle for very different mesh sizes.

From coarse, medium and fine mesh the value of settlement at middle of the embankment is almost same, whereas, for the very fine mesh the settlement value is slightly higher (Figure 4.39).

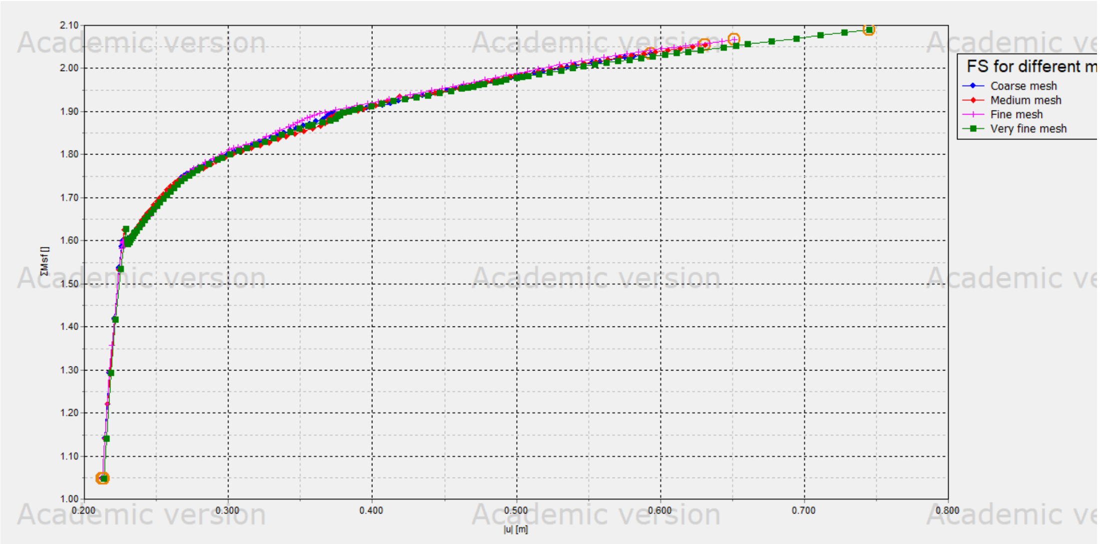


Figure 4.39: Factor of safety of the embankment at middle for very different mesh sizes.

From the above graph for all types of mesh sizes the value of factor of safety of the embankment at middle is about 2.0. The safety value is slightly lower for very fine mesh size analysis.

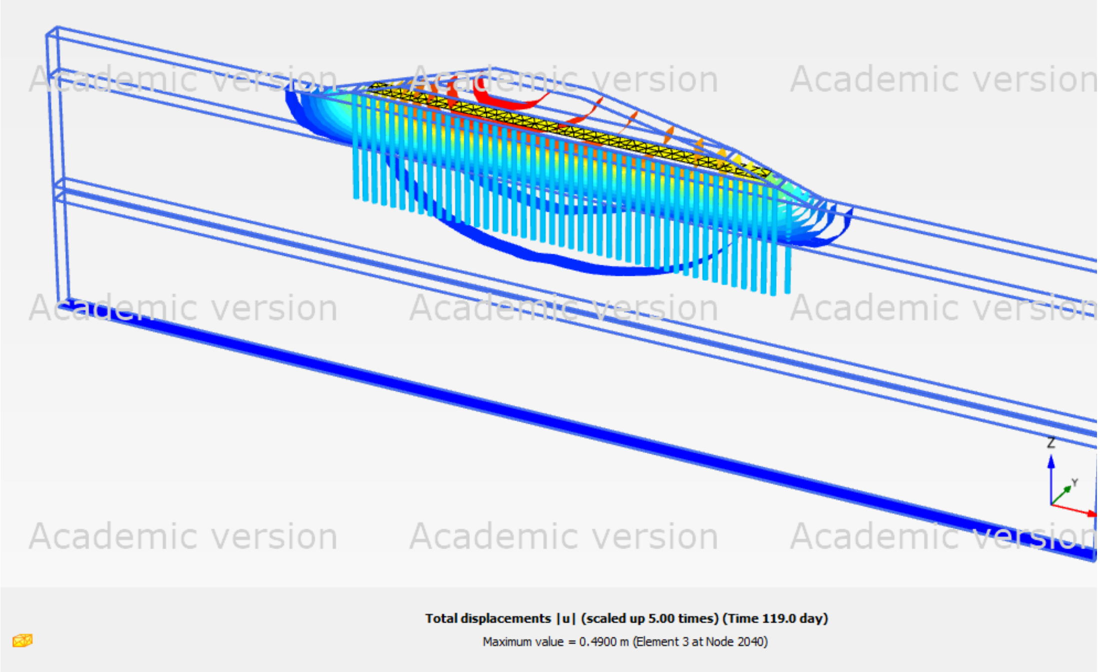
Observing the analysis of embankment models for different mesh sizes it is evident that the mesh size has very little effect on the estimation of consolidation settlement and factor of safety. However, the calculation time increases with the increase of coarseness of the mesh elements.

4.3.6.7 Effect of Soil model on safety and settlement estimation

In Plaxis, different soil models are available to specify the stress-strain behavior of soils. Linear Elastic Model, Mohr-Coulomb model, Hardening soil model, Hardening soil model with small strain (HS small model), Soft Soil creep mode, Soft soil model are commonly used soil model available in PLAXIS 3D. Every soil model requires different soil parameters and applicability for different types of soils and projects. Table 2.3 presents the applicability of soil model for different types of soils in Plaxis 3D.

From the table, it is understandable that for clay soil soft soil model is very good; for sandy and silty soil HS small model is best, the Hardening soil model is fairly applicable, Mohr-Coulomb Model is unsophisticated for PLAXIS model.

We have used the Hardening soil model for sandy and silty soil, where triaxial test data is available; for clayey soil, where consolidation test is available, we have used the soft soil model. However, where the required laboratory data is not available, we used the Mohr-Coulomb soil model for modeling purposes. To understand the effect of different soil models for a particular soil type, we analyzed two embankment models with different soil models. For one case, the subsoil's silty clay and fine sand are modeled using the hardening soil model; for another case, a simple Mohr-Coulomb soil model is used for the subsoil. The soft clay layer is modeled using the soft soil model in both cases. Figure 4.40 and 4.41 present the effect of soil model on embankment settlement.



Total displacements |u| (scaled up 5.00 times) (Time 119.0 day)

Maximum value = 0.4900 m (Element 3 at Node 2040)

Figure 4.40: Total settlement for Mohr-Coulomb soil model used for sub-soil sandy soils

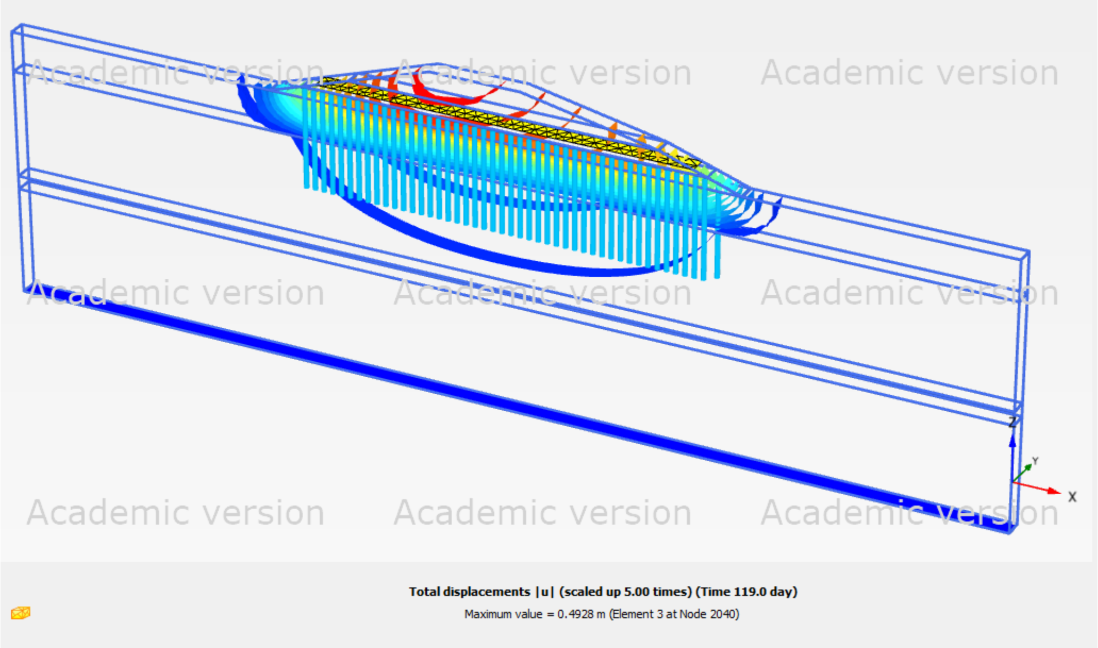


Figure 4.41: Total settlement for Hardening soil model used for sub-soil sandy soils

To closely observe the effect of soil model, we selected a point, toe of the embankment at landside, and analyzed the model for both cases. Figure 4.42 and 4.43 presents the effect of soil model on the settlement and safety of the embankment with time.

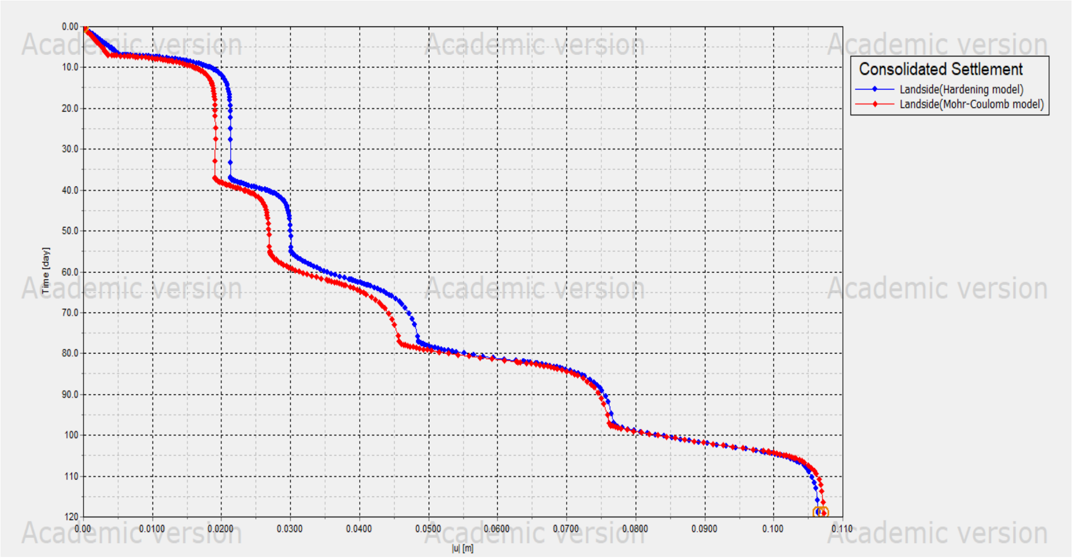


Figure 4.42: Comparison of toe settlement for Hardening soil model and Mohr-Coulomb soil model.

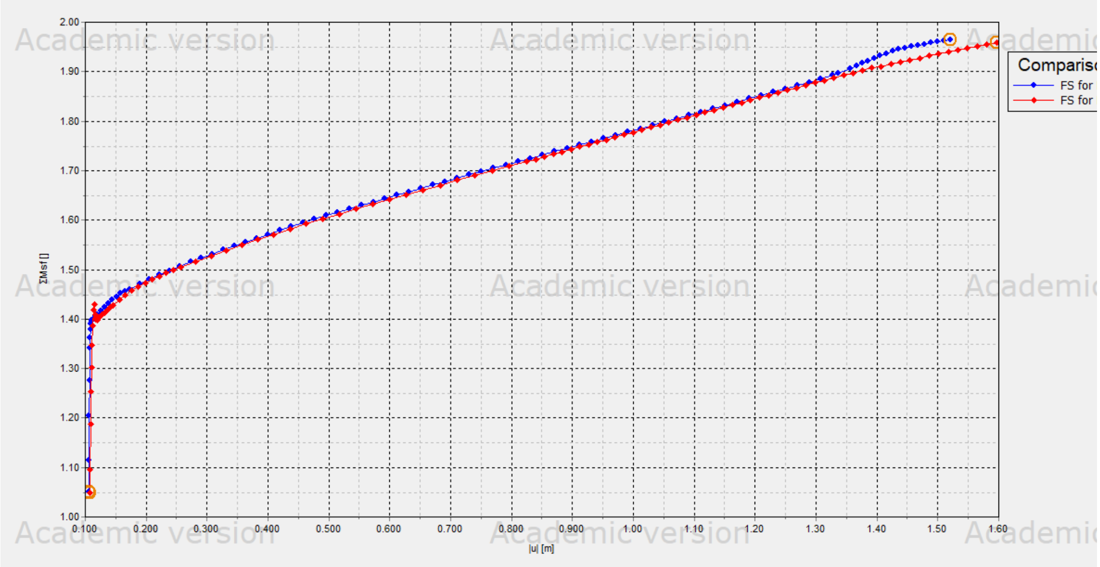


Figure 4.43: Comparison of FS at toe (landside) for Hardening soil model and Mohr-Coulomb soil model.

4.3.7 Validation of Embankment settlement and factor of safety

As previously discussed, validation is an important part for any numerical modeling. For this study, the newly constructed superdyke at Mirasarai has been modeled for settlement and safety analysis; and at the same time the performance of the superdyke was monitored for evaluating the model performance. The results are compared in the next sections.

4.3.7.1 Result from field observation

To measure the settlements at different locations of the embankment sections, settlement plates were places at predefined depth. One section of embankment, where settlements are known from field data, is selected to compare the field result with the finite element model consolidation settlement analysis. Figure 4.44, 4.45, 4.46 presents the settlement of the constructed embankment at the center, local side and sea side. Table 4.13 presents the summary of the measured settlement of the embankment at different locations.

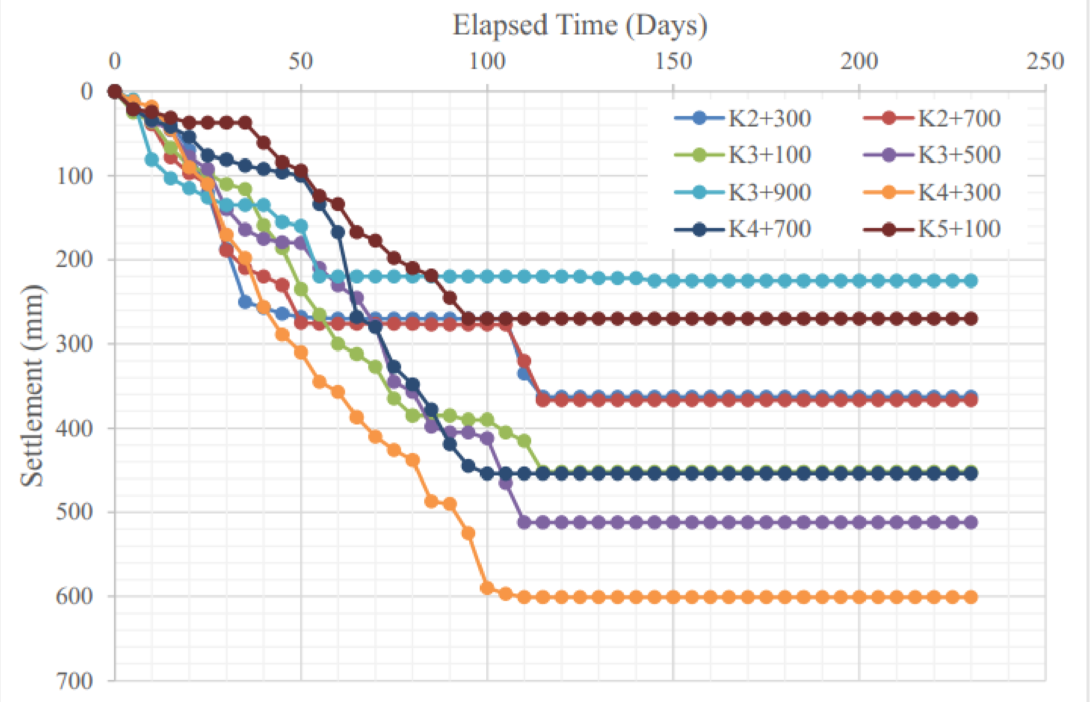


Figure 4.44: Measured settlement at the centerline of the embankment at different locations.

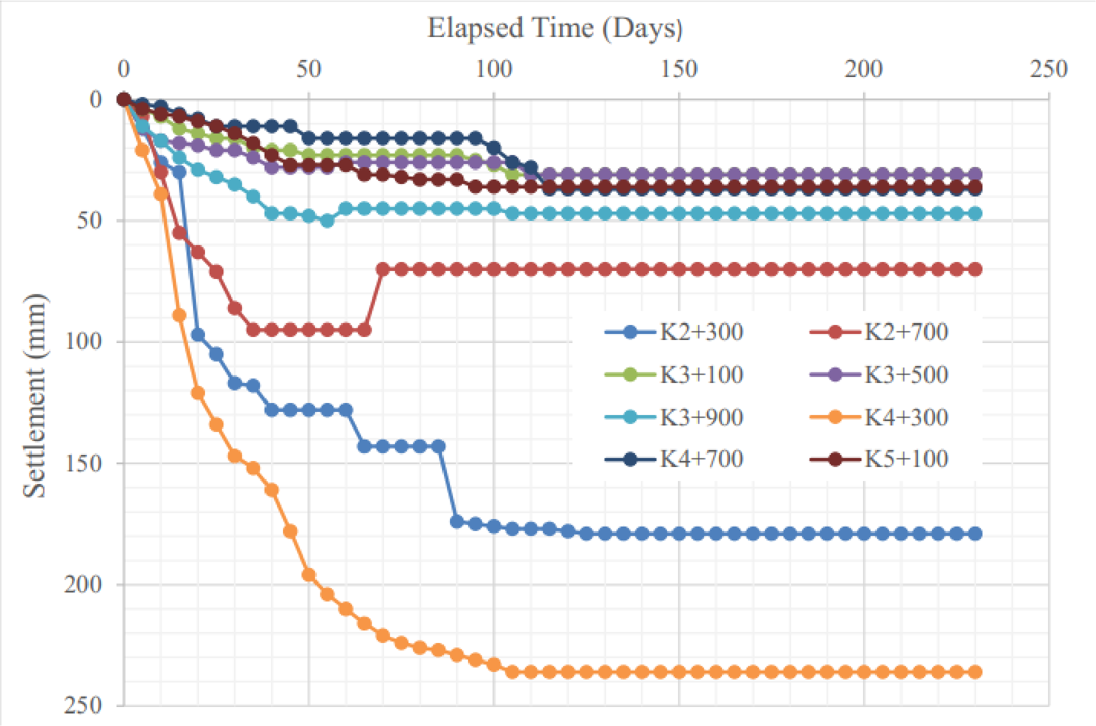


Figure 4.45: Measured settlement at the local side of the embankment at different locations.

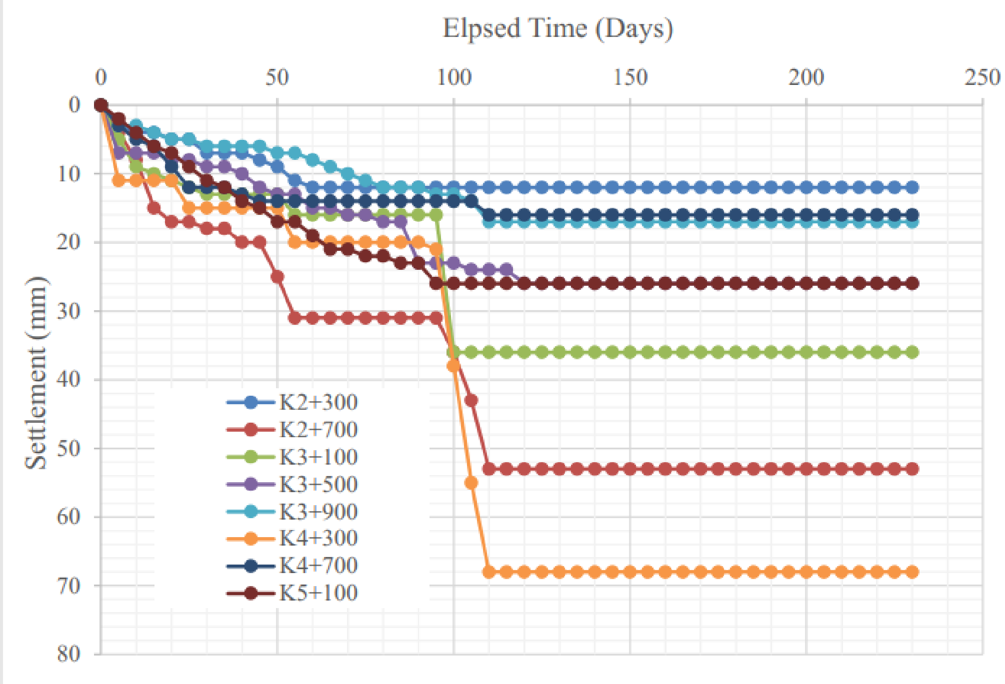


Figure 4.46: Measured settlement at the sea side of the embankment at different locations.

Table 4.13: Measured total consolidation settlement at the embankment center and toes at different chainages.

Chainage	**Elapsed time (day)**	**Settlement at center of embankment (mm)**	**Settlement at embankment toe (mm)**	
			Land side	**Sea side**
K2+300	115	363	179	12
K2+700	115	367	70	53
K3+100	115	452	31	36
K3+500	115	512	34	26
K3+900	66	225	47	17
K4+300	111	601	236	68
K4+700	101	454	37	16

4.3.7.2 Results from Plaxis Modeling

Two locations (K3+900 and K4+700) are selected to model embankment to observe settlement with time, where soil profile and soil parameters are taken from the article specified earlier. The model results for the location K3+900, settlement at the center, middle, and sea side of the embankment, are shown in Figure 4.47 and 4.48. The factor of safety of the embankment, estimated by PLAXIS, is shown in Figure 4.49.

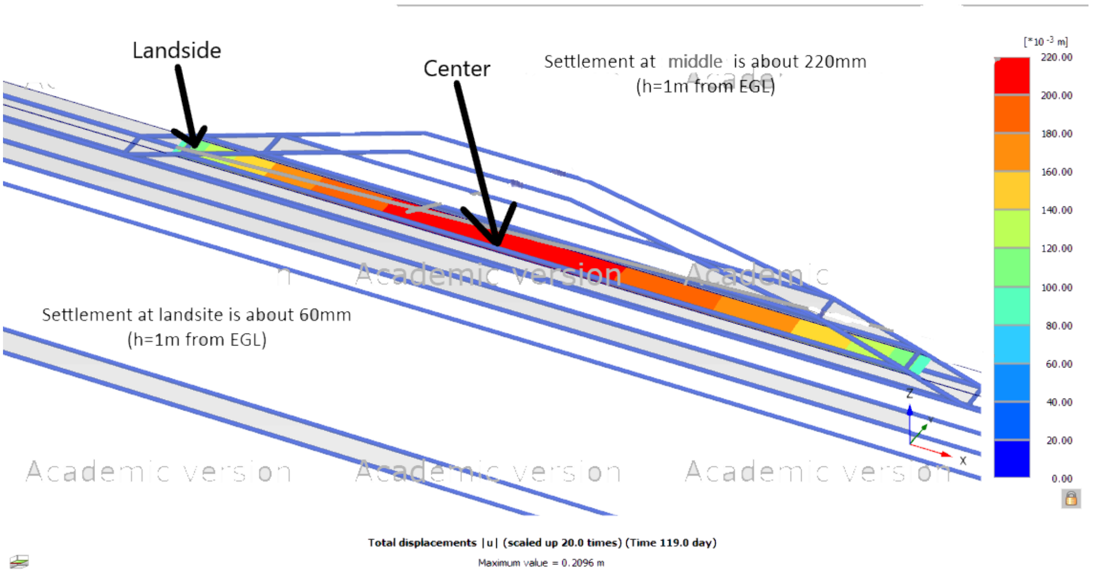


Figure 4.47 Consolidation settlement of the Mirasarai embankment (K3+900) at the center and landside.

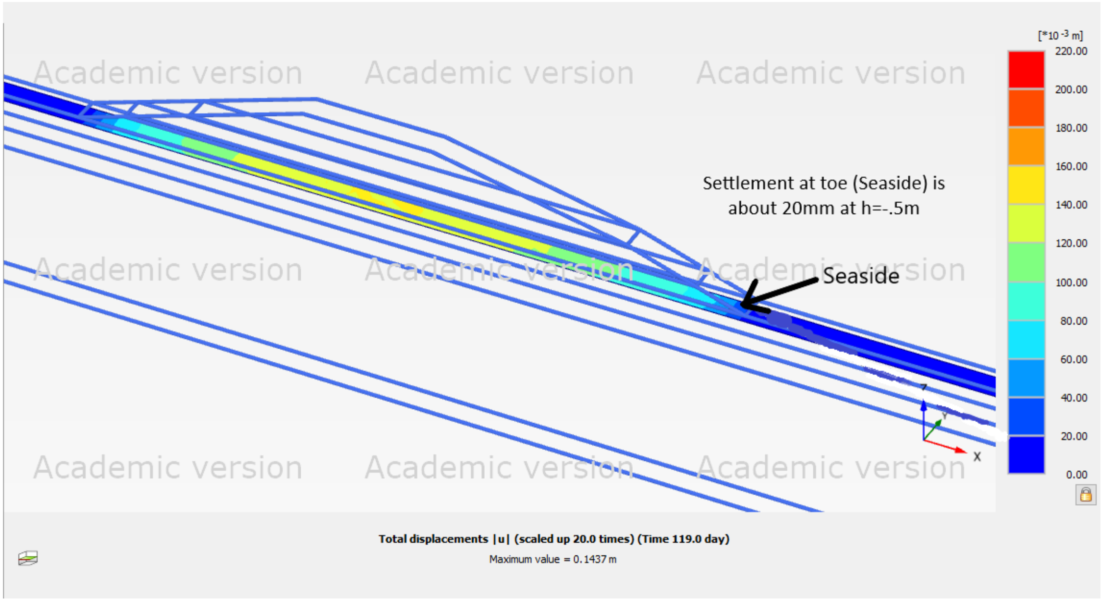


Figure 4.48 Consolidation settlement of the Mirasarai embankment (K3+900) at the center and seaside.

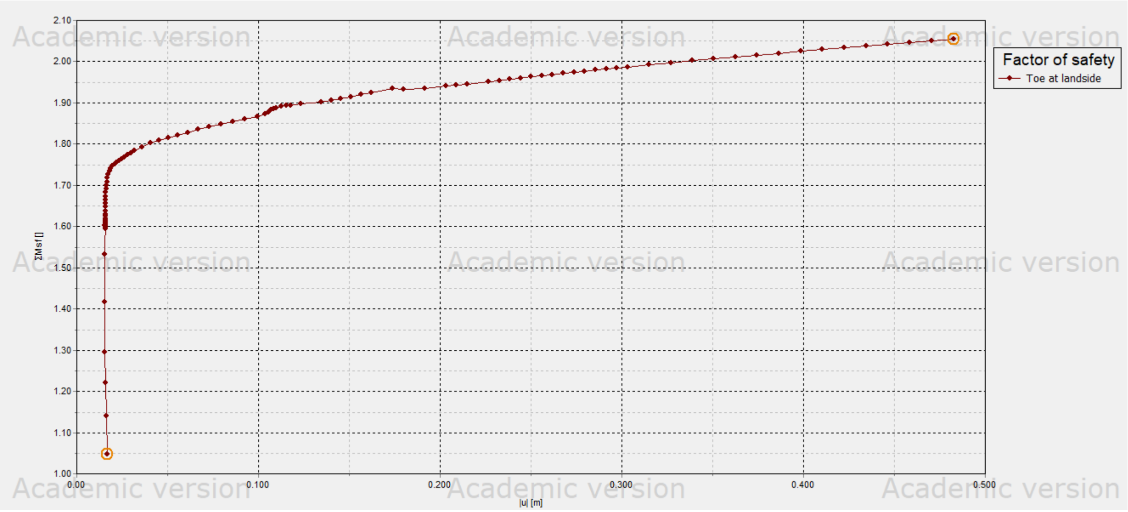


Figure 4.49: Factor of the safety of the Mirasarai embankment (K3+900)

4.3.7.3Comparison of model result with field observation

The main concern of this section is to compare the settlement and safety of the selected embankment section from field observation and from embankment model result. During the implementation of the Mirasarai, Chittagong embankment settlement plates were installed to observe the settlement of the embankment with time at different locations (Figure 4.20).

The values of the observed settlement and calculated factor of safety is stated in Table 4.9 and 4.18; and the results of the numerical model is presented in section 4.3.7.2. Table 4.14 presents the of model results with field observation of the Mirasarai embankment. From the table, the consolidation settlement of the modeled embankment at the center is about 220 mm (field observation value is 225mm), at the landside point the settlement value is about 60mm (field observation value is 47mm), and at the seaside point the settlement value is about 20 mm (field observation value is 17mm). The calculated factor of safety of the embankment using Low’s (1989) is about 2.17 and the result from model embankment (Figure 4.49) shows the factor of safety of the embankment is about 2.1

Table 4.14: Comparison of model results with field observation of the Mirasarai embankment.

Location	**Time elapse after construction**	**Result from field observations**				**Result from PLAXIS model**			
		Settlement at different positions (mm)				**Settlement at different positions (mm)**			
Chainage	Days	At the center (mm)	Land side (mm)	Sea side (mm)	FS Low(1989)	At the center (mm)	Land side (mm)	Sea side (mm)	FS (PLAXIS)
K3+900	66	225	47	17	2.17	220	60	20	2.1
K4+700	101	454	37	16	1.88	490	40	25	1.9

For the estimation of settlement of the embankment, the Plaxis 3D model result is close enough with the field observation, better than the conventional theoretical estimation. The factor of safety of the embankment calculated from Plaxis model is also comparable with the theoretical estimation.

4.4 Modeling and Analysis of Coastal Embankments of Polders

The major objective of this study is to assess the geotechnical stability of the selected Polders. All of the Polders are modeled in PLAXIS 3D to evaluate their conditions against the major cyclone and storm surges the area suffered in the last decades. For every case, factor of safety, displacement of the Polders due to storm surge, and failure mechanism are summarized and presented in tables. All the pictures of settlement and failure mechanism off the Polders are presented in Appendix D.

4.4.1 Background of the study of the coastal embankments of polders

Bangladesh suffers enormous damage as a result of floods and storm surges every year which results in serious social and economic losses. Hundreds of people lose their valuable life and infrastructures like embankments, roads, bridges, become damaged. Especially, the coastal regions of Bangladesh suffer most due to regular cyclones and storm surges every year. Although the government of Bangladesh has improved the severity of damages through Cyclone Preparedness Program (CPP), due to the lack of effective warning system, still the country suffers sever consequence of cyclone and storm surges. Keeping the goals of sustainable development goals (SDG) in mind, Bangladesh University of Engineering and Technology (BUET), Institute of Water and Flood Management, Kyoto University started a research project titled “Research Project on Disaster Prevention/Mitigation Measures against Floods and Storm Surges in Bangladesh” with the financial support of Japan Science and Technology (JST) and Japan International Cooperation Agency (JICA). The project targeted three SDG goals, Goal 11: Sustainable cities and communities), Goal 6: Clean Water and Sanitation, and GOAL 13: Climate action. (SATREPS, 2013.). This project aimed to build flood and storm surge hazard maps, suggest strategies to limit damage from riverbank erosion and levee collapse, develop warning and evacuation systems, and work on forecasting and responding to flood-driven dispersion of hazardous substances. The prime objective was to build resilient local communities.

The project research was divided in five components. The objectives of the components are as follow:

i. Component one objective: Flood disaster risk assessment.

ii. Component two objective: Development of improved storm surge evacuation warning systems for Bangladesh coast.

iii. Component three objective: Land protection measures against bank erosion and levee break

iv. Component four objective: Study on flood assisted spreading of deposited toxic substances and possible mitigation measures

v. Component five objective: Disaster management strategy for resilient society

The component three was primarily concern with the investigation of geotechnical properties of coastal polder embankments and impact of major cyclones that might affect the embankments. Several geotechnical test programs were performed at different locations of polder areas. The soil sample collected during the test programs are tested in Geotechnical Engineering laboratory of Bangladesh university of Engineering and Technology. The detailed test program and geotechnical property investigation report are presented in Chapter 3 of this thesis. Another important part of this research was to estimate surge depth and thrust force faced this region during the major cyclones. Dr. Anisul Haque and his research team generated the effect of major cyclones by simulation of 170 pseudo-cyclones by applying numerical model Delft3D, analytical model DFM (Haque, et al., 2019; Akter, M. (2014). The summary of the cyclone effects are presented in Chapter 2.

4.4.2 Analysis of Bhola Polder Embankment

Bhola is one of the most severely affected Polder in the coast of Bangladesh. The Polder has been repaired through CEIP project (Figure 1.2; BWDB, 2013). The Soil properties of the Bhola Polder is presented in Table 4.15, based on geotechnical investigation reports (Table 3.15). The Polder is analyzed for different consolidation conditions: safety at the end of consolidation, rapid drawdown, slow drawdown and very slow water level change. For all the cases, settlement and the safety status of the Polder is presented in Table 4.16. The Bhola region was severely affected during cyclone SIDR with different intensity at different location. To evaluate the safety status of Bhola polder for different combination of surge height and thrust forces, the embankment model was analyzed for different combinations. All the figures of displacement and safety status of Bhola Polder embankments are presented in Appendix D**.**

4.4.3 Analysis of Patharghata, Barguna Polder Embankment

Barguna is one of the disaster prone Polder in the coast of Bangladesh. The Polder has been repaired through CEIP project (Figure 1.2; BWDB, 2013). The Soil properties of the Bhola Polder is presented in Table 4.18, based on geotechnical investigation reports (Table 3.15). The Polder is analyzed for different consolidation conditions: safety at the end of consolidation, rapid drawdown, slow drawdown and very slow water level change. For all the cases, settlement and the safety status of the Polder is presented in Table 4.19. The Barguna region was severely affected during cyclone SIDR with different intensity at different location. To evaluate the safety status of Bhola polder for different combination of surge height and thrust forces, the embankment model was analyzed for different combinations. All the figures of displacement and safety status of Barguna Polder embankments are presented in Appendix D**.**

4.4.4 Analysis of Satkhira Polder Embankment

Polders of Satkhira region are subjected to tidal surge regularly, every year this region has to face cyclone with storm surges, being near the saline. Satkhira is very important in economy due to agriculture, fisheries, vegetables, and the dairy industries. The failure of the Polder in this region cause drastic economic damage to the locality. The Soil properties of the Satkhira Polder is presented in Table 4.21, based on geotechnical investigation reports (Table 3.15).

The Polder is analyzed for different consolidation conditions: safety at the end of consolidation, rapid drawdown, slow drawdown and very slow water level change. For all the cases, settlement and the safety status of the Polder is presented in Table 4.21.

The Satkhira region was severely affected during cyclone SIDR with different intensity at different location. To evaluate the safety status of Bhola polder for different combination of surge height and thrust forces, the embankment model was analyzed for different combinations. All the figures of displacement and safety status of Satkhira Polder embankments are presented in Appendix D**.**

4.4.5 Analysis of Laxmipur, Noakhali Polder Embankment

The people of Noakhali play a vital role in Bangladesh's economy, especially in the remittance sector. Agriculture plays a vital role in the regional economy. 30% of the regional GDP comes from agriculture. That is why safety of the embankments are really important for agriculture. The Soil properties of the Noakhali Polder is presented in Table 4.24, based on geotechnical investigation reports (Table 3.15). The Polder is analyzed for different consolidation conditions: safety at the end of consolidation, rapid drawdown, slow drawdown and very slow water level change. For all the cases, settlement and the safety status of the Polder is presented in Table 4.25. The Noakhali region was severely affected during cyclone 1991 with different intensity at different location. To evaluate the safety status of Bhola polder for different combination of surge height and thrust forces, the embankment model was analyzed for different combinations. All the figures of displacement and safety status of Noakhali Polder embankments are presented in Appendix D**.**

4.4.6 Analysis of Anowara, Chittagong Polder Embankment

Anowara, Chittagong is situated just behind the Bay of Bengal. It has to withstand cyclones and storm surges. To protect the locality, as a first line of defense, stability of embankment is very important. The Soil properties of the Anowara Polder is presented in Table 4.27, based on geotechnical investigation reports (Table 3.15). The Polder is analyzed for different consolidation conditions: safety at the end of consolidation, rapid drawdown, slow drawdown and very slow water level change. For all the cases, settlement and the safety status of the Polder is presented in Table 4.28. The Anowara, Chittagong region was severely affected during cyclone 1991 with different intensity at different location. To evaluate the safety status of Bhola polder for different combination of surge height and thrust forces, the embankment model was analyzed for different combinations. All the figures of displacement and safety status of Anowara Polder embankments are presented in Appendix D**.**

4.4.7 Analysis of Moheskhali, Cox's Bazar Polder Embankment

Moheskhali is an important location for economy. BEZA has allotted about 510 acre lands for Petrochemical and Gas industry.

According to the plan, petrochemical refinery, warehouse of petrochemical products and LPG terminal will be built here soon.

The stability of the Moheskhali Polder is particularly important for economy. The Soil properties of the Anowara Polder is presented in Table 4.30, based on geotechnical investigation reports (Table 3.15). The Polder is analyzed for different consolidation conditions: safety at the end of consolidation, rapid drawdown, slow drawdown and very slow water level change. For all the cases, settlement and the safety status of the Polder is presented in Table 4.31. The Moheskhali, Cox's Bazar region was severely affected during cyclone 1991 with different intensity at different location. To evaluate the safety status of Bhola polder for different combination of surge height and thrust forces, the embankment model was analyzed for different combinations. All the figures of displacement and safety status of Moheskhali Polder embankments are presented in Appendix D.

4.4.8 Analysis of Sitakunda Polder Embankment

Sitakunda is one of the major Upazilla in Chittagong for the ship breaking industry. The stability of Sitakunda is important for the industry area and people living there. The Soil properties of the Anowara Polder is presented in Table 4.33, based on geotechnical investigation reports (Table 3.15). The Polder is analyzed for different consolidation conditions: safety at the end of consolidation, rapid drawdown, slow drawdown and very slow water level change. For all the cases, settlement and the safety status of the Polder is presented in Table 4.31. The Sitakunda region was severely affected during cyclone 1991 with different intensity at different location. To evaluate the safety status of Bhola polder for different combination of surge height and thrust forces, the embankment model was analyzed for different combinations. All the figures of displacement and safety status of Sitakunda Polder embankments are presented in Appendix D.

Table 4.15: Soil properties for Bhola Polder embankment analysis.

Properties of soil for Charfassion, Bhola Polder Embankment Stability Analysis									
Soil location	**Thickness (m)**	**Soil Type**	**Soil model**	**Cohesion C′ (kN/m^2)**	**Angle of Friction φ'(degree)**	**Shear Wave Velocity (V) (m/sec)**	**Shear Modulus (Mpa)**	**Compression Index (c_c)**	**Swelling Index (c_s)**
Embankment	4.5m	Silty Clay	Mohr-columb	10	5	100	16	-	-
Sub-soil	4.5m	Silty Clay	Soft Soil	2	30	-	-	0.199	0.044
Sub-soil	4.5m	Fine Sand	Mohr-columb	0	36	200	70	-	-

Table 4.16: Safety status of Bhola Polder embankment for different conditions

Charfassion, Bhola Polder Embankment Stability Analysis					
Embankment Soil 4.5m (Silty Clay)		**Analysis type**	**Time**	**Total Displacements**	**Factor of Safety**
Cohesion C (kN/m^2)	Angle of Friction φ'(degree)	Consolidation	Days	mm	
10	28	Safety after construction	93	303	1.9
10	28	Rapid Drawdown (4.5m to 0m)	7	420	1.2
10	28	Slow Drawdown (4.5m to 0m)	30	840	1.6
10	28	High water level to very low water	100	300	1.8

Table 4.17: Safety status of Bhola Polder embankment for different surge height and thrust forces (SIDR).

Combinations for Charfassion, Bhola Polder Embankment Stability Analysis					
Embankment Soil 3.5m (Silty Clay)		**Surge Depth (m)**	**Thrust Force (kN/m)**	**Factor of Safety (FS)**	**Total Displacement**
Cohesion C (kN/m^2)	Angle of Friction φ'(degree)	From bottom of Embankment	Cyclone SIDR		(mm)
30	50	5	9.5	1.8	288
30	50	3.5	25.75	1.7	298
30	50	4	37	Collapse	Collapse

Table 4.18: Soil properties for Patharghata, Barguna Polder embankment analysis.

Properties of soil for Patharghata, Barguna Polder Embankment Stability Analysis									
Soil location	**Thickness (m)**	**Soil Type**	**Soil model**	**Cohesion C' (kN/m^2)**	**Angle of Friction φ'(degree)**	**Shear Wave Velocity (V) (m/sec)**	**Shear Modulus (Mpa)**	**Compression Index (c_c)**	**Swelling Index (c_s)**
Embankment	6m	Silty Clay	Mohr-columb	36	23	155	40	-	-
Sub-soil	13.5m	Silty Clay	Soft Soil	15	20	-	-	0.128	0.028
Sub-soil	10.5m	Fine Sand	Mohr-columb	0	35	240	100	-	-

Table 4.19: Safety status of Patharghata, Barguna embankment for different conditions

Patharghata, Barguna Polder Embankment Stability Analysis					
Embankment Soil 6m (Silty Clay)		**Analysis type**	**Time**	**Total Displacements**	**Factor of Safety**
Cohesion C (kN/m^2)	Angle of Friction φ'(degree)	Consolidation	Days	mm	
36	23	Safety after construction	112	326	2.26
36	23	Rapid Drawdown (5.5m to 0m)	7	69.5	1.87
36	23	Slow Drawdown (5.5m to 0m)	30	103.8	1.95
36	23	High water level to very low water	100	250	2.17

Table 4.20: Safety status of Barguna Polder embankment for different surge height and thrust forces (SIDR).

Combinations for Barguna, Patharghata Polder Embankment Stability Analysis					
Embankment Soil 3.5m (Silty Clay)		**Surge Depth (m)**	**Thrust Force (kN/m)**	**Factor of Safety (FS)**	**Total Displacement**
Cohesion C (kN/m^2)	Angle of Friction φ'(degree)	From bottom of Embankment	Cyclone SIDR		(mm)
36	23	5	70	1.73	329.7
36	23	6.5	55	1.66	298.6
36	23	5.5	36	1.93	298

Table 4.21: Soil properties for Satkhira Polder embankment analysis.

Properties of soil for Satkhira Polder Embankment Stability Analysis									
Soil location	**Thickness (m)**	**Soil Type**	**Soil model**	**Cohesion C′ (kN/m^2)**	**Angle of Friction φ'(degree)**	**Shear Wave Velocity (V) (m/sec)**	**Shear Modulus (Mpa)**	**Compression Index (c_c)**	**Swelling Index (c_s)**
Embankment	3.5m	Silty Clay	Mohr-	10	24	123	25	-	-
Sub-soil	4m	Silty Clay	Soft Soil	10	24	123	25	0.157	0.029
Sub-soil	10.5m	Fine Sand	Mohr-	6	23	131	30	-	-
Sub-soil	12m	Fine Sand	Mohr-	0	35	263	120	-	-

Table 4.22: Safety status of Satkhira embankment for different conditions

Satkhira Polder Embankment Stability Analysis (Normal Analysis)					
Embankment Soil 6m (Silty Clay)		**Analysis type**	**Time**	**Total Displacements**	**Factor of Safety**
Cohesion C (kN/m^2)	Angle of Friction φ'(degree)	Consolidation	Days	mm	
10	24	Safety after construction	75	162	1.81
10	24	Rapid Drawdown (5.5m to 0m)	7	57.4	1.58
10	24	Slow Drawdown (5.5m to 0m)	30	79.5	1.68
10	24	High water level to very low water	100	129.5	1.79

Table 4.23: Safety status of Satkhira Polder embankment for different surge height and thrust forces (SIDR).

Combinations for Satkhira Polder Embankment Stability Analysis					
Embankment Soil 3.5m (Silty Clay)		**Surge Depth (m)**	**Thrust Force (kN/m)**	**Factor of Safety (FS)**	**Total Displacement**
Cohesion C (kN/m^2)	Angle of Friction φ'(degree)	From bottom of Embankment	Cyclone SIDR		(mm)
10	24	3	1.39	1.86	162.1
10	24	3.5	3.3	1.52	144.5
10	24	2.15	0.8	1.77	146.2

Table 4.24: Soil properties for Laxmipur, Noakhali Polder embankment analysis.

Properties of soil for Laxmipur, Noakhali Polder Embankment Stability Analysis									
Soil location	**Thickness (m)**	**Soil Type**	**Soil model**	**Cohesion C′ (kN/m^2)**	**Angle of Friction φ'(degree)**	**Shear Wave Velocity (V) (m/sec)**	**Shear Modulus (Mpa)**	**Compression Index (c_c)**	**Swelling Index (c_s)**
Embankment	3.5m	Silty	Soft Soil	30	20	-	-	0.017	0.016
Sub-soil	2.5m	Silty	Soft Soil	30	20	-	-	0.017	0.016
Sub-soil	6m	Fine	Mohr-	1	30	185	60	-	-
Sub-soil	10m	Sand	Mohr-	0	35	270	130	-	-

Table 4.25: Safety status of Laxmipur, Noakhali embankment for different conditions

Laxmipur, Noakhali Polder Embankment Stability Analysis					
Embankment Soil 6m (Silty Clay)		**Analysis type**	**Time**	**Total Displacements**	**Factor of Safety**
Cohesion C (kN/m^2)	Angle of Friction φ'(degree)	Consolidation	Days	mm	
30	20	Safety after construction	105	273.5	3.83
30	20	Rapid Drawdown (5.5m to 0m)	7	49.5	2.68
30	20	Slow Drawdown (5.5m to 0m)	30	76.4	3.4
30	20	High water level to very low water	100	122	3.76

Table 4.26: Safety status of Laxmipur, Noakhali Polder embankment for different surge height and thrust forces (Cyclone 1991).

Combinations for Laxmipur, Noakhali Polder Embankment Stability Analysis					
Embankment Soil 3.5m (Silty Clay)		**Surge Depth (m)**	**Thrust Force (kN/m)**	**Factor of Safety (FS)**	**Total Displacement**
Cohesion C (kN/m^2)	Angle of Friction φ'(degree)	From bottom of Embankment	Cyclone 1991		(mm)
30	20	5	30	0.68	4.12 (m)
30	20	3.5	16	1.76	404
30	20	3	8	3	270

Table 4.27: Soil properties for Anowara, Chittagong Polder embankment analysis.

Properties of soil for Anowara, Chittagong Polder Embankment Stability Analysis									
Soil location	**Thickness (m)**	**Soil Type**	**Soil model**	**Cohesion C′ (kN/m^2)**	**Angle of Friction φ'(degree)**	**Shear Wave Velocity (V) (m/sec)**	**Shear Modulus (Mpa)**	**Compression Index (c_c)**	**Swelling Index (c_s)**
Embankment	3.5m	Silty	Mohr-columb	10	28	175	50	-	-
Sub-soil	3m	Silty	Soft Soil	4.6	28	-	-	0.259	0.016
Sub-soil	6m	Silty	Mohr-columb	5	30	140	30	-	-

Table 4.28: Safety status of Anowara, Chittagong embankment for different conditions

Anowara, Chittagong Polder Embankment Stability Analysis					
Embankment Soil 3.5m (Silty Clay)		**Analysis type**	**Time**	**Total Displacements**	**Factor of Safety**
Cohesion C (kN/m^2)	Angle of Friction φ'(degree)	Consolidation	Days	mm	
10	28	Safety after construction	101	269	2.19
10	28	Rapid Drawdown (3.5m to 0m)	5	28.5	1.71
10	28	Slow Drawdown (3.5m to 0m)	30	60.4	1.9
10	28	High water level to very low water	100	125	2.1

Table 4.29: Safety status of Anowara, Chittagong Polder embankment for different surge height and thrust forces (cyclone 1991).

Combinations for Anowara, Chittagong Polder Embankment Stability Analysis					
Embankment Soil 3.5m (Silty Clay)		**Surge Depth (m)**	**Thrust Force (kN/m)**	**Factor of Safety (FS)**	**Total Displacement**
Cohesion C (kN/m^2)	Angle of Friction φ'(degree)	From bottom of Embankment	Cyclone 1991		(mm)
5	30	2.8	45	0.67	28010
5	30	2.3	13	1.7	273
5	30	2.5	62.5	1.5	880
5	30	3.8	7	1.16	347
10	30	2.8	45	0.76	14130
10	30	2.3	13	1.88	262
10	30	2.5	62.5	1.62	265
10	30	3.8	7	1.36	265
15	30	2.8	45	0.97	4981
15	30	2.3	13	2.075	260
15	30	2.5	62.5	1.79	261
15	30	3.8	7	1.54	262

All the figures of displacement and safety status of Anowara, Chittagong Polder embankment are presented in **Appendix D.**

Table 4.30: Soil properties for Moheskhali, Cox's Bazar Polder embankment analysis.

Properties of soil for Moheskhali, Cox's Bazar Polder Embankment Stability Analysis (Normal Analysis)									
Soil location	**Thickness (m)**	**Soil Type**	**Soil model**	**Cohesion C′ (kN/m^2)**	**Angle of Friction φ'(degree)**	**Shear Wave Velocity (V) (m/sec)**	**Shear Modulus (Mpa)**	**Compression Index (c_c)**	**Swelling Index (c_s)**
Embankment	4.5m	Silty	Soft Soil	40	23	-	-	0.150	0.013
Sub-soil	4.5m	Fine	Mohr-columb	2	28	200	65	-	-
Sub-soil	5m	Sand	Mohr-columb	0	50	355	220	-	-

Table 4.31: Safety status of Moheskhali, Cox's Bazar embankment for different conditions

Moheskhali, Cox's Bazar Polder Embankment Stability Analysis (Normal Analysis)					
Embankment Soil 6m (Silty Clay)		**Analysis type**	**Time**	**Total Displacements**	**Factor of Safety**
Cohesion C (kN/m^2)	Angle of Friction φ'(degree)	Consolidation	Days	mm	
40	23	Safety after construction	84	237	2.53
40	23	Rapid Drawdown (5.5m to 0m)	7	472	2.14
40	23	Slow Drawdown (5.5m to 0m)	30	504	2.14
40	23	High water level to very low water level(4.5m to -4.5m)	100	478	2.53

Table 4.32: Safety status of Moheskhali, Cox's Bazar Polder embankment for different surge height and thrust forces (cyclone 1991).

Combinations for Moheskhali, Cox's Bazar Polder Embankment Stability Analysis					
Embankment Soil 3.5m (Silty Clay)		**Surge Depth (m)**	**Thrust Force (kN/m)**	**Factor of Safety (FS)**	**Total Displacement**
Cohesion C (kN/m^2)	Angle of Friction φ'(degree)	From bottom of Embankment	Cyclone 1991		(mm)
40	23	4	28	2.51	246.6
40	23	5	40.84	1.1	24.5(m)
40	23	3.5	11	2.5	241

Table 4.33: Soil properties for Sitakunda Polder embankment analysis.

Properties of soil for Sitakunda Polder Embankment Stability Analysis (Normal Analysis)									
Soil location	**Thickness (m)**	**Soil Type**	**Soil model**	**Cohesion C′ (kN/m^2)**	**Angle of Friction φ'(degree)**	**Shear Wave Velocity (V) (m/sec)**	**Shear Modulus (Mpa)**	**Compression Index (c_c)**	**Swelling Index (c_s)**
Embankment	3m	Fine Sand	Mohr-column	5	25	190	60	-	-
Sub-soil	6m	Silty Clay	Soft Soil	30	20	-	-	0.186	0.016
Sub-soil	16m	Sand	Mohr-column	0	35	255	115	-	-

Table 4.34: Safety status of Sitakunda Polder for different conditions.

Sitakunda Polder Embankment Stability Analysis (Normal Analysis)					
Embankment Soil 6m (Silty Clay)		**Analysis type**	**Time**	**Total Displacements**	**Factor of Safety**
Cohesion C (kN/m^2)	Angle of Friction φ'(degree)	Consolidation	Days	mm	
5	25	Safety after construction	86	123	1.6
5	25	Rapid Drawdown (5.5m to 0m)	7	20.4	1.57
5	25	Slow Drawdown (5.5m to 0m)	30	29.37	1.6
5	25	High water level to very low water	100	160.2	1.59

Table 4.35: Safety status of Sitakunda Polder embankment for different surge height and thrust forces (Cyclone 1991).

Combinations for Sitakunda Polder Embankment Stability Analysis					
Embankment Soil 3.5m (Silty Clay)		**Surge Depth (m)**	**Thrust Force (kN/m)**	**Factor of Safety (FS)**	**Total Displacement**
Cohesion C (kN/m^2)	Angle of Friction φ'(degree)	From bottom of Embankment	Cyclone 1991		(mm)
5	25	2	6.25	1.62	123
5	25	3	29.83	0.7	123(m)
5	25	5	19.3	Collapse	Collapse

4.4.9 Comparison of stability analysis between limit equilibrium and finite element analysis

The limit equilibrium method is commonly used procedure for slope stability analysis, compared with finite element analysis. However, with the increase of computational facility Finite Element Methods are also being used for slope stability analysis. Slope stability analysis using the finite element method has been widely accepted in the literature for many years. Both methods are useful to analyze homogeneous and inhomogeneous slopes. The most common limit equilibrium techniques are methods of slices, such as the ordinary method of slices (Fellenius) and the Bishop simplified, Spencer, and Morgenstern-Price methods. In recent years there have been rapid developments in the fields of computational methods, of particular relevance to slope stability analysis are the limit equilibrium and finite element methods (Liu, et al. 2014).

Hammouri, et al. (2008) and Liu, et al. (2015) studied the advantages and disadvantages of limit equilibrium and finite element methods. They informed that when employing limiting equilibrium methods to study slopes, many computational challenges and numerical inconsistencies may emerge in determining the critical slip surface and thus creating a factor of safety (depending on the geology). One benefit of finite element over limiting equilibrium is that no assumptions regarding the shape or position of the critical failure surface are required. Furthermore, the method can be easily used with others to determine stresses, motions, and pore pressures in embankments, as well as to monitor progressive failure. In recent softwares, for limit equilibrium based analysis have been featured with auto search of critical slopes. Kim et al. (1999) analyzed slopes using both the limit equilibrium method and limit analysis method and found the results from the two approaches were generally in good agreement for homogeneous slopes. In this study GEO5 software has been used for analysis of slope stability for limit equilibrium procedures and PLAXIS 3D has been used for finite element analysis of slopes. For comparison of results of this study, by finite element method and limit equilibrium method, Moheskhali and Anowara Polders are selected and analyzed using both methods. The results of the Polders are summarized in Table 4.36 and 4.37.

Table 4.36: Factor of Safety Analysis of Moheskhali Polder using both LEM and FEM method.

Factor of Safety Analysis of Moheskhali Polder						
Analysis type	**Limit Equilibrium (GEO 5)**					**PLAXIS 3D**
	Bishop	**Fellenious**	**Spencer**	**Janbu**	**Morgenstern-Price**	
Normal	2.61	2.57	2.82	2.72	2.72	2.53
Rapid Drawdown	2.16	2.18	2.4	2.26	2.31	2.14
Surge depth 5m and thrust force 40.84 kN						
	2.47	2.39	2.5	2.49	2.49	2.27
Surge depth 4m and thrust force 28 kN						
	2.47	2.44	2.6	2.57	2.57	2.51
Surge depth 3.5m and thrust force 11 kN						
	2.47	2.44	2.7	2.57	2.57	2.5

Table 4.37: Factor of Safety Analysis of Anowara Polder using both LEM and FEM method.

Factor of Safety Analysis of Anowara Polder						
Analysis type	**Limit Equilibrium (GEO 5)**					**PLAXIS 3D**
	Bishop	**Fellenious**	**Spencer**	**Janbu**	**Morgenstern-Price**	
Normal	1.94	1.86	1.97	1.99	1.99	2.19
Rapid Drawdown	1.57	1.52	1.6	1.6	1.6	1.71
Surge depth 3.8m and thrust force 7 kN						
	1.35	1.29	1.43	1.41	1.41	1.16
Surge depth 2.5m and thrust force 62.5 kN						
	1.68	1.59	1.68	1.55	1.55	1.5
Surge depth 2.3m and thrust force 13 kN						
	1.79	1.71	1.82	1.84	1.84	1.88

From the observations, for almost every cases factor of safety results from both LEM methods and FEM method are almost same. However, the result from finite element method is more realistic than limit equilibrium methods. Because the method is so general that it can be used to model many complex situations with a high degree of realism. This includes things like nonlinear stress-strain behavior, nonhomogeneous conditions, and changes in geometry during the building of an embankment (Dunkan, 1996). Additionally, settlement values and failure mechanism of embankments can be predicted in PLAXIS 3D software.

4.5 Parametric study

To study the effect of Polder embankment slopes and soil properties on stability, parametric study has been performed for one region. Anowara, Chittagong Polder embankment has been selected for study the effect of change in slope of the embankment and change in soil properties.

4.5.1 Effect of change in slope

Due to weathering, tidal flood, or effect of cyclones, the geometry of the coastal embankments changes with time. To study the effect of change in slopes (landside and riverside), coastal embankment of Anowara Polder has been analyzed for different slope combinations, keeping the other properties same. Following cases are analyzed to study the effect of alteration of slopes on slope stability: Case 1: Riverside: 2:1; Land side: 1:1; Case 2: Riverside: 1.5:1; Land side: 1:1, Case 3: Riverside: 1:1; Land side: 1:1. The safety status of the Anowara Polder embankment for different slope combinations are presented in Table 4.38 to 4.40. From the results it is apparent that as the slopes are becoming stepper the factor of safety of the Anowara Polder embankment is decreasing.

4.5.1 Effect of change in soil properties

Due to large volume of earthwork, during construction it is difficult to maintain same soil properties at all sections of the embankment. In addition, due to natural and manmade causes, the properties of soil used for embankment construction can change with time. To study the effect of change in embankment soil, coastal embankment of Anowara Polder has been analyzed for different shear strength (adhesion, angle of friction) combinations, keeping the slopes of landside and riverside same. The results of Anowara Polder embankment for different soil properties are presented Table 4.41 to 4.43. It is evident that with the change in soil properties, safety status of the embankment changes.

Table 4.38: Anowara, Chittagong Polder Embankment Stability Analysis (Normal Analysis) (Riverside: 2:1; Land side: 1:1)

Anowara, Chittagong Polder Embankment Stability Analysis (Normal Analysis) (Riverside: 2:1; Land side: 1:1)					
Embankment Soil 3.5m (Silty Clay)		**Analysis type**	**Time**	**Total Displacements**	**Factor of Safety**
Cohesion C (kN/m^2)	Angle of Friction φ'(degree)	Consolidation	Days	mm	
10	28	Safety after	101	269	2.19
10	28	Rapid Drawdown	5	28.5	1.71
10	28	Slow Drawdown	30	60.4	1.9
10	28	High water level to	100	125	2.1

Table 4.39: Anowara, Chittagong Polder Embankment Stability Analysis (Normal Analysis) (Riverside: 1.5:1; Land side: 1:1)

Anowara, Chittagong Polder Embankment Stability Analysis (Normal Analysis) (Riverside: 1.5:1; Land side: 1:1)					
Embankment Soil 3.5m (Silty Clay)		**Analysis type**	**Time**	**Total Displacements**	**Factor of Safety**
Cohesion C (kN/m^2)	Angle of Friction φ'(degree)	Consolidation	Days	mm	
10	28	Safety after	98	276	2.05
10	28	Rapid Drawdown	5	36.05	1.57
10	28	Slow Drawdown	30	66.67	1.74
10	28	High water level to	100	131	2.03

Table 4.40: Anowara, Chittagong Polder Embankment Stability Analysis (Normal Analysis) (Riverside: 1:1; Land side: 1:1)

Anowara, Chittagong Polder Embankment Stability Analysis (Normal Analysis) (Riverside: 1:1; Land side: 1:1)					
Embankment Soil 3.5m (Silty Clay)		**Analysis type**	**Time**	**Total Displacements**	**Factor of Safety**
Cohesion C (kN/m^2)	Angle of Friction φ'(degree)	Consolidation	Days	mm	
10	28	Safety after	99	274	1.95
10	28	Rapid Drawdown	5	50.1	1.43
10	28	Slow Drawdown	30	89.05	1.64
10	28	High water level to	100	157.4	1.92

Table 4.41: Anowara, Chittagong Polder Embankment Stability Analysis (Riverside: 2:1; Land side: 1:1) against cyclone 1991.

Combinations for Anowara, Chittagong Polder Embankment Stability Analysis (Riverside: 2:1; Land side: 1:1)					
Embankment Soil 3.5m (Silty Clay)		**Surge Depth (m)**	**Thrust Force (kN/m)**	**Factor of Safety (FS)**	**Total Displacement**
Cohesion C (kN/m^2)	Angle of Friction φ'(degree)	From bottom of Embankment	Cyclone 1991		(mm)
10	30	2.8	45	0.76	14130
10	30	2.3	13	1.88	262
10	30	2.5	62.5	1.62	265
10	30	3.8	7	1.36	265

Table 4.42: Anowara, Chittagong Polder Embankment Stability Analysis (Riverside: 1.5:1; Land side: 1:1) against cyclone 1991.

Combinations for Anowara, Chittagong Polder Embankment Stability Analysis (Riverside: 1.5:1; Land side: 1:1)					
Embankment Soil 3.5m (Silty Clay)		**Surge Depth (m)**	**Thrust Force (kN/m)**	**Factor of Safety (FS)**	**Total Displacement**
Cohesion C (kN/m^2)	Angle of Friction φ'(degree)	From bottom of Embankment	Cyclone 1991		(mm)
10	28	2.8	45	-	8.09 (m)
10	28	2.3	13	1.76	270
10	28	2.5	62.5	1.42	274
10	28	3.8	7	1.33	272

Table 4.43: Combinations for Anowara, Chittagong Polder Embankment Stability Analysis (Riverside: 1:1; Land side: 1:1) against cyclone 1991.

Combinations for Anowara, Chittagong Polder Embankment Stability Analysis (Riverside: 1:1; Land side: 1:1)					
Embankment Soil 3.5m (Silty Clay)		**Surge Depth (m)**	**Thrust Force (kN/m)**	**Factor of Safety (FS)**	**Total Displacement**
Cohesion C (kN/m^2)	Angle of Friction φ'(degree)	From bottom of Embankment	Cyclone 1991		(mm)
10	28	2.8	45	1.12	268.1
10	28	2.3	13	1.78	267
10	28	2.5	62.5	1.33	275
10	28	3.8	7	1.29	274

4.6 Stability map of Polders against Cyclone SIDR and Cyclone 1991

Estimating safety status of earth embankments is a challenging issue. For any given situation, the value of the factor of safety should be proportional to the uncertainty in its calculation and the consequences of failing. The required factor of safety should be bigger when there is more uncertainty about the shear strength and other conditions and when the consequences of failure are worse. Table 4.44 presents the recommended factor of safety by the U.S. Army Corps of Engineers' slope stability manual.

Table 4.44: Factor of Safety Criteria from U.S. Army Corps of Engineers' Slope Stability Manual (U.S. Army Corps of Engineers', 2003).

Types of slopes	**For End of Construction**	**For Long-Term Steady Seepage**	**For Rapid Drawdown**
Slopes of dams, levees, and dikes, and other embankment and excavation slopes	1.3	1.5	1.0-1.2

Dunkan (2014) presented recommended factor of safety based on cost and consequence of slope failure. The values are presented in Table 4.45.

Table 4.45: Recommended minimum values of factor of safety (Duncan, 2014).

Cost and Consequence of Slope Failure	**Uncertainty of Analysis Conditions**	
	Small	Large
Cost of repair comparable to incremental cost to construct more conservatively designed slope	1.25	1.5
Cost of repair much greater than incremental cost to construct more conservatively designed slope	1.5	2.0 greater

For this study, considering the cost of rebuilding and consequence of the failure of the coastal Polders the minimum factor of safety value for the stability is considered as 1.5. However, for rapid drawdown failure cases the safety value more than 1.25 is considered as safe.

Cyclone SIDR

Cyclone Sidr, which was a category IV storm on the Saffir-Simpson scale from I to V hit the southwest coast of Bangladesh on November 15, 2007, with winds as fast as 240 km/h, waves as high as 5 meters, and storm surges as high as 10 meters in some places. A lot of infrastructure, like homes, roads, bridges, embankments, and utility and service buildings, was destroyed by the risk event. About one million homes near the southwest coast were hit hard, and another 1.3 million were struck in some way. About 3,406 people were thought to have died. Thirty out of Bangladesh's 64 districts were hurt by Cyclone Sidr. Nineteen coastal areas were pretty much destroyed (Haque and Jahan, 2016). Figure 4.50 shows the path of cyclone SIDR.

After the devastating impact of Cyclone SIDR the Polders in the areas are improved through Coastal Embankment Improvement Project (CEIP- Phase I). The embankments are modeled in PLAXIS and analyzed against thrust forces as they encountered during the SIDR. The results are presented in Table 4.16, 4.18, and 4.20.. Figure 4.51 shows the current safety status of Polders if the area was affected by Cyclone like SIDR again.

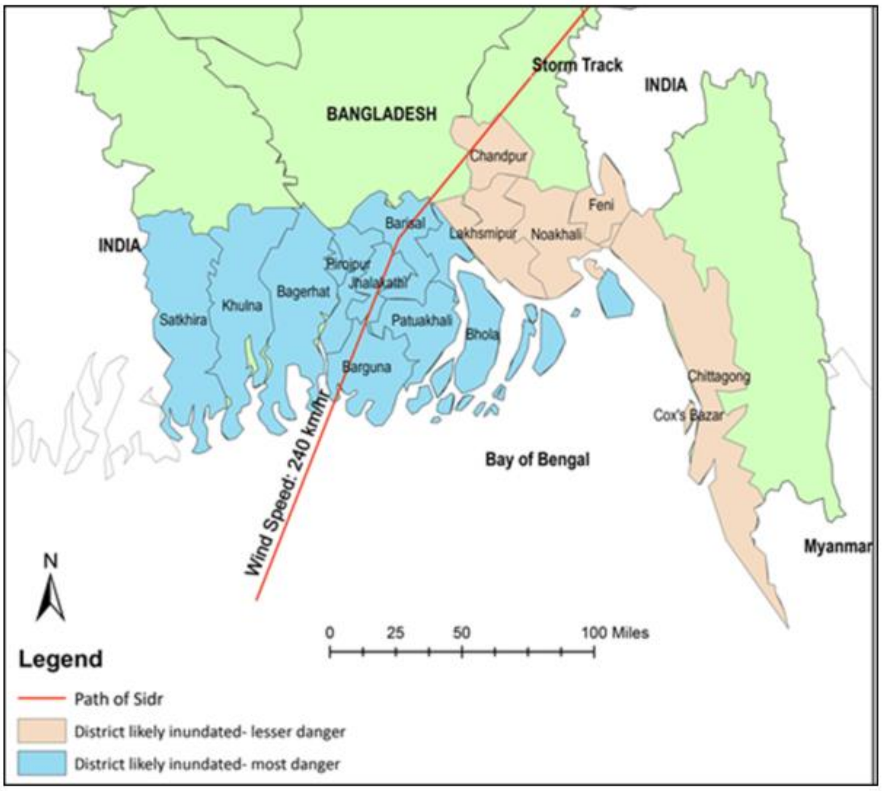


Figure 4.50: The path of cyclone SIDR (Haque and Jahan, 2016).

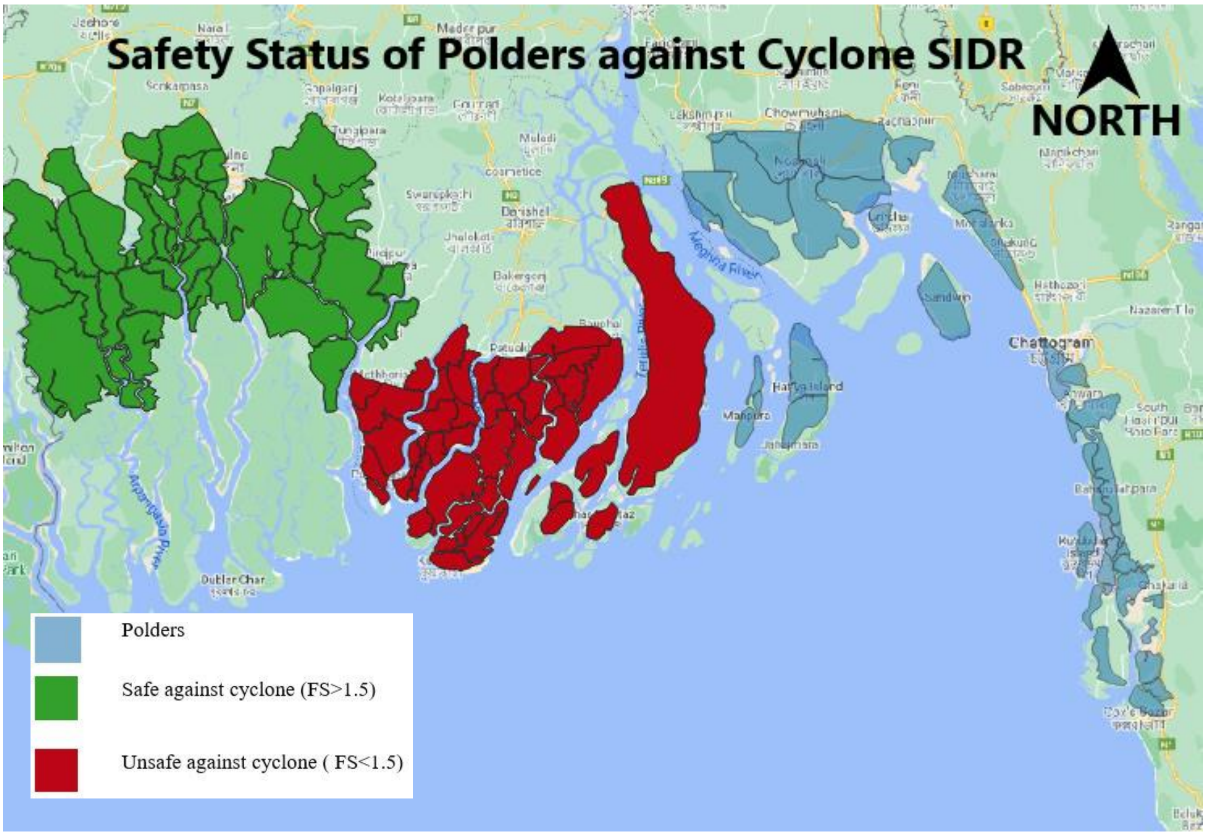


Figure 4.51: Safety Status of Polders against Cyclone SIDR.

The safety status of the Polders can vary on several conditions. The geometry of the Polders are not same at every locations, soil property and compaction is not uniform, the landfall direction of the cyclone is also important factor. Difference in some of the controlling parameters could result in lower safety in different location of the Polders.

Cyclone 1991

The 1991 cyclone of Bangladesh was the worst and deadliest tropical cyclone to hit Bangladesh on April 29, 1991. It hit near Chittagong, which is in the southeast of the country. About 138,000 people died and 1.72 billion dollars' worth of damage was done by the cyclone (Mohit, et al. 2018).

