STUDY OF THE EFFECTS OF WIND AND PASSENGER CROWDING ON THE SAFETY INLAND PASSENGER VESSELS

BY

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ABSTRACT

The chronological development of the intact stability criteria has been reviewed. The methodologies adopted for evolving a new stability criteria have been studied. The influence of different parameters on stability of inland passenger vessels has been investigated. It is found that wider vessels are not necessarily more stable, correction due to trim is not significant and the effect of waves is more severe in smaller vessels. The still water stability, stability against beam wind and passenger crowding of six representative double decker passenger launches plying in the inland waters of Bangladesh have been evaluated. The stability of these vessels have also been assessed with 'Strathclyde Method' and 'Lyapunov Method'. Results indicate that smaller vessels are less stable and passenger crowding is a more serious threat than wind heel. The necessity for evolving a suitable criteria for inland passenger vessels has been highlighted. A methodology for the same has also been recommended.

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TO MY PARENTS

RUKSANA

AND

AMIN

C O N T E N T S

CHAPTER 4 INVESTIGATION OF THE EFFECTS OF PARAMETERS ON STABILITY

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NOMENCLATURE

A	The lateral projected area above the waterline (m^2)/ Area under the GZ curve (m-rad).
A_1	Restoring area (m-rad).
A_2	Excitation area (m-rad).
A_{30}	Area under GZ curve upto 30 degrees.
A_{40}	Area under GZ curve upto 40 degrees.
A_{30-40}	Area under GZ curve between 30 and 40 degrees.
a	Transverse movement of the C.G. of the passengers in the awthwart direction (m).
A_{mid}	Midship area.
B	Breadth of vessel (m).
b	Mean breadth across which passengers can move in the awthwart direction in a single compartment (m).
C_b	Block coefficient.
C_m	Midship coefficient.
C_p	Prismatic coefficient.
C_{vp}	Vertical Prismatic coefficient.
C_{wp}	Water plane area coefficient.
D	Displacement (tonne) / Depth of vessel (m)
D1MT	Change of displacement for one meter change of trim (tonne / m)
D_{pc}	Stability lever due to passenger crowding (m).
D_{FW}	Displacement in fresh water (tonne).
D_{SW}	Displacement in salt water (tonne).
D_W	Heeling lever caused by constant wind (m).

$1.5D_W$ Heeling lever caused by wind gust (m).

f Floor area of a single compartment (m^2) / freeboard (m).

f_{min} Minimum allowable freeboard under load line regulations.

GM Metacentric height (m).

GZ Righting arm (m).

GZ_{max} Maximum righting arm (m).

GZ_s Righting arm at static angle of heel (m).

I_{fsm} Moment of inertia of free surface (m^4).

KB Vertical distance from keel to the center of buoyancy (m).

KG Vertical distance from keel to C.G. of vessel (m).

KM_T Height from keel to transverse metacentre (m).

KM_L Height from keel to longitudinal metacentre (m).

KN Perpendicular distance from keel to buoyancy force (m).

L Length of vessel (m).

l The distance between the centre of the lateral projected area above waterline and the centre of longitudinal projected area of the hull under water line, the later is generally taken at half the draft for simplicity (m).

L_{bp} Length between perpendiculars (m).

LCB Distance of longitudinal center of buoyancy from amidship.

LCF Distance of longitudinal center of floatation from amidship.

L_f Freeboard length of vessel (m).

L_H Height of wave (m).

L_{pp} Length between perpendiculars (m).

L_W Length of wave (m).

L_{wl}	Length at water line
MCT1M	Moment to change trim by One meter (Tonne x m / m)
n	Number of passengers in a single compartment.
S.Area	Wetted surface area.
V	Steady wind velocity (knots).
V_W	Steady wind velocity at 19.6 meter above sea level (m).
W	Total weight of passengers (tonnes).

Greek Letters

$\varnothing$	Angle of deck immersion (degrees).
θ	Angle of inclination / heeling angle (degrees).
θ_o	Static angle of heel.
θ_1	Maximum windward angle.
θ_2	Maximum leeward angle.
θ_r	Angle of rolling.
$\theta_{r,max}$	Maximum allowable angle of rolling.
θGZ_{max}	Angle of maximum GZ.
θ_v	Angle of vanishing stability.

ABBREVIATIONS

BIWTA	Bangladesh Inland Water Transport Authority.
BIWTC	Bangladesh Inland Water Transport Corporation.
BMT	British Maritime Technology Ltd.
BSRA	British Ship Research Institute.
BUET	Bangladesh University of Engineering & Technology.
B/D ratio	Breadth to Depth ratio.
DOS	Department of Shipping.
IMCO	Intergovernmental Maritime Consultative Organisation.
IMO	International Maritime Organisation.
ISO	Inland Shipping Ordinance.
IWT	Inland Water Transport.
L/B ratio	Length to Breadth ratio
MOS	Ministry of Shipping.
MSO	Merchant Shipping Ordinance.
NMI	National Maritime Institute.
RINA	Royal Institution of Naval Architects.
SOLAS	Safety of Life At Sea.
sp.gr	specific gravity.
USCG	United States Coast Guard.

CHAPTER 1

INTRODUCTION

1.1 General:

Bangladesh is a riverine country. The gentle alluvial deltaic plain which stretches over 1,43,998 square kilometers is the product of three mighty rivers running off the Himalayas viz., the Ganges-Padma, the Brahmaputra-Jamuna and the Meghna. There are 8,433 kilometers of navigable natural inland waterways in the monsoon season which shrink to approximately 5,222 kilometers in the dry season[1(*)]. Not only do the three major rivers and their innumerable tributeries like the Rupsa, the Surma, the Lakhya, the Dhaleswari, the Bhaguakul, the Pusur, the Kushiyara etc. give a good coverage to most areas of the country when flowing at low level, but also give almost complete access to all parts when in flood. The geographical features have made Bangladesh one of the most difficult areas in the world for which to provide a modern surface transport system suitable for guaranteed communication all over the year. In almost all parts of the country, the highways and railways

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* Numbers in the superscripts indicate references at the end of the thesis.

require embankments, sometimes as high as 6 meters, so that they are usable during floods. The necessity of constructing numerous bridges on the wide rivers, which keep on changing their courses, inhibits the development of surface transport systems of road and rail.

Importance of water transport sector in the daily necessity of the people as well as the infrastructure of business and commerce can hardly be overemphasized. Being the cheapest mode, water transport is always preferred over any other mode except where navigable waterway is absent or the time is of vital importance. Consequently, the number of vessels, both passenger and cargo has been rising steadily during the last few years. It is true that siltations of major rivers is causing a threat to the shipping industry, but the statistics[2] indicate that the magnitude of expansion of inland water transport fleet negates the alarms being raised by certain quarters. The number of cargo vessels have increased from 615 in the year 1983-84 to 889 in the year 1986-87. From the year 1982-83 to 1987-88 (provisional figures) the goods movement by railway has reduced by 9.84%, by road it has increased by 12.6% while the increase in water transport was 26.33 %[10].

Almost one third of the imports through Chittagong Port and two thirds through Mongla Port are carried to hinterland by vessels of different sizes and types[3]. Due to absence of liner service between the ports and major locations inside the country e.g., Dhaka, Narayanganj, Bhairab, importer of small quantity of cargo have to depend on road transport system. However, water transport is almost the exclusive means of goods movement to the interior of the country by mechanised and non-mechanised vessels and boats.

As far as the movement of passengers are concerned, due to enormous expansion of the road network in the country during the last few years, the balance has shifted heavily away from the water transport facilities. As a result, the number of mechanised passenger vessels have increased by only 7.9% from 1983-84 to 1986-87. Nevertheless, passenger launches are still the major mode of transport for the people of the southern portion of the country. The people living in the offshore islands like, South Hatiya, Sandwip etc. are solely dependent on the passenger services of the public sector organisation Bangladesh Inland Water Transport Corporation (BIWTC). A large number of the passenger launches are categorized as typical Double Decker Passenger Launches. These are characterized by large size (generally over 25 meters) and huge superstructures. Double decker launches play a major role in the movement of passengers in the inland waters. These vessels are almost the sole means of communication from the capital city to the southern districts like Barisal, Bhola, Pirojpur, Borguna etc. In addition, these vessels also carry a small quantity of cargo. But this small cargo is expected to make a significant influence on the stability of the vessels. Unfortunately, these vessels have been allowed to operate without adequate study of their stability.

Mechanisation of country boats and advent of steel bodied small mechanised boats have dramatically changed the pattern of inland water transportation system. The vessels use engines which are normally intended for agricultural use. The number of such vessels are unknown, but believed to be in tens of thousands. There are, infact, two types of such vessels, i) old fashioned wooden country boats with propulsion fitted, ii) large dingy boats of simple hard chine flat bottom construction. The government has exempted them from the requirements of the Inland Mechanically Propelled Vessels Act (IMPV Act). There have been numerous accidents involving such vessels. Maritime administrations have found no means of regulating these vessels and minimize accidents.

But unfortunately, the water transport sector has never got the attention it deserves from the planners, researchers and aid-givers in Bangladesh. As a matter of fact, beyond fitting crafts with engines, the watercrafts remain nearly the same as they were one hundred years ago. It is a pity that every year countless people are killed in accidents in our rivers. Truely speaking, launch disasters have become an annual tragedy of Bangladesh. Infact, little or nothing has been done to improve the safety on passenger vessels of the country in the past.

1.2 Inland Passenger Vessel; Experience from Crash Programme:

It is not true that nothing has been done to upgrade the stability of the passenger vessels plying in our inland waterways. An experiment was carried out for introduction of a standard designed passenger vessel. The project started in 1976, a year which saw several tragic accidents involving passenger vessels. The project was known as 'Crash Programme' and was technically assisted by Dutch experts. But the experience gained from the programme is not a very pleasant one. In the discussion of safety passenger vessels, it is essential that the 'Crash Programme' be also discussed and the unpleasant experience gained from the programme is utilised in any future programme.

The design of those vessels were drawn up by Dutch experts and subsequent model tests were carried out in the Delft University Towing Tank in the Netherlands. The hull dimension was fixed at 18.3 meter (60 feet) long, 5.5 meter (18 feet) wide, 1.83 meter (6 feet) in depth and having a draft of 1.37 meter (4.5 feet). These were powered by engines of 150 to 200 BHP. The government took a crash programme, from which the title was derived, to deploy one hundred such vessels in a short time. The two public sector development financing institutes (DFI) viz., Bangladesh Shilpa Bank and Bangladesh Shilpa Rin Sangstha were instructed to extend loan on easy terms for the project. In the first stage 40 such vessels were sanctioned.

But the performance of the vessels were, at best, seriously disappointing. It was from the point of view of the operating economics. The engine power was excessively high compared to conventional vessels of similar size and capacity. The fuel consumption was very high compared to the passenger capacity and so were the fare collections. The speed of the vessels were also not satisfactory. As a result, the vessels stopped operation within a few days of going into service. Some were operated as tug boats for quite a while. Banks were not getting repayment. The matter was ultimately forwarded to the Department of Naval Architecture and Marine Engineering of B.U.E.T. The author was fortunately a member of the team investigating the matter. Two separate reports were prepared and presented[4,5]. The conclusions were that, though the vessels were apparently safe for the passenger, it did not have the techno-economic characteristics required for such vessels. The stability was achieved only by increasing the breadth in proportion to the length and depth/draft. Such a wrong decision was taken because the matters were handled by foreign experts who had little or no knowledge about the socio-economic environment of the country and taste, pattern, capability etc. of the passengers. Had a Towing Tank been available in the country, necessary trials and experiments could be performed to get the most optimum combination of techno-economic aspect, static and dynamic stability etc. This could have helped in coming out with a suitable design which would have been successful in operation also.

1.2.1 Sunken Deck Passenger Vessels:

There have been indigenous attempts for improving stability of passenger vessels. One of the methods, quite widely adopted, is the sunken deck concept. The deck of the vessels is lowered from the top end of the side shells. These vessels are termed as 'sunken deck' vessels. The concept originated from the foremen level and was not backed by any technical expertise. The argument presented in favour of the concept is that due to lowering of the deck, the whole accommodation is lowered and it will have positive affect on the centre of gravity. But there appear to be little technical soundness in the argument.

As long as the initial stability is concerned, the metacentric height is the only factor concerned. Due to large breadth these vessels already have high GM. There is absolutely no necessity of increasing it. But at large angles the hull shape plays a major role in determining stability. The author had earlier addressed the matter and had shown that the large angle stability of such vessels are much lower than ordinary vessels[6].

This is due to the fact that due to the change in the hull geometry, the ratio of the breadth to depth increases drastically, which is already very high in ordinary vessels. As will be shown later in the thesis that large breadth to draft ratio does not always contribute to stability. In fact, sometimes it is the other way round. In our country, the depth of such vessels are generally measured upto the top end of the side shells. But this is not as per standard practice. Depth is generally measured upto the lowest point of the deck at side[7]. Due to this anomaly in depth measurement, the actual freeboard of such vessels may even be negative at moderate overload. It has also been observed that there are non watertight openings just over the deck in the side shell[8]. This is for overboard discharge of deckwashing waters. At moderate overload this may become source of deck flooding. Due to the sideshells extending above the deck, rain water will create large free surface and seriously jeorpadise stability.

1.3 Passenger Vessels: Stability, Comfort, Safety and Socio-Economic Aspect:

The stability and rolling motion of a vessel in the simplest possible form can be explained with Figures 1.1, 1.2, 1.3. Figure 1.1 shows a vessel in upright condition. The Center of Gravity (CG) of the vessel is located at point G. The buoyancy of the vessel works through the point B. The vertical distances are generally measured from Keel (point K). In the upright condition the two forces are at static equiilibrium. If the vessel is listed to either port or starboard side, the shape of the underwater portion of the hull changes. Although the magnititude of the buoyancy force remains equal to the displacement of the vessel, but due to the change in the underwater shape the center of buoyancy B changes its location to B'* (Figure 1.2). The amount of shift depends on the hull geometry and the angle of heeling. At small inclination (less than 7 degrees), the direction of the buoyancy force cuts the centrline of the vessel at a point called metacenter 'M'. The location of the center of gravity of the vessel, in the ideal condition, remains in the same place.

The vertical distance between center of gravity and the metacenter, called the metacentric height GM is the first index of stability. The distance is positive if the point 'M' is vertically above the point 'G'. Figure 1.2 and 1.3 are distinguished by the matter that the value of GM is positive in the former and negative in the latter. As can be seen from the two figures that at inclinations the weight of the vessel and the buoyancy force form a couple. If the GM is positive (Figure 1.2), the couple will tend to bring the vessel back to upright position. But if the GM is negative (Figure 1.3) the couple will try to upset the vessel. In other words the vessel is termed stable if the GM is positive and unstable if GM negative. A stable vessel will tend to get upright when listed by some agent like wind, wave etc., what is normally experienced in water crafts. It appears from Figure 1.3 that a vessel with negative GM will capsize even after small initial inclination. A review of stability at large angles in any text book of naval architecture will suggest that the vessel will not necessarily capsize but will remain floated inclined to a certain angle to either port or starboard side.

In the design and operation of passenger vessels, however, stability is not the only governing criteria, but three factors are of profound significance. These are (i) safety (ii) comfort and (iii) speed. While improving one quality of the vessel, the designer can not just simply ignore any other. It should be remembered that the launch is the home of its crew as well as the passengers for hours together and the influence of rolling upon comfort is, therefore, extremely important. Rolling moment affect the human organism intensely and harmfully when they are harsh and violent. An important role in the incidence of seasickness is played by the equillibrium apparatus located in the organ of hearing. Disturbances of this apparatus, as a result of inertial effects brought about by the rolling motions, induce the symptoms of seasickness. It has been established by the observations that the symptoms of seasickness become particularly pronounced if the linear accelaration taking place during the motions, exceeds 1/10th of gravitational accelaration[9]. The problem of stabilizing the rolling motion of ships can not at the present time be considered entirely solved, although significant advances have been made in this direction. The successful treatment of this problem is of great interest both to merchant and naval shipbuilding. In merchant shipbuilding stabilization of motions is of particular significance for passenger vessels, since it improves the conditions of their habitability and thereby enhances their reputation with the travellers.

The stability and comfort to the passengers make conflicting demands to the designer. The time period of rolling is inversely proportional to the square root of the metacentric height, i.e., the initial index of stability. If more stability is required, the metacentric height need to be increased and it will result in increase in rolling period and consequently discomfort to the passengers. However, there are solutions. A antirolling device like bilge keel will make no influence on the intact stability but will reduce the rolling period giving comfort to the passengers. In fact, this bilge keel will also improve the stability of the vessel in real case.

However, truely speaking, the accidents involving passenger vessels in our inland waters can not be attributed solely to stability or any major fault in the design of the vessels. In fact, the problem is not purely a technical one but rather socio-economic in nature. The initial stability of inland passenger vessels seem to be satisfactory from the point of view of safety. But while in operation, the upper decks of the passenger vessels are sometimes abnormally overloaded. Such a situation may arise under the following circumstances.

(i) There being no checks on overloading on launches, they carry passengers and other commodities much beyond their maximum capacity, specially during festivals. In an overloaded launch, it is simply that many passengers move upto topmost deck in search of space.

(ii) At the time of crisis the panic stricken passengers rush to the topmost deck. It is needless to mention that their sudden upward movement seriously reduces the stability of the launch.

(iii) Moreover, during emergency the passengers usually run towards the port side if the vessel is inclined towards the starboard side and vice versa. Any one acquainted with the theory of ship motion will realize that such movement of passengers seriously intensify the rolling motion of the vessel aggravating the situation further.

(iv) In extreme cases, the passengers may run towards the side of the vessel and jump onto the river for fear of life. This again makes the tossing vessel more violent.

CHAPTER 2

INLAND WATER TRANSPORT SECTOR:

ADMINISTRATION, INFRASTRUCTURE AND STATISTICS

2.1 General:

The maritime administration of the country is looked after by two different organisations, namely, (i) Bangladesh Inland Water Transport Authority (BIWTA), an autonomous organisation under the Ministry of Shipping of the Government of Bangladesh and (ii) Department of Shipping (DOS), a directorate under the same ministry. The former organisation (BIWTA) deals with infrastructure facilities concerning inland shipping and maintain statistics of the same. The Department of Shipping is mainly concerned with overseas shipping, and performs only regulatory functions in inland shipping.

The statistics presented in this chapter are mainly adopted from reference-1. Some information is also taken from sources of the Department of Shipping, but these are mentioned in the proper place.

2.2 Responsibilities and Functions of BIWTA:

The Bangladesh Inalnd Water Transport Authority was set up in November' 1958 for development, maintenance and control of inland water transport and of certain inland navigable waterways of Bangladesh[1].

The authority has the following statutory functions:-

(i) Carry out river conservancy works including river training works for navigational purposes and for provisions of aids to navigation, including marks, buoys, lights and semaphore signals.

ii) Disseminate navigational and meteorological information including publishing river charts.

iii) Maintain pilotage and hydrographic survey service.

iv) Draw up programmes for dredging requirements and priorities for efficient maintenance of existing navigable waterways and for resusciation of dead or drying rivers, channels or canals including development of new channel and canals for navigation.

v) Develop, maintain and operate inland river ports, landing ghats and terminal facilities in such ports or ghats.

vi) Carry out removal of wrecks and obstructions in inland navigable waterways.

vii) Conduct traffic surveys to establish passenger and cargo requirements on the main rivers, feeders and creek routes.

viii) Develop the most economical facilities for passenger traffic to ensure comfort, safety and speed on mechanised crafts.

ix) Fix minimum and maximum fares and freight rates for inland water transport on behalf of the government.

x) Approval time table for passenger services.

xi) Develop rural water transport by progressing of schemes for modernizing and mechanizing country crafts.

xii) Ensure co-ordination of inland water transport with other forms of transport, with major sea ports, and with trade and agricultural interests for the optimum utilisation of the available transport capacity.

xiii) Conduct research in matters relating to inland water transport including development of:

(a) craft design
(b) technique of towage
(c) landing and terminal facilities
(d) port installations

xiv) Arrange programmes of technical training for inland water transport personnel within and outside Bangladesh.

xv) Maintain liason with the shipyards and ship design industries to meet the requirements of the inland water transport fleet repairs and new constructions.

xvi) Maintain liason with the government and facilitate import of repair materials for inland water transport industry.

xvii) Prepare plans or schemes for carrying out any of the above mentioned functions.

xviii) Any other function or functions which the government may, from time to time, prescribe.

The authority also performs a number of other functions beyond what have been stated above.

The major technical departments of the BIWTA are Engineering, Hydrography, Mechanical & Marine Engineering, Planning, Marine Workshop, Conservancy & Pilotage, Deck Personnel Training Center. The Mechanical & Marine Engineering Department is entrusted with the responsibility of approval of drawings of inland vessels and scrutiny of stability.

2.2.1 Transport System at a Glance[1]:

i) Length of Waterways: 24,140 Km.
Rainy season

ii) Length of Rivers: 13,623 Km.
(Within the country)

iii) Principal Rivers: Padma(366 Km.), Meghna(228 Km.), Jamuna or Brahmaputra (291 Km.), Surma (399 Km.), Kushiara (300 Km.), Karnaphuly (193 Km.), (In all about 230 rivers including 230 tributeries and branches).

iv) Navigable Waterways: 8,433 Km. (Rainy season)
5,222 Km. (Dry season)

v) No of inland river ports developed by BIWTA: 11 (listed in section 2.2.3)

vi) No. of Coastal Island Ports (Developed by BIWTA): 22

vii) No of Ferry Ghats developed by BIWTA: 5 (Aricha, Nagarbari, Daulatdia, Bhuapur, Shirajganj)

viii) No. of launch ghats: 1,410

ix) No. of launch ghats: 114
(developed by BIWTA)

x) No. of Passenger: 262
Vessels' Routes

xi) No. of Time Tables: 639
issued

xii) No. of Registered : 2,423
Mechanised vessels

xiii) No. of Registered : 868
Non-mechanised
vessels

xiv) No. of Passengers
carried

a) By Motor launch : 48.50 million

b) By Steamer : 4.82 million

xv) Quantum of cargo: 4.838 million tonnes.
carried

xvi) No of country boats operating commercially:

Cargo:	1,02,000
Passenger	1,89,000

2.2.2 Statistics of Vessels, Routes, Goods and Passenger Carrying:

2.2.2.1 Total IWT Registered Fleet:

The total number of registered inland vessels of different categories are shown below. These vessels are registered under Inland Shipping Ordinance (ISO).