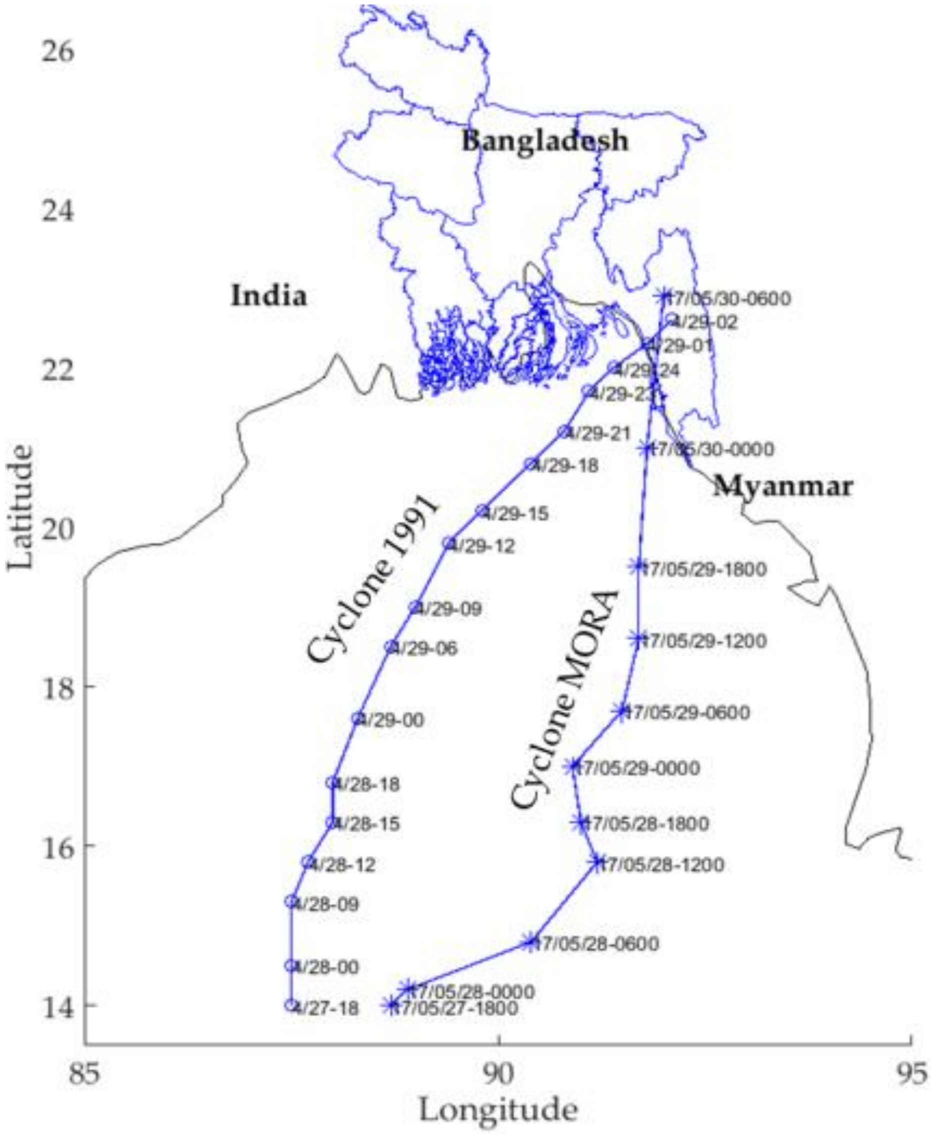


Figure 4.52: The path of cyclone 1991 (Mohit, et al. 2018).

After the devastating Cyclone the Polders were improved through CERP project. The embankments are modeled in PLAXIS and analyzed against thrust forces as they encountered during the Cyclone 1991. The results are presented in Table 4.26, 4.29, 4.32, and 4.35. Figure 4.53 shows the current safety status of Polders if the area was affected by Cyclone like 1991 again.

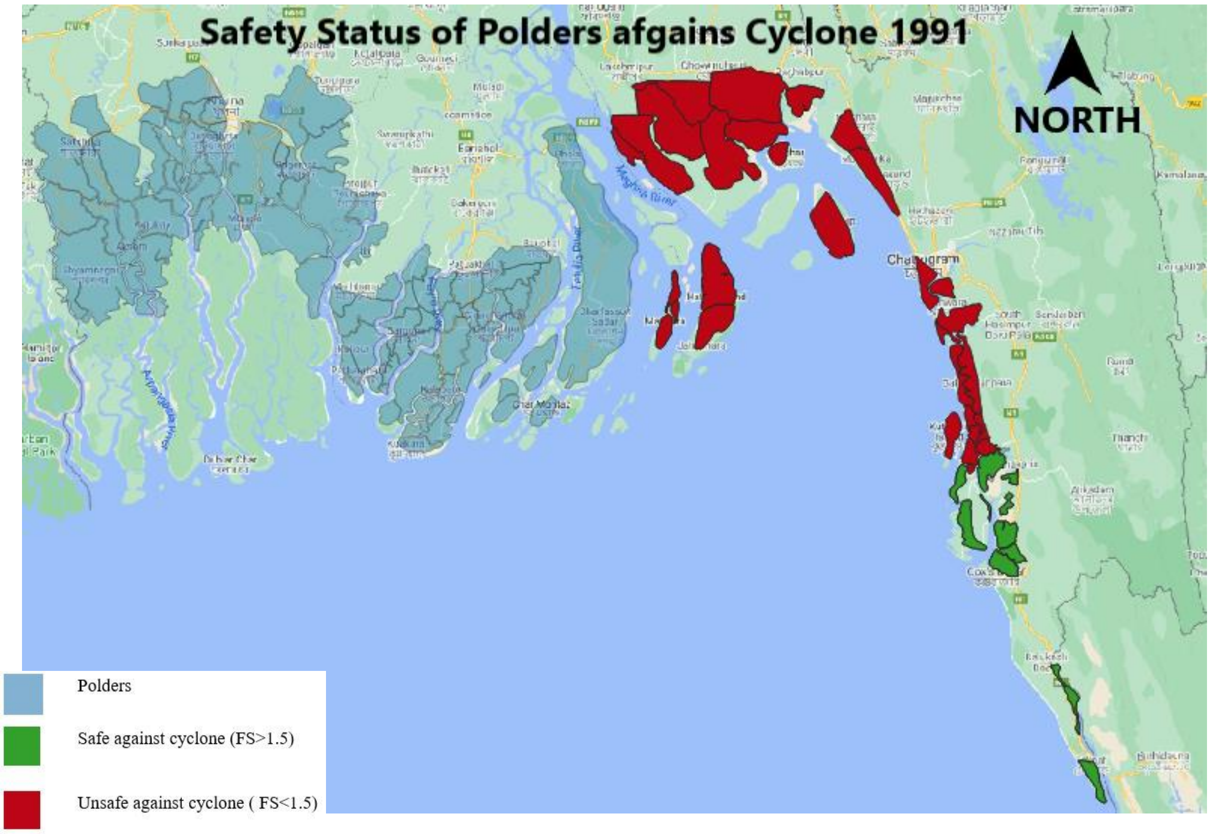


Figure 4.53: Safety Status of Polders against Cyclone 1991.

4.7 Summary

The whole coast of Bangladesh is susceptible to cyclones and thrust forces at regular intervals. Starting from 1960's the government of Bangladesh is spending millions of dollars to reinforce the Polders. As a result, the amount of loss due to storm surges and cyclones has been truncated in recent decades. However, though there are efforts to make the region safe against storm surges, still the geotechnical part of the improvement projects are neglected. Due to the poor construction quality, lack of maintenance, the coastal embankments are still unsafe even after improvement through CERP and CEIP. Especially the Polders are unsafe against Rapid drawdown case and when they are prone to high value thrust forces. From parametric study it is clear that soil type and slope of seaside and landside of the Polder have great effect on safety status of the Polders. So, selection of good materials and maintenance are very important to make the Polders safe against cyclones and storm surges.

Chapter 5
CONCLUSION AND RECOMMENDATION

5.1 Conclusions

This research investigates the geotechnical status of some recently improved Polders in Bangladesh. For this study purpose the whole coastal region has been divided into seven regions based on local geology. From this study one Polder from each region (total seven) has been selected for study. SPT test was performed in each location and soil samples were collected for geotechnical parametric study in the laboratory. Relevant geotechnical investigations: Classification of soil, Grain-size analysis, Atterberg's limit tests, Consolidation test, Direct shear test, Tri-axial tests are performed in the laboratory. The selected Polders are modeled using geotechnical properties available from field and laboratory test results. Relevant mechanical properties of soils for numerical modeling, which are not available from laboratory test results, are estimated from research based empirical correlations. To assess the stability of the Polders and settlement potential, the Polders are analyzed by finite element method using PLAXIS 3D software. The model has been validated by field observation of a recently constructed superdyke at Chittagong. The safety status of two Polders are further checked by limit equilibrium method using GEO5 software.

From the whole study of the coastal Polders following conclusions can be made:

(i) The PLAXIS 3D model used for assessing the safety condition of the selected coastal embankment Polders has been validated with a newly constructed superdyke project at Mirasarai, Chittagong. The model predicted settlement values of the superdyke at different locations are close to the field observed values with an average error of about 11%.

(ii) From the result of Standard Penetration Test, we can see the presence of clayey silt or fine sand at the top 5 to 10m and the SPT value ranges from 2 to 5 in the top layers in the Polders. The section of the embankment of the Polders are not uniform. There are some locations where the Polders are narrow and there are evidence of local failures. During future cyclones those weak points would work as trigger for embankment failures.

(iii) Results from two methods: finite element and limit equilibrium method, it is apparent that both method estimates almost same result for stability analysis of the Polder embankments. However, the finite element method can additionally predict the potential displacement value and likely failure mechanism for every case of study which is not available in limit equilibrium method.

(iv) The effect of mesh size and soil models are analyzed for the PLAXIS model and from parametric study it is found that selection of mesh size and soil model have very insignificant effect on safety status calculation and settlement estimation. For this study Mohr-Coulomb model is used for Silty Sand and Fine Sand, and Soft Soil model is used for Soft clay, Silty Clay, medium mesh size is used for all Polder embankment models in this study.

(v) All the Polders are analyzed for consolidation analysis, rapid drawdown, slow drawdown, very slow change in water level cases. The Polders are further analyzed against surge depth and thrust forces of severe cyclones like Cyclone SIDR and Cyclone 1991.

(vi) One Polder embankment from each Polder region is selected for detailed analysis. Total seven Polders are selected from the seven regions.

(vii) For the case of Bhola Polder embankment the factor of safety values ranges from 1.2 to 1.8. The Polder seems unsafe for the rapid drawdown case. From the analysis against Cyclone SIDR, for one condition, urge depth 4m and thrust force 45 kN, the embankment collapsed in analysis. Therefore, the safety condition of Bhola Polder is really poor against cyclones.

(viii) For Barguna Polder, the factor of safety values ranges from 1.87 to 2.26. Even against the cyclone SIDR surge depth and thrust forces the Polder region is safe with a minimum safety factor value of 2.41.

(ix) For Satkhira Polder model, the safety values ranges from 1.5 to 1.8, that is the Polders are just safe, below the recommended value of 2.0. Against SIDR surge depth and thrust forces the safety values were just above 1.5.

(x) In case of Noakhali Polder, the safety values for different conditions were well above recommended value of 2.0. However, against the Cyclone 1991 thrust forces and surge depth the safety values ranges from 0.68 to 3. That is for some definite conditions the Polder region is unsafe.

(xi) For Anowara Polder the safety values are around 2.0. However, the region is very unsafe against Cyclone 1991, as the model result predict with factor of safety as low as 0.67 to 0.76 for some thrust force and surge depth conditions.

(xii) The Moheskhali Polder shows factor of safety result above 2.0 for normal analysis conditions. However, against the Cyclone 1991 the safety factor dropped to 1.1.

(xiii) Results from Sitakunda Polder model shows safety values just above 1.5 for the normal analysis cases. However, when the Polder region is analyzed against cyclone 1991 thrust and surge the factor of safety value dropped to 0.67. For one condition, surge depth 5m and thrust force 19kN, the model collapsed which indicates the poor condition of the Polder region.

(xiv) Form most of the model study, the safety value of the Polders are just greater than 1.5, whereas a safety value of 2.0 is recommended for better performance of the Polders. And, for a considerable cases the Polders fail to meet the recommended factor of safety value. Even for some case the Polder collapsed.

(xv) Polders of Bhola, Patuakhali regions found unsafe against severe cyclones like SIDR; and Polders in Moheskhali, Anowara, Noakhali found unsafe against severe cyclones like 1991.

(xvi) Parametric study of the Anowara Polder show that change in soil properties and the slope of the landside and seaside of the Polder have great impact on the safety status of the Polders. With the increase in vertical slope of the Polder riverside and landside the factor of safety values decreased.

5.2 Recommendations for future study

(i) This study is limited only to only one Polder from each region. Total studied Polder number is seven, where there are 123 Polders in the coastal area of Bangladesh. More rigorous study on other Polders is necessary.

(ii) For field investigation purpose, only SPT tests were performed in this study. For detailed investigation CPT tests should be performed.

(iii) Only there tests were performed in each Polder at 0.5km interval. As the soil type varies largely in this type of Polders, number of locations for test should be increased.

(iv) In this study, the geometry of the Polders (height, slope, width) is taken based on field observation using tape. For better evaluation, the geometry of the Polders should be measured by modern survey equipment.

(v) From the parametric study it is marked that the change in geometry of the Polders effect the stability conditions, that is why Polders should be analyzed at regular intervals to study the safety condition and this could help to take necessary improvement measures before severe damages.

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APPENDIX A

CYCLONE AND POLDER DATA

Table A1: Historical Cyclone in Bangladesh from 1582 to 2020 (After Hossain and Mullick, 2020)

Serial No	**Date/ Month/ Year**	**Affected Area**	**Type of Distribution**	**Deaths**
1.	1582	Bakerganj Coast (presently in Barisal and Patuakhali).	Severe Cyclonic Storm with a core of Cyclone winds	200,000 people
2.	1585	Eastern Meghna estuary	Unknown	Unknown
3.	1699	Sunderban	Severe Cyclonic Storm	50,000 people
4.	1760	Sunderban	Severe Cyclonic Storm	Unknown
5.	1765	Chattogram	Severe Cyclonic Storm	Unknown
6.	1767	Bakerganj Coast (presently In Barisal)	Severe Cyclonic Storm	30,000 people
7.	1797 (May-June)	Chattogram	Cyclonic Storm with a core of Cyclone winds	Unknown
8.	1822 (May-June)	Barisal	Severe Cyclonic Storm with a core of Cyclone winds	50,000 People Cattle killed = 100,000. Storm wave swept away the collectorate records.
9.	1823 (2 June)	Chattogram	Cyclonic Storm	Unknown
10	1824 (8 June)	Chattogram	Heavy Storm (Severe Cyclonic Storm)	Unknown

11	1831 (31 October)	Barisal	Cyclonic Storm	22,000 people
12	1839 (3-5June)	Head Bay (Bengal Coast)	Cyclonic Storm	Unknown
13	1839 (19-21 September)	Sunderban	Cyclonic Storm	Unknown
14	1844 (11May)	Noakhali and Chattogram coast	Cyclonic Storm	Unknown
15	1847	Various locations in Bengal coast	Cyclonic Storm	75,000 people
16	1849 (12-13 May)	Chattogram	Cyclonic Storm	Unknown
17	1850 (23-28 April)	North Bengal	Cyclonic Storm	Unknown
18	1852 (12-15 May)	Sunderban	Cyclonic Storm	Unknown
19	1869 (13-17 May)	Various locations in Bengal coast	Cyclonic Storm	Unknown
20	1869 (5-10 June)	North Bengal	Cyclonic Storm	Unknown
21	1872 (October)	Cox’s Bazar	Cyclonic Storm	Unknown
22	1876 (27 October-1 November) **“(The Great Backerganj Cyclone of 1876)”**	Patuakhali Noakhali and Chattogram coast	Severe Cyclonic Storm with a core of Cyclone winds	200,000 people

23	1895 (October)	Sunderban	Cyclonic Storm	Unknown
24	1897 (24 October)	Chattogram and Kutubdia island	Cyclonic Storm	14,000 people
25	1898 (May)	Teknaf	Tropical cyclone with storm surge	Unknown
26	1901 (November)	Western Sunderban	Cyclonic Storm	Unknown
27	1904 (November)	Sonadia coast	Cyclonic Storm	143 people
28	1909 (16 October)	Chattogram	Cyclonic Storm	698 people
29	1909 (December)	Cox's Bazar	Cyclonic Storm	Unknown
30	1911 (April)	Teknaf	Cyclonic Storm	120,000 people
31	1913 (October)	Muktagachha upazila (Mymensingh District)	Cyclonic Storm	500 people
32	1917 (24 September)	Sunderban	Cyclonic Storm	432 people
33	1919 (September)	Barisal	Cyclonic Storm	40,000 people
34	1922 (April)	Teknaf	Cyclonic Storm	Unknown
35	1923 (May)	Teknaf	Cyclonic Storm	Unknown
36	1926 (May)	Cox’s Bazar	Cyclonic Storm	606 people
37	1941 (26 May)	Eastern Meghna estuary	Cyclonic Storm	7,000 people
38	1942 (October)	Sunderban	Cyclonic Storm	Unknown

39	1948 (17-19 May)	Between Noakhali and Chattogrm	Cyclonic Storm	1200 people
40	1950 (15-20 November)	Patuakhali	Cyclonic Storm	Unknown
41	1958 (16-19 May)	Eastern Meghna estuary	Cyclonic Storm	870 people
42	1958 (21-24 October)	Noakhali and West Meghna estuary	Cyclonic Storm	12,000 people
43	1960 (25-29 May)	Sunderban Coast (landfall at Sunderban)	Cyclonic Storm	106 people
44	1960 (9-10 October)	Meghna estuary (landfall,at Noakhali)	Severe Cyclonic Storm	3,000 People.
45	1960 (30-31 October)	Chattogram coast (landfall at Chattogram)	Severe Cyclonic Storm	10,000 people
46	1961 (6-9 May)	Meghna estuary (landfall near Feni river)	Severe Cyclonic Storm	11,468 people
47	1961 (27-30 May)	Chattogram-Noakhali coast	Cyclonic storm	10,466 people
48	1962 (26-30 October)	Feni-Chattogram Coast	Severe Cyclonic Storm	50,000 people
44	1960 (9-10 October)	Meghna estuary (landfall,at Noakhali)	Severe Cyclonic Storm	3,000 people.
45	1960 (30-31 October)	Chattogram coast (landfall at Chattogram)	Severe Cyclonic Storm	10,000 people
46	1961 (6-9 May)	Meghna estuary (landfall near Feni river)	Severe Cyclonic Storm	11,468 people

47	1961 (27-30 May)	Chattogram-Noakhali coast	Cyclonic storm	10,466 people
48	1962 (26-30 October)	Feni-Chattogram	Severe Cyclonic Storm	50,000 people
49	1963 (28-29 May)	Noakhali-Cox's Bazar Coast (landfall near Near Chattogram)	Severe Cyclonic storm	11,520 people
50	1963 (5-8 June)	Sunderban)	Cyclonic storm	Unknown
51	1963 (25-29 October)	Teknaf	Cyclonic storm	Unknown
52	1965 (11-12 May) **“Barishal Cyclone”**	Barisal-Chattogram coast (landfall between Barisal and Noakhali)	Cyclonic storm	19,279 people
53	1965 (31 May-1 June)	Chattogra m Coast (landfall near Chattogram)	Severe Cyclonic storm	12,000 people
54	1965 (14-15 December)	Cox's Bazar-Teknaf Coast (landfall Near Cox's Bazar)	Cyclonic storm	873 people
55	1966 (1 October)	Chattogra m and Sandwip (landfall near Chattogram)	Cyclonic storm	850 people
56	1966 (12 December)	Cox's Bazar	Cyclonic Storm	Unknown
57	1967 (11 October)	Sunderban Noakhali Coas (landfall at Noakhali)	Cyclonic Storm	Unknown

58	1967 (23-24 October)	Chattogra m-Cox's Bazar coast (landfall in between)	Cyclonic Storm	128 people
59	1969 (11 October)	Khulna coast	Cyclonic Storm	175 people
60	1970 (5-7 May)	Chattogram Teknaf Coast (landfall at Cox's Bazar)	Cyclonic Storm	18 people
61	1970 (7-13 November) **“Bhola Cyclone”**	Khulna-Chattogram coast (landfall at Hatia)	Severe CyclonicStorm	300,000 people
62	1971 (7-8 May)	Meghna estuary	Cyclonic Storm	Unknown
63	1971 (5-6 November)	Chattogram coast(landfall near Chattogram)	Cyclonic Storm	Unknown
64	1971 (28-30 November)	Sunderban coast	Cyclonic Storm	11,000 people
65	1973 (16-18 November)	Chattogram coast	Cyclonic Storm	Unknown
66	1973 (6-9 December)	Sunderban-Patuakhali coast (landfallat Sunderban)	Cyclonic Storm	Unknown
67	1974 (13-15 August)	Khulna coast	Cyclonic Storm	600 people
68	1974 (24-28 November)	Cox's Bazar-Chattogram-offshore Islands (landfallat Chattogram)	Cyclonic Storm	200 people
69	1975 (9-12 May)	Sunderban-Bhola-Chattogram coast	Severe cyclonic storm	5 people
70	1976 (19-20 October)	Meghna estuary	Cyclonic Storm	Unknown

71	1977 (9-12 May)	Sunderban-Chattogram coast (landfall at Sunderban)	Cyclonic Storm	Unknown
72	1978 (30 September-3 October)	Sunderban Khulna coast	CyclonicStorm	Unknown
73	1983 (15October)	Chattogram-Feni coast (landfall near Chattogram)	Cyclonic Storm	43 people
74	1983 (9 November)	Chattogram-Teknaf Coast (landfall between Chattogram and Cox'sBazar)	Severe Cyclonic Storm	Unknown
75	1985 (24-25 May) **"Urir Char Cyclone"**	Noakhali-Cox's Bazar coast (landfall at Sandwip)	Severe cyclone	11,069 people
76	1986 (9 November)	Barguna-Chattogram coast	Cyclonic Storm	14 people
77	1988 (29-30 November)**"Cyclone 04B"**	Sunderban	Severe cyclonic storm	5,708 people
78	1990 (7-8 October)	Barguna-Noakhali coast	Cyclonic Storm	Unknown
79	1991 (29 April)	Patuakhali-Cox's Bazar coast (landfall north of Chattogram)	Catastrophic cyclone	138,000 people
80	1997 (19 May)	Coastal belt of Bangladesh	Cyclonic Storm	155 people
81	2007 (15 November) **"Cyclone Sidr"**	Coastal belt of Bangladesh	Cyclonic Storm	3,363 people

82	2008 (8 May) **“Cyclone Nargis”**	Coastal belt of Bangladesh	Cyclonic Storm	3500 people
83	2009 (25 May) **“Cyclone Aila”**	Offshore 15 Districts of Southwestern part of Bangladesh	Cyclonic Storm	150 people
84	2013 (16 May) **“Cyclone Mahasen”**	Chattogram	Cyclonic Storm	17 people
85	2016 (21 May) **“Cyclone Roanu”**	Chattogram	Cyclonic Storm	26 people
86	2017 (28 May) **“Cyclone Mora”**	Cox’s Bazar	Cyclonic Storm	7 people
87	2019 (4 May) **“Cyclone Fani”**	Coastal belt of Bangladesh (northeast ward) Eastern coast of India	Cyclone with the strongest storm	12 people
88	2020 (21 May) **“Cyclone Amphan”**	Patuakhali, Satkhira, Pirojpur, Bhola and Barguna	Cyclone with the strongest storm	18 people

Table A2: Polders in Bangladesh.

District Name	Name of Upozilla	Polder number						
Jossore	Keshabpur	24						
Satkhira	Tala	6-08 Ext	6-8	16	25			
Satkhira	Satkhira Sadar	6-08 Ext	1	2	6-8			
Satkhira	Kalaroa	6-08 Ext						
Satkhira	Debhata	1	3					
Satkhira	Assasuni	2	4	6-8	7/2			
Satkhira	Kaliganj	3	4	5				
Satkhira	Shyamnagar	5	7/1	15				
khulna	Koyra	14/1	13-14/2	10-12				
khulna	Paikgachha	10-12	9	23	18/19			
		20	20/1	21	22			
khulna	Dumuria	17/1	17/2	26	29			
		25	27/1	27/2				
khulna	Batiaghata	29	28/1	28/2	30			
		31	34/2					
khulna	Phultala	25						

khulna	Khan Jahan Ali	25						
khulna	Daulatpur	25	28/1					
khulna	Khalishpur	28/1						
khulna	Dacope	31 (part)	32	33				
Bagerhat	Mollahat	36/1						
Bagerhat	Chitalmari	36/1	36/2					
khulna	Rupsa	36/1	34/2					
Bagerhat	Fakirhat	36/1	34/1	34/2				
Bagerhat	Bagerhat Sadar	36/1	36/2	34/1	34/2			
		34/3	35/3	37				
Bagerhat	Kachua	36/2	37					
Bagerhat	Rampal	34/2	35/3	35/2				
Bagerhat	Mongla	35/2						
Bagerhat	Morrelganj	35/2	35/1	37				
Bagerhat	Sarankhola	35/1						
Pirojpur	Zianagar	37	38					
Pirojpur	Pirojpur Sadar	38						
Pirojpur	Bhandaria	39/2C						

Gopalganj	Kotali Para	SB-1						
Barisal	Agailjhara	SB-2						
Barisal	Wazirpur	SB-2	SB-3					
Barguna	Patharghata	40/1	40/2	39/1A				
Barguna	Bamna	39/1 BandD	39/2A					
Pirojpur	Mathbaria	39/1 BandD	39/2A					
Barguna	Betagi	BCN	41/7A	41/7B				
Patuakhali	Mirzaganj	MRP	41/7					
Patuakhali	Dumki	ITL	DLK					
Patuakhali	Patuakhali Sadar	ITL	DLK	43/2A	43/2D	43/2E	55/2A	
Barguna	Barguna Sadar	41/6A	41/6B	41/1	41/2	41/3	41/4	
		41/5	42					
Barguna	Amtali	45	44	43/1	43/2F	43/1A		
Barguna	Kala Para	44	43/1**B**	46	47/3	47/4	47/5	
		47/1	48	54				
Patuakhali	Galachipa	43/2B	43/2C	55/1	55/2B	55/2C	55/2A	
		49	50-51	52-53A	52-53B	55/4	55/3	
Patuakhali	Dashmina	55/2C	55/2A	55/2D				

Patuakhali	Bauphal	55/2A	55/2E	55/2E	55/2D			
Bhola	Char Fasson	56/57						
Bhola	Lalmohan	56/57						
Bhola	Tazumuddin	56/57						
Bhola	Burhanuddin	56/57						
Bhola	Daulathkan	56/57						
Bhola	Bhola Sadar	56/57						
Lakshmipur	Kamalnagar	59/2E	59/2	59/3A				
Lakshmipur	Ramgati	59/2E	59/3	59/3A				
Noakhali	Subarnachar	59/4	59/3A	59/3B				
Lakshmipur	Lakshmipur Sadar	59/3A	59/1B					
Noakhali	Noakhali Sadar (Sudharam)	59/3A	59/1B	59/3B	59/1A	59/3C		
Noakhali	Begumganj	59/1B	59/1A					
Noakhali	Kabirhat	59/3B	59/1A	59/3C				
Noakhali	Companigonj	59/3B	59/1A	59/3C				
Noakhali	Senbagh	59/1A						
Feni	Daganbhuiyan	59/1A						
Feni	Sonagazi	60						

Bhola	Manpura	58/1	58/2	58/3				
Noakhali	Hatiya	73/1A and 73/1B	73/2					
Chittagong	Mirsharai	61/2						
Chittagong	Sitakunda	61/1						
Chittagong	Pahartali	62						
Chittagong	Halishahar	62						
Chittagong	Double Mooring	62						
Chittagong	Chittagong Port	62						
Chittagong	Patenga	62						
Chittagong	Khulshi	62						
Chittagong	Sandwip	72						
Chittagong	Patiya	63/2						
Chittagong	Anowara	63/1A	63/1B					
Chittagong	Banshkhali	64/1A	4/2A	4/1C	64/1B			
Cox's Bazar	Pekua	4/2A	64/2B					
Cox's Bazar	Maheshkhali	70	69					
Cox's Bazar	Kutubdia	71	66/4					
Cox's Bazar	Chakaria	65	65/A-3	65/A	65/A-1	66/4		

Cox's Bazar	Cox'S Bazar Sadar	66/3	66/2	66/1				
Cox's Bazar	Ramu	66/2	66/2					
Cox's Bazar	Ukhia	67/A						
Cox's Bazar	Teknaf	67	67/B					

Table A3: Calculated thrust forces for Cyclone 1991 (Mahin, 2014).

District	Thana	Cyclone wind speed (Km/Hr)	Surge Depth (m)	Thrust Force (kN/m)	Surge Velocity (m/s)
Barguna	Amtali	70.36	0.25	1.35	0.54
Barguna	Bamna	59.40	1.53	2.34	0.44
Barguna	Barguna Sadar	64.14	1.05	1.09	0.37
Barguna	Betagi	62.57	0.93	1.21	0.53
Barguna	Patharghata	57.23	0.52	1.77	0.47
Barisal	Agailjhara	46.87	0.00	0.38	0.00
Barisal	Babuganj	57.48	1.14	1.63	0.59
Barisal	Bakerganj	70.08	0.31	2.70	0.22
Barisal	Banari Para	50.60	0.80	0.64	0.29
Barisal	Gaurnadi	50.31	0.08	0.61	0.01
Barisal	Hizla	60.82	2.78	1.17	0.48
Barisal	Barisal Sadar (Kotwali)	64.82	1.15	3.69	0.54
Barisal	Mehendiganj	66.03	1.72	4.48	0.67

Barisal	Muladi	55.40	1.27	1.34	0.41
Barisal	Wazirpur	50.56	0.43	1.33	0.49
Bhola	Bhola Sadar	77.52	1.53	7.28	0.74
Bhola	Burhanuddin	96.62	0.88	4.52	0.68
Bhola	Char Fasson	113.34	1.67	17.04	1.37
Bhola	Daulatkhan	87.80	2.20	1.40	0.30
Bhola	Lalmohan	109.84	0.33	4.43	0.59
Bhola	Manpura	142.11	3.08	8.27	1.08
Bhola	Tazumuddin	112.42	4.09	8.59	0.77
Jhalokati	Jhalokati Sadar	56.65	0.55	0.46	0.11
Jhalokati	Kanthalia	58.92	0.95	0.90	0.36
Jhalokati	Nalchity	62.66	1.08	0.38	0.14
Jhalokati	Rajapur	57.29	0.83	0.85	0.15
Patuakhali	Bauphal	83.69	1.36	6.61	0.77
Patuakhali	Dashmina	91.79	1.38	4.40	0.52
Patuakhali	Dumki	72.71	1.54	2.42	0.41
Patuakhali	Galachipa	87.56	1.02	3.98	1.14
Patuakhali	Kala Para	72.28	0.45	2.18	0.61
Patuakhali	Mirzaganj	66.07	1.50	1.78	0.51
Patuakhali	Patuakhali Sadar	73.37	1.06	1.76	0.50
Pirojpur	Bhandaria	54.57	1.62	1.51	0.62
Pirojpur	Kawkhali	52.86	4.32	0.85	0.58
Pirojpur	Mathbaria	54.25	1.11	1.42	0.72
Pirojpur	Nazirpur	46.06	0.90	0.41	0.48
Pirojpur	Pirojpur Sadar	49.72	1.39	0.95	0.56

Pirojpur	Nesarabad (Swarupkati)	51.22	1.82	0.47	0.15
Pirojpur	Zianagar	50.68	1.46	0.63	0.73
Chandpur	Chandpur Sadar	55.54	2.29	1.04	0.63
Chandpur	Faridganj	61.36	0.91	0.77	0.21
Chandpur	Haim Char	60.27	9.10	0.78	0.15
Chandpur	Hajiganj	58.41	0.52	1.02	0.23
Chandpur	Kachua	55.04	0.00	0.51	0.00
Chandpur	Matlab Dakshin	52.34	0.00	0.48	0.00
Chandpur	Matlab Uttar	47.43	1.99	1.37	0.46
Chandpur	Shahrasti	64.31	0.31	0.58	0.08
Chittagong	Anowara	201.18	0.82	43.69	0.45
Chittagong	Bayejid Bostami	171.28	0.00	6.40	0.00
Chittagong	Banshkhali	204.09	0.44	62.47	1.35
Chittagong	Bakalia	180.22	3.92	7.40	0.16
Chittagong	Boalkhali	161.34	0.29	13.60	0.22
Chittagong	Chandanaish	167.92	0.43	11.68	0.57
Chittagong	Chandgaon	171.75	1.83	7.11	0.19
Chittagong	Chittagong Port	197.53	4.10	11.95	0.49
Chittagong	Double Mooring	189.74	1.02	4.21	0.00
Chittagong	Fatikchhari	118.35	0.00	3.35	0.09
Chittagong	Halishahar	191.94	0.04	10.08	0.05
Chittagong	Hathazari	151.48	0.37	12.92	0.59
Chittagong	Kotwali	183.87	1.44	11.82	0.29
Chittagong	Khulshi	183.08	0.00	7.27	0.00

Chittagong	Lohagara	170.83	0.00	8.04	0.00
Chittagong	Mirsharai	112.44	0.41	6.25	0.48
Chittagong	Pahartali	187.44	0.00	0.65	0.00
Chittagong	Panchlaish	178.38	0.00	9.07	0.00
Chittagong	Patiya	174.18	0.21	16.31	0.15
Chittagong	Patenga	205.47	2.47	29.83	0.69
Chittagong	Rangunia	139.62	0.35	6.09	0.26
Chittagong	Raozan	145.10	0.28	15.26	0.49
Chittagong	Sandwip	156.34	5.18	19.30	0.86
Chittagong	Satkania	176.62	0.59	14.78	0.50
Chittagong	Sitakunda	150.19	0.20	7.01	0.51
Cox'S Bazar	Chakaria	170.90	1.22	35.95	1.27
Cox'S Bazar	Cox'S Bazar Sadar	150.11	0.97	28.10	1.19
Cox'S Bazar	Kutubdia	216.46	3.14	55.79	1.92
Cox'S Bazar	Maheshkhali	176.50	2.83	40.84	2.36
Cox'S Bazar	Pekua	195.23	0.57	36.60	1.74
Cox'S Bazar	Ramu	136.56	0.36	11.04	0.49
Cox'S Bazar	Teknaf	100.15	0.98	5.41	0.42
Cox'S Bazar	Ukhia	119.16	0.10	5.84	0.58
Feni	Chhagalnaiya	90.66	0.31	2.40	0.81
Feni	Daganbhuiyan	90.16	0.00	1.62	0.00
Feni	Feni Sadar	91.38	0.26	2.48	0.18
Feni	Fulgazi	81.70	0.00	1.73	0.00
Feni	Parshuram	75.86	0.00	1.73	0.00
Feni	Sonagazi	103.45	1.58	4.15	0.61

Lakshmipur	Kamalnagar	87.61	0.00	4.77	0.00
Lakshmipur	Lakshmipur Sadar	77.03	0.79	2.23	0.56
Lakshmipur	Roypur	67.27	0.86	2.64	0.34
Lakshmipur	Ramganj	67.45	0.00	1.96	0.00
Lakshmipur	Ramgati	102.57	0.16	8.32	0.94
Noakhali	Begumganj	86.42	0.00	0.94	0.00
Noakhali	Chatkhil	73.14	0.00	1.56	0.00
Noakhali	Companiganj	109.77	2.12	6.35	0.77
Noakhali	Hatiya	154.32	2.38	30.93	2.58
Noakhali	Kabirhat	101.59	0.00	2.47	0.00
Noakhali	Senbagh	85.68	0.00	1.03	0.00
Noakhali	Sonaimuri	78.92	0.00	0.75	0.00
Noakhali	Subarnachar	120.51	3.56	16.46	1.15
Noakhali	Noakhali Sadar (Sudharam)	95.58	0.00	0.72	0.00
Gopalganj	Gopalganj Sadar	36.30	0.22	0.19	0.10
Gopalganj	Kashiani	32.54	0.18	0.20	0.19
Gopalganj	Kotali Para	42.04	0.00	0.21	0.00
Gopalganj	Muksudpur	33.76	0.02	0.20	0.10
Gopalganj	Tungi Para	40.48	0.26	0.32	0.10
Shariatpur	Bhedarganj	50.11	0.37	0.59	0.33
Shariatpur	Damudya	50.88	0.00	0.27	0.00
Shariatpur	Gosairhat	53.69	0.84	0.95	0.22
Shariatpur	Naria	45.55	4.23	1.96	0.58
Shariatpur	Shariatpur Sadar	45.28	0.00	0.12	0.00

Shariatpur	Zanjira	41.06	4.04	0.77	0.52
Bagerhat	Bagerhat Sadar	40.90	0.00	0.13	0.00
Bagerhat	Chitalmari	41.65	0.20	0.29	0.22
Bagerhat	Fakirhat	36.99	0.00	0.21	0.00
Bagerhat	Kachua	44.98	0.62	0.18	0.06
Bagerhat	Mollahat	37.60	0.16	0.22	0.13
Bagerhat	Mongla	43.76	0.36	1.34	0.52
Bagerhat	Morrelganj	46.52	0.64	0.73	0.35
Bagerhat	Rampal	38.90	0.50	0.20	0.14
Bagerhat	Sarankhola	49.88	0.96	1.72	0.48
Jessore	Abhaynagar	26.97	0.10	0.32	0.00
Jessore	Bagher Para	22.22	0.00	0.00	0.00
Jessore	Chaugachha	16.88	0.00	0.01	0.00
Jessore	Jhikargachha	19.40	0.00	0.03	0.00
Jessore	Keshabpur	24.77	0.00	0.02	0.00
Jessore	Kotwali	20.97	0.00	0.00	0.00
Jessore	Manirampur	23.11	0.00	0.03	0.00
Jessore	Sharsha	17.80	0.00	0.03	0.00
Khulna	Batiaghata	33.31	1.24	0.92	0.28
Khulna	Dacope	37.16	2.42	1.22	0.80
Khulna	Daulatpur	30.93	0.00	0.00	0.00
Khulna	Dumuria	29.23	0.11	0.44	0.14
Khulna	Dighalia	31.40	0.87	0.47	0.15
Khulna	Khalishpur	31.95	0.00	0.17	0.00
Khulna	Khan Jahan Ali	29.90	0.00	0.00	0.00

Khulna	Khulna Sadar	33.48	3.39	0.41	0.06
Khulna	Koyra	35.24	1.53	3.34	0.99
Khulna	Paikgachha	30.49	1.03	2.11	0.60
Khulna	Phultala	28.24	0.03	0.00	0.00
Khulna	Rupsa	34.95	0.31	0.39	0.19
Khulna	Sonadanga	32.53	0.00	0.22	0.00
Khulna	Terokhada	33.94	0.22	0.59	0.14
Narail	Kalia	31.79	0.45	0.35	0.07
Narail	Lohagara	28.43	0.31	0.22	0.15
Narail	Narail Sadar	26.48	0.00	0.15	0.00
Satkhira	Assasuni	27.64	1.14	0.38	0.31
Satkhira	Debhata	23.43	0.31	0.04	0.10
Satkhira	Kalaroa	20.95	0.00	0.03	0.00
Satkhira	Kaliganj	25.64	0.17	0.39	0.04
Satkhira	Satkhira Sadar	22.72	0.04	0.03	0.03
Satkhira	Shyamnagar	30.76	1.67	1.56	1.09
Satkhira	Tala	25.91	0.04	0.00	0.00

Table A4: Calculated thrust forces for Cyclone SIDR (Mahin, 2014).

District	Thana	Cyclone wind speed (Km/Hr)	Surge Depth (m)	Thrust Force (kN/m)	Surge Velocity (m/s)
Barguna	Amtali	158.26	0.48	70.87	2.43
Barguna	Bamna	186.34	1.91	54.98	2.10
Barguna	Barguna Sadar	157.07	1.31	59.81	1.55
Barguna	Betagi	157.77	0.90	36.53	1.37
Barguna	Patharghata	191.01	0.99	46.70	2.01
Barisal	Agailjhara	106.35	0.00	2.70	0.00
Barisal	Babuganj	132.54	1.27	12.18	1.43
Barisal	Bakerganj	188.41	0.41	21.68	0.74
Barisal	Banari Para	128.62	0.80	5.71	0.48
Barisal	Gaurnadi	109.41	0.09	5.70	0.01
Barisal	Hizla	111.23	3.15	4.50	0.68
Barisal	Barisal Sadar (Kotwali)	152.79	1.35	15.81	0.95
Barisal	Mehendiganj	130.69	2.05	19.18	0.90
Barisal	Muladi	112.83	1.53	3.91	0.26
Barisal	Wazirpur	121.41	0.45	11.28	0.78
Bhola	Bhola Sadar	146.04	1.81	33.42	1.44
Bhola	Burhanuddin	164.16	1.01	37.30	1.68
Bhola	Char Fasson	179.96	1.81	49.36	2.33
Bhola	Daulatkhan	149.24	2.10	9.41	0.37
Bhola	Lalmohan	173.34	0.36	25.75	1.17
Bhola	Manpura	142.43	3.14	25.20	1.72

Bhola	Tazumuddin	148.28	3.91	13.67	1.15
Jhalokati	Jhalokati Sadar	157.20	0.65	11.65	0.59
Jhalokati	Kanthalia	192.36	0.94	26.61	1.31
Jhalokati	Nalchity	178.81	1.11	20.64	0.88
Jhalokati	Rajapur	181.06	0.76	20.56	0.67
Patuakhali	Bauphal	198.70	1.01	43.89	1.77
Patuakhali	Dashmina	216.18	1.64	49.07	1.67
Patuakhali	Dumki	207.68	1.61	35.33	1.06
Patuakhali	Galachipa	204.29	1.80	81.40	3.28
Patuakhali	Kala Para	202.23	0.75	51.36	1.58
Patuakhali	Mirzaganj	115.79	1.60	14.87	1.00
Patuakhali	Patuakhali Sadar	130.71	1.12	27.47	0.94
Pirojpur	Bhandaria	183.83	1.63	25.40	0.67
Pirojpur	Kawkhali	161.91	3.72	16.89	0.78
Pirojpur	Mathbaria	187.97	1.29	40.06	1.45
Pirojpur	Nazirpur	124.57	0.94	5.22	1.15
Pirojpur	Pirojpur Sadar	152.05	1.36	12.81	0.64
Pirojpur	Nesarabad (Swarupkati)	141.37	2.08	10.36	0.67
Pirojpur	Zianagar	168.32	1.60	24.50	0.53
Chandpur	Chandpur Sadar	83.21	2.41	1.68	0.76
Chandpur	Faridganj	88.48	1.00	1.03	0.22
Chandpur	Haim Char	97.54	9.35	4.34	0.97
Chandpur	Hajiganj	78.87	0.56	1.77	0.31
Chandpur	Kachua	72.04	0.00	1.42	0.00

Chandpur	Matlab Dakshin	74.30	0.00	1.12	0.00
Chandpur	Matlab Uttar	70.92	2.14	2.11	1.23
Chandpur	Shahrasti	80.14	0.29	1.02	0.20
Chittagong	Anowara	75.09	0.75	5.07	0.41
Chittagong	Bayejid Bostami	76.41	0.00	0.99	0.00
Chittagong	Banshkhali	72.98	0.37	5.56	0.48
Chittagong	Bakalia	75.25	3.61	3.51	0.08
Chittagong	Boalkhali	70.73	0.22	4.52	0.57
Chittagong	Chandanaish	68.47	0.45	1.49	0.20
Chittagong	Chandgaon	74.49	1.86	0.58	0.62
Chittagong	Chittagong Port	78.49	3.70	1.75	0.59
Chittagong	Double Mooring	77.31	0.90	1.10	0.00
Chittagong	Fatikchhari	72.73	0.01	1.46	0.18
Chittagong	Halishahar	78.61	0.02	4.50	0.05
Chittagong	Hathazari	75.35	0.49	1.22	0.30
Chittagong	Kotwali	76.21	1.28	2.01	0.34
Chittagong	Khulshi	77.33	0.00	0.91	0.00
Chittagong	Lohagara	67.17	0.00	0.86	0.00
Chittagong	Mirsharai	78.75	0.40	3.15	0.51
Chittagong	Pahartali	78.56	0.00	0.65	0.00
Chittagong	Panchlaish	76.09	0.00	1.37	0.00
Chittagong	Patiya	71.61	0.16	2.48	0.11
Chittagong	Patenga	78.35	1.91	2.55	0.45
Chittagong	Rangunia	66.56	0.52	2.78	0.54
Chittagong	Raozan	70.98	0.36	1.93	0.60

Chittagong	Sandwip	91.37	4.59	7.02	0.76
Chittagong	Satkania	68.86	0.54	1.38	0.19
Chittagong	Sitakunda	79.44	0.19	3.76	0.56
Cox'S Bazar	Chakaria	67.91	0.91	3.26	0.91
Cox'S Bazar	Cox'S Bazar Sadar	66.20	0.76	3.40	0.60
Cox'S Bazar	Kutubdia	75.01	2.47	5.31	0.94
Cox'S Bazar	Maheshkhali	70.88	2.14	5.49	1.48
Cox'S Bazar	Pekua	71.65	0.36	2.83	0.45
Cox'S Bazar	Ramu	63.21	0.27	1.41	0.23
Cox'S Bazar	Teknaf	55.96	1.08	2.44	0.45
Cox'S Bazar	Ukhia	60.88	0.10	1.72	0.64
Feni	Chhagalnaiya	73.57	0.42	1.78	0.82
Feni	Daganbhuiyan	82.52	0.00	0.69	0.00
Feni	Feni Sadar	77.60	0.29	2.19	0.48
Feni	Fulgazi	71.91	0.00	0.74	0.00
Feni	Parshuram	68.90	0.00	0.66	0.00
Feni	Sonagazi	83.41	1.53	2.51	0.84
Lakshmipur	Kamalnagar	117.76	0.00	9.44	0.02
Lakshmipur	Lakshmipur Sadar	103.69	0.87	6.73	0.71
Lakshmipur	Roypur	101.57	0.94	6.95	0.64
Lakshmipur	Ramganj	89.52	0.00	3.94	0.00
Lakshmipur	Ramgati	122.29	0.19	6.71	0.89
Noakhali	Begumganj	93.08	0.00	0.61	0.00
Noakhali	Chatkhil	90.05	0.00	3.35	0.00
Noakhali	Companiganj	92.51	2.29	4.43	0.47

Noakhali	Hatiya	123.36	1.88	15.38	1.33
Noakhali	Kabirhat	94.74	0.00	0.93	0.00
Noakhali	Senbagh	84.65	0.00	0.31	0.00
Noakhali	Sonaimuri	87.90	0.00	0.65	0.00
Noakhali	Subarnachar	107.75	3.29	9.34	0.84
Noakhali	Noakhali Sadar (Sudharam)	103.00	0.00	1.74	0.00
Gopalganj	Gopalganj Sadar	84.55	0.23	1.59	0.41
Gopalganj	Kashiani	72.68	0.16	1.72	0.37
Gopalganj	Kotali Para	96.68	0.00	1.25	0.00
Gopalganj	Muksudpur	71.45	0.02	1.69	0.15
Gopalganj	Tungi Para	100.15	0.27	0.82	0.20
Shariatpur	Bhedarganj	83.55	0.55	1.63	0.73
Shariatpur	Damudya	92.36	0.00	1.16	0.00
Shariatpur	Gosairhat	98.21	0.68	2.18	0.22
Shariatpur	Naria	78.07	4.72	2.06	0.73
Shariatpur	Shariatpur Sadar	84.36	0.00	1.37	0.00
Shariatpur	Zanjira	72.82	4.55	1.76	1.03
Bagerhat	Bagerhat Sadar	116.15	0.00	2.61	0.00
Bagerhat	Chitalmari	110.33	0.21	1.59	0.04
Bagerhat	Fakirhat	100.32	0.00	2.06	0.00
Bagerhat	Kachua	131.76	0.63	4.40	0.12
Bagerhat	Mollahat	96.08	0.18	1.20	0.05
Bagerhat	Mongla	127.34	0.41	15.40	0.97
Bagerhat	Morrelganj	147.79	0.64	16.90	0.54

Bagerhat	Rampal	112.31	0.55	7.21	0.60
Bagerhat	Sarankhola	156.52	1.45	23.98	1.90
Jessore	Abhaynagar	66.62	0.10	0.38	0.01
Jessore	Bagher Para	52.98	0.00	0.02	0.00
Jessore	Chaugachha	42.11	0.00	0.02	0.00
Jessore	Jhikargachha	48.91	0.00	0.24	0.00
Jessore	Keshabpur	63.32	0.00	0.17	0.00
Jessore	Kotwali	51.19	0.00	0.01	0.00
Jessore	Manirampur	57.85	0.00	0.28	0.00
Jessore	Sharsha	45.56	0.00	0.16	0.00
Khulna	Batiaghata	89.78	1.29	7.96	0.41
Khulna	Dacope	106.06	2.30	11.57	1.24
Khulna	Daulatpur	79.22	0.00	0.01	0.00
Khulna	Dumuria	76.10	0.11	1.26	0.21
Khulna	Dighalia	79.17	0.71	0.96	0.26
Khulna	Khalishpur	82.57	0.00	0.55	0.00
Khulna	Khan Jahan Ali	75.61	0.00	0.01	0.00
Khulna	Khulna Sadar	88.17	2.60	1.14	0.14
Khulna	Koyra	94.05	1.47	5.95	0.69
Khulna	Paikgachha	82.07	1.04	2.16	0.55
Khulna	Phultala	70.66	0.01	0.01	0.00
Khulna	Rupsa	91.71	0.38	1.68	0.29
Khulna	Sonadanga	84.99	0.00	1.17	0.00
Khulna	Terokhada	85.77	0.28	1.23	0.26
Narail	Kalia	77.13	0.45	1.11	0.14

Narail	Lohagara	65.32	0.31	1.17	0.21
Narail	Narail Sadar	62.81	0.00	0.81	0.00
Satkhira	Assasuni	73.13	1.13	1.39	0.46
Satkhira	Debhata	60.89	0.32	0.36	0.16
Satkhira	Kalaroa	53.88	0.00	0.28	0.00
Satkhira	Kaliganj	66.92	0.15	0.80	0.18
Satkhira	Satkhira Sadar	58.88	0.05	0.38	0.06
Satkhira	Shyamnagar	77.95	1.47	3.32	0.41
Satkhira	Tala	67.55	0.04	0.01	0.01

APPENDIX B

Table B1: Shear Wave Velocity for Anowara Polder.

Depth (m) (From top)	Soil type	SPT value (N)	Share Wave velocity (m/sec) (Ansary,2015)	Share Wave velocity (m/sec) Anbazhagan, Kumar and Sitharam (2013)	Share Wave velocity (m/sec) Rahman, Kamal and Siddiqua (2018)	Share Wave velocity (m/sec) Chatterjee, Choudhury (2013)
0m-3m	Silty Clay	9	158.1	251.21	212.77	182.46
3m-9m	Silty Clay	3	154.0	163.67	146.29	118.62
9m-12m	Silty Clay	3	165.0	163.67	146.29	118.62
12m-16.5m	Silty Clay	6	213.8	214.47	185.29	155.65

Table B2: Shear Modulus for Anowara Polder.

Depth (m) (From top)	Soil type	SPT value N_{60}	$N_{160} = C_N * N_{60}$	Shear Modulus G_{max} (Mpa) Kramer (1996)	Shear Modulus G_{max} (Mpa) Anbazhagan, P. et al. (2012)	Shear Modulus G_{max} (Mpa) Imai, T. and Tonouchi, K. (1982)	Shear Modulus G_{max} (Mpa) Ohsaki, Y. and Iwasaki, R. (1973)
0m-3m	Silty	9	12	69.33	64.62	65.50	65.36
3m-9m	Silty	3	2	32.84	13.83	33.62	29.96
9m-12m	Silty	3	2	32.84	11.70	33.62	29.96
12m-	Silty	6	3	52.62	18.20	51.21	49.01

Table B3: Shear Strength parameter for Anowara Polder.

Depth (m) (From top)	Soil type	SPT value (N_{60})	Angle of friction(φ') Das et, al. (2017)	Angle of friction(φ') Wolff(1989)	Angle of friction(φ') Hatanaka and Uchida (1996)	Undrained cohesion C_u Kulhawy and Mayne (1990)	Undrained cohesion (C_u) Hettiarachchi and Brown(2009)	Undrained Cohesion(C_u) Ansary and Urmi (2017)
0m-3m	Silty Clay	9	24.3	29.8	35.6	36.9	54	70
3m-9m	Silty Clay	3	20.1	28.0	27.7	12.3	18	15
9m-12m	Silty Clay	3	20.1	28.0	28.8	12.3	18	15
12m-16.5m	Silty Clay	6	22.2	28.9	31.4	24.6	36	43

Table B4: Void ratio and Poisson's ratio for Anowara Polder.

Depth (m) (From top)	Soil type	SPT value N_{60}	Void ratio (e) Anbazhagan, P. et al.(2017)	Poissons ratio (ϑ) Kumar, R. et al. (2016)
0m-3m	Silty Clay	9	0.7	0.29
3m-9m	Silty Clay	3	0.8	0.23
9m-12m	Silty Clay	3	0.8	0.23
12m-16.5m	Silty Clay	6	0.7	0.26

Table B5: Shear Wave Velocity for Barguna Polder.

Depth (m) (From top)	Soil type	SPT value	Share Wave velocity (m/sec) (Ansary,2015)	Share Wave velocity (m/sec) Anbazhagan, Kumar and Sitharam (2013)	Share Wave velocity (m/sec) Rahman, Kamal and Siddiqua (2018)	Share Wave velocity (m/sec) Chatterjee, Choudhury (2013)
0m-6m	Clayey Silt	5	160	157	168	143
6m-19.5m	Clayey Silt	4	200	140	156	132
19.5m-30m	Fine Sand	22	348	334	278	250

Table B6: Shear Modulus for Barguna Polder.

Depth (m) (From top)	Soil type	SPT value	$N_{160} = C_N * N_{60}$	Shear Modulus G_{max} (Mpa) Kramer (1996)	Shear Modulus G_{max} (Mpa) Anbazhagan, P. et al. (2012)	Shear Modulus G_{max} (Mpa) Imai, T. and Tonouchi, K. (1982)	Shear Modulus G_{max} (Mpa) Ohsaki, Y. and Iwasaki, R. (1973)
0m-6m	Clayey Silt	5	5	46	50	42	63
6m-19.5m	Clayey Silt	4	2	40	24	36	53
19.5m-30m	Fine Sand	22	7	127	66	116	200

Table B7: Shear Strength parameter for Barguna Polder.

Depth (m) (From top)	Soil type	SPT value (N_{60})	Angle of friction(φ') Das et, al. (2017)	Angle of friction(φ') Wolff(1989)	Angle of friction(φ') Hatanaka and Uchida (1996)	Undrained cohesion (C_u) Kulhawy and Mayne (1990)	Undrained cohesion (C_u) Hettiarachchi and Brown(2009)	Undrained cohesion (C_u) Ansary and Urmi (2017)
0m-6m	Clayey Silt	5	22	29	30	30	21	33
6m-19.5m	Clayey Silt	4	21	28	26	24	16	24
19.5m -30m	Fine Sand	22	33	33	32	-	-	-

Table B8: Void ratio and Poisson's ratio for Barguna Polder.

Depth (m) (From top)	Soil type	SPT value N_{60}	Void ratio(e) Anbazhagan, P. et al.(2017)	Poisson's ratio (ϑ) Kumar, R. et al. (2016)
0m-6m	Clayey Silt	5	0.73	0.25
6m-19.5m	Clayey Silt	4	0.75	0.24
19.5m-30m	Fine Sand	22	0.61	0.42

Table B9: Shear Wave Velocity for Bhola Polder.

Depth (m) (From top)	Soil type	SPT value (N)	Share Wave velocity (m/sec) (Ansary,2015)	Share Wave velocity (m/sec) Anbazhagan, Kumar and Sitharam (2013)	Share Wave velocity (m/sec) Rahman, Kamal and Siddiqua (2018)	Share Wave velocity (m/sec) Chatterjee, Choudhury (2013)
0m-4.5m	Clayey Silt	5	105	130	135	120
4.5m-10.5m	Fine Sand	6	192	172	179	153
10.5m-18m	Clayey Silt	6	218	172	179	153

Table B10: Shear Modulus for Bhola Polder.

Depth (m) (From top)	Soil type	SPT value(N_{60})	$N_{160} = C_N * N_{60}$	Shear Modulus G_{max} (Mpa) Kramer (1996)	Shear Modulus G_{max} (Mpa) Anbazhagan, P. et al. (2012)	Shear Modulus G_{max} (Mpa) Imai, T. and Tonouchi, K.	Shear Modulus G_{max} (Mpa) Ohsaki, Y. and Iwasaki, R. (1973)
0m-4.5m	Clayey Silt	5	6	46.5	55.5	42.2	39.4
4.5m-10.5m	Fine Sand	6	4	52.6	45.0	47.8	45.2
10.5m-18m	Clayey Silt	6	3	52.6	34.4	47.8	45.2

Table B11: Shear Strength parameter for Bhola Polder.

Depth (m) (From top)	Soil type	SPT value (N_{60})	Angle of friction(φ') Das et, al. (2017)	Angle of friction(φ') Wolff(1989)	Angle of friction(φ') Hatanaka and Uchida (1996)	Undrained cohesion (C_u) Kulhawy and Mayne (1990)	Undrained cohesion (C_u) Hettiarachchi and Brown(2009)	Undrained cohesionC_u Ansary and Urmi (2017)
0m-4.5m	Clayey Silt	5	21.5	28.6	30.8	30.0	20.5	33.3
4.5m-10.5m	Fine Sand	6	22.2	28.9	29.4	-	-	-
10.5m-18m	Clayey Silt	6	22.2	28.9	27.8	36.0	24.6	42.5

Table B12: Void ratio and Poisson’s ratio: for Bhola Polder.

Depth (m) (From top)	Soil type	SPT value (N_{60})	Void ratio(e) Anbazhagan, P. et al.(2017)	Poisson’s ratio(ϑ) Kumar, R. et al. (2016)
0m-4.5m	Clayey Silt	5	0.73	0.25
4.5m-10.5m	Fine Sand	6	0.72	0.26
10.5m-18m	Clayey Silt	6	0.72	0.26

Table B13: Shear Wave Velocity for Laxmipur, Noakhali Polder.

Depth (m) (From top)	Soil type	SPT value (N)	Share Wave velocity (m/sec) (Ansary,2015)	Share Wave velocity (m/sec) Anbazhagan, Kumar and Sitharam (2013)	Share Wave velocity (m/sec) Rahman, Kamal and Siddiqua (2018)	Share Wave velocity (m/sec) Chatterjee, Choudhury (2013)
0m-3.5m	Clayey Silt	5	141	157	168	143
3.5m-6m	Clayey Silt	5	160	157	168	143
6m-12m	Fine Sand	12	238	245	226	199
12m-22m	Fine Sand	25	334	356	290	262

Table B14: Shear Modulus for Laxmipur, Noakhali Polder.

Depth (m) (From top)	Soil type	SPT value (N_{60})	$N_{160} = C_N * N_{60}$	Shear Modulus G_{max} (Mpa) Kramer (1996)	Shear Modulus G_{max} (Mpa) Anbazhagan, P. et al. (2012)	Shear Modulus G_{max} (Mpa) Imai, T. and Tonouchi, K. (1982)	Shear Modulus G_{max} (Mpa) Ohsaki, Y. and Iwasaki, R. (1973)
0m-3.5m	Clayey Silt	5	6	46	35	42	39
3.5m-6m	Clayey Silt	5	7	46	39	42	39
6m-12m	Fine Sand	12	12	84	63	77	77
12m-22m	Fine Sand	25	19	139	96	126	134

Table B15: Shear Strength parameter for Laxmipur, Noakhali Polder.

Depth (m) (From top)	Soil type	SPT value (N_{60})	Angle of friction(φ') Das et, al. (2017)	Angle of friction(φ') Wolff(1989)	Angle of friction(φ') Hatanaka and Uchida (1996)	Undrained cohesion(C_u) Kulhawy and Mayne (1990)	Undrained cohesion (C_u) Hettiarachchi and Brown(2009)	Undrained cohesion (C_u) Ansary and Urmi (2017)
0m-3.5m	Clayey Silt	5	21.5	28.6	31.3	30.0	20.5	33.3
3.5m-6m	Clayey Silt	5	21.5	28.6	30.1	30.0	20.5	33.3
6m-12m	Fine Sand	12	26.4	30.6	32.7	-	-	-
12m-22m	Fine Sand	25	35.5	34.3	34.6	-	-	-

Table B16: Void ratio and Poisson's ratio for Laxmipur, Noakhali Polder.

Depth (m) (From top)	Soil type	SPT value (N_{60})	Void ratio (e) Anbazhagan, P. et al.(2017)	Poisson's ratio (ϑ) Kumar, R. et al. (2016)
0m-3.5m	Clayey Silt	5	0.73	0.25
3.5m-6m	Clayey Silt	5	0.73	0.32
6m-12m	Fine Sand	12	0.66	0.45
12m-22m	Fine Sand	25	0.60	0.25

Table B17: Shear Wave Velocity for Moheskhali Polder.

Depth (m) (From top)	Soil type	SPT value (N)	Share Wave velocity (m/sec) (Ansary,2015)	Share Wave velocity (m/sec) Anbazhagan, Kumar and Sitharam (2013)	Share Wave velocity (m/sec) Rahman, Kamal and Siddiqua (2018)	Share Wave velocity (m/sec) Chatterjee, Choudhury (2013)
0m-4.5m	Silty Clay	5	149	157	168	143
4.5m-9m	Fine sand	10	212	223	213	186
9m-14m	Dense Sand	50	360	507	367	340

Table B18: Shear Modulus for Moheskhali Polder.

Depth (m) (From top)	Soil type	SPT value (N_{60})	$N_{160} = C_N * N_{60}$	Shear Modulus G_{max} Mpa) Kramer (1996)	Shear Modulus G_{max} Mpa) Anbazhagan, P. et al. (2012)	Shear Modulus G_{max} (Mpa)	Shear Modulus G_{max} Mpa) Ohsaki, Y. and Iwasaki, R. (1973)
0m-4.5m	Silty Clay	5	6	46.5	32.1	42.2	39.4
4.5m-9m	Fine sand	10	8	74.5	43.7	67.6	66.7
9m-14m	Dense Sand	50	30	222.5	154.5	201.9	226.6

Table B19: Shear Strength parameter for Moheskhali Polder.

Depth (m) (From top)	Soil type	SPT value (N_{60})	Angle of friction (φ') Das et, al. (2017)	Angle of friction (φ') Wolff(1989)	Angle of friction (φ') Hatanaka and Uchida	Undrained cohesion (C_u) Kulhawy and Mayne	Undrained cohesion(C_u) Hettiarachchi and Brown(2009)	Undrained cohesion (C_u) Ansary and Urmi (2017)
0m-4.5m	Silty Clay	5	21.5	29.2	68.4	33.1	18.8	65.9
4.5m-9m	Fine sand	10	25.0	29.9	71.6	-	-	-
9m-14m	Dense Sand	50	53.0	30.6	81.0	-	-	-

Table B20: Void ratio and Poisson’s ratio for Moheskhali Polder.

Depth (m) (From top)	Soil type	SPT value (N_{60})	Void ratio (e) Anbazhagan, P. et al.(2017)	Poisson’s ratio (ϑ) Kumar, R. et al. (2016)
0m-4.5m	Silty Clay	5	0.7	0.25
4.5m-9m	Fine sand	10	0.7	0.3
9m-14m	Dense Sand	50	0.6	0.45

Table B21: Shear Wave Velocity for Satkhira Polder.

Depth (m) (From top)	Soil type	SPT value (N)	Share Wave velocity (m/sec) (Ansary,2015)	Share Wave velocity (m/sec) Anbazhagan, Kumar and Sitharam (2013)	Share Wave velocity (m/sec) Rahman, Kamal and Siddiqua (2018)	Share Wave velocity (m/sec) Chatterjee, Choudhury (2013)
0m-3.5m	Silty clay	3	123	121	141	118
3.5m-7.5m	Silty clay	3	147	121	141	118
7.5m-18m	Fine Sand	5	208	157	168	143
18m-30m	Fine Sand	25	359	356	290	262

Table B22: Shear Modulus for Satkhira Polder.

Depth (m) (From top)	Soil type	SPT value (N_{60})	$N_{160} = C_N * N_{60}$	Shear Modulus G_{max} Mpa) Kramer (1996)	Shear Modulus G_{max} Mpa) Anbazhagan, P. et al. (2012)	Shear Modulus G_{max} (Mpa) Imai, T. and Tonouchi, K. (1982)	Shear Modulus G_{max} Mpa) Ohsaki, Y. and Iwasaki, R. (1973)
0m-3.5m	Silty clay	3	4	32.8	21.6	29.8	26.7
3.5m-7.5m	Silty clay	3	4	32.8	20.2	29.8	26.7
7.5m-18m	Fine	5	4	46.5	21.0	42.2	39.4
18m-30m	Fine	25	16	138.9	86.1	126.0	133.8

Table B23: Shear Strength parameter for Satkhira Polder.

Depth (m) (From top)	Soil type	SPT value (N_{60})	Angle of friction (φ') Das et, al. (2017)	Angle of friction (φ') Wolff(1989)	Angle of friction (φ') Hatanaka and Uchida (1996)	Undrained cohesion (C_u) Kulhawy and Mayne (1990)	Undrained cohesion(C_u) Hettiarachchi and Brown(2009)	Undrained cohesion (C_u) Ansary and Urmi (2017)
0m-3.5m	Silty clay	3	20	28	29	18	12	15
3.5m-7.5m	Silty clay	3	20	28	28	18	12	15
7.5m-18m	Fine Sand	5	22	29	29	-	-	-
18m-30m	Fine Sand	25	36	34	38	-	-	-

Table B24: Void ratio and Poisson’s ratio for Satkhira Polder.

Depth (m) (From top)	Soil type	SPT value (N_{60})	Void ratio (e) Anbazhagan, P. et al.(2017)	Poisson’s ratio (ϑ) Kumar, R. et al. (2016)
0m-3.5m	Silty clay	3	0.8	0.23
3.5m-7.5m	Silty clay	3	0.8	0.23
7.5m-18m	Fine Sand	5	0.7	0.25
18m-30m	Fine Sand	25	0.6	0.45

Table B25: Shear Wave Velocity for Sitakunda Polder.

Depth (m) (From top)	Soil type	SPT value (N)	Share Wave velocity (m/sec) (Ansary,2015)	Share Wave velocity (m/sec) Anbazhagan, Kumar and Sitharam (2013)	Share Wave velocity (m/sec) Rahman, Kamal and Siddiqua (2018)	Share Wave velocity (m/sec) Chatterjee, Choudhury (2013)
0m-3m	Sandy Silt	9	158	211	205	179
3m-9m	Silty Clay	5	176	157	168	143
9m-25m	Fine Sand	20	324	318	269	241

Table B26: Shear Modulus for Sitakunda Polder.

Depth (m) (From top)	Soil type	SPT value (N_{60})	$N_{160} = C_N * N_{60}$	Shear Modulus G_{max} Mpa) Kramer (1996)	Shear Modulus G_{max} Mpa) Anbazhagan, P. et al. (2012)	Shear Modulus G_{max} (Mpa) Imai, T. and Tonouchi, K. (1982)	Shear Modulus G_{max} Mpa) Ohsaki, Y. and Iwasaki, R. (1973)
0m-3m	Sandy Silt	9	12	69	65	63	62
3m-9m	Silty Clay	5	5	46	28	42	39
9m-25m	Fine Sand	20	11	119	60	108	113

Table B27: Shear Strength parameter for Sitakunda Polder.

Depth (m) (From top)	Soil type	SPT value (N_{60})	Angle of friction (φ') Das et, al. (2017)	Angle of friction (φ') Wolff(1989)	Angle of friction (φ') Hatanaka and Uchida (1996)	Undrained cohesion (C_u) Kulhawy and Mayne (1990)	Undrained cohesion(C_u) Hettiarachchi and Brown(2009)	Undrained cohesion (C_u) Ansary and Urmi (2017)
0m-3m	Sandy Silt	9	24	30	36	54	37	70
3m-9m	Silty Clay	5	22	29	30	30	21	33
9m-25m	Fine Sand	20	32	33	35	-	-	-

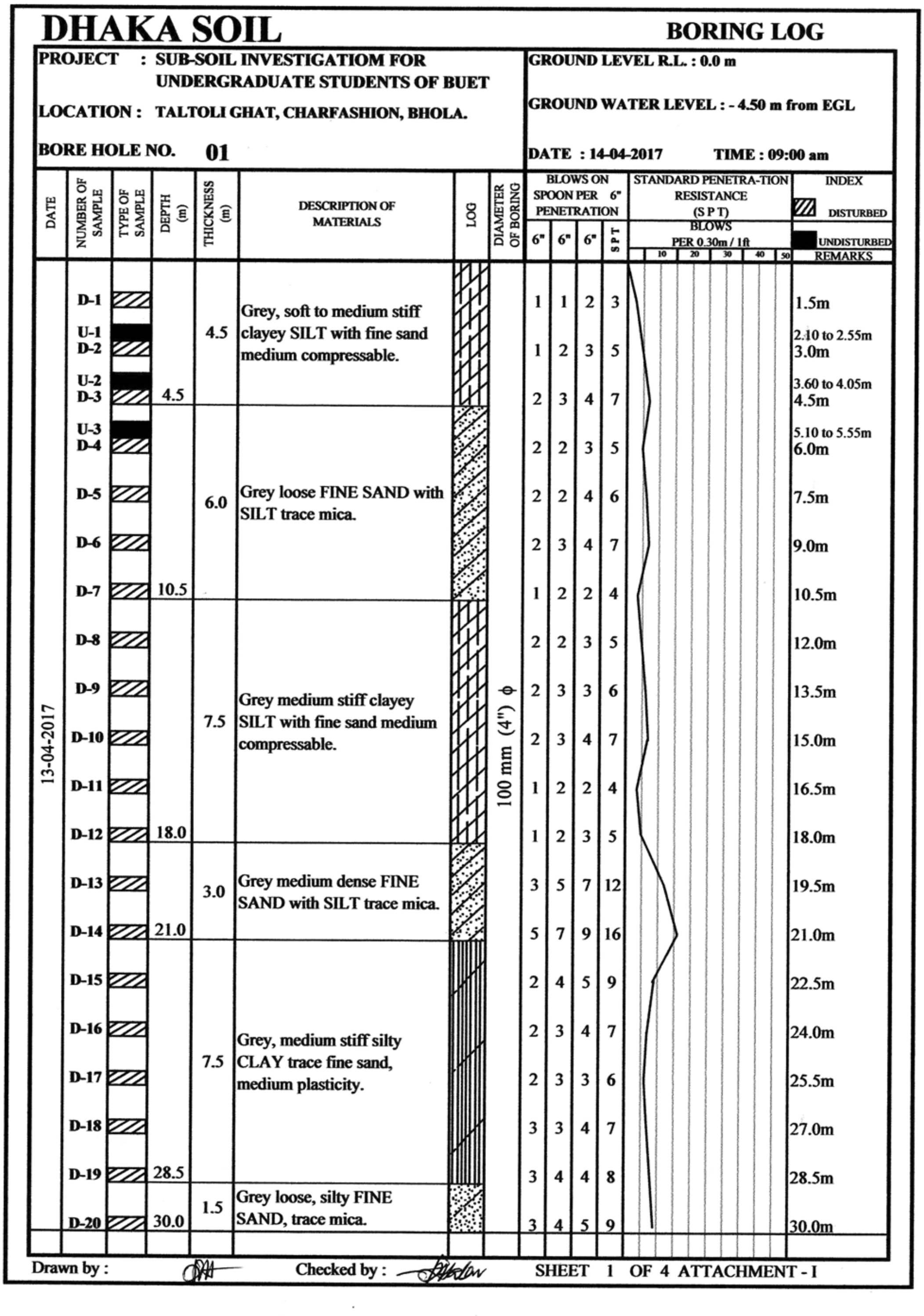
Table B28: Void ratio and Poisson's ratio for Sitakunda Polder.

Depth (m) (From top)	Soil type	SPT value (N_{60})	Void ratio (e) Anbazhagan, P. et al.(2017)	Poisson's ratio (ϑ) Kumar, R. et al. (2016)
0m-3m	Sandy Silt	9	0.68	0.29
3m-9m	Silty Clay	5	0.68	0.25
9m-25m	Fine Sand	20	0.67	0.40

Appendix C

SPT Profiles for Polder Locations

SPT test location: Charfashion, Bhola



DHAKA SOIL **BORING LOG**

PROJECT : SUB-SOIL INVESTIGATIOM FOR UNDERGRADUATE STUDENTS OF BUET
LOCATION : TALTOLI GHAT, CHARFASHION, BHOLA.
BORE HOLE NO. 01

GROUND LEVEL R.L. : 0.0 m
GROUND WATER LEVEL : - 4.50 m from EGL
DATE : 14-04-2017 TIME : 09:00 am

INDEX: ▨ DISTURBED ■ UNDISTURBED

DATE	NUMBER OF SAMPLE	TYPE OF SAMPLE	DEPTH (m)	THICKNESS (m)	DESCRIPTION OF MATERIALS	DIAMETER OF BORING	BLOWS ON SPOON PER 6" PENETRATION 6"	6"	6"	SPT	REMARKS
13-04-2017	D-1	▨		4.5	Grey, soft to medium stiff clayey SILT with fine sand medium compressable.	100 mm (4") ϕ	1	1	2	3	1.5m
	U-1	■									2.10 to 2.55m
	D-2	▨					1	2	3	5	3.0m
	U-2	■									3.60 to 4.05m
	D-3	▨	4.5				2	3	4	7	4.5m
	U-3	■									5.10 to 5.55m
	D-4	▨		6.0	Grey loose FINE SAND with SILT trace mica.		2	2	3	5	6.0m
	D-5	▨					2	2	4	6	7.5m
	D-6	▨					2	3	4	7	9.0m
	D-7	▨	10.5				1	2	2	4	10.5m
	D-8	▨		7.5	Grey medium stiff clayey SILT with fine sand medium compressable.		2	2	3	5	12.0m
	D-9	▨					2	3	3	6	13.5m
	D-10	▨					2	3	4	7	15.0m
	D-11	▨					1	2	2	4	16.5m
	D-12	▨	18.0				1	2	3	5	18.0m
	D-13	▨		3.0	Grey medium dense FINE SAND with SILT trace mica.		3	5	7	12	19.5m
	D-14	▨	21.0				5	7	9	16	21.0m
	D-15	▨		7.5	Grey, medium stiff silty CLAY trace fine sand, medium plasticity.		2	4	5	9	22.5m
	D-16	▨					2	3	4	7	24.0m
	D-17	▨					2	3	3	6	25.5m
	D-18	▨					3	3	4	7	27.0m
	D-19	▨	28.5				3	4	4	8	28.5m
	D-20	▨	30.0	1.5	Grey loose, silty FINE SAND, trace mica.		3	4	5	9	30.0m

Drawn by : Checked by : SHEET 1 OF 4 ATTACHMENT - I

DHAKA SOIL

BORING LOG

PROJECT : SUB-SOIL INVESTIGATIOM FOR UNDERGRADUATE STUDENTS OF BUET

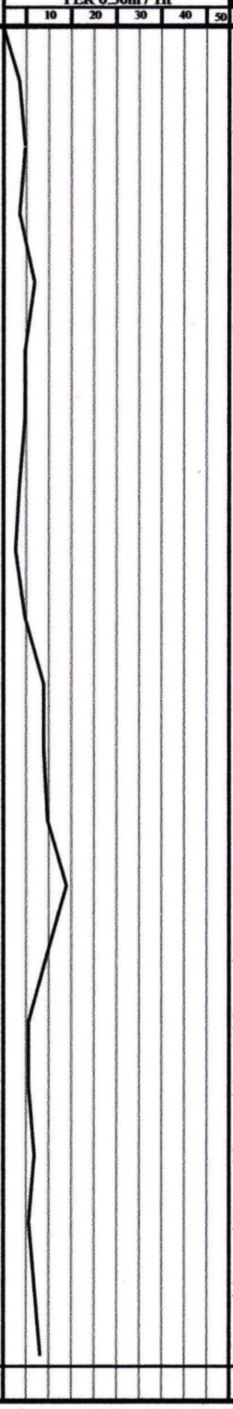
LOCATION : TALTOLI GHAT, CHARFASHION, BHOLA.