Type	Private Sector		Public Sector		Total	
	No. of Vessel	No. of Pass.	No. of. Vessel	No. of Pass.	No. of Vessel	No. of Pass.
Passenger:						
Vessels	133	42,656	13	4,551	146	47,208
Vessels (Bay Cross)	-	-	11	2,504	11	2,504
Vessels (Steam)	-	-	6	4,690	6	4,690
Launches	1,266	98,885	-	-	1,266	98,885
Ferries	-	-	20	2,772	20	2,772
Sea trucks	-	-	2	260	2	260

Type	Private Sector		Public Sector		Total	
	No. of Vessel	Capacity tonnes	No. of. Vessel	capacity tonnes	No. of Vessel	capacity tonnes
Cargo:						
Self-propelled	644	113,437	8	2,358	652	115,795
Tanker (inland)	12	4,213	-	-	12	4,213
Tanker (Bay cross)	25	22,970	13	10,504	38	33,474
Coaster	74	55,176	20	15,434	94	70,610
Dumb Barge:						
Flat (Dry)	43	22,356	39	27,034	82	49,390
Flat (POL)	2	1,103	-	-	2	1,103
Barge (Dry)	492	128,343	204	58,458	696	186,801
Barge (POL)	21	5,571	-	-	21	5,571
Barge (Bay Cross)	-	-	35	24,766	35	24,766
Boat	29	3,767	3	236	32	4,003

Type	Private Sector		Public Sector		Total	
	No. of Vessel	Capacity BHP	No. of. Vessel	capacity BHP	No. of Vessel	capacity BHP
Towing vessels						
Motor (inland)	132	30,107	44	23,279	176	53,386
Motor (Bay Cross.)	-	-	6	5,440	6	5,440
Steam (Inland)	6	(NHP)91	-	-	6	(NHP) 91

2.2.2.2 Waterway Lengths:

a) Total length of waterways	-	13,679 Km.
b) Navigable waterways (Monsoon)	-	8,433 Km.
c) Navigable waterways (Dry season)	-	5,222 Km.

2.2.2.3 Water Mileages Maintained by BIWTA:

i) 12' draft :	Trunk Routes	:	652 Km.
ii) 6' draft :	Transit Routes	:	1,352 Km.
iii) 3' draft :	Secondary Routes	:	1,545 Km.
iv) Estuary rough water			
a) Chittagong - St.Martins Island		:	218.7 Km.
b) Chittagong - South Hatiya		:	102.8 Km.
c) Chittagong - Raimangal		:	394.7 Km.
d) 6' contour line -	Hiron point, Dhulasar, Under char, Manpura		240.9 Km.
e) St-Martins Island - Teknaf			31.5 Km.
		Total	4,538.0 Km.

2.2.2.4 Passenger Service:

a)	Routes served	:	262
b)	Stations serves	:	1,410
c)	No of recorded passenger vessel operators	:	455

2.2.2.5 Annual Cargo Carrying Statistics (1984-85):

	Cargo carried	Tonne	TKm.	Average Lead
i)				
	a) Overseas	41,69,964	1,01,28,17,901	242.89
	b) Inland	6,68,998	16,50,92,871	246.78
	Total	48,38,962	1,17,79,10,772	243.43
	International (Between B'desh and India)	9,792	35,27,687	360.30

ii) Statistical Indicator (Excluding International Traffic)

a) Tonne Kilometer carried over one Km. of route	:	0.259 million TKm.
b) Tonne Kilometer per day of 24 hours	:	3.230 million TKm.
c) Tonne Kilometer per tonne of carrying capacity per day of 24 hours	:	6.510 million TKm.

2.2.2.6 Passenger Carried:

Sector	Length of waterways(Km.)	Number million	Passenger Km. million	Average Lead Km.
Private	8,610	48.50	1350.0	27.83
Public	1,423	4.82	260.0	53.95
Total	---	53.52	1610.0	30.20

2.2.2.7 Latest Short Statistics:

The latest figure available from the Bangladesh Bureau of Statistics[10] are as follows:

a) Passenger vessel (1986-87)	-	1,557
b) Cargo Vessel (1986-87)	-	889
c) Country boats (cargo) (1987-88)	-	108,000
d) Country boats (passenger) (1987-88)	-	200,000
e) Movement of goods by waterways (1987-88, provisional) ('000 tonnes)	-	20,222

2.2.3 River Ports:

Following eleven inland river ports have been developed and provided with modern port facilities. These ports are directly controlled, managed and administered by the Ports & Traffic Department of the BIWTA.

i) Dhaka Port :- Position Lat 23° - 42' - 30" N. and Long 90° - 25' 00" E. Formally opened in 1965. Facilities : 2 Nos. of two storied terminal buildings, 3 RCC jetties, 2 ramps and 20 pontoon jetties.

ii) Narayanganj Port :- Position Lat 23^{o} - 37' 00" N. and Long 90^{o} - 31' 15" E. Formally opened in 1965. Facilities : 1 No. of two storied terminal building, 8 RCC jetties, 10 pontoon jetties, 8 godowns covering 62,000 square feet.

iii) Chandpur Port :- Position Lat 23^{o} - 14' - 00" N. and Long 90^{o} - 39' 00" E. Formally opened in 1967. Facilities : 1 No. of one storied terminal building, 8 pontoon jetties.

iv) Barisal Port :- Position Lat 22^{o} - 43' - 00" N. and Long 90^{o} - 23' 30" E. Formally opened in 1967. Facilities : 2 No. of floating terminal building, one terminal shed, and 9 pontoon jetties.

v) Khulna Port :- Position Lat 22^{o} - 49' - 00" N. and Long 89^{o} - 34' 00" E. Formally opened in 1967. Facilities : 1 No. of two storied terminal building, 1 RCC jetty, two Quay walls of total 183 sq. ft. 8 pontoon jetties, 2 godowns covering 4,217 sq. ft.

vi) Patuakhali Port :- Position Lat 22^{o} - 22' - 00" N. and Long 90^{o} - 21' 00" E. Formally opened in 1975. Facilities : 1 No. of one storied terminal buildings and 2 pontoon jetties.

vii) Baghabari Port (Pabna) :- Position Lat 24^{o} - 47' - 00" N. and Long 89^{o} - 34' 00" E. Formally opened in 1983. Facilities : 2 ramps with 2 jetties and transit shed of 10,800 sq. ft.

viii) Aricha Port :- Position Lat 23^{o} - 50' - 00" N. and Long 89^{o} - 47' 00" E. Formally opened in 1983. Facilities : 1 terminal shed, 1 pontoon, 3 ferryghats with pontoons and two Ro Ro ferryghats.

ix) Nagarbari Port :- Position Lat 23^{o} - 58' - 00" N. and Long 89^{o} - 40' 00" E. Formally opened in 1983. Facilities : one terminal, one pontoon jetty, one ferryghat with pontoon and two Ro Ro ferryghats.

x) Daulatdia Port :- Position Lat 23° - 47' - 00" N. and Long 89° - 46' 00" E. Formally opened in 1983. Facilities : One landing pontoon and two Ro Ro ferryghat pontoons.

xi) Kazirhat Port :- Position Lat 23° - 53' - 00" N. and Long 89° - 40' 00" E. Formally opened in 1983. The port is under development.

2.2.4 Route Control

The implementation of the Route Control Rules could not be made effective due to circumstances beyond the control of the BIWTA. A tentative route list under rule 3 of the BIWTA Rules 1957 (Application of Route and Grant of Route Permit) has been prepared and approved. Control on Private Sector passenger service is excercised through approved time table as per Time & Fare Table Approval Rules, 1970 mentioning word "Route Permit & Time Table".

For smooth and efficient operation and control on the waterways and entire navigable waterways has been divided into several zones as under:

DHAKA ZONE

Boundary: The zone comprise of Dhaka, Munshiganj and Gazipur districts and also includes Tangail and parts of Jamalpur districts. It is bounded in the North by the old Brahmaputra River (including the river), in the East by the Bandar and the Lakhya River (excluding the rivers), in the North-West by the Railway line from Jamalpur to Jagannathganj Ghat (excluding the ghat), in the West by the Jamuna upto Aricha at its confluences with the Padma, in the South-West by the Padma upto Chandpur (Excluding Chandpur). It does not include Taltala on the Dhaleshwari, but include station on the left bank on the Jamuna.

NARAYANGANJ ZONE

Boundary: The zone comprises of the Comilla, Narayanganj and part of Brahmanbaria Districts and the half of Mymensingh and Jamalpur Districts. The zone is indicated in the North by the boundary of the country, in the West by the Brahmaputra (excluding the river) and then by the boundary of the Dhaka zone (vide para 1 above), in the East by the Dhaleswari River (including the river upto Durgapur and then by the railway line upto Bhairab and in the South by the Chandpur-Laksam railway line (including Chandpur).

BARISAL ZONE

Boundary: The zone comprises of Faridpur, Bakerganj, Patuakhali, Barguna, Jhalkathi, Bhola and Pirojpur districts and western half of the Laxmipur districts. It is bounded in the North and North-East by the Ganges/Padma upto its confluence with Meghna near Gazaria (excluding stations on the left bank and Charbadrasan on the right), in the East by the Meghna upto Chandpur (excluding stations on its left bank) and then following the railway lines upto Maijdi and in the West by Bara-Madhumati (excluding the river) and by Baleswar (including the river).

KHULNA ZONE

Boundary: The zone comprises of Khulna, Jessore, Kushtia, Gopalganj, Bagerhat, Satkhira, Magura, Jenidha and Narail districts. It is bounded in the North by the Ganges, in the East by the boundaries of the Barisal Zone (vide para 3 above), in the West by the boundaries of the country and in the South by the Bay of Bengal.

NORTHERN (SIRAJGANJ) ZONE

Boundary: The zone comprises of Dinajpur, Rangpur, Bogra, Rajshahi, Pabna, Tangail, Jamalpur and Sirajganj districts. It extends in the North and West upto the Brahmaputra (including the river) and the boundary of the Dhaka Zone (vide para 1 above), and in the South upto the Padma (including the river and the Goalundo Ghat).

SYLHET ZONE:

Boundary: The zone comprises of the whole of Sylhet, Sunamganj, Hobiganj and Maulavibazar districts, Netrokona and greater part of Kishorganj district and the remaining half of Brahmanbaria district. Shaped roughly like a triangle, it is bounded in the North and the South-East by the boundaries of the country and in the West by the boundaries of the Narayanganj Zone (vide para 2 above).

CHITTAGONG ZONE

Boundary: The zone comprises of Chittagong, Chittagong Hill Tracts, Rangamati, Bandarban and the remaining half of the Noakhali district. It is bounded in the North by Laksam-Chauddagram road and Tripura, in the West by Laksam-Maijdi railway line and Shahbazpur (excluding the channel), in the East and the South by the boundaries of the country.

A.	No. of time table issued:	635
B.	No. of operators:	450
C.	No. of Launches maintaining time table:	770
D.	No. of launch routes:	260
E.	No. of launch ghats:	1400
F.	Length of waterways over which passenger: launches issued with time table (Km.).	5350

Extent of passenger service-Public sector (BIWTC)

A. Steamer service	i) Dhaka-Barisal-Khulna
	ii) Dhaka-Barisal
	iii) Chittagong-Barisal
	iv) Barisal-Patuakhali
	v) Patuakhali-Khepupara
B. L.C.T. service	i) Kumira-Guptachara
	ii) Chittagong-Hatiya
	iii) Chittagong-Kutubdia
C. Sea-truck and 80' prototype service	i) Patuakhali-Amtali
	ii) Bahadurabad-Chilmari
	iii) Cox's Bazar-Maheshkhali
	iv) Hatiya-Charjabbar
	v) Barguna-Patharghata
D. Ferry Service	i) Aricha-Daulatdia
	ii) Aricha-Nagarbari
	iii) Sirajganj-Bhuapur

2.3 Department of Shipping (DOS):

This organisation is a directorate under the Ministry of Shipping of the Government of Bangladesh. The office is headed by a Director-General under whom is a i) Chief Engineer and Ship Surveyor, ii) Chief Nautical Surveyor and iii) Director of Shipping. As mentioned earlier DOS is mainly concerned with overseas shipping. The function of this department with inland shipping is mainly looked after by the Inspectorate of Inland Shipping headed by a Chief Inspector. The function includes carrying out annual survey of vessels under Inland Shipping Ordinance (ISO) and register the vessel with the Registrar of Inland Ships. This department also carry out investigations of marine accidents and identify the person(s) responsible. Punitive actions are also taken. A major task of this department is to conduct professional Competency Certificate Examinations of crews of inland vessels. The surveyors of this department compare the construction of the vessels with approved drawings, supervises the inclining tests carried on inland vessels and also check the stability. Presently an effort is underway by this department for preparing rules for design and construction of inland vessels.

Following a series of tragic passenger vessel disasters in early parts of 1986, a consultant of the International Maritime Organisation (IMO) advised the Government of Bangladesh to reorganize this department and assign all statutory functions to it, including the design approval process which is presently being looked after by the Mechanical and Marine Engineering Department of BIWTA. This has reportedly been accepted by the Government of Bangladesh and is awaiting implementation.

2.4 Marine Accidents: Some Statistical Figures:

The Inland Shipping Inspectorate of the Department of Shipping maintains detail record of marine accidents in the inland waters of the country. It is a part of their investigations procedure. But the data are not published regularly. Some information are also available with the BIWTA. The first systematic data of passenger vessel accidents was published by Khalil[11] in 1985. This contained information on all accidents involving such vessels from 1981 to 1985 mentioning the names of the vessels involved, place of accident, cause of the accident and the loss of lives.

The annual figures of accidents and losses of lives since 1981 are given below

Year	No. of Accidents	No. of Deaths
1981	10	60
82	4	0
83	7	50
84	11	115
85	12	80
86	11	426
87	11	51
88	11	108
89	5	32
90 (till Apr.)	8	162

As regards the cause of the accidents, an analysis is reproduced from the above referenced paper.

Causes	Percentage of Accidents
Overloading	40.43
Collision	38.30
Heavy Weather	17.02
Foundering	4.25

The sources of the data are the DOS and BIWTA. The tables above merely displays official records of casualties. And one must not forget that, in most of the tragedies, the official figures for death toll are usually lower than the actual loss of lives. An example of this may be found in the case of M.V. Bugdadia III which capsized in the river Buriganga on the 23rd

March, 1985. The official record of casualty was only 62 lives as against 250 lives reported by the Bangladesh Observer, a leading english daily, on the following day. There are many reasons for such discrepancies. In most of the cases, the salvage team reach the remote places of occurance quite late and by that time many of the dead bodies are washed away by the current before being counted. Consequently, the official casualty figures are based on only the dead bodies of the victims stuck up in the hold of the sunken launch.

The Bangladesh Observer of Dhaka published a new item on 9th March, 1988 reporting that since independance (till 1987) there have been 193 accidents involving passenger launches and the total death toll is 1,815. Also that about 2,000 mechanised passenger vessels are plying without registration. In other words the actual number of passenger vessels is about 2,000 more than registered.

As regards the number of accidents involving cargo and other types of vessels, there is no consolidated statistical figures that could be located anywhere in the country. The author had earlier supervised a research project[12] to quantify the amount of cargo losses in inland shipping. It was very surprising that no governmental agency have minimum concern regarding this matter. In fact, evil practices appear to dominate the sector. Foodgrain and fertilizer movement are the two major items of shipping in inland traffic. The Food Department of the Government of Bangladesh and the Bangladesh Chemical Industries Corporation are the consignors and/or consignees. It is always found that in papers, the transit loss are almost always just marginally less than what are allowed by the terms of contract with the carrier. It is a unbelievable statement. The realities are known to everyone concerned with shipping. The concerned agencies can not shoulder off the responsibilities. For example, the Bangladesh Chemical Industries Corporation does not make it mandatory to ensure the fertilizers cargo. The freight paid to the carriers are barely enough for the insurance and fuel, not to mention the crew wages, maintenance and profit to the carrying contractor. Major events, like the capsize of a fertilizer carrying boat few months back are the ones which can not be buried altogether.

2.5 Weather Statistics:

Wind is an important parameter in assessing stability of passenger vessels. The Meteorological Department is responsible for accumulation of meteorological and weather data which are recorded at about 100 weather sub-stations throughout the country. Data of temperature, humidity, rainfall, barometric pressure, wind direction and velocity etc. are recorded an published in the form of total or average of each month[13]. For stability analysis, however, the wind velocity is important. But the average figures are of no use and maximum wind velocities experienced during Nor-Westers or severe land based storms are important. In case of cyclonic storms, nationwide early warnings are generally transmitted and precautionary steps are taken. Water crafts do not ply and take shelter at safe locations. In case of land based storms such precautions are not always possible since these are generated almost suddenly and with little or no warning. Though not published formally, it has been possible to collect data on some most severe storms experienced by the country during the last thirty years[14]. These are as follows.

Some severe Nor'Westers/tornados

Date	Place of Occurance	Area Affected (Sq. mile)	Duration (mins)	Estimated wind speed (Knots)	People killed	People injured	Property Mil. Taka
26.04.89	Saturia, Manikganj	58	-	205	526	Uncounted	Not Estimated
01.04.77	Faridpur	20	2 - 3	175	500	6000	12.0
09.05.76	Narayanganj	1	1 - 2	130	1	42	Not Estimated
10.04.74	Faridpur	10 - 15	12 - 15	130	46	Uncounted	Not Estimated
11.04.74	Bogra	10 - 12	10 - 15	130	28	75	10.0
17.04.73	Manikganj	8	8 - 10	175	100	1000	10.0
14.04.69	Demra	60 - 65	5 - 7	350*	922	16511	40 - 50

* Recording devices failed to measure wind velocity. Estimation was made by American expert from the study of the severity of devastations.

It was also gathered[14] that on an average 25 Nor-Westers or tornados with wind intensity of 50 knots or more hit any part of the country or the other in a year.

CHAPTER 3

LITERATURE REVIEW

3.1 Introduction:

The arts, science and technology of shipbuilding is one of the oldest in the history of mankind. The first known history of formal ship construction rules dates back to 1760. However, advancements in the field of ship stability assessment have been relatively much slower. Although the number of disasters involving ships were enormous and thousands of human lives were lost every year, the naval architects and maritime administrators were in fact doing little to prevent stability related losses of ships. As a result of loss of the passenger ship Titanic in 1913 resulting in death of 1513 people, an international convention titled 'Safety Of Life At Sea' SOLAS was signed in 1929. Subsequent amendments were carried out in 1948, 1960 and in 1974. However, SOLAS Convention have contributed little towards improving intact stability of seagoing, coastal or inland vessels. It has mainly concentrated on life saving, fire prevention, fire fighting and other statutory matters. The topic of damaged stability was also covered by the SOLAS Convention. The reason was that Titanic capsized after being severely damaged due to collision with an iceberg.

A large number of marine disasters can be attributed to the intact stability. However, advancement in the field of intact stability has been, at best, much slower. The first suggestion for a comprehensive intact stability criteria appeared in 1939[15]. But statutory authorities started implementing such criteria only in the 1960s. Before the advent of electronics computers naval architects used to concentrate their efforts for evolving methods for accurate and quick calculations of hydrostatic curves and cross curves of stability. Methodical series charts for calculation of stability were first published by Prohaska[16] in 1947 and subsequently amended several times. This was the first step towards understanding the capsize behavior of vessels. However, mere calculation of stability parameters could contribute little towards assessing stability. With the advent of electronic digital computers naval architects could calculate the stability particulars at as many angles, trims, displacements as required in very short time. Consequently, efforts were concentrated on assessment of stability. By that time model test facilities had also advanced considerably, so were the analytic and numerical tools for computations relating to rolling and capsize. As a result, during the last quarter century, there has been considerable advancements in the field of intact stability assessment, but still lagging much behind other branches of maritime technology. One of the reasons is that the phenomenon of ship capsize is yet not thoroughly understood. As a result the research and experiments have been too diverge. Many authors have attempted to promote better understanding of the applicability and shortcomings of the proposed and practices stability criteria.

Instead of converging to a common understanding, professionals differing more and more on how to assess stability. Newer methodologies are being proposed for the purpose. In fact research towards evolving such criterion have been very widespread resulting in a very large number of propositions. IMCO convention on safety of fishing vessels in 1977 suggested no less than seven methods of examining stability. The diversity in formulations is also apparent from Appendix-A and Appendix-B. The author has been in a difficult position in compiling the results and observations available with the literatures studied. The review presented in the following are arranged in the following way

Section 3.2 discusses the most early forms of stability assessment and criteria. These do not have the capability of substantiating in the present knowledge and practice in stability assessment and are only of historical interest.

Section 3.3 gives a brief chronology of the major stability criteria adopted by different statutory authorities.

Section 3.4 contains review and critical discussions on the common methodologies adopted for intact stability assessment.

Section 3.5 reports some new concepts of stability assessment or supplementing the existing methods and regulations.

3.2 Early Methods:

The process of evolution of intact stability criteria has been too slow. Before 1746 no standard for stability assessment had even been proposed.

Between 1746 and 1929 only three technical proposals were presented. Theses were restricted to the concept of metacentric height (GM). In 1868 Reed[17] published a paper, first of its kind, suggesting ideas of ballasting vessels, reducing speed, avoid ice accumulation etc. for safe voyage of ships. Denny[18] made some important contribution towards understanding the stability aspect of ships. Under US Steamboat Act of 1838, vessels were required to have 'adequate stability' and to be in 'all respect seaworthy'. The most remarkable of the propositions made upto 1929 was that of Bile[19] in 1922 which simply required the GM to be greater than 305 mm (1.0 ft.) in lightship conditions. Skinner[20] investigated stability of small vessels which also contributed towards understanding stability.

There were then little or no idea about how the restoring arm (GZ) varied with inclination, specially when the metacentric height is negative. As a result there were even instances where a vessel with negative GM was floating inclined to the angle of loll but the master thought the listing to be due to unsymmetric loading. It was mainly because no efficient computational method for locating the centroid of the underwater volume had evolved till then. At small angles GZ is equal to GM $\sin\theta$. The necessity of taking into account the restoring arms (GZ) at large angle of inclination was realized. As a result, computational and experimental methods for assessing the GZ started evolving.

In 1929 American Marine Standards Committee formulated wind heel and passenger heel criteria applicable for passenger vessels. This was adopted by the USCG in the same year. This is probably first such criteria. This later extended to cargo vessels in 1952.

It was not until the end of the nineteenth century that attempts were made to evaluate a safe minimum of stability[21]. The lack of basic understanding of the physics of ships capsizing in rough seas and the influence of different stability parameters on ships safety prevented the follow-up of the proposals such as those put forward by Benjamin[22] or Pierrottet[23]. either as statutory requirements or as recommendations.

3.3 Chronology of Stability Regulations

3.3.1 Still Water Criteria

3.3.1.1 Rahola's Criteria

The first major proposal for a formal intact stability criteria was from Rahola[15] in 1939. In his doctoral research he investigated a number of disasters in Europe and proposed that to ensure a safe vessel GZ-20^{o} and GZ-30^{o} be more than 0.14 m and 0.20 m respectively, GZ_{max} should occur at an angle greater than 35^{o} (Figure-3.1). He also showed in one of his graphs that if the area under the GZ curve upto GZ_{max} is less than 0.04 m-rad there were consistent casualties. Though he did not propose, but apparently indicated that the area under the GZ curve should form a part of the stability criteria.

Rahola's work was much ahead of its time and it took decades to adopt the same or similar regulations. By 1960s it had received worldwide attention and conditional acceptance by a number of countries. For example, the USCG adopted only the righting energy part of Rahola's criteria and required the righting energy to the maximum GZ - or the angle of downflooding - or the angle 40^{o}, whichever is minimum, be at least 0.78 m-rad. They did not adopt Rahola's GZ of 0.20 m. West German maritime administration required ships to comply in all loading condition: at least 0.20 m righting arm at 30^{o}.

3.3.1.2 SOLAS Conventions

SOLAS convention of 1928, 1948 and 1960 requires no stability criteria. The 1974 convention include criteria for grain carrying. There were provisions for supplying stability data to the master to enable him in safely handling the ship. But the content, extent or any other particulars of the data are not specified. However, the 1948, 1960 and 1974 conventions included damaged stability requirements of passenger vessels with successive modifications. This was expected to take care of the intact stability also.

The necessity of incorporation of the intact stability criteria for different type of vessels was emphasized in the 1960 conference of IMO. It was felt necessary that separate criteria should be evolved for passengers vessels, fishing vessels, cargo ships etc. and stability information furnished to the master should also be standardized.

3.3.1.3 IMO Activities:

IMO started the search for a suitable stability criteria in May, 1962. However, a consensus at IMO was arrived as late as in 1968 and resolution A.167 (Appendix-A) applicable to cargo and, passenger vessels under 100 m length and A.168 applicable to fishing vessels were passed. The former one required:

The area under the GZ curve;

(i) upto 30° (A_{30})	>= 0.055 m-rad
(ii) upto 40° (A_{40})	>= 0.090 m-rad
(iii) between 30° and 40° (A_{30-40})	>= 0.030 m-rad
(iv) GZ_{30}	>= 0.20 m
(v) θGZ_{max}	>= 25°
(vi) GM	>= 0.35 m for L <=70 m
	>= 0.15 m for L <=70 m

The same is illustrated in Figure-3.2.

The analysis followed, in principle, the earlier approach by Rahola[15] but study included a much larger number of ships which had successful stability records and those which had capsized. The recommendation were later adopted in the Torremolinos Convention of 1977.

A proposal has been recently put forward by the Federal Republic of Germany to the IMO[24]. The rules are related to the simple statical righting lever curves which is directly derived from the hull form and the vertical position of the center of gravity of the vessel.

3.3.2 Evolution of Weather Criteria

In formulating the criteria discussed above, ship's environment and external forces such as wind, wave, passenger crowding etc. were not under consideration. In fact, most of the disasters can be attributed to one of these factors. For example, S.S. Poseidon was overturned by a single wave.

3.3.2.1 USCG Weather Criteria:

Pierrottet[23] proposed a standard in 1935 to assess stability in beam wind. This was ultimately refined and presented by Sarchin and Goldberg in 1962 and was soon accepted by the US Coast Guard (USCG). This was, in fact, first such criterion taking account of environment. The method consists of superimposing the wind heeling lever curve over the GZ curve and computing i) GZ_s i.e., the GZ at the first intersection of the GZ and wind lever curve. ii) GZ_{max} and iii) The areas A_1 and A_2 (figure 3.3) To satisfy the criteria two conditions must be met: i) GZ_s/GZ_{max} can not be greater than 0.60 and ii) The ratio of the areas A_1 and A_2 can not be more than 1.40. In Figure (3.3) θ_r is the angle of rolling, normally assumed 25^o. θ_1 is the maximum windward angle, i.e., θ_r windward of the angle of intersection of righting and heeling arm curves.

The wind lever D_w is estimated by the following equation.

$$D_w = 0.194 \times 10^{-4} \times A \times l \times V^2 \times \cos^2(\theta)/D \quad .....(3.1)$$

Where V is the steady wind speed in Knots, θ is the inclination and D is the Displacement in tonnes.

3.3.2.2 IMO Activities:

Soon after the adoption of A.167 and A.168 in 1968, IMO started concentrating on a weather criteria, i.e., criteria to take account of wind wave and other excitations. The first step was to agree on a model for the approach. For this purpose collections of wave and wind data was essential. A joint team of experts from eight organizations was assigned with this huge task. After studying wind effects, wave heights, statistics on wave groups, spectra of various sea areas, stability related casualty records, the group opined, among other things, that waves should be accounted for in spectral form and disaster may take place due to poor navigation in an otherwise not an extreme sea[21].

They made an assessment of factors affecting stability and stated that the following were sufficiently dealt with by A.167 and A.168.

- Free surface
- Loading and ballasting
- Wetting of deck cargo
- Icing
- Crowding of passengers

- Rudder action

There are, however, reservations regarding the groups observation on ballasting and rudder action.

The group opined that only three factor remains to be looked at:

(i) Water trapped on deck, (ii) Waves and (iii) Wind

Based on the data accumulated and analyzed by the experts, a long term and a short term program were taken up by IMO in 1974. The long term one consists of theoretical and experimental work concerning capsize phenomenon, identification of relevant parameters, formulation of ship resonance with wind and sea, performance of comparative calculations and analysis of casualty data. An attempt was made in the 1977 Torremolinos Convention to also include certain requirements related to the external forces affecting ships in a seaway and during fishing or towing operations. But a consensus could not be achieved. However, a guideline for evaluation of severe wind and rolling in fishing vessels was adopted and two years later it was accepted as an addition to A.167. This guidance did not contain specific value of the constants which was left to be decided by the national administrations. However, in the meanwhile, a number of flag administrations like US Coast Guard had already introduced their own beam wind criteria. Dutch, Russian and British standards were studied and found to differ considerably. Roll amplitude and assumptions regarding flooding angle appear to have most significant effects. After standardizing the concerned parameters IMO introduced weather criteria in 1985 (IMO Resolution A 14/562) which is explained in Figure 3.4.

In the Figure θ_2, i.e., leeward angle is the minimum of

i) downflooding angle

ii) Second intercept of the heeling lever and GZ curve

iii) 50 degrees.

θ_r is the same as in USCG criteria.

The wind lever D_W is defined by the following equation:

$$D_W = 0.2014 \times 10^{-4} \times A \times 1 \times V^2 / D \quad \ldots\ldots\ldots\ldots\ldots(3.2)$$

$$1.5D_W = 1.5 \times D_W$$

Symbols have same meanings as in equation 3.1

For a vessel to be considered stable, the restoring area A_1 should be greater than excitation area A_2 (Figure 3.4).

It is interesting to note that the above eqaution is similar to equation 3.1 except that i) In equation (3.2) the wind heel lever D_W is constant and independat of inclination and ii) Value of the numerical constant differs slightly.

In equations 3.1 and 3.2, the steady wind speed is generally assumed to be 100 knots. But occassionally there are gusty winds of high intensity acting for a short period of time but causes capsize. The IMO criteria

(Equation 3.2 and Figure 3.4) takes account of the same. The gust wind moment, denoted by $1.5D_W$, is assumed to be 50% higher than steady moment D_W.

Few more criteria have been proposed which takes into account the external forces.

3.3.2.3 German and Dutch Standard:

The weather criteria adopted by the West German administration (also later introduced in the Netherlands) is the one proposed by Wendel[25]. To satisfy the criteria the static angle of heel θ_o, i.e., the angle of intersection of the restoring arm and the wind heel curves, should not exceed 25 degrees. If the angle of heel is 25 degrees then at 55 degrees the righting arm, after deduction for free surface and wind moments, should be at least 20 cm. For reduced angle of heel the requirements for the righting arm is changed and becomes slightly relaxed. The 25 degrees limit is not strictly from the view point of stability but with respect to safe operation of machinery and penetration of water through openings of the hull.

3.3.3 Passenger Heel Criteria:

Crowding of passengers poses the most serious hazard to the stability of passenger vessels. The requirements of the 1929 American Marine Standards Committee and USCG passenger heel criteria are:

(i) The static wind heel θ_0 angle should not be more than 14^o and should not reduce freeboard by more than half.

(ii) When the passenger and crews are placed so that their center of gravity is at one sixth of the breadth from the center line, the resulting heel should not exceed the limit fixed by the wind heel.

The same criteria was applied to cargo vessels from 1952.

The criteria were later modified and requirements were set that i) The ratio of static heel GZ to maximum GZ should not exceed 0.60, ii) excitation area to restoring area in the GZ curve should be less than 0.40 and iii) static angle of heel should not be greater than 15^o. The IMO additional requirements for passenger vessels are follows:

i) The angle of heel on account of crowding of passengers to one side should not exceed 10^o.

ii) The angle of heel on account of turning should not exceed 10^o.

3.3.4 <u>Fishing Vessel Criteria:</u>

Due to its operational requirements, fishing vessels have the worst stability records. Consequently, the stability requirements for the fishing vessels (Res A.168) required higher metacentric height than

A.167 and. In addition, there were recommendations for i) icing ii) practice on portable fish hold subdivision iii) freeing ports iv) hatch coaming and v) suggestions for fisherman. Some of the recommendations were included in the Recommendations On The Construction of Fishing Vessels Affecting the Vessel's Stability and Crew Safety.

A large number of small fishing boats (less than 30 m in length) are built without plans and drawings. It is unrealistic to expect these vessels be required to satisfy these criteria. A suitable modified criteria[26] alongwith the Code of Practice Concerning the Accuracy of Stability Information was adopted in 1971.

Later in 1977 the criteria for fishing vessels was updated and adopted in a IMO arranged convention[27]. The rules are applicable to fishing vessels less than 24 m in length and over. For smaller vessels Voluntary Guidelines were prescribed in 1979[28]. But the necessity of extensive research and investigations for such vessels were emphasized.

Investigations into the disaster of a fishing trawlers led to some proposals for improvements of the 1977 Torremolinos Conventions.

3.3.5 <u>Tow Boat Criteria:</u>

The USCG criteria for towing boats introduced in 1972 consists of three parts. The first part is similar to A.167 and also contains a limit for angle of vanishing stability (θ_v). The second part is a weather criterion similar to that of passenger vessels (Figure 3.3). The third part is a two section pull criteria, either of these being acceptable. The first sections is similar to Murphay's[29] criteria with a safety factor of 2.0. The second section contains provisions for i) static heeling angle θ_o, ii) area between righting arm and heeling arm curve. Roach[30] used casualty data of tow boats and in 1954 developed a criteria for towboats. Murphay[29] criteria for towing vessels, first described by Captain C.P. Murphay in 1957, consists of estimating the heeling angle due to rudder turned at 45^o with full propeller power and tow line. The resulting heel should not immerse the deck. However, his prediction was found to be about half that of Roach's prediction. The USCG criteria for towing vessels issued on 1st December, 1972 required θ_v minimum 60^o.

3.3.6 Offshore Supply Boat Criteria:

Functional requirements of the offshore supply vessels necessitates a wide beam. This peculiar hull geometry causes steepness in the GZ curve. Maximum GZ occurs at an angle lower than 25 degrees i.e., minimum requirements in A.167 and A.168. Consequently a separate set of criteria was developed for such vessels[31]. However, to compensate, the requirements for the area under the GZ curve were made more stringent and a bare minimum limit of 15^o was set for the angle of maximum GZ.

3.4 Methodologies of Stability Assessment: A Critical Review:

3.4.1 Philosophy of Intact Stability Assessment:

The parameters affecting ship stability can be divided into two main groups: i) Causes which at least in principle can be controlled and ii) Causes which are beyond human control. Examples of the first group are shifting of insufficient secured cargo or moving weight,distribution of cargo (longitudinal and vertical), free surface effects etc. Effects of wind and wave, 'random' free surface (which can neither be foreseen nor prevented) can be treated to be factors beyond control, the effects can only be minimized by proper design. The usual approach, at the designers' and operators' end, is to take sufficient care so that the factors harmful to stability is minimized. On the other hand, efforts are done to quantify, as accurately as possible, the effects of uncontrollable parameters.

The safety measurement in the strict sense would be on an absolute scale or ratio scale. In this scale the vessel's capability to withstand capsizing is measured directly. Since the mechanism of vessel's motion is not yet thoroughly understood and the number of uncertainties in the process is enormous, an absolute or ratio scale can not be used in stability analysis. Stability criteria may be looked into as an ordinal level i.e., a level lower than an absolute one. In fact, stability criteria are scales for comparing stability of vessels. Though the basic aim of both levels are same, i.e., the philosophy of modeling, there exists a difference.

Krappinger[32] criticized discrimination of criteria as still water and weather because both are based on same physical relationship. He argued that a more rational classification of stability criteria seems possible by grading their efficacy. One possibility to do this is to introduce a measure of the discriminated ability of a particular criteria as proposed by Krappinger[33] himself. This was done to make the criteria more specific to the subject vessel. Another possibility is to state how widely the limiting values of various criteria scatter for a set of different ships. Such a study was carried out Blume and Hattendroff[34].

There have been differing views on how to make best use of the evolved criteria and tap benefit out of it. For example, USCG conceived that the designs come out from the design table and it can be most effectively upgraded there. So it (USCG) recommended the IMO criteria A.167 to naval architects and designers. But the concept in Europe was more regimented one, so it is implemented as a part of statutory requirements.

Hormann[35] proposed three simultaneous means of approaching the problem of stability in focus:

- analysis of capsizing events
- model simulation
- mathematical methods

Hormann[36] also reported that model experiments revealed the fact that even for vessels of the same type, similar size, the limiting values of the stability particulars can not be fixed without taking into account the hull form.

3.4.2 Classification of Criteria:

3.4.2.1. Classification Based on Purpose

Henrickson[37] classified criteria as i) general criteria which are derived statistically (e.g. A.167, Rahola), ii) specific criteria formulated to assess resistance against specified upsetting force or moment (e.g., IMO weather criterion).

The general criteria have the advantage of implicitly taking care of all sorts of hazards, based on actual experience, and for evaluation of stability knowledge of the types of hazards and dynamics of vessel motion are not essential. The disadvantages are that the statistical base may not be a valid one, correct measure of stability may not have been used, the effects of variation of environment can not be assessed and vessels with unusual forms can not be evaluated.

On the otherhand, specific criteria have the advantages of being capable of suggesting modifications for improving stability against certain excitations. Also the environmental condition is specified and better chances that the vessels of new types being properly evaluated. The disadvantages are that the hazard must be clearly and completely defined and for evaluation of stability thorough knowledge of motion dynamics is required.

3.4.2.2. Classification Based on Principle:

Based on the fundamental principle laid behind, the stability criteria adopted, proposed or being ivestigated can be broadly divided into the following categories. In fact, most of the criteria are combinations of these:

(i) Statical stability methods
(ii) Moment balance methods
(iii) Energy balance methods
(iv) Motion stability methods

i) Statical Stability methods:

These involve no explicit use of external forces or motion characteristics. The requirements in such methods are generally combinations of a) metacentric height b) righting arm (GZ) at some specified inclinations and c) areas under GZ curve. These are also called still water criteria. Strictly speaking, area under the GZ curve is an energy but it is customary to treat these under the statical category.

Some criteria are exclusively based on GM alone, examples of which can be seen in Appendices B and C, Obviously, the most serious limitation of such criteria is that the righting arm remains exclusive function of GM only upto a mere 7^{o}. It can not distinguish between vessels having the same GM but different GZ curve. For example, a cargo vessel with a 3.50

ft. GM may have the stability vanishing at 90^{o}, but an offshore supply vessel with 7.85 ft. GM may have the righting arm vanishing at 43^{o} [38]. But GM based criteria will predict the offshore vessel to be more stable. A number of examples of other nature can also be cited. Non linearities observed in motion of small vessel can put serious restriction on the concept of GM criteria. However, when the vessel type and the range of size, proportion, form operating conditions etc are all specified, GM based criteria are simple but very effective tools.

Rahola[15], IMO resolutions A.167, A.168 are examples of combinations mentioned above. These methods always serve a useful purpose in drawing comparison between different hull forms and vertical distribution of weight. The obvious physical meaning of the rules are clear to naval architects and ship officers. However, the external forces such as steady winds, gusts etc. sea state and other factors are not taken into consideration. It is difficult, in fact almost impossible, to formulate a general requirement, based upon statical stability curves, which will be reasonable and at the same time providing adequate margin to ships of all types and sizes. Efforts are being made to compute and expermentally measure the righting arms considering the dynamics of motion.

ii) Moment balance methods:

If the rate of application of excitation forces like wind, wave impact etc. and their variation with time are much slower than the frequency of response of the vessel in roll, this method can be applied. In this method, balance is drawn between moments of weight of the vessel, buoyancy force and other forces acting on it to assess a vessel's safety level. Examples are provisions in the USCG, Steel[39], Wendel[40], Abicht et al[41]. Though, compared to GM criteria, moment balance is a comprehensive approach, even then most of the information embedded in the righting arm curve remains untapped. If time dependent excitation such as gust wind, gun recoil etc. are involved, the moment balance approach is no more sufficient. In such cases, energy balance must be considered. This method, however, have not been adopted generally.

iii) Work or energy balance method:

Examples of such method are proposal by Moseley[42] Pierrottet[23], Sarchin and Goldberg (also USCG)[43], IMO resolutions A 14/562 (1985)[44] and Strathclyde University[45]. A balance is drawn between restoring and excitation energies. The angle of rolling is generally taken equal to 25^{o}. The energies are generally computed from upright condition.

These methods bring us closer to reality in discriminating between 'safe' and 'unsafe' conditions. They are at best, however, fairly simple models of the real world and present only a quasidynamic picture, specially of the influence of the wave motion. The Strathclyde method is probably the ultimate form of development of such criteria. This method is described later in this paper in Appendix D and in figure 3.5.

Barrie[46] has shown that the alteration of the wave profile due to the presence of the vessel (termed as wave diffraction) can also significantly alter the GZ curve, specially for small vessels. Barrie also commented that possibly for this reason small vessels deserve different considerations.

The Strathclyde Method can be criticized on many accounts. Firstly, it does not contain any new fundamental concept. This can be seen to be mere refinement of the method prescribed in reference 43 and figure-3.3, made possible due to advanced knowledge of ship motion and taking advantage of high speed computers. Secondly, the extreme windward angle θ_1 and leeward angle θ_2 are found in the same way as in IMO criteria and without assigning any sound argument. Some people have described it to be deterministic in nature because the exact mechanism of capsize is studied. The above argument can be contradicted on the ground that the limiting values θ_1 and θ_2 is probabilistic because this was adopted in earlier rules after studying cases of disaster. The roll damping moment has been calculated by Ikeda's[47] method. The treatment does not include moments which depends on instantaneous roll velocity or acceleration, nor due to wave field generated by the motion of the ship. These are, however, related to added mass, damping etc. and may be incorporated as simplified model terms.

Before practicing the Strathclyde method, the method for calculating damping, Ikeda's or any other method has to be validated. Also this method has to be shaped to a compact form, like the existing ones before it could be adopted in practice.

Inspite of the above mentioned limitations such criteria use conventional principle and procedures which are familiar to naval architects, as a result an adoption is not very dificult.

(iv) Motion stability methods:

Criteria involving a balance of forces or couples are termed as 'static stability' criteria and those involving work or energy are referred to as 'dynamic stability' criteria. However, in true sense, the later is not a dynamic concept since forces and energy involved in the dynamics of a vessel's motion is not taken into account. This is mainly because before the advent of high speed electronic computers the knowledge of motion dynamics was very much restricted and not matured enough to be incorporated into such complex application. Moreover, there was a continued search for identifying the exact reason and mechanism of capsizing, not simply fixing a criteria by studying the capsizing cases. A number of small vessels satisfying the statutory requirements were lost in seas[48]. Subsequent investigations, researches and model testing revealed that ship dynamics such as roll damping, excitation by wave, refraction of the incident wave by the ships hull etc. were the factors to which the loss could be attributed. It was felt necessary to evolve a realistic stability criterion involving all such parameters. Such methods have been developed which cater dynamic effects such as resonance with encounter frequency, jump phenomenon etc. Clearly, static or quasi-static methods can not cope adequately with these. Rigorous mathematical treatments form the core of such methods. Lyapunov's function is the most widely studied technique. Other techniques includes Mathieu equation, roll/yaw coupling, non linear roll response etc. In fact, the only such criteria given a concrete shape till, now is probably the Lyapunov Method which is elaborated in Appendix-E. This is based on Lyapunov function and have been evolved at NMI under the 'SAFESHIP' project.

Disadvantages of these are, firstly, that naval architects are not yet familiar with these concepts and secondly, such new forms of stability criteria may need considerable validation from practical experience to be generally accepted.

3.4.3 Intact Stability Research Strategy:

There have been numerous research works on investigation of different aspects of stability and formulation of criteria. But most of the researchers have dealt mainly the aspect of their interest only. These have contributed immensely towards understanding the influences of different external parameters on stability. Hull response as function of hull parameters have also been studied extensively. However, these present fractional pictures of the entire aspect of stability. Comprehensive research project to study stability of ships is almost unknown except for the 'SAFESHIP' project initiated by the British Government[92]. As part of the project a number of research projects were taken up and was participated by a number of universities, research organizations etc. The topic investigated include environmental demand, analogue computer simulation, mathematical modeling, model experiments and full scale experiments. Studies on environmental demand was intended to accumulate and analyze data on wind, wave, icing etc. for use in stability assessment. The feasibility of developing and applying risk analysis as a basis for assessment of ship safety from capsize was investigated with a view of improving design criteria. The rolling behavior of ships were simulated on a analogue hybrid computer, firstly with a single degree of freedom and ultimately extending to six degrees.

Program on mathematical modelling was taken up by four organizations independently. To the best knowledge of the author two of these programs have resulted in concrete proposals. The then National Maritime Institute attempted mathematical modelling based on the theory of Markov processes to describe probability distribution of roll amplitude. A single degree of freedom equation was used with non linear damping. The program at the Strathclyde University have produced a method of stability assessment, termed as Strathclyde method, which has the potential of being adopted as a statutory requirements. It involves computation of excitation and restoring energy. The roll damping is also accounted for and the vessel is supposed to be in motion. The effects of wave of specific length, height and direction is also considered. The method is described later in this thesis (Appendix-D) and also discussed previously. An effort at British Ship Research Association (presently BMT) to devise stability criteria by making use of the derived equations of motion and the direct stability assessment method resulted in the evolvement of Lyapunov function which is explained in Appendix-E and also discussed previously.

3.4.4 Limitations of Existing Stability Criteria and Research for Improvement:

3.4.4.1 IMO Still Water Criteria:

In technology no tool is for unlimited use. Obviously, same is the case with IMO Still Water Criteria (A.167). But the average ship for which the criteria fits best has not been specified, except for length not to exceed 100 m and no lower limit. As a result, naval architects and ship masters are often not aware that the limiting values may not be valid in a particular case or in a particular combination of environment and loading condition. Stability Criteria A.167 have limited applicability for passenger vessels much larger than 100 m and very small ones. Discussions at IMCO's subcommittee on subdivision, stability and load lines in 1977 and 1978 uncovered the fact that some national administrations have used the IMO code for stability for vessels much longer and smaller than 100 m. Some delegates had mentioned that this code appears to restrict the larger vessels too much and is apparently not enough for small vessels[49]. Rahola[15] himself had specifically stated that small and large vessels need different criteria. The criteria were found to be less effective in light or ballast conditions than while loaded. For vessels with small draft, the stability should better be judged by the weather criteria[50].

When the still water criteria were developed and formulated it was understood that this criteria implicitly takes care of all kind of heeling moments and of the waves. Ultimately, it became obvious that the assumption were correct in some cases only. So newer criteria were proposed and some of them adopted. But the same purpose could not possibly be achieved by suitably modifying the still water criteria to care of hull proportions and forms. The implicitness mentioned above could probably be made valid for much wider types and size of vessels. Such a work was done by Blume and Hattendroff[51]. The concept, that a more complicated and larger set of criteria ensure more stable vessel, is not necessarily true, sometime it is the other way round. Krappinger and Sharma[52] showed that a criterion derived by properly combining different characteristics of the righting arm lever curve provides a better discrimination between safe and unsafe ships of a sample than if the characteristics are used individually.