BORE HOLE NO. 02

GROUND LEVEL R.L. : 0.0 m

GROUND WATER LEVEL : - 4.50 m from EGL

DATE : 14-04-2017 TIME : 09:00 am



DATE	NUMBER OF SAMPLE	TYPE OF SAMPLE	DEPTH (m)	THICKNESS (m)	DESCRIPTION OF MATERIALS	LOG	DIAMETER OF BORING	BLOWS ON SPOON PER 6" PENETRATION 6"	6"	6"	SPT	STANDARD PENETRA-TION RESISTANCE (S P T) BLOWS PER 0.30m / 1ft	INDEX ▨ DISTURBED ■ UNDISTURBED REMARKS
13-04-2017	D-1	▨		10.5	Grey, soft to medium stiff silty CLAY trace fine sand, medium plasticity.		100 mm (4") ϕ	1	2	2	4		1.5m
	U-1	■											2.10 to 2.55m
	D-2	▨						1	2	3	5		3.0m
	D-3	▨						1	2	2	4		4.5m
	U-2	■											5.10 to 5.55m
	D-4	▨						2	3	4	7		6.0m
	U-3	■											6.60 to 7.05m
	D-5	▨						2	2	3	5		7.5m
	D-6	▨						1	2	3	5		9.0m
	D-7	▨	10.5					1	2	2	4		10.5m
	D-8	▨		10.5	Grey soft to stiff clayey SILT with fine sand medium compressable.			1	1	2	3		12.0m
	D-9	▨						1	2	3	5		13.5m
	D-10	▨						2	3	6	9		15.0m
	D-11	▨						3	4	5	9		16.5m
	D-12	▨						4	4	6	10		18.0m
	D-13	▨						4	6	8	14		19.5m
	D-14	▨	21.0					3	4	6	10		21.0m
	D-15	▨		9.0	Grey, medium stiff silty CLAY trace fine sand, medium plasticity.			2	3	3	6		22.5m
	D-16	▨						2	3	3	6		24.0m
	D-17	▨						2	3	4	7		25.5m
	D-18	▨						2	3	3	6		27.0m
	D-19	▨						2	3	4	7		28.5m
	D-20	▨	30.0					2	3	5	8		30.0m

Drawn by :

Checked by :

SHEET 2 OF 4 ATTACHMENT - I

DHAKA SOIL

BORING LOG

PROJECT : SUB-SOIL INVESTIGATIOM FOR UNDERGRADUATE STUDENTS OF BUET

LOCATION : TALTOLI GHAT, CHARFASHION, BHOLA.

BORE HOLE NO. 04

GROUND LEVEL R.L. : 0.0 m

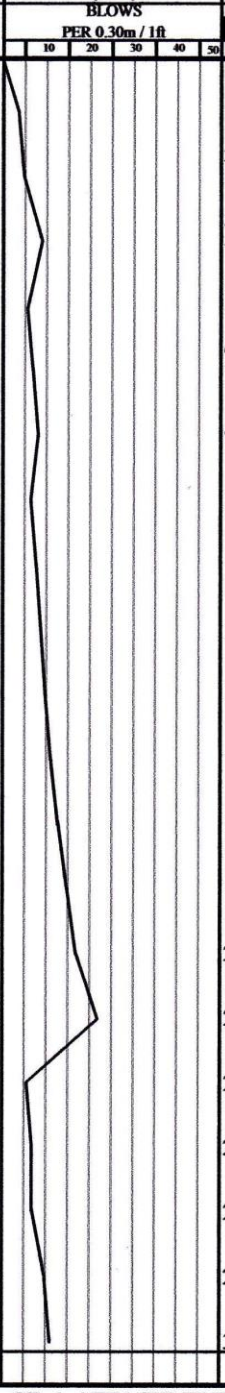
GROUND WATER LEVEL : - 4.50 m from EGL

DATE : 15-04-2017 TIME : 09:00 am

INDEX: ▨ DISTURBED ■ UNDISTURBED

DATE	NUMBER OF SAMPLE	TYPE OF SAMPLE	DEPTH (m)	THICKNESS (m)	DESCRIPTION OF MATERIALS	LOG	DIAMETER OF BORING	BLOWS ON SPOON PER 6" PENETRATION 6"	6"	6"	SPT	REMARKS
14-04-2017	D-1	▨		4.5	Light grey, medium stiff to stiff silty CLAY trace fine sand, medium plasticity.		100 mm (4") ϕ	1	2	2	4	1.5m
	U-1	■										2.10 to 2.55m
	D-2	▨						1	2	3	5	3.0m
	U-2	■										3.60 to 4.05m
	D-3	▨	4.5					3	4	5	9	4.5m
	U-3	■		4.5	Grey, medium stiff clayey SILT with fine sand medium compressable.							5.10 to 5.55m
	D-4	▨						2	3	3	6	6.0m
	U-4	■										6.60 to 7.05m
	D-5	▨						2	3	4	7	7.5m
	D-6	▨	9.0					3	4	4	8	9.0m
	D-7	▨		12.0	Grey medium dense FINE SAND with SILT trace mica.			3	3	4	7	10.5m
	D-8	▨						3	4	4	8	12.0m
	D-9	▨						3	4	5	9	13.5m
	D-10	▨						3	4	6	10	15.0m
	D-11	▨						3	4	7	11	16.5m
	D-12	▨						3	4	9	13	18.0m
	D-13	▨						4	6	9	15	19.5m
	D-14	▨	21.0					4	7	10	17	21.0m
	D-15	▨	22.5	1.5	Grey medium dense silty FINE SAND, trace mica.			6	10	12	22	22.5m
	D-16	▨		4.5	Grey, medium stiff silty CLAY trace fine sand, medium plasticity.			2	3	3	6	24.0m
	D-17	▨						2	3	4	7	25.5m
	D-18	▨	27.0					2	3	4	7	27.0m
	D-19	▨		3.0	Grey medium dense FINE SAND with SILT trace mica.			3	4	6	10	28.5m
	D-20	▨	30.0					3	5	6	11	30.0m

STANDARD PENETRA-TION RESISTANCE (S P T) BLOWS PER 0.30m / 1ft



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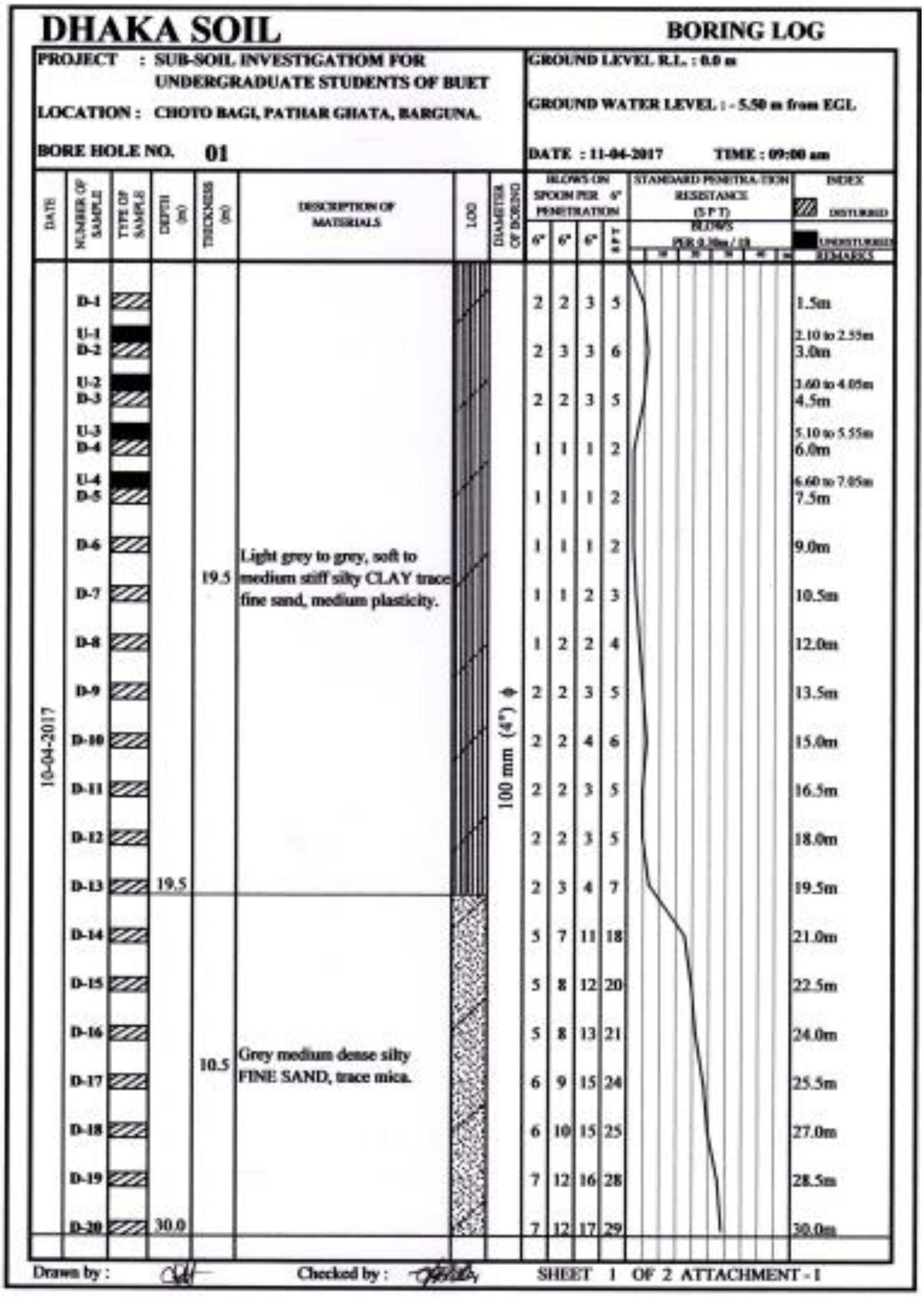


DHAKA SOIL **BORING LOG**

PROJECT : SUB-SOIL INVESTIGATIOM FOR UNDERGRADUATE STUDENTS OF BUET

LOCATION : CHOTO BAGI, PATHAR GHATA, BARGUNA.

BORE HOLE NO. 01

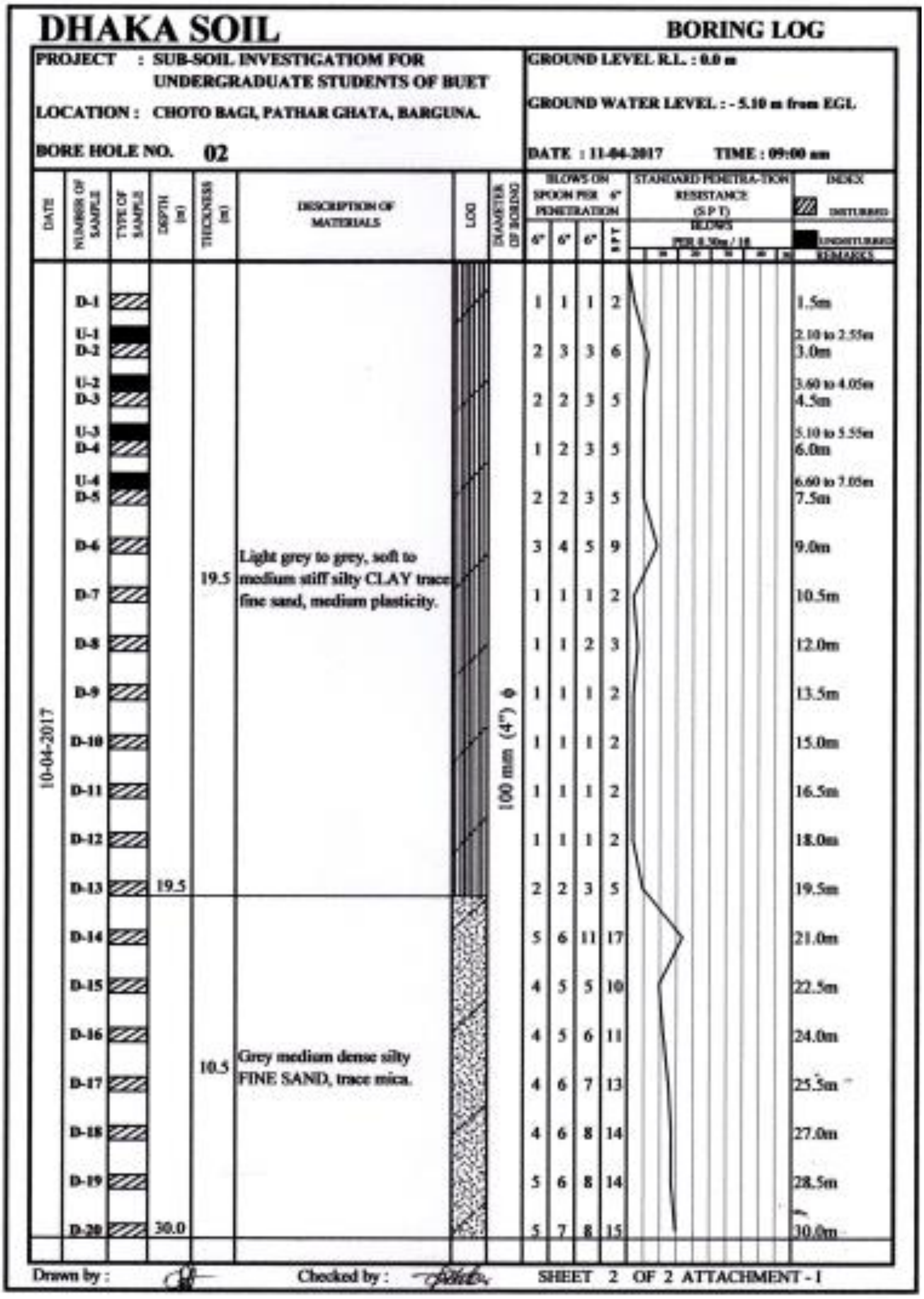
GROUND LEVEL R.L. : 0.0 m

GROUND WATER LEVEL : - 5.50 m from EGL

DATE : 11-04-2017 TIME : 09:00 am

DATE	NUMBER OF SAMPLE	TYPE OF SAMPLE	DEPTH (m)	THICKNESS (m)	DESCRIPTION OF MATERIALS	LOG	DIAMETER OF BORING	BLOWS ON SPOON PER 6" PENETRATION				STANDARD PENETRATION RESISTANCE (S P T) BLOWS PER 0.30m / 10	INDEX ▨ DISTURBED ■ UNDISTURBED REMARKS
								6"	6"	6"	SPT		
10-04-2017	D-1	▨		19.5	Light grey to grey, soft to medium stiff silty CLAY trace fine sand, medium plasticity.		100 mm (4") ϕ	2	2	3	5		1.5m
	U-1	■											2.10 to 2.55m
	D-2	▨						2	3	3	6		3.0m
	U-2	■											3.60 to 4.05m
	D-3	▨						2	2	3	5		4.5m
	U-3	■											5.10 to 5.55m
	D-4	▨						1	1	1	2		6.0m
	U-4	■											6.60 to 7.05m
	D-5	▨						1	1	1	2		7.5m
	D-6	▨						1	1	1	2		9.0m
	D-7	▨						1	1	2	3		10.5m
	D-8	▨						1	2	2	4		12.0m
	D-9	▨						2	2	3	5		13.5m
	D-10	▨						2	2	4	6		15.0m
	D-11	▨						2	2	3	5		16.5m
	D-12	▨						2	2	3	5		18.0m
	D-13	▨	19.5					2	3	4	7		19.5m
	D-14	▨		10.5	Grey medium dense silty FINE SAND, trace mica.			5	7	11	18		21.0m
	D-15	▨						5	8	12	20		22.5m
	D-16	▨						5	8	13	21		24.0m
	D-17	▨						6	9	15	24		25.5m
	D-18	▨						6	10	15	25		27.0m
	D-19	▨						7	12	16	28		28.5m
	D-20	▨	30.0					7	12	17	29		30.0m

Drawn by : Checked by : SHEET 1 OF 2 ATTACHMENT - I



DHAKA SOIL **BORING LOG**

PROJECT : SUB-SOIL INVESTIGATIOM FOR UNDERGRADUATE STUDENTS OF BUET

LOCATION : CHOTO BAGI, PATHAR GHATA, BARGUNA.

BORE HOLE NO. 02

GROUND LEVEL R.L. : 0.0 m

GROUND WATER LEVEL : - 5.10 m from EGL

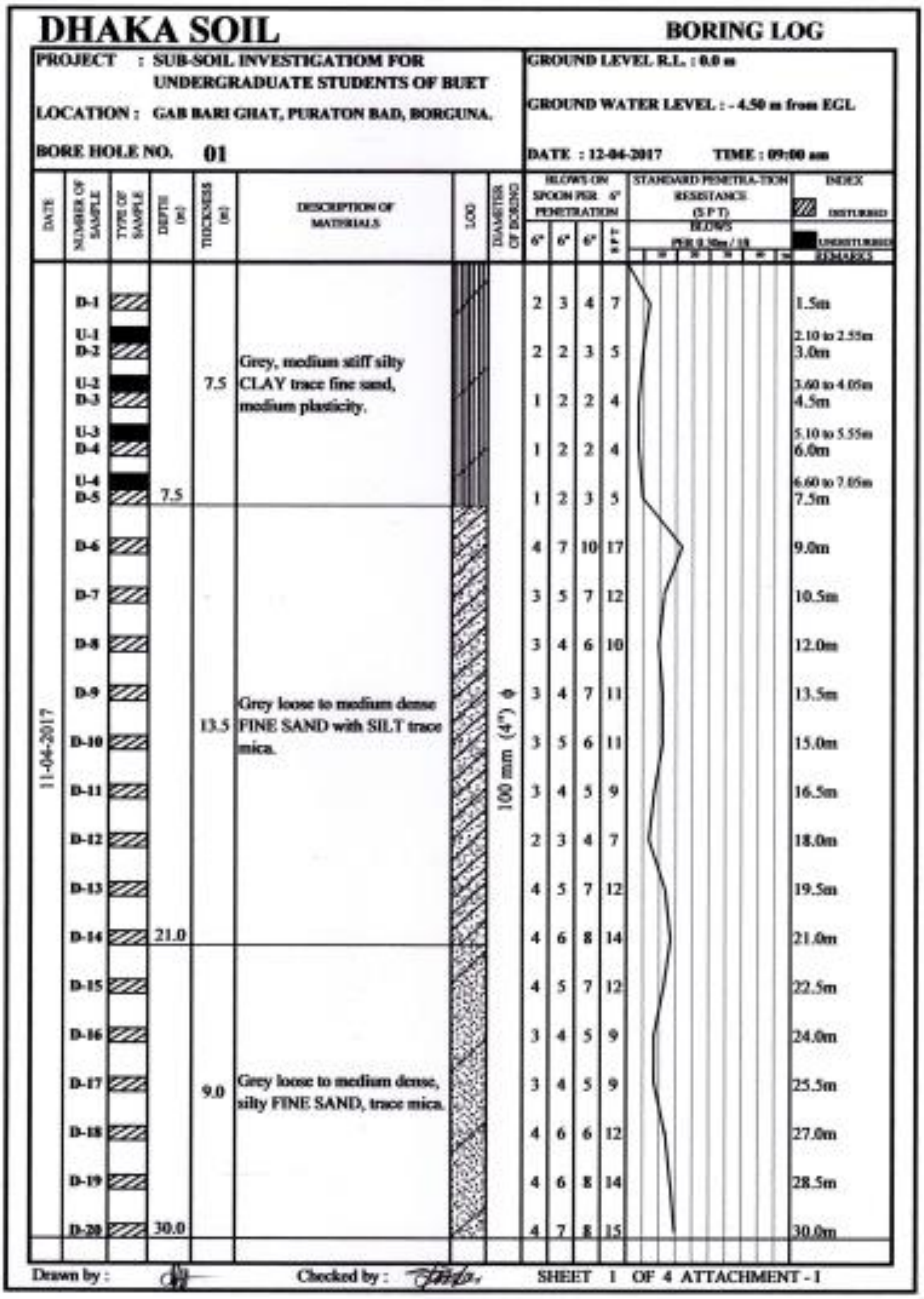
DATE : 11-04-2017 TIME : 09:00 am

INDEX: ▨ DISTURBED ■ UNDISTURBED

DATE	NUMBER OF SAMPLE	TYPE OF SAMPLE	DEPTH (m)	THICKNESS (m)	DESCRIPTION OF MATERIALS	DIAMETER OF BORING	BLOWS ON SPOON PER 6" PENETRATION 6"	6"	6"	SPT	REMARKS
10-04-2017	D-1	▨		19.5	Light grey to grey, soft to medium stiff silty CLAY trace fine sand, medium plasticity.	100 mm (4") ϕ	1	1	1	2	1.5m
	U-1	■									2.10 to 2.55m
	D-2	▨					2	3	3	6	3.0m
	U-2	■									3.60 to 4.05m
	D-3	▨					2	2	3	5	4.5m
	U-3	■									5.10 to 5.55m
	D-4	▨					1	2	3	5	6.0m
	U-4	■									6.60 to 7.05m
	D-5	▨					2	2	3	5	7.5m
	D-6	▨					3	4	5	9	9.0m
	D-7	▨					1	1	1	2	10.5m
	D-8	▨					1	1	2	3	12.0m
	D-9	▨					1	1	1	2	13.5m
	D-10	▨					1	1	1	2	15.0m
	D-11	▨					1	1	1	2	16.5m
	D-12	▨					1	1	1	2	18.0m
	D-13	▨	19.5				2	2	3	5	19.5m
	D-14	▨		10.5	Grey medium dense silty FINE SAND, trace mica.		5	6	11	17	21.0m
	D-15	▨					4	5	5	10	22.5m
	D-16	▨					4	5	6	11	24.0m
	D-17	▨					4	6	7	13	25.5m
	D-18	▨					4	6	8	14	27.0m
	D-19	▨					5	6	8	14	28.5m
	D-20	▨	30.0				5	7	8	15	30.0m

Drawn by : Checked by : SHEET 2 OF 2 ATTACHMENT - I

<u>**SPT test location: Puraton Bad, Barguna**</u>



DHAKA SOIL **BORING LOG**

PROJECT : SUB-SOIL INVESTIGATIOM FOR UNDERGRADUATE STUDENTS OF BUET

LOCATION : GAB BARI GHAT, PURATON BAD, BORGUNA.

BORE HOLE NO. 01

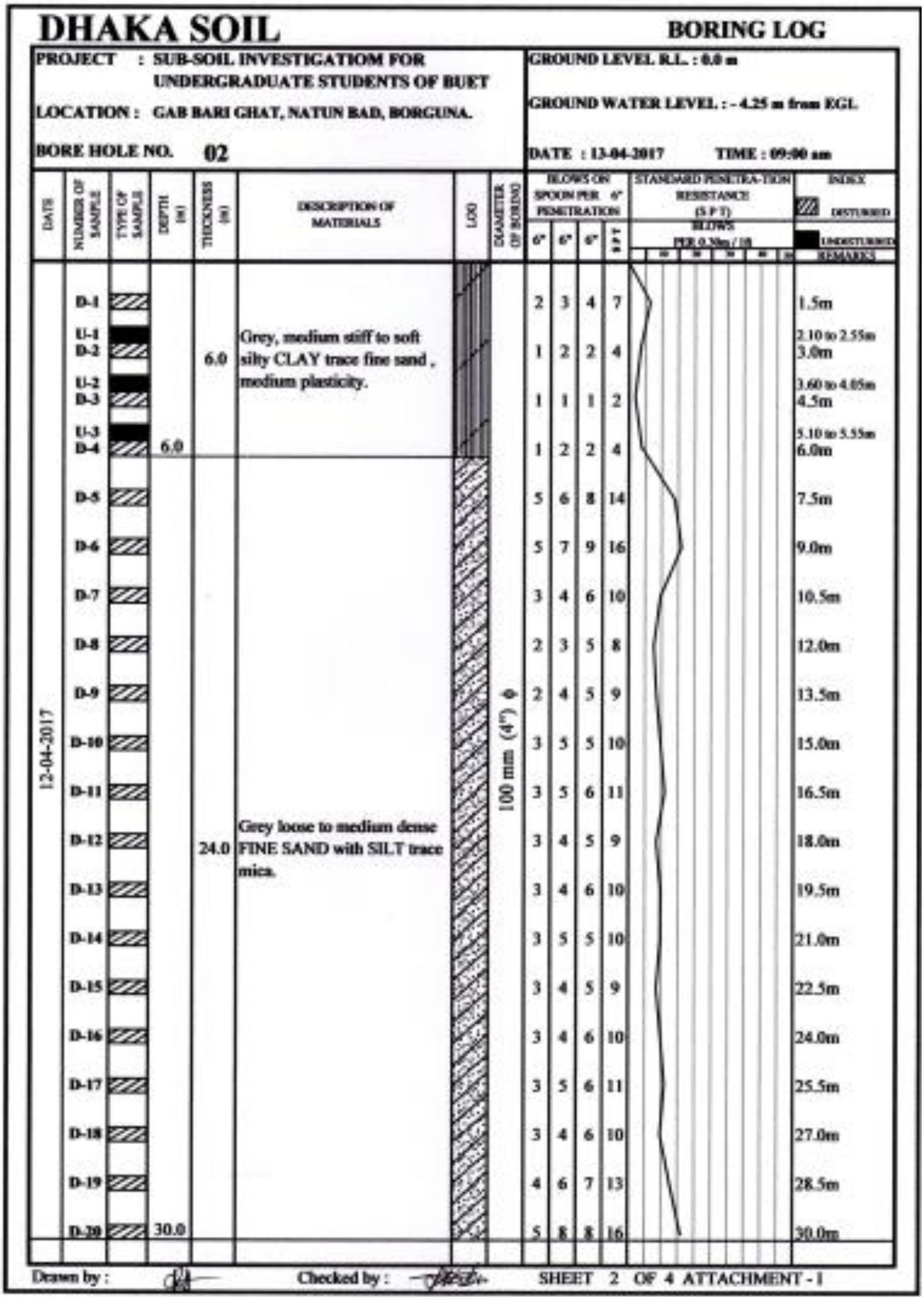
GROUND LEVEL R.L. : 0.0 m

GROUND WATER LEVEL : - 4.50 m from EGL

DATE : 12-04-2017 TIME : 09:00 am

DATE	NUMBER OF SAMPLE	TYPE OF SAMPLE	DEPTH (m)	THICKNESS (m)	DESCRIPTION OF MATERIALS	LOG	DIAMETER OF BORING	BLOWS ON SPOON PER 6" PENETRATION 6"	6"	6"	SPT	STANDARD PENETRA-TION RESISTANCE (S P T) BLOWS PER 0.30m / 10	INDEX ▨ DISTURBED ■ UNDISTURBED REMARKS
11-04-2017	D-1	▨		7.5	Grey, medium stiff silty CLAY trace fine sand, medium plasticity.		100 mm (4") ϕ	2	3	4	7		1.5m
	U-1	■											2.10 to 2.55m
	D-2	▨						2	2	3	5		3.0m
	U-2	■											3.60 to 4.05m
	D-3	▨						1	2	2	4		4.5m
	U-3	■											5.10 to 5.55m
	D-4	▨						1	2	2	4		6.0m
	U-4	■											6.60 to 7.05m
	D-5	▨	7.5					1	2	3	5		7.5m
	D-6	▨		13.5	Grey loose to medium dense FINE SAND with SILT trace mica.			4	7	10	17		9.0m
	D-7	▨						3	5	7	12		10.5m
	D-8	▨						3	4	6	10		12.0m
	D-9	▨						3	4	7	11		13.5m
	D-10	▨						3	5	6	11		15.0m
	D-11	▨						3	4	5	9		16.5m
	D-12	▨						2	3	4	7		18.0m
	D-13	▨						4	5	7	12		19.5m
	D-14	▨	21.0					4	6	8	14		21.0m
	D-15	▨		9.0	Grey loose to medium dense, silty FINE SAND, trace mica.			4	5	7	12		22.5m
	D-16	▨						3	4	5	9		24.0m
	D-17	▨						3	4	5	9		25.5m
	D-18	▨						4	6	6	12		27.0m
	D-19	▨						4	6	8	14		28.5m
	D-20	▨	30.0					4	7	8	15		30.0m

Drawn by : Checked by : SHEET 1 OF 4 ATTACHMENT - 1



DHAKA SOIL **BORING LOG**

PROJECT : SUB-SOIL INVESTIGATIOM FOR UNDERGRADUATE STUDENTS OF BUET

LOCATION : GAB BARI GHAT, NATUN BAD, BORGUNA.

BORE HOLE NO. 02

GROUND LEVEL R.L. : 0.0 m

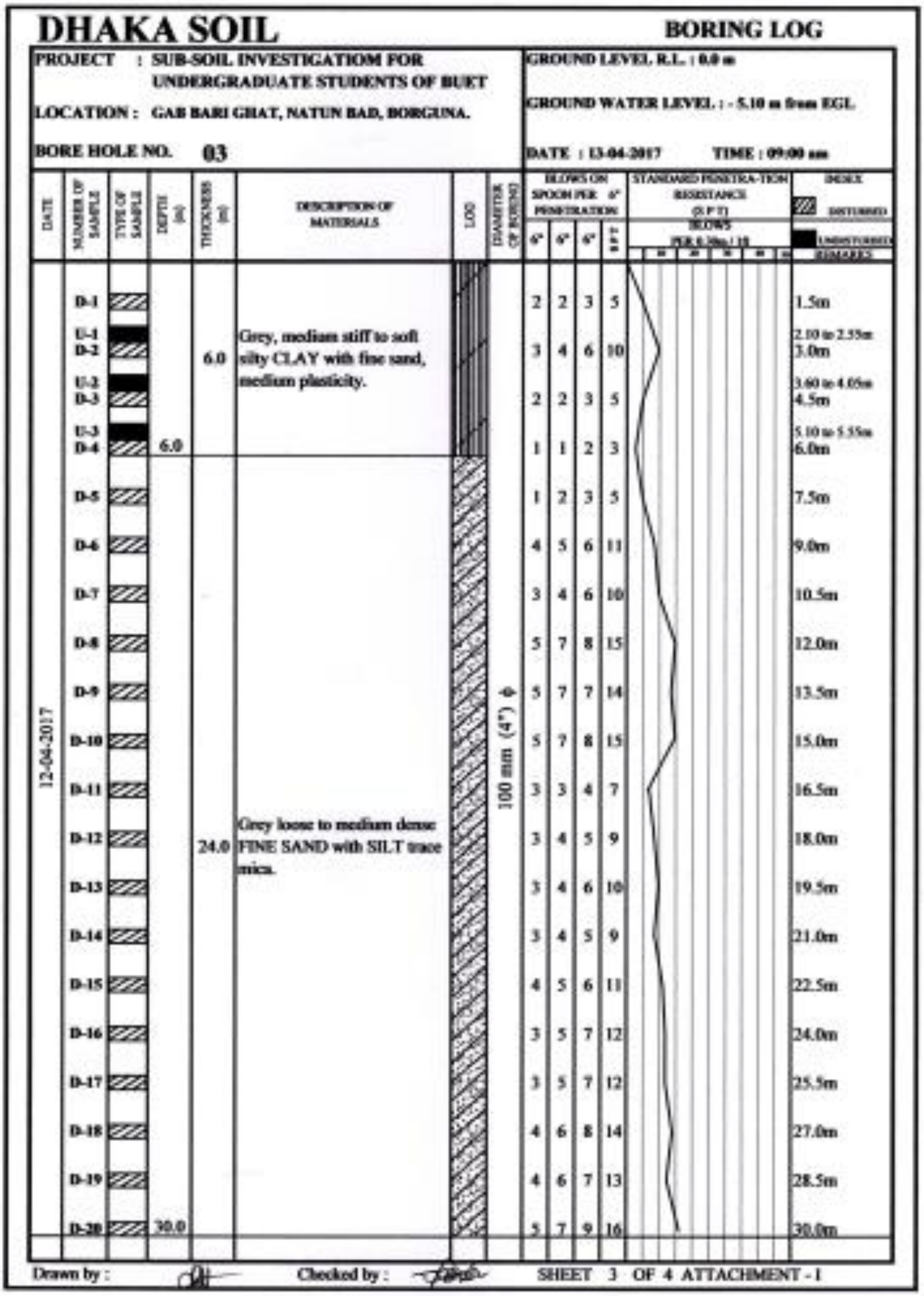
GROUND WATER LEVEL : - 4.25 m from EGL

DATE : 13-04-2017 TIME : 09:00 am

INDEX: ▨ DISTURBED ■ UNDISTURBED

DATE	NUMBER OF SAMPLE	TYPE OF SAMPLE	DEPTH (m)	THICKNESS (m)	DESCRIPTION OF MATERIALS	LOG	DIAMETER OF BORING	BLOWS ON SPOON PER 6" PENETRATION 6"	6"	6"	SPT	STANDARD PENETRA-TION RESISTANCE (S P T) BLOWS PER 0.30m / 1ft	REMARKS
12-04-2017	D-1	▨		6.0	Grey, medium stiff to soft silty CLAY trace fine sand , medium plasticity.		100 mm (4") Φ	2	3	4	7		1.5m
	U-1	■											2.10 to 2.55m
	D-2	▨						1	2	2	4		3.0m
	U-2	■											3.60 to 4.05m
	D-3	▨						1	1	1	2		4.5m
	U-3	■											5.10 to 5.55m
	D-4	▨	6.0					1	2	2	4		6.0m
	D-5	▨		24.0	Grey loose to medium dense FINE SAND with SILT trace mica.			5	6	8	14		7.5m
	D-6	▨						5	7	9	16		9.0m
	D-7	▨						3	4	6	10		10.5m
	D-8	▨						2	3	5	8		12.0m
	D-9	▨						2	4	5	9		13.5m
	D-10	▨						3	5	5	10		15.0m
	D-11	▨						3	5	6	11		16.5m
	D-12	▨						3	4	5	9		18.0m
	D-13	▨						3	4	6	10		19.5m
	D-14	▨						3	5	5	10		21.0m
	D-15	▨						3	4	5	9		22.5m
	D-16	▨						3	4	6	10		24.0m
	D-17	▨						3	5	6	11		25.5m
	D-18	▨						3	4	6	10		27.0m
	D-19	▨						4	6	7	13		28.5m
	D-20	▨	30.0					5	8	8	16		30.0m

Drawn by : Checked by : SHEET 2 OF 4 ATTACHMENT - I



DHAKA SOIL

BORING LOG

PROJECT : SUB-SOIL INVESTIGATIOM FOR UNDERGRADUATE STUDENTS OF BUET

LOCATION : GAB BARI GHAT, NATUN BAD, BORGUNA.

BORE HOLE NO. 03

GROUND LEVEL R.L. : 0.0 m

GROUND WATER LEVEL : - 5.10 m from EGL

DATE : 13-04-2017 TIME : 09:00 am

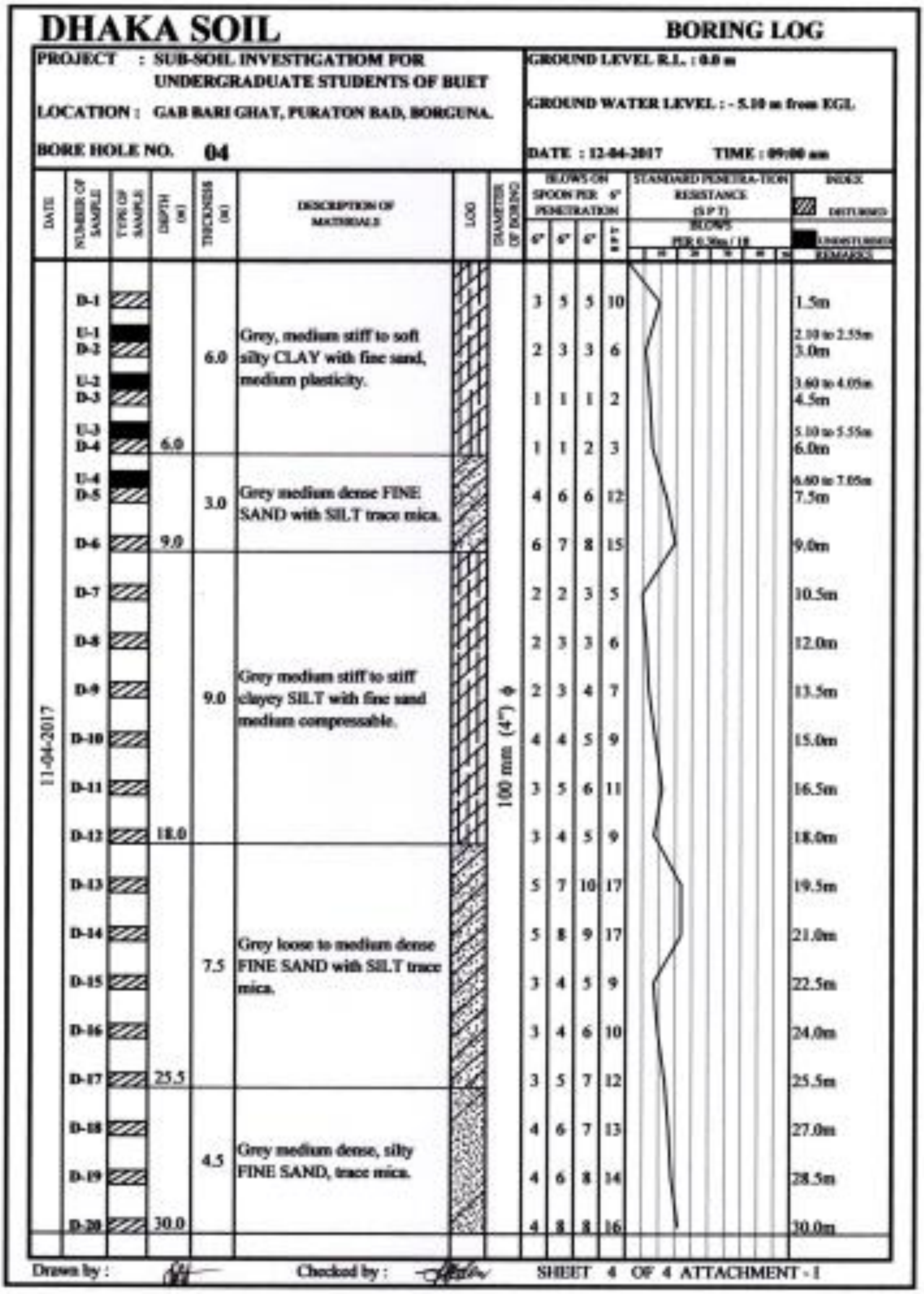
INDEX: ▨ DISTURBED ■ UNDISTURBED

DATE	NUMBER OF SAMPLE	TYPE OF SAMPLE	DEPTH (m)	THICKNESS (m)	DESCRIPTION OF MATERIALS	LOG	DIAMETER OF BORING	BLOWS ON SPOON PER 6" PENETRATION 6"	6"	6"	SPT	REMARKS
12-04-2017	D-1	▨					100 mm (4") ϕ	2	2	3	5	1.5m
	U-1	■										2.10 to 2.55m
	D-2	▨		6.0	Grey, medium stiff to soft silty CLAY with fine sand, medium plasticity.			3	4	6	10	3.0m
	U-2	■										3.60 to 4.05m
	D-3	▨						2	2	3	5	4.5m
	U-3	■										5.10 to 5.55m
	D-4	▨	6.0					1	1	2	3	6.0m
	D-5	▨						1	2	3	5	7.5m
	D-6	▨						4	5	6	11	9.0m
	D-7	▨						3	4	6	10	10.5m
	D-8	▨						5	7	8	15	12.0m
	D-9	▨						5	7	7	14	13.5m
	D-10	▨						5	7	8	15	15.0m
	D-11	▨						3	3	4	7	16.5m
	D-12	▨		24.0	Grey loose to medium dense FINE SAND with SILT trace mica.			3	4	5	9	18.0m
	D-13	▨						3	4	6	10	19.5m
	D-14	▨						3	4	5	9	21.0m
	D-15	▨						4	5	6	11	22.5m
	D-16	▨						3	5	7	12	24.0m
	D-17	▨						3	5	7	12	25.5m
	D-18	▨						4	6	8	14	27.0m
	D-19	▨						4	6	7	13	28.5m
	D-20	▨	30.0					5	7	9	16	30.0m

Drawn by :

Checked by :

SHEET 3 OF 4 ATTACHMENT - I



DHAKA SOIL **BORING LOG**

PROJECT : SUB-SOIL INVESTIGATIOM FOR UNDERGRADUATE STUDENTS OF BUET

LOCATION : GAB BARI GHAT, PURATON BAD, BORGUNA.

BORE HOLE NO. 04

GROUND LEVEL R.L. : 0.0 m

GROUND WATER LEVEL : - 5.10 m from EGL

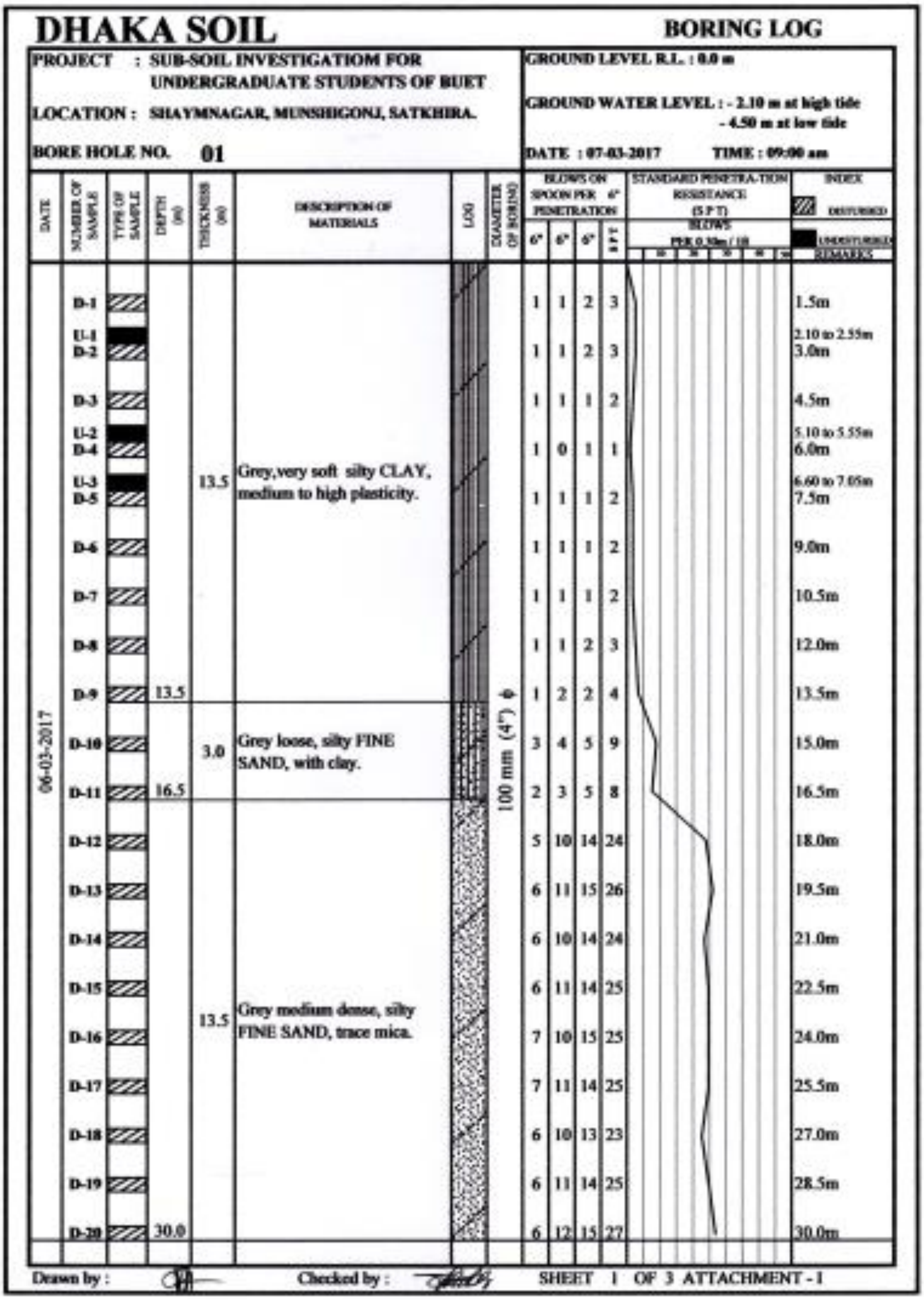
DATE : 12-04-2017 TIME : 09:00 am

INDEX: ▨ DISTURBED ■ UNDISTURBED

DATE	NUMBER OF SAMPLE	TYPE OF SAMPLE	DEPTH (m)	THICKNESS (m)	DESCRIPTION OF MATERIALS	DIAMETER OF BORING	6"	6"	6"	SPT	REMARKS
11-04-2017	D-1	▨		6.0	Grey, medium stiff to soft silty CLAY with fine sand, medium plasticity.	100 mm (4") ϕ	3	5	5	10	1.5m
	U-1	■									2.10 to 2.55m
	D-2	▨					2	3	3	6	3.0m
	U-2	■									3.60 to 4.05m
	D-3	▨					1	1	1	2	4.5m
	U-3	■									5.10 to 5.55m
	D-4	▨	6.0				1	1	2	3	6.0m
	U-4	■		3.0	Grey medium dense FINE SAND with SILT trace mica.						6.60 to 7.05m
	D-5	▨					4	6	6	12	7.5m
	D-6	▨	9.0				6	7	8	15	9.0m
	D-7	▨		9.0	Grey medium stiff to stiff clayey SILT with fine sand medium compressable.		2	2	3	5	10.5m
	D-8	▨					2	3	3	6	12.0m
	D-9	▨					2	3	4	7	13.5m
	D-10	▨					4	4	5	9	15.0m
	D-11	▨					3	5	6	11	16.5m
	D-12	▨	18.0				3	4	5	9	18.0m
	D-13	▨		7.5	Grey loose to medium dense FINE SAND with SILT trace mica.		5	7	10	17	19.5m
	D-14	▨					5	8	9	17	21.0m
	D-15	▨					3	4	5	9	22.5m
	D-16	▨					3	4	6	10	24.0m
	D-17	▨	25.5				3	5	7	12	25.5m
	D-18	▨		4.5	Grey medium dense, silty FINE SAND, trace mica.		4	6	7	13	27.0m
	D-19	▨					4	6	8	14	28.5m
	D-20	▨	30.0				4	8	8	16	30.0m

Drawn by : Checked by : SHEET 4 OF 4 ATTACHMENT - I

SPT test location: Munshigong, Satkhira



DHAKA SOIL **BORING LOG**

PROJECT : SUB-SOIL INVESTIGATIOM FOR UNDERGRADUATE STUDENTS OF BUET
LOCATION : SHAYMNAGAR, MUNSHIGONJ, SATKHIRA.
BORE HOLE NO. 01

GROUND LEVEL R.L. : 0.0 m
GROUND WATER LEVEL : - 2.10 m at high tide
- 4.50 m at low tide
DATE : 07-03-2017 TIME : 09:00 am

DATE	NUMBER OF SAMPLE	TYPE OF SAMPLE	DEPTH (m)	THICKNESS (m)	DESCRIPTION OF MATERIALS	LOG	DIAMETER OF BORING	BLOWS ON SPOON PER 6" PENETRATION 6"	6"	6"	SPT	STANDARD PENETRA-TION RESISTANCE (S P T) BLOWS PER 0.30m / 10 10 20 30 40 50	INDEX ▨ DISTURBED ■ UNDISTURBED REMARKS
06-03-2017	D-1	▨		13.5	Grey,very soft silty CLAY, medium to high plasticity.		100 mm (4") ϕ	1	1	2	3		1.5m
	U-1	■											2.10 to 2.55m
	D-2	▨						1	1	2	3		3.0m
	D-3	▨						1	1	1	2		4.5m
	U-2	■											5.10 to 5.55m
	D-4	▨						1	0	1	1		6.0m
	U-3	■											6.60 to 7.05m
	D-5	▨						1	1	1	2		7.5m
	D-6	▨						1	1	1	2		9.0m
	D-7	▨						1	1	1	2		10.5m
	D-8	▨						1	1	2	3		12.0m
	D-9	▨	13.5					1	2	2	4		13.5m
	D-10	▨		3.0	Grey loose, silty FINE SAND, with clay.			3	4	5	9		15.0m
	D-11	▨	16.5					2	3	5	8		16.5m
	D-12	▨		13.5	Grey medium dense, silty FINE SAND, trace mica.			5	10	14	24		18.0m
	D-13	▨						6	11	15	26		19.5m
	D-14	▨						6	10	14	24		21.0m
	D-15	▨						6	11	14	25		22.5m
	D-16	▨						7	10	15	25		24.0m
	D-17	▨						7	11	14	25		25.5m
	D-18	▨						6	10	13	23		27.0m
	D-19	▨						6	11	14	25		28.5m
	D-20	▨	30.0					6	12	15	27		30.0m

Drawn by : Checked by : SHEET 1 OF 3 ATTACHMENT - I

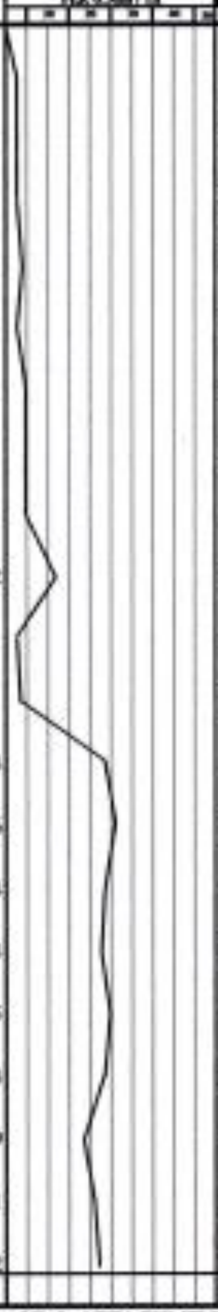
DHAKA SOIL

BORING LOG

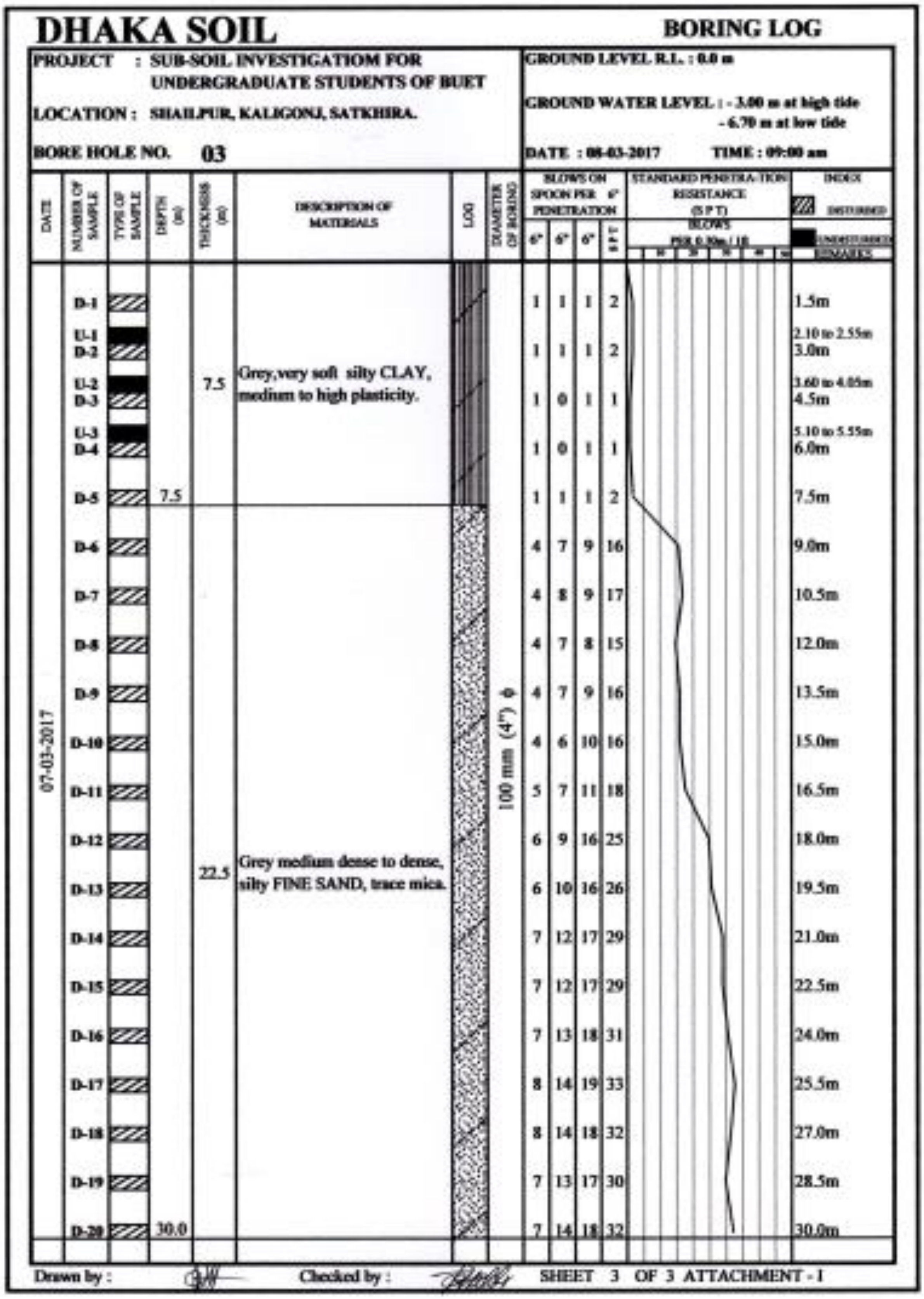
PROJECT : SUB-SOIL INVESTIGATIOM FOR UNDERGRADUATE STUDENTS OF BUET
LOCATION : SHAYMNAGAR, MUNSHIGONJ, SATKHIRA.
BORE HOLE NO. 02

GROUND LEVEL R.L. : 0.0 m
GROUND WATER LEVEL : - 2.10 m at high tide
- 4.50 m at low tide
DATE : 06-03-2017 TIME : 09:00 am

DATE	NUMBER OF SAMPLE	TYPE OF SAMPLE	DEPTH (m)	THICKNESS (m)	DESCRIPTION OF MATERIALS	LOG	DIAMETER OF BORING	BLOWS ON SPOON PER 6" PENETRATION 6"	6"	6"	S P T	STANDARD PENETRA-TION RESISTANCE (S.P.T) BLOWS PER 0.30m / 10	INDEX ▨ DISTURBED ■ UNDISTURBED REMARKS
05-03-2017	D-1	▨		4.5	Grey, soft silty CLAY, medium to high plasticity.		100 mm (4") ϕ	1	1	2	3		1.5m
	U-1	■											2.10 to 2.55m
	D-2	▨						1	1	2	3		3.0m
	U-2	■											3.60 to 4.05m
	D-3	▨	4.5					1	1	2	3		4.5m
	U-3	■		12.0	Grey loose, silty FINE SAND, with clay.								5.10 to 5.55m
	D-4	▨						2	2	2	4		6.0m
	D-5	▨						1	1	2	3		7.5m
	D-6	▨						1	2	3	5		9.0m
	D-7	▨						1	2	3	5		10.5m
	D-8	▨						2	2	3	5		12.0m
	D-9	▨						3	5	7	12		13.5m
	D-10	▨						1	1	2	3		15.0m
	D-11	▨	16.5					1	2	2	4		16.5m
	D-12	▨		9.0	Grey medium dense, silty FINE SAND, trace mica.			6	11	13	24		18.0m
	D-13	▨						6	12	14	26		19.5m
	D-14	▨						5	11	13	24		21.0m
	D-15	▨						5	10	13	23		22.5m
	D-16	▨						6	11	14	25		24.0m
	D-17	▨	25.5					6	10	14	24		25.5m
	D-18	▨	27.0	1.5	Dark grey medium dense, FINE SAND, with decomposed wood, with mica.			6	9	10	19		27.0m
	D-19	▨		3.0	Grey medium dense, silty FINE SAND, trace mica.			6	9	12	21		28.5m
	D-20	▨	30.0					6	10	12	22		30.0m



Drawn by : Checked by : SHEET 2 OF 3 ATTACHMENT - I



DHAKA SOIL

BORING LOG

PROJECT : SUB-SOIL INVESTIGATIOM FOR UNDERGRADUATE STUDENTS OF BUET

LOCATION : SHAILPUR, KALIGONJ, SATKHIRA.

BORE HOLE NO. 03

GROUND LEVEL R.L. : 0.0 m

GROUND WATER LEVEL : - 3.00 m at high tide
- 6.70 m at low tide

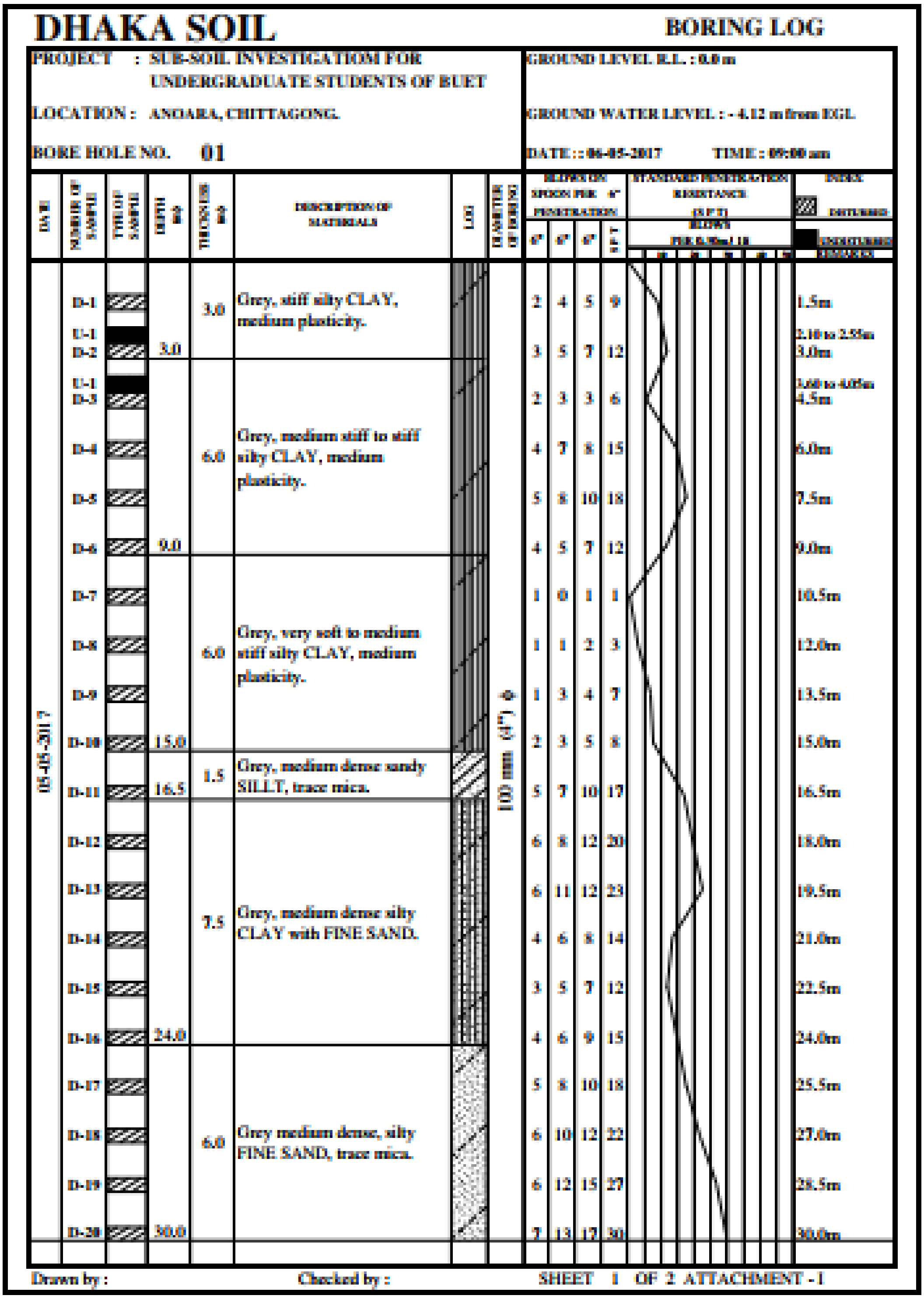
DATE : 08-03-2017 **TIME :** 09:00 am

INDEX: ▨ DISTURBED ■ UNDISTURBED

DATE	NUMBER OF SAMPLE	TYPE OF SAMPLE	DEPTH (m)	THICKNESS (m)	DESCRIPTION OF MATERIALS	LOG	DIAMETER OF BORING	BLOWS ON SPOON PER 6" PENETRATION 6"	6"	6"	S P T	STANDARD PENETRA-TION RESISTANCE (S P T) BLOWS PER 0.30m / 1ft	REMARKS
07-03-2017	D-1	▨		7.5	Grey,very soft silty CLAY, medium to high plasticity.		100 mm (4") ϕ	1	1	1	2		1.5m
	U-1	■											2.10 to 2.55m
	D-2	▨						1	1	1	2		3.0m
	U-2	■											3.60 to 4.05m
	D-3	▨						1	0	1	1		4.5m
	U-3	■											5.10 to 5.55m
	D-4	▨						1	0	1	1		6.0m
	D-5	▨	7.5					1	1	1	2		7.5m
	D-6	▨		22.5	Grey medium dense to dense, silty FINE SAND, trace mica.			4	7	9	16		9.0m
	D-7	▨						4	8	9	17		10.5m
	D-8	▨						4	7	8	15		12.0m
	D-9	▨						4	7	9	16		13.5m
	D-10	▨						4	6	10	16		15.0m
	D-11	▨						5	7	11	18		16.5m
	D-12	▨						6	9	16	25		18.0m
	D-13	▨						6	10	16	26		19.5m
	D-14	▨						7	12	17	29		21.0m
	D-15	▨						7	12	17	29		22.5m
	D-16	▨						7	13	18	31		24.0m
	D-17	▨						8	14	19	33		25.5m
	D-18	▨						8	14	18	32		27.0m
	D-19	▨						7	13	17	30		28.5m
	D-20	▨	30.0					7	14	18	32		30.0m

Drawn by : Checked by : SHEET 3 OF 3 ATTACHMENT - I

SPT test location: Anowara, Chittagong



DHAKA SOIL **BORING LOG**

PROJECT : SUB-SOIL INVESTIGATIOM FOR UNDERGRADUATE STUDENTS OF BUET

LOCATION : ANOARA, CHITTAGONG.

BORE HOLE NO. 01

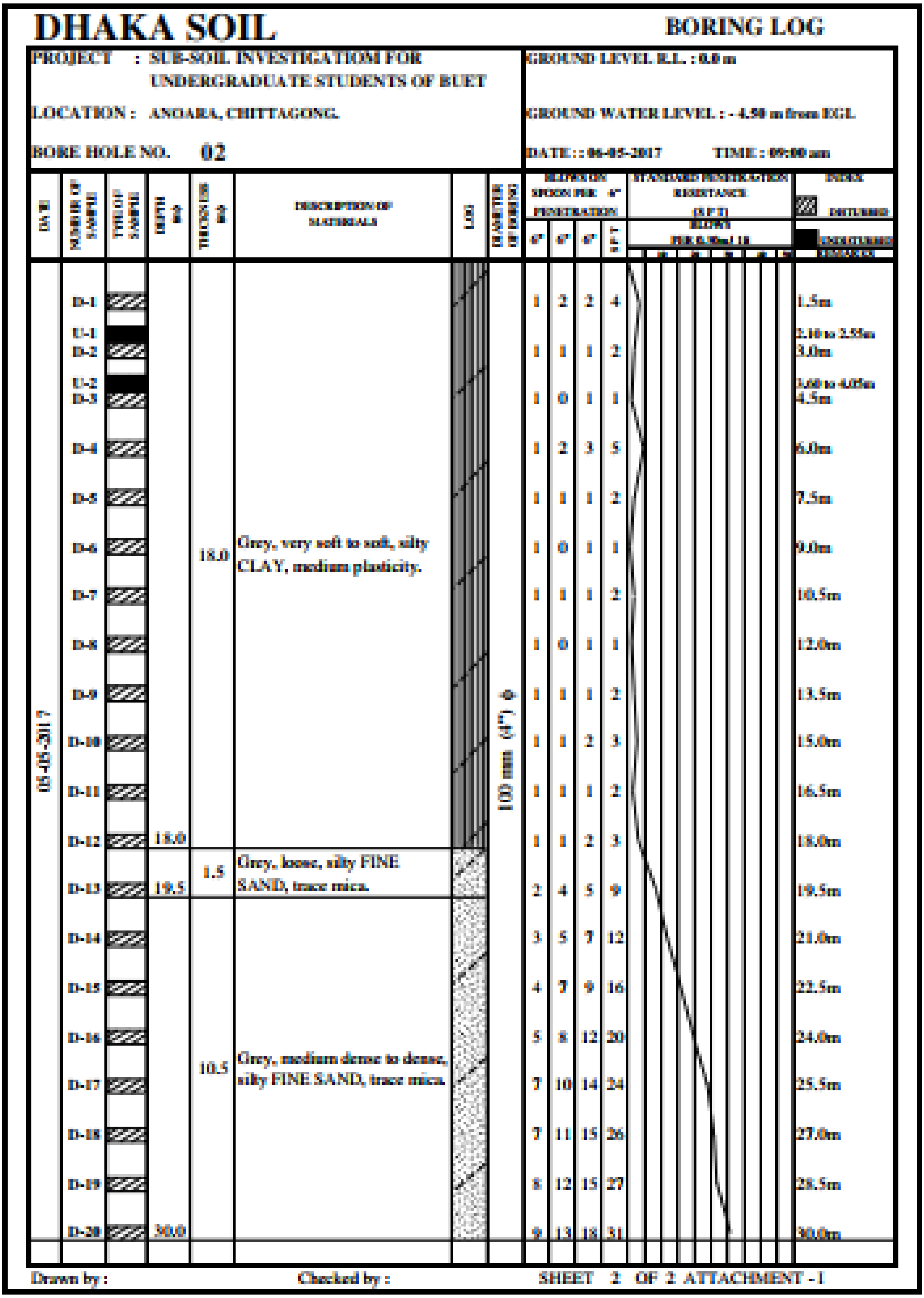
GROUND LEVEL R.L. : 0.0 m

GROUND WATER LEVEL : - 4.12 m from EGL

DATE :: 06-05-2017 TIME : 09:00 am

DATE	NUMBER OF SAMPLE	TYPE OF SAMPLE	DEPTH (m)	THICKNESS (m)	DESCRIPTION OF MATERIALS	DIAMETER OF BORING	BLOWS ON SPOON PER 6" PENETRATION 6"	6"	6"	SPT	INDEX ▨ DISTURBED ■ UNDISTURBED REMARKS
05-05-2017	D-1	▨		3.0	Grey, stiff silty CLAY, medium plasticity.	100 mm (4") ϕ	2	4	5	9	1.5m
	U-1	■									2.10 to 2.55m
	D-2	▨	3.0				3	5	7	12	3.0m
	U-1	■									3.60 to 4.05m
	D-3	▨		6.0	Grey, medium stiff to stiff silty CLAY, medium plasticity.		2	3	3	6	4.5m
	D-4	▨					4	7	8	15	6.0m
	D-5	▨					5	8	10	18	7.5m
	D-6	▨	9.0				4	5	7	12	9.0m
	D-7	▨		6.0	Grey, very soft to medium stiff silty CLAY, medium plasticity.		1	0	1	1	10.5m
	D-8	▨					1	1	2	3	12.0m
	D-9	▨					1	3	4	7	13.5m
	D-10	▨	15.0				2	3	5	8	15.0m
	D-11	▨	16.5	1.5	Grey, medium dense sandy SILLT, trace mica.		5	7	10	17	16.5m
	D-12	▨		7.5	Grey, medium dense silty CLAY with FINE SAND.		6	8	12	20	18.0m
	D-13	▨					6	11	12	23	19.5m
	D-14	▨					4	6	8	14	21.0m
	D-15	▨					3	5	7	12	22.5m
	D-16	▨	24.0				4	6	9	15	24.0m
	D-17	▨		6.0	Grey medium dense, silty FINE SAND, trace mica.		5	8	10	18	25.5m
	D-18	▨					6	10	12	22	27.0m
	D-19	▨					6	12	15	27	28.5m
	D-20	▨	30.0				7	13	17	30	30.0m

Drawn by : Checked by : SHEET 1 OF 2 ATTACHMENT - I



DHAKA SOIL **BORING LOG**

PROJECT : SUB-SOIL INVESTIGATIOM FOR UNDERGRADUATE STUDENTS OF BUET

LOCATION : ANOARA, CHITTAGONG.

BORE HOLE NO. 02

GROUND LEVEL R.L. : 0.0 m

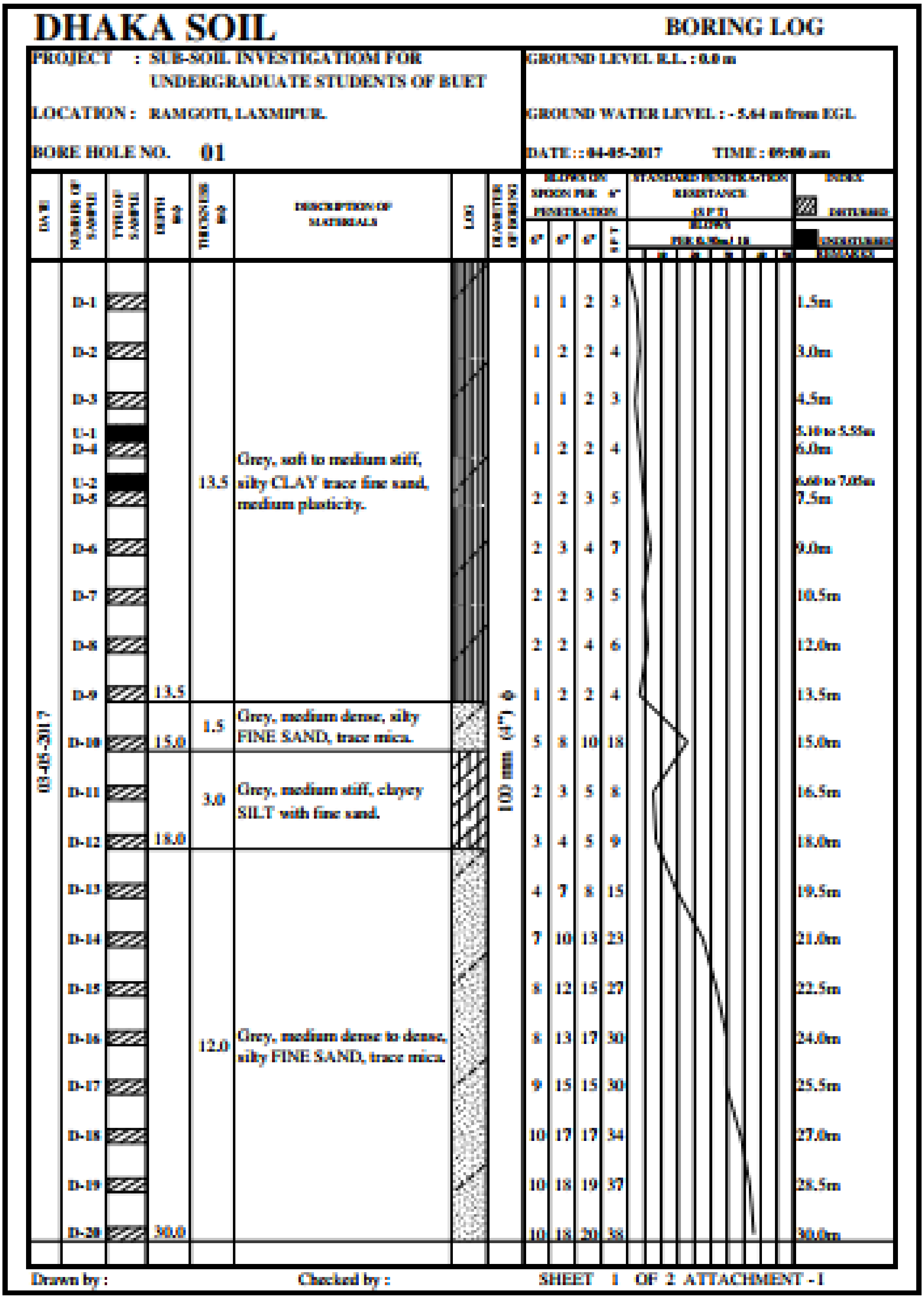
GROUND WATER LEVEL : - 4.50 m from EGL

DATE : : 06-05-2017 TIME : 09:00 am

DATE	NUMBER OF SAMPLE	TYPE OF SAMPLE	DEPTH (m)	THICKNESS (m)	DESCRIPTION OF MATERIALS	DIAMETER OF BORING	6"	6"	6"	SPT	REMARKS
05-05-2017	D-1	▨		18.0	Grey, very soft to soft, silty CLAY, medium plasticity.	100 mm (4") φ	1	2	2	4	1.5m
	U-1	■									2.10 to 2.55m
	D-2	▨					1	1	1	2	3.0m
	U-2	■									3.60 to 4.05m
	D-3	▨					1	0	1	1	4.5m
	D-4	▨					1	2	3	5	6.0m
	D-5	▨					1	1	1	2	7.5m
	D-6	▨					1	0	1	1	9.0m
	D-7	▨					1	1	1	2	10.5m
	D-8	▨					1	0	1	1	12.0m
	D-9	▨					1	1	1	2	13.5m
	D-10	▨					1	1	2	3	15.0m
	D-11	▨					1	1	1	2	16.5m
	D-12	▨	18.0				1	1	2	3	18.0m
	D-13	▨	19.5	1.5	Grey, loose, silty FINE SAND, trace mica.		2	4	5	9	19.5m
	D-14	▨		10.5	Grey, medium dense to dense, silty FINE SAND, trace mica.		3	5	7	12	21.0m
	D-15	▨					4	7	9	16	22.5m
	D-16	▨					5	8	12	20	24.0m
	D-17	▨					7	10	14	24	25.5m
	D-18	▨					7	11	15	26	27.0m
	D-19	▨					8	12	15	27	28.5m
	D-20	▨	30.0				9	13	18	31	30.0m

Drawn by : Checked by : SHEET 2 OF 2 ATTACHMENT - I

SPT test location: Ramgoti, Laxmipur



DHAKA SOIL **BORING LOG**

PROJECT : SUB-SOIL INVESTIGATIOM FOR UNDERGRADUATE STUDENTS OF BUET

LOCATION : RAMGOTI, LAXMIPUR.

BORE HOLE NO. 01

GROUND LEVEL R.L. : 0.0 m

GROUND WATER LEVEL : - 5.64 m from EGL

DATE : : 04-05-2017 TIME : 09:00 am

INDEX: ▨ DISTURBED ■ UNDISTURBED

DATE	NUMBER OF SAMPLE	TYPE OF SAMPLE	DEPTH (m)	THICKNESS (m)	DESCRIPTION OF MATERIALS	LOG	DIAMETER OF BORING	BLOWS ON SPOON PER 6" PENETRATION 6"	6"	6"	SPT	REMARKS
03-05-2017	D-1	▨		13.5	Grey, soft to medium stiff, silty CLAY trace fine sand, medium plasticity.		100 mm (4") ϕ	1	1	2	3	1.5m
	D-2	▨						1	2	2	4	3.0m
	D-3	▨						1	1	2	3	4.5m
	U-1	■										5.10 to 5.55m
	D-4	▨						1	2	2	4	6.0m
	U-2	■										6.60 to 7.05m
	D-5	▨						2	2	3	5	7.5m
	D-6	▨						2	3	4	7	9.0m
	D-7	▨						2	2	3	5	10.5m
	D-8	▨						2	2	4	6	12.0m
	D-9	▨	13.5					1	2	2	4	13.5m
	D-10	▨	15.0	1.5	Grey, medium dense, silty FINE SAND, trace mica.			5	8	10	18	15.0m
	D-11	▨		3.0	Grey, medium stiff, clayey SILT with fine sand.			2	3	5	8	16.5m
	D-12	▨	18.0					3	4	5	9	18.0m
	D-13	▨		12.0	Grey, medium dense to dense, silty FINE SAND, trace mica.			4	7	8	15	19.5m
	D-14	▨						7	10	13	23	21.0m
	D-15	▨						8	12	15	27	22.5m
	D-16	▨						8	13	17	30	24.0m
	D-17	▨						9	15	15	30	25.5m
	D-18	▨						10	17	17	34	27.0m
	D-19	▨						10	18	19	37	28.5m
	D-20	▨	30.0					10	18	20	38	30.0m

Drawn by : Checked by : SHEET 1 OF 2 ATTACHMENT - I

DHAKA SOIL

BORING LOG

PROJECT : SUB-SOIL INVESTIGATIOM FOR UNDERGRADUATE STUDENTS OF BUET

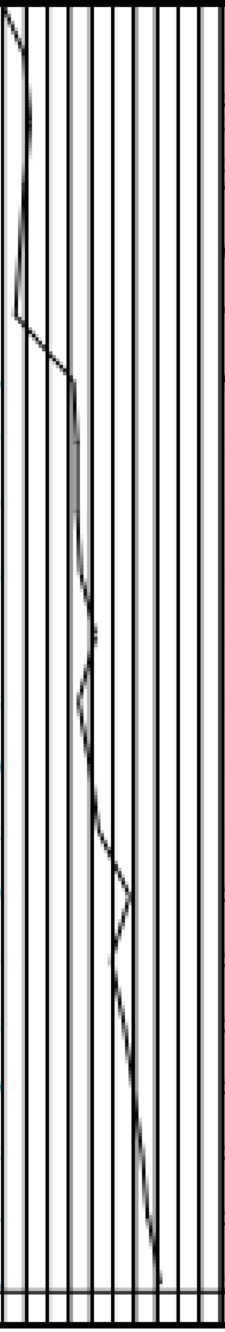
LOCATION : RAMGOTI, LAXMIPUR.

BORE HOLE NO. 02

GROUND LEVEL R.L. : 0.0 m

GROUND WATER LEVEL : - 6.0 m from EGL

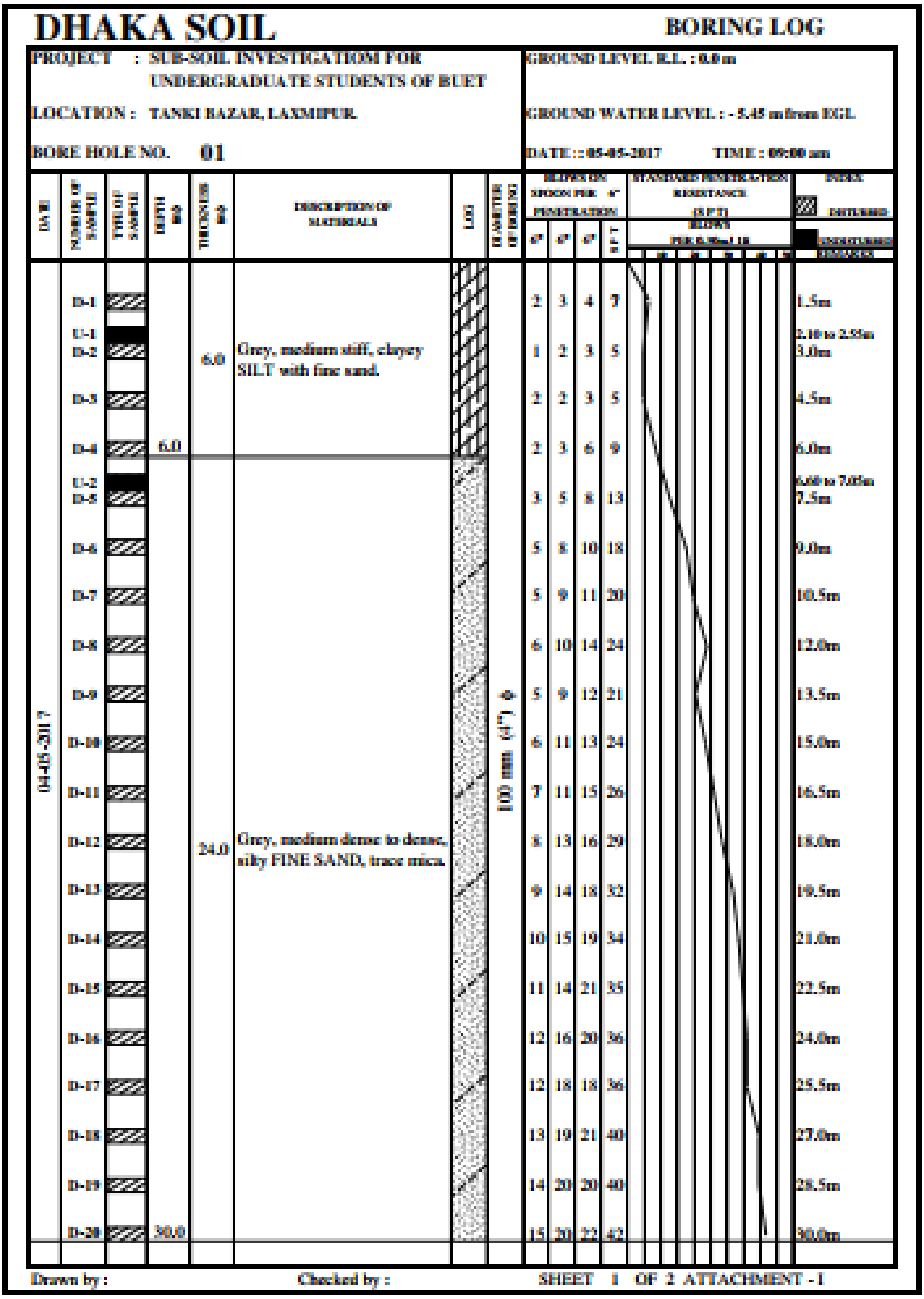
DATE :: 04-05-2017 **TIME :** 09:00 am



DATE	NUMBER OF SAMPLE	TYPE OF SAMPLE	DEPTH (m)	THICKNESS (m)	DESCRIPTION OF MATERIALS	LOG	DIAMETER OF BORING	BLOWS ON SPOON PER 6" PENETRATION 6"	6"	6"	SPT	INDEX ▨ DISTURBED ■ UNDISTURBED REMARKS
03-05-2017	D-1	▨		7.5	Grey, medium stiff to soft, silty CLAY trace fine sand, medium plasticity.		100 mm (4") ϕ	1	2	3	5	1.5m
	U-1	■										2.10 to 2.55m
	D-2	▨						2	2	4	6	3.0m
	U-2	■										3.60 to 4.05m
	D-3	▨						2	2	3	5	4.5m
	D-4	▨						2	2	2	4	6.0m
	D-5	▨	7.5					1	1	2	3	7.5m
	D-6	▨		22.5	Grey, medium dense to dense, silty FINE SAND, trace mica.			4	6	10	16	9.0m
	D-7	▨						5	6	11	17	10.5m
	D-8	▨						6	7	10	17	12.0m
	D-9	▨						6	8	10	18	13.5m
	D-10	▨						7	10	11	21	15.0m
	D-11	▨						5	8	10	18	16.5m
	D-12	▨						6	10	10	20	18.0m
	D-13	▨						7	10	12	22	19.5m
	D-14	▨						7	11	18	29	21.0m
	D-15	▨						8	12	13	25	22.5m
	D-16	▨						8	13	15	28	24.0m
	D-17	▨						8	15	15	30	25.5m
	D-18	▨						9	15	17	32	27.0m
	D-19	▨						9	16	18	34	28.5m
	D-20	▨	30.0					10	16	20	36	30.0m

Drawn by : Checked by : SHEET 2 OF 2 ATTACHMENT - 1

SPT test location: Tanki Bazar, Laxmipur



DHAKA SOIL

BORING LOG

PROJECT : SUB-SOIL INVESTIGATIOM FOR UNDERGRADUATE STUDENTS OF BUET

LOCATION : TANKI BAZAR, LAXMIPUR.

BORE HOLE NO. 01

GROUND LEVEL R.L. : 0.0 m

GROUND WATER LEVEL : - 5.45 m from EGL

DATE : : 05-05-2017 TIME : 09:00 am

DATE	NUMBER OF SAMPLE	TYPE OF SAMPLE	DEPTH (m)	THICKNESS (m)	DESCRIPTION OF MATERIALS	DIAMETER OF BORING	BLOWS ON SPOON PER 6" PENETRATION 6"	6"	6"	SPT	REMARKS
04-05-2017	D-1	▨		6.0	Grey, medium stiff, clayey SILT with fine sand.	100 mm (4") φ	2	3	4	7	1.5m
	U-1	■									2.10 to 2.55m
	D-2	▨					1	2	3	5	3.0m
	D-3	▨					2	2	3	5	4.5m
	D-4	▨	6.0				2	3	6	9	6.0m
	U-2	■		24.0	Grey, medium dense to dense, silty FINE SAND, trace mica.						6.60 to 7.05m
	D-5	▨					3	5	8	13	7.5m
	D-6	▨					5	8	10	18	9.0m
	D-7	▨					5	9	11	20	10.5m
	D-8	▨					6	10	14	24	12.0m
	D-9	▨					5	9	12	21	13.5m
	D-10	▨					6	11	13	24	15.0m
	D-11	▨					7	11	15	26	16.5m
	D-12	▨					8	13	16	29	18.0m
	D-13	▨					9	14	18	32	19.5m
	D-14	▨					10	15	19	34	21.0m
	D-15	▨					11	14	21	35	22.5m
	D-16	▨					12	16	20	36	24.0m
	D-17	▨					12	18	18	36	25.5m
	D-18	▨					13	19	21	40	27.0m
	D-19	▨					14	20	20	40	28.5m
	D-20	▨	30.0				15	20	22	42	30.0m

INDEX ▨ DISTURBED ■ UNDISTURBED

Drawn by : Checked by : SHEET 1 OF 2 ATTACHMENT - 1

DHAKA SOIL

BORING LOG

PROJECT : SUB-SOIL INVESTIGATIOM FOR UNDERGRADUATE STUDENTS OF BUET

LOCATION : TANKI BAZAR, LAXMIPUR.

BORE HOLE NO. 02

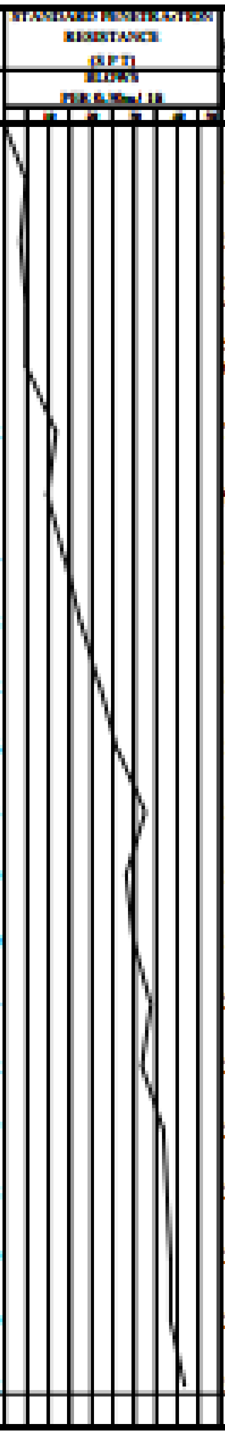
GROUND LEVEL R.L. : 0.0 m

GROUND WATER LEVEL : - 5.34 m from EGL

DATE : : 05-05-2017 TIME : 09:00 am

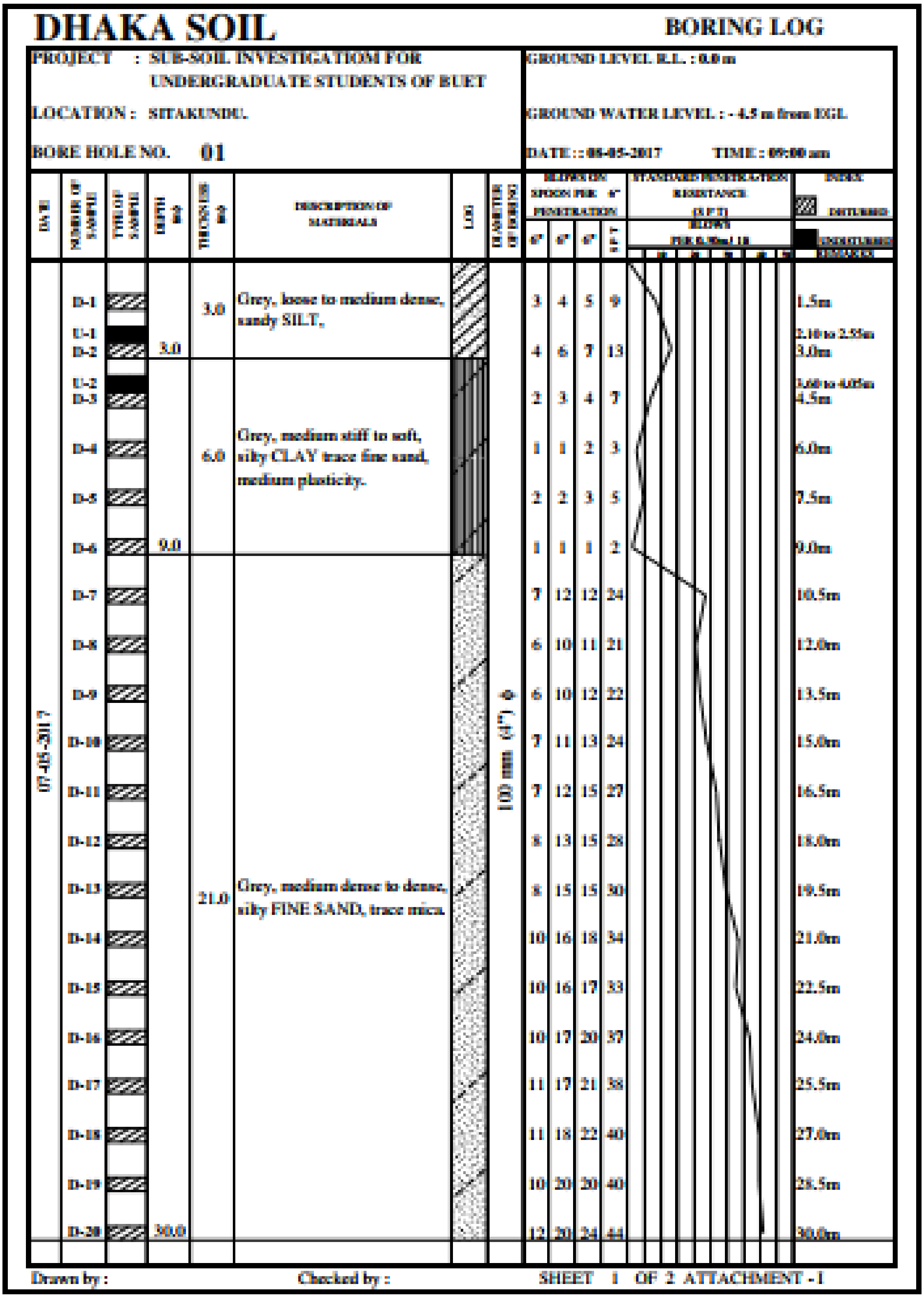
DATE	NUMBER OF SAMPLE	TYPE OF SAMPLE	DEPTH (m)	THICKNESS (m)	DESCRIPTION OF MATERIALS	LOG	DIAMETER OF BORING	BLOWS ON SPOON PER 6" PENETRATION 6"	6"	6"	SPT	INDEX ▨ DISTURBED ■ UNDISTURBED REMARKS
04-05-2017	D-1	▨	1.5	1.5	Grey, loose, silty FINE SAND, trace mica (Filling).		100 mm (4") φ	2	2	3	5	1.5m
	D-2	▨						1	2	2	4	3.0m
	U-1	■										3.60 to 4.05m
	D-3	▨						2	2	3	5	4.5m
	U-2	■										5.10 to 5.55m
	D-4	▨		9.0	Grey, medium stiff, to stiff, clayey SILT with fine sand.			2	2	3	5	6.0m
	D-5	▨						3	5	7	12	7.5m
	D-6	▨						1	2	3	5	9.0m
	D-7	▨	10.5					4	6	8	14	10.5m
	D-8	▨						5	8	10	18	12.0m
	D-9	▨						6	10	12	22	13.5m
	D-10	▨						7	13	13	26	15.0m
	D-11	▨						7	18	15	33	16.5m
	D-12	▨						8	14	15	29	18.0m
	D-13	▨						8	15	15	30	19.5m
	D-14	▨		19.5	Grey, medium dense to dense, silty FINE SAND, trace mica.			9	16	18	34	21.0m
	D-15	▨						9	16	16	32	22.5m
	D-16	▨						10	17	20	37	24.0m
	D-17	▨						10	18	20	38	25.5m
	D-18	▨						9	18	21	39	27.0m
	D-19	▨						10	19	20	39	28.5m
	D-20	▨	30.0					12	20	22	42	30.0m

STANDARD PENETRATION RESISTANCE (S.P.T) BLOWS PER 0.30m/1ft



Drawn by : Checked by : SHEET 2 OF 2 ATTACHMENT - 1

SPT test location: Sitakundu



DHAKA SOIL **BORING LOG**

PROJECT : SUB-SOIL INVESTIGATIOM FOR UNDERGRADUATE STUDENTS OF BUET

LOCATION : SITAKUNDU.

BORE HOLE NO. 01

GROUND LEVEL R.L. : 0.0 m

GROUND WATER LEVEL : - 4.5 m from EGL

DATE : : 08-05-2017 TIME : 09:00 am

DATE	NUMBER OF SAMPLE	TYPE OF SAMPLE	DEPTH (m)	THICKNESS (m)	DESCRIPTION OF MATERIALS	LOG	DIAMETER OF BORING	BLOWS ON SPOON PER 6" PENETRATION 6"	6"	6"	SPT	INDEX / REMARKS
07-05-2017	D-1	▨		3.0	Grey, loose to medium dense, sandy SILT,		100 mm (4") Φ	3	4	5	9	1.5m
	U-1	■										2.10 to 2.55m
	D-2	▨	3.0					4	6	7	13	3.0m
	U-2	■										3.60 to 4.05m
	D-3	▨		6.0	Grey, medium stiff to soft, silty CLAY trace fine sand, medium plasticity.			2	3	4	7	4.5m
	D-4	▨						1	1	2	3	6.0m
	D-5	▨						2	2	3	5	7.5m
	D-6	▨	9.0					1	1	1	2	9.0m
	D-7	▨		21.0	Grey, medium dense to dense, silty FINE SAND, trace mica.			7	12	12	24	10.5m
	D-8	▨						6	10	11	21	12.0m
	D-9	▨						6	10	12	22	13.5m
	D-10	▨						7	11	13	24	15.0m
	D-11	▨						7	12	15	27	16.5m
	D-12	▨						8	13	15	28	18.0m
	D-13	▨						8	15	15	30	19.5m
	D-14	▨						10	16	18	34	21.0m
	D-15	▨						10	16	17	33	22.5m
	D-16	▨						10	17	20	37	24.0m
	D-17	▨						11	17	21	38	25.5m
	D-18	▨						11	18	22	40	27.0m
	D-19	▨						10	20	20	40	28.5m
	D-20	▨	30.0					12	20	24	44	30.0m

STANDARD PENETRATION RESISTANCE (S.P.T) BLOWS PER 0.30m/ 1ft

▨ DISTURBED

■ UNDISTURBED

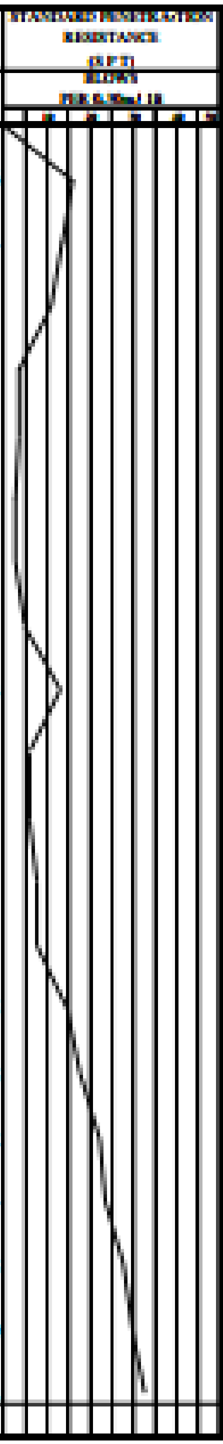
Drawn by : Checked by : SHEET 1 OF 2 ATTACHMENT - 1

DHAKA SOIL

BORING LOG

PROJECT : SUB-SOIL INVESTIGATIOM FOR UNDERGRADUATE STUDENTS OF BUET
LOCATION : SITAKUNDU.
BORE HOLE NO. 02

GROUND LEVEL R.L. : 0.0 m
GROUND WATER LEVEL : - 4.85 m from EGL
DATE : : 08-05-2017 TIME : 09:00 am

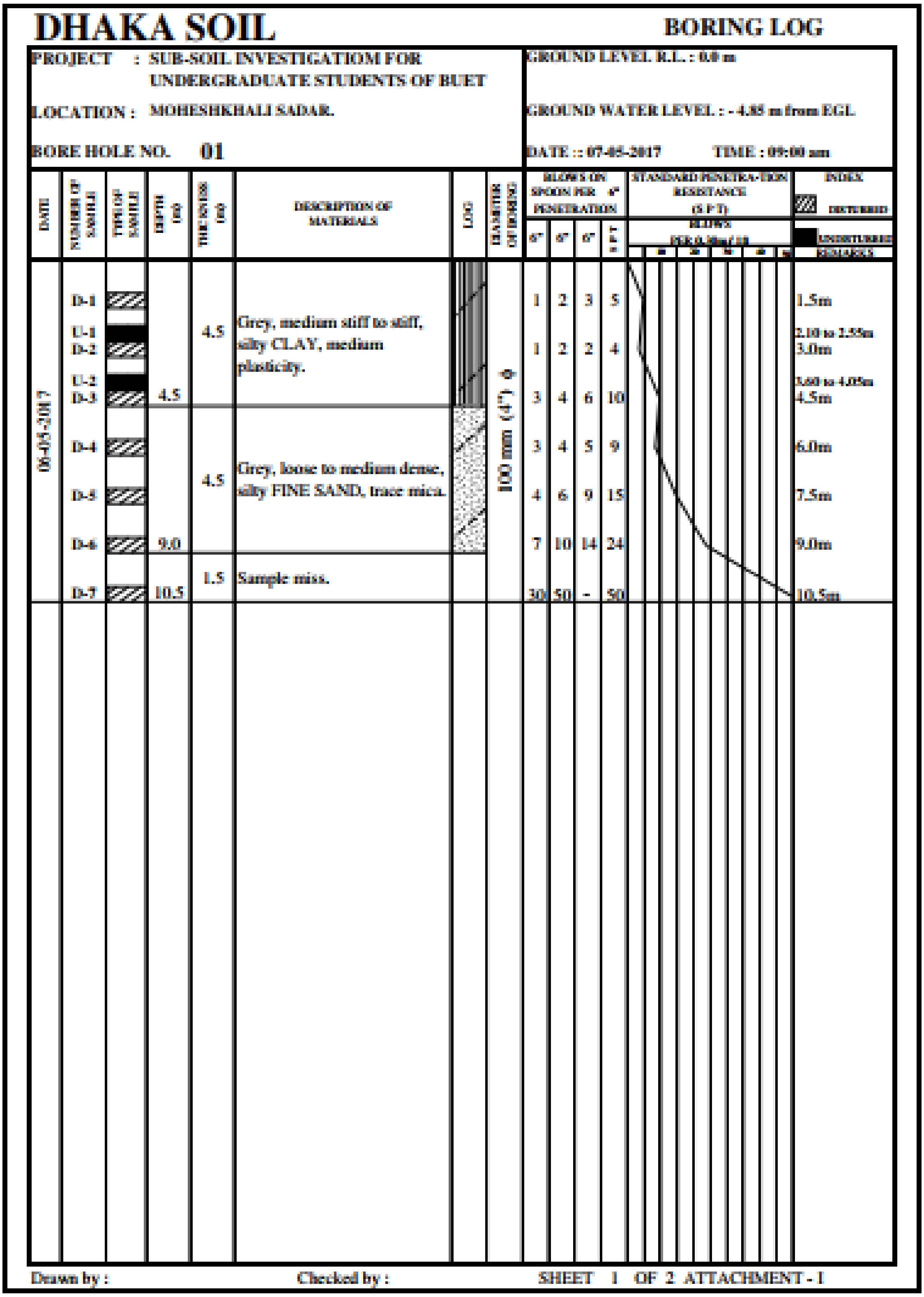


INDEX: ▨ DISTURBED ■ UNDISTURBED

DATE	NUMBER OF SAMPLE	TYPE OF SAMPLE	DEPTH (m)	THICKNESS (m)	DESCRIPTION OF MATERIALS	LOG	DIAMETER OF BORING	6"	6"	6"	SPT	REMARKS
07-05-2017	D-1	▨		3.0	Grey, stiff, clayey SILT with fine sand.		100 mm (4") φ	4	8	8	16	1.5m
	U-1	■										2.10 to 2.55m
	D-2	▨	3.0					4	6	8	14	3.0m
	U-2	■		16.5	Grey, soft to medium stiff, silty CLAY, medium plasticity.							3.60 to 4.05m
	D-3	▨						3	4	7	11	4.5m
	D-4	▨						1	2	2	4	6.0m
	D-5	▨						1	2	2	4	7.5m
	D-6	▨						1	1	2	3	9.0m
	D-7	▨						1	1	2	3	10.5m
	D-8	▨						2	2	3	5	12.0m
	D-9	▨						3	5	8	13	13.5m
	D-10	▨						2	3	3	6	15.0m
	D-11	▨						3	3	3	6	16.5m
	D-12	▨						2	4	4	8	18.0m
	D-13	▨	19.5					2	3	5	8	19.5m
	D-14	▨		10.5	Grey, medium dense to dense, silty FINE SAND, trace mica.			4	6	9	15	21.0m
	D-15	▨						5	8	10	18	22.5m
	D-16	▨						6	10	12	22	24.0m
	D-17	▨						7	10	14	24	25.5m
	D-18	▨						8	13	15	28	27.0m
	D-19	▨						8	15	15	30	28.5m
	D-20	▨	30.0					9	15	18	33	30.0m

Drawn by : Checked by : SHEET 2 OF 2 ATTACHMENT - 1

SPT test location: Moheskhali



DHAKA SOIL

BORING LOG

PROJECT : SUB-SOIL INVESTIGATIOM FOR UNDERGRADUATE STUDENTS OF BUET

LOCATION : MOHESHKHALI SADAR.

BORE HOLE NO. 01

GROUND LEVEL R.L. : 0.0 m

GROUND WATER LEVEL : - 4.85 m from EGL

DATE :: 07-05-2017 TIME : 09:00 am

DATE	NUMBER OF SAMPLE	TYPE OF SAMPLE	DEPTH (m)	THICKNESS (m)	DESCRIPTION OF MATERIALS	DIAMETER OF BORING	BLOWS ON SPOON PER 6" PENETRATION 6"	6"	6"	SPT	REMARKS
06-05-2017	D-1	▨		4.5	Grey, medium stiff to stiff, silty CLAY, medium plasticity.	100 mm (4") φ	1	2	3	5	1.5m
	U-1	■									2.10 to 2.55m
	D-2	▨					1	2	2	4	3.0m
	U-2	■									3.60 to 4.05m
	D-3	▨	4.5				3	4	6	10	4.5m
	D-4	▨		4.5	Grey, loose to medium dense, silty FINE SAND, trace mica.		3	4	5	9	6.0m
	D-5	▨					4	6	9	15	7.5m
	D-6	▨	9.0				7	10	14	24	9.0m
	D-7	▨	10.5	1.5	Sample miss.		30	50	-	50	10.5m

STANDARD PENETRA-TION RESISTANCE (S P T) BLOWS PER 0.30m/ 1ft

INDEX ▨ DISTURBED ■ UNDISTURBED

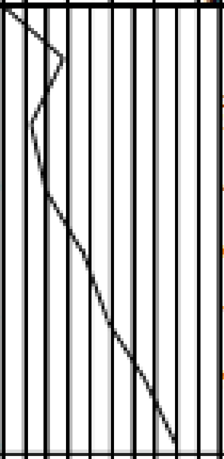
Drawn by : Checked by : SHEET 1 OF 2 ATTACHMENT - I

DHAKA SOIL

BORING LOG

PROJECT : SUB-SOIL INVESTIGATIOM FOR UNDERGRADUATE STUDENTS OF BUET	GROUND LEVEL R.L. : 0.0 m
LOCATION : MOHESHKHALI SADAR.	GROUND WATER LEVEL : - 5.34 m from EGL
BORE HOLE NO. 02	DATE :: 07-05-2017 TIME : 09:00 am

INDEX: ▨ DISTURBED ■ UNDISTURBED

DATE	NUMBER OF SAMPLE	TYPE OF SAMPLE	DEPTH (m)	THICKNESS (m)	DESCRIPTION OF MATERIALS	LOG	DIAMETER OF BORING	BLOWS ON SPOON PER 6" PENETRATION 6"	6"	6"	S P T	STANDARD PENETRA-TION RESISTANCE (S P T) BLOWS PER 0.30m / 1ft	REMARKS
08-05-2017	D-1	▨		3.0	Grey, stiff to medium stiff, clayey SILT with fine sand.		100 mm (4") φ	4	6	8	14		1.5m
	U-1	■											2.10 to 2.55m
	D-2	▨	3.0					2	3	4	7		3.0m
	D-3	▨		3.0	Grey, loose, medium to FINE SAND.			3	4	6	10		4.5m
	D-4	▨	6.0					5	8	10	18		6.0m
	D-5	▨		3.0	Grey, medium dense, silty FINE SAND, trace mica.			6	12	12	24		7.5m
	D-6	▨	9.0					8	15	18	33		9.0m
	D-7	▨	10.5	1.5	Grey very dense, FINE SAND with silt & shell.			72	50	-	50		10.5m

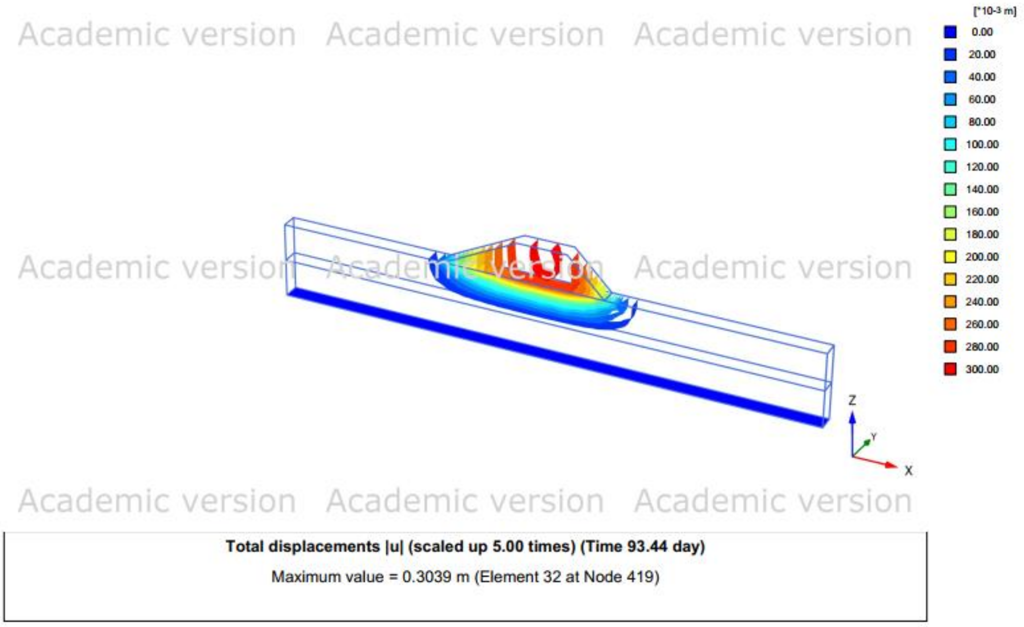
Drawn by : Checked by : SHEET 2 OF 2 ATTACHMENT - I

APPENDIX D

Model Results of Coastal Polders

Results of Bhola Polder analysis

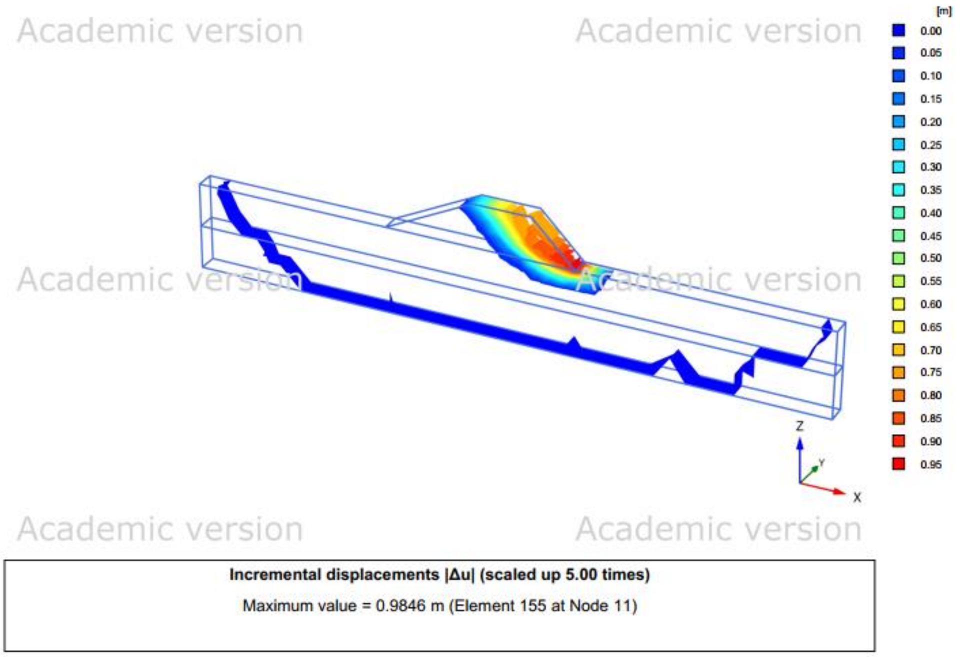
Consolidation Analysis



Total displacements |u| (scaled up 5.00 times) (Time 93.44 day)

Maximum value = 0.3039 m (Element 32 at Node 419)

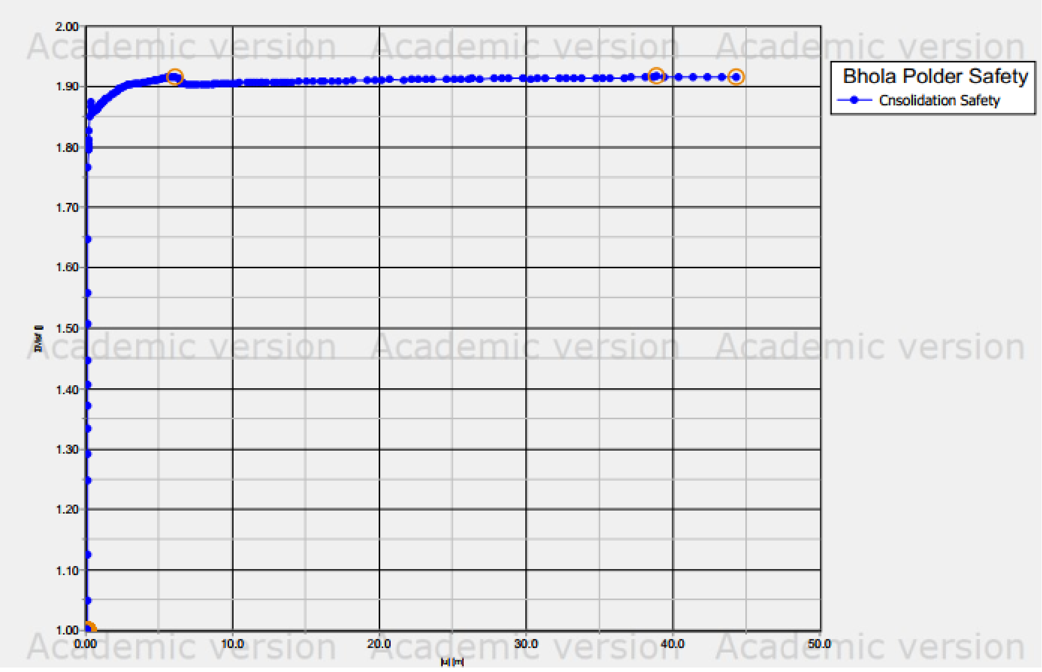
Consolidation settlement of Bhola Polder



Incremental displacements |Δu| (scaled up 5.00 times)

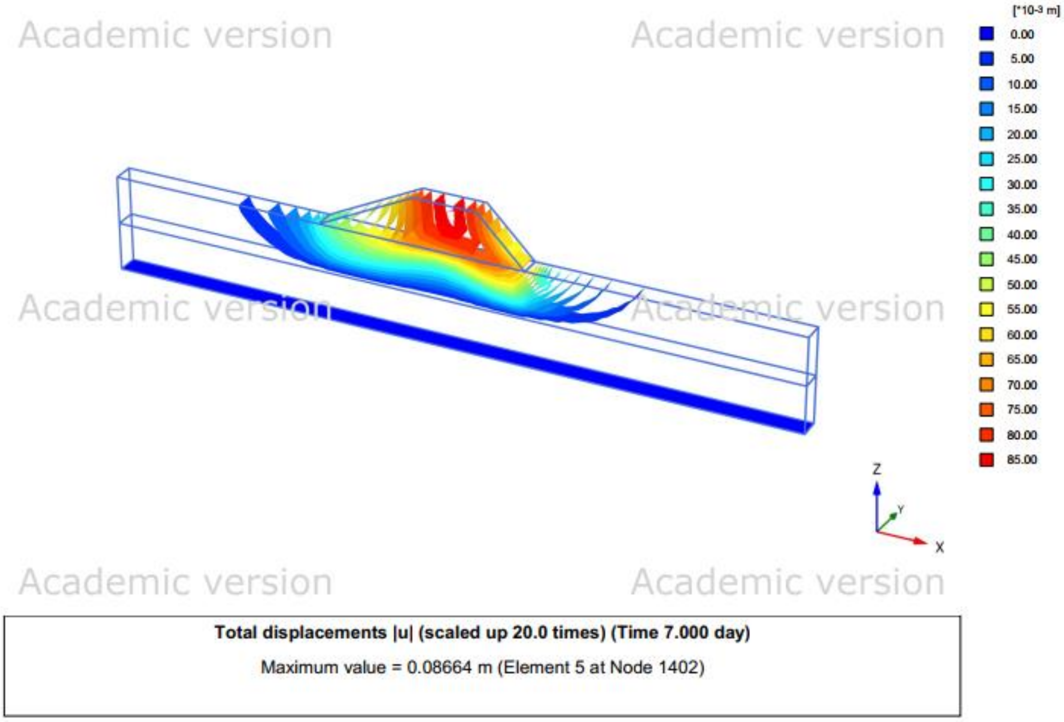
Maximum value = 0.9846 m (Element 155 at Node 11)

Likely Failure Mechanism for Consolidation settlement of Bhola Polder



Consolidation Factor of Safety of Bhola Polder

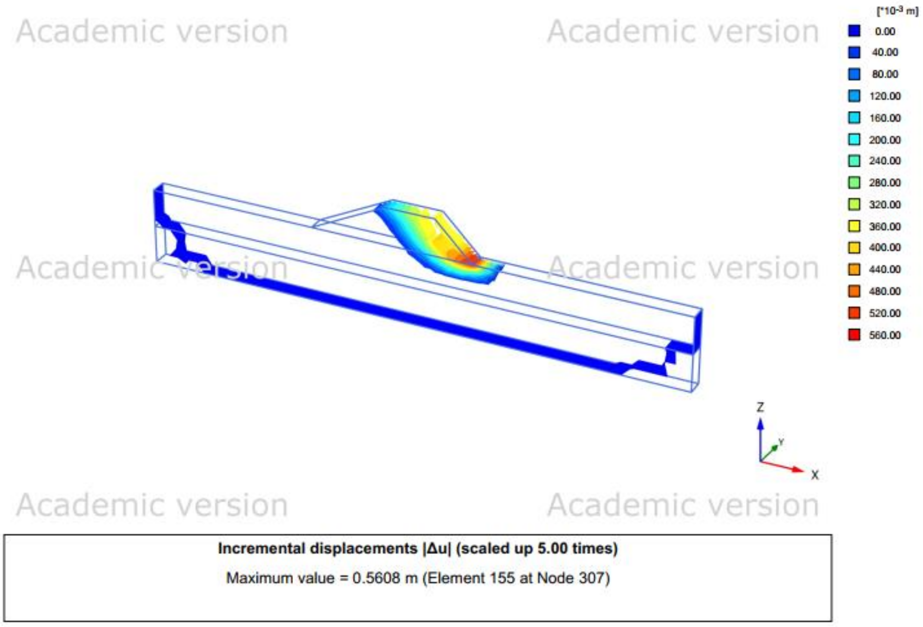
Rapid Drawdown (7 days)



Total displacements |u| (scaled up 20.0 times) (Time 7.000 day)

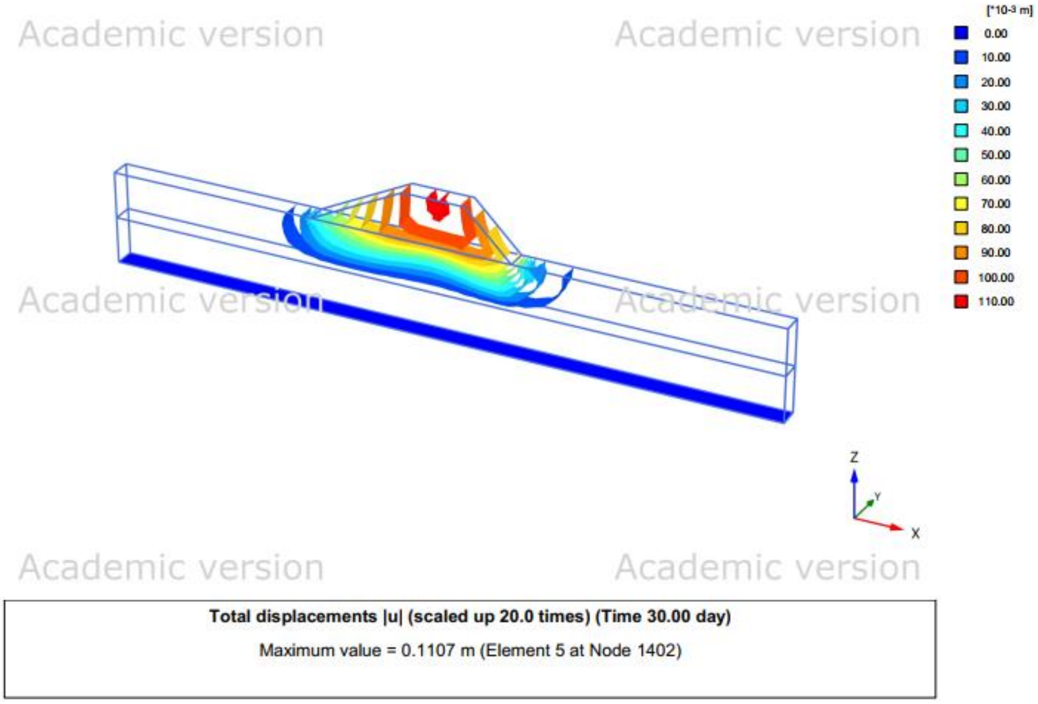
Maximum value = 0.08664 m (Element 5 at Node 1402)

Rapid Drawdown settlement of Bhola Polder

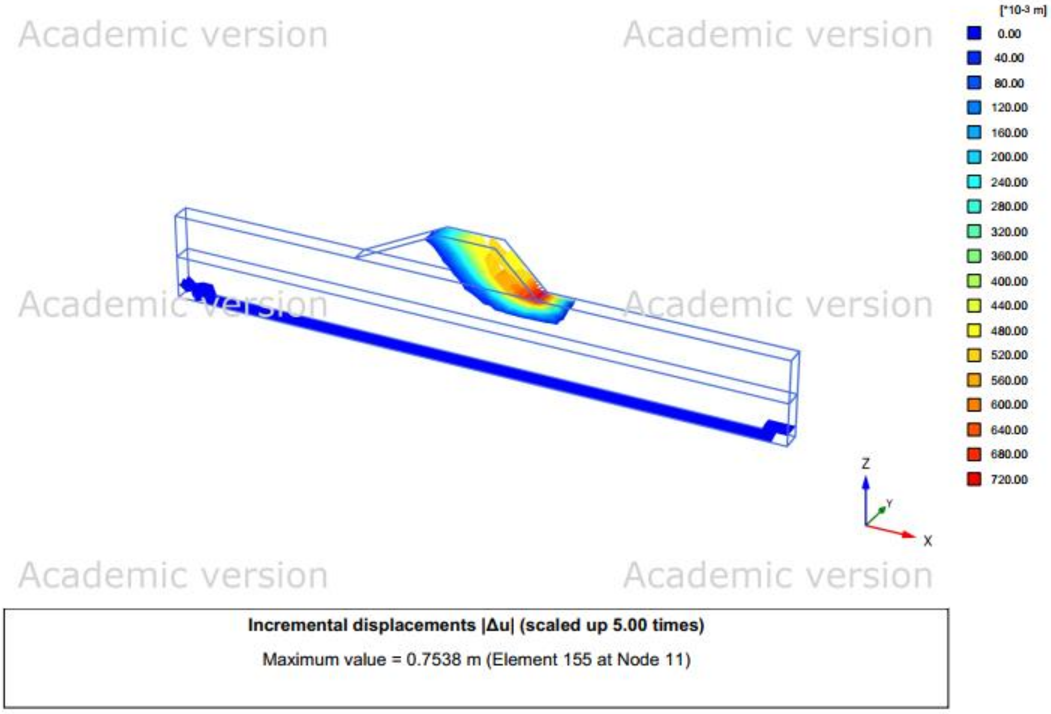


Likely failure mechanism for Rapid Drawdown condition of Bhola Polder

Slow Drawdown (30 days)



Slow Drawdown settlement of Bhola Polder

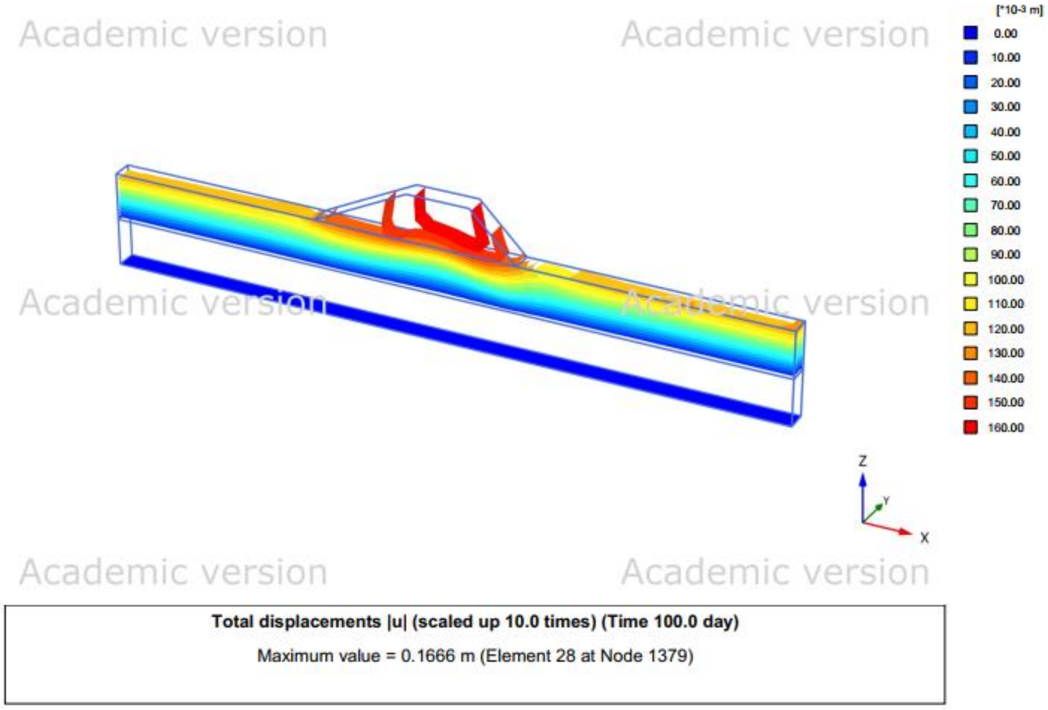


Incremental displacements |Δu| (scaled up 5.00 times)

Maximum value = 0.7538 m (Element 155 at Node 11)

Slow Drawdown likely failure mechanism of Bhola Polder

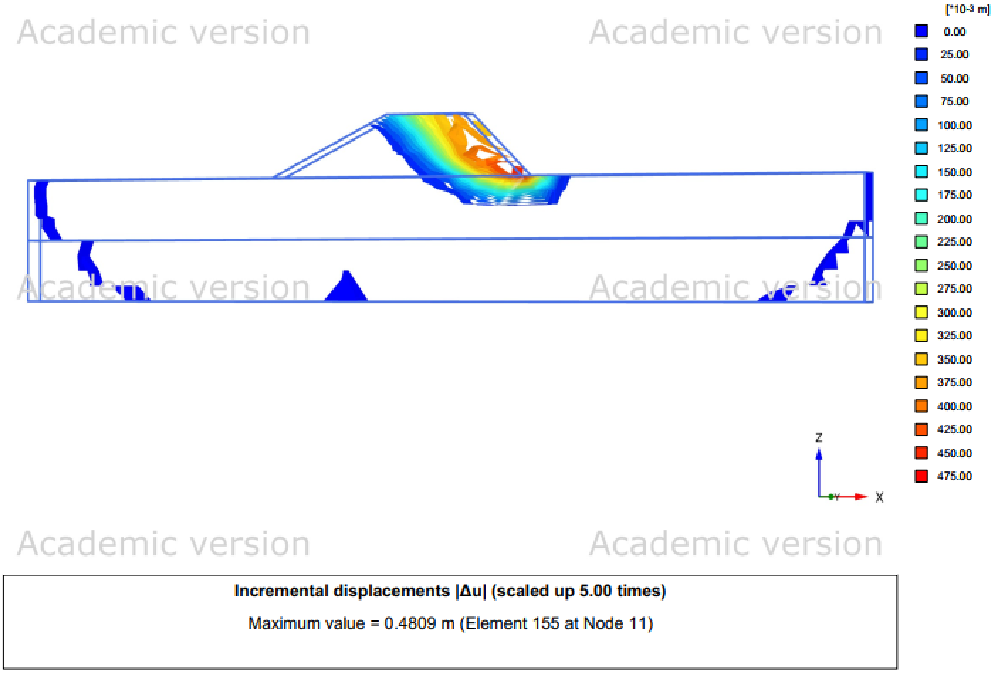
Change in water level (high level to borehole level) over time (100 days)



Total displacements |u| (scaled up 10.0 times) (Time 100.0 day)

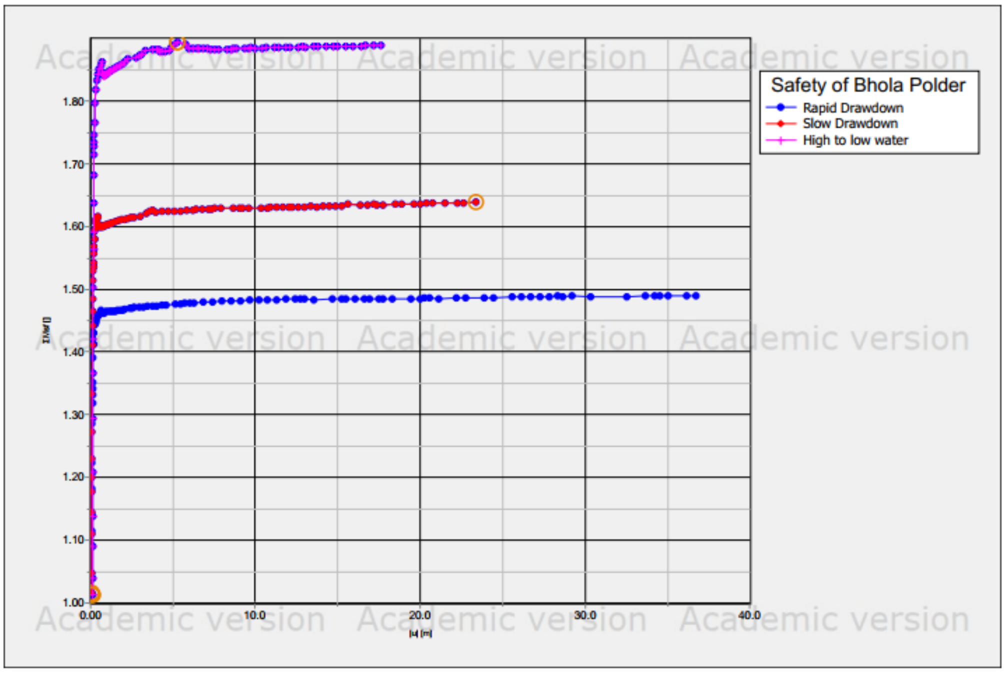
Maximum value = 0.1666 m (Element 28 at Node 1379)

Change in water level (high level to borehole level) settlement of Bhola Polder



Likely failure mechanism of change in water level (high level to borehole level) of Bhola Polder

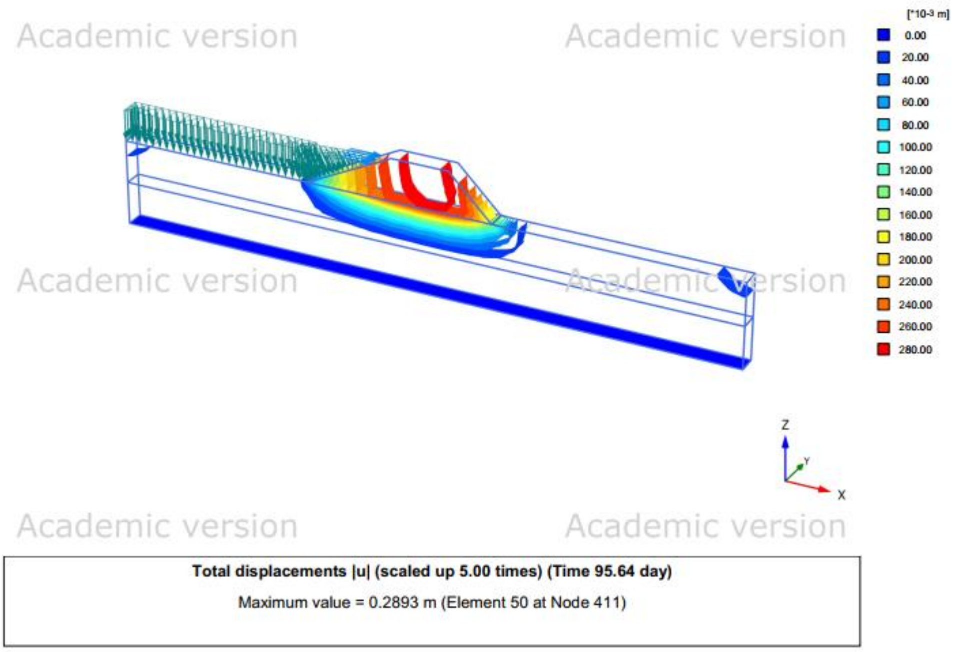
Factor of safety of Rapid Drawdown, Slow Drawdown, and change in water level (high level to borehole level) of Bhola Polder



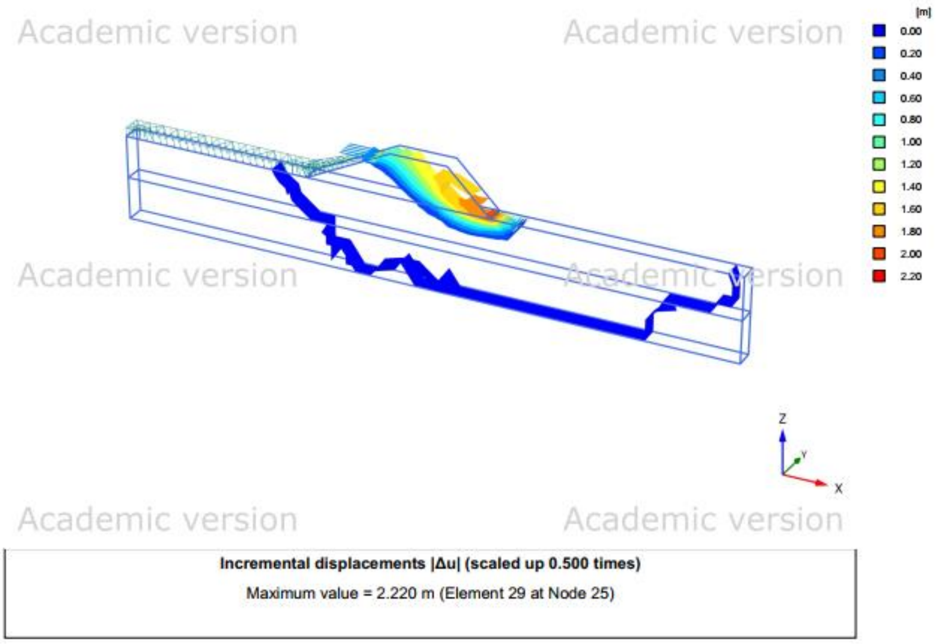
Factor of safety of Rapid Drawdown, Slow Drawdown, and change in water level (high level to borehole level) of Bhola Polder.