The current stability criteria A.167 and A.168 have proved to be reasonably effective for ships upto 100 m in length (but not very small ones), with usual hull shape, proportion, form and in loaded condition.

As the size of the vessel increases, a lower limiting value in the same criteria may be acceptable. Since for the same GZ and area under the GZ curve, the righting energy increases proportionately with the displacement. But the excitation energy like that of wave or wind increases at a lower order.

Nickum[53] proposed three sorts of modification to IMO stability regulations:

i) The national administration should be fully familiar with the worst or most severe operating condition of the vessel, so that the worst stability can be assessed.

ii) The GZ curve should be trim corrected.

iii) The stability data to be provided to the master should be extensive and standardized. At the same time, trainings provided to the master should also be uniform.

Cleary[54] suggested that the hull form should be the fundamental consideration of a stability criteria.

3.4.4.1.1 Loaded Condition Versus Ballast/Light Condition:

As a consequence of loss of few vessels in ballast conditions, doubts were expressed that the IMO criteria do not apply to vessels in ballast conditions.

Investigation into the accident of a coastal oil tanker[55] showed that at the loaded condition the stability particulars were within acceptable limits. For example the areas under the GZ curve upto 30 degrees (A_{30}) was 0.055 m-rad, exactly what is required by the statutory requirements. But the same tanker capsized at ballast condition while the A_{30} was as high as 0.096 m-rad.

This is a serious limitation and IMO is trying to evolve a more versatile one. Some other investigation and model experiments[56] revealed that the IMO criteria do not apply to fishing and towing vessels when KG/draft ratio exceeds 1.4. The Russians reported a similar finding, the IMO criteria do not apply when KG/depth ratio exceeds 0.85.

Nickum[53] observed that at ballast conditions, there is a significant trim by stern. But GZ is generally calculated for even keel condition. As a result, there exists a large difference between calculated fixed trim GZ and real magnitudes. The difference becomes critical in some types of vessels e.g., hard chine, bulbous bow etc.

Two means were proposed by Nickum[53] for assessing stability at ballast condition. These are:

(i) The GZ curve may be modified in the following way;

$$GZ_{\theta} = K\ (D_o/D)\ GZ_{\theta o}$$

K = Modifying factor $\neq 1.0$

D_o = Displacement in loaded condition

D = Displacement in light condition

GZ_{θ} = Modified GZ

$GZ_{\theta o}$ = Calculated GZ

The criteria A.167 or A.168 to be applied to $GZ_{\theta o}$ values.

(ii) To develop a weather criteria similar to that of Sarchin and Goldberg[43].

This second proposal was preferred to the first one because of being a more scientific approach.

3.4.4.1.2 <u>Case of Limiting Angle of Vanishing (θ_v):</u>

Neither the Rahola Criteria[15] nor IMO A.167 had any requirement for minimum value of θ_v. This was considered at the time of adoption of A.167. But ultimately no such requirement was added. Necessities were felt at different levels and many discussions were held. For example, the USCG criteria for towing vessels issued on 1st December, 1972 required θ_v minimum 60^o. Following capsize of a Norwegian flag vessel HELLAND HANSEN in 1976, the concerned flag state introduced rules implicitly requiring $\theta_v > 80$ degrees. Statistical data of vessels considered safe and the capsized ones indicated that it will not be possible to agree on a acceptable minimum value of θ_v. An international consensus could not be achieved in this regard due to the facts stated below.

(i) Calculated value of θ_v depends on trim, wave particulars, orientation of vessels with wave, superstructures etc.

(ii) At large angles the GZ value are influenced greatly by factors like free surface, shift of cargo, suspended weight etc. So theoretical calculation of GZ at large angles (where GZ generally vanishes) bears less practical significance.

(iii) A large minimum acceptable value of θ_v would obviously be desirable because it is likely to ensure a safe vessel. But this may, however, not be practical for certain vessels like offshore supply boats or vessels designed for shallow water.

(iv) No theoretical technique is known which can predict the influence of θ_V on probability of capsize.

(v) An arbitrary limit might on one hand fail to contribute to stability and on the other hand appear as a design constraint.

Further it was observed that the existing criteria which is concerned with the GZ curve upto 40 degrees automatically ensures a reasonably large value of θ_V. In light of the above mentioned facts, the possibility of incorporation of θ_V in the stability criteria was dropped.

3.4.4.1.3 Requirements for Minimum Metacentric Height:

The minimum allowable metacentric height in A.167 was originally 0.35 m., there was none in Rahola's[15] criteria. But most of the delegates at the IMO conventions did not find any necessity of requiring a minimum value of GM, since while the other items of A.167 are in force, the value of GM will never be governing. It was also agreed by most members that a lower value of GM may also be acceptable. Consequently, this requirement was relaxed to 0.15 m for vessel of certain types and over 70 m in length.

3.4.4.2 Weather Criteria:

Soon after the adoption of A.167 and A.168 in 1968, IMO started working on a criteria to assess stability against external excitations. In the fist few years after adoption, A.167 and A.168 were apparantly serving well their purpose. But as the number of disasters started increasing, investigations revealed that there are some common causes of capsize of undamaged ships. Resonant rolling, following sea, deck load, bulk cargo shift, steady wind, wind gusts etc. are some of the major ones. This causes either a shift in the vertical C.G., or a heeling moment or a steady heeling due to wind or a change in the underwater volume or impulse heeling or a combination thereof resulting in loss of the vessel. Reference 58 goes on to explaining in detail the mechanism of such type of capsizes. The necessity of stability criteria taking into account such factors were realized. Before then, the efforts of the international professionals in stability were to measure a vessels stability by one general criteria and assume or presume or hope that enough reserve could be built into that one evaluation to accommodate the other tasks or risks which the vessel might have to undergo. But this approach was basically deficient by concept, the main reason being the fact that the permissible limits in actual situations are not known.

Efforts at IMO for formulation of a weather criteria did not take momentum till 1977. However, the data accumulated by earlier efforts (reported in section 3.3.2.2) was of immense help. As a result a weather criteria was adopted in 1985[44] which has been discussed earlier. At the IMO session it was also agreed that this weather criteria is an interim measure and will remain effective until results from theoretical researches are available.

The wind heel lever calculated by the weather criteria was formulated for vessels with bilge keel. But what happens if the bilge keel is removed is not in the regulations.

In criticism of the USCG wind heel criteria Numata[59] showed that the time domain histories of the capsize phenomenon indicates that it is essentially random and capsize does not necessarily occur always when rolling to a large windward angle is experienced by the vessel.

Amy et al[60] reported that computer simulation of capsizing did not relate to the behavior assumed in the classic weather criterion. The capsizing appeared to be more of a random event which depended upon the phasing of the roll, wave slope and wind gust. In turn, they proposed a simplified wind heel criterion illustrated in Figure-3.6. In formulating this criterion it was assumed that the probability of occurrence of an extreme roll angle is in some way related to the r.m.s. roll angle and that capsizing will occur when the effective roll angle exceeds the range of stability.

Wendel's method[39] takes care of regular wave, weight shifting and wind heel simultaneously.

3.4.5 Investigation of Effects of Different Parameters:

3.4.5.1 Effects of Wave:

Kempf[61] was the first to note in 1938 that stability is greatly influenced by the presence of wave. He also pointed out that when the crest is at the midship, the stability increases from the still water figure and reduces similarly when trough at midship.

The necessity of assessing stability in following seas was realized much before adoption of A.167 and A.168. But numerous researches led to no conclusion except for agreeing to Kempf's finding that the worst condition is generally encountered when the crest is at amidship. To estimate the effects two approaches were considered.

(i) An analytic approach based on non-linear system is to be developed and results analysed statistically.

(ii) Quasi static approach assuming a sinusoidal wave and crest amidship.

Some model tests and calculations have been performed and results published. For example, tank test of the model of a containership showed that the minimum safe limit of GZ_{max} in following sea was four times the limit set by A.167[37].

Following the adoption of A.167 and A.168 it was realized that the statutory requirements should also take account of external forces. To initiate studies on the matter IMO formed a specialists group which started working in 1975. Most of the efforts were spent in investigating the wind parameter. The effects of waves, which is more complicated and random, was not paid the proportionate importance.

Paulling[62] investigated the phenomenon by theory and by experiments and reported that the worst GZ in wave may be only 50% of what is in still water. The situation may be more severe. While a vessel was floating in still water the stability was adequate, but when the same vessel encountered wave and crest at amidship the GZ curve may become altogether negative[63].

Kerwin and Grim[64] carried more rigorous analytic treatments of the same and reported that capsize will occur when the ratio of encounter period in a following sea to the natural period of roll is 1/2, 1, 3/2 .... This is irrespective of GZ curve or any other hull parameter directly.

Paulling[65] carried out experiments on a 30 ft. model of a fast cargo liner in the San Francisco Bay. The purpose was to investigate the capsize behavior in waves. Three modes of capsize were identified:

i) Low cycle resonance: As the vessel rolls in a seaway, the GZ value fluctuates with inclination and wave crest position. When the vessel is at the extreme roll position, it may happen that, due to shift of the crest position, the GZ decreases. Consequently, there will be a surplus of energy which will increase the rolling speed and, as a result, the extreme roll angle will also become higher. If this process is repeated in the next roll cycle, which will be in the case of resonance, the motion will result in a ultimate capsize.

ii) Pure loss of stability: If the crest is in such a position that the stability is minimum and relative speed between the wave and vessel is such that the crest remains in that position for sufficient time, pure loss of stability may result.

iii) Broaching: In case of the wave hitting the vessel from the stern, a significant portion of the rudder may come out of water. In such a situation the master may not be able to steer the vessel to his desire. Ultimately, the vessel may turn parallel to the troughs and capsize.

The length, shape, spectral density etc. of waves vary significantly from open sea to sheltered, inland and shallow water. The relevant data available to date are mainly for the open sea.

Model test of trawlers by Hogben and Wills[66] showed that for a beam wave the worst situation is encountered when the ratio of wave encounter to roll natural frequency is about 0.88. But the maximum leeward roll occurs at a ratio of 1.0.

3.4.5.2 Water on Deck:

USSR and Poland recommended taking the water trapped in deck into account - a feature already incorporated in their national requirements.

Nickum[57] pointed out that the principle of linear superpositioning is generally applied for water-on-deck criteria. This is not valid for small vessels with small freeboards because of motion non-linearities.

3.4.6 Novel Concepts of Stability Assessment:

3.4.6.1 Concept of Probability:

While the probability concept proved useful to understand safety and also has lead to progress in many fields, it soon turned out that it is not always possible to apply it practically. The reasons are the same as for the non-applicability of the absolute scale[33]. Moreover, even if the probability of a vessel not capsizing could be estimated with sufficient accuracy, the most daunting task would have been to fix the acceptable limit the probability. For example, the question of minimizing the total mortality as well as relationship between safety and economics would have to be considered. But at the same time no one could probably put a price tag on a life. Research work on individual risk taking behavior has shown that "rationally determined acceptable risks" do not necessarily get public acceptance. In 1962 Krappinger[67] proposed use of 'probability of capsizing' as stability criterion. The procedure was applied to some ships by Abicht[68]. But as yet it has not been possible to prove the superiority of this method over conventional criteria. The efficiency of this method was found no better but the complexities were much more. This might be one reason that the probability based criterion did not ultimately become acceptable.

Without analytic approach it will probably not be possible to incorporate the effects of hull parameters in stability criteria. The environmental studies will provide data to enable probabilistic to be assigned to such estimated motions.

It is desired that each and every factor related to ship stability be quantified in terms of risk i.e., probability. Otherwise a rational criteria can not be found. The present method (A.167 and A.168) can be upgraded only when a large number of cases of disasters occurring in diverse sea conditions and involving wide variety of ships have taken place and relevant data accumulated. But waiting for accidents to take place to make room for formulate of better stability standards will definitely not be ethically acceptable.

Hogben and Wills[66] pointed out that the weather criteria like that of IMO, in which a standard magnitude of wind speed has been taken, in fact assesses the worst situation of stability with a level of risk in a certain geographical location. They collected the wave and wind data in a number of measuring stations and compiled the same in such a way as to be convenient for assessment of stability of ships. An important point is that the effects of wind and wave are accounted for simultaneously. These offer a reasonable and tractable basis for estimating the risk to be encountered in service. They adopted the technique of recording wave data first and then incorporate that of the wind. The result was a joint probability distribution of wind and wave.

3.4.6.2 Risk and Reliability Analysis:

Caldwell and Yang[69] remarked that estimation of risks will help derive acceptable limiting values in criteria like in IMO A.167. As a result of ever expanding practice of risk analysis in complex engineering fields, necessity is being felt to incorporate this concept also in stability assessment of ships. The steps involved are: i) accumulation of external and internal data, ii) deciding a suitable methodology and iii) agree on acceptable level of risk.

Caldwell and Yang[69] suggested that i) annual risk of vessel capsize be not greater than 10^{-5} and ii) annual risk of death due to capsize be no greater than 10^{-4}.

For use of risk analysis in stability assessment, Caldwell and Yang[69] suggested more work and discussions concerning i) the establishment of acceptable model of capsize for definition of safety margin, ii) statistical data concerning variabilities and dependencies, both internal and external, iii) agreement on a standard procedure for defining operational profile and environmental conditions and v) target levels of acceptable risks.

3.4.6.3 Mathematical Modelling:

The mathematical modeling investigated by the then British Ship Research Association (presently BMT) aimed at deriving realistic model of coupled large amplitude rolling motion to provide:

(i) A time-domain simulation of roll time histories to provide an insight into the mechanism of large amplitude roll motion build-up.

(ii) To devise stability criteria by making use of the derived equations of motion and the direct stability assessment method.

As a result of rigorous analytic treatments a method, termed Lyapunov method, has been devised to assess stability of ships[70]. The basic principle has been manifested in two ways both of which are explained in Appendix-E.

The results of the treatments by Saraiva[70] is a domain of roll angle versus roll velocity for a vessel subjected to a specified excitation (Figure 3.7). A motion starting within the domain will end up in an upright vessel. If the motion starts outside, it is predicted to capsize. Using the same principle, Phillips[80] have proposed a slightly different method which is also described in Appendix-E (Figure 3.8).

Though this method brings the assessment method closest to reality, there are certain reservations. Odabashi[71] showed that Lyapunov Method gives a conservative estimate of the degree of stability. The methods of roll friction damping are based on theory and supported by experimental findings. The least certain part of the theoretical prediction of roll damping is now thought to be vortex-shedding component.

The shortcomings of this is that, firstly, only one criterion for the derivative of the Lyapunov Function V negative, i.e., e < PSI1 (Equation

E.12) was considered. The other determined from equations 12 and 13 was ignored. Secondly, Due to the presence of an arbitrary function 'h' (Equation E.6) the result is not unique. Phillips[80] has reported an uniformity in this function. This uniformity is valid for a certain type of vessels and further studies may lead to a generalized expression of 'h'. The mathematical analysis prescribes the criteria to be the necessary condition for stability, but not sufficient. This is due to the first shortcoming described above. Another drawback is that the angle of downflooding is not considered in this analysis. In fact, there is not merit in working with the GZ curve beyond this angle. The GZ curve is considered upto the angle of vanishing stability.

3.4.6.4 Model Testing:

As part of the 'SAFESHIP' project model experiments were carried out to estimate parameters required for mathematical modeling, analogue simulation etc[92]. The experiments carried out may be summarized under three main headings:

(i) Forced Rolling Experiments: This consists of forced rolling by a sinusoidal roll moment generator causing large amplitude rolling at resonance. Linear and non-linear damping coefficients are also obtained.

(ii) Roll Restoring Moments: Experiments are carried in circulating water channel to estimate the GZ curve in following waves.

(iii) Ship Motion Responses: Data of the ship motion response is collected to validate the theoretical model. Measurements are done in unidirectional waves for both small and large amplitude motion.

The results were mainly used for obtaining basic data on ship capsize, not comparison with results from other methods.

Hormann[36] pointed out that to get a conclusive result about 40-50 models of the same type of vessels need to be tested. This will be a costly process. An alternative is to test 4-5 models and apply analytic tools to extend the results of the experiments.

3.4.6.5 Full Scale Trials:

Full scale trials were carried out in the North Sea on a 64 m Fishery Protection Vessel to provide comparative data on the measured motion responses in a number of moderate and severe sea states in relation to theoretical and model prediction.

Spouge and Collins[72] carried out seakeeping trials of a Fishery Protection Vessel and suggested that a comparison of model experiments and theoretical predictions and roll motion records from seakeeping trials can be used to validate roll prediction and to help judge the practicality of roll stability criteria.

3.4.6.6 Analytic Treatments:

Bishop et al [73] carried out rigorous analytic treatments of the motion of a model of EDITH TERKOL, trawler which capsized in ballast condition. The observations were that the liability to capsize is not just determined by the sea or the vessel itself, but also by the mode of operation. They also concluded a series of quick events demanded too much to the helmsman of the vessel and consequently it capsized. The factors was that due to light weight the vessel showed divergence in motion, due to small GM and large forward speed the vessel started having unstable oscillatory motion etc. They finally concluded, among other things, that a following sea is more dangerous than head sea, trim by bow is accompanied by serious hazard and high Froude accompanied by transom stern may contribute to capsize.

Bovet[74] has carried out time domain computation of capsizing in following seas. The results were in good agreement with some experimental findings.

Analytic tools for extending model test results, as proposed by Hormann[36], has been mentioned above.

3.4.6.7. Statistical Method:

Roberts and Standing[75] proposed an approximate stochastic theory for predicting the rolling motion of a ship in irregular wave. By combining the results from the theory with information on the long term weather climate, it has been possible to predict the long term statistics of roll motion. The results agreed very well with that from some model tests. This result can be used in criteria, like IMO Weather Criteria, to assess stability on a probabilistic concept.

A more conventional method for predicting the long term distribution of ship motion is given by Spouge[76] which takes full account of roll non-linearities and voluntary changes of speed and heading due to the masters' efforts to minimize critical response in severe seas (Figure-3.9). From a practical point of view this approach could be useful in assessing the motion of vessel during its lifetime but it is not able to deal with parametric excitation and zero encounter frequency.

3.4.6.8. Simulation:

Brook[77] carried out simulation to determine the roll response of a vessel in irregular seaway. Subsequent comparisons were carried between i) experimental and theoretical roll damping coefficient, ii) model tests and full scale trials of roll motion and iii) seakeeping and simulation results.

The conclusions were that i) the methods for estimating damping coefficient of Ikeda[47] and Bearman et al[78] are suitable for different type of hull form, ii) the double exponential distribution which is fitted to the extreme roll angles from a simulation allows more meaningful data to be obtained from which a vessel's safety can be assessed, iii) vessels which has large natural roll period does not respond to wave action but the wind effects in such vessels can be significant iv) capsize may also occur even when the static angle of heel is acceptable but the vessel is hit by a gust and v) for criteria purpose, roll has to be coupled with sway and non-linear wave damping will critically affect the validity of any stability criteria which relies on equation of motion (e.g. Lyapunov Method)

Results of computer simulation carried out Amy et al[60] have been explained in article 3.4.4.2

3.5 On The Practice of Computation of Stability Particulars:

Stability of vessels are also largely influenced by trim attained while in service. But the usual practice is to calculate the relevant particulars assuming even keel condition and applying the same on trimmed vessels. This topic has been extensively investigated later in this thesis. This anomaly between calculated and actual values may lead to serious errors. Nickum[53] pointed that trim correction in GZ will be significant if the vessel has a raised forecastle deck, long flat deck aft and relatively low freeboard at the stern. Stroch[79] drew comparisons of trim corrected and constant trim GZ curves of a crab boat. Such boats generally have the above mentioned characteristics. Constant trim curve showed the GZ had a large positive magnitude at 60^{o}. But the trim corrected curve vanished at only 38^{o}. Upto 10^{o} the curves were coincident.

Error in interpreting watertightness in superstructure may be disastrous. Nickum[53] cited examples where a vessel apparently satisfying all requirements of IMO (except for GZ_{max} 0.02 m lower than required) capsized in a calm clear weather and nominal wave. The GZs were calculated for watertight pilothouse, but in reality it was not so. The buoyancy of the pilothouse deducted, the stability particulars reduced sharply. So he emphasized on standardization of GZ calculation procedure.

3.6 Considerations for Evolution of Rational Stability Criteria

The most urgent necessity of the research strategy for evolution of stability standards is a well concerted and organized program. In the past, formulation of a large number of criteria by individual flag administrations have created confusions for the designers and operators. This has also hindered agreement to a consensus on the matter. Too lenient rules may put human lives and costly ships into serious risk. On the other hand, too stringent requirements may restrict the designer seriously. A criteria has to be well thought one. An universallly applicable criteria may never be evolved. There has to be a provision for shaping the rules and make it suitable for the type of vessel considered. Shipowners and administrators will naturally insists on simple criteria, may be even without going into detail GZ calculation. Such thing may never be possible. But a criteria should be as simple as possible.

The science of ship stability assessment is essentially a complex one. Even though extensive works have been done, a 'rational' criteria appears to be, at best, far thing. A search will probably never end. This is mainly because with the passage of time novel ship types and floating structures will be evolving. Design and construction of Small Water Plane Area Twin Hull (SWATH) have already aggravated the problem. Stability and Safety of floating oil rigs operating at offshore is still a matter of serious issue. Floating mineral exploration platform and exploitation ships operating in deep seas may start operating soon. This will lead to added complexities. Faster computers and computation techniques, improved model testing facilities are the hopes for future.

CHAPTER 4

INVESTIGATION OF EFFECTS OF PARAMETERS ON STABILITY

4.1 General

This chapter deals with analysis of stability characteristics of inland double decker passenger vessels plying in the river routes of Bangladesh. The general hydrostatic particulars and effects of hull proportion, form, trim, flooding, wave etc are discussed.

For the purpose of carrying out the analysis eighteen vessels of the said type has been selected from the existing fleet. The particulars of the vessels are shown in Table 4.1 which has been prepared in ascending order of the length. The extreme lengths roughly represent the extreme of the fleet also. This chapter will concentrate on the study of the hydrostatic particulars, stability characteristics and specially effects of different parameters which influence stability. The usual approach is to calculate the KN value (GZ if the value of KG is known) (Figures 1.2 and 1.3) for displacements corresponding to important loading conditions. The curve of KN or GZ, whichever is applicable, is drawn and analysed. If a wide range of loading conditions (from lightship to overload condition) is considered, such a method will make the presentation impractically voluminous. An alternative is to calculate and plot the the maximum allowable KG to satisfy the criteria A.167 (Appendix A). To be considered stable, a vessel, at all displacements, has to satisfy this criteria. If the value of KG, at any loading condition, exceeds this maximum allowable value, the vessel is termed unstable at that loading condition. This maximum allowable KG is with particular reference to A.167. For any other criteria the limit is no more valid. In the rest of this chapter, this index will mostly be used to measure and compare stability.

4.2 Hydrostatic Particulars:

The hydrostatic particulars of the vessels have been computed and presented in Table 4.1. The values corresponds to minimum free board under load line regulations[81] which is given in the following.

$$f_{min} = 300 \text{ mm} \qquad L_f <= 24 \text{ m}$$

$$f_{min} = 300 + \{(L_f-24) \times 8\} \text{ mm} \qquad 24 \text{ m} < L_f <= 45 \text{ m}$$

$$f_{min} = 300 + \{(L_f-24) \times 9\} \text{ mm} \qquad 45 \text{ m} < L_f <= 55 \text{ m}$$

$$f_{min} = 300 + \{(L_f-24) \times 10\} \text{ mm} \qquad 55 \text{ m} < L_f <= 60 \text{ m}$$

where f_{min} is the minimum allowable freeboard and L_f is the 'Freeboard Length', normally taken 96% of L_{bp} except in ships of unusual shape in which case the definition is complex.

4.2.1 Displacement:

Table 4.1 indicates that though the vessels are arranged in ascending order of length, the displacements are not in the same order. This is mainly because of varying Breadth/Depth (B/D) and Length/Breadth (L/B) ratios. The same is true for waterplane area. The LCFs are aft of amidships in all vessels so is the LCBs except vessels 8, 11 and 12. Vessel 1 has the shortest transverse KM (3.256 m) and vessel 18 has the highest (7.452 m). The rest are unevenly distributed. In fact, except vessel no 18 the KM is below 5.5. The magnitude of longitudinal KM varies from 32.479 meter (vessel 2) to 109.261 (vessel 18). The height of the center of buoyancy from keel (KB) is mainly function of the draft and influenced slightly by other factors. This is specially true for beamy vessels since section fairing slashes a small fraction from the cross section area. The other parameters viz., wetted surface area, moment to change trim by 1 meter, displacement for 1 meter trim, midship area etc., do not influence transverse stability to a significant extent. Only wetted surface area contributes to roll damping which is accounted for only in the state-of-the art methods.

4.2.2 Hull Proportion:

The L/B ratio varies from 3.642 meter (vessel 2) to 5.271 meter (vessel no 13). Displacement being proportional to length and everything else remaining same, the L/B ratio does not itself influence stability and the righting arm remains the same. However, longer hull requires higher free board and consequently proportionately less displacement at the load line. The length also influences the vessel's stability against beam wind and passenger crowding. These will be discussed elaborately later in this thesis. The B/D ratio is the most vital parameter in transverse stability. Beamier vessels results in higher KM and consequently, higher GM and initial stability. The Depth/Draft (D/d) ratio, in fact, depends on Length/Depth (L/D) ratio in a non-linear fashion. This is because draft is depth minus freeboard and the later, as stated earlier, is a function of length only. This ratio D/d does not very much influence the initial stability.

4.2.3 Form Coefficients:

Table 4.1 also shows that the form coefficients C_b {D/(LxBxd)}, C_m {Midship area/(Bxd)}, C_{wp} (Waterplane area/(LxB)}, C_p {D/(midship area x L)}, and C_{vp} {D/(waterplane area x d)} in the subject vessels are almost uniform. For example, the C_b varies from 0.6095 (vessel no 4) to a maximum of 0.7065 (vessel no 17) and the rest are more or less evenly distributed within the range. Similar are the cases of other coefficients. Unlike other parameters, the water plane area coefficient C_{wp} and for that matter C_{vp} significantly influence the initial stability.

Compared to the initial stability (i.e., stability at small angles), the affair of stability at large angle is much more complex. The rest of this chapter will investigate the effects of different parameters, including those discussed above alongwith some other aspects of stability.

4.3 Investigations on the Effects of Breadth/Draft (B/D) Ratio and Trim on Stability:

4.3.1 (B/D) Ratio:

B/D ratio is the most important parameter in both small and large angle stability. Beamy vessels have higher metacentric height and so considered more stable. Transverse BM increases with second power of breadth. However, the metacentric height is not the only parameter. The complex hull shape dictates the magnitude of the righting arm GZ or say KN.

4.3.1.1 Results of Computation:

Figure 4.1 through 4.18 shows the variation of the maximum allowable KG of the basic hull forms of the subject vessels when altered to varying B/D ratio (2.5 to 7.0 at steps of 0.50). The figures does not represent the the maximum allowable KG of the subject vessels because the B/D ratio of all the vessels have been tuned to the same values. However, since the form coefficients are unchanged, these figures are expected to give some indications as to how the the maximum allowable KG varies with B/D ratio and form parameters. A look into these figures indicates some common features. These are:

(i) The the maximum allowable KG decreases monotonously with increase in breadth (B/D ratio) except at left upper end of the curve. But the displacements at this region have no practical significance.

(ii) Upto a B/D ratio of 5.0 ~ 5.5, the maximum allowable KG decreases with increase in displacement. At higher breadths, the maximum allowable KG has a maxima at an intermediate displacement and at the extreme B/D the maximum allowable KG increases with displacement.

In addition, the following observations are also made which are not necessarily common to all.

(i) Unlike any other vessel, the hull form of vessel 1 results in almost equal maximum allowable KG for B/D ratio 2.5 and 3.0 at and around designed displacements. None of the form coefficients of this vessel lies in any extreme. So it is not possible to attribute this uniqueness to any specific parameter.

(ii) Vessels with higher value of C_b tends to loose stability more rapidly at extreme B/D ratio.

4.3.1.2 <u>Discussions on Results:</u>

The observations listed above deserves discussion and interpretation. A common understanding is that beamier vessels are more stable. But the figures suggests reverse. This anomaly should be clarified. It is true that the value of KN increases with increased breadth, so is the GZ. A study of the stability particulars i.e., KN curves and the subsequent computation of the maximum allowable KG to satisfy IMO Res A.167 revealed that at B/D ratio 3.0 and higher the last item of the criteria (i.e., criterion F; maximum GZ should occur at an angle greater than 25 degrees) always becomes the governing item. That is, as the G starts rising up, the limit of the criterion F is reached first. This criterion is not dependent simply on the value of KN or GZ but on the nature of the GZ curve. Thus IMO criteria A.167 does not necessarily indicate the magnitude of KN or GZ.

IMO publications do not contain justification or elaboration to support incorporation of each item. So it is not possible to identify the deficiency in the stability of the subject vessels. Earlier in this thesis it was reported that the Offshore Supply Vessels generally have large breadths to fulfill its functional requirements. As a result the US Coast Guard found that it is not feasible for those vessels to satisfy the criterion F. To compensate this deficiency, the requirements of criterion F has been reduced to bare minimum of 15 degrees and other limits have been raised to a suitable extent. How would the maximum allowable KG had varied had there been no criterion F ? Figures 4.19 to 4.29 show that the absence of criterion F would have allowed a much higher magnittude of KG. Also the maximum allowable KG would have decreased with increase in displacement and higher breadths would have allowed higher magnitude of KG.

4.3.1.3 Contribution of Hull Proportion:

It is important to find out what causes steepness in the GZ curve. The waterplane area at inclined positions have been calculated for vessel no 1, 4, 7, 11, 15 and 18 and plotted in Figure 4.30. The values corresponds to minimum required freeboard. The reduction in waterplane area from upright condition to 40 degrees inclination are 56.3%, 57.3%, 56.8%, 60.7%, 55.6% and 65.0% for the vessels respectively. This steep reduction in the waterplane are is due to the fact that as breadth increases, deck immersion takes place at smaller angles. This is because the freeboard is dictated by the length only. A study of the Table 4.1 leads to infer that higher B/D ratio does not necessarily cause steeper reduction in inclined water plane area. This may be because other parameters like C_b, C_v. etc may also have significant influence. In Table 4.1, the B/D ratio of all vessels, except vessel no 18, are in a very close range. That is why the influence of other parameters were probably decisive in establishing relative magnitude of the percentage reduction of the waterplane area. However, vessel 18 has a much higher B/D ratio compared to the rest and consequently highest reduction. Figures 4.31, 4.32 and 4.33 shows the KN curves of the subject vessels at the f_{min} freeboard. From Figure 4.32 and Table 4.1, it is evident that vessel 8 and vessel 10 has almost equal KM_T but the later vessel with slightly lower B/D ratio has the maxima of its GZ curve shifted to the right side. Figures 4.31, 4.32 and 4.33 offers many opportunities for similar comparisons. Table 4.1 also suggests that suitable form parameters may also offset the effects of high B/D ratio, to a certain extent, on the reduction of waterplane area and consequently stability.

It is interesting to note that at B/D ratio higher than 3.0, which is in fact the case of most type of inland vessels, criterion F sets the limit of maximum allowable KG at all displacements. So for such types of vessels, the entire criteria A.167 may be replaced by the last item only. This is not the picture with coastal and ocean going ships even with B/D=3.0. Due to presence of watertight superstructures, poop, forecastle and other erections in those vessels, the reduction in waterplane is retarded. In fact, the GZ increases more steeply even after deck immersion[85].

4.3.1.4 Variation of Maximum Allowable KG with B/D Ratio at Loaded Displacement:

Figures 4.34 to 4.51 shows how the maximum allowable KG changes with B/D ratio at displacements corresponding to f_{min}, 1.5 f_{min}, 0.5 f_{min}. The later two displacements are considered to get an indication of how does this maximum allowable KG changes with displacement around the f_{min} freeboard. The figures reveals that all vessels behave in exactly similar way except for quantitative limits. The maximum allowable KG is attained at a B/D ratio just over 3.0. Also in this region the maximum allowable KG reduces with increased displacement. As the B/D ratio decreases from this point the maximum allowable KG decreases for all the three displacements considered. Computations have been done for B/D ratio upto 2.0. As the B/D value increases from the maxima of the curves, the maximum allowable KG decreases, the rate being faster at lower displacements. In fact, the difference between different displacements reduces and gets minimum at B/D between 5.0 and 6.0 and in this region the relation between displacement and maximum allowable KG reverses, i.e., more KG can be tolerated at higher displacement. A close look into Figures 4.34 to 4.51 will also show that the maximum allowable KG of a vessel will be more sensitive to B/D ratio and displacement if the LCB and LCF are more away from the midship.

4.3.1.5 Variation of KN Curve with B/D Ratio:

A natural question is how does the KN or GZ curve of a vessel changes with B/D ratio? Figures 4.52 to 4.54 shown the KN diagram of vessel no 4, 11 and 16 at displacement corresponding to f_{min}. The figures are similar. As B/D increases KM_T also increases, the KN increases rapidly at smaller angles. However, the angle of maximum KN appears to have inverse relation with B/D ratio. Maxima is reached earlier as B/D increases. Consequently, higher B/D ratio results in lower KN at large angles. The transition takes place at an angle around 45 degrees in all the three vessels plotted. This also explains why vessels with higher B/D ratio have a lower allowable limit of KG and this is only due to the maximum GZ occuring at smaller angles. It may be noted that upto 40 degrees inclination KN is always higher for higher B/D. Consequently, each item except 'F' of IMO criteria A.167 will indicate better stability margin for beamier vessel.

As discussed in the previous chapter that offshore supply boats are also characterized by high B/D ratio. This is due to the fact that functional requirements of those vessels require larger breadth. As a result, those vessels also can not satisfy the requirements for angle of maximum GZ.

An alternate criteria with bare minimum required angle of GZmax equal to 15 degrees and more stringent value of the other items have been adopted for those vessels.

4.3.2 Effects of Trim:

It is convention for the designers to design vessels to float on even keel. Exceptions are vessels like tugboat and some other service crafts which are sometimes designed with rise of keel. However, the stability parameters are computed for the designed keel condition. But vessels do not always ply on the designed keel, specially at light, ballast and under adverse loading conditions. At light condition trim is reduced to minimum with the help of ballasting tanks. But the vessels under consideration i.e., inland passenger vessels of Bangladesh, do not generally have any arrangement of ballasting. As a result, the draft forward at lightship condition sometime become negative. The stability, however, is analysed assuming the vessels to be on designed keel. It is important to quantify the deviations of the stability particulars (i.e., KN, GZ, the maximum allowable KG etc) with trim.

4.3.2.1 Influence of Rolling Motion on Trim:

The geometry of the fore and aft bodies of the vessels are completely different. When a vessel floats freely, she adjusts her trim in such a way as to place the longitudinal center of buoyancy (LCB) at the same vertical line as the longitudinal center of gravity (LCG). As the vessel starts rolling motion, the LCB will shift, the amount depending on the shapes of forward and aft bodies. But the LCG will remain in the same place. The vessel will tend to change trim with rolling. In other words, rolling motion is inevitably accompanied by pitching motion. However, this pitching motion is not the concern of the present study. The considerations are purely static and is aimed at estimating the change of stability particulars with rolling motion.

4.3.2.2 Procedure of Analysis:

Stability particulars of the subject vessels at different trim conditions are considered. Particulars have been computed for even keel condition five trim conditions both by bow and stern. The trim conditions assumed are 0.25, 0.50, 0.75, 1.00 and 1.25 times the depth of the particular vessel.

4.3.2.3 Results and Discussions:

4.3.2.3.1 Trim by Bow:

Figures 4.55 to 4.72 shows the variations of the maximum allowable KG with trim by bow and displacement. In the following, until discussions are started on trim by stern, unless mentioned otherwise, the term 'trim' will indicate trim by bow.

Figures indicates that at high displacements the maximum allowable KG increases with increased trim. The exception is vessel 1 where the maxima occurs at intermediate trim. The stability of vessels 17 and 18 appear to be most sensitive to trim and the rest of the vessels almost equally influenced. Vessels 7, 12, 13 and 14, however, being the least influenced ones. As the displacement decreases, the relation between trim and the maximum allowable KG starts reversing. At very low displacements higher trim results in lower maximum allowable KG. However, vessels 1, 5, 8, 13, 15, 17 and 18 are with exceptions. In vessels 1 and 13 even keel condition remains least stable at all displacements followed by a trim by 0.25 D. At higher trims the relation between trim and the maximum allowable KG are heterogeneous throughout the entire displacements range. Vessel 5 remains less stable at smaller trim at all displacements. But the curve of maximum allowable KG is less steep at lower displacement. Also, at lower displacements the maxima occurs between 0.75 D and 1.00 D trim. Vessel 8 is similar to most of the rest except at very high trim, the curve get unusually steep at low displacements. In vessel 15 the effects of trim gradually diminishes as displacement reduces and ultimately almost vanishes at very small displacements. The curves for vessel 17 are very similar to those for vessel 1 and 13, except for, as mentioned earlier, the stability of this vessel is highly sensitive to trim. Vessel 18 appears to have higher stability at higher trim at higher displacements. But as the displacement reduces, the differences between the curves for 1.25 D, 1.00 D, 0.75 D, and 0.50 D starts narrowing down. The difference almost vanishes at one point and at even lower displacements the relative magnitudes starts changing.

4.3.2.3.2 Trim by Stern:

The relation between trim by stern, displacement and the maximum allowable KG of the subject vessels are shown in Figures 4.73 to 4.90. 'Trim' from now on will mean trim by stern. A study of the figures will reveal that the effects of trim by stern on stability are almost uniform in all vessels except for some deviations in vessels 17 and 18. At very low displacements higher trim causes reduction in the maximum allowable KG. As the displacement increases, the vessel appears less sensitive to stability and at an intermediate range becomes almost insensitive. Above that range, the relation between stability and trim reverses. Higher trim results in higher maximum allowable KG. However, as displacement continues to increase, the relation starts reversing again and the curves start intersecting each other. Vessels 1, 4 and 13 are the least and vessels 6 and 11 are the most sensitive ones. Vessels 17 and 18 behaves similarly and are the most sensitive ones, the latter being more. In the rest of the vessels, at low displacements, stability reduces as trim increases. But in vessel 17 this does not hold true for even keel and trim of 0.25 D. In vessel 18 no such relation can be said to exist. As the displacement increases, like all other vessel studied, the differences between the curves starts narrowing down but in a bit different way. At higher displacements, unlike the rest of the vessels, higher trim does not always cause increase in the maximum allowable KG. Also the intersection of the curves at the right end does not exist. Table 4.1 shows that the vessels 17 and 18 has highest B/D ratio. So it can be infered that higher B/D ratio results in stability characteristics more sensitive to trim. No other proportion or form parameter of these vessels lie in the extreme of the vessels considered.

4.3.2.4 Possible Extent of Trim Correction:

The above discussions suggest that trim corrections may be significant is some vessels. If the even keel stability is marginal and the vessel floats with significant trim, necessary checks should be made. Most critical situation is probably is the lightship condition where both the magnitude of trim and the effects of trim may be high. For example, vessel 18 displaces 214 tonnes at light condition with a trim of 1.925 meter (trim/Depth = 0.844). From Figure 4.97 the following values are found:

Trim	Even Keel	0.57 m (0.25 D)	1.14 m (0.50 D)	1.71 m (0.75 D)	2.28 m (1.00 D)	2.85 m 1.25 D)
Maximum Allowable KG	2.312 m	2.104 m	2.549 m	1.971 m	1.924 m	1.971 m

Inclining test results shows the KG to be 2.298 m at light condition. The even keel calculation shows the stability to be O.K. But if the above values are plotted the maximum allowable KG, for the actual trim condition, stands a 1.953 m i.e., a negative margin of 0.345 m. The situation may vary widely with hull form. For example in the case of crab boat[79] discussed in the preceeding chapter the enormous superstructure foreward will cause the center of buoyancy shift considerably in the foreward direction with inclination. This will result in both loss of directional stability and reduction of stability at large inclinations. In vessels with large superstructure aft (e.g. coastal and seagong vessels), the LCB will move aft with inclination and obviously the stability will also be altered significantly.

4.3.2.5 Estimation of Change of Trim with Rolling:

As mentioned earlier, rolling is inevitable associated with shift of LCB in ship shape bodies. Consequently vessels tend to take a new trim. It is, however, very difficult to estimate the change of trim because it involves evaluation of the added mass, frictional damping for pitching motion etc. A static approach will be adopted here to get an idea about the maximum possible effect that can take place. It is assumed that as the vessel rolls, the trim changes smoothly so as to keep the position of the LCB undisturbed. Had the vessel not changed its trim, the positions of LCB at f_{min} freeboard displacement and at different inclinations has been calculated for vessels 1, 4, 7, 11, 15 and 18. The results are plotted in Figure 4.91. For quantitative assessment the most critical case(s) need(s) to be identified. Vessel 18 makes the job easy. Its stability is most sensitive to trim and the LCB of this vessel is the most disturbed by rolling motion. From upright condition to 60 degrees inclination the LCB shifts (0.392 - 0.309) = 0.083 m towards the bow. From Table 4.1 the moment to change trim 1 meter is found to be 1260.7 tonnes-meter. So the resultant trim will be 0.036 meter (0.016 D) which is expected to alter the stability negligibly. However, since at lightship condition the geometry of the fore and aft bodies are much dissimilar, the change in trim may be more significant. These will add to complexities of the lightship condition as stated earlier. Experiences have revealed that a slight trim by bow causes wet deck and resultant capsize. Steering related disasters are also very common under such conditions. This vessel (vessel 18) will be on even keel at upright, loaded conditions. But as it rolls it will get somewhat trimmed by bow. The master will maneuver the vessel to compromise with the wave. The result can be an ultimate capsize.

4.4 Effects of Flooding/Free Surface:

Presence of free liquid surface is always detrimental to stability. It causes a virtual increase in the KG. In computation of stability, presence of free liquid surface, if any, should be taken care of. The usual location of the free liquid surface are fuel oil tanks, fresh water tanks and in oil tanker/water barges, the cargo hold. Service tanks are generally small and do not influence stability. The subject vessels do not generally have large fuel or water tanks. The present study aims at quantifying, if one compartment of the main hull is flooded due to leakage in the hull or as a result of damage. The problem is basically of damaged stability but will be treated here with pure static approach.

4.4.1 Methods of Estimation:

The conventional approach of incorporating the free surface effects is the wall sided formula. Most of the text books recommend this method.

The free surface moment $I_{fsm} = (I_{fs}/sp.gr.)*\sin(\theta)$

I_{fs} is the moment of inertia of the free liquid surface at upright condition, sp.gr is the specific gravity of the liquid in the tank and θ is the angle of inclination. IMO recommends a certain method for estimation of the free surface moment[83]. Though not mentioned in the relevant publications but the this method is apparently intended to estimate the moment that will develop when the compartment is filled to the most damaging condition.

4.4.2 Procedure of Analysis:

The object of the study is to estimate the free surface moment by direct computation and draw comparison with the wall sided and IMO method. The requirements for the maximum length of subdivision under SOLAS Convention of 1974[84] involves calculation of the floodable length and multiplying the same by a 'Factor of Subdivision', which reduces with length and higher for passenger vessel than for cargo ships. A number of other parameters, like volume of machinery space, margin line, passenger or cargo capacity etc. are also involved in the process of fixing the maximum allowable distance between bulkheads. Stability in damaged condition is also calculated with permebility to be dictated or guided by the rules adopted.

Draft Inland Shipbuilding Rules of Bangladesh[81] are rather simple and allows a maximum bulkhead spacing of 0.15 L + 6.5 meter. It is assumed that each vessel has a compartment of this maximum allowed size at the midship. The vessels studied are no 1, 4 7, 11, 15 and 18. The compartments are assumed to be partially flooded with water. The wall sided and the IMO formula are independent of the amount of flooding. Direct computations have been performed to estimate the moment due to shifting of the liquid with rolling. The compartments have been assumed to be 5%, 10%, 25%, 50% and 75% filled with 100% permeability.

4.4.3 Results and Discussion:

Results of the computations have been plotted as in Figure 4.92 to 4.97. The following observations may be noted:

(i) For very small amount of flooding, the moment becomes virtually constant above 20 degrees inclination.

(ii) Direct computation results indicate that the worst condition will arise when the compartment will be flooded to an amount between 50% and 75% of capacity. The exact quantity depends on the hull form and the angle of heel.

(iii) The IMO formula indicate a flooding extent between 25% and 50% and at all inclinations are much lower that the maximum computed moments.

(iv) The wall sided formula can at best be used upto 20 degrees inclination. In high beam vessel (e.g., vessel 18) the limit may be as low as 10 degrees. Above this limit the wall sided formula indicates free surface moment much higher that actual.

It may be noted that in case of rolling the picture is much more complicated than what appears here. This is because there exists a time lag between the rolling of the vessel and shifting of the liquid and realistic pictures can only be obtained with rigorous calculations and supporting model tests.

4.5 Effects of wave:

It is customary for the naval architects to compute the stability particulars for vessels floating on still and calm water. But in actual conditions vessels are inevitably poised on waves. So it is important to investigate how the stability parameters changes when the vessel is placed on wave compared to when in calm water. During the last few years researchers have realized the importance of taking the wave into account. However, investigations of the effects of wave in the stability of a particular vessel is at best limited. Some of the publications studied only contain qualitative pictures. Only the proposed 'Strathclyde Method', explained earlier in the thesis, involves rigorous investigations of the effects of wave on stability. Six vessels from Table 4.1 have been selected for investigations. These are vessel

1, 4, 7, 11, 15 and 18. The results are plotted in Figure 4.98 to Figure 4.103.