Analysis result of Bhola Polder against Cyclone SIDR

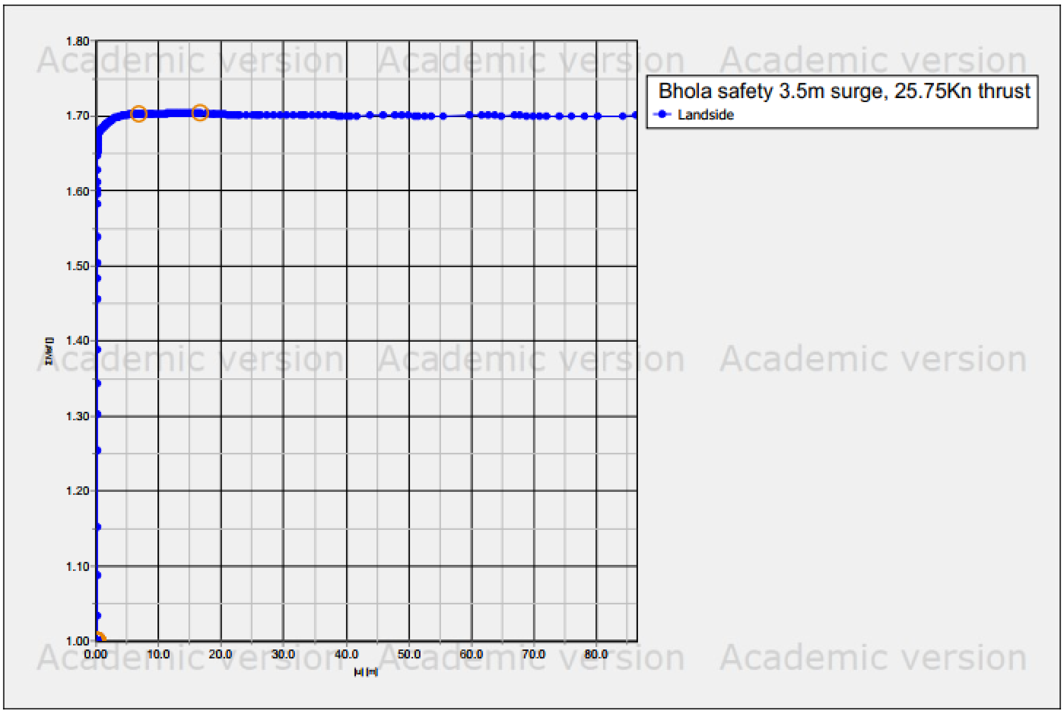
Surge height 3.5m and thrust force 25.75kN



Total settlement for Surge height 3.5m and thrust force 25.75 kN for Bhola Polder

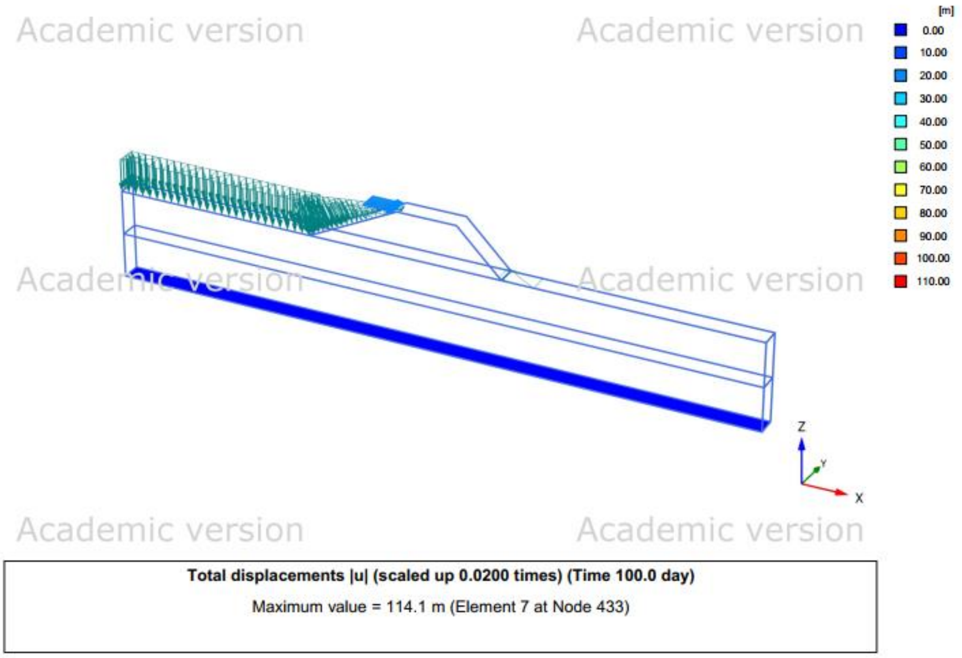


Likely failure mechanism for Surge height 3.5m and thrust force 25.75 kN for Bhola Polder



Factor of safety for Surge height 3.5m and thrust force 25.75 kN for Bhola Polder

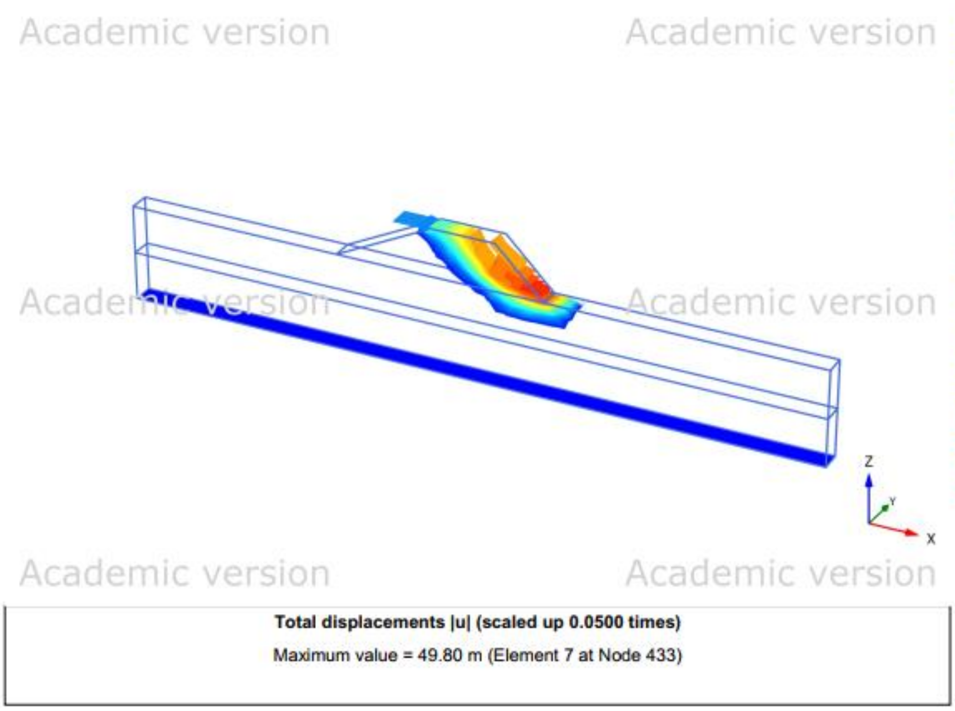
Surge height 4m and thrust force 37 kN kN:



Total displacements |u| (scaled up 0.0200 times) (Time 100.0 day)

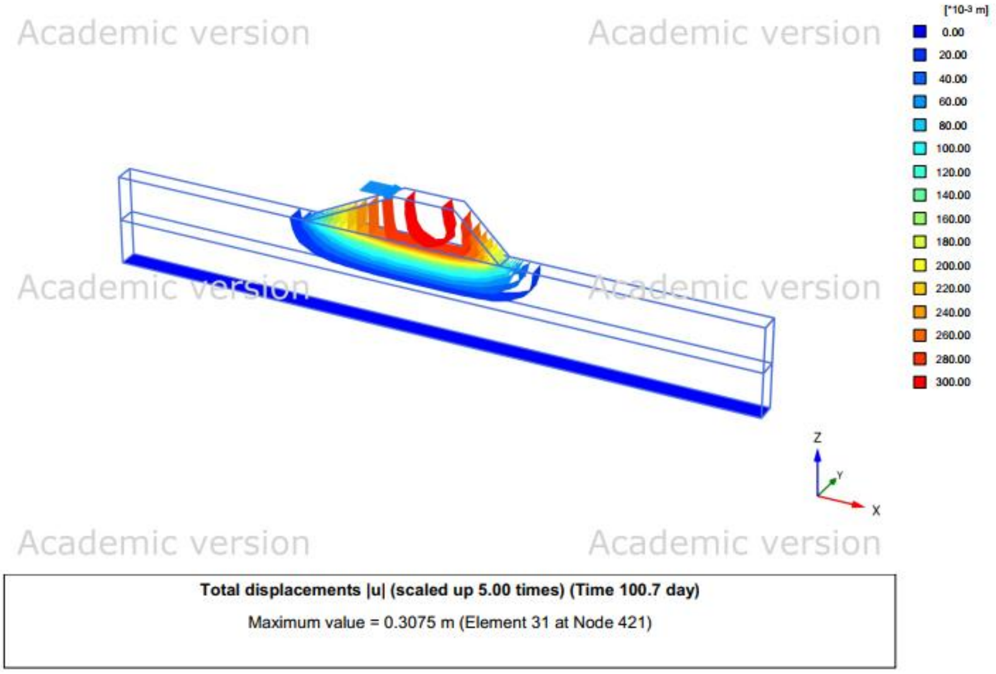
Maximum value = 114.1 m (Element 7 at Node 433)

Total settlement for Surge height 4m and thrust force 37 kN for Bhola Polder (Collapse)

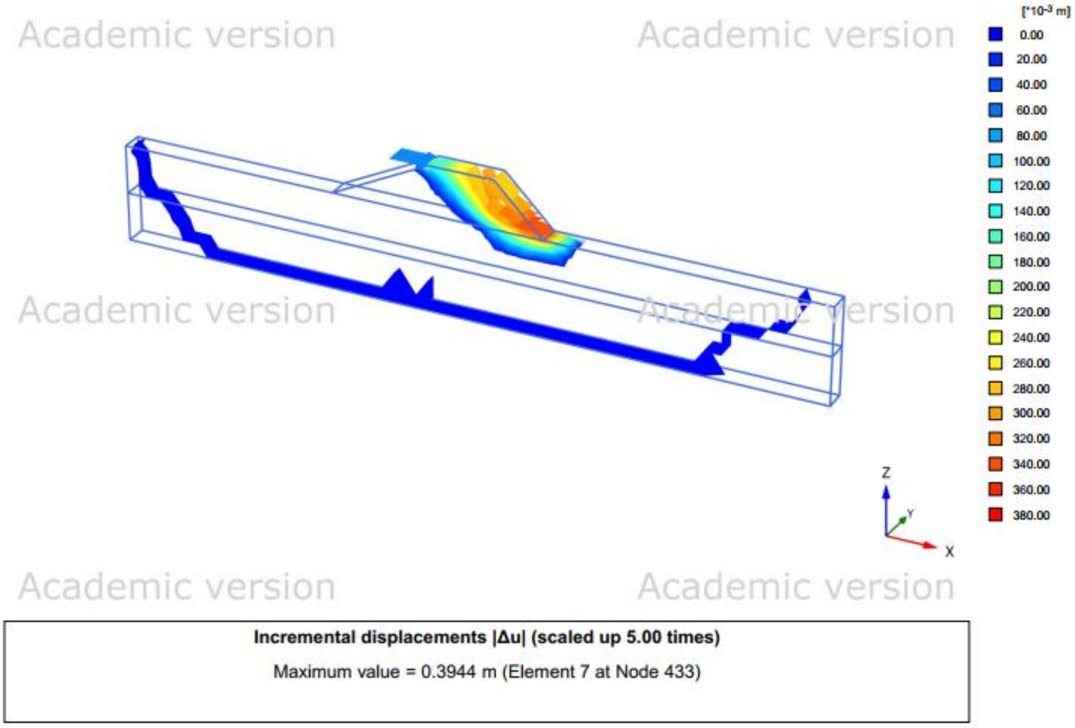


Likely failure mechanism for Surge height 4m and thrust force 37 kN for Bhola Polder (collapse)

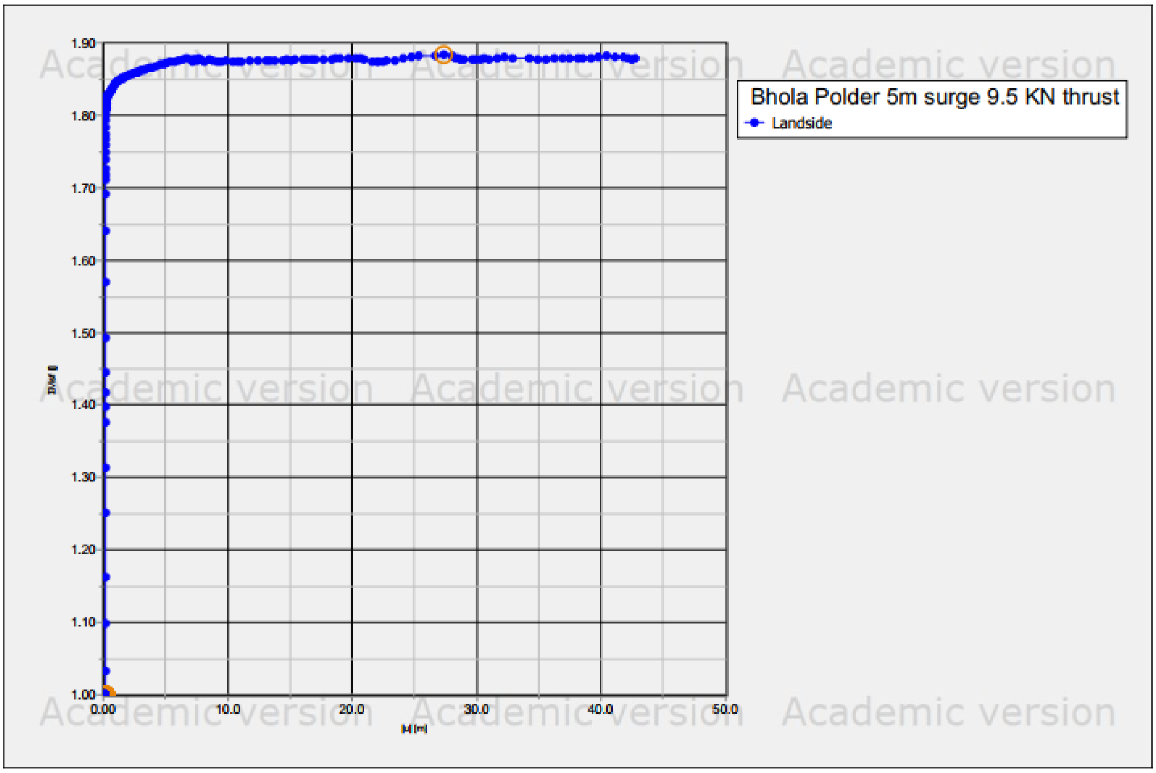
Surge height 5m and thrust force 9.5 kN



Total settlement for Surge height 5m and thrust force9.5 kN for Bhola Polder



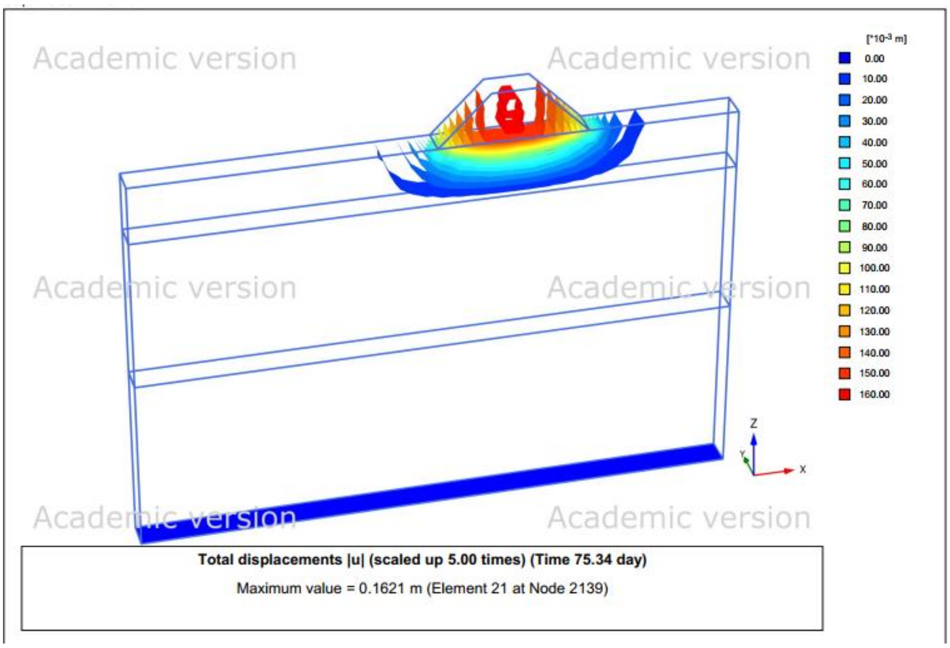
Likely failure mechanism for Surge height 5m and thrust force9.5 kN for Bhola Polder



Factor of safety for Surge height 5m and thrust force 9.5 kN for Bhola Polder

Results of Satkhira Polder analysis

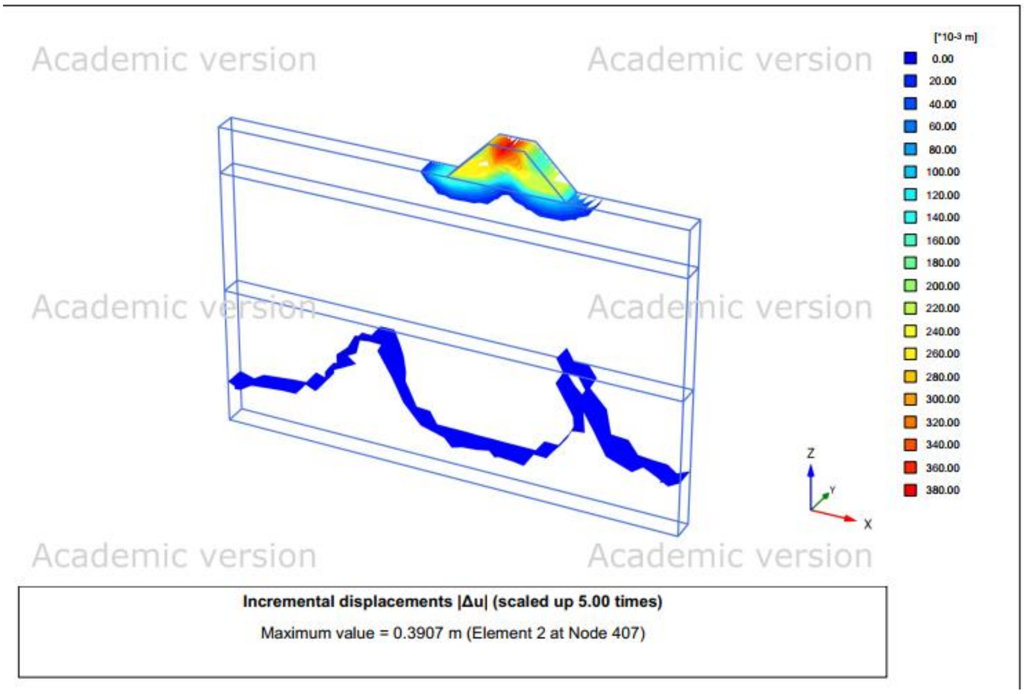
Consolidation Analysis



Total displacements |u| (scaled up 5.00 times) (Time 75.34 day)

Maximum value = 0.1621 m (Element 21 at Node 2139)

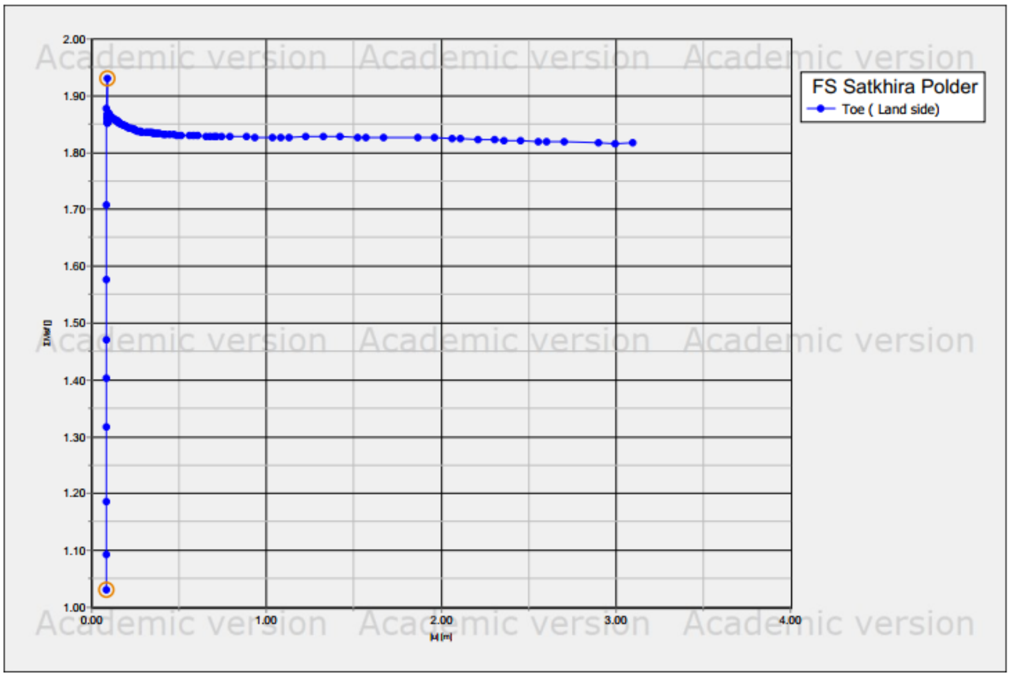
Consolidation settlement of Satkhira Polder



Incremental displacements |Δu| (scaled up 5.00 times)

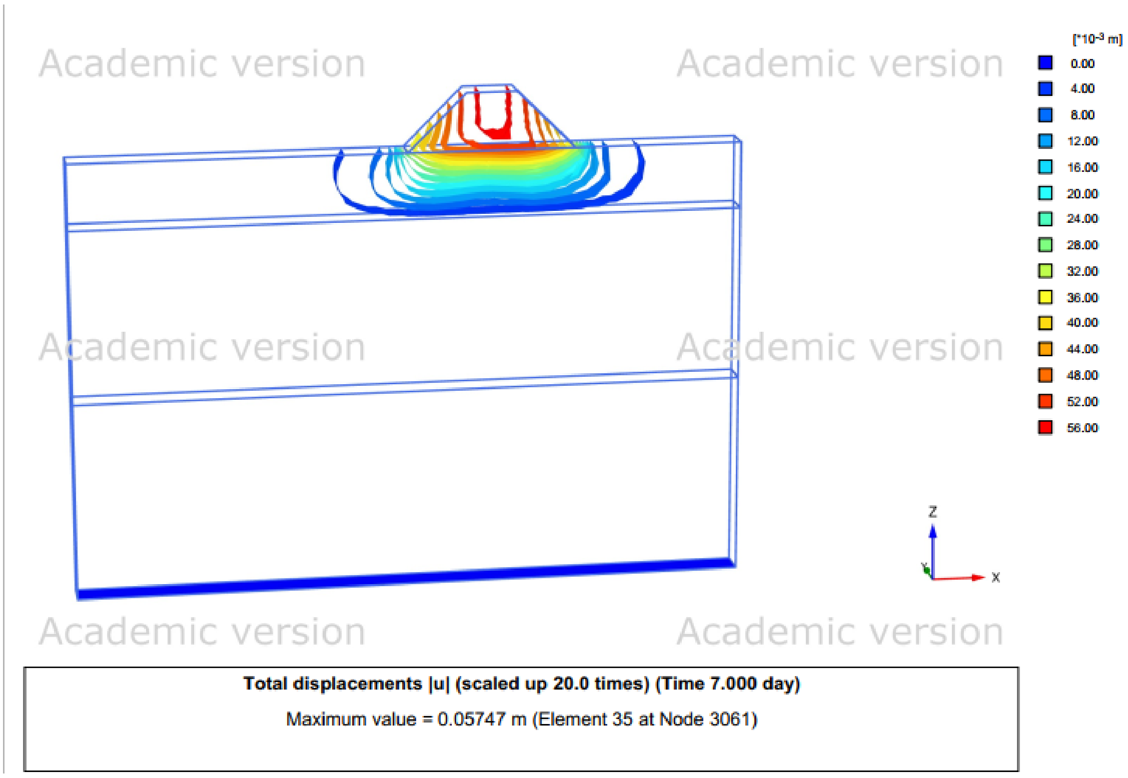
Maximum value = 0.3907 m (Element 2 at Node 407)

Likely Failure Mechanism for Consolidation settlement of Satkhira Polder

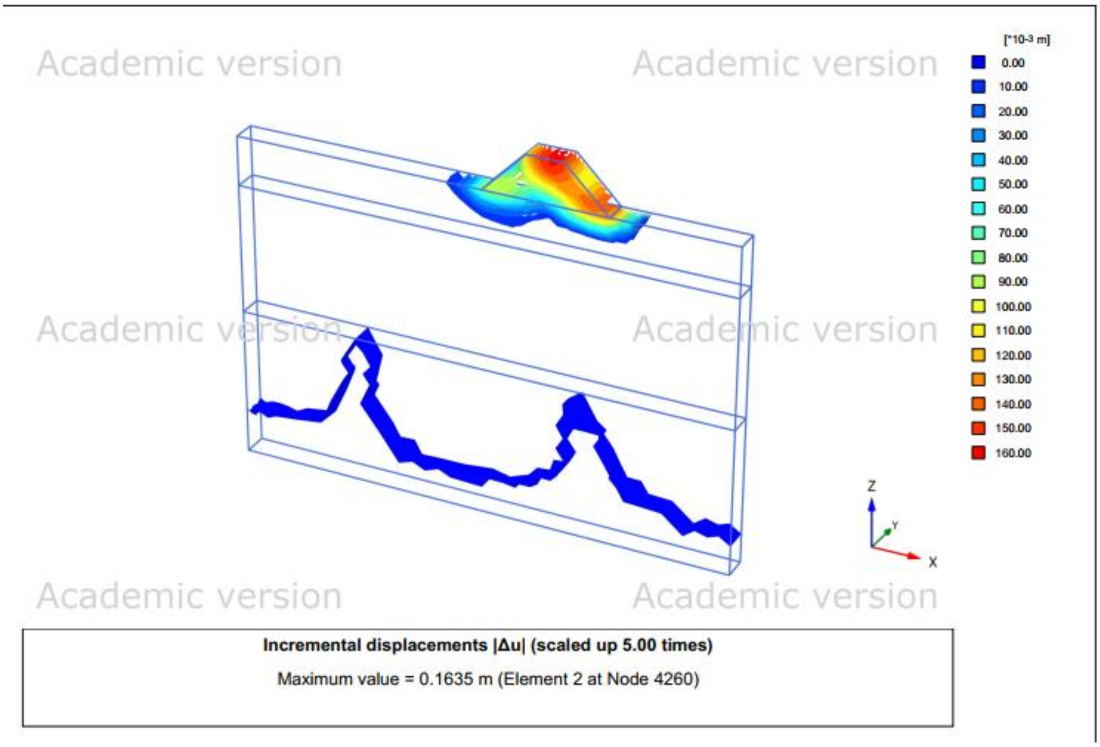


Consolidation Factor of Safety of Satkhira Polder

Rapid Drawdown (7 Days)



Rapid Drawdown settlement of Satkhira Polder

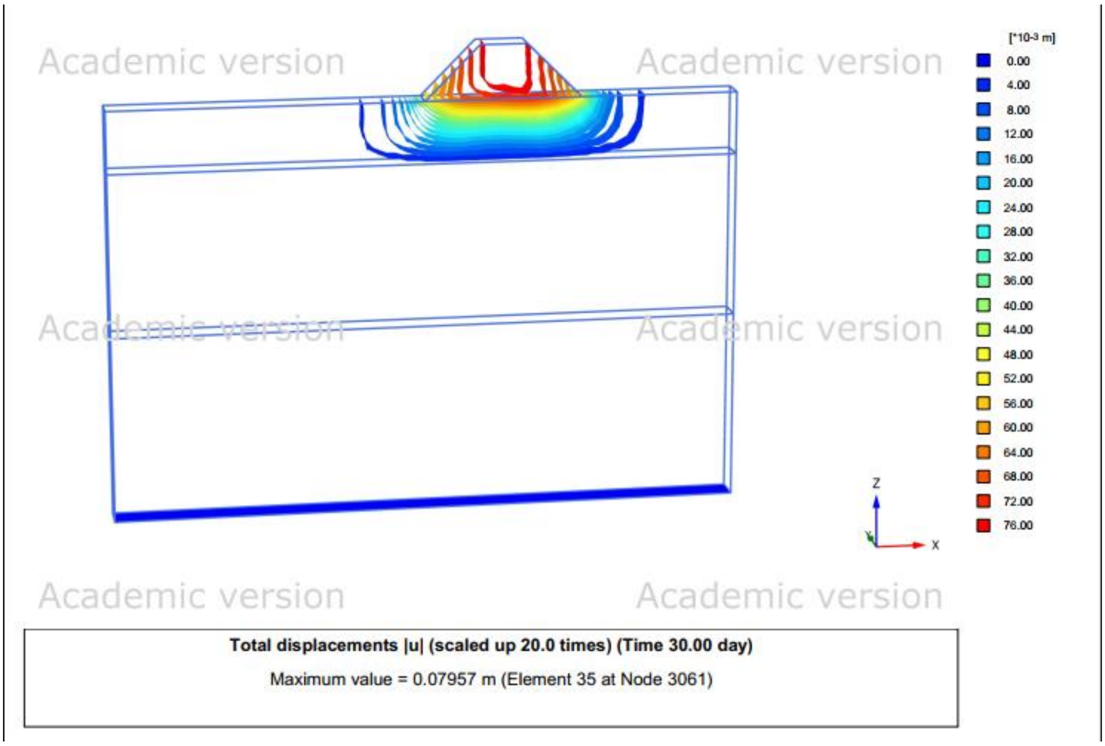


Incremental displacements |Δu| (scaled up 5.00 times)

Maximum value = 0.1635 m (Element 2 at Node 4260)

Likely failure mechanism for Rapid Drawdown condition of Satkhira Polder

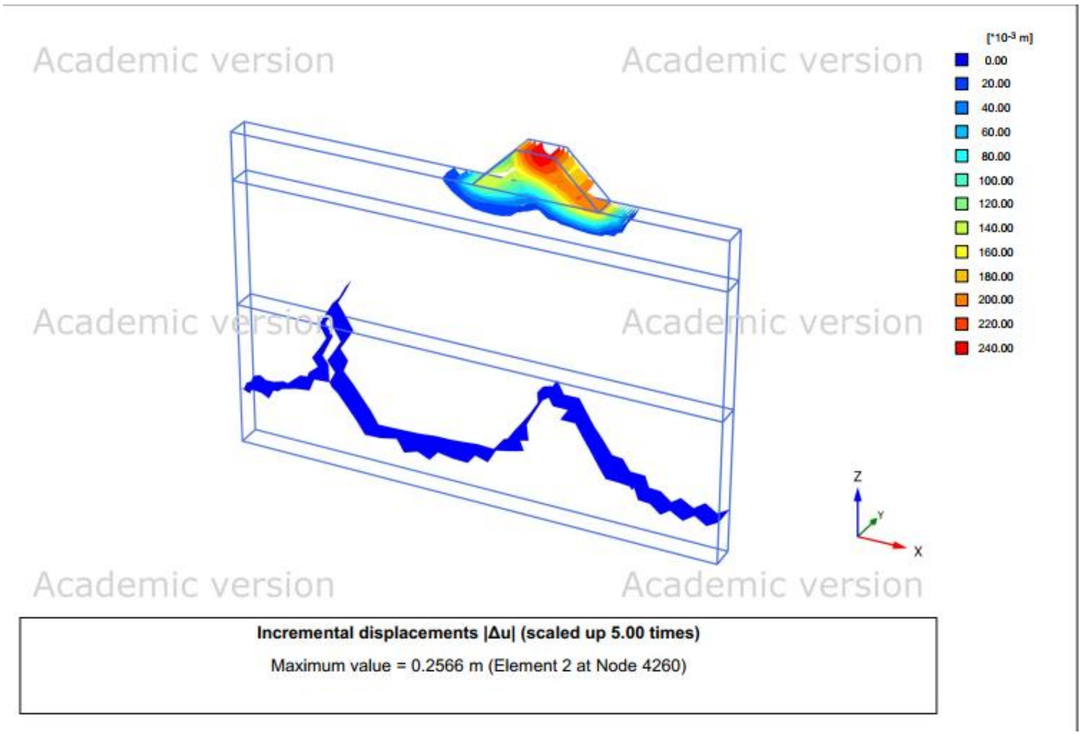
Slow Drawdown (30 Days)



Total displacements |u| (scaled up 20.0 times) (Time 30.00 day)

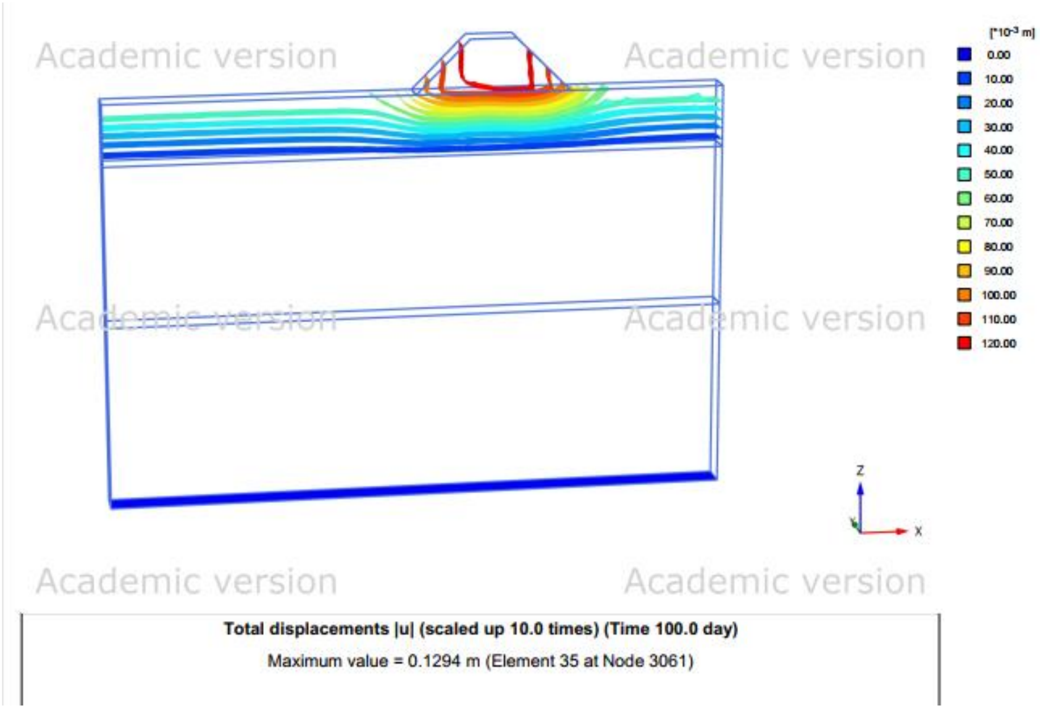
Maximum value = 0.07957 m (Element 35 at Node 3061)

Slow Drawdown settlement of Satkhira Polder

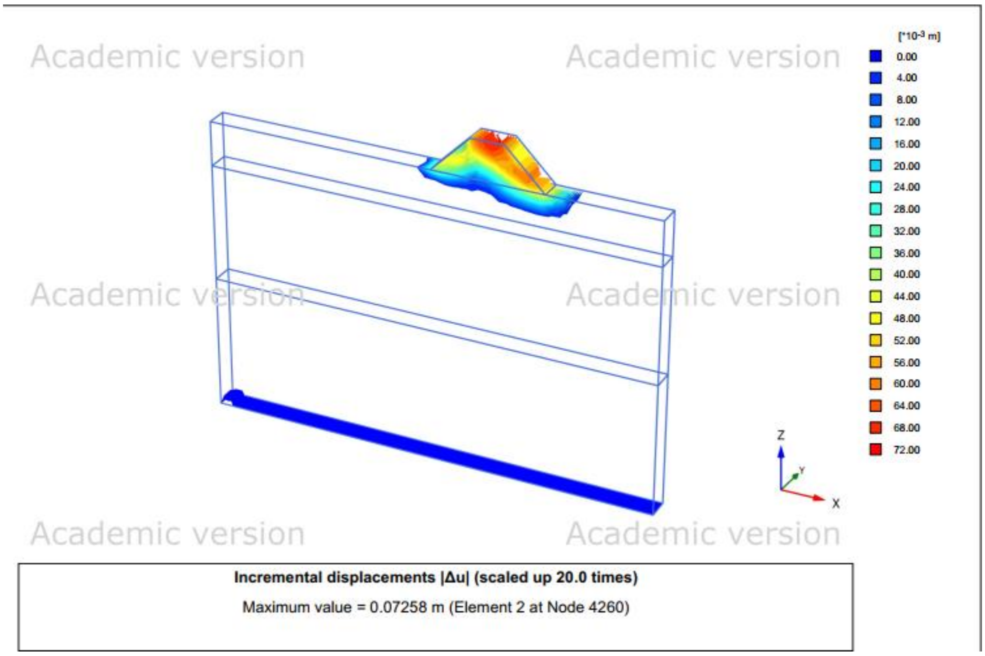


Slow Drawdown likely failure mechanism of Satkhira Polder

Change in water level (high level to borehole level) over time (100 days)

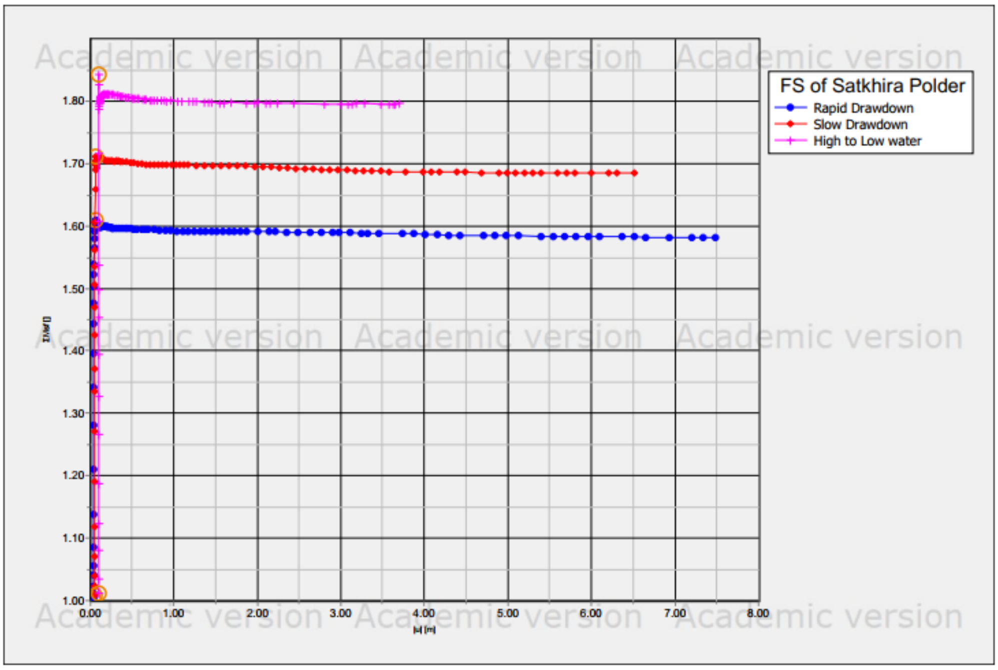


Change in water level (high level to borehole level) settlement of Satkhira Polder



Likely failure mechanism of change in water level (high level to borehole level) of Satkhira Polder

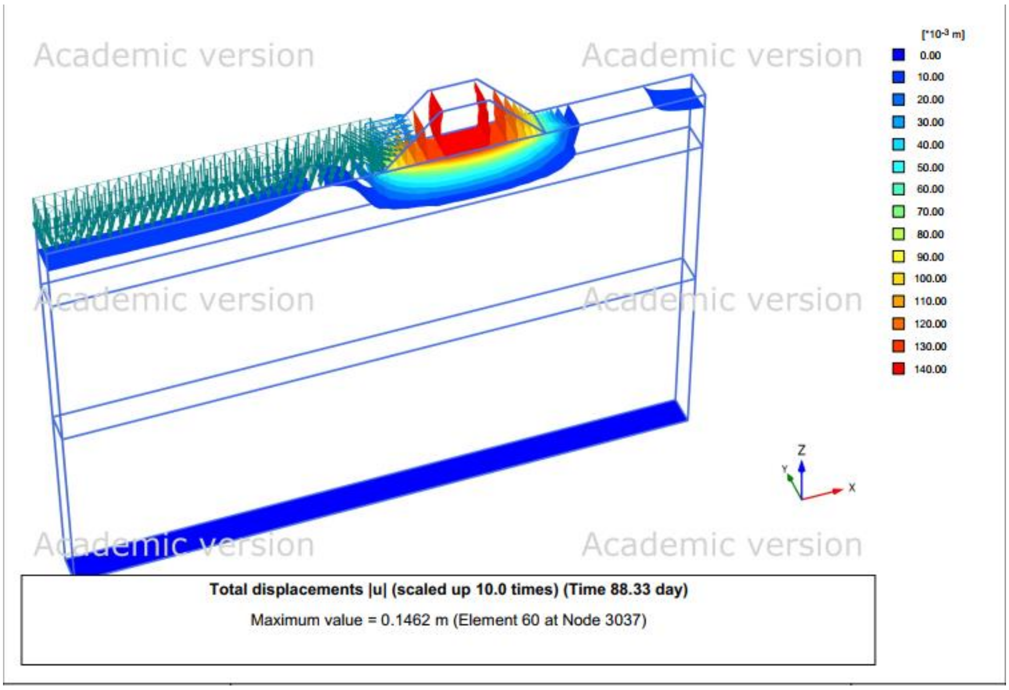
Factor of safety of Rapid Drawdown, Slow Drawdown, and change in water level (high level to borehole level) of Satkhira Polder



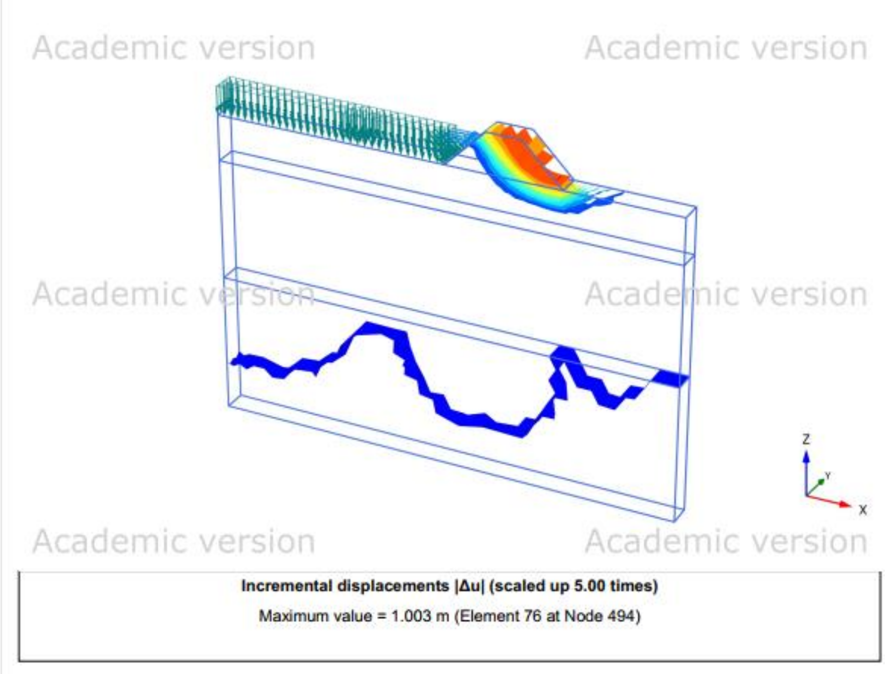
Factor of safety of Rapid Drawdown, Slow Drawdown, and change in water level (high level to borehole level) of Satkhira Polder.

Analysis result of Satkhira Polder against Cyclone SIDR

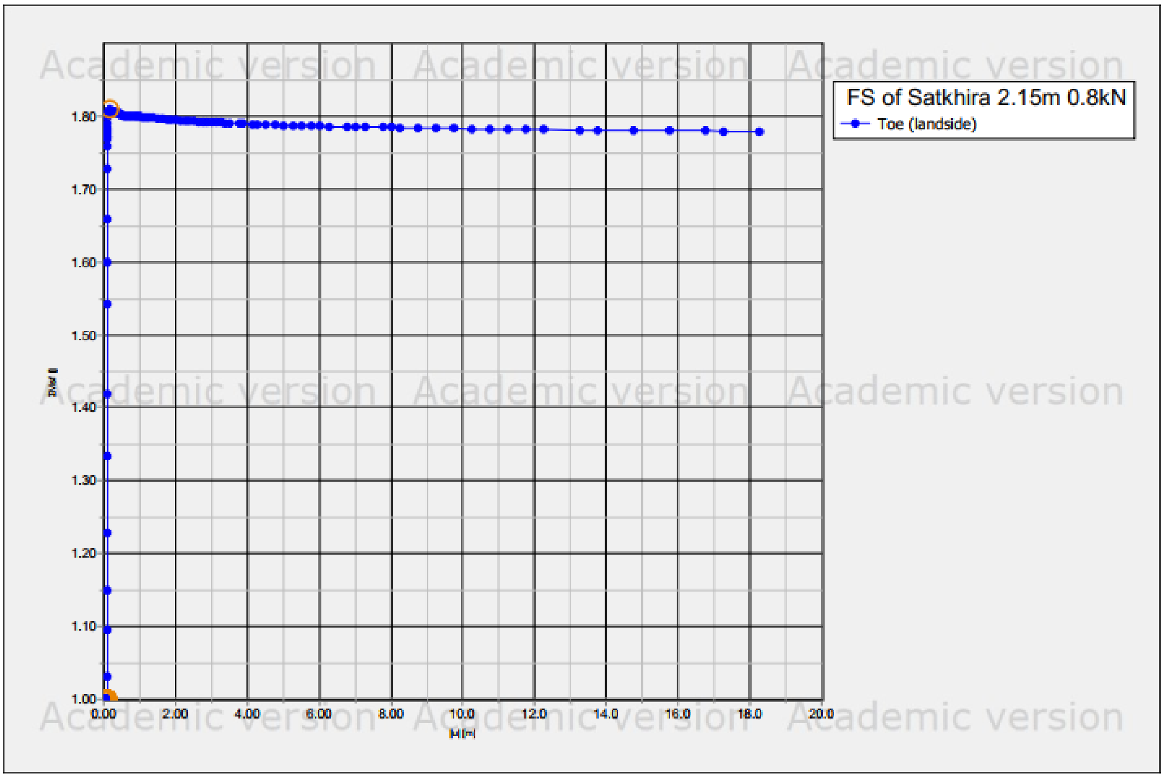
Surge height 0.8m and thrust force 2.15 kN



Total Settlement for Surge height 0.8m and thrust force 2.15 kN for Satkhira Polder

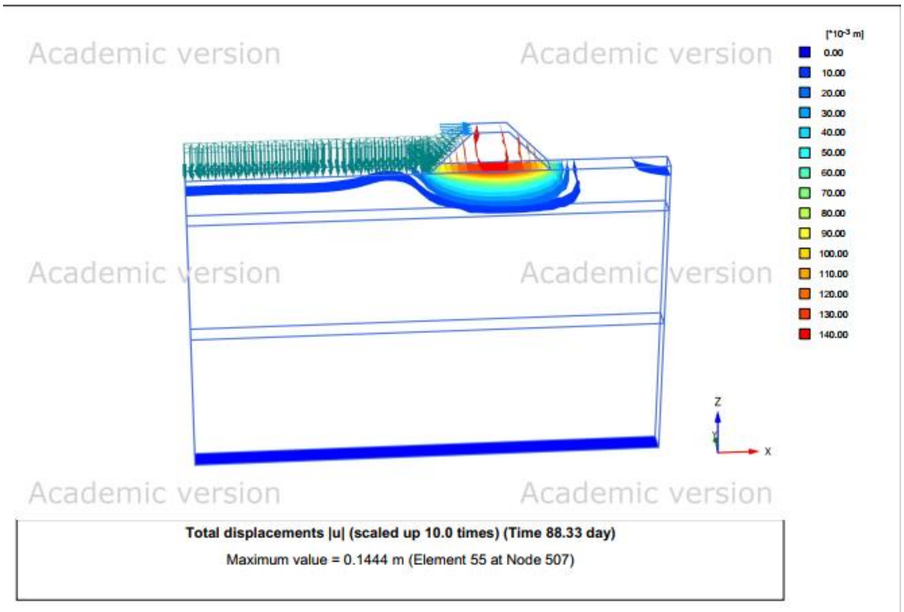


Likely Failure Mechanism for Surge height 0.8m and thrust force 2.15 kN for Satkhira Polder



Factor of safety for Surge height 0.8m and thrust force 2.15 kN for Satkhira Polder

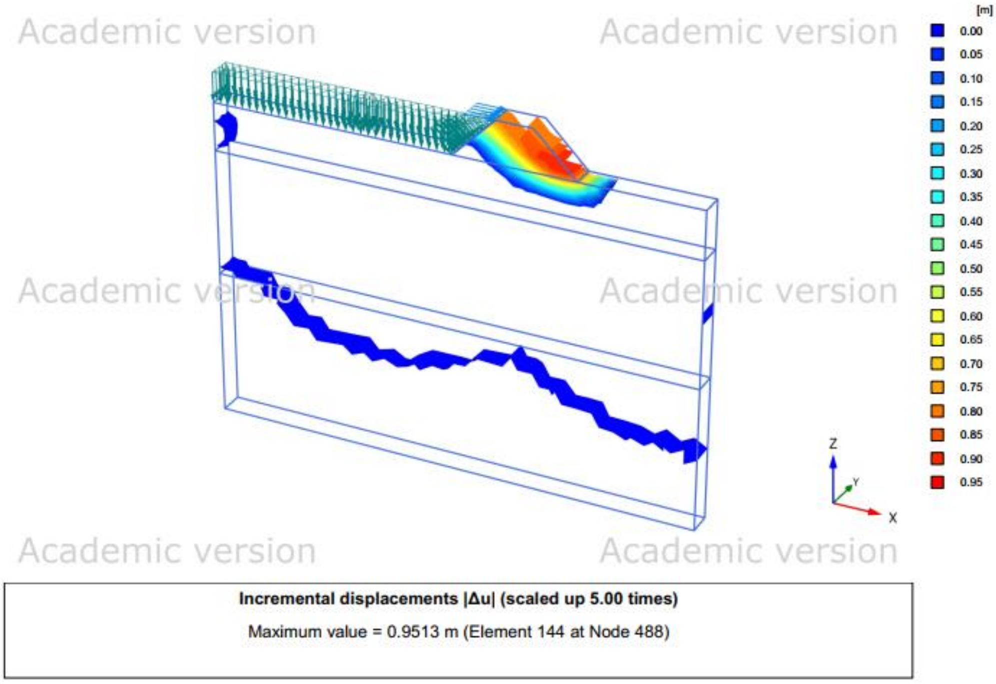
Surge height 3.3m and thrust force 3.5 kN



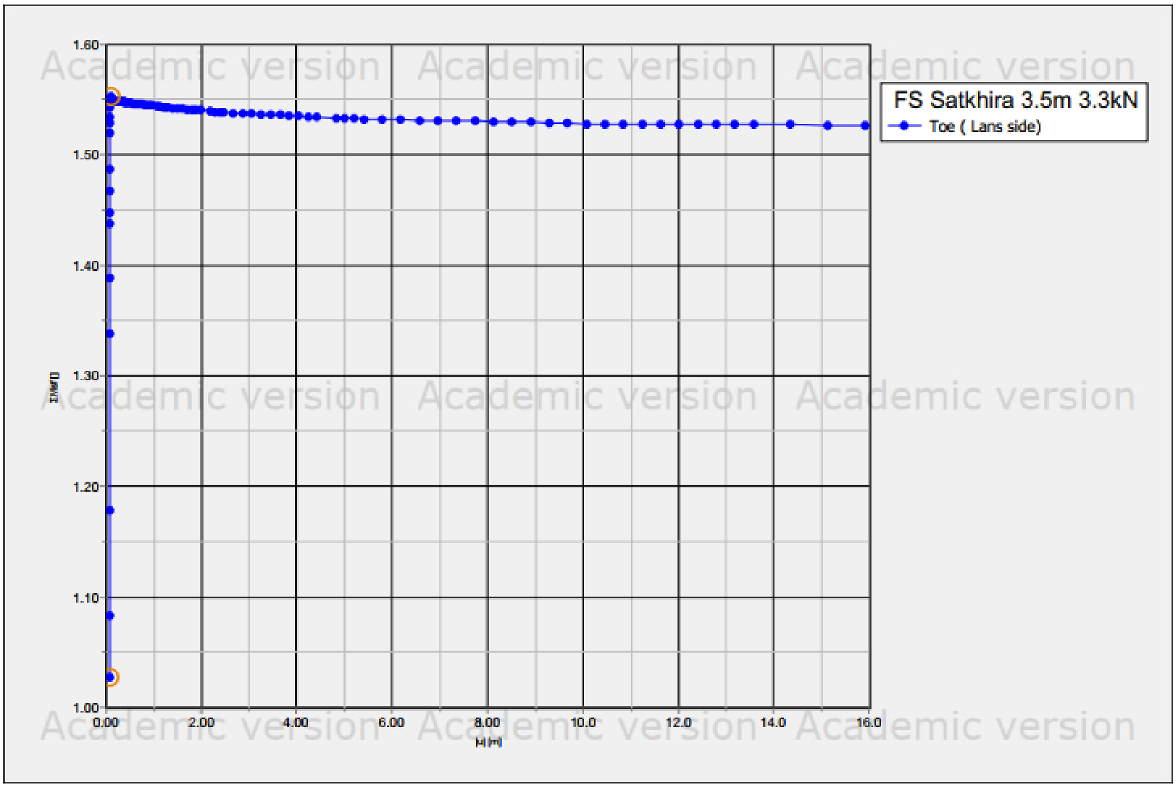
Total displacements |u| (scaled up 10.0 times) (Time 88.33 day)

Maximum value = 0.1444 m (Element 55 at Node 507)

Total Settlement for Surge height 3.3m and thrust force 3.5 kN for Satkhira Polder

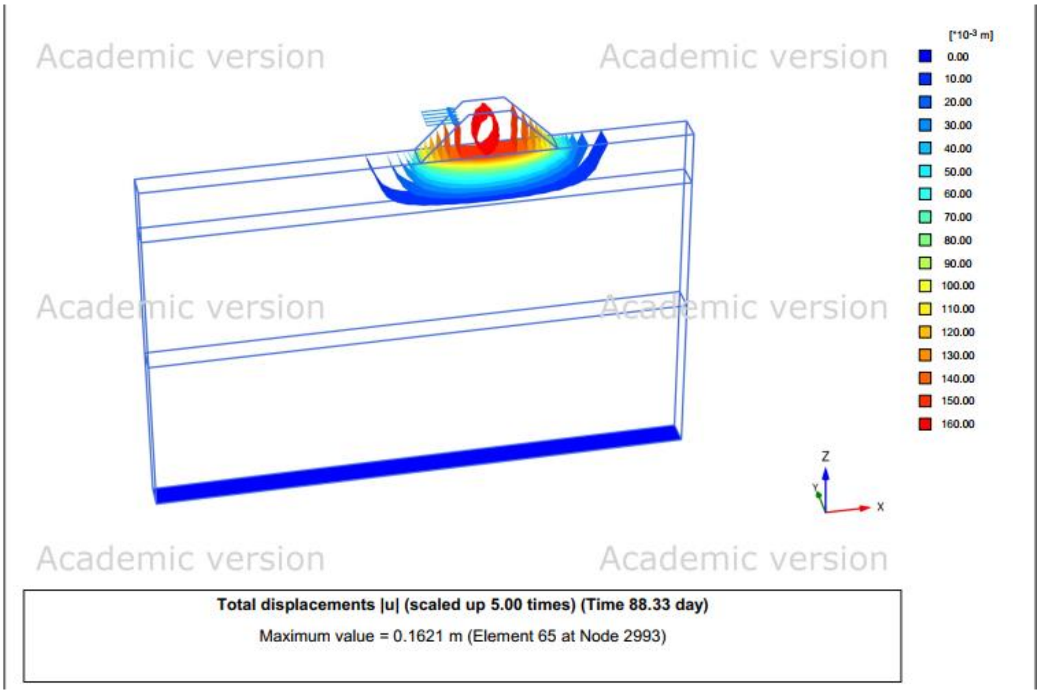


Likely Failure Mechanism for Surge height 3.3m and thrust force 3.5 kN for Satkhira Polder

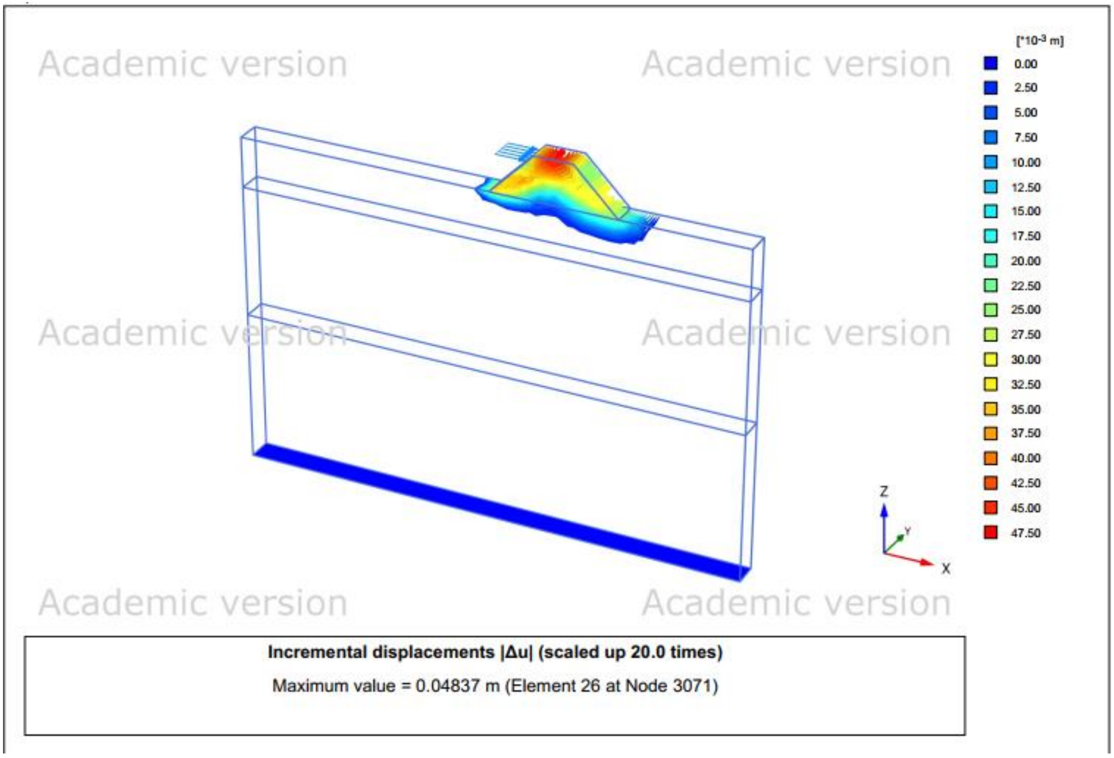


Factor of safety for Surge height 3.3m and thrust force 3.5 kN for Satkhira Polder

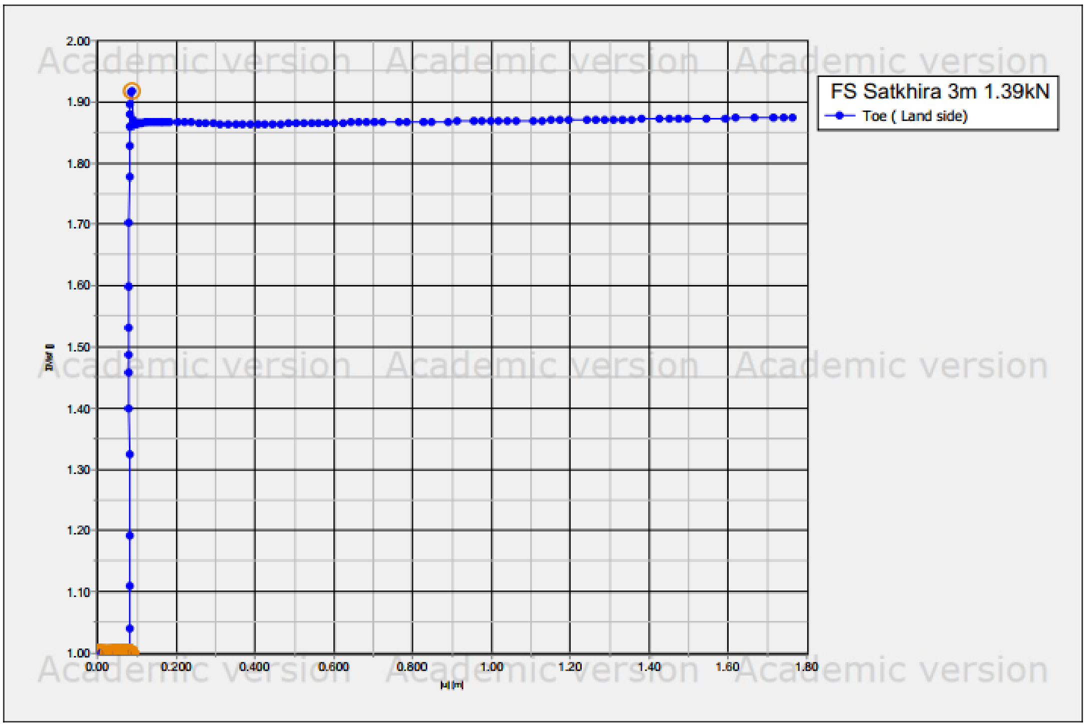
Surge height 3.0m and thrust force 1.39 kN



Total Settlement for Surge height 3.0m and thrust force 1.39 kN for Satkhira Polder



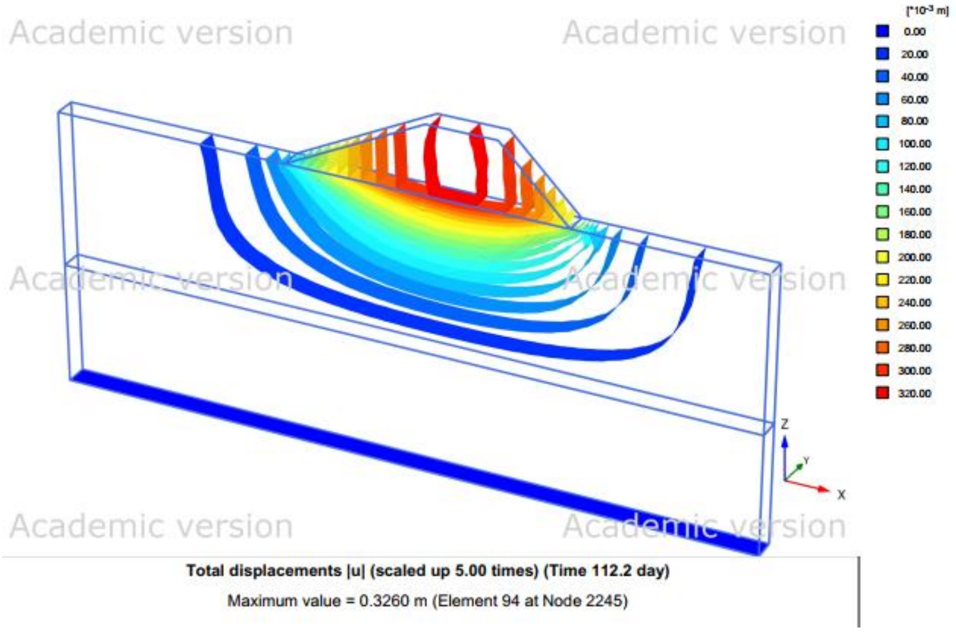
Likely Failure Mechanism for Surge height 3.0m and thrust force 1.39 kN for Satkhira Polder



Factor of safety for Surge height 3.0m and thrust force 1.39 kN for Satkhira Polder

Results of Barguna Polder analysis

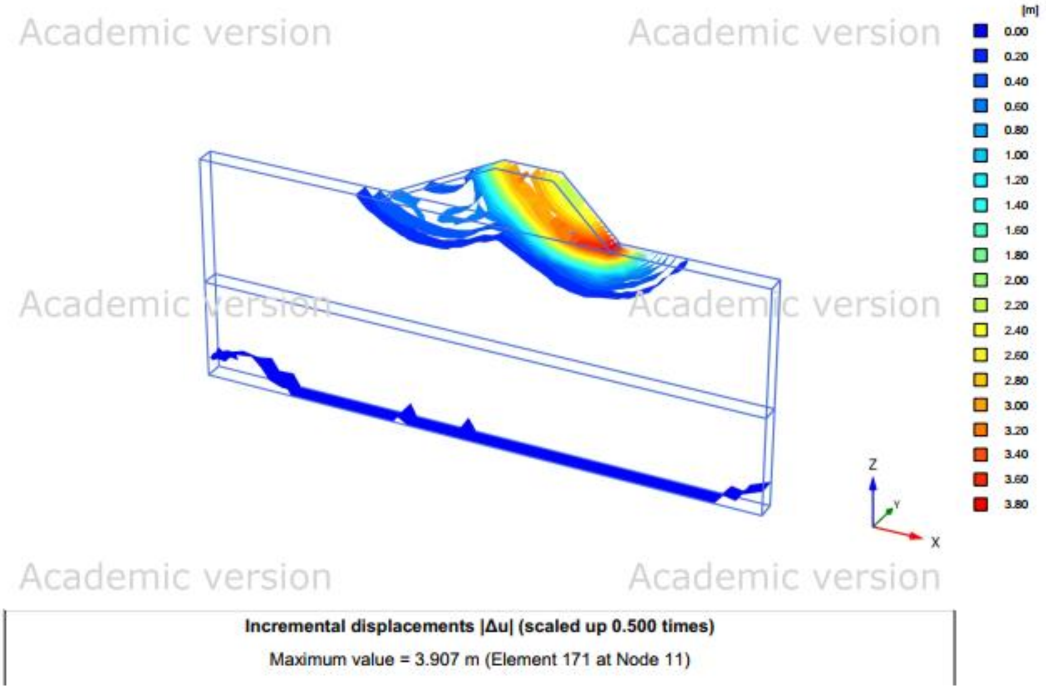
Consolidation Analysis



Total displacements |u| (scaled up 5.00 times) (Time 112.2 day)

Maximum value = 0.3260 m (Element 94 at Node 2245)

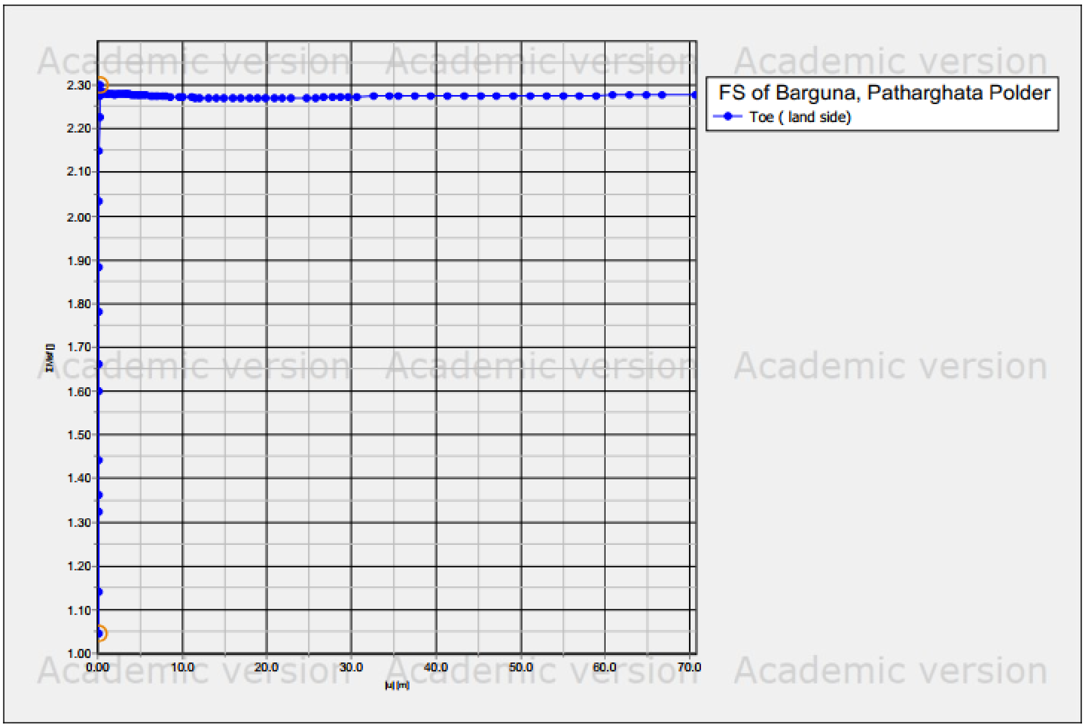
Consolidation settlement of Barguna Polder



Incremental displacements |Δu| (scaled up 0.500 times)

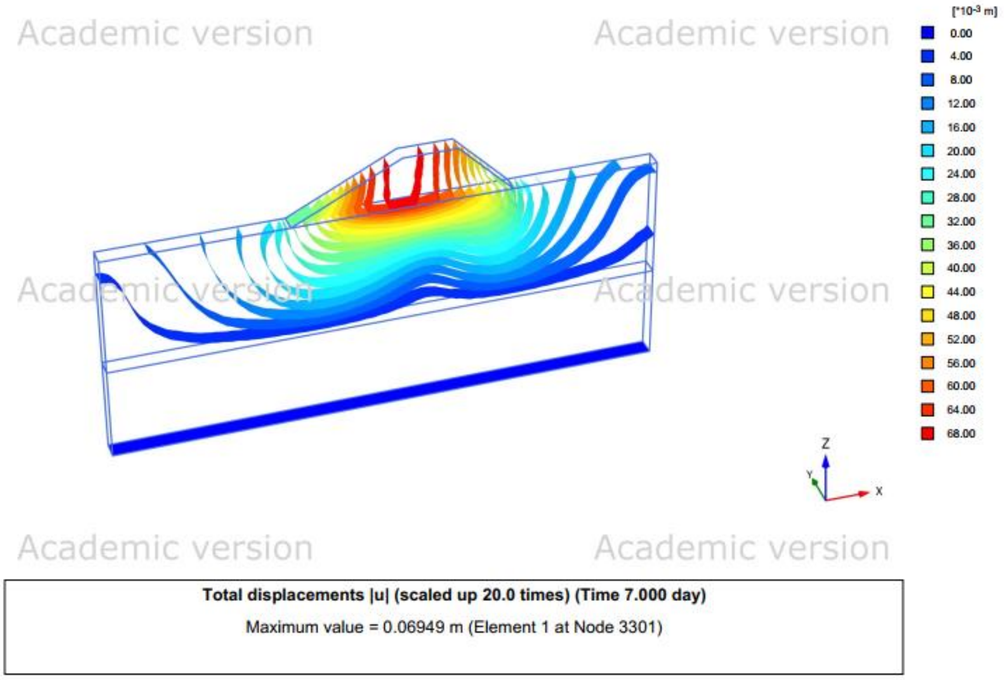
Maximum value = 3.907 m (Element 171 at Node 11)

Likely Failure Mechanism for Consolidation settlement of Barguna Polder



Consolidation Factor of Safety of Barguna Polder

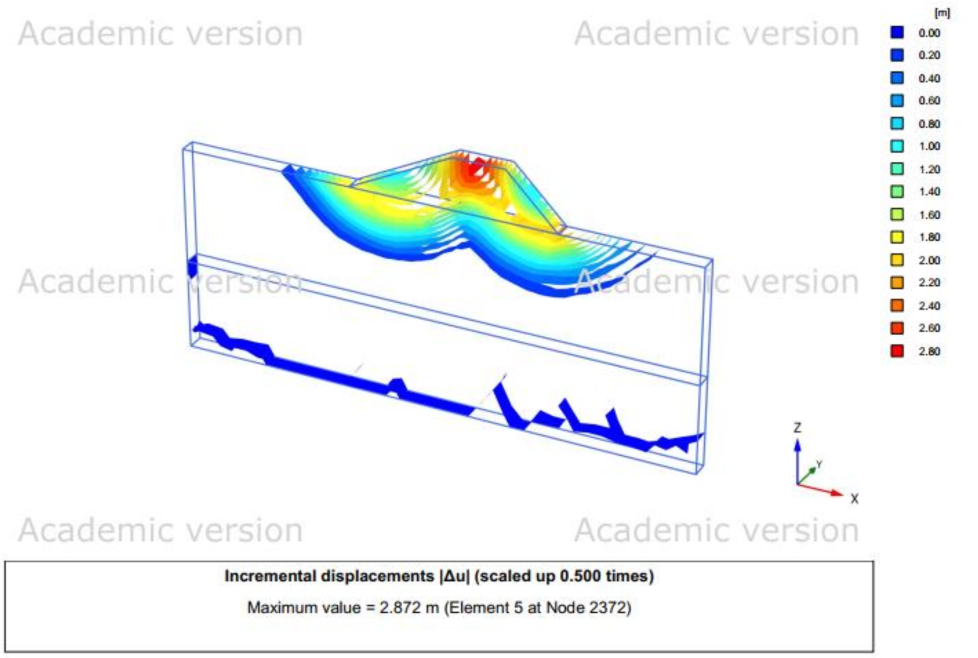
Rapid Drawdown (7 days)



Total displacements |u| (scaled up 20.0 times) (Time 7.000 day)

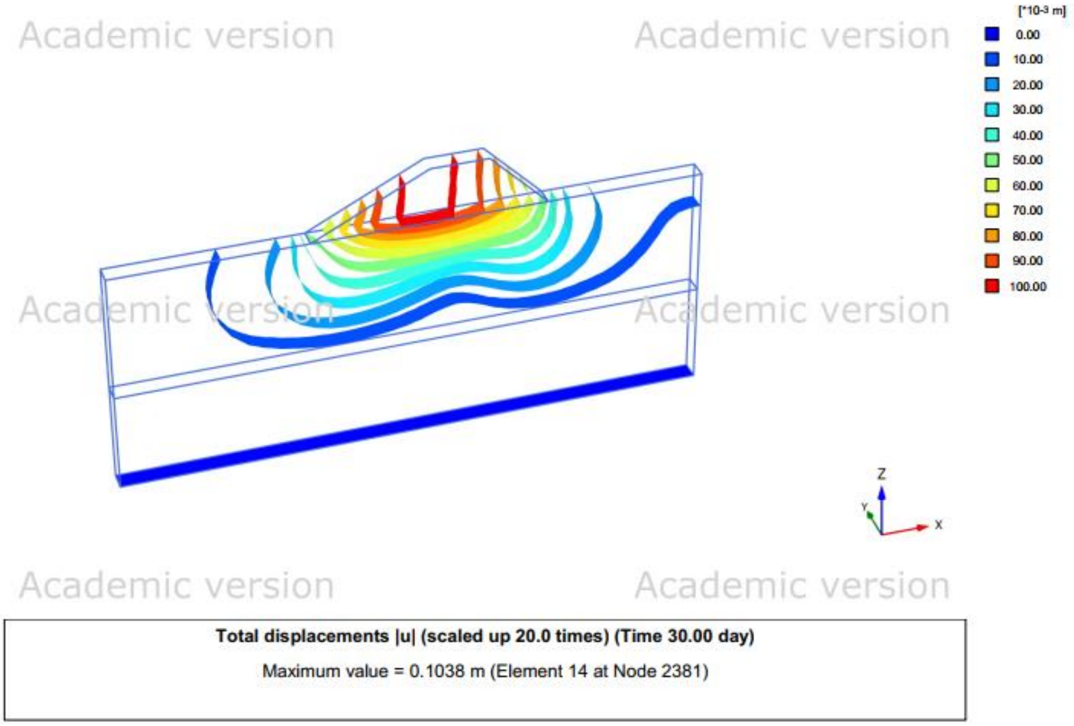
Maximum value = 0.06949 m (Element 1 at Node 3301)

Rapid Drawdown settlement of Barguna Polder

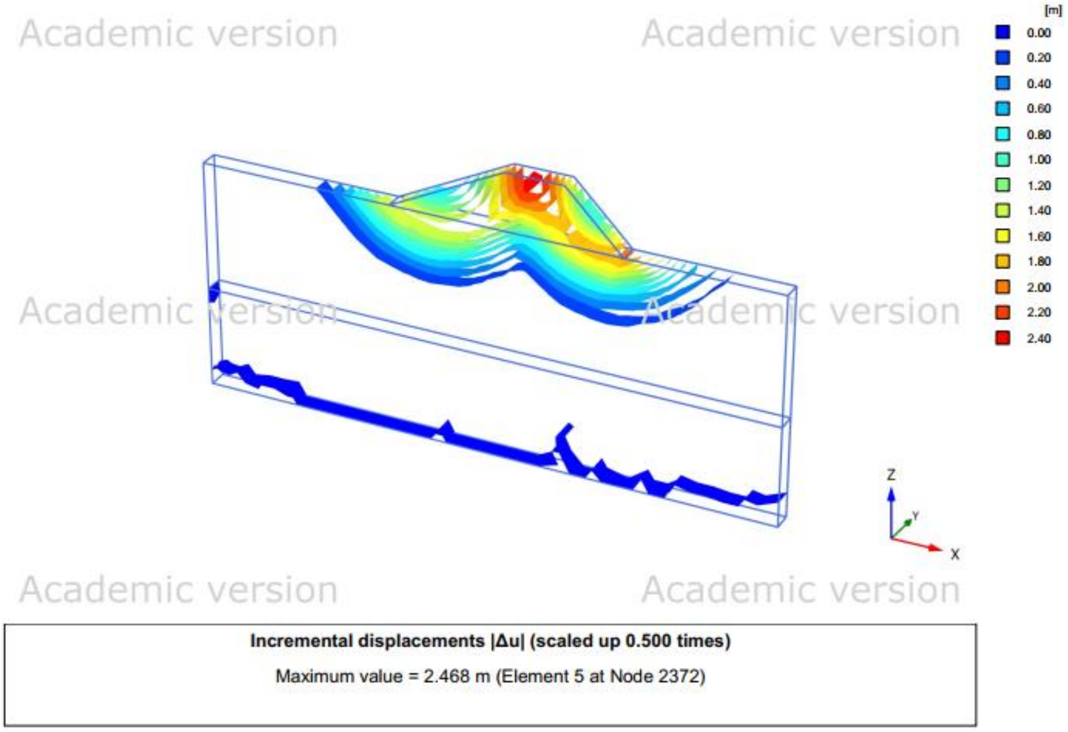


Likely failure mechanism for Rapid Drawdown condition of Barguna Polder

Slow Drawdown (30 days)



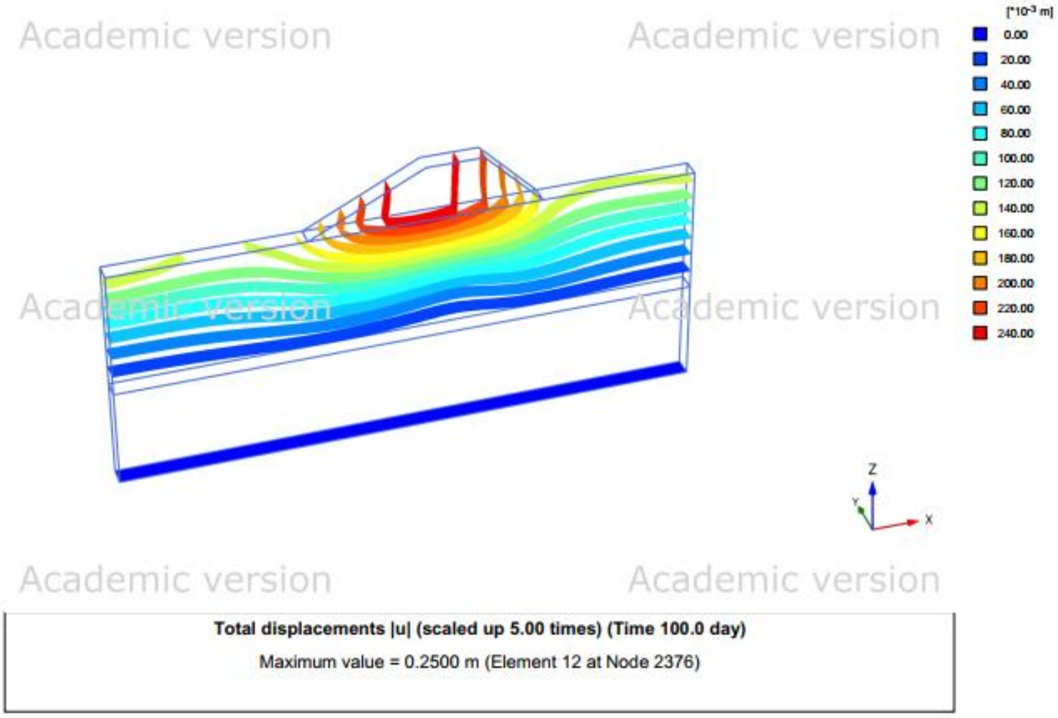
Slow Drawdown settlement of Barguna Polder



Incremental displacements |Δu| (scaled up 0.500 times)

Maximum value = 2.468 m (Element 5 at Node 2372)

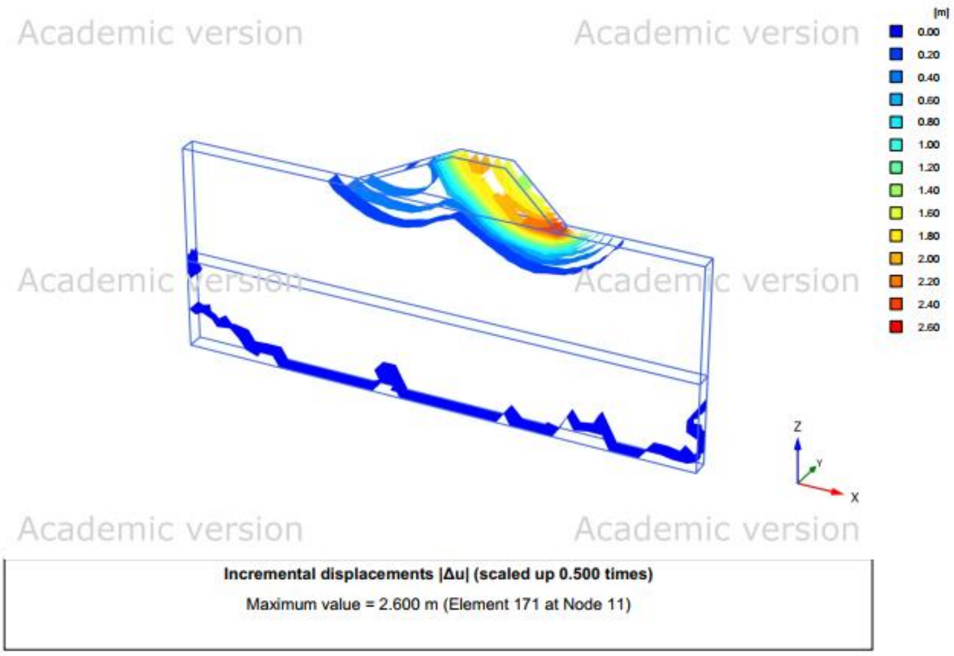
Slow Drawdown likely failure mechanism of Barguna Polder



Total displacements |u| (scaled up 5.00 times) (Time 100.0 day)

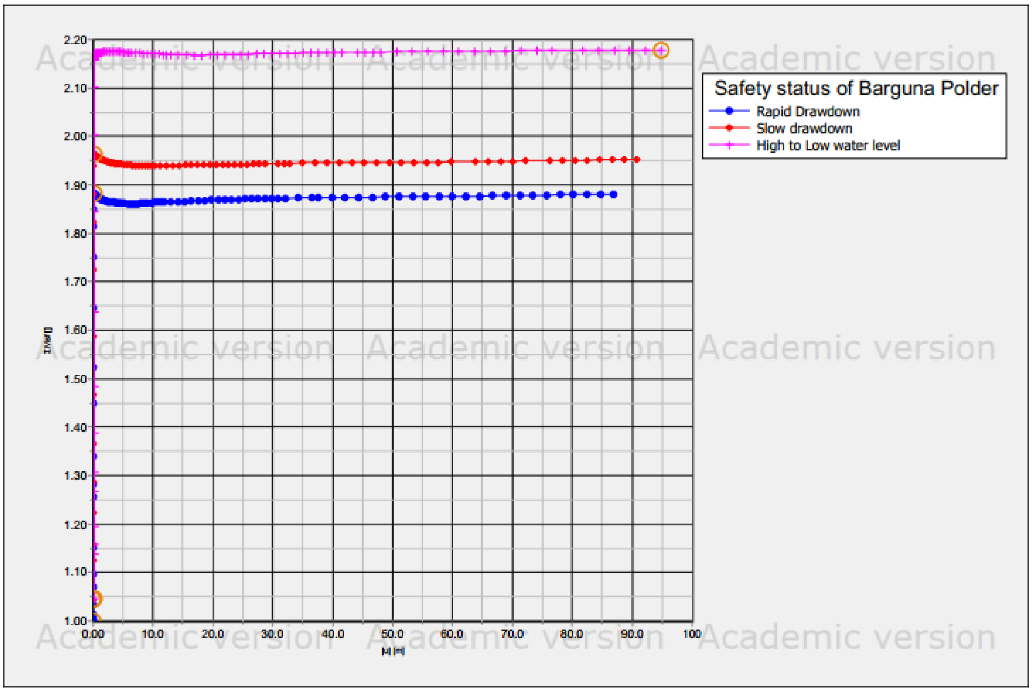
Maximum value = 0.2500 m (Element 12 at Node 2376)

Change in water level (high level to borehole level) settlement of Barguna Polder



Likely failure mechanism of change in water level (high level to borehole level) of Barguna Polder

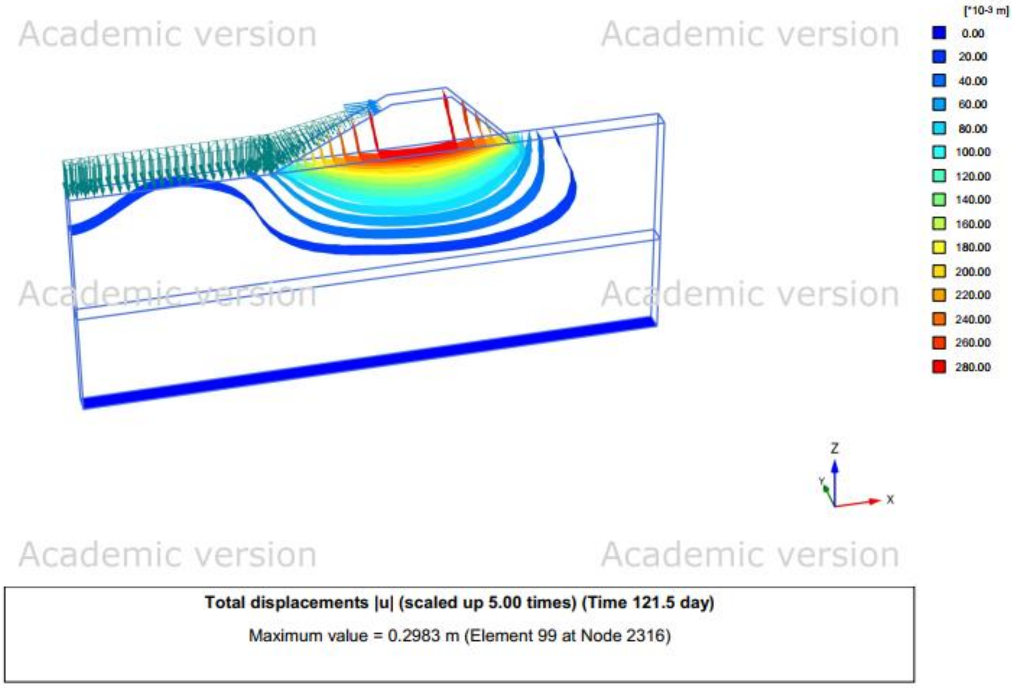
Factor of safety of Rapid Drawdown, Slow Drawdown, and change in water level (high level to borehole level) of Barguna Polder



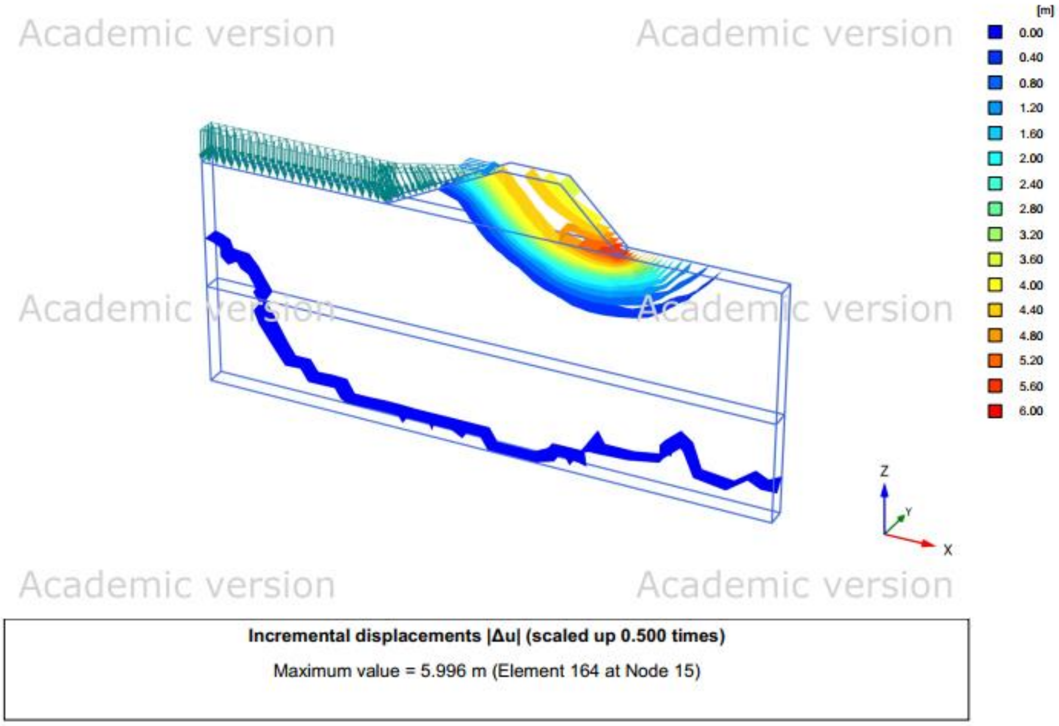
Factor of safety of Rapid Drawdown, Slow Drawdown, and change in water level (high level to borehole level) of Barguna Polder.