4.5.1 Estimation of Wave Parameters:

The influence of wave on stability depends on, in addition to hull form, i) wave profile, ii) wave length, iii) wave height, iv) the orientation of the wave with the vessel's center line v) the position of the wave crest (or say trough) etc.

4.5.1.1 Wave Profile:

In the present analysis trochoidal waves are assumed since this is the most commonly used method. In computation of ship structural strength, such wave profiles are always used. Literatures on the 'Strathclyde Method' does not spell out the wave profile assumed, but it is also expected to be a trochoidal one. The parametric representation of the profile is[93]

$$X = \{ L_w / (2 \times PI)\} \theta + (H_w / 2) \times Sin(\theta) - X_0$$

$$Z = (H_w / 2) \{ 1 - Cos(\theta) \}$$

Where:

L_w is the length of the wave.

H_w is the height of the wave.

X is the longitudinal distance of the wave profile from aft perpendicular of the vessel - taken positive foreward.

Z is the vertical distance of the wave profile from the crest to the wave surface, taken positive downward.

X_0 is the distance of the crest from A.P. and have the same sign convention as for X.

θ is the parameter.

4.5.1.2 Wave Length:

To conform with the 'Strathclyde Method', the length of the wave is taken equal to that of the vessel i.e., L_{wl}.

4.5.1.3 Wave Height:

The estimation of the waveheight is the most delicate task because this will have the most significant influence on stability. Ordinarily this estimation is based on physical recordings in concerned geographical region. The recordings are generally presented statistically. A number of regressional models are available for estimation of waveheight as an exclusive function of wavelength. Unfortunately, all such formulas are applicable to oceanic environment. Three such equations are as follows[88]:

$$H_W = L_W / (4.14 + 0.14\, L_W) \qquad (4.1)$$

$$H_W = 0.607\, L_W^{\,0.5} \qquad (4.2)$$

$$H_W = L_W / (10.0 + 0.05\, L_W) \qquad (4.3)$$

where H_W is the wave height and L_W is the wave length (both in meter).

In the 'Strathclyde Method' an average of the three formulas are considered.

Moskowitz and Pierson[86] applied Similarity Theory on spectral form for fully developed wind sea. Based on the results of the same, Islam[87]. proposed an equation for estimation of wave height as an exclusive function of wind speed. This is a logical approach because waves are mainly produced by wind. The equation is as follows:

$$H_{1/3} = 5.68\, V_w^2\, 10^{-3} \qquad (4.4)$$

where $H_{1/3}$ is the average of three wave height in meters and V_w is the wind speed in Knots at 19.5 meter altitude.

Table 4.2 and 4.3 show the waveheights predicted by the above mentioned formulas. Since there are no records of waveheight measurements in the rivers of Bangladesh it is not possible to conclude if any of the above formula are suitable for application in inland rivers of this country. But physical observations suggests that waveheights shown in the above tables are probably too high compared to actual waves even in the worst conditions. In view of the above explained situation some judgments need to be used.

The wind load on the lateral area above the waterline is a function of the nominal wind speed and hull parameters. Kuo[88] et al suggested from some experimental findings that in inland waters the load will be one half of what would have been in open sea in the same vessel and with same nominal wind speed. The author infers from the same findings that the waveheights in inland waters could probably also be reduced from open sea condition. If the extent of reduction is assumed 50% and the values in the Table 4.2 modified accordingly, the figures, when compared with physical observations appear to be quite realistic. In the rest of the work the waveheight is taken one half of the assumed magnitude in the 'Strathclyde Method'.

4.5.1.4 <u>Vessel's Orientation with Wave:</u>

Vessels orientation with the wave is also expected to influence stability significantly. There have been numerous experiments / computations about capsize behavior in following and quartering waves. The whole picture is naturally very complicated. Following seas are generally considered to result in the worst conditions of stability. Since no study involving inland passenger vessels has been carried out till now, It can not be said with full confidence that the same is true for such vessels also. Experimental methods may be the only way of determining the actual variation of stability with wave. Vessel speed is also expected to play important role. Vessels interaction with the wave will alter the wave profile, a phenomenon called wave diffraction. Barrie[46] showed that this can alter the stability significantly. However, such an extensive investigations are beyond the scope of this work. The vessels are supposed to be poised on a trochoidal wave of length and height mentioned previously. The vessel is static i.e., no velocity. The direction of travel of the wave is parallel to the vessels centerline. Wave diffraction is ignored.

4.5.2 Procedure of Analysis:

Six vessels have been selected for investigation of wave on stability. These are vessel 1, 4, 7, 11, 15 and 18. The GZ values have been calculated at 10 degrees interval and for 16 equally spaced (1/16 spacing) positions of wave crest. The value of KG had been obtained from inclining test results. The results are for displacement corresponding to f_{min}. Trochoidal wave profile is assumed.

4.5.3 Results and Discussions:

Though results have been computed for sixteen positions of the crest of the wave, but for convenience in plotting and making it understandable, GZ curves for eight positions (1/8 spacing) has been plotted (Figures 4.98 to Fig 4.103). A study of the figures will suggest the following.

The presence of wave may greatly influence stability even at small angles. The apparent metacentric height may fluctuate greatly when the vessel is rolling in wave. Smaller vessels appear to be more sensitive ones. This is, in fact, more severe than what are appearing in the figures. Due to non linearities in the relation between wavelength and waveheight, the waves becomes less steep as the length reduces. The curves for vessel 1 is most diverge and those for vessel 18 is least. For example, in vessel 1 at 20 degrees inclination the minimum value of GZ is 60% of the maximum, while in vessel 18 the corresponding figure is only 86.5%. The divergence reduces monotonically as the length of the vessel increases. Whether or not the parameters like breadth, depth, form parameters, proportions etc. have any significant influence is subject to a more extensive study.

It is generally said that, compared to the still water value, the GZ curve generally shifts upward when the crest is at amidship. The reverse when crests are at the ends. But the actual computation results are not that uniform. In figures for vessel 1, 4 and 7 it appears that the still water GZ always have an intermediate value, more exactly more than the average of the extremes. But in vessel 11, 15 and 18 the still water GZ, above a certain inclination, is higher than for any position of the wave. This limit is roughly 18, 17 and 11 degrees for vessels 11, 15 and 18 respectively. At lower inclination still water GZ have intermediate values. At higher inclinations the effects of position of the crest reduces uniformly. For the largest three vessels (vessel 11, 15 and 18) the effects almost vanishes. Also at high inclinations the effects of the wave also reduces gradually.

The vessel 1 has the least GZ at 10 degrees when the crest is at A.P.. But as the crest moves slightly (L/8) forward, the GZ increases drastically and little more when the crest is 0.25 L forward of aft end. As the wave moves more forward, the value changes more randomly. At higher inclinations the GZ for the crest at 0.25 L forward of A.P. remains maximum. This is also slightly higher or equal to the value of GZ when the crest is 0.125 L forward of A.P. But for other positions of the wave the fluctuation is random and reduces gradually as inclination increases.

In vessel 4 the GZ value is very low when the crest is at aft. But when the crest is 0.125 L forward of A.P. the value of GZ is drastically higher. But as the wave proceeds, the GZ value changes randomly. The same are true for vessel 7. The fluctuations of GZ for positions of crest is more random in vessels 11, 15 and 18. But as mentioned earlier, the amount of variation is comparatively less. Some other characteristics of the curves of these vessels are explained earlier.

Henrickson's[37] reported that when the vessel is poised on wave, the initial stability does not reduces significantly. The results of the present study indicate that the GZ curve may fluctuate even at small angles to a considerable extent. The deviations may be attributed to a number of parameters. The most important is probably the waveheight which does not change linearly with wave. The effects may be greatly influenced by the length of the vessel itself. In fact, due to the wave becoming less steep for smaller vessels, the effects should have been less. However, if compared with Bovet's[63] prediction that in wave the GZ curve may become altogether negative, even when it was positive in calm water, the findings here are less severe. In the present study, the difference in the length of the vessels 1 and 18 is only 23.5 meters. But this has resulted in a significant variation in the influence of wave position on the curve. Thus for much longer vessels with much different proportions and forms and in oceanic waves, the nature of the GZ curve may change altogether. However, it should be noted that in the stability analysis of inland passenger vessels, the effects of wave should be taken into account. This is specially true for smaller ones. It may be pointed out that only in the 'Strathclyde Method', the fluctuations discussed above is taken into consideration and the stability is assessed for the worst situation or combination of situations.

One would probably agree that the actual effects of wave on stability can probably not be estimated by statical calculations only, at least quasi-static approach is essential. Some results of model tests are mentioned in the preceeding chapter. In fact, the observations reported by Kerwin and Grim[64] and that of Paulling[65] can only be done with model tests, no analytic tools have yet been developed to even indicate anything of that sort. Correct estimation of the wave parameters are also very vital.

CHAPTER 5

STABILITY ANALYSIS

5.1 Outline of the Analysis:

This chapter deals with the actual stability analysis of six vessels out of the eighteen studied in the preceding chapter. These are vessel no 1, 4, 7, 11, 15 and 18. The selections were made on the ground that the inclining test results of these vessels were made available. The KG at the loaded conditions were estimated for each vessel. The loaded displacements are the ones corresponding to the minimum allowable freeboard defined in the previous chapter. In the rest of this chapter the stability will be assessed for the loaded conditions and the estimated KGs.

The stability analysis will consist of five items:

(i) IMO Intact Stability Criteria (IMO Res A.167)

(ii) Stability against beam wind on lateral projected area above the load water line.

(iii) Stability against passengers crowding to one side

(iv) Strathclyde Method

(v) Lyapunov Method

5.1.1 A Review of the Criteria Considered:

The IMO Intact Stability Criteria is related exclusively to the GZ curve at calm water. No parametric excitation like wind, wave, passenger crowding etc. are taken into considerations. The capability of this criteria to assess the stability of vessel in a realistic environment is, obviously, seriously restricted. As a result, in order to ensure stability against the hazards mentioned above, vessels must satisfy other criteria also. The most common excitation is generated by the wind. The stability is most seriously hampered when wind hits the vessel from the beam side. Two criteria will be considered here to assess the related stability of the vessels. The first one, in fact, is the first such criteria formally proposed. This was subsequently adopted by the US Coast Guard for vessels under 150 tonnes displacement. The other one, quite similar to the first one, is the statutory requirement of the IMO.

The second important hazard is the crowding of panicked passengers to one side in case of storms and severe rolling. The criteria adopted by the US Coast Guard is considered here.

Unfortunately, the above mentioned criteria deals with different forms of excitations separately. In fact, in the real world, all form of excitations may appear simultaneously. For example, in storms an otherwise calm water will generate waves, wind load will be of highest intensity and consequently the panicked passengers will get crowded to one side. Compartments and deck may get flooded. A realistic criteria must take all of these factors into consideration simultaneously.

Moreover, these criteria are based on static considerations. The vessel is considered static at upright or inclined positions. A capsize mechanism is essentially a dynamic one, so the frictional damping plays a vital role in capsize behavior of vessels. For example, fitting of a bilge keel or any other roll damping device will result in a longer roll period. Physical observations suggests that the vessel will become more comfortable as well as less chances of getting capsized. But the above discussed criteria fail to distinguish between the same hull with and without roll damping device. A realistic criteria must have this feature included in it. The Strathclyde Method and the Lyapunov Method are free from such limitations. However, these methods, discussed earlier in this thesis, are yet to be validated. Consequently, till now no formal regulation which is formulated with these methods has been adopted by any statutory body / organization. Some are reported to be under considerations. Few parameters are not standardized. The assumptions in this study will be clearly mentioned. In addition, some subjective judgment has to be used to make the results more realistic.

Inland passenger vessels of Bangladesh almost inevitably ply overloaded. This probably can not be stopped altogether. So a more realistic approach is to incorporate a margin in the criteria to take care of at least moderate overloadings. In the relevant context a 20% overloading may be termed moderate. The author had investigated the stability of three such vessels (none of those are considered anywhere in this thesis) at designed load and at 20% overload[89,90]. The results showed that an overloading of such an extent can significantly jeopardize stability.

The values of different parameters used in this chapter are given in Table 5.1.

The aspect of stability assessment has been elaborately discussed in Chapter 3 of this thesis. Obviously, the discussions of this chapter refer to the contents of Chapter 3. To make the length concise specific references and repetitions of discussions are avoided.

The analysis given in the following are for the loaded conditions. But previous discussions have suggested that the stability at light or ballast condition may sometimes be worse than at full load. The criteria do not probably equally apply to light vessels (e.g., the limiting value of KG/Depth or KG/Draft as mentioned in Chapter 3) and at least some modifications may be essential like the suggestions of Nickum[53].

5.2 The GZ Curve and IMO Res A.167:

The GZ curve for the six vessels are given in figure 5.1. IMO Intact Stability Criteria is given in Appendix C. The comparison for the actual and required values are given in Table 5.2. The table shows that each of the vessels has a fairly high metacentric height, much above the required limit. The area under the GZ curve upto 30^{o} are also well in excess of the limit. The same is true for area upto 40^{o} (vessel 1 is just marginally higher than required). Vessels 1 and 4 have failed to satisfy the requirements for area under the curve between 30^{o} and 40^{o}. For vessel 1 the value is very small. In fact, for this vessel, there is no merit in computing the area upto 40° since the stability vanishes at only 37.75 degrees. The GZ at 30° should be minimum 0.20 m. Again vessel 1 and 4 are lagging, the smaller one more severely. The last item of the criteria required the GZ to occur at an angle not below 25°, preferably 30° or above. In this item none of the subject vessels could qualify. Vessel 4 is the worst and vessel 15 is the best. The last row of the Table 5.2 show that the angles of vanishing stability (θ_V) are very small. This also reduces with the size of the vessel. Conventionally, in case of passenger vessels, θ_V should not be less than 70 degrees. The poor values of the Table suggests that for the type of vessels considered here, a minimum value of θ_V should form a part of criteria. It is worth pointing out the Table 5.2 indicate better stability of larger vessels. Exception is the θ_V. It has already been explained, in the previous chapter, that for B/D ratio in excess of 3.0, θ_V always dictates the maximum allowable KG and for higher B/D a lower limit is generally allowed. It can also be noted from the same table and Table 4.1 that higher B/D ratio will contribute to larger metacentric height. And this, in turn, can improve each item of the stability criteria except for θ_V. This can only be improved by reducing B/D. But the reasons for which a limiting value of θ_V could not be fixed is explained in Chapter 3.

5.3 Stability Against Beam Wind:

5.3.1 US Coast Guard Criteria:

This criteria was proposed by Sarchin and Goldberg in 1962[43]. It was later adopted for USCG, the regulatory body in the US for vessels over 150 tonnes. The method has been explained in section 3.3.2.1

This equations 3.1 and 3.2 were basically formulated for coastal and seagoing ships. Kuo[88] with the help of some experimental results, suggested that the above mentioned equations, if used for inland vessels, should have a correction factor of 0.5. This factor has been incorporated in the present study. The parameters were measured from the relevant drawings and value of Displacement taken from Table 4.1. The wind speed is generally taken 100 knots for coastal and seagoing vessels. Wind data available from the meteorology department[14] suggests that 50 knots may be a suitable magnitude for assessing stability of inland vessels.

5.3.1.1 Results and Discussions:

Table 5.3 shows that larger vessels are safer against beam wind. The criteria for the value of GZ_s/GZ_{max} is satisfied by all vessels with quite a good margin. Vessels 1 and 4 failed to have the minimum required value of A_1/A_2, for the smaller vessel the figure is very poor. It is very difficult to explain the exact reason of such behavior. However, the first row of the Table 5.3 shows that the smaller vessels have larger heeling arm coefficient {Heeling arm = Heeling arm coefficient x $Cos^2(\theta)$, refer to Equation 3.1}. This is because as the length of the vessel increases, the denominator (displacement) increases much more rapidly than the numerator (windage area) of the equation 3.1. This causes reduction in the heeling arm coefficient. It may also be observed in the figure that smaller vessels have much lower GM and GZ values. Both of these have contributed to lower safety against beam wind. As will be seen later, for the same reason, smaller vessels show poorer stability in all conditions. However, there has been one exception also in this case. Vessel 18 is 9.0 meter longer than vessel 15 but has a higher value of GZ_s/GZ_{max} and lower value of A_1/A_2. The trend in the table suggested higher A_1/A_2 for vessel 18 than vessel 15. The possible reason of this deviation deserves critical analysis. Due to higher B/D ratio vessel 18 has a higher metacentric height. But for the same reason the maxima of the GZ curve is reached sooner (19^o for vessel 18 compared to 23.75^o for vessel 15). It is also noted from Table 5.3 that the leeward angle θ_2 (defined in 3.3.2.2) are same for the two vessels (50 degrees). The static angle of heel (defined in 3.3.2.3) and the maximum windward angles (defined in 3.3.2.1) are also very close. The benefits of high metacentric height due to large B/D ratio is mostly available upto the maxima of the GZ curve. Thereafter the curve drops sharply and the area under the curve increases at a much lower rate. In vessel 18 the area A_1 is computed upto much beyond the maxima of the GZ curve. But area A_2 is computed just 5^o above maxima. The high B/D ratio has contributed more to A_2 than to A_1. This possibly explains the anomaly.

5.3.2 Beam Wind and IMO Criteria:

The IMO criteria for stability against beam wind is explained in section 3.3.2.2, equation 3.2 and Figure 3.4. The equation 3.2 is meant for coastal and seagoing vessels. As discussed earlier that for the same nominal wind speed the wind lever can be reduced to one half for inland vessels. The same correction is adopted in this case also.

In Figure 3.4 angle of rolling θ_r in the same as in the USCG criteria (i.e., 25^o). In Chapter 3 it had been pointed out that this assumptions for the magnitude of θ_r may be too conservative for smaller vessels. Just to have an idea about how the relevant figures changes with the value of θ_r, calculations have also been done for $\theta_r = 20^o$.

5.3.2.1 Results and Discussions:

Computational results are given in Table 5.4. The corresponding item names are distinguished by the symbols (25^o) and (20^o) respectively in the table. The results are uniform and shows that the two smallest vessels (vessel 1 and 4) do not satisfy the criteria even for $\theta_r = 20^o$. The rest four (vessel 7, 11, 15 and 18) are safe against wind even when θ_r=25^o. Vessel 7 is just marginal. The deviation observed for vessel 18 in Table 5.3 does not exist in this method. The reason may be that i) due to the gust being taken into account the wind heeling lever is 50% higher at upright condition than in USCG criteria and ii) the wind lever being constant in this method is even much higher in larger inclinations. Both of these contributes to θ_2 being lower in this criteria. Due to the reasons explained article 5.2.1.1, this lower value of θ_2 has prevented the area A_1 of vessel 18 getting more benefits of high metacentric height.

5.4 Stability Against Crowding of Passengers:

Crowding of panicked passengers during storms or in case of severe rolling is a serious hazard experienced by passenger vessels. This is particularly serious for the type of vessels under investigation. The reasons being that

i) The number of passengers per unit area are much higher than in case of coastal or seagoing passenger vessels.

ii) There are no longitudinal or transverse partitions separating the passengers. As a result they can move a large distance in both directions.

Both of the above mentioned factors contribute to the generation of a huge moment in both longitudinal and transverse direction. The component in the longitudinal direction influences the pitching motion and trim which are not under consideration. The awthwart movement of passengers is related to transverse stability. When a vessel gets heavily listed to the, say, port side, the passengers move to the starboard direction. This, at the first instance causes increase in the righting arm GZ. But the vessel soon gets listed to the other side. The increase in GZ, in fact, accelarates the motion of the vessel. But the passengers can not so quickly shift their position to the other side. This is the worst condition which causes reduction in the righting arm GZ. In the upright condition the CG of the passengers are assumed to be in the center line of the vessel. For the seagoing vessels, the CG of the passengers when crowded to one side is assumed to be one sixth of the breadth away from the center line. But due to the two peculiarities of the subject vessels mentioned previously, the shift of the CG is assumed to be one fourth of the breadth.

5.4.1 US Coast Guard Criteria for Passengers Vessels:

This method of assessing stability against crowding of passengers consists of superimposing the passenger crowding lever curve over the GZ curve (Figure 3.10). The passenger crowding lever is given by the following formula:

$$D_{pc} = W \times l \times \cos(\theta) / D \quad \text{.......................(5.1)}$$

Where D_{pc} is the stability lever due to passenger crowding (meter), W is the total weight of passenger (tonnes), l is the average awthwart movement of the passengers. θ, and D have the same meanings as in equation 3.1 and 3.2

A Vessel is considered stable if:

i) GZ_s/GZ_{max} do not exceed 0.60

ii) A_2/A_1 does not exceed 0.40 (Figure 3.10).

A_1 is the area under the GZ curve and A_2 is the shaded area in the figure 3.10.

The results of the computations are given in Table 5.5. Results show that, like the case of wind load, vessel 1 and 4 are the unsafe ones. These vessels could not satisfy any of the items of the criteria. Each of the rest (vessel 7, 11, 15 and 18) has satisfied both the items. Also the longer vessels appear to be more stable. There is, however, an exception similar to USCG wind criteria and involving same vessel (vessel 18). The reasons are also probably the same.

5.4.2 <u>Japanese Criteria for Stability Against Passenger Crowding:</u>

Kansai Society of Naval Architects of Japan[91] recommends the following criteria for passenger crowding in passenger vessels.

$$GZ_{\emptyset'} >= \{1.71\ Al + 0.214 \sum(7 - \frac{n}{a})\ nb\} / (100\ D) \quad \text{.........(5.2)}$$

where Ø is the angle of deck immersion and Ø' satisfies tan(Ø') = 0.8 x tan(Ø) and the summation taken over all passenger compartments.

A and l has the asme meaning as in equation 3.1

a = floor are of a single compartment (m).

b = distance across which the passengers can move in the awthwart compartment in a single compartment.

n = number of passengers in single compartment

Other symbols have their usual meanings:

Table 5.6 shows the value of the angle Ø and Ø' of the subject vessels.

It appears that the value of $\emptyset'$ is between 4.21 and 4.61 degrees. So $GZ_{\emptyset'}$ will be equal to GM x Sin($\emptyset'$) i.e., exclusive function of metacentric height GM. In other words this criterion, applied to the inland passenger vessels, is concerned only with the initial region of the GZ curve and consequently on the GM alone. So the ability of this criterion to predict the stability during actual rolling (inclination goes much beyond 4.5 degrees) is very much restricted. As have been observed earlier that the metacentric height (GM) of the vessels are very high only due to high B/D ratio. The author had earlier investigated three such vessels (mentioned previously). This criterion applied to those vessels indicated a margin of safety much higher than the USCG criterion. In light of the above discussions this criterion is not tested here for assessment of stability in passenger crowding.

5.5 Stability Assessment with Strathclyde Method:

5.5.1 Estimation of Parameters and Coefficients:

This method of assessment has been explained in Chapter 3 and Appendix D of this thesis. For actual computation the necessary parameters, coefficients need to be guessed or assumed. Due to the absence of any statutory regulation or standardization, the assumptions rests mainly on the author. The strategy adopted in searching for possible capsize situation has been to choose each parameter, where appropriate, in such a way as to give the most realistic combination of relevant parameters. On this basis the following input information is used:

i) Wave length : The length of the wave is taken equal to L_{wl} of the vessel.

ii) Wave height : Method of estimation is as explained in the preceding chapter.

iii) Vessel service speed : Taken 10 knots for all vessels considered.

iv) Wave direction : Following.

v) Frequency of Oscillation: For the extreme half roll cycle it is taken to be equal to the encounter frequency using the vessels service speed.

vi) Critical roll cycle: For computation of the critical roll cycle the GZ curve for 16 positions of the wave crest, or say trough, calculated. $GZ(\theta,t)$ was numerically plotted and the critical roll cycle was identified.

vii) Wind heeling : Calculated according to weather criteria as in article 5.3.2. of this thesis.

viii) Extreme windward angle θ_1 (defined in 3.3.2.1): Same as in IMO wind heeling criteria (article 5.3.2 of this thesis). That is 25 degrees windward from the first intersection of the GZ and wind heeling curves.

However, Kuo et al[88] made the following comments when applying this criteria to a few vessels.

"In some cases, however, the restoring arm is so small relative to wind heeling lever that the first intersection occurs at quite a large angle of heel. In severe instances this can result in a very small windward roll angle being used, or the windward roll angle can actually be on the leeward side!

In view of this problem, the method of determining of this angle has been re-examined. It was found that the empirical formula adopted for this calculation was derived from roll motion studies performed by the Russian and by the Japanese, the former measuring from the upright in applying their weather criterion and the latter measuring from the first intersection between wind heeling lever and restoring arm. This implies that either method of setting the initial roll angle may be used with equal justification. Furthermore, in the way the dangerous situation depicted in the weather criteria evolves, it is assumed that the vessel rolls to windward in the presence of waves only so that the presence of bias due to wind appears to be contradictory.

Finally, the windward roll angle is taken to provide useful mean of discrimination between the likely rolling behavior of ships, and as such serves to model such differences within the assessment method. The absolute value is not of vital importance as long as it remains within the realistic bound"

Fortunately, Table 5.4 shows that the first intersection between the GZ and wind heeling curves occur at very small angles (between 0.8 and 4.8 degrees). As a result the maximum windward angle is more than 20 degrees on the windward side. In the light of the foregoing observations, it was decided to adopt the same windward angle as in IMO wind heel criterion.

ix) The maximum leeward angle θ_2 (defined in 3.3.2.2): Same as in IMO criteria, i.e., minimum of 1) second intersection of wind heel and GZ curves, 2) downflooding angle and 3) 50 degrees.

x) Roll damping: calculated by Ikeda's method.

5.5.2 Results and Discussions:

The results of the computations are given in Table 5.7. The maximum windward angle varies between 22.25 to 24.25 degrees. The deviation from Table 5.4 is due to the fact that the critical roll cycle is considered here, unlike the still water GZ curve considered in IMO criteria. The maximum leeward angle is smallest in vessel 1 (33^o) and maximum for vessel 15 and 18 (50^o). Actually, in vessels 1, 4, 7 and 11 this angle is the second intersection of the GZ and wind heeling curves while for the two largest vessels (15 and 18) the intersection occur at an angle greater than 50^o. So the 50^o limit is enforced. For vessel 1 and 4 the restoring area A_1 is less than excitation area A_2 and hence can be termed unsafe. In the case of vessel 1 A_1 is less than one half of of A_2. But for the vessels 7, 11, 15 and 18 $A_1 > A_2$. It may be observed in the USCG wing heel criteria the restoring area needs to be 40% higher than excitation area. If that concept is applied here then vessel 7 and 11 also do not qualify.

In the analysis for the IMO wind heel criteria (article 5.3.2 of this thesis) computations were also performed to assess the stability if the angle of rolling θ_r is taken 20 degrees. Some arguments are also presented there. In this analysis, however, the maximum θ_r for which the criteria is satisfied is also computed for each vessel. Results are given in the last column which shows that longer vessel can tolerate higher value of θ_r (15^o for vessel 1 and 42.25^o for vessel 18).

The stability of these vessels have been assessed for excitations by wind load only. This method has the versatility of assessing the stability of a vessel subject to several simultaneous excitations. What is only required is a tool for estimating transverse moments created by the excitation agents. This moment divided by the displacement of the vessel gives the excitation lever. The heeling curve is replaced by a curve of the sum of all the excitations. For example, in the case of passenger crowding, the resultant heeling may be estimated by equation 5.1 and the wind heeling curve will be replaced by the summation of equations 3.1 and 5.1. The rest of the steps will be similar.

5.5.3 Evolving Usable Criteria:

Before recommending a realistic criteria based on this method for inland passenger vessels, the following items have to be validated and standardized.

i) Whether the maximum windward angle should be from the upright condition or from the first intersection of the GZ and wind heel curve.

ii) The method for fixing the maximum leeward angle.

iii) Formula for estimation of wind load

iv) The method for estimating the roll damping coefficient.

v) The minimum acceptable value of A_1/A_2.

Formulation and enforcement of statutory criteria must be preceded by extensive model tests. Full scale trials are also necessary.

5.6 Stability Assessment with Lyapunov Method:

5.6.1 Evaluation of 'h' Function:

While assessing stability with Lyapunov function the most important task is the arbitrary function 'h'. This function has to satisfy some conditions which are mentioned in Chapter 3 and in Appendix E. However, no indication of its analytic expression is available. Phillips[80] and Saraiva[70] have experimented with an equation of the form:

$$h=a\theta + b\theta^3 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5.5)$$

where a and b are constants depending upon hull parameters and excitations. θ is the angle of inclination.

As a consequence of the assumptions made for the 'h' function the following conditions for the same is automatically satisfied:

i) $h(0) = F(0)$

ii) $h' > 0.0$ ....(5.6)

In selecting the values of 'a' and 'b' in equation 5.5, care should be taken to satisfy the following conditions:

iii) $h(\theta_v) = F(\theta_v)$

...........(5.7)

iv) $h(\theta) < F(\theta)$

Phillips[80] also proved that :

v) $a > 0.0$

vi) $b > 0.0$ ....(5.8)

vii) $c > a$
where $c= f(\theta_h)$ and θ_h is defined as $\{(c-a)/b\}^{0.5}$

Formal experimentas performed by Phillips[80] on eight ships confirmed an earlier impression that coefficients 'a' and 'b' , although arbitrary, tend to iterate toward a narrow range of values when a Lyapunov value is searched by using appropriate methods explained previously in this thesis. The results of these experiments as summarized by Phillips are as follows;

ix) 'a' tend to lie in the range
$(c - 0.1) < a <= (c - 0.01)$

x) 'b' tend to lie in the range
$0.1\ E\text{-}6 < b < 0.1\ E\text{-}5$ ....(5.9)

xi) 'a' and 'b' tend to decrease with increased excitations.

xii) As a consequence of (xi) θ_h tend to increase with excitation.

In the present analysis the value of 'b' was assumed average of the limits as given in condition (x) above (i.e., 5.5 x 10^{-7}). The most optimum 'h' function, obviously, should result in the widest 'span of intersection' as explained previously in Chapter 3. However, as a criteria, Phillips[80] suggested that the ratio of the (i) area between the PSI1 (defined in equation E.16, Appendix E) curve and the excitation lever and (ii) area under the PSI1 curve may be the index of stability. To conform with the later basis the value of 'a' was optimized to get the maximum area under the PSI1 curve (defined in Appendix-E). However, it was finalized when the resulting 'h' functions satisfied other conditions mentioned above. The steps are explained below:

(a) Condition (2.iv) is satisfied as long as the 'F' function, at all inclinations, was greater than function 'h'. In case it was not so , value of 'a' was reduced iteratively at very small intervals.

(b) Interaction of the value of 'a' was performed until condition (iii) was satisfied.

(c) The relation between the values of 'c' and 'a' were ignored (condition viii, ix and xii).

(d) The values of 'a' was calculated with only hull parameters (restoring and friction) as the inputs. This is because the process of adjusting 'a' and 'b' for excitation is a very complicated one.

5.6.2 Estimation of Parameters and Coefficients:

This method of stability assessment has been explained elaborately in Chapter 3 and in Appendix E. Since compared to Saraiva's[70] method Phillips'[80] scheme has got more potentials of being adopted as a statutory criteria, it is employed in actual analysis. As in the case of Strathclyde Method a number of parameters and coefficients are not standardized in this case also. Before an actual computation is performed the values have to be assumed or guessed.

The roll damping coefficient was calculated by Ikeda's method[47]. Other necessary parameters were estimated in the same way as was done in the Strathclyde Method. However, a major difference with the Strathclyde Method is the absence of time dependent GZ curve in this analysis. Instead a still water GZ curve is used. This is because the expression for the PSI1 function was derived with the assumptions that the GZ function will be an odd one. A detail explanation is given in Appendix D. This method, however, is basically capable of dealing with time dependent GZ curve with the vessel floating in waves. But the mathematics will get several fold more complicated.

The maximum excitation lever (which is generally at the upright condition) is taken to be constant at all inclinations. Stability have been assessed for wind load and passenger crowding separately and combined. The results are given in Table 5.8.

5.6.3 Results and Discussions:

Figures in the table 5.8 indicate that the value of 'a' increases with length of the vessel. For excitation by wind load and passenger crowding no Lyapunov bound exists for vessels 1, 4, 7 and 11 i.e., these vessels can not be termed stable. For vessel 15 the span of intersection is (30.0 - 12.75) = 18.25 degrees. But the ratio of the area is only 2.32%. The corresponding figures for vessel 18 is 36.75 degrees and 16.982 %. As far as analytic treatments are concerned, simple existance of Lyapunov bound is the indication of the vessel being stable. But practical considerations recommends a margin of safety. The minimum acceptable limit for the ratio of A_2/A_1 is not available. But the figure for vessel 15 (2.32%) appears too low while for vessel 18 it seems quite satisfactory.

For wind load only all vessels have a Lyapunov bound. The span of intersection is wider for longer vessel, so is the case of A_2/A_1. The minimum value of the latter parameter for vessel 1 (9.093%) can probably be termed acceptable. Other vessels have fairly large values. For vessel 18 (85.142%) it is on the very high side.

For passenger crowding only, no bound exists for vessels 1, 4 and 7. For vessel 11 the value of A_2/A_1 is marginal (2.958%) and vessel 15 may be on the safe side. Vessel 18, again, has a quite a large margin of safety.

5.6.4 Evolving Usable Criteria:

For evolving a realistic criteria the remarks made for the Strathclyde Method also apply equally for this method. The most serious drawback of this method is that naval architects, designers and professionals are not yet fully familiar such approach to stability assessment. Neither the PSI1 nor the 'h' functions have any practical interpretation. To be made generally acceptable, attempts should be made to correlate the mathematical terms with physical parameters. To assist the designers in coming out with safe design, extensive guidelines should be prepared. 'h' function should also be standardized.

CHAPTER 6

CONCLUSIONS

The conclusions of the thesis may be summarized as follows:

(i) The water transport sector is, and will remain in future, a major mode of inland movement of passengers in Bangladesh. Hence the stability of passenger launches deserves serious attention.

(ii) The task of stability assessment of vessels is still an unresolved issue. To evolve a suitable stability criteria of the inland passenger launches, extensive analytic and experimental works are required.

(iii) The investigation reveals that a wider beam does not necessarily result in a more stable vessel. Sometimes it is the other way round, especially when the beam is excessively large. The effects of trim on stability is insignificant. But rolling may result in trim by bow, a slight of which may cause disaster during turning. The effect of wave is more severe for smaller vessels. For estimating free surface effects wall sided formula gives highly conservative results while the IMO formula does not represent the worst situation.

(vi) Stability analysis of six representative inland double decker passenger launches of Bangladesh indicates that the vessels do not satisfy all of the still water, wind heel and passenger heel criteria. Smaller vessels appear to be less stable. Passenger heeling appears to be a more serious hazard than the wind. Assessment by Strathclyde Method and Lyapunov Method give similar results.

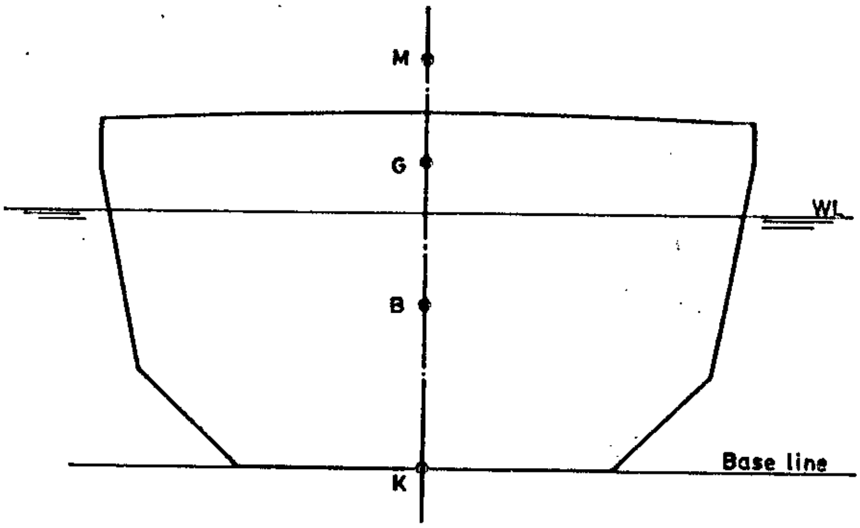

Fig. 1.1 : Vessel floating upright.

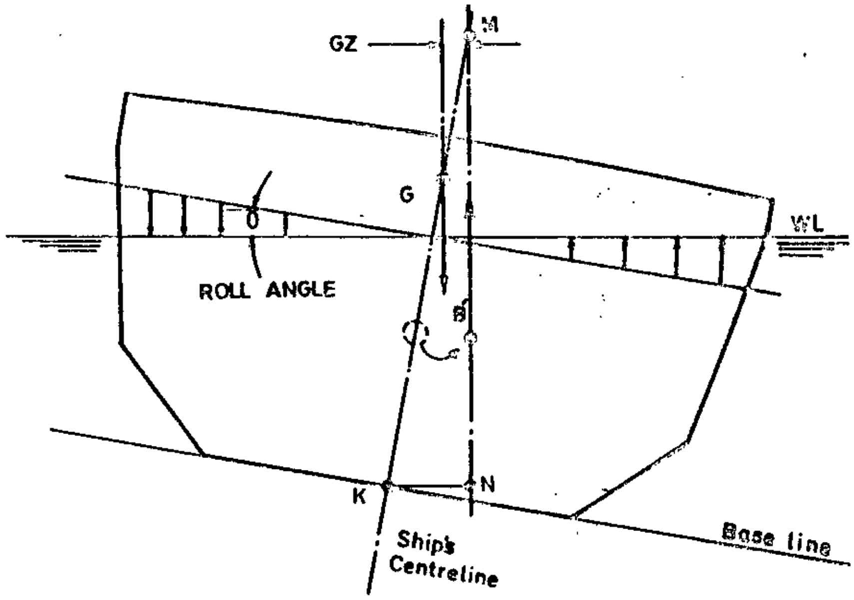

Fig 1.2 : Vessel inclined with positive GM.

(Vessel initially stable)

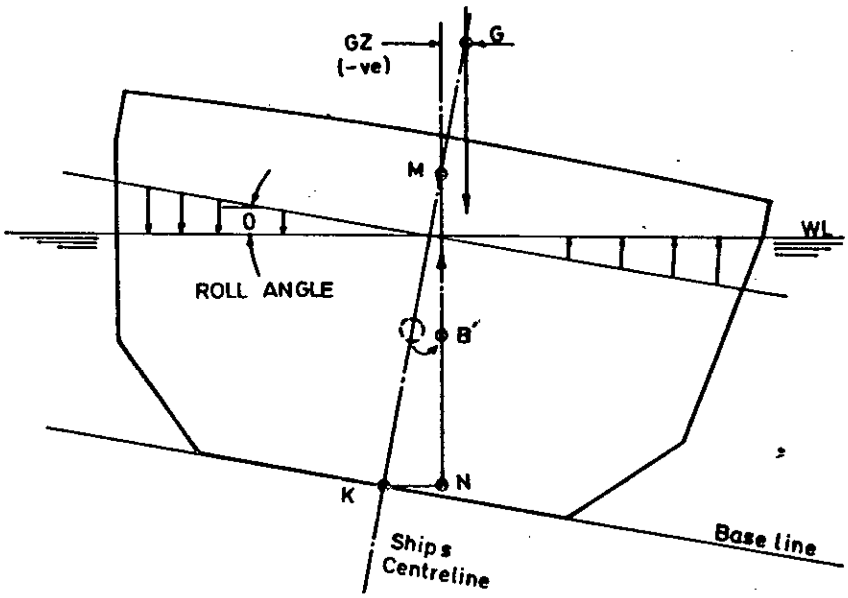

Fig. 1.3 : Vessel inclined with negative GM

(Vessel initially unstable)

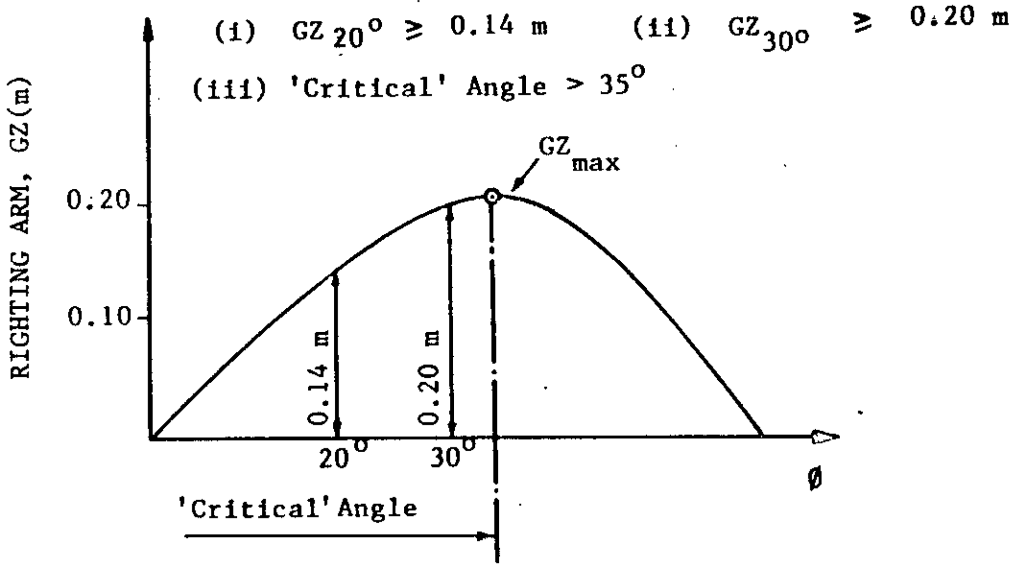

Fig. 3.1 : Rahola's Criteria
(Reference 15)

IMO Criteria:

(i) $A \geq 0.055$ m-rads (ii) $A + B \geq 0.090$ m-rads

(iii) $B \geq 0.030$ m-rads (iv) $GZ_{30^o} \geq 0.20$ m

(v) $\theta\ GZ_{max} \geq 25^o$ (vi) $GM_o \geq 0.35$ m for $L \leq 70$ m

0.15 m for $L > 70$ m

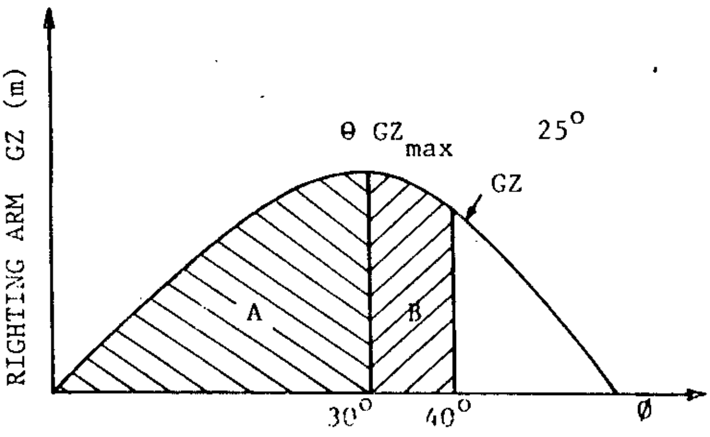

Fig 3.2 : IMO Res. A.167

(Reference 83)

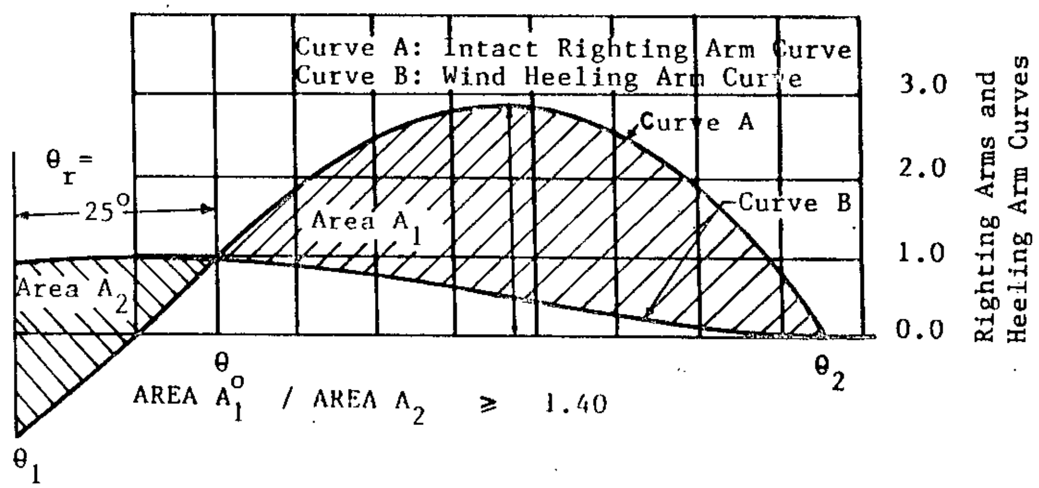

Fig. 3.3 : Criteria proposed by Sarchin and Goldberg (Reference 43)

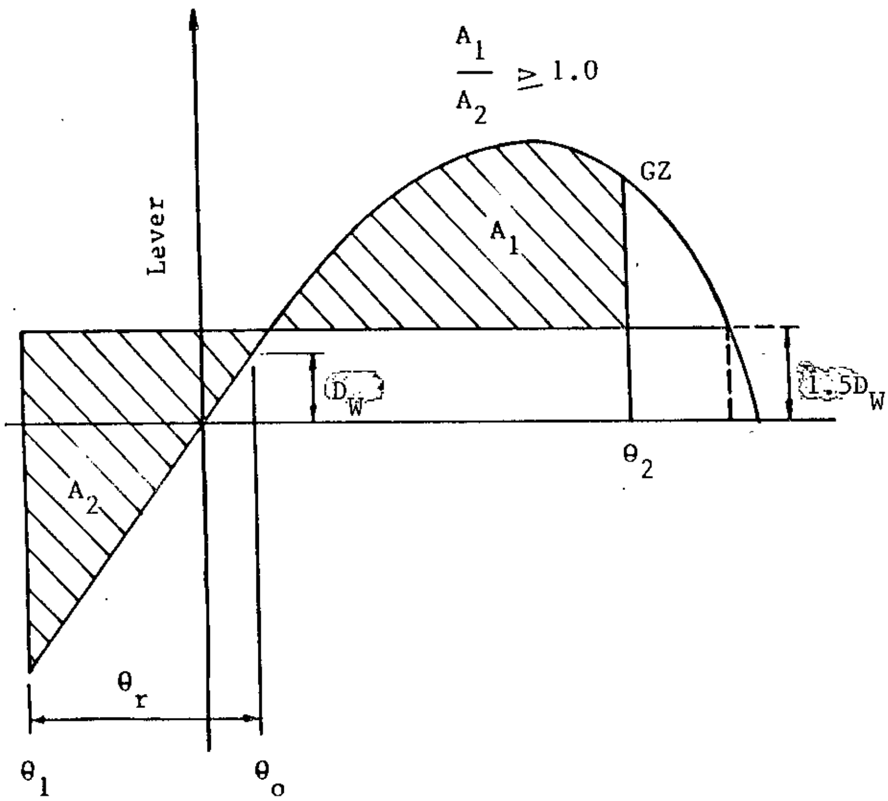

Fig. 3.4 : IMO weather criteria.