Analysis of Barguna Polder against Cyclone SIDR

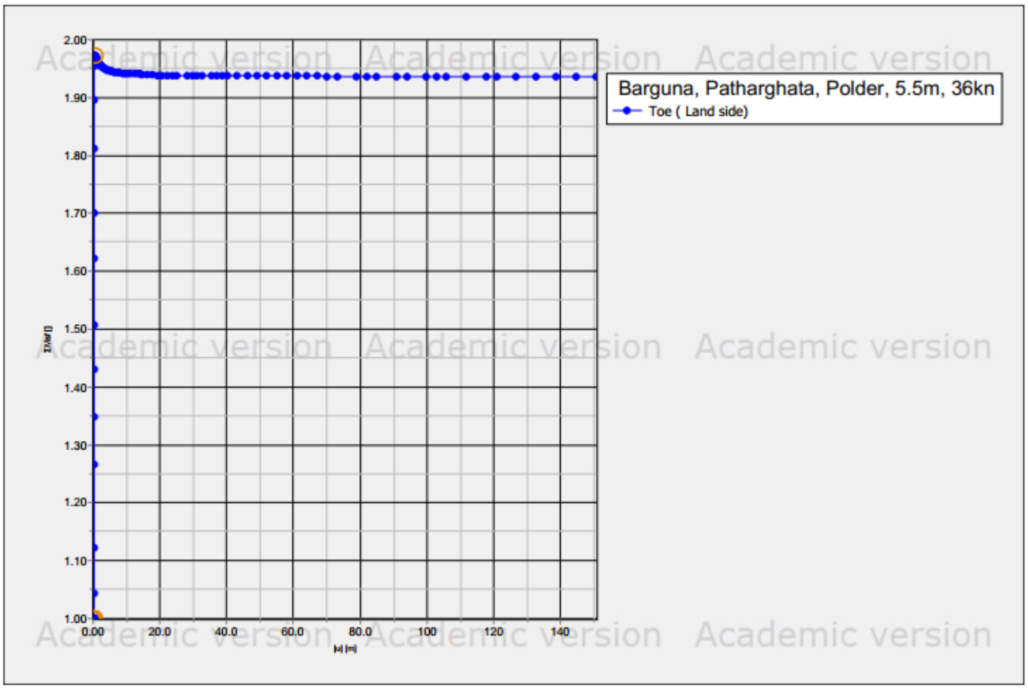
Surge height 5.5 m and thrust force 36kN



Total settlement for Surge height 5.5 m and thrust force 36kN for Barguna Polder

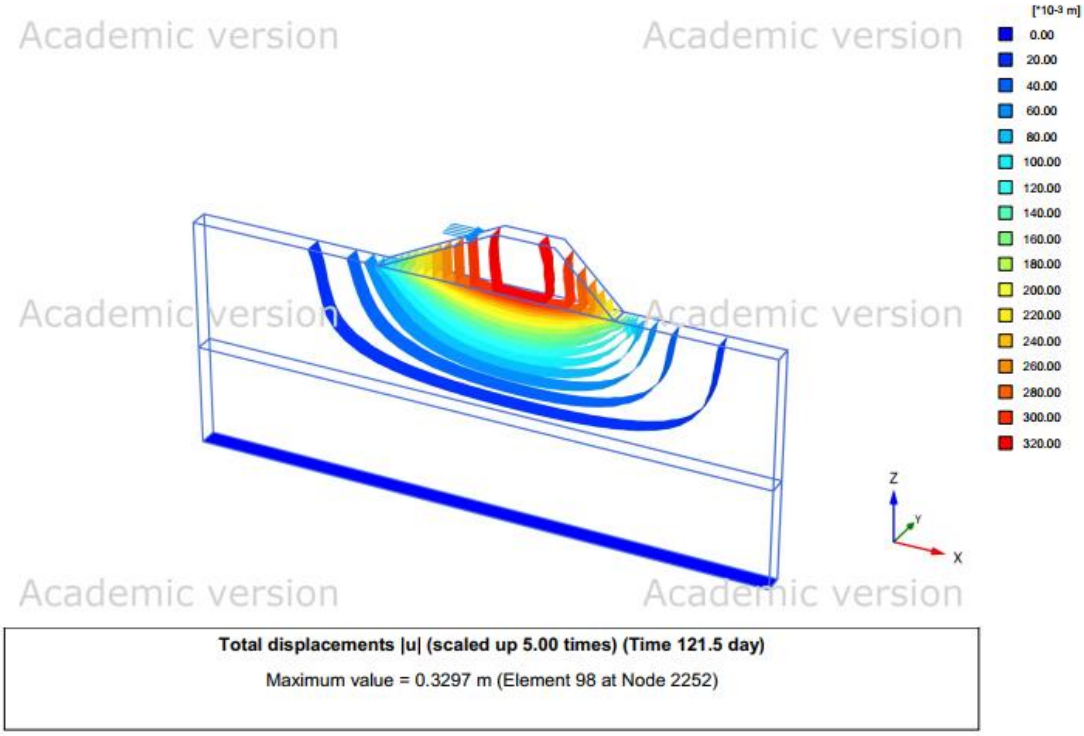


Failure pattern for Surge height 5.5 m and thrust force 36 kN for Barguna Polder



Factor of safety of Barguna Polder against Surge height 5.5 m and thrust force 36kN

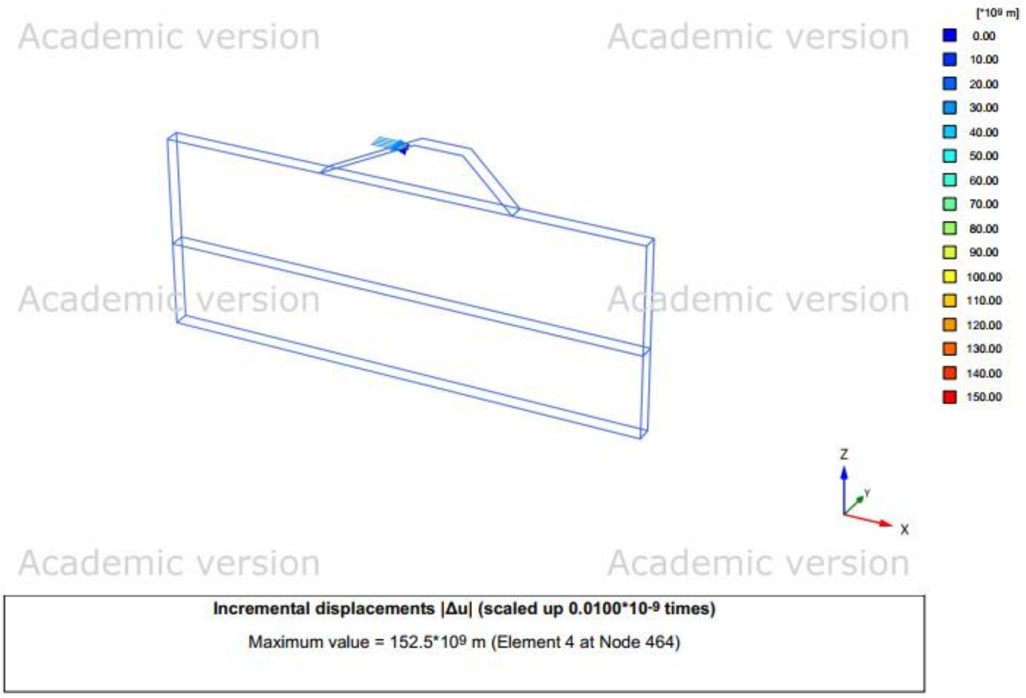
Surge height 5.0 m and thrust force 70kN



Total displacements |u| (scaled up 5.00 times) (Time 121.5 day)

Maximum value = 0.3297 m (Element 98 at Node 2252)

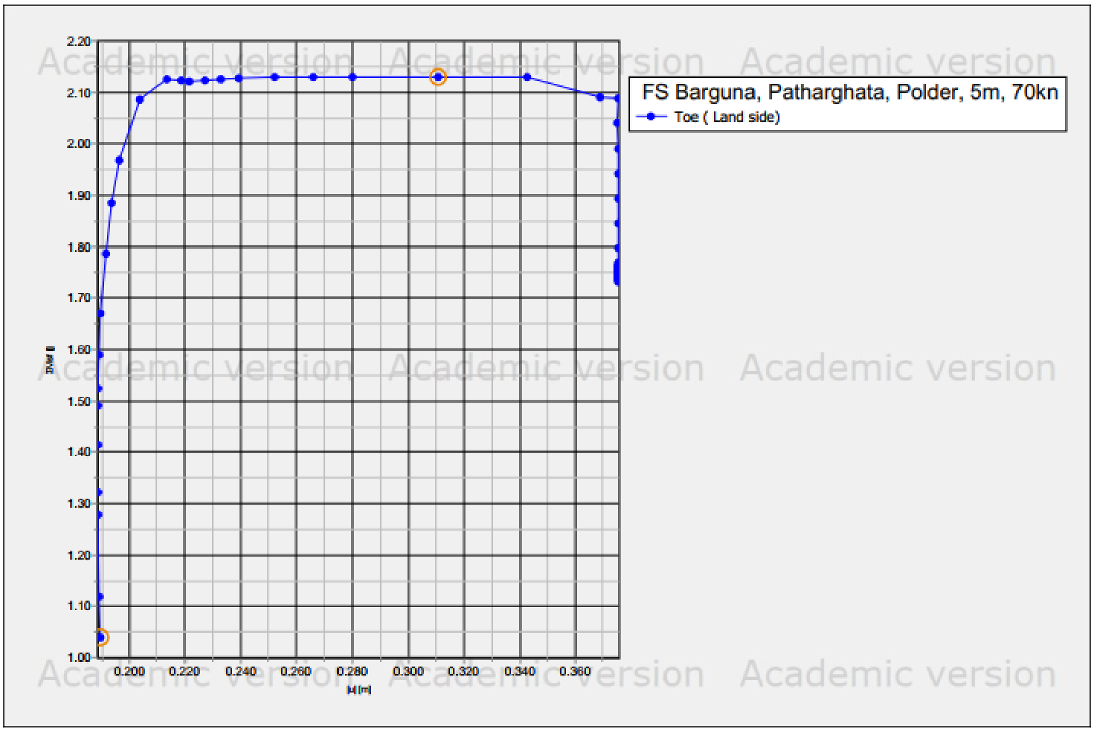
Total settlement for Surge height 5.0 m and thrust force 70kN for Barguna Polder



Incremental displacements |Δu| (scaled up 0.0100*10⁻⁹ times)

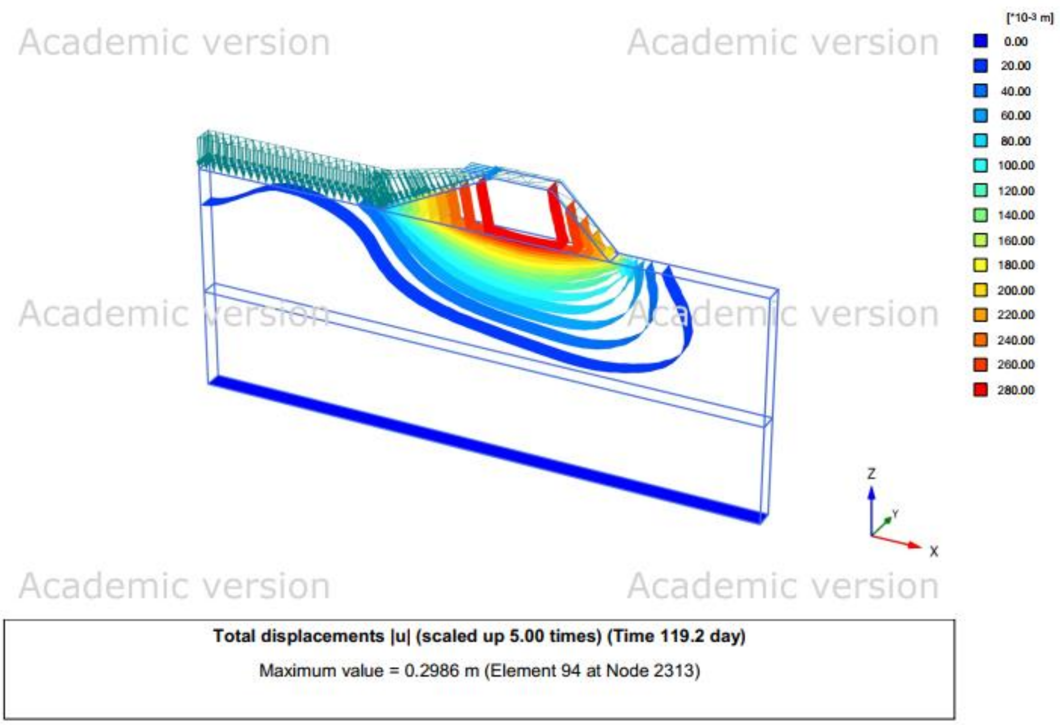
Maximum value = 152.5*10⁹ m (Element 4 at Node 464)

Failure pattern for Surge height 5.0 m and thrust force 70kN for Barguna Polder



Factor of safety of Barguna Polder against Surge height 5.0 m and thrust force 70 kN

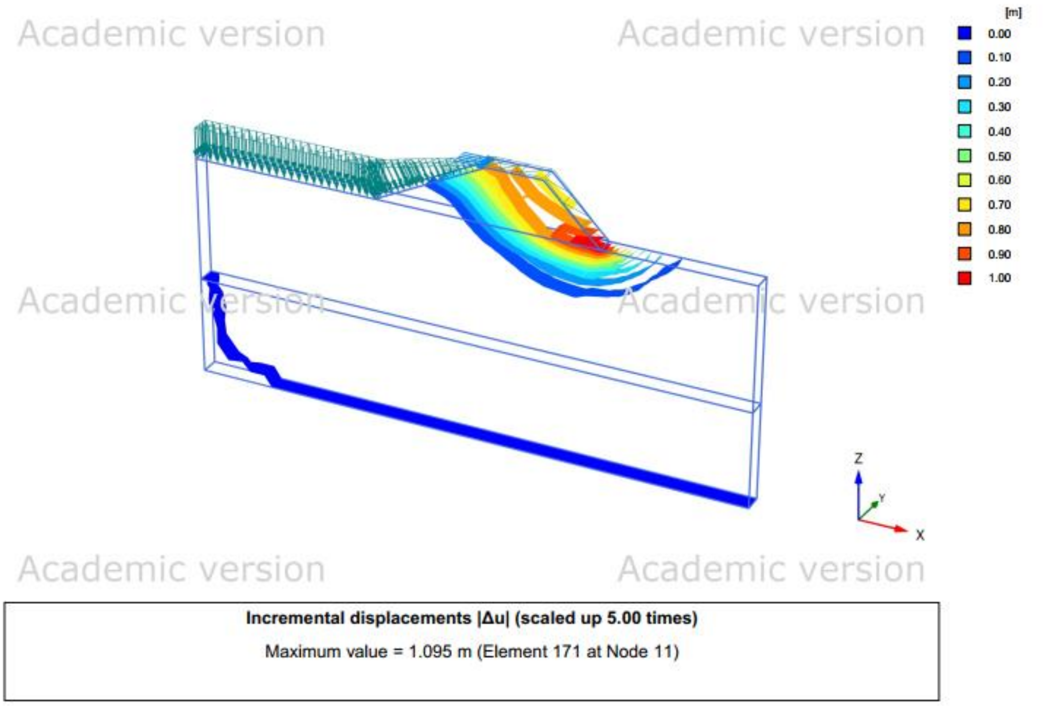
Surge height 6.5 m and thrust force 55kN



Total displacements |u| (scaled up 5.00 times) (Time 119.2 day)

Maximum value = 0.2986 m (Element 94 at Node 2313)

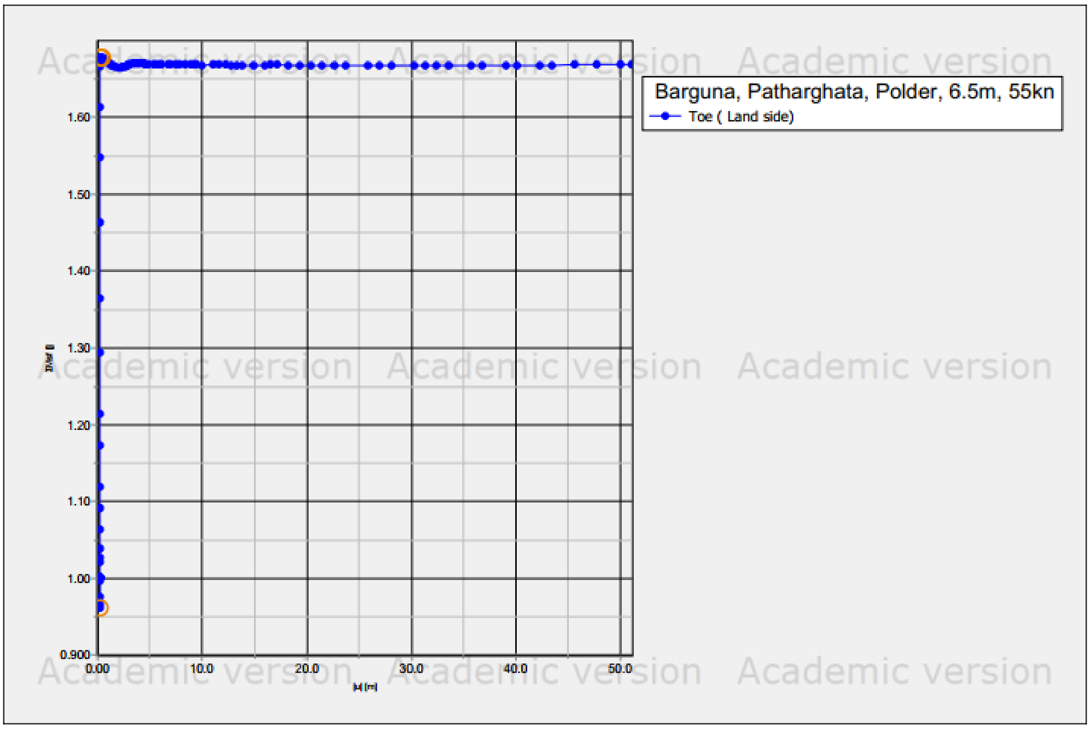
Total settlement for Surge height 6.5 m and thrust force 55kN for Barguna Polder



Incremental displacements |Δu| (scaled up 5.00 times)

Maximum value = 1.095 m (Element 171 at Node 11)

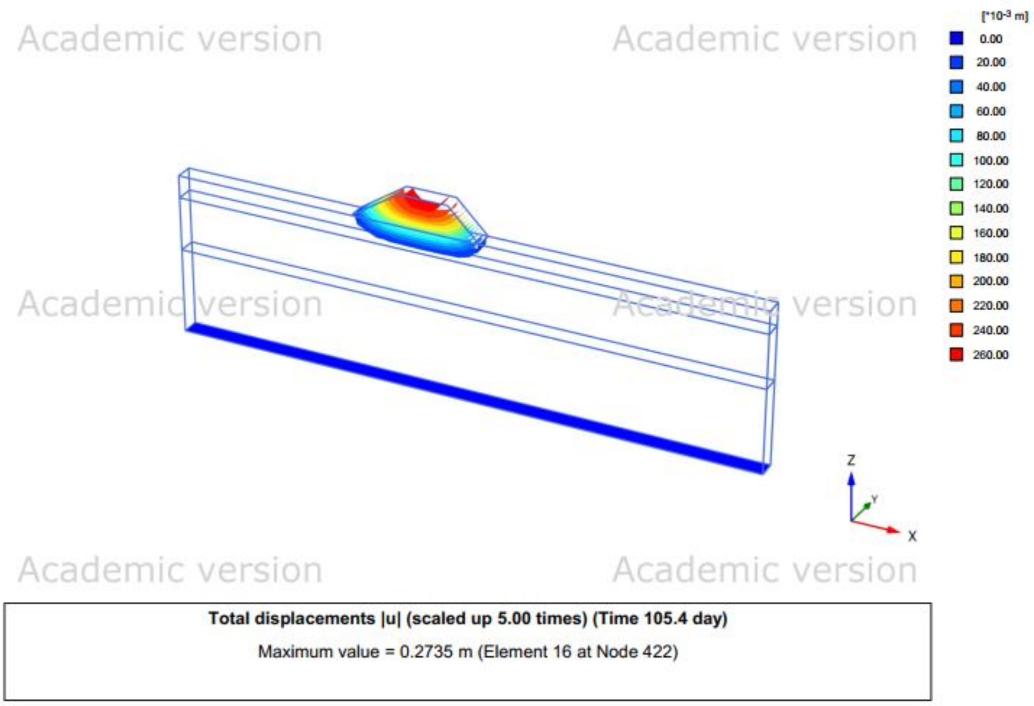
Failure pattern for Surge height 6.5 m and thrust force 55kN for Barguna Polder



Factor of safety of Barguna Polder against Surge height 6.5 m and thrust force 55 kN

Results of Noakhali Polder analysis

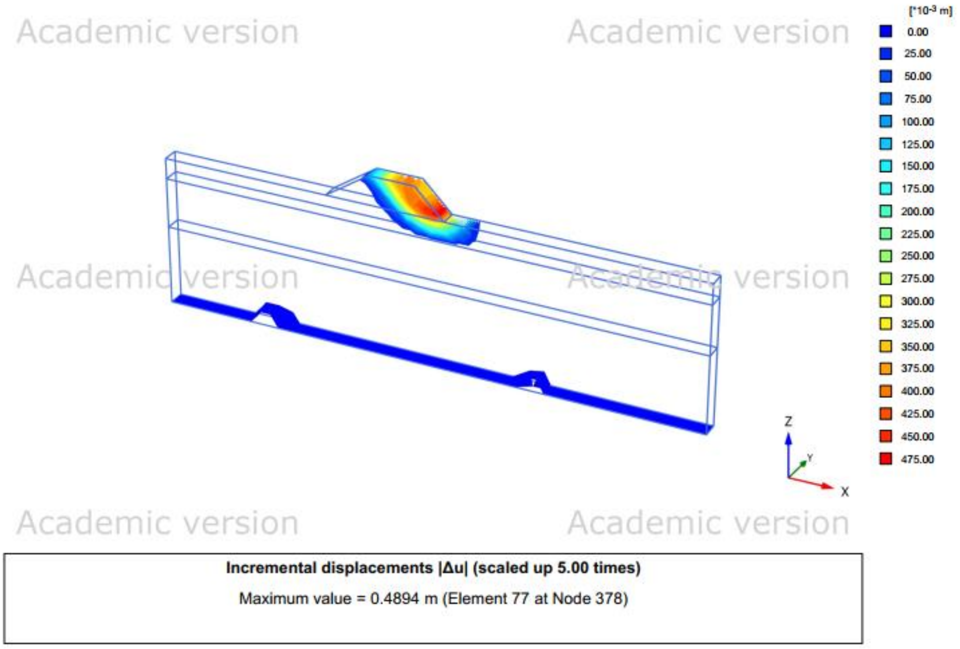
Consolidation Analysis



Total displacements |u| (scaled up 5.00 times) (Time 105.4 day)

Maximum value = 0.2735 m (Element 16 at Node 422)

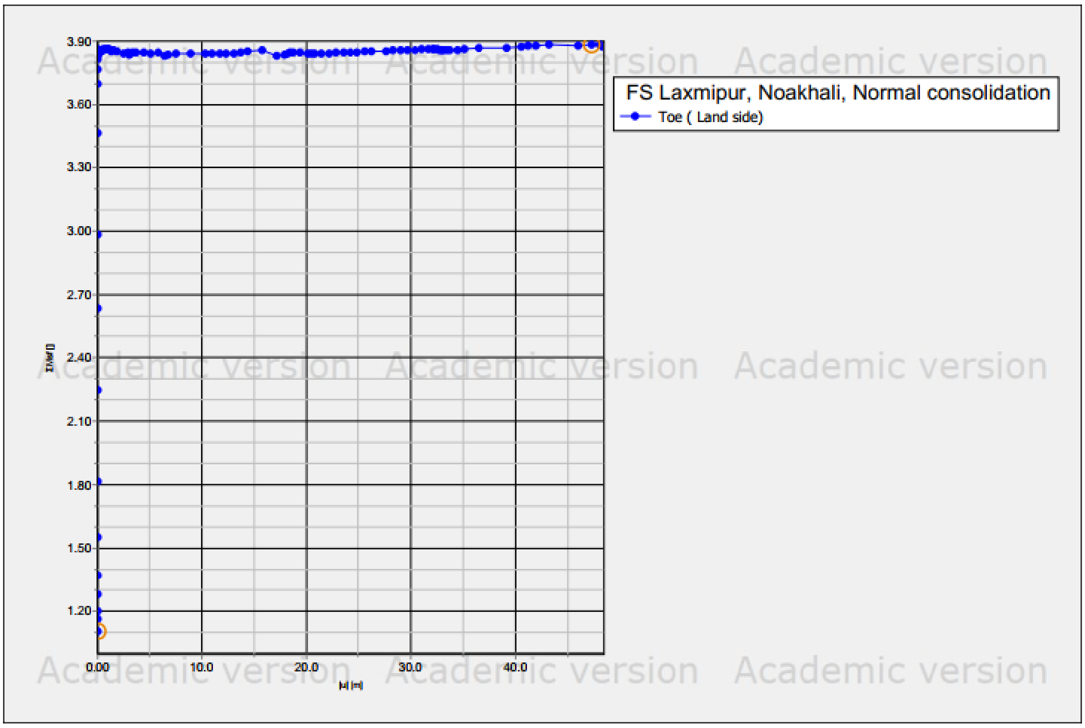
Consolidation settlement for Noakhali Polder



Incremental displacements |Δu| (scaled up 5.00 times)

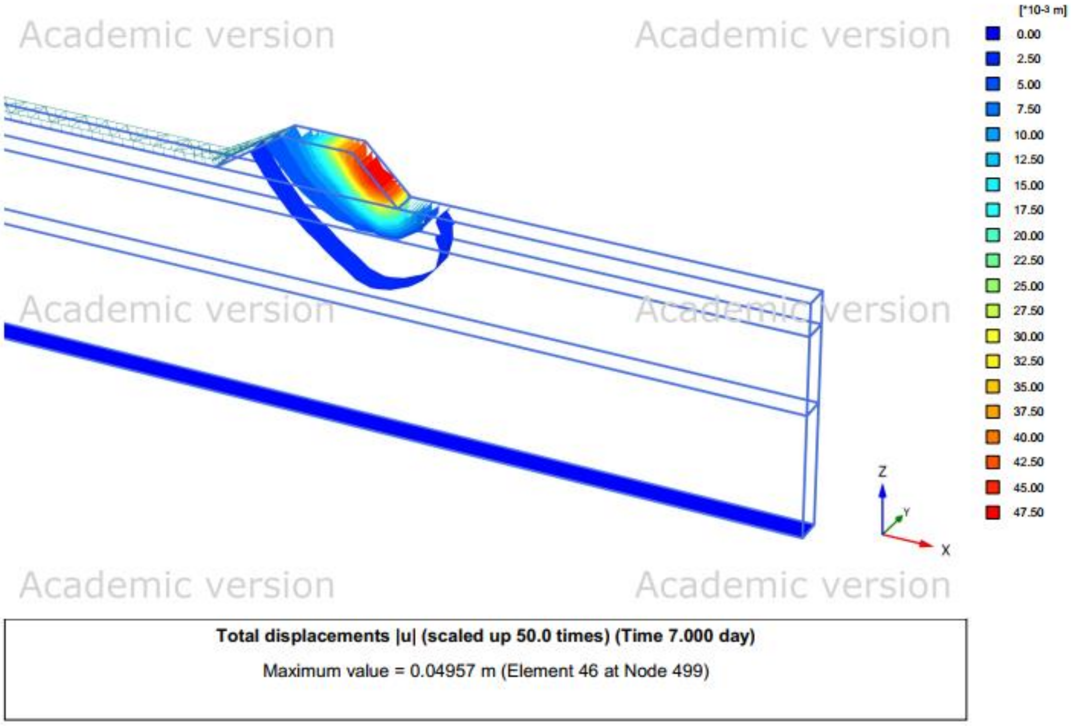
Maximum value = 0.4894 m (Element 77 at Node 378)

Likely Failure Mechanism for Consolidation settlement of Noakhali Polder



Consolidation Factor of Safety of Noakhali Polder

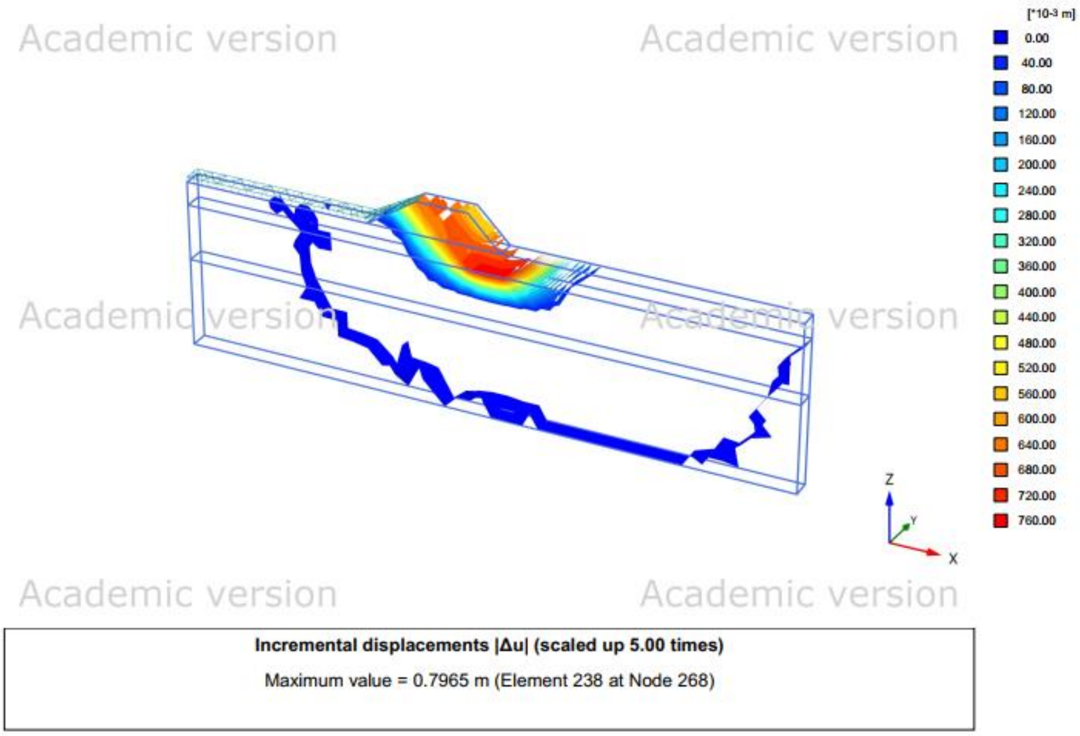
Rapid Drawdown (7 days)



Total displacements |u| (scaled up 50.0 times) (Time 7.000 day)

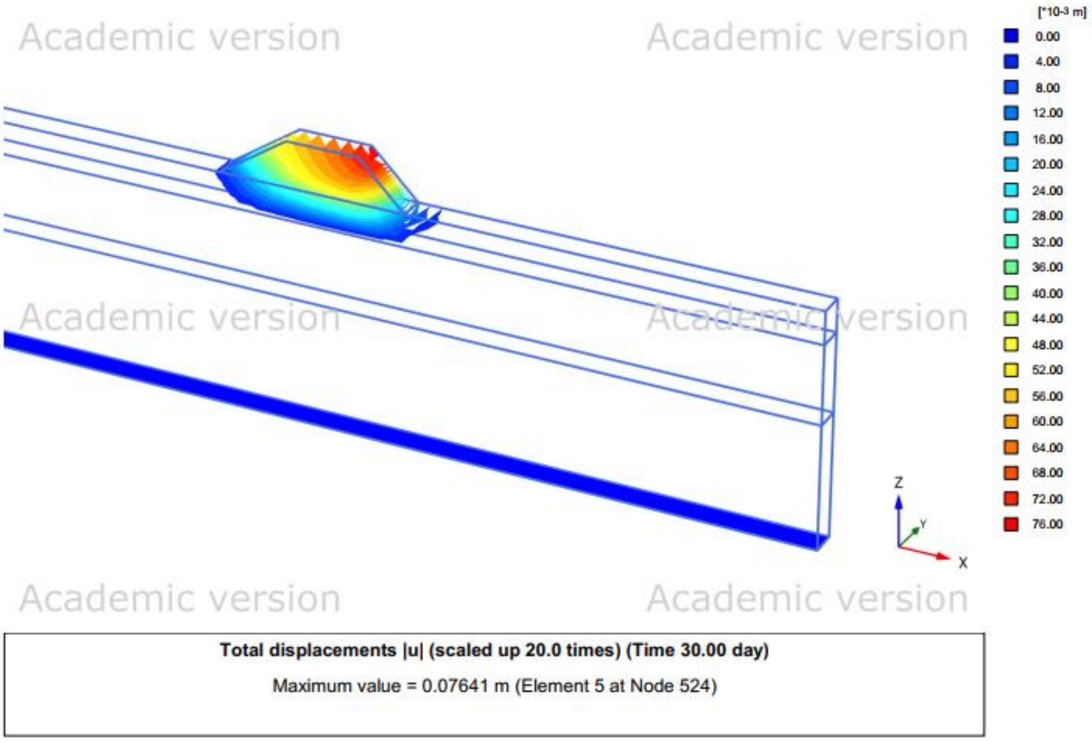
Maximum value = 0.04957 m (Element 46 at Node 499)

Rapid Drawdown settlement of Bhola Polder

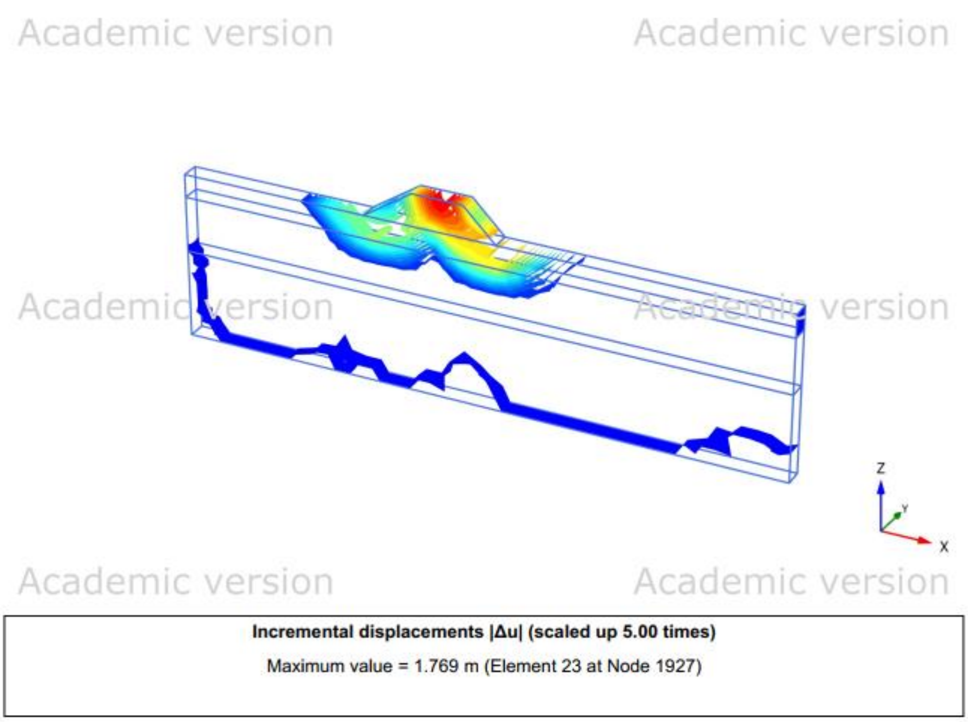


Likely failure mechanism for Rapid Drawdown condition of Bhola Polder

Slow Drawdown (30 days)



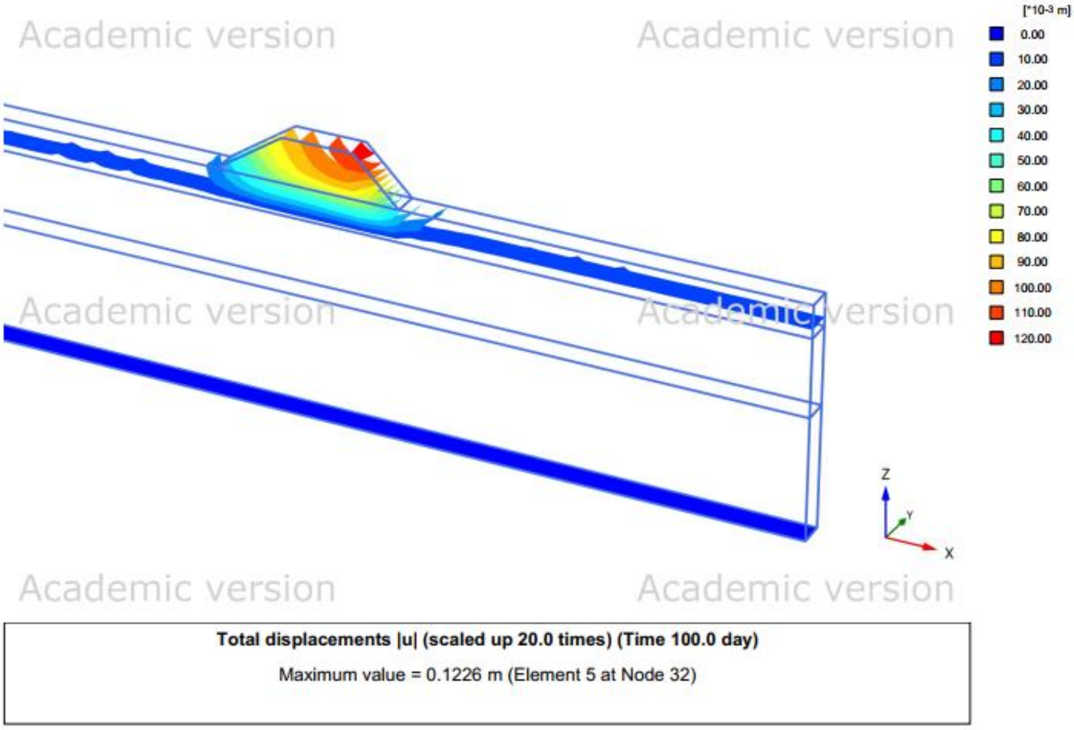
Slow Drawdown settlement of Noakhali Polder



Incremental displacements |Δu| (scaled up 5.00 times)

Maximum value = 1.769 m (Element 23 at Node 1927)

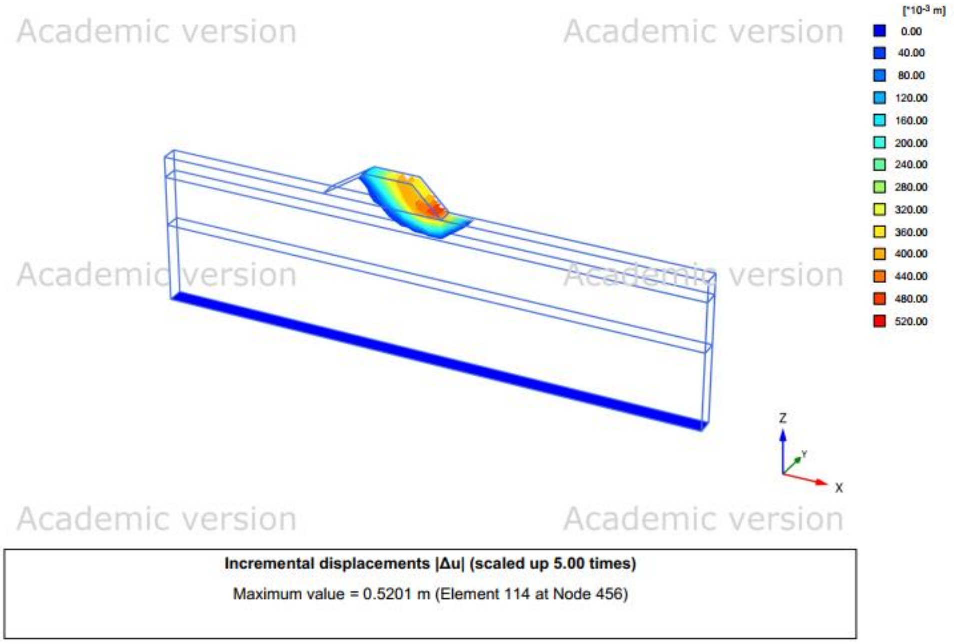
Slow Drawdown likely failure mechanism of Noakhali Polder



Total displacements |u| (scaled up 20.0 times) (Time 100.0 day)

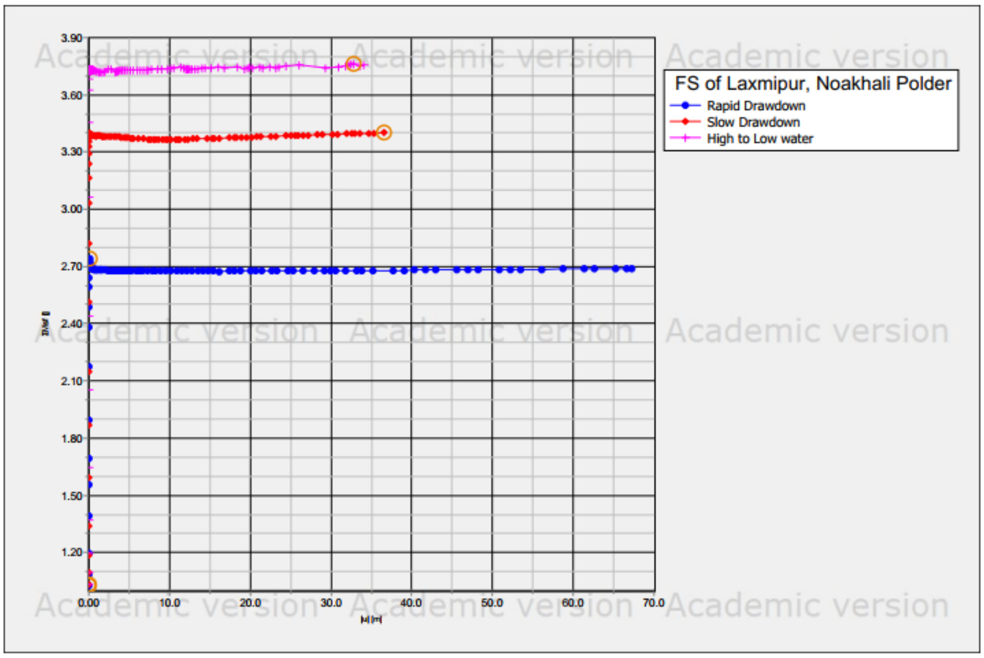
Maximum value = 0.1226 m (Element 5 at Node 32)

Change in water level (high level to borehole level) settlement of Noakhali Polder



Likely failure mechanism of change in water level (high level to borehole level) of Noakhali Polder

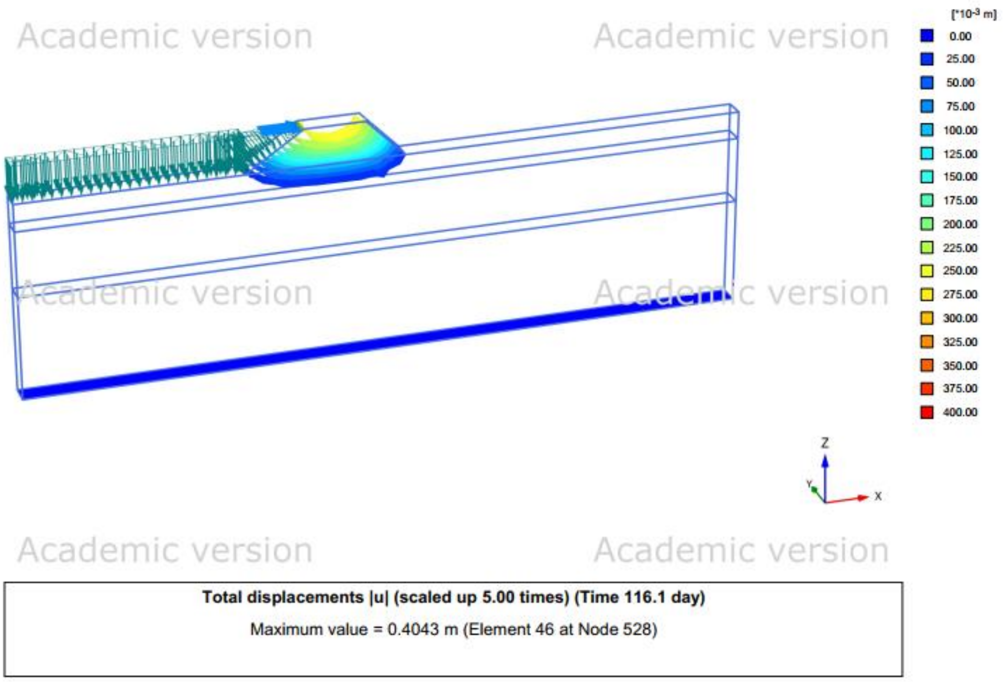
Factor of safety of Rapid Drawdown, Slow Drawdown, and change in water level (high level to borehole level) of Noakhali Polder:



Factor of safety of Rapid Drawdown, Slow Drawdown, and change in water level (high level to borehole level) of Noakhali Polder.

Analysis of Noakhali Polder against Cyclone 1991

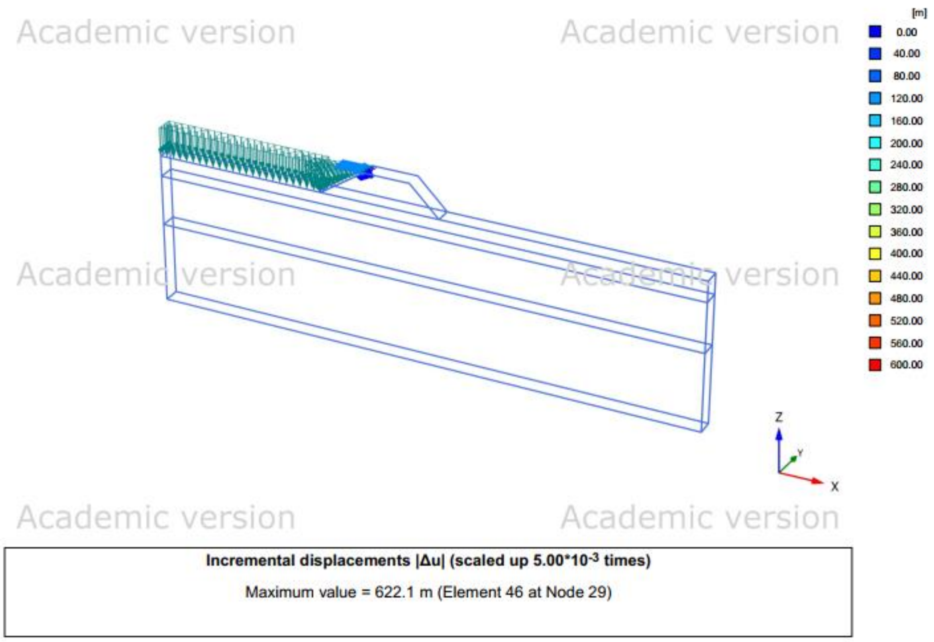
Surge height 3.5m and thrust force 16KN



Total displacements |u| (scaled up 5.00 times) (Time 116.1 day)

Maximum value = 0.4043 m (Element 46 at Node 528)

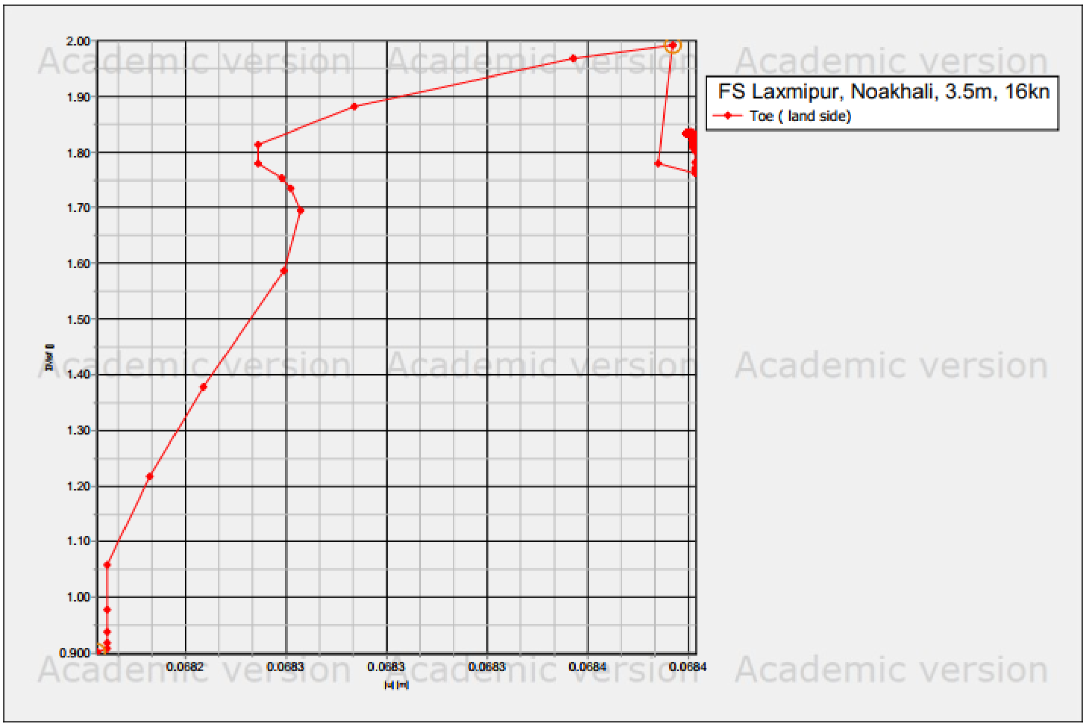
Total settlement for Surge height 3.5m and thrust force 16 KN for Noakhali Polder



Incremental displacements |Δu| (scaled up 5.00*10^{-3} times)

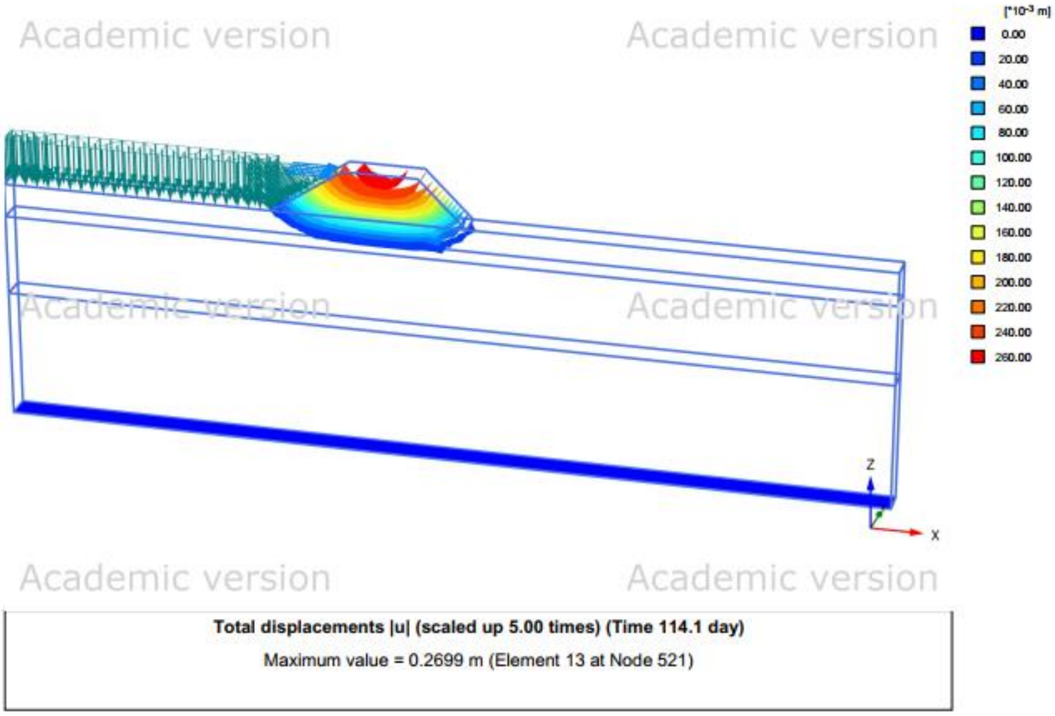
Maximum value = 622.1 m (Element 46 at Node 29)

Likely Failure mechanism for Surge height 3.5m and thrust force 16 kN for Noakhali Polder

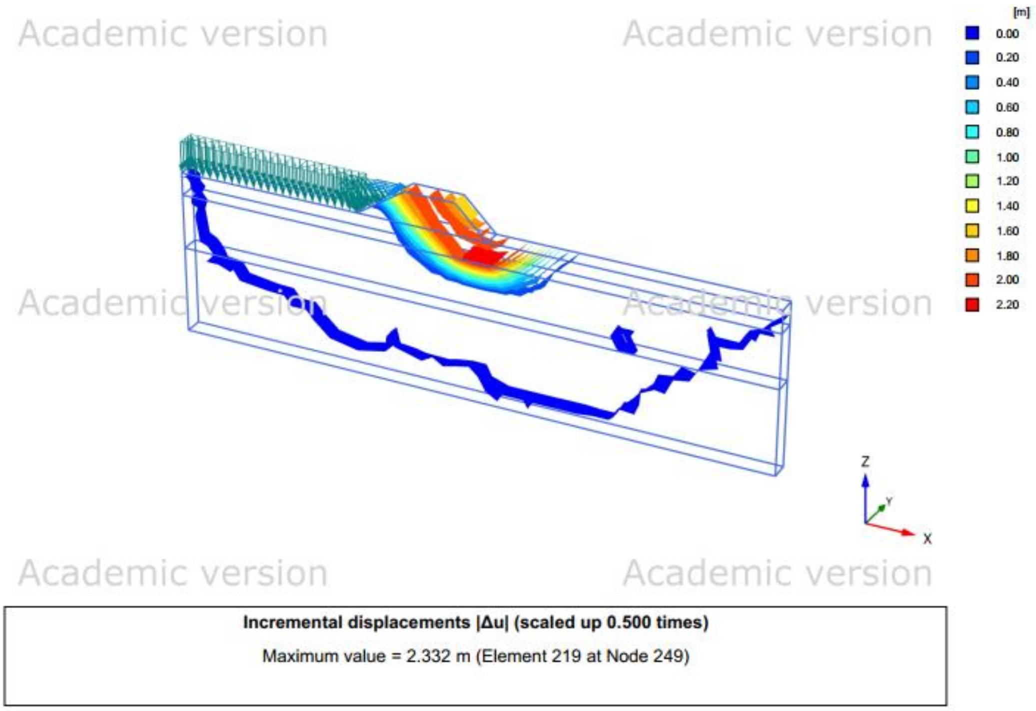


Factor of safety for Surge height 3.5m and thrust force 16 kN for Noakhali Polder

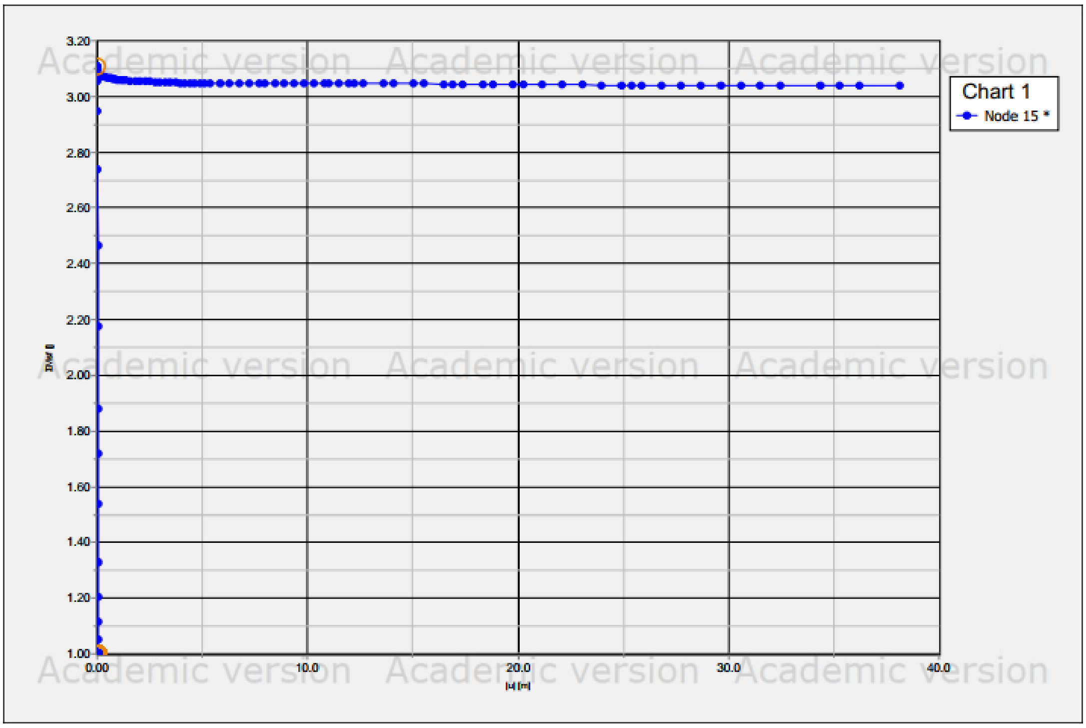
Surge height 3.0m and thrust force 8kN



Total settlement for Surge height 3.0m and thrust force 8 kN for Noakhali Polder

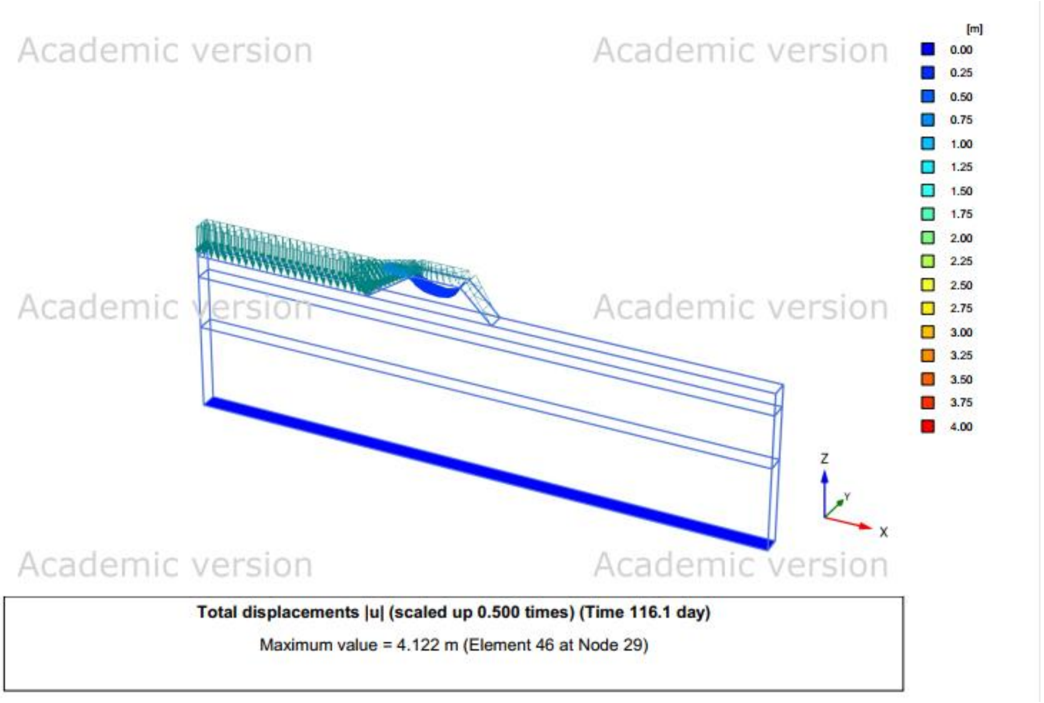


Likely failure mechanism for Surge height 3.0m and thrust force 8 kN for Noakhali Polder

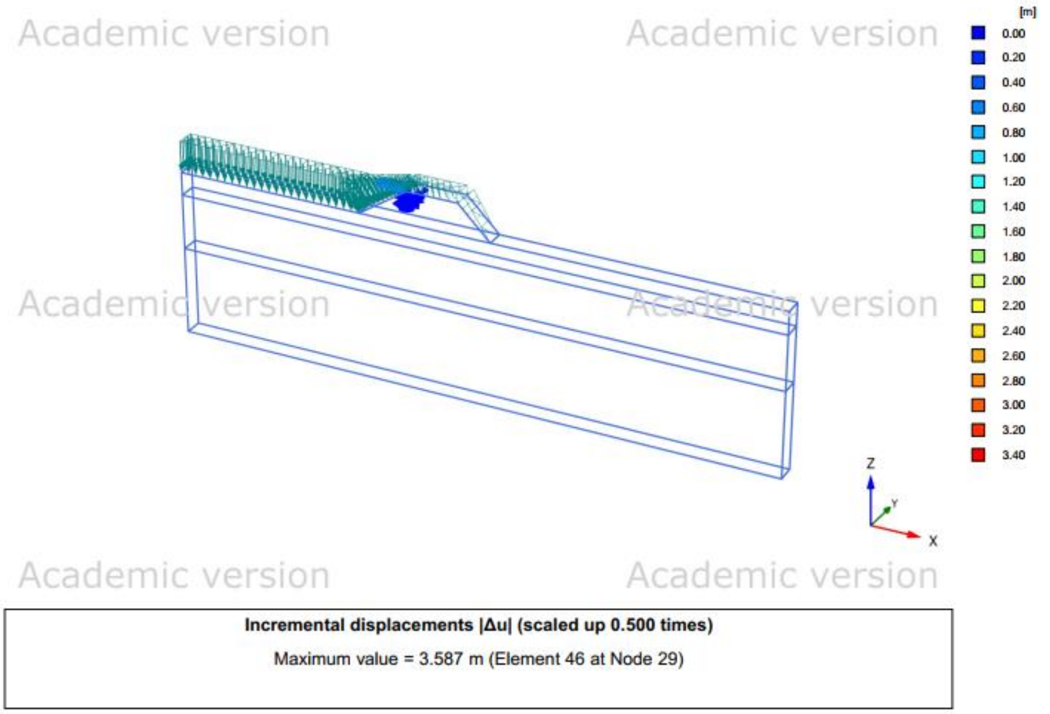


Factor of safety for Surge height 3.0m and thrust force 8 kN for Noakhali Polder

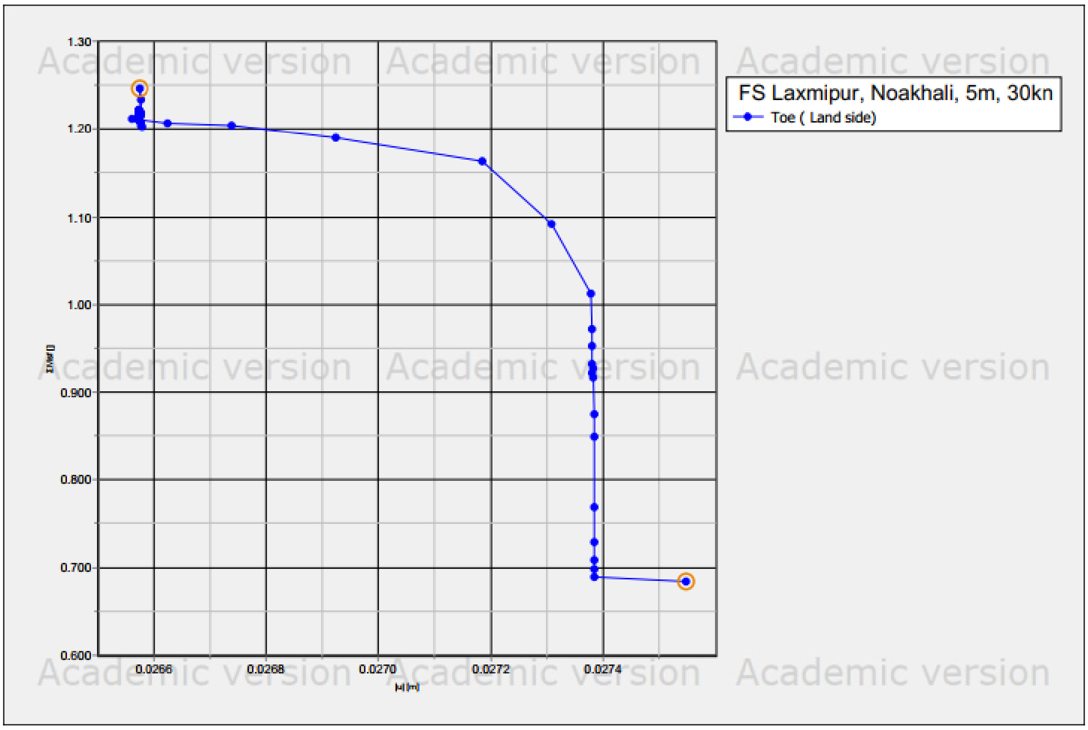
Surge height 5.0m and thrust force 30kN



Total settlement for Surge height 5.0m and thrust force 30 kN for Noakhali Polder

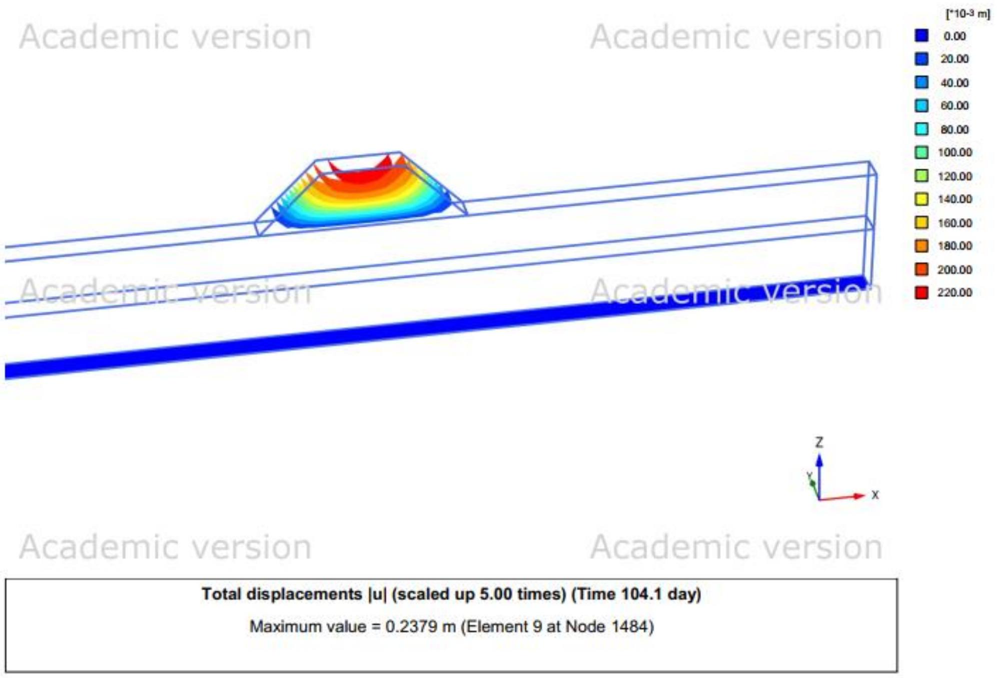


Likely failure mechanism for Surge height 5.0m and thrust force 30 kN for Noakhali Polder

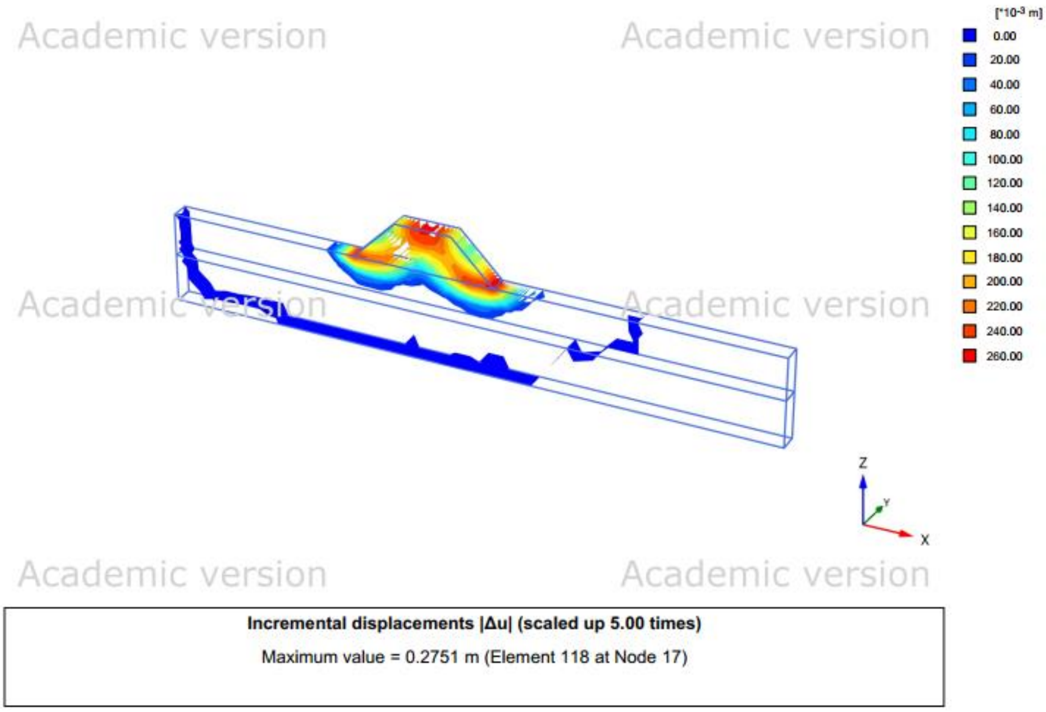


Factor of safety for Surge height 5.0m and thrust force 30 kN for Noakhali Polder

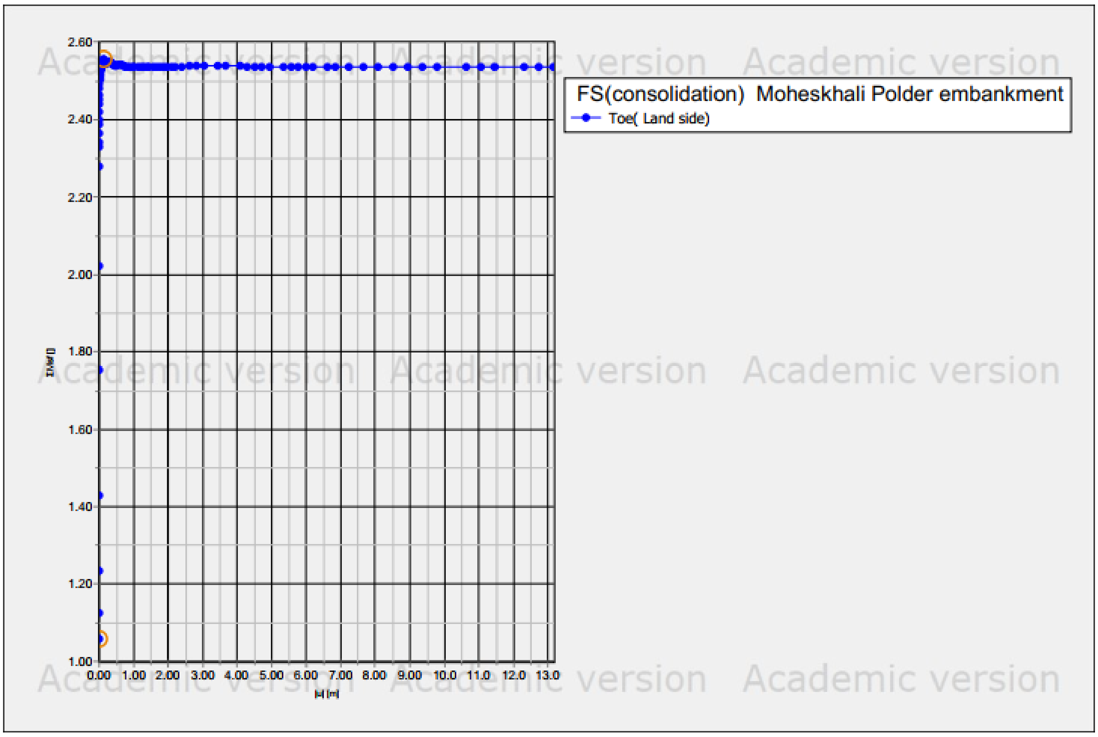
Results of Moheskhali Polder analysis



Consolidation settlement of Mohaskhali Polder.

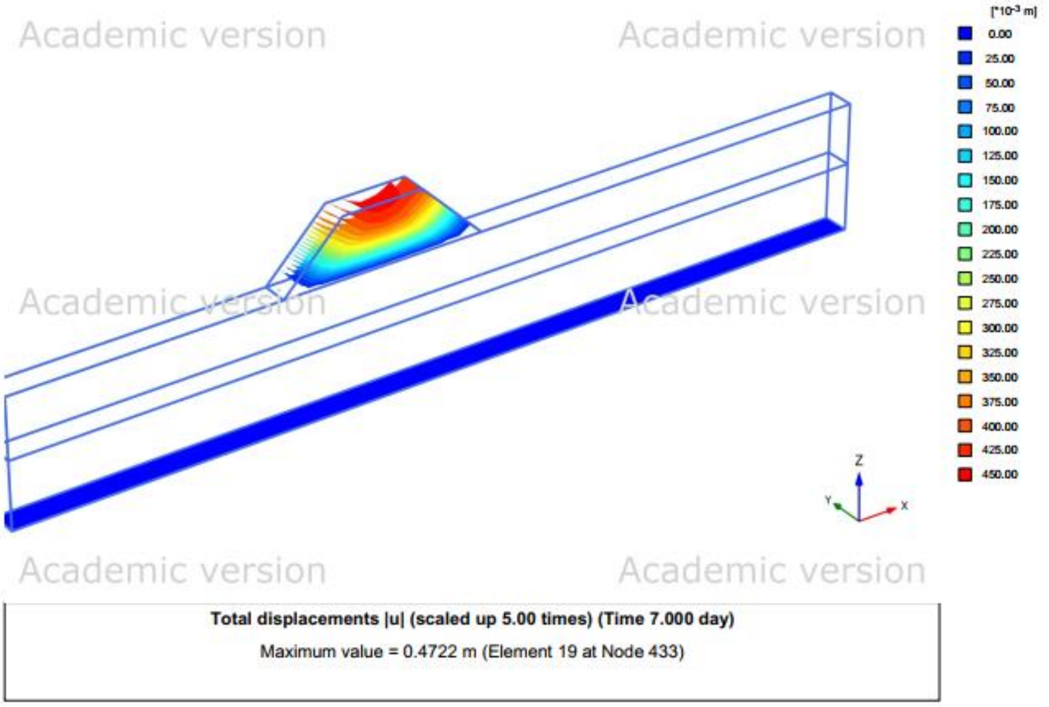


Likely Failure Mechanism for Consolidation settlement of Mohaskhali Polder.

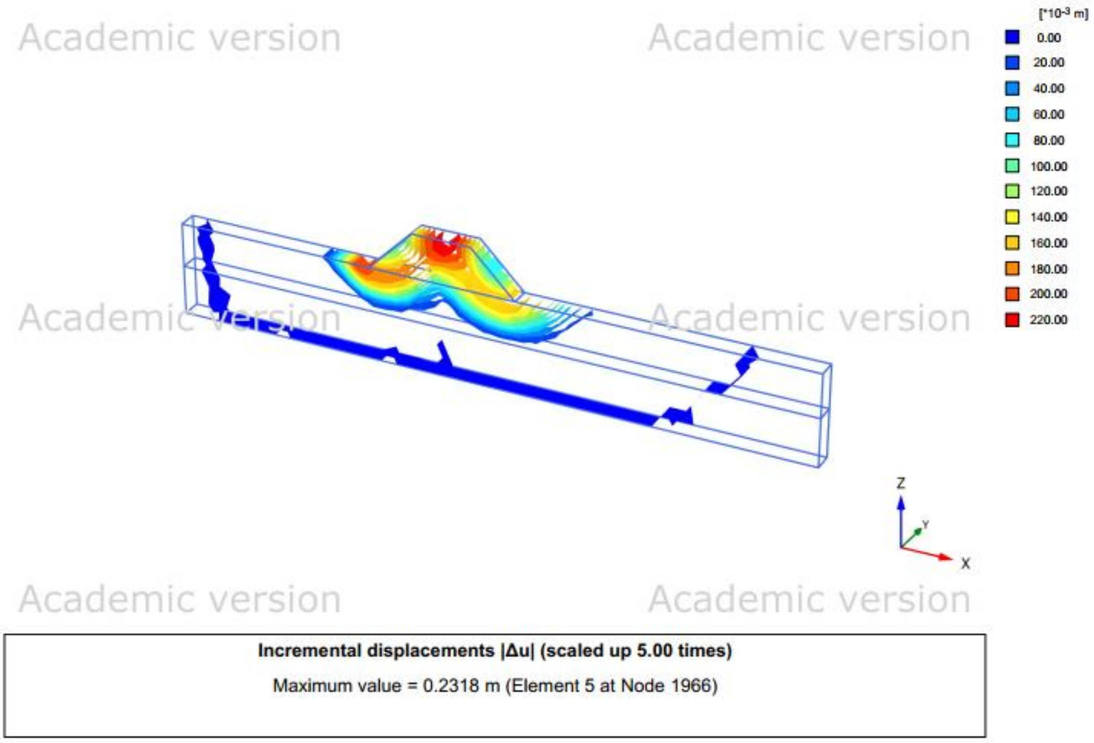


Consolidation Factor of Safety of Mohaskhali Polder.

Rapid Drawdown (7 days)



Rapid Drawdown settlement of Mohaskhali Polder.

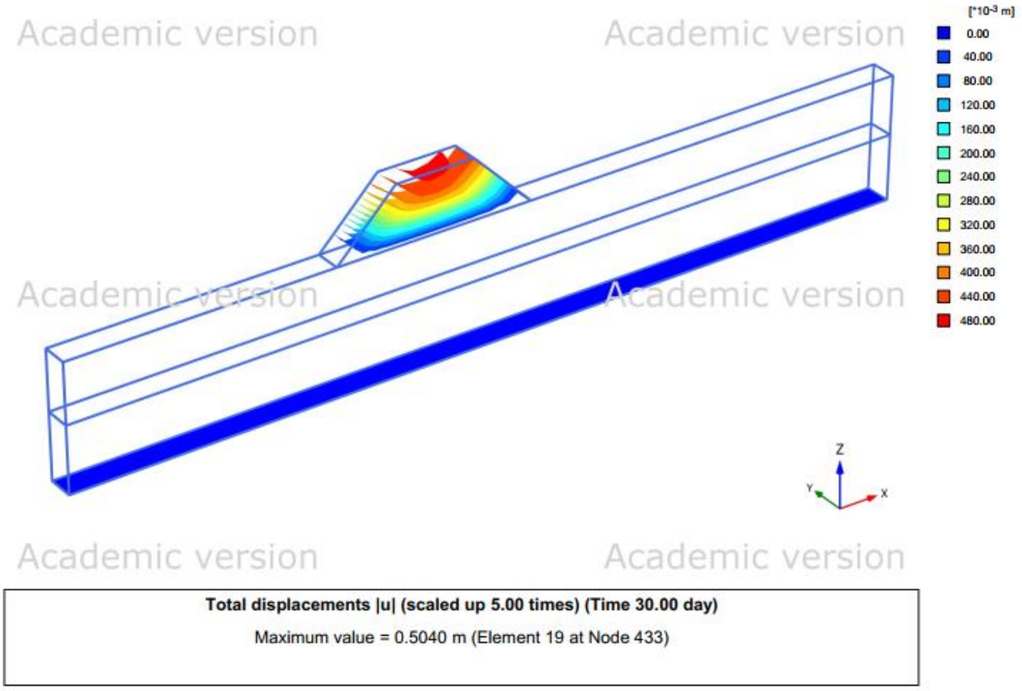


Incremental displacements |Δu| (scaled up 5.00 times)

Maximum value = 0.2318 m (Element 5 at Node 1966)

Likely failure mechanism for Rapid Drawdown condition of Mohaskhali Polder.

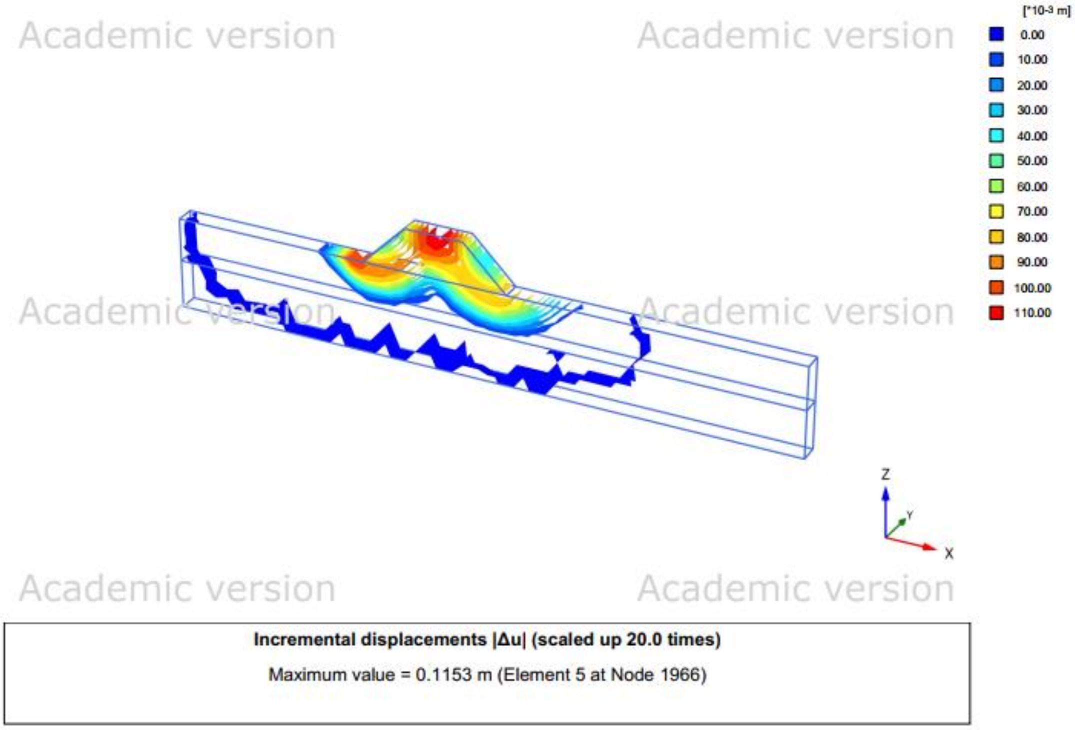
Slow Drawdown (30 days)



Total displacements |u| (scaled up 5.00 times) (Time 30.00 day)

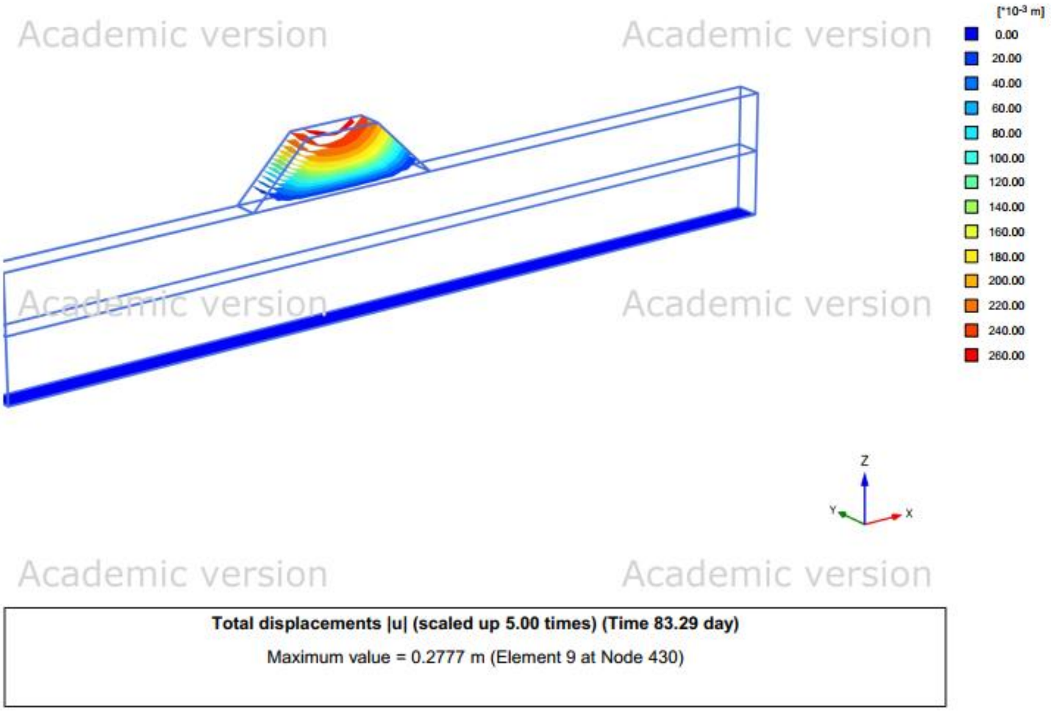
Maximum value = 0.5040 m (Element 19 at Node 433)

Slow Drawdown settlement of Mohaskhali Polder.

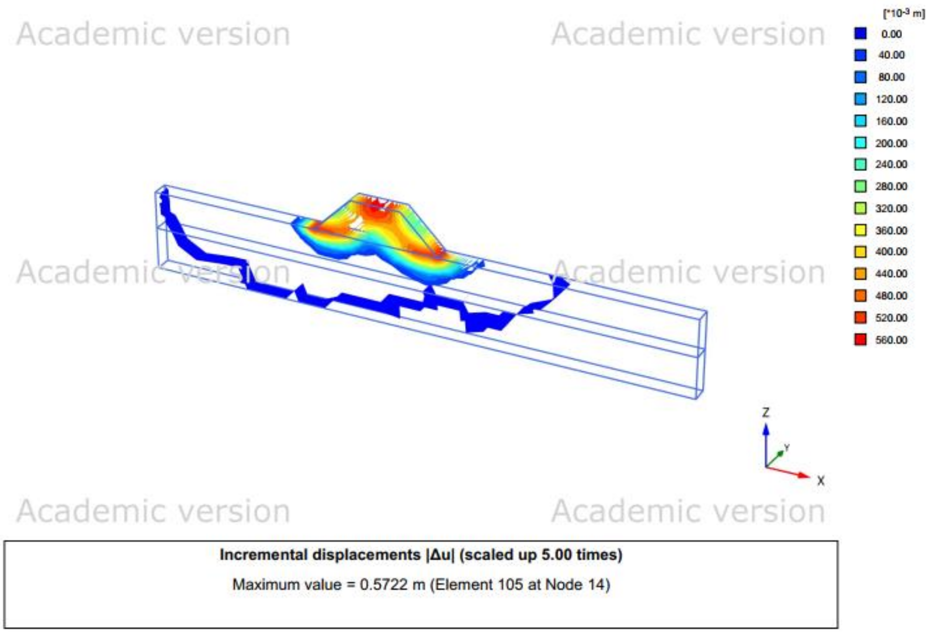


Slow Drawdown likely failure mechanism of Mohaskhali Polder.

Change in water level (high level to borehole level) over time (100 days)

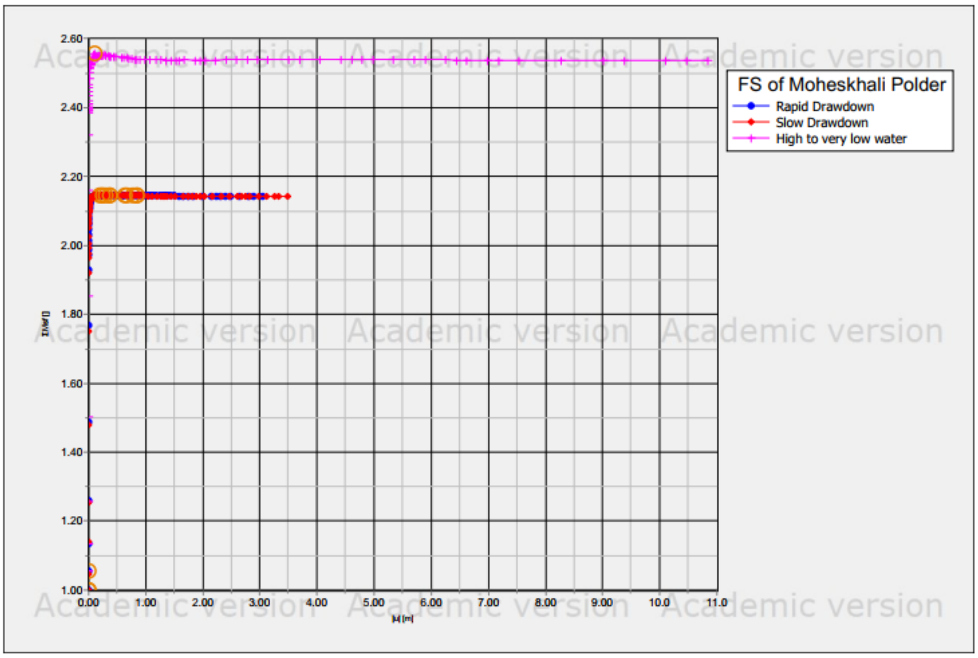


Change in water level (high level to borehole level) settlement of Mohaskhali Polder.



Likely failure mechanism of change in water level (high level to borehole level) of Mohaskhali Polder.

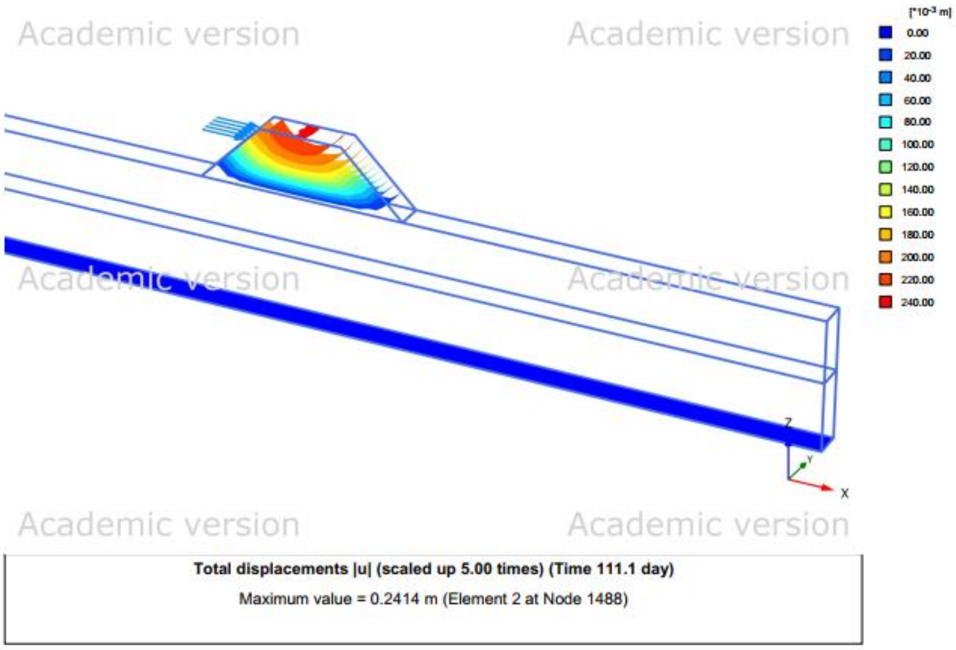
Factor of safety of Rapid Drawdown, Slow Drawdown, and change in water level (high level to borehole level) of Bhola Polder



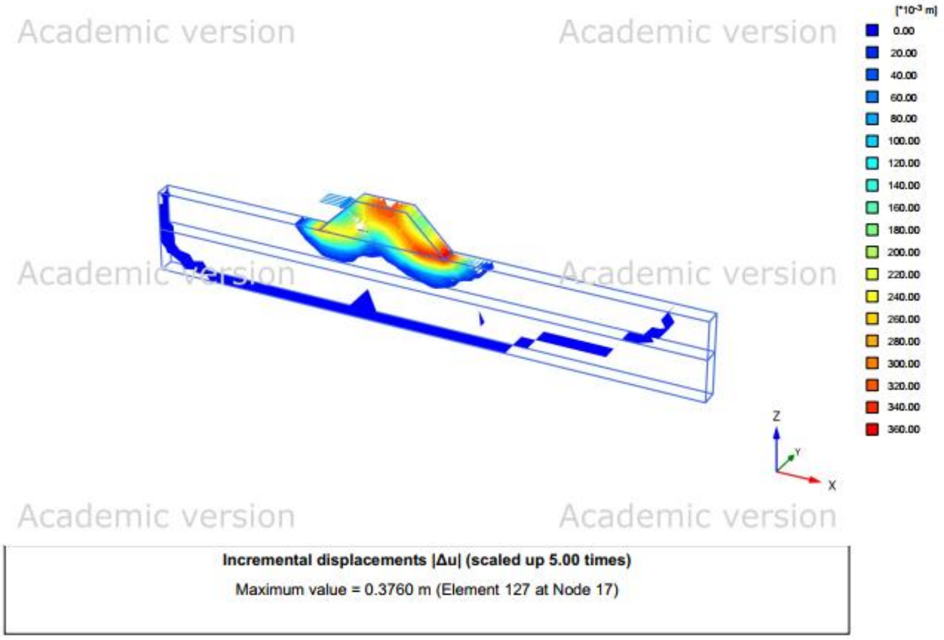
Factor of safety of Rapid Drawdown, Slow Drawdown, and change in water level (high level to borehole level) of Mohaskhali Polder.

Analysis of Moheskhali Polder against Cyclone 1991

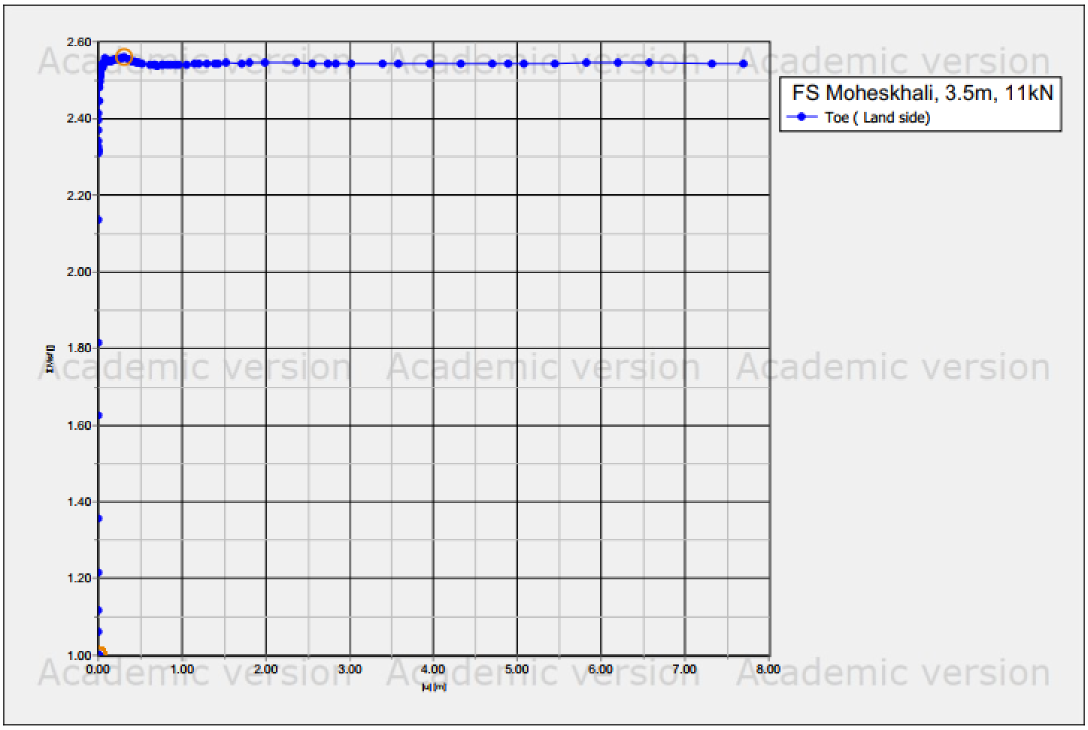
Surge height 3.5m and thrust force 11 kN



Total Settlement of Moheskhali Polder against Surge height 3.5m and thrust force 11 kN

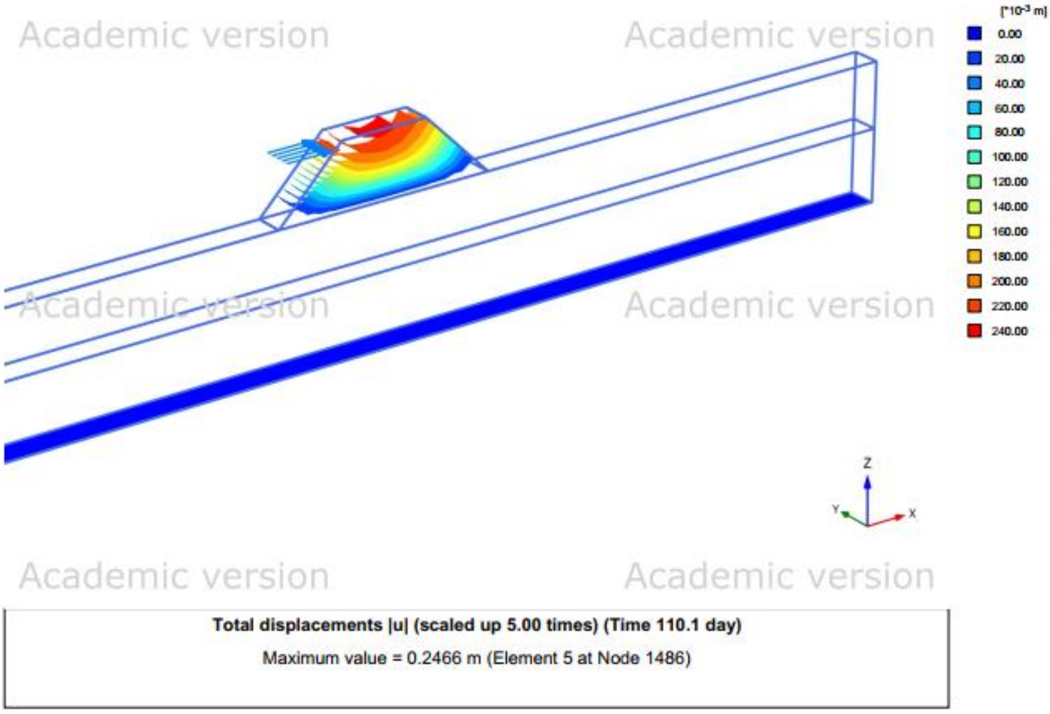


Failure mechanism of Moheskhali Polder against Surge height 3.5m and thrust force 11 kN

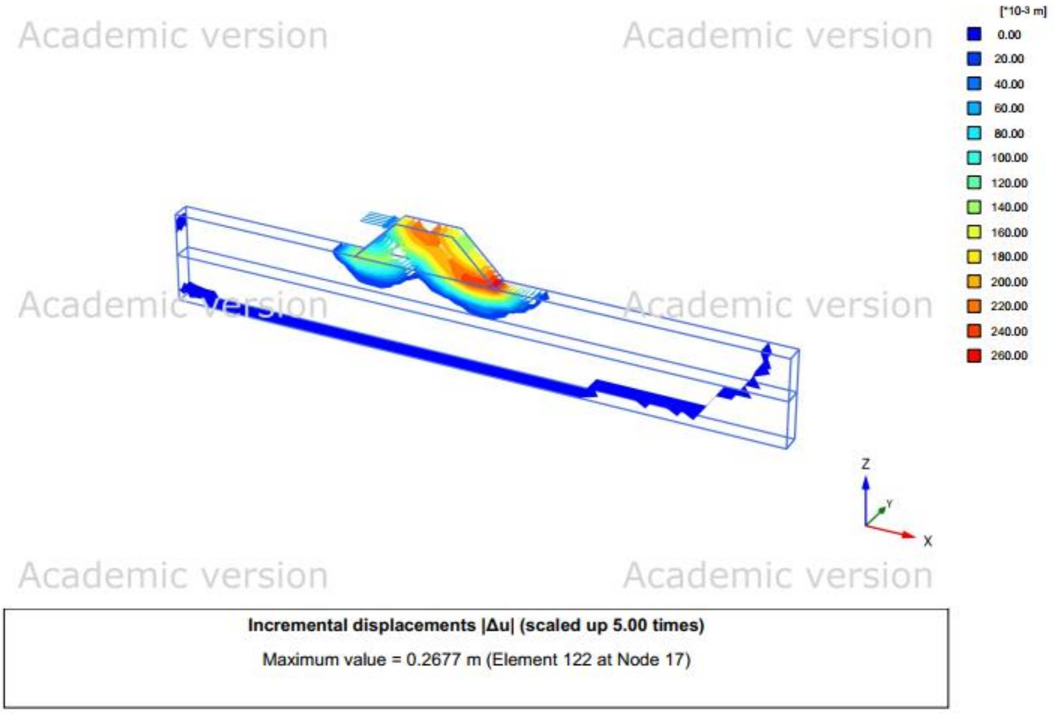


Factor of safety of Moheskhali Polder against Surge height 3.5m and thrust force 11 kN

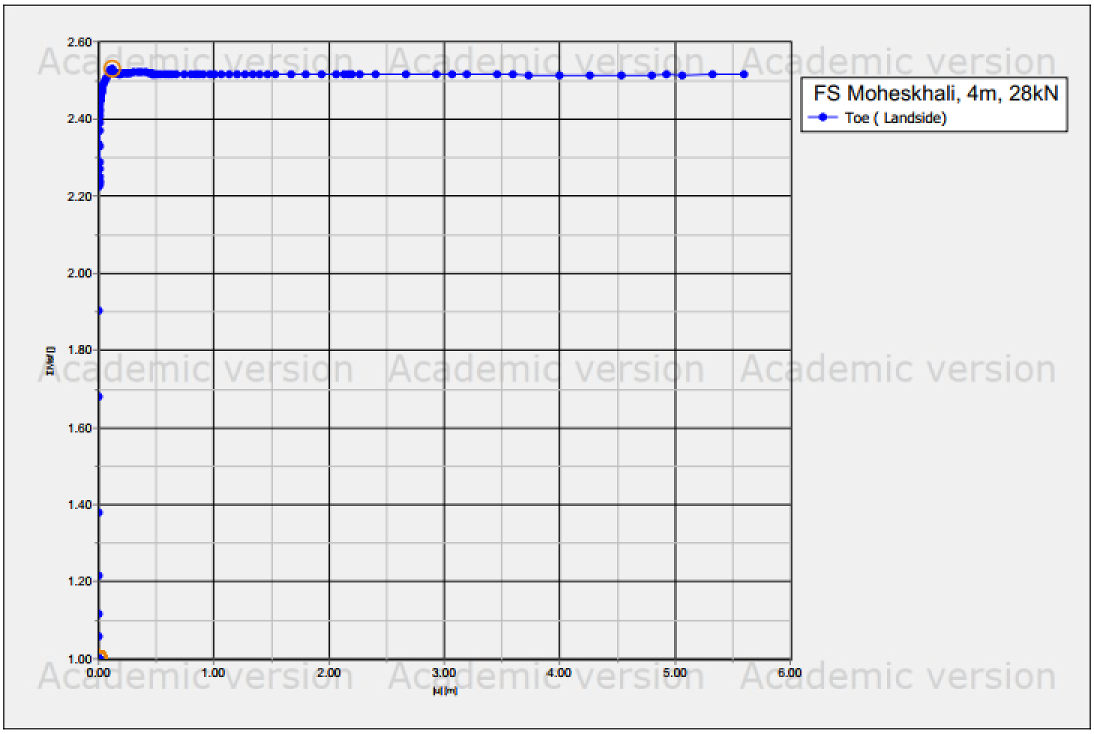
Surge height 4m and thrust force 28 kN



Total settlement of Moheskhali Polder against Surge height 4m and thrust force 28 kN

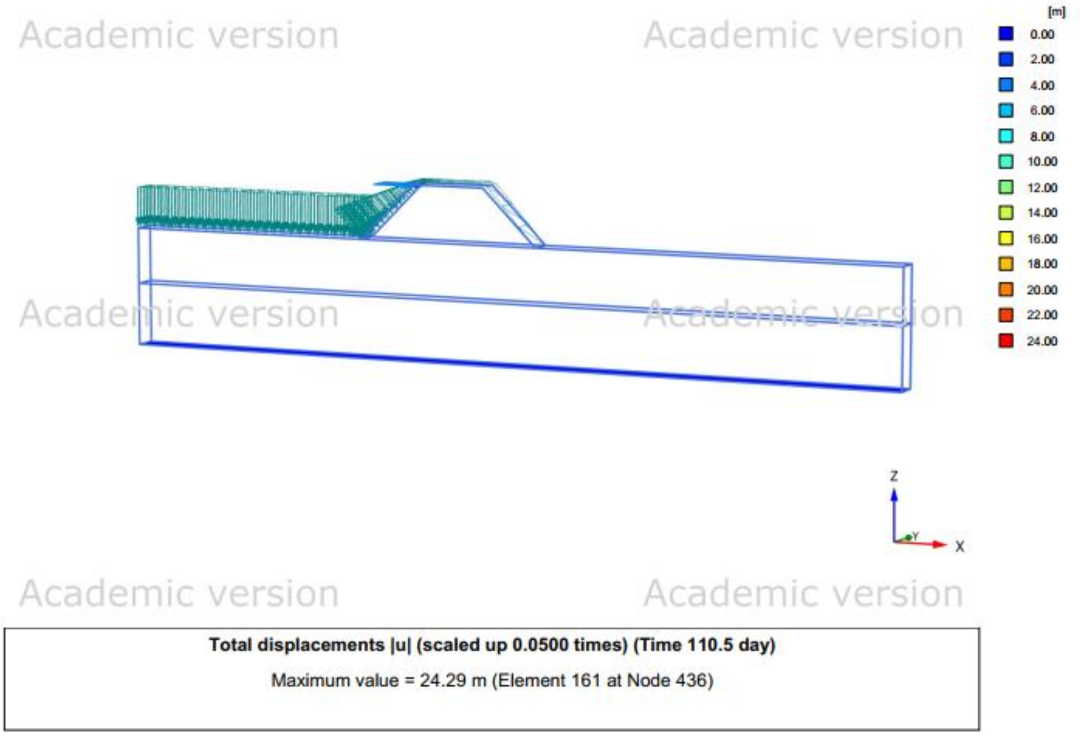


Likely failure mechanism of Moheskhali Polder against Surge height 4m and thrust force 28 kN

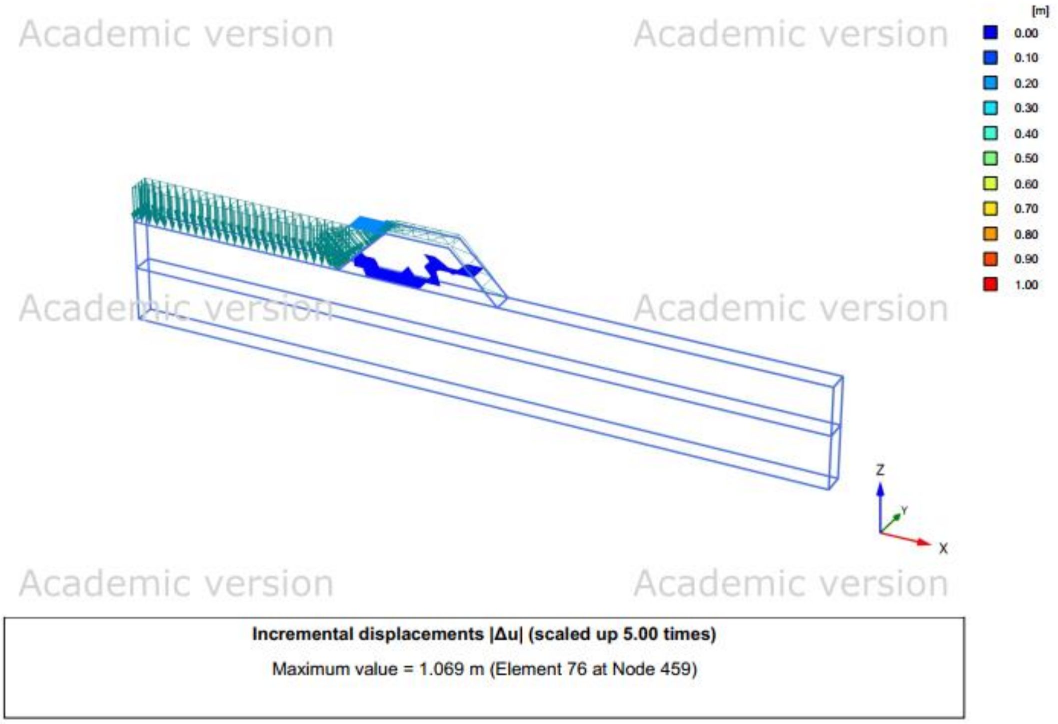


Factor of safety of Moheskhali Polder against Surge height 4m and thrust force 28 kN

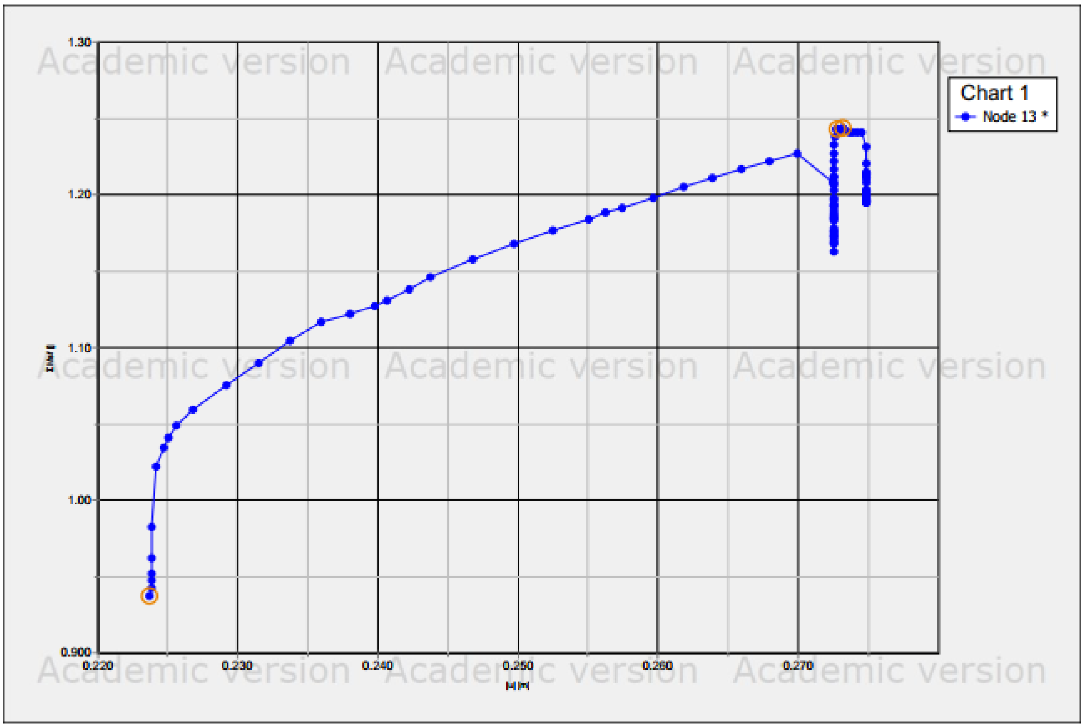
Surge height 5m and thrust force 40.8 kN



Total settlement of Moheskhali Polder against Surge height 5m and thrust force 40.8 kN



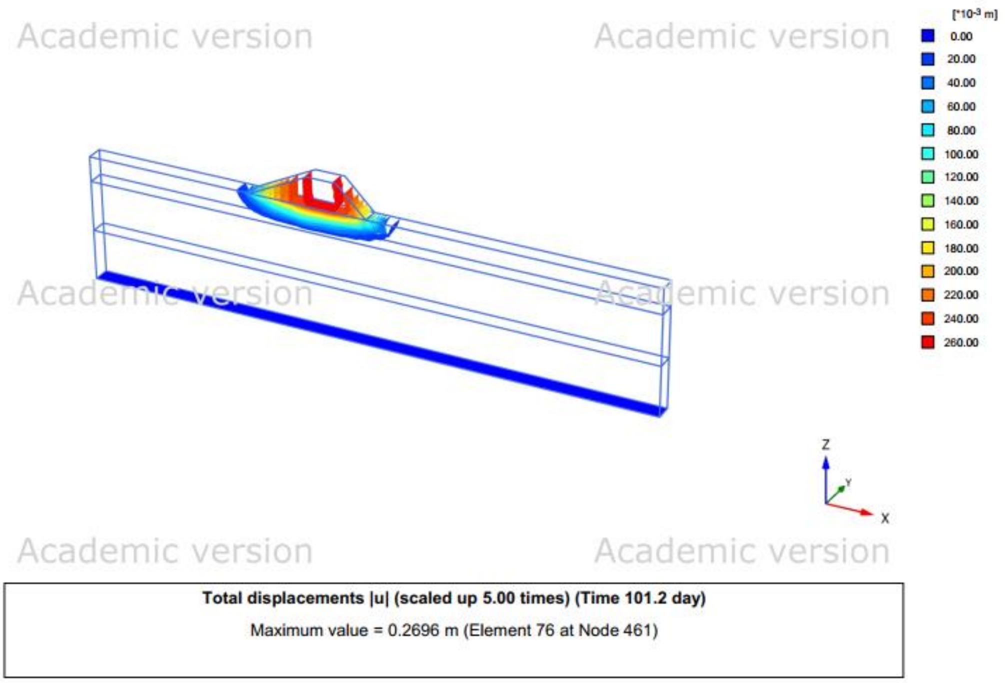
Failure mechanism of Moheskhali Polder against Surge height 5m and thrust force 40.8 kN



Factor of safety of Moheskhali Polder against Surge height 5m and thrust force 40.8 kN

Results of Anowara, Chittagong Polder analysis

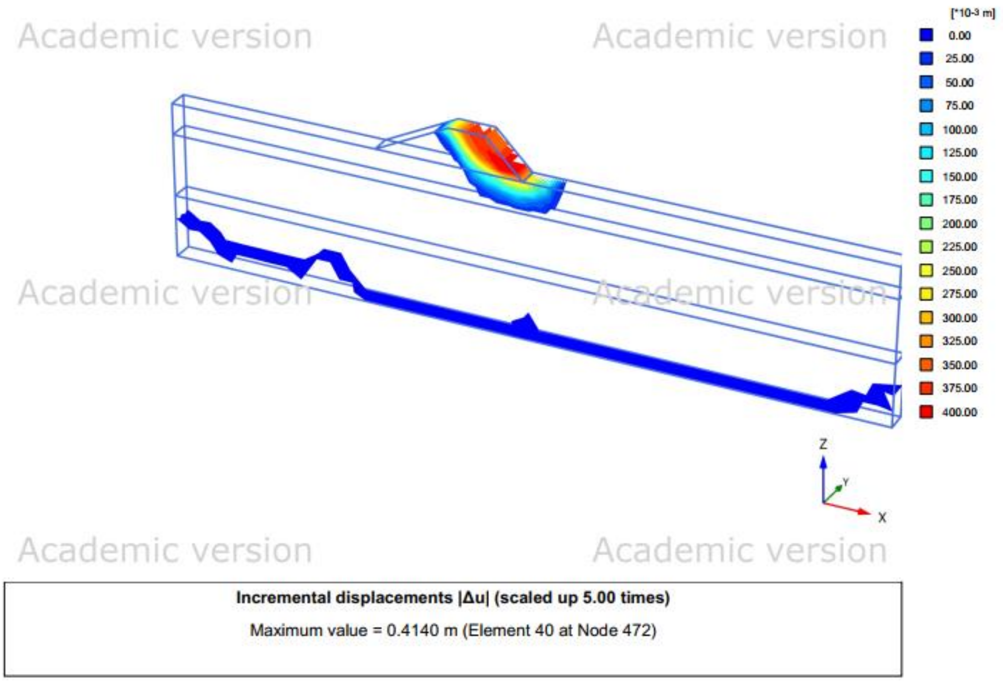
Consolidation Analysis



Total displacements |u| (scaled up 5.00 times) (Time 101.2 day)

Maximum value = 0.2696 m (Element 76 at Node 461)

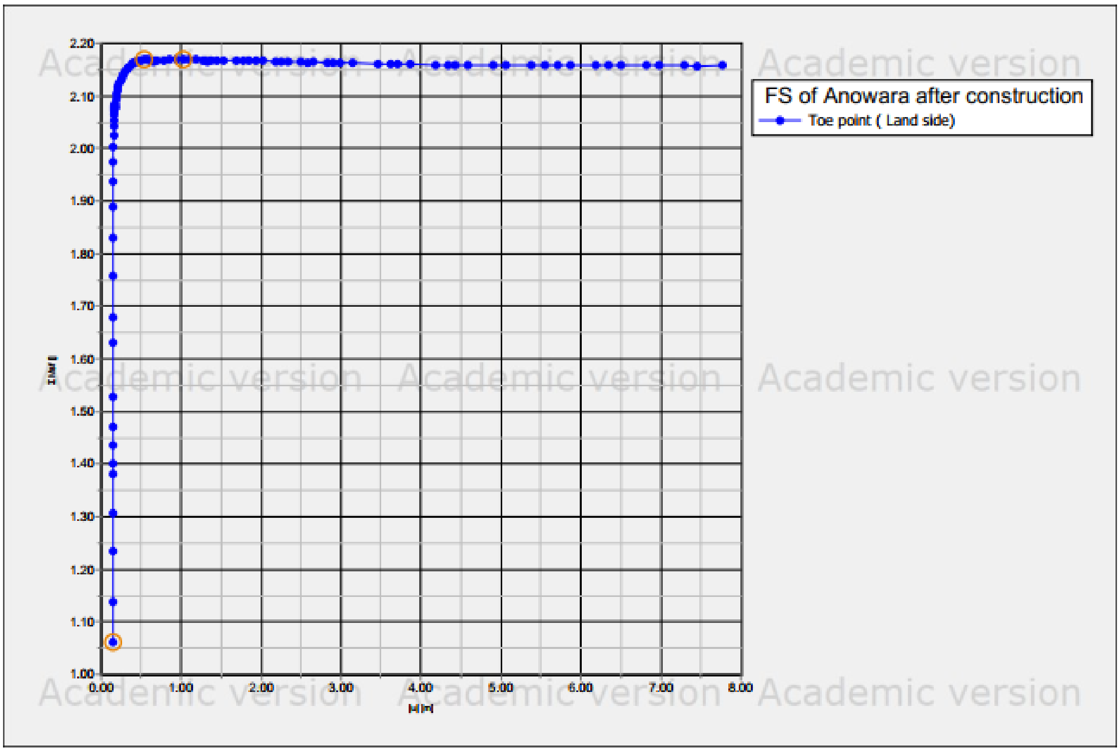
Consolidation settlement of Anowara Polder



Incremental displacements |Δu| (scaled up 5.00 times)

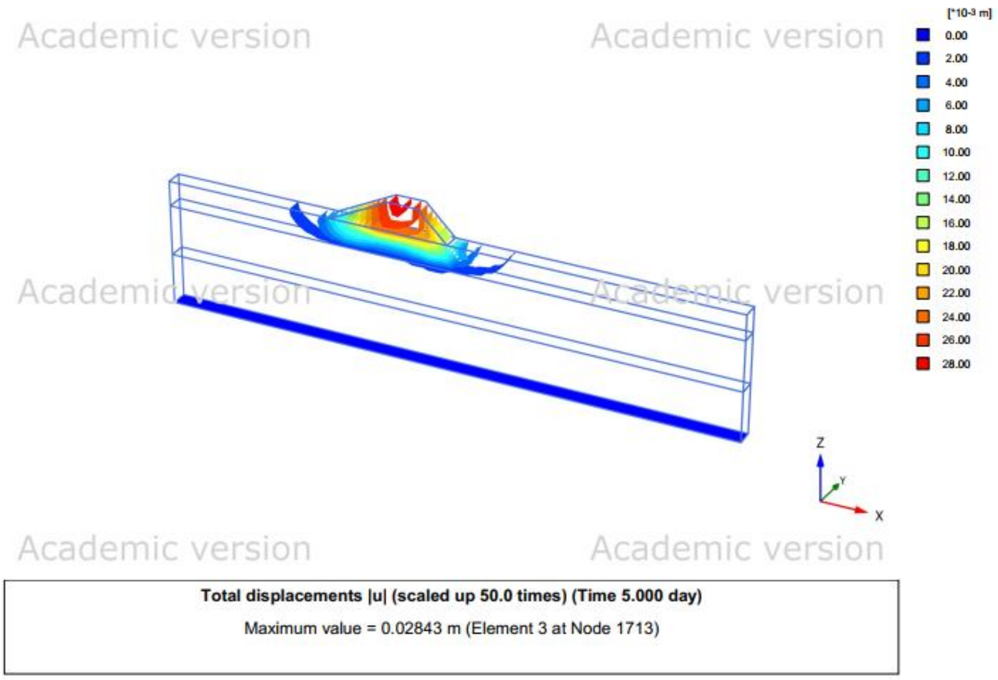
Maximum value = 0.4140 m (Element 40 at Node 472)

Likely Failure Mechanism for Consolidation settlement of Anowara Polder



Consolidation Factor of Safety of Anowara Polder

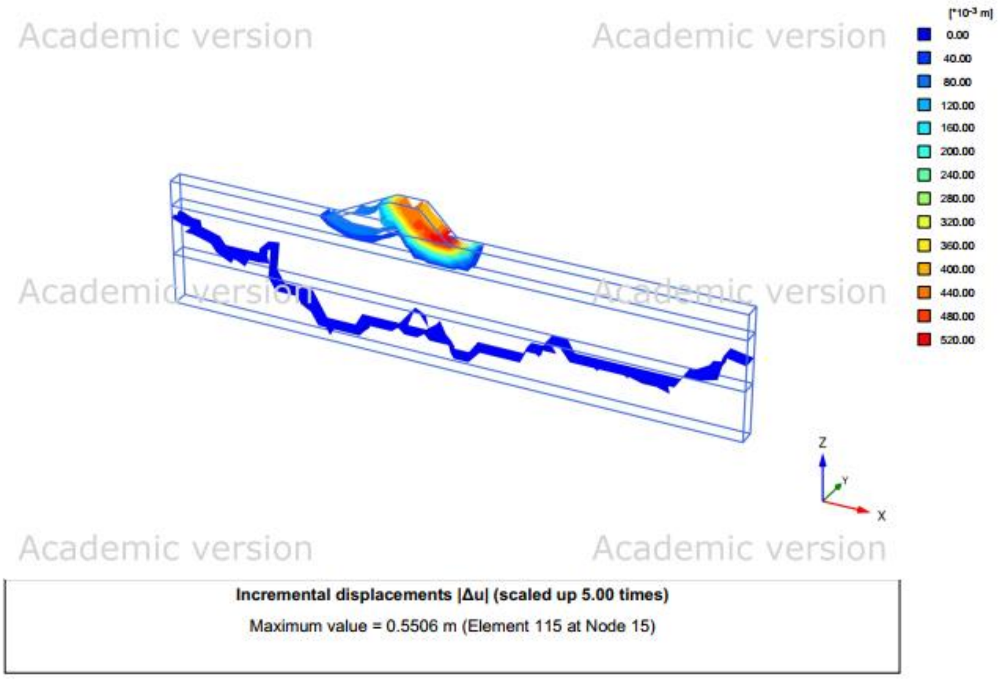
Rapid Drawdown (7 days)



Total displacements |u| (scaled up 50.0 times) (Time 5.000 day)

Maximum value = 0.02843 m (Element 3 at Node 1713)

Rapid Drawdown settlement of Anowara Polder

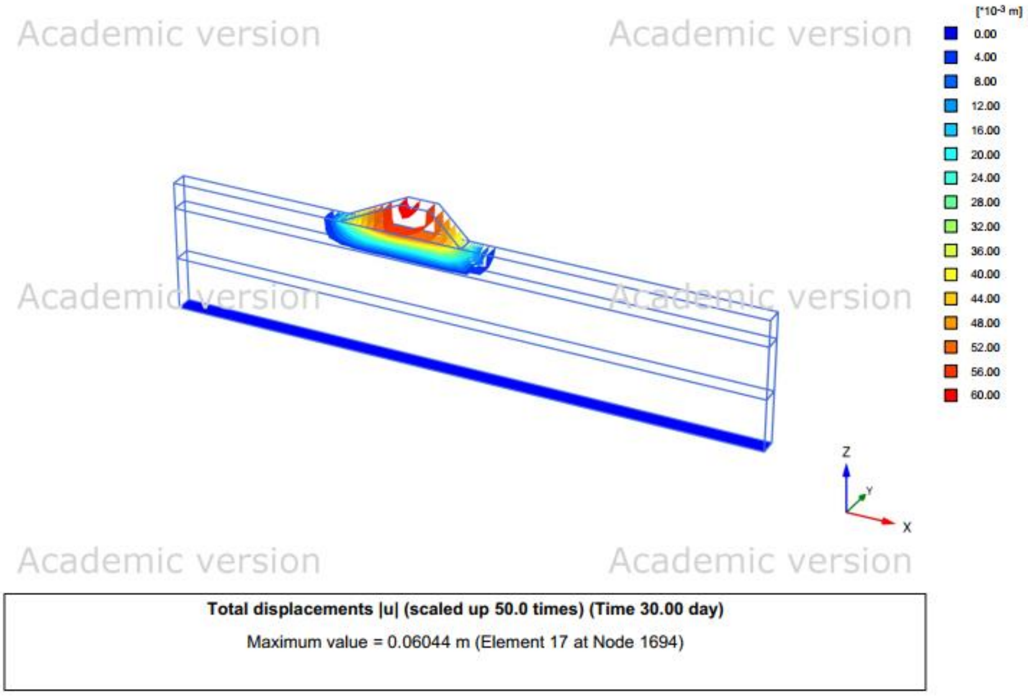


Incremental displacements |Δu| (scaled up 5.00 times)

Maximum value = 0.5506 m (Element 115 at Node 15)

Likely failure mechanism for Rapid Drawdown condition of Anowara Polder

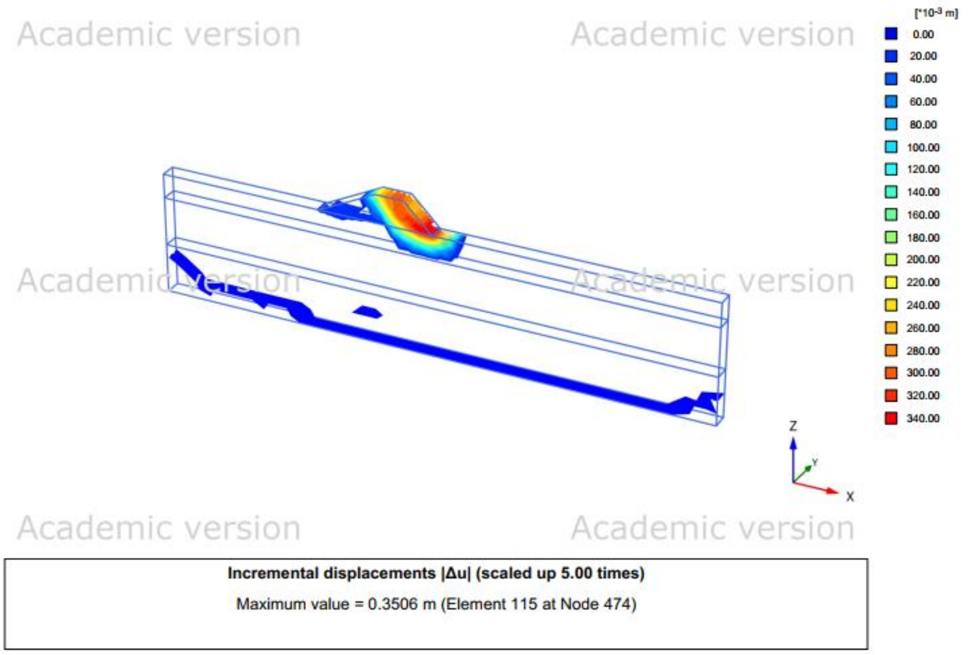
Slow Drawdown (30 days)



Total displacements |u| (scaled up 50.0 times) (Time 30.00 day)

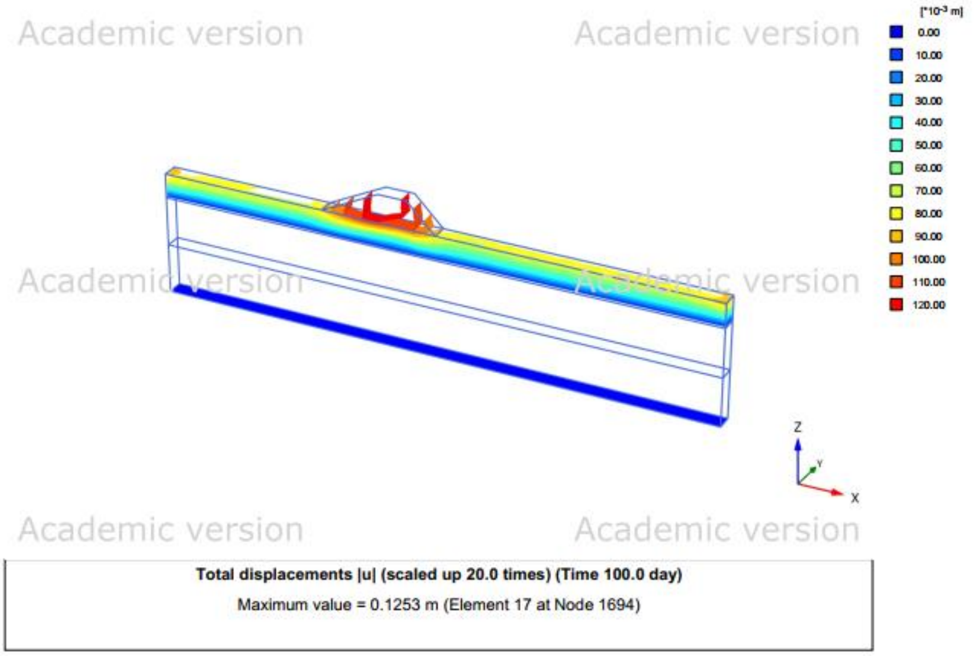
Maximum value = 0.06044 m (Element 17 at Node 1694)

Slow Drawdown settlement of Anowara Polder

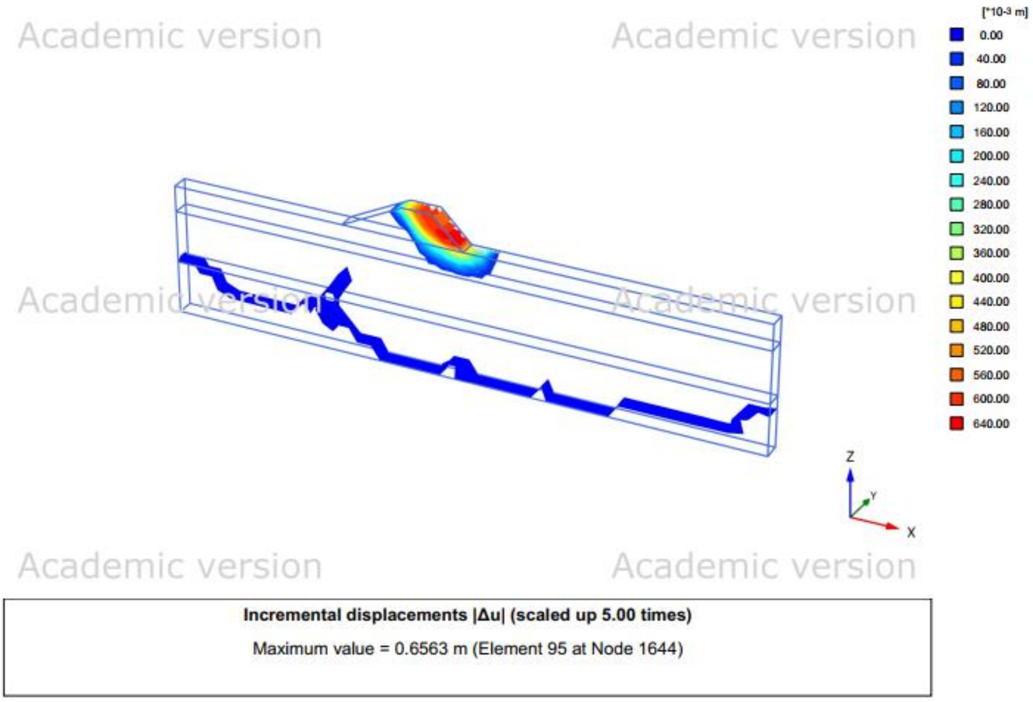


Slow Drawdown likely failure mechanism of Anowara Polder

Change in water level (high level to borehole level) over time (100 days)

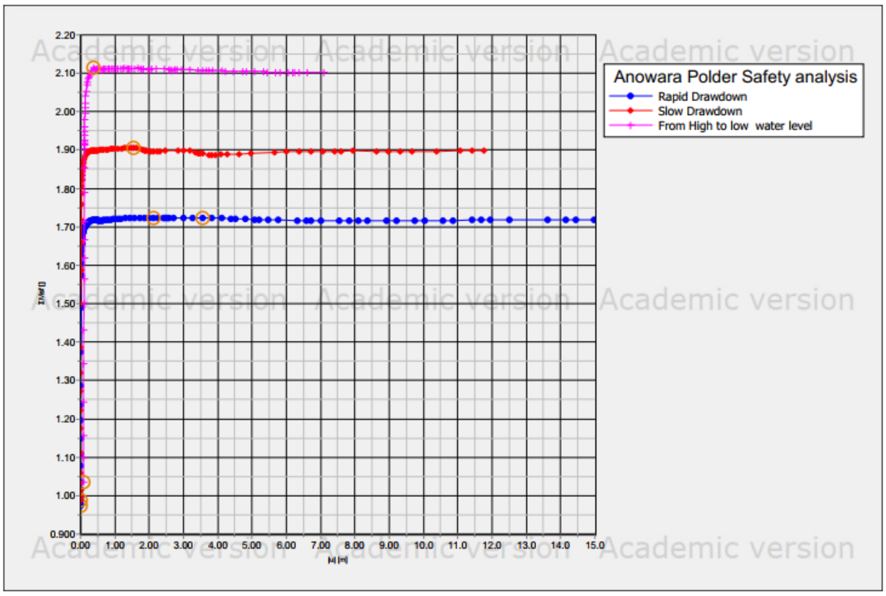


Change in water level (high level to borehole level) settlement of Anowara Polder



Likely failure mechanism of change in water level (high level to borehole level) of Anowara Polder

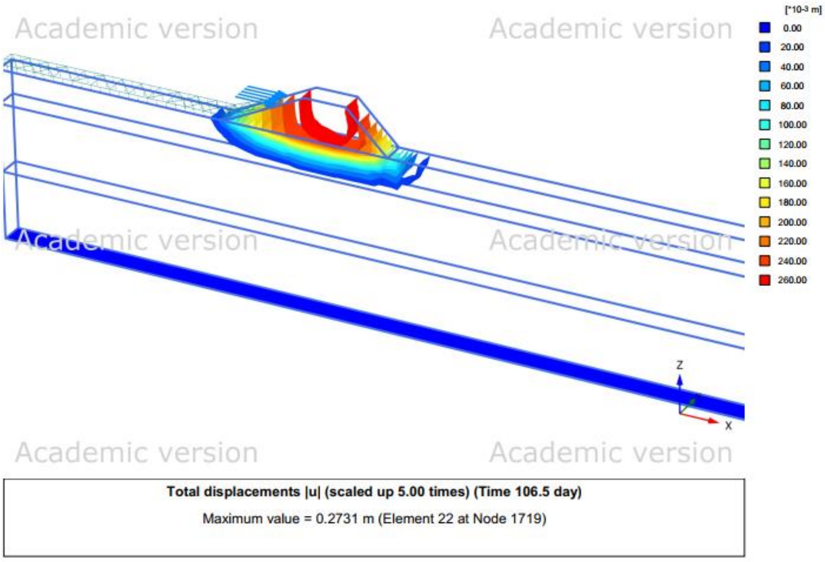
Factor of safety of Rapid Drawdown, Slow Drawdown, and change in water level (high level to borehole level) of Anowara Polder



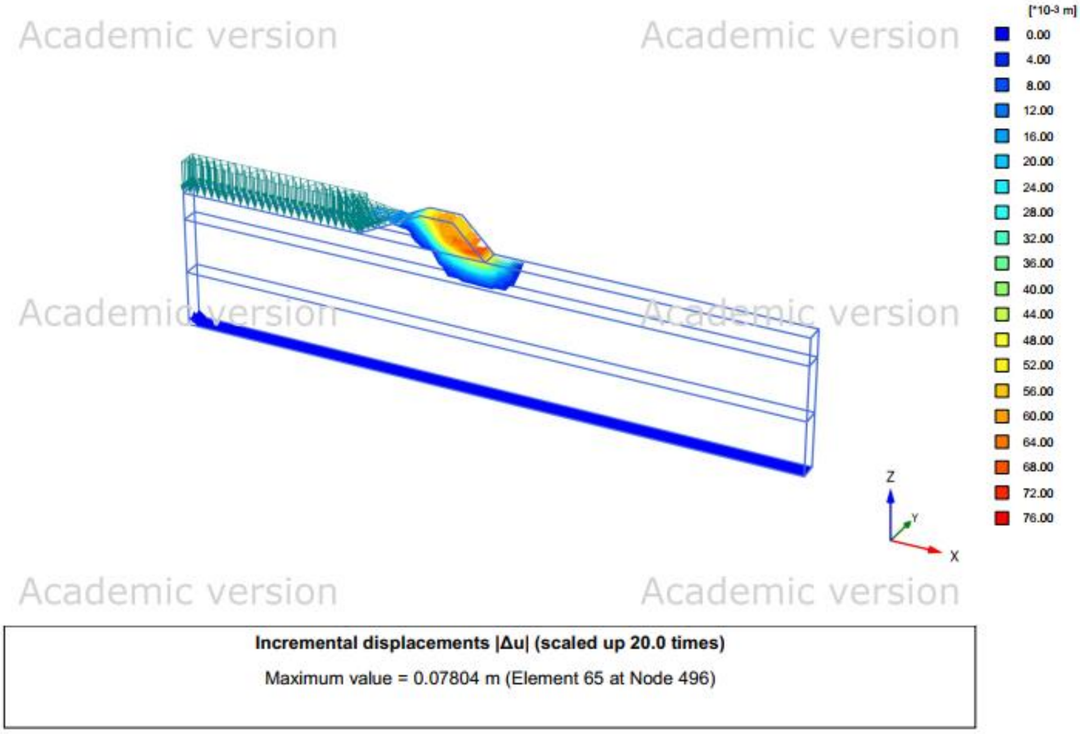
Factor of safety of Rapid Drawdown, Slow Drawdown, and change in water level (high level to borehole level) of Anowara Polder.

Analysis of Anowara Polder against Cyclone 1991

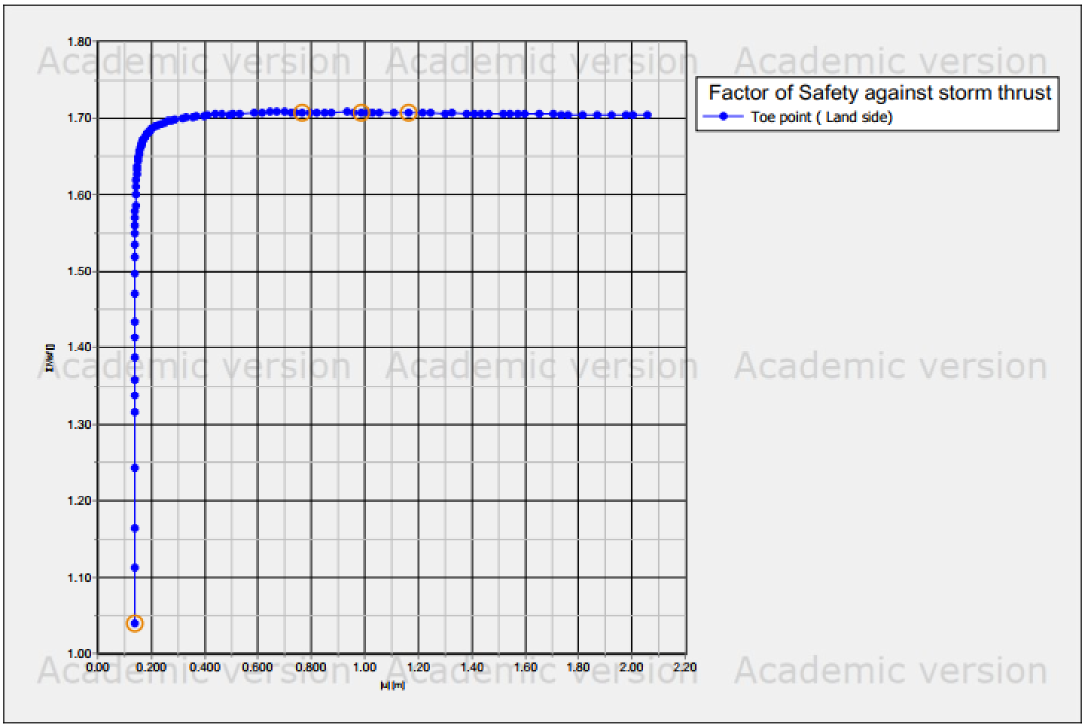
Surge height 2.3 m and thrust force 13 kN



Settlement of Anowara Polder against surge height 2.3 m and thrust force 13 kN

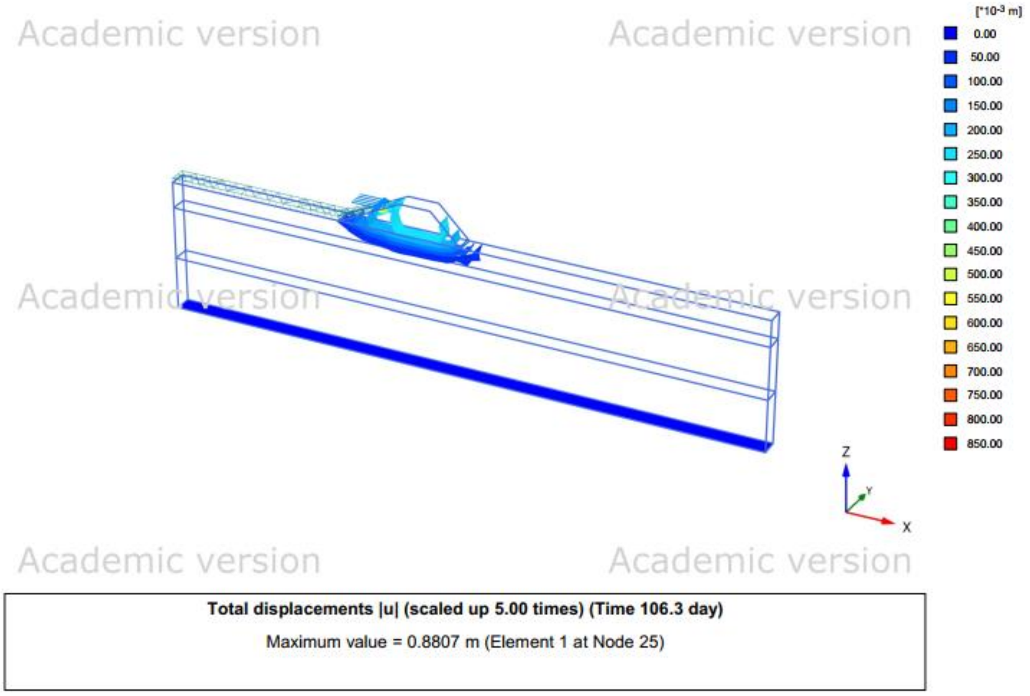


Failure mechanism of Anowara Polder against surge height 2.3 m and thrust force 13 kN



Factor of safety of Anowara Polder against surge height 2.3 m and thrust force 13 kN

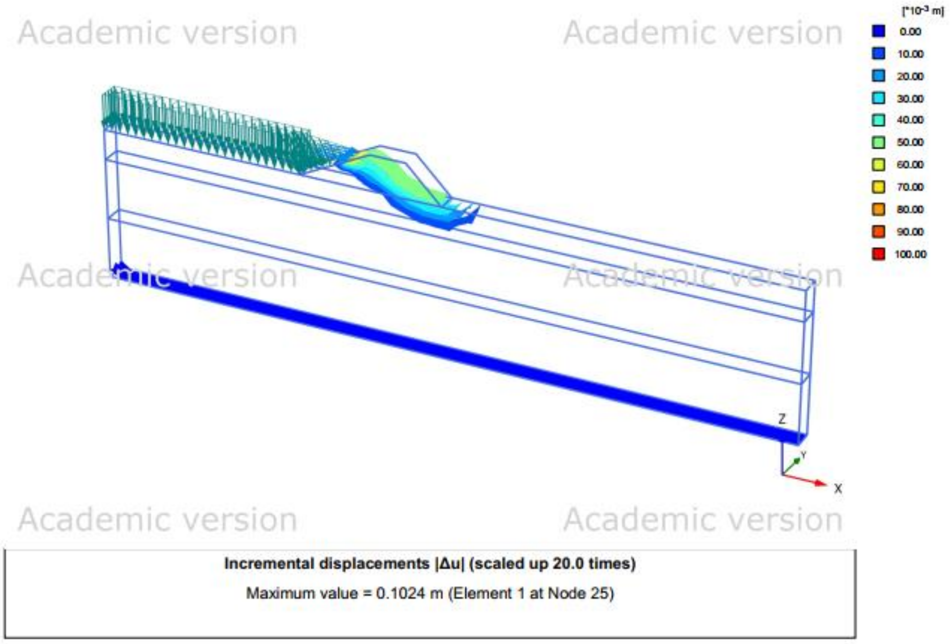
Surge height 2.5 m and thrust force 62.5 kN



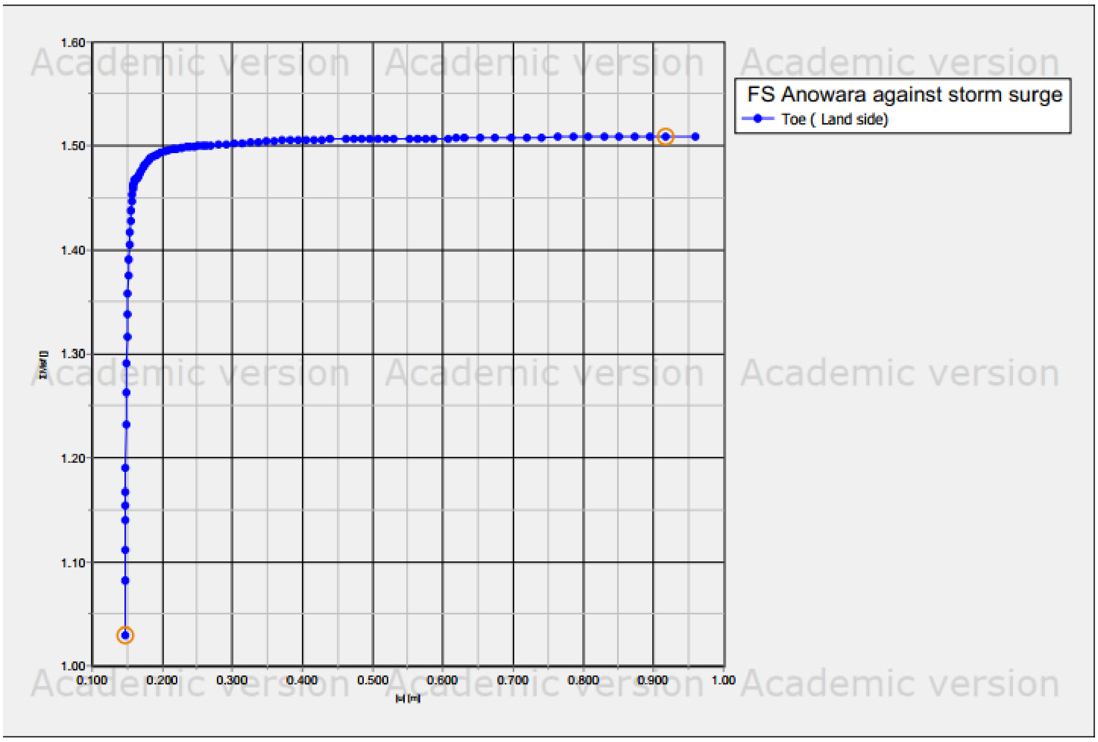
Total displacements |u| (scaled up 5.00 times) (Time 106.3 day)

Maximum value = 0.8807 m (Element 1 at Node 25)

Settlement of Anowara Polder against Surge height 2.5 m and thrust force 62.5 kN

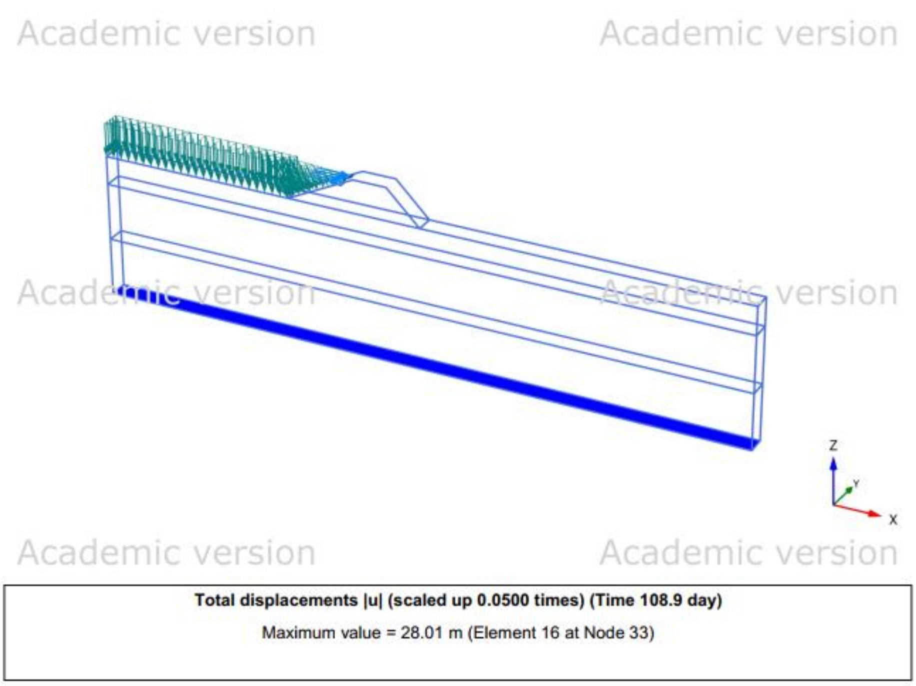


Failure mechanism of Anowara Polder against Surge height 2.5 m and thrust force 62.5 kN



Factor of safety of Anowara Polder against Surge height 2.5 m and thrust force 62.5 kN

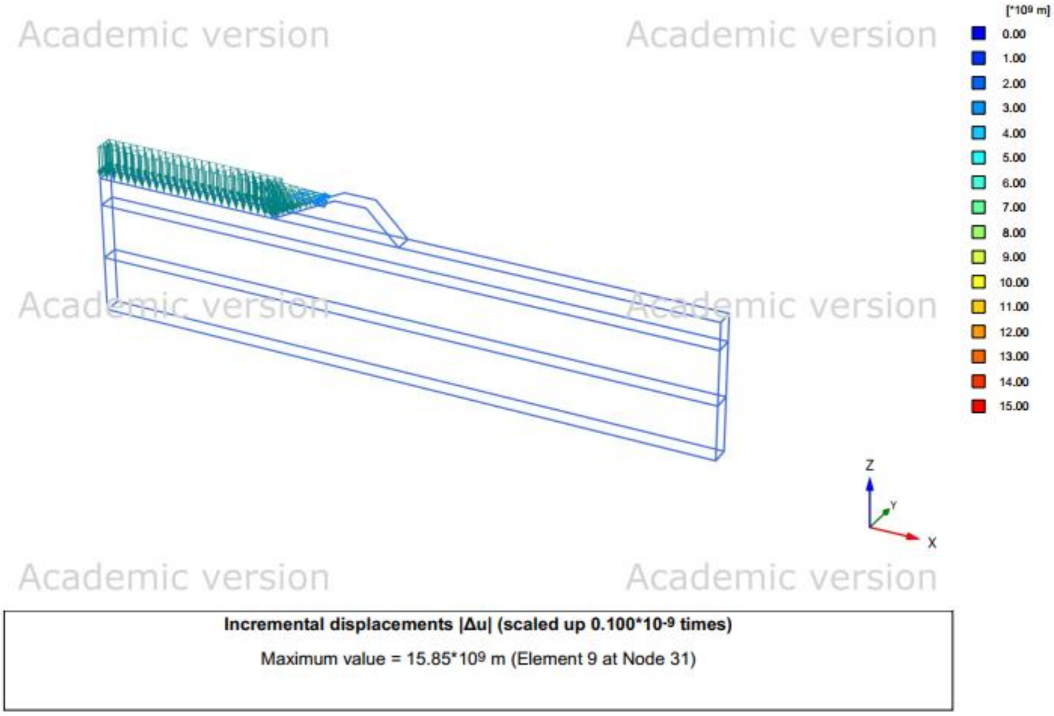
Surge height 2.8 m and thrust force 45 kN



Total displacements |u| (scaled up 0.0500 times) (Time 108.9 day)

Maximum value = 28.01 m (Element 16 at Node 33)

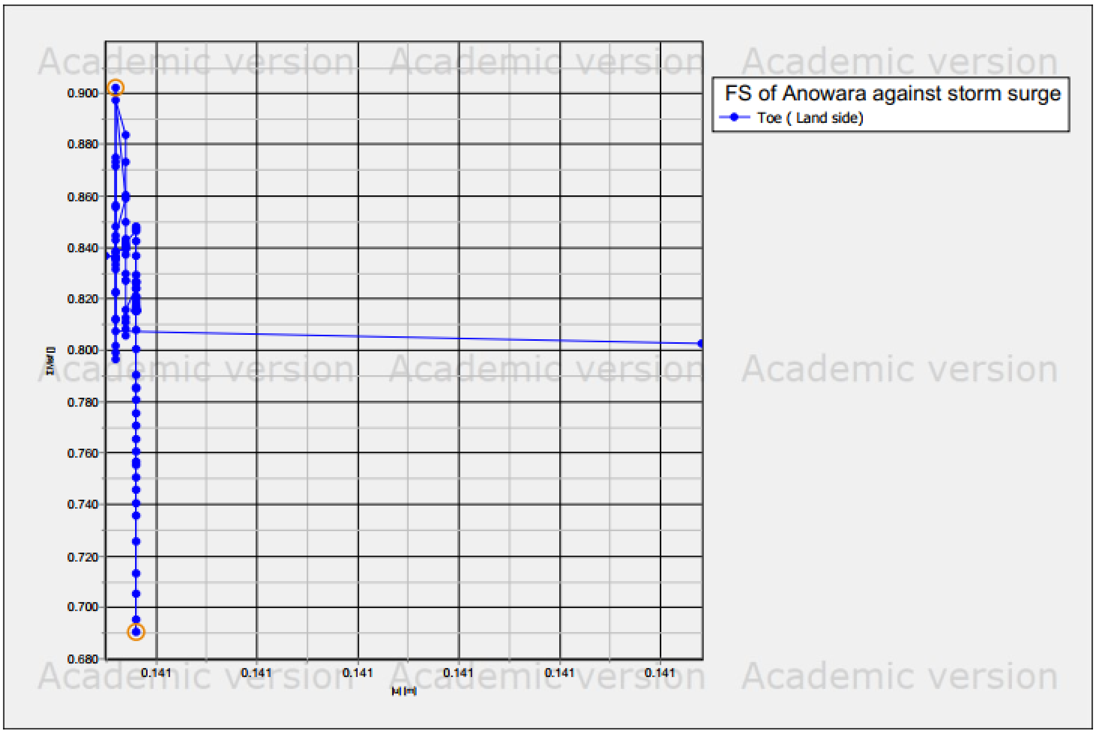
Total settlement of Anowara Polder against Surge height 2.8 m and thrust force 45 kN



Incremental displacements |Δu| (scaled up $0.100*10^{-9}$ times)

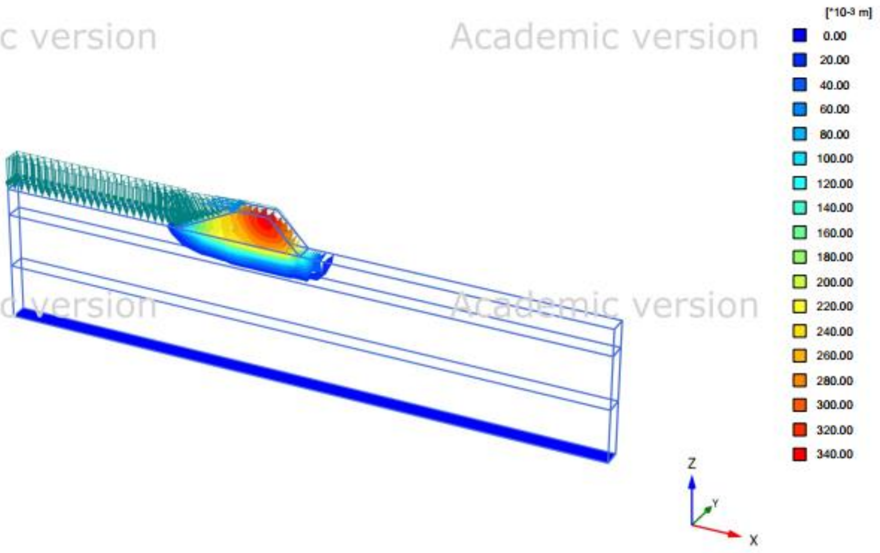
Maximum value = $15.85*10^{9}$ m (Element 9 at Node 31)

Failure mechanism of Anowara Polder against Surge height 2.8 m and thrust force 45 kN



Factor of safety of Anowara Polder against Surge height 2.8 m and thrust force 45 kN

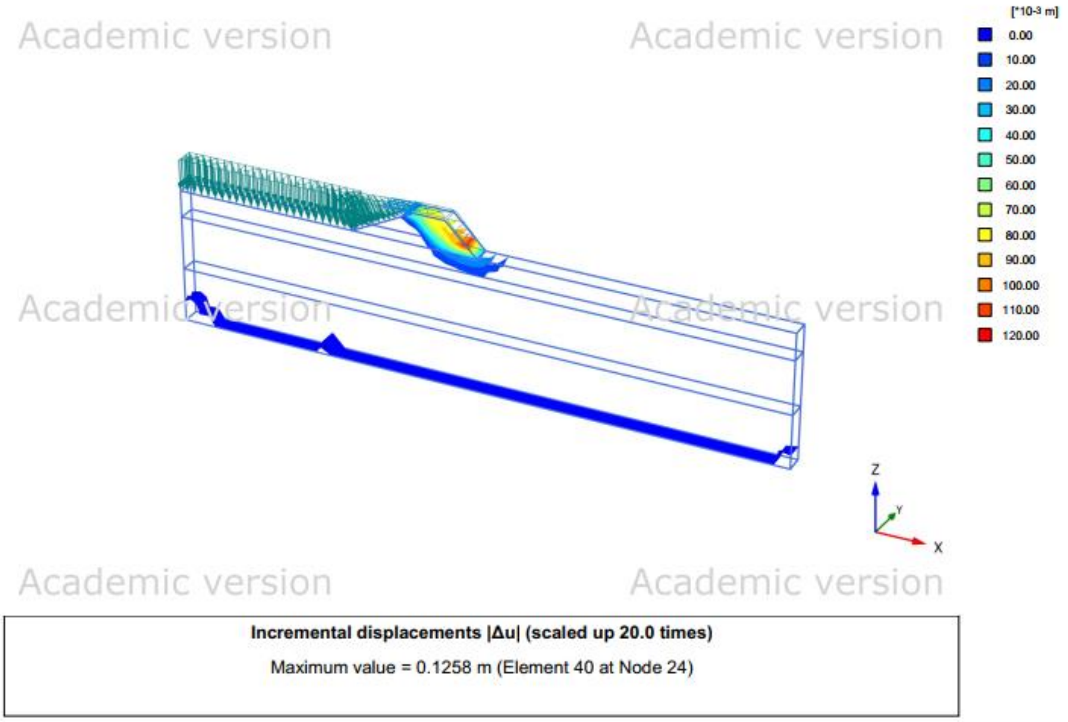
Surge height 3.8 m and thrust force 7 kN



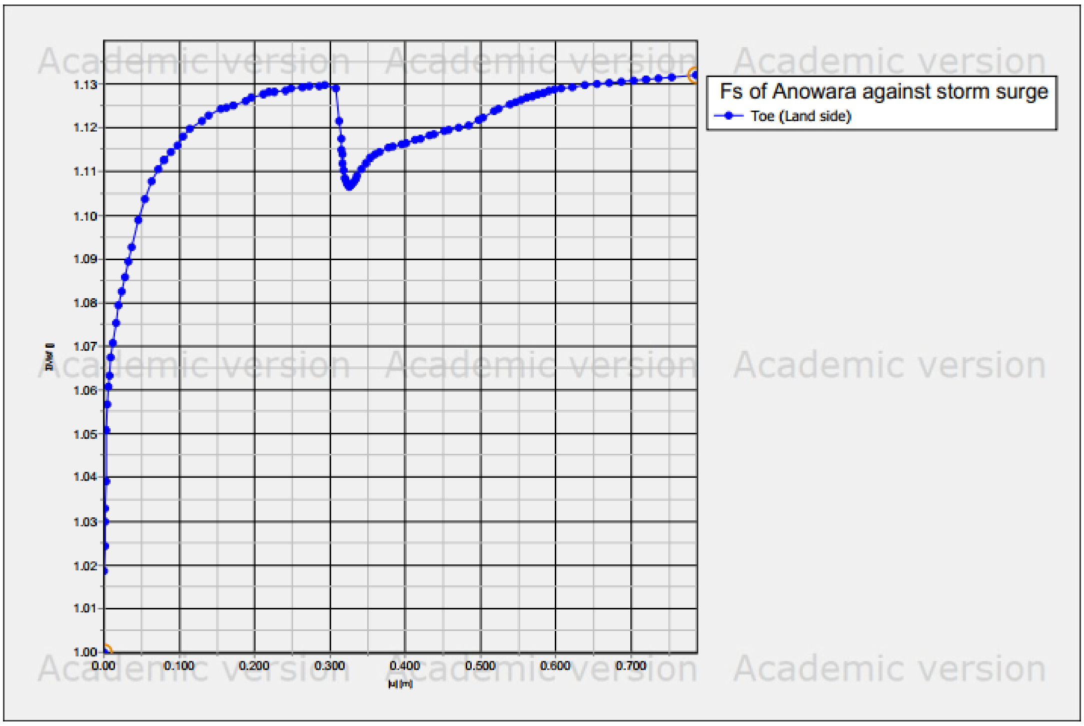
Total displacements |u| (scaled up 5.00 times) (Time 106.3 day)

Maximum value = 0.3474 m (Element 32 at Node 487)

Total settlement of Anowara Polder against Surge height 3.8 m and thrust force 7 kN



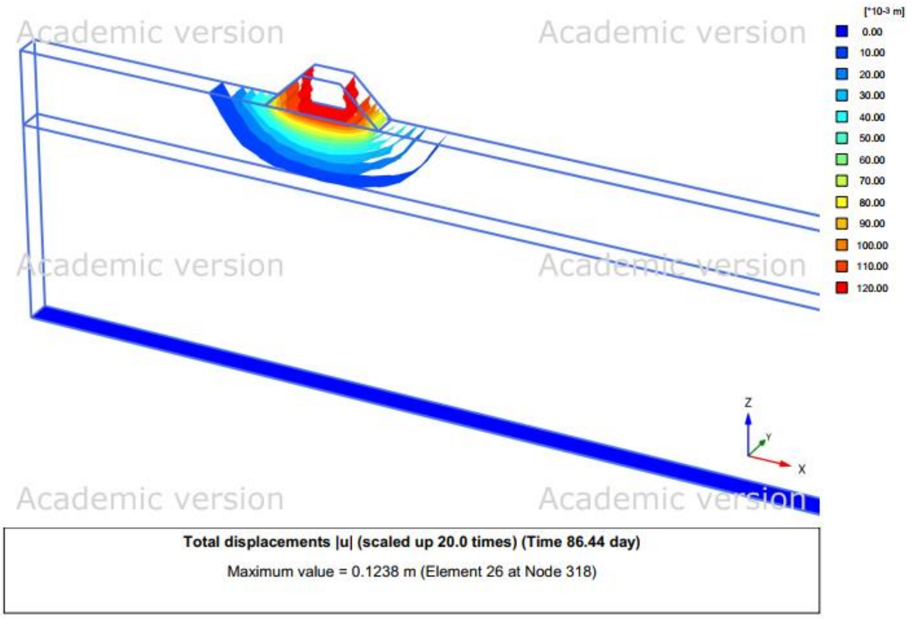
Failure mechanism of Anowara Polder against Surge height 3.8 m and thrust force 7 kN



Factor of safety of Anowara Polder against Surge height 3.8 m and thrust force 7 kN

Results of Sitakunda Polder analysis

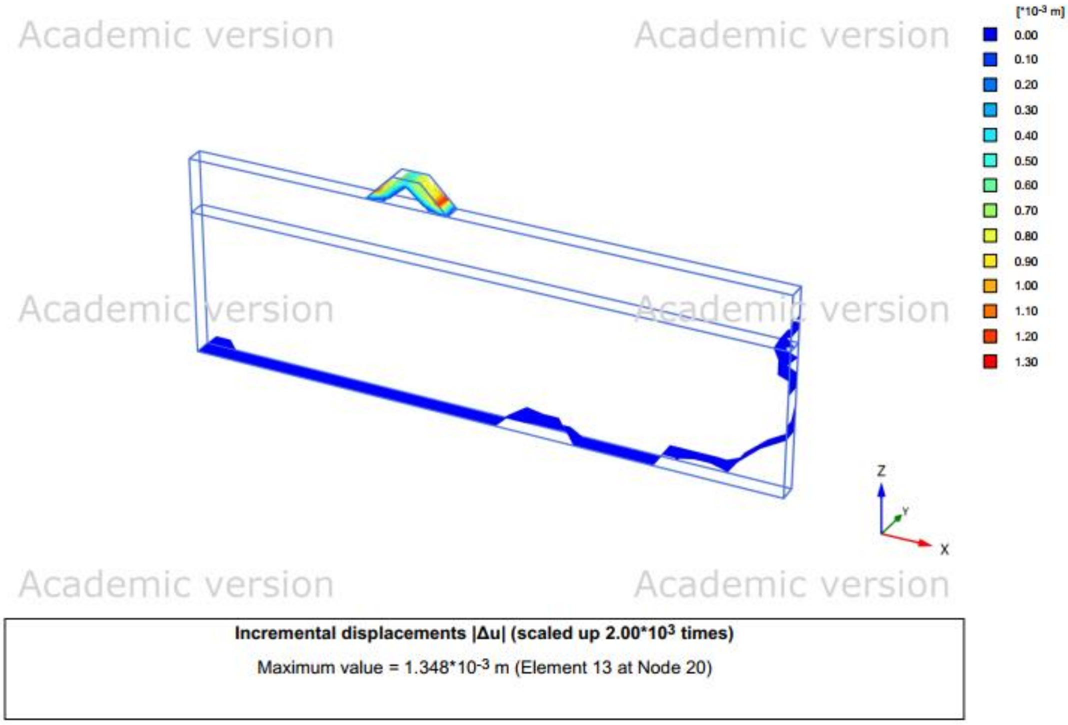
Consolidation Analysis



Total displacements |u| (scaled up 20.0 times) (Time 86.44 day)

Maximum value = 0.1238 m (Element 26 at Node 318)

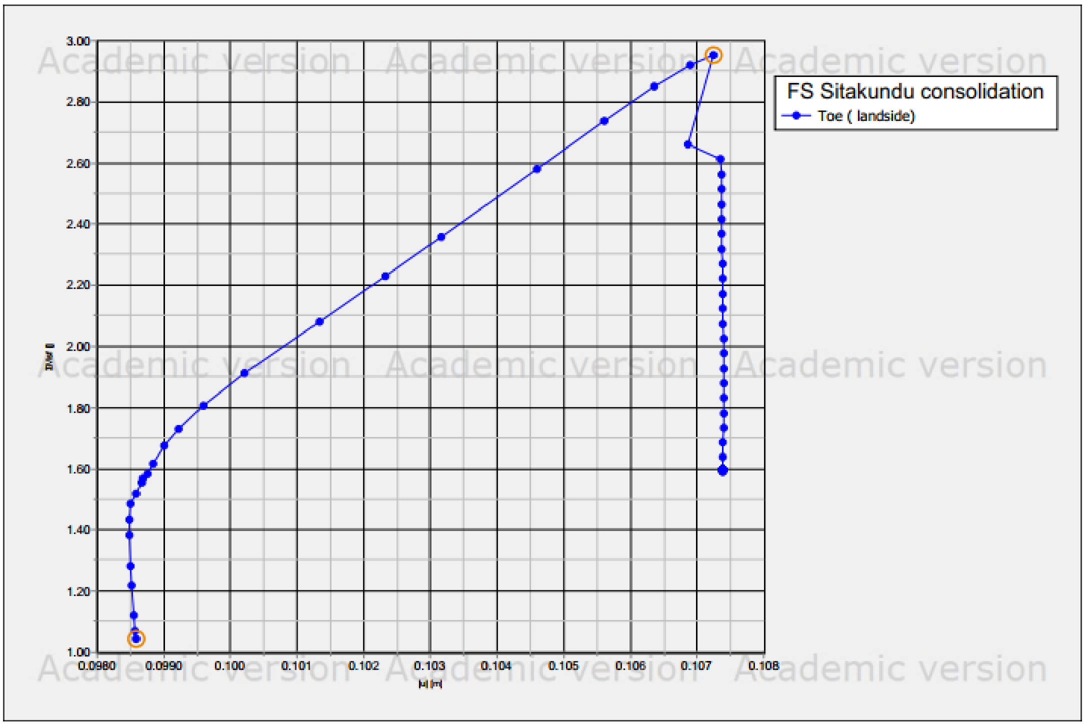
Consolidation settlement of Sitakunda Polder



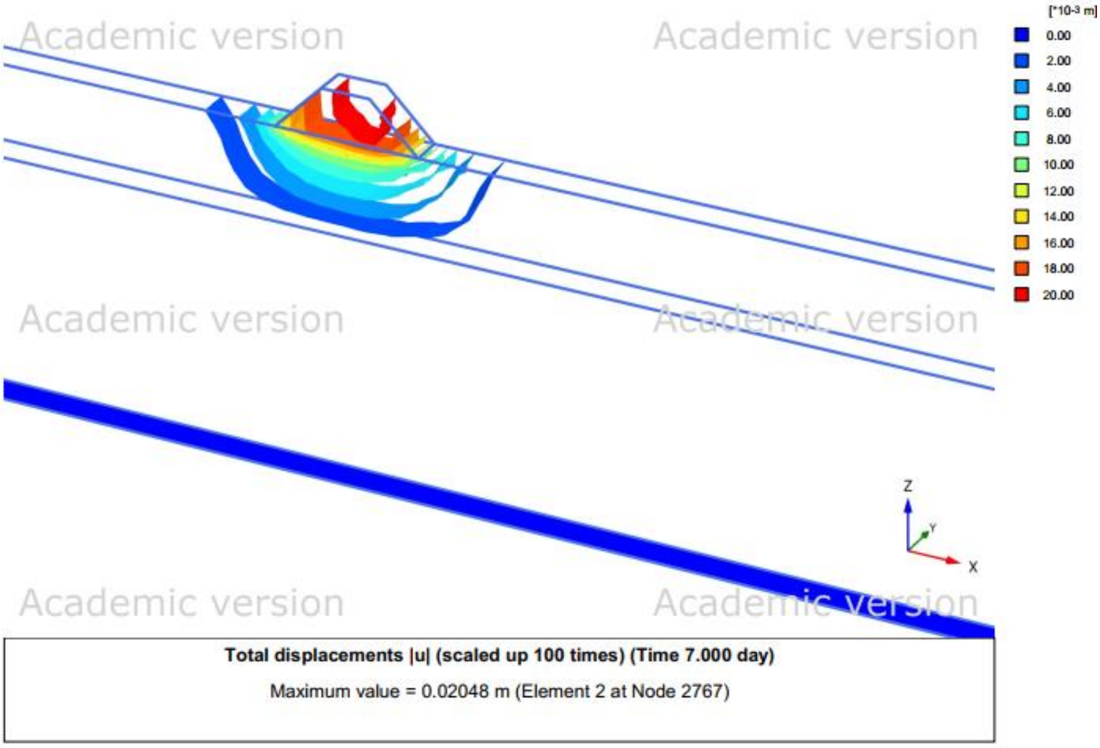
Incremental displacements |Δu| (scaled up 2.00*10^3 times)

Maximum value = 1.348*10^{-3} m (Element 13 at Node 20)

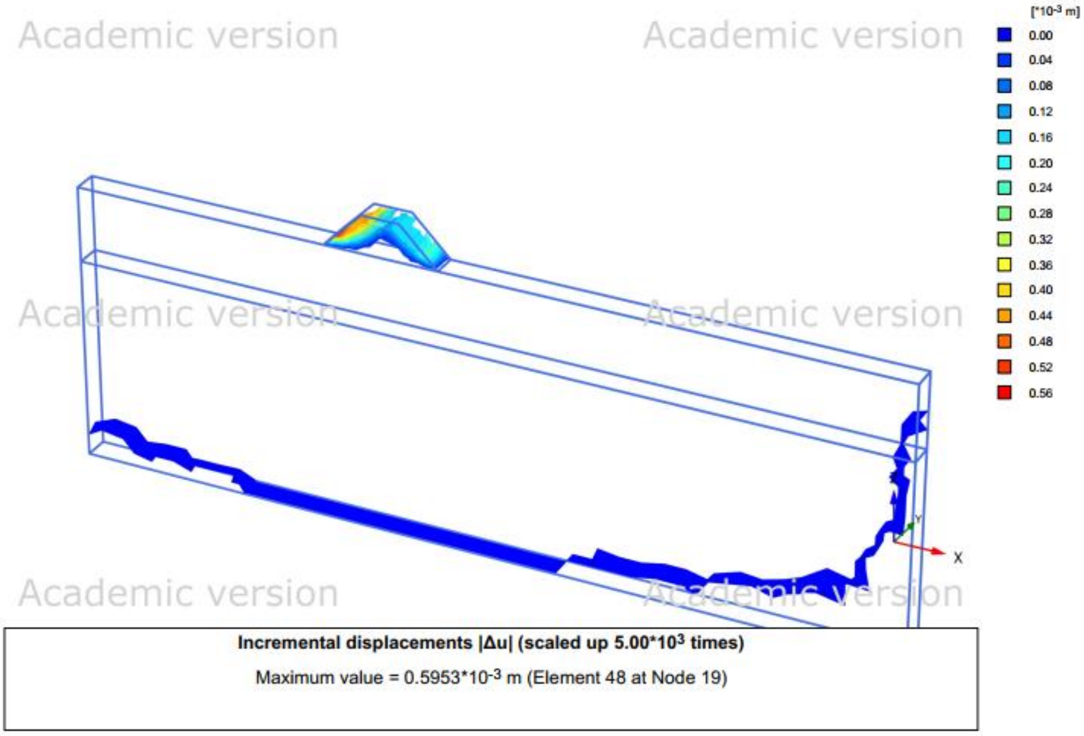
Failure Mechanism for Consolidation settlement of Sitakunda Polder



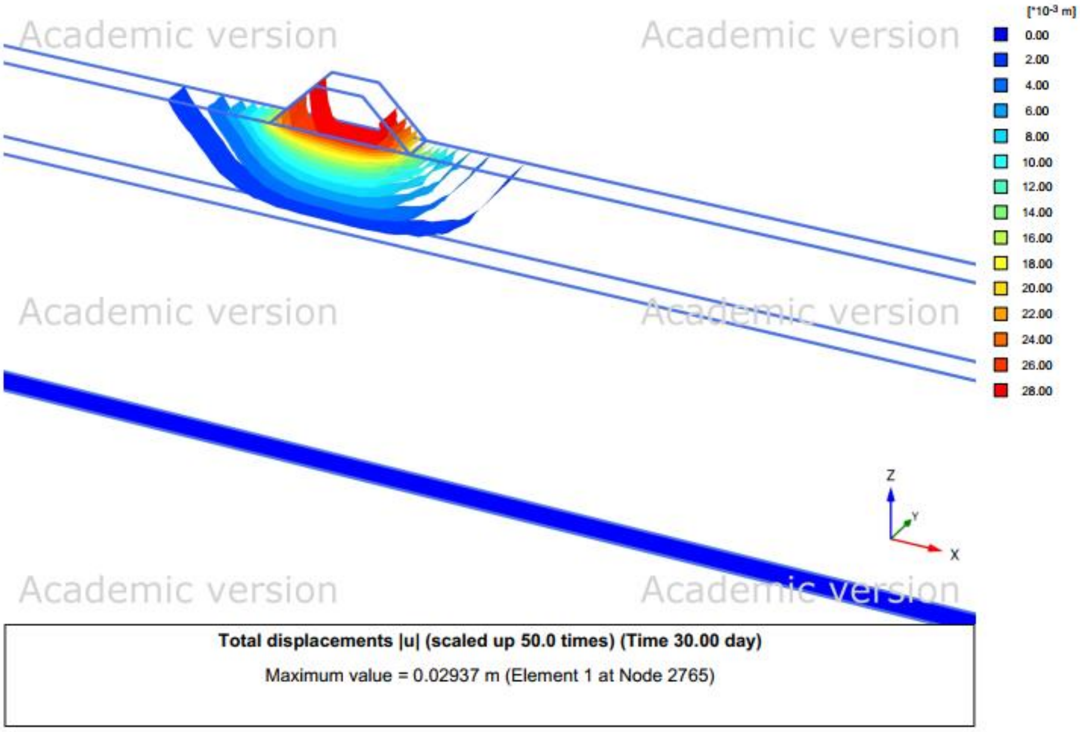
Consolidation Factor of Safety of Sitakunda Polder.



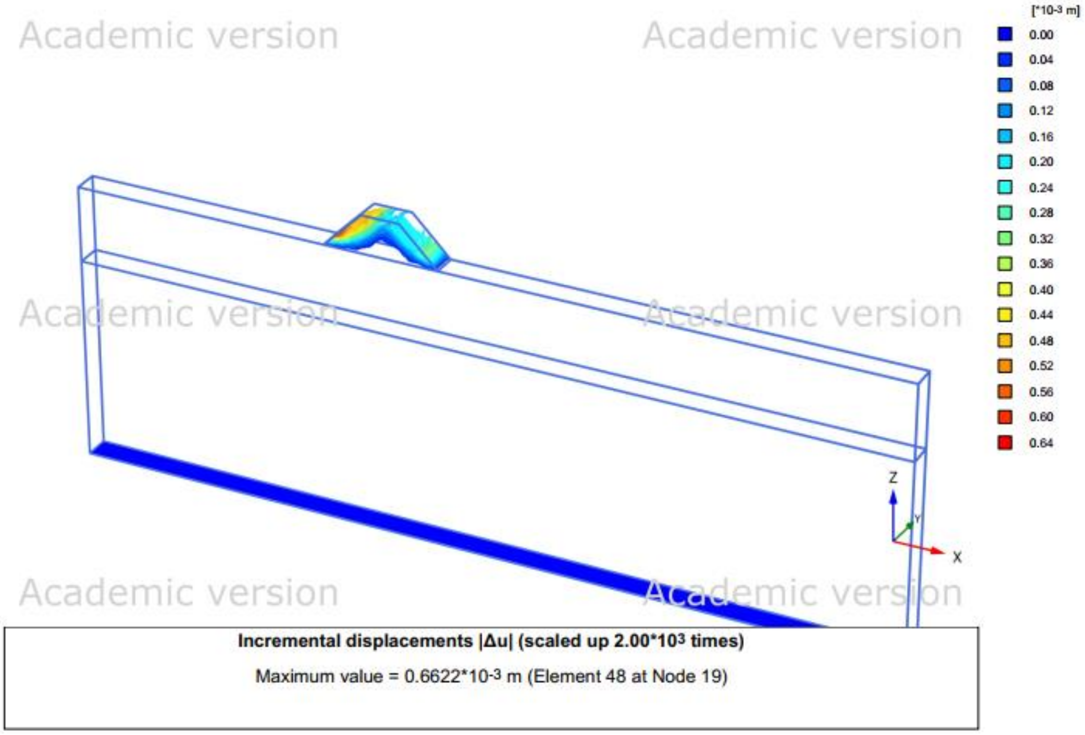
Rapid Drawdown settlement of Sitakunda Polder.



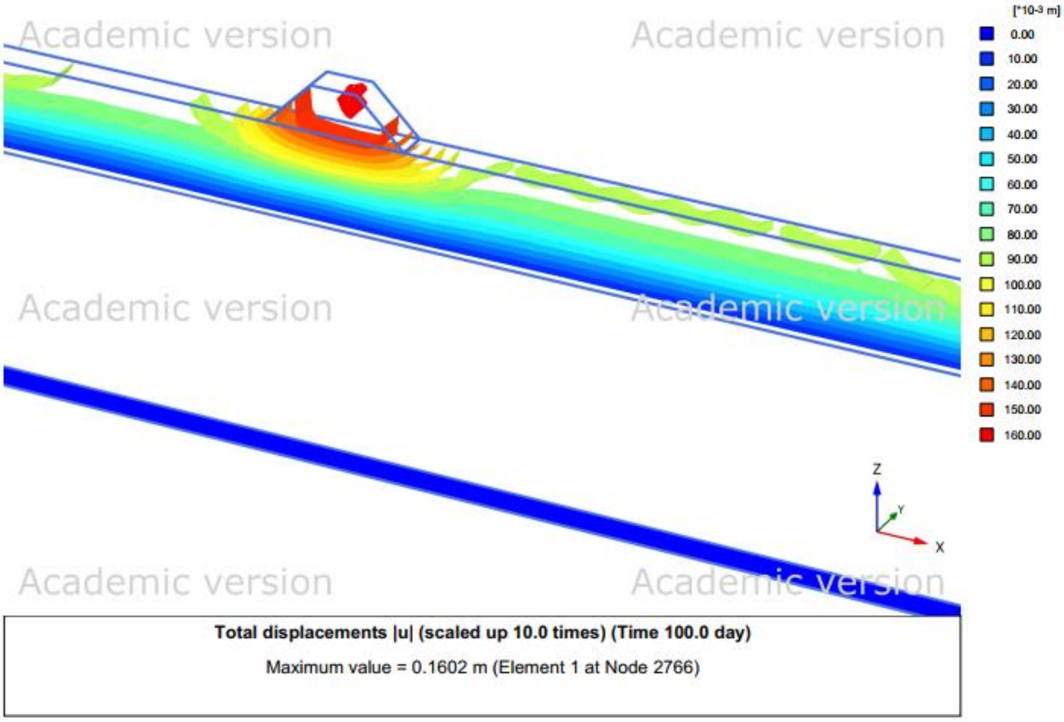
Likely failure mechanism for Rapid Drawdown condition of Sitakunda Polder.



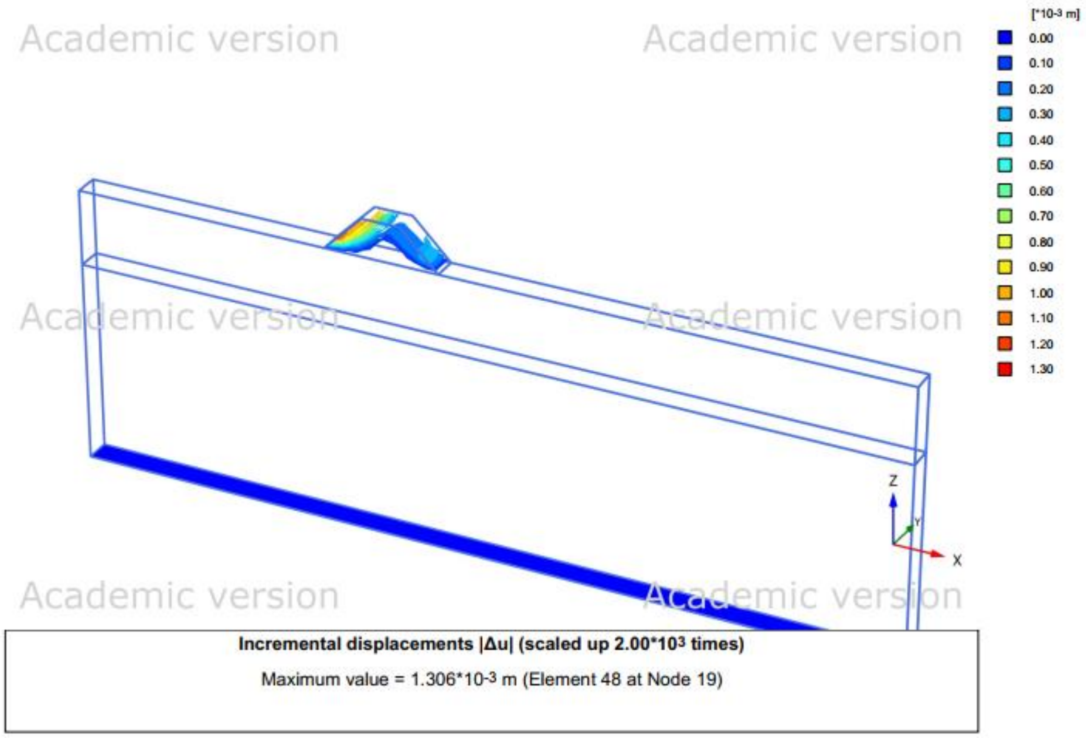
Slow Drawdown settlement of Sitakunda Polder.



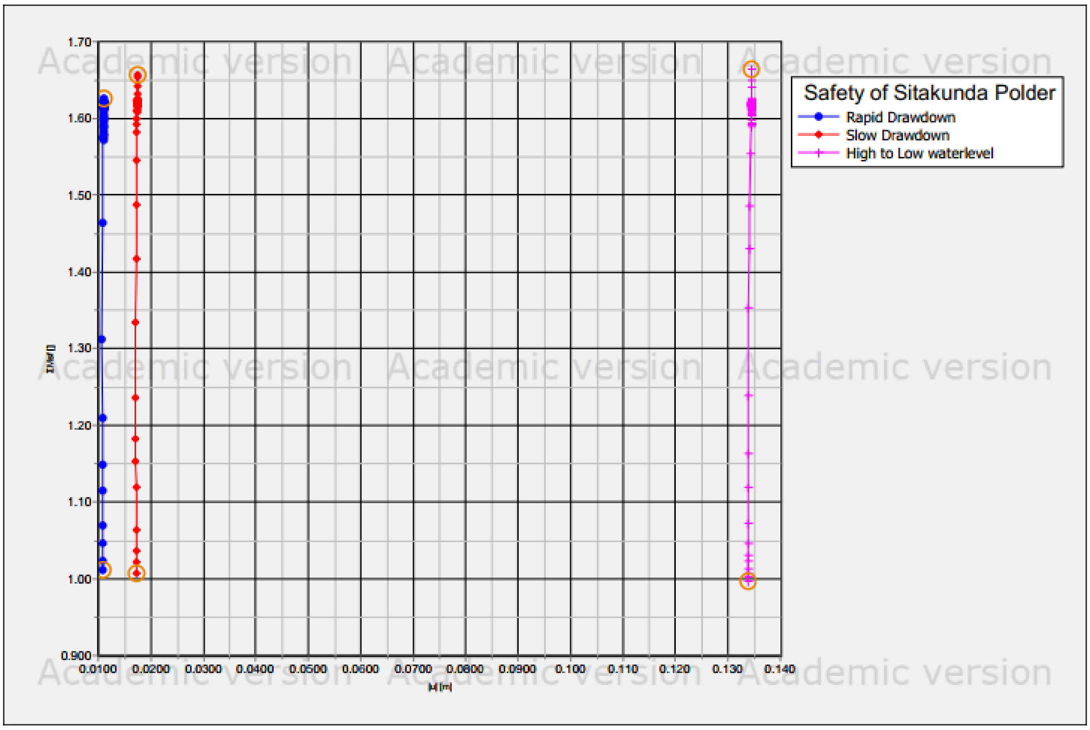
Slow Drawdown likely failure mechanism of Sitakunda Polder.



Change in water level (high level to borehole level) settlement of Sitakunda Polder.



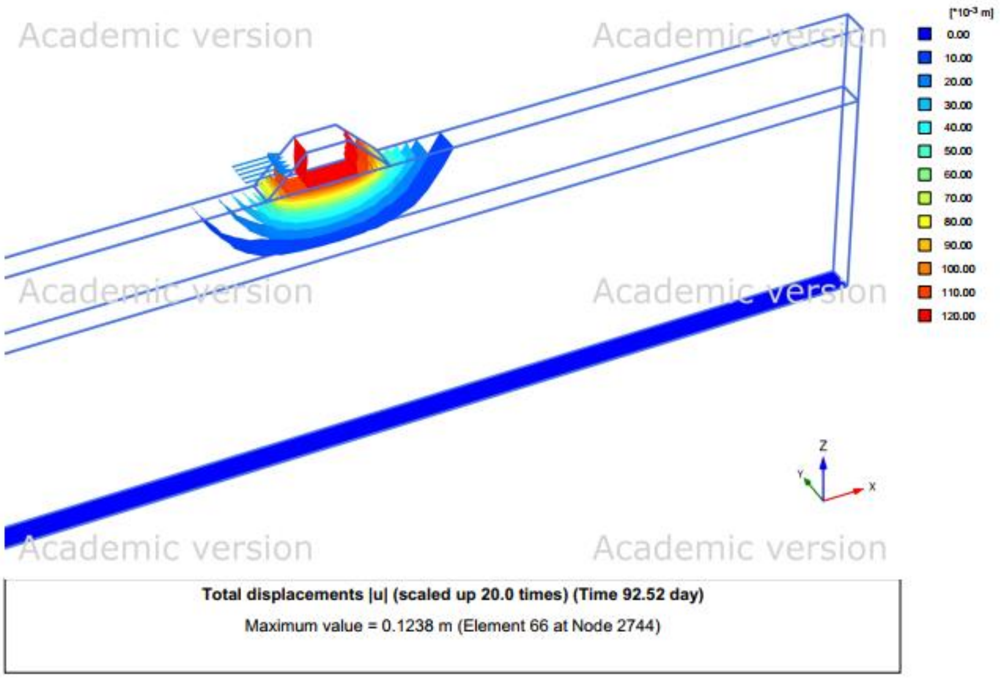
Likely failure mechanism of change in water level (high level to borehole level) of Sitakunda Polder.



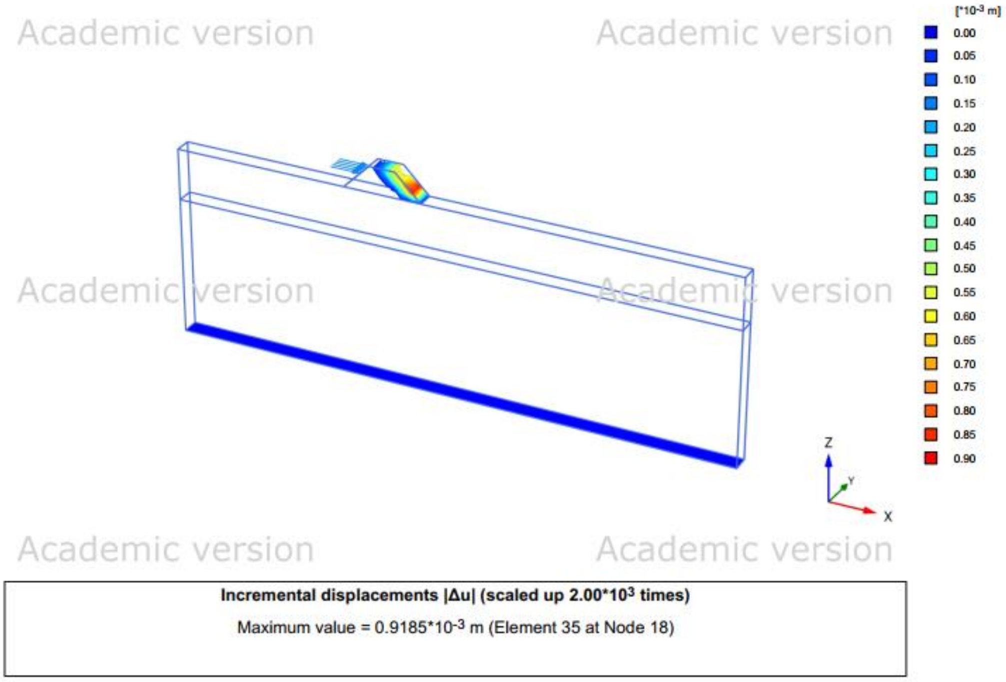
Factor of safety of Rapid Drawdown, Slow Drawdown, and change in water level (high level to borehole level) of Sitakunda Polder.

Analysis of Sitakunda Polder against Cyclone 1991

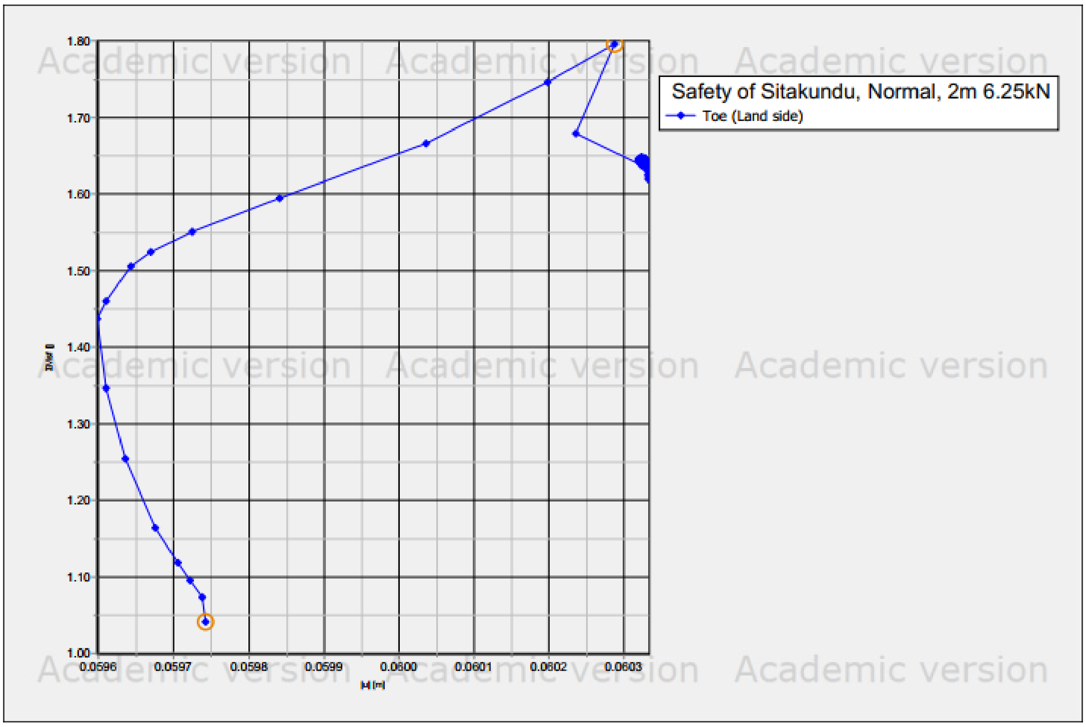
Surge height 6m and thrust force 6.25kN



Total settlement of Sitakunda Polder against Surge height 6m and thrust force 6.25kN

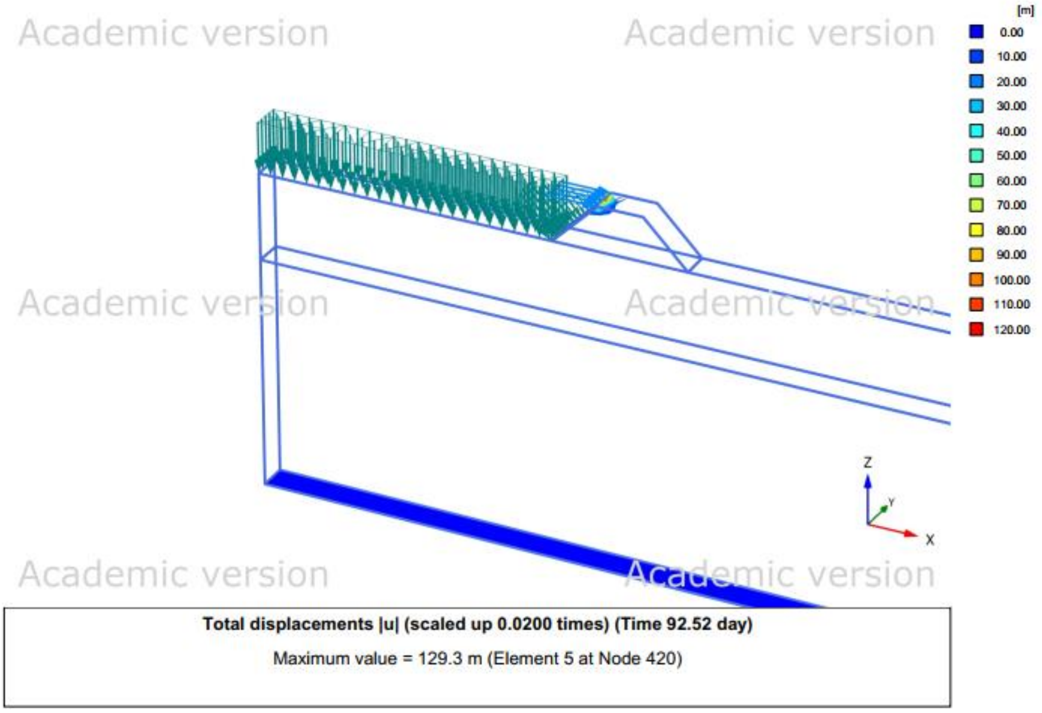


Failure mechanism of Sitakunda Polder against Surge height 6m and thrust force 6.25kN



Factor of safety of Sitakunda Polder against Surge height 6m and thrust force 6.25kN

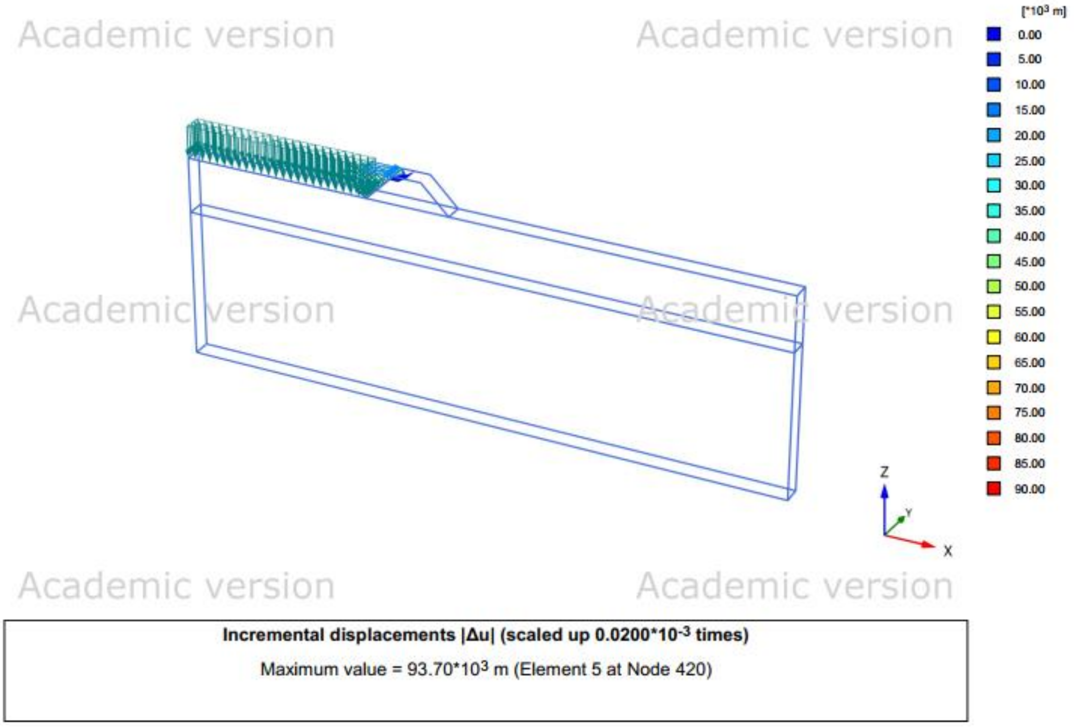
Surge height 3m and thrust force 29.23kN



Total displacements |u| (scaled up 0.0200 times) (Time 92.52 day)

Maximum value = 129.3 m (Element 5 at Node 420)

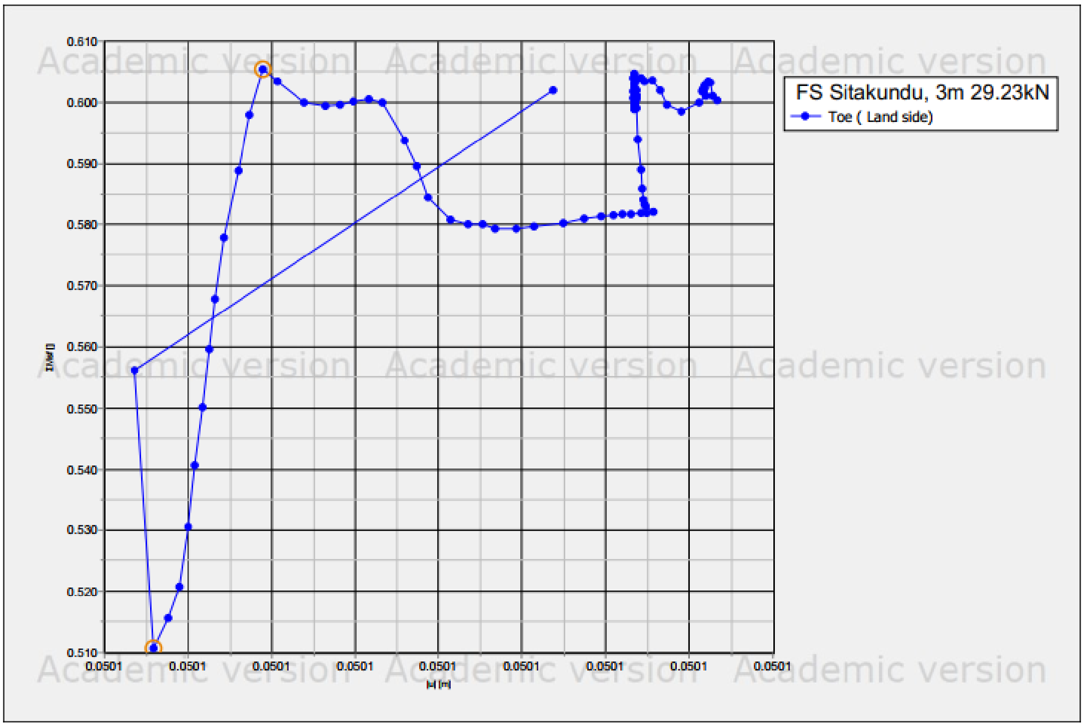
Total settlement of Sitakunda Polder against Surge height 3m and thrust force 29.23kN



Incremental displacements |Δu| (scaled up 0.0200*10^{-3} times)

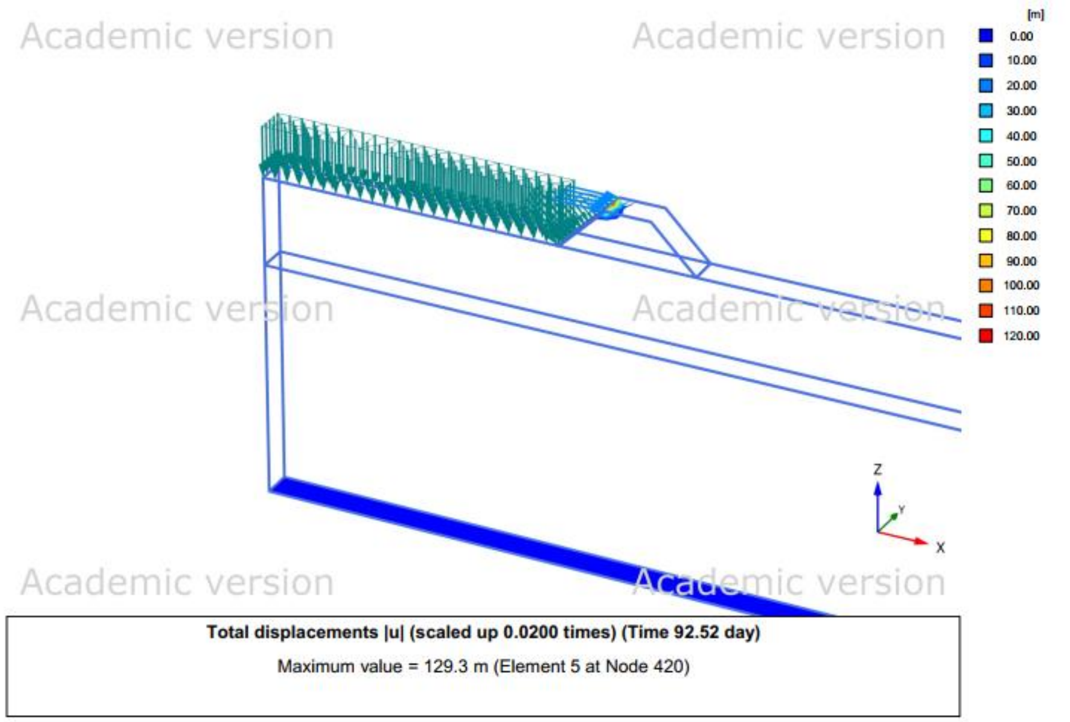
Maximum value = 93.70*10^{3} m (Element 5 at Node 420)

Failure mechanism of Sitakunda Polder against Surge height 3m and thrust force 29.23kN

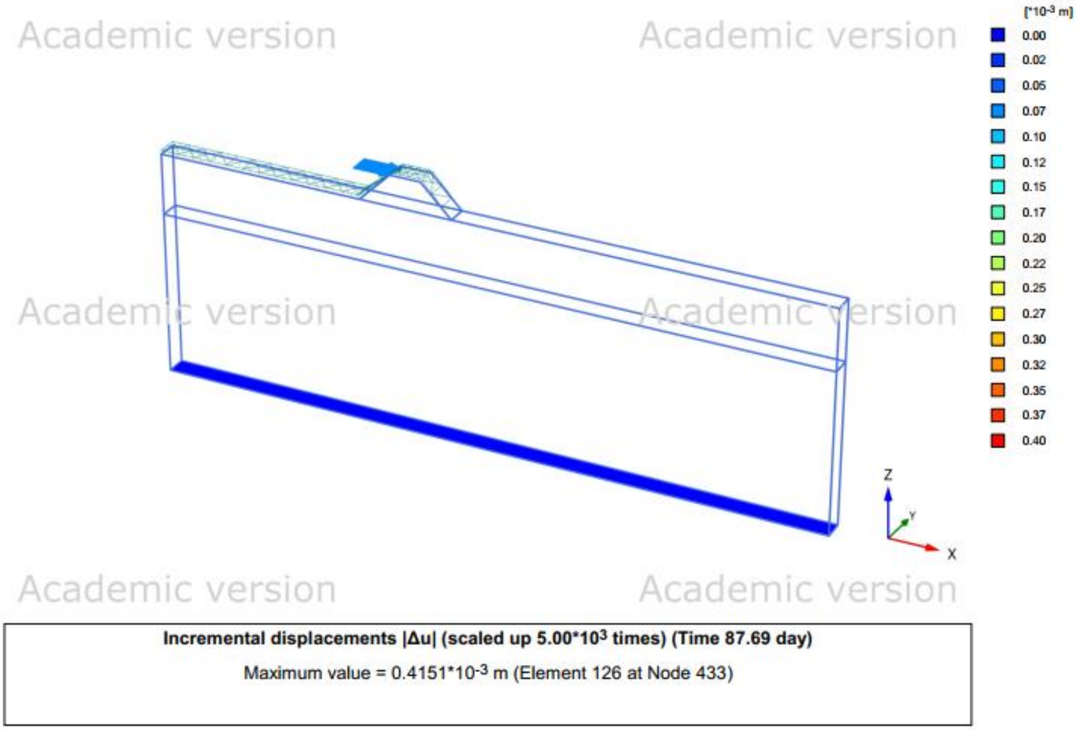


Factor of safety of Sitakunda Polder against Surge height 3m and thrust force 29.23kN

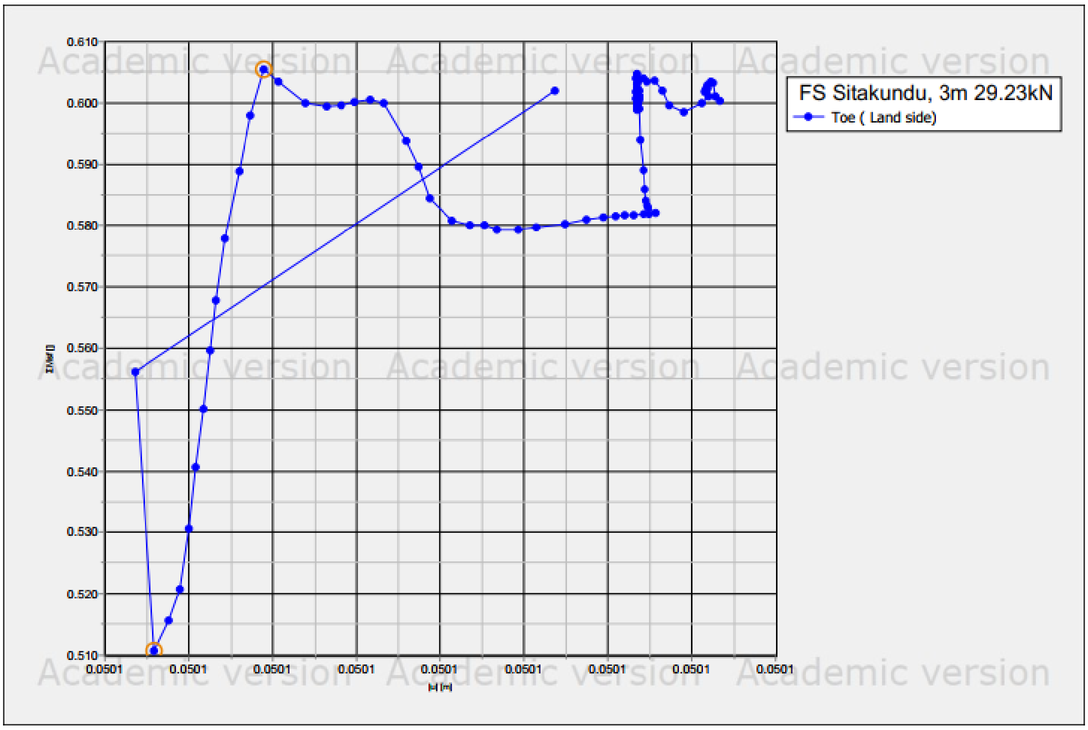
Surge height 5m and thrust force 19.3kN



Total settlement of Sitakunda Polder against Surge height 5m and thrust force 19.3kN



Failure mechanism of Sitakunda Polder against Surge height 5m and thrust force 19.3kN



Factor of safety of Sitakunda Polder against Surge height 5m and thrust force 19.3kN