(Reference 44)

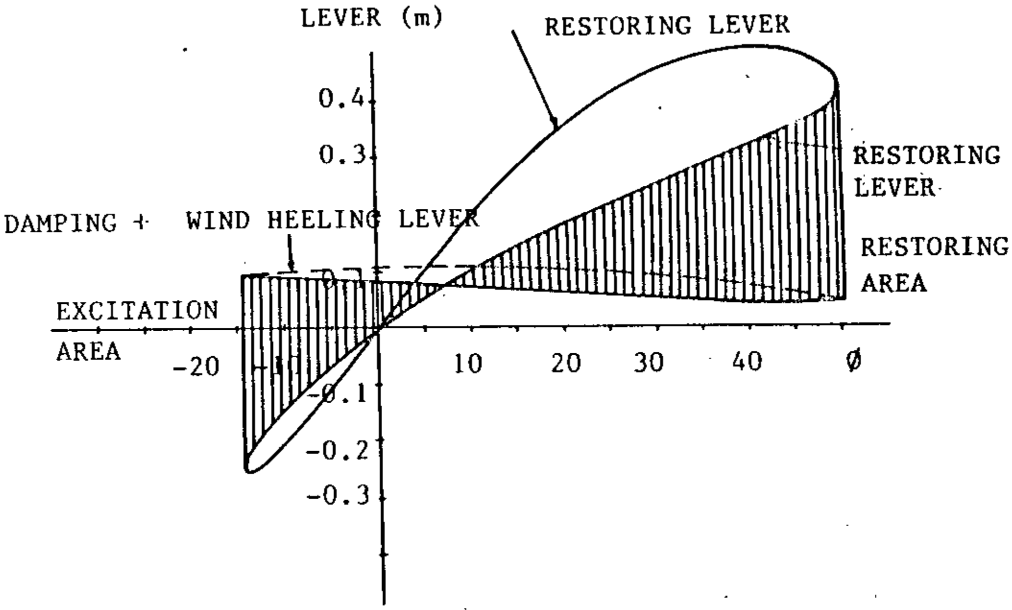

Fig. 3.5 : Strathclyde Method
(Butterfly Diagram)

(Reference 88)

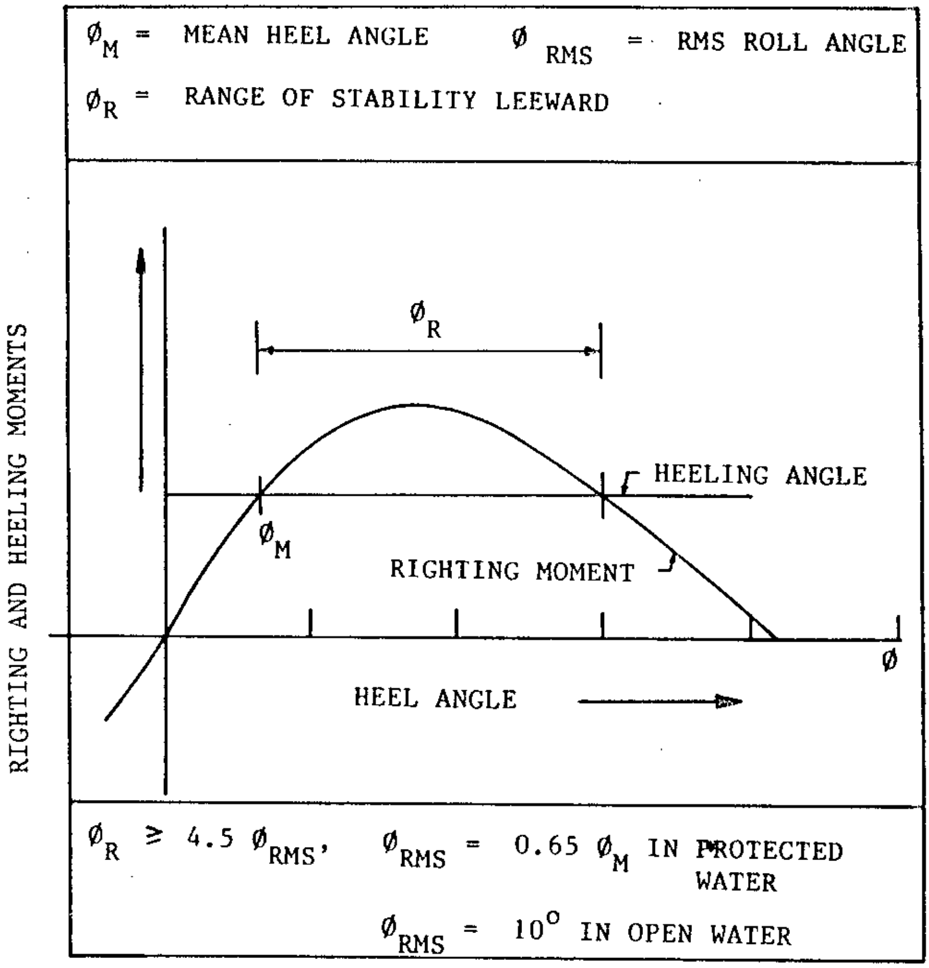

Fig. 3.6 : Simplified Wind Heel Criterion Developed by Amy et. al. (Reference 60)

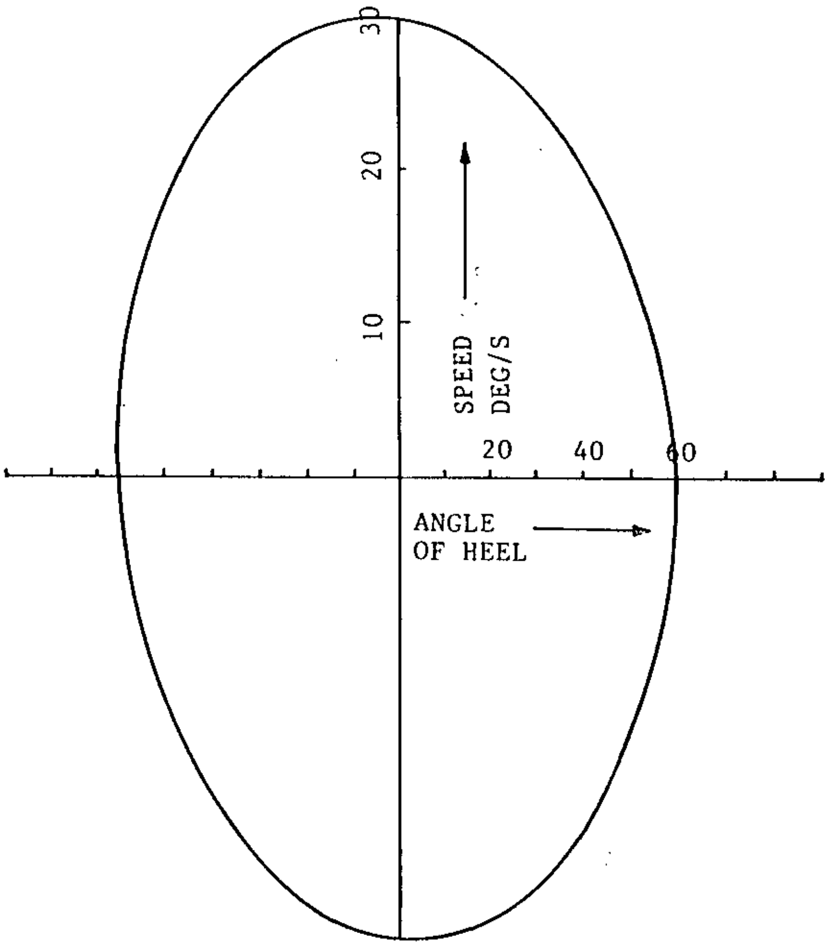

Fig. 3.7 : Lyapunov Method
(Domain of Stability
Developed by Saraiva)

(Reference 70)

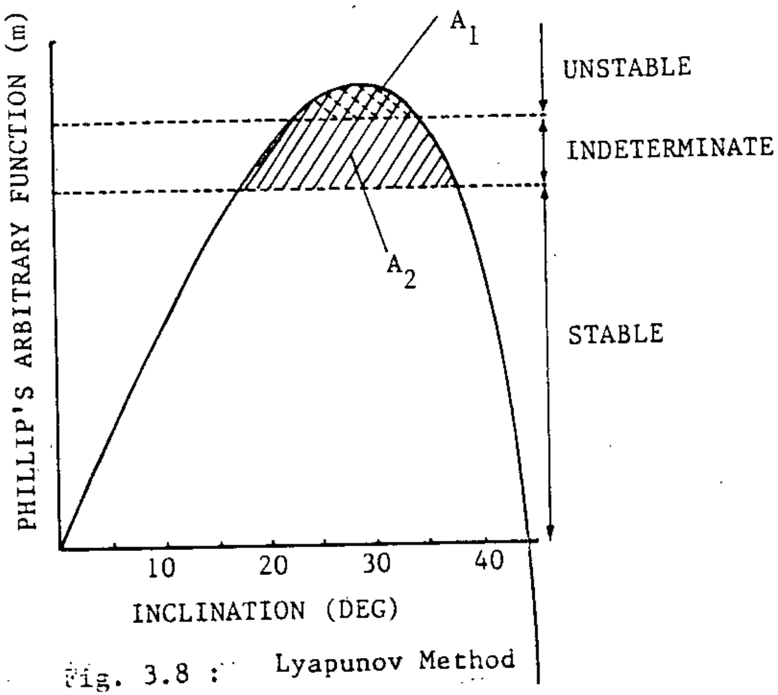

Fig. 3.8 : Lyapunov Method
(Phillip'S Scheme)
(Reference 80)

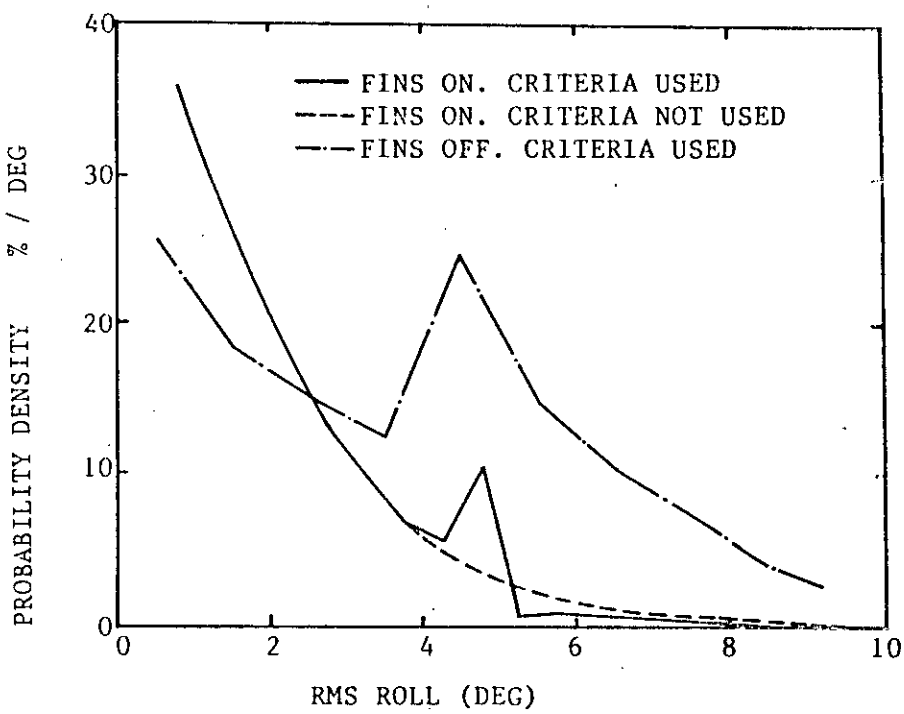

Fig. 3.9 : Prediction of long-term roll response developed by Spouge

(Reference 72)

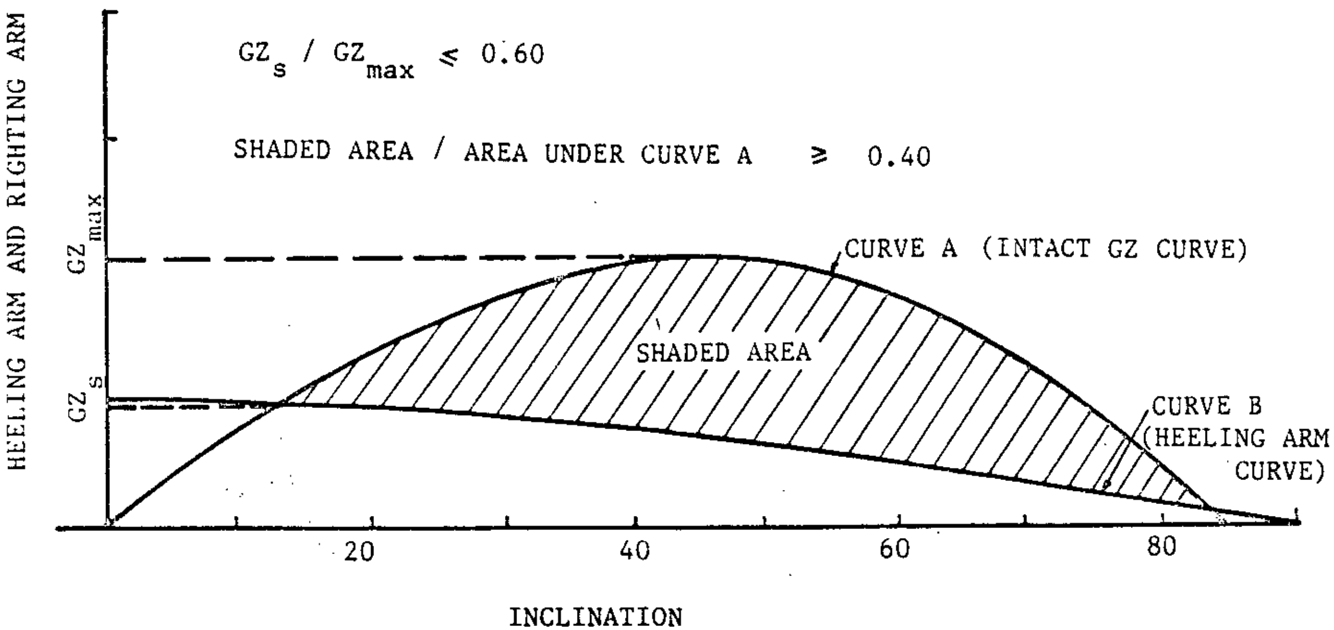

Fig. 3.10 : Passenger Crowding Criteria of U.S. Coast Guard (Reference 82)

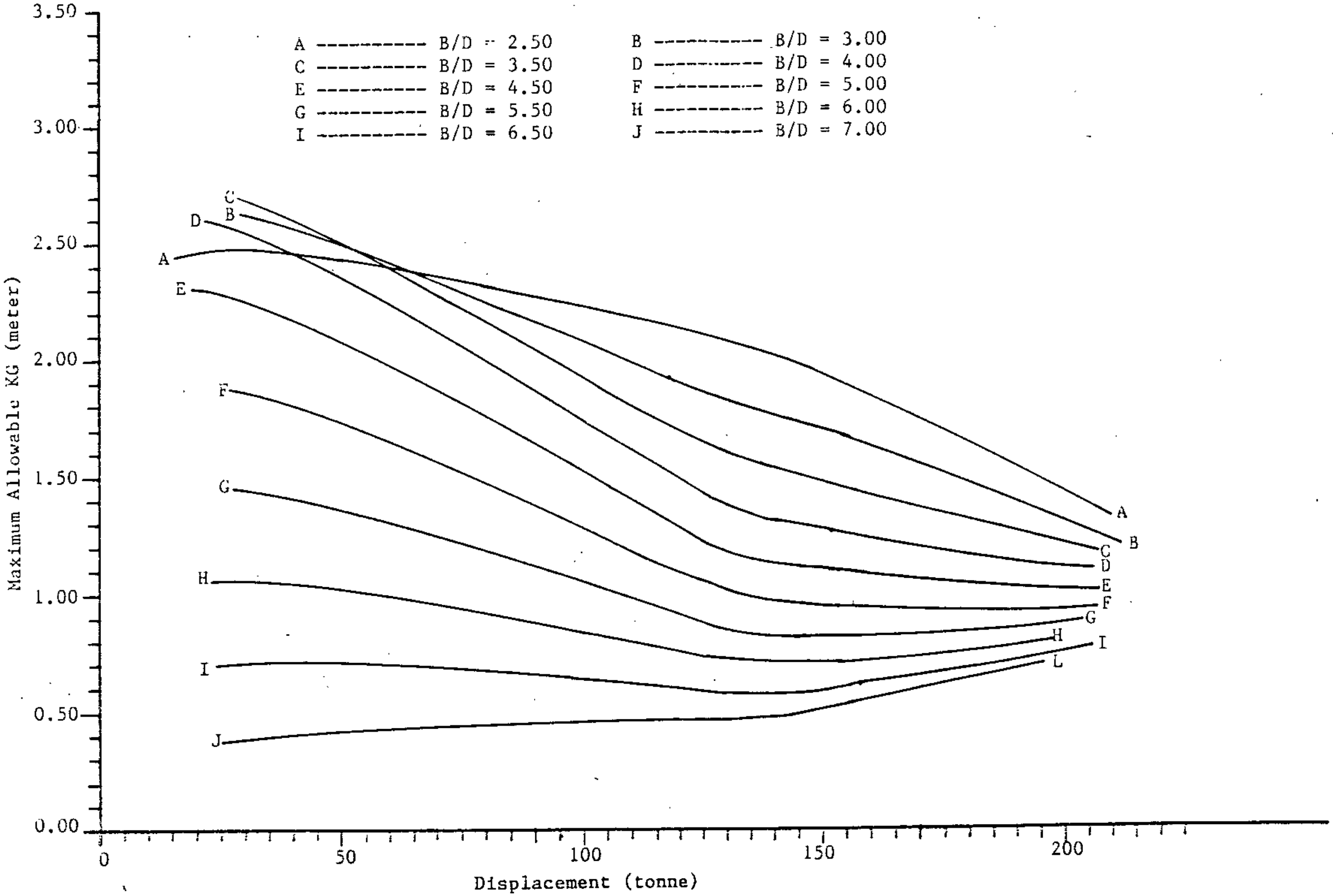

Fig. 4. 1 : Variation of maximum allowable KG with displacement and B/D ratio

(Vessel No. 1)

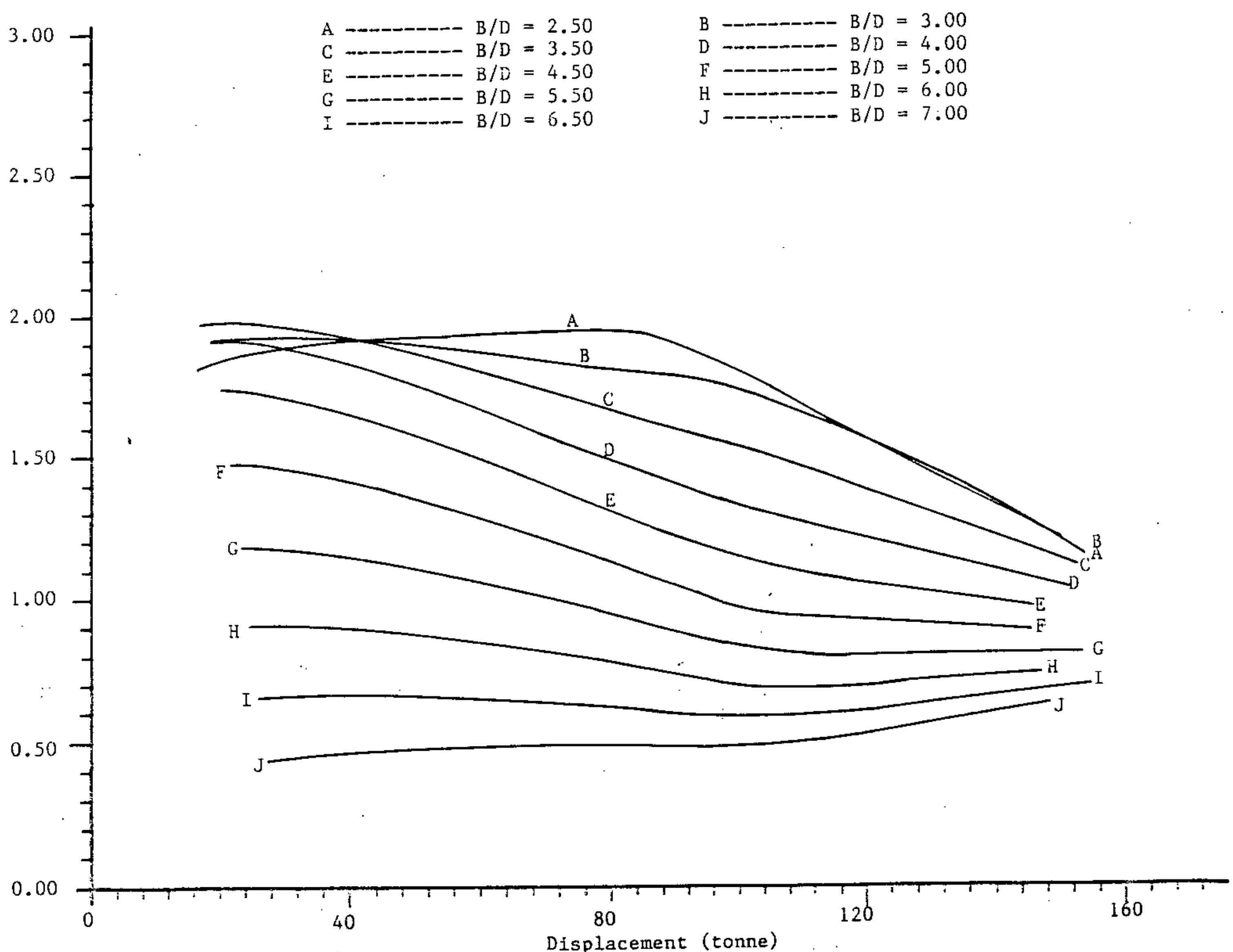

Fig. 4. 2 : Variation of maximum allowable KG with displacement and B/D ratio

(Vessel No. 2)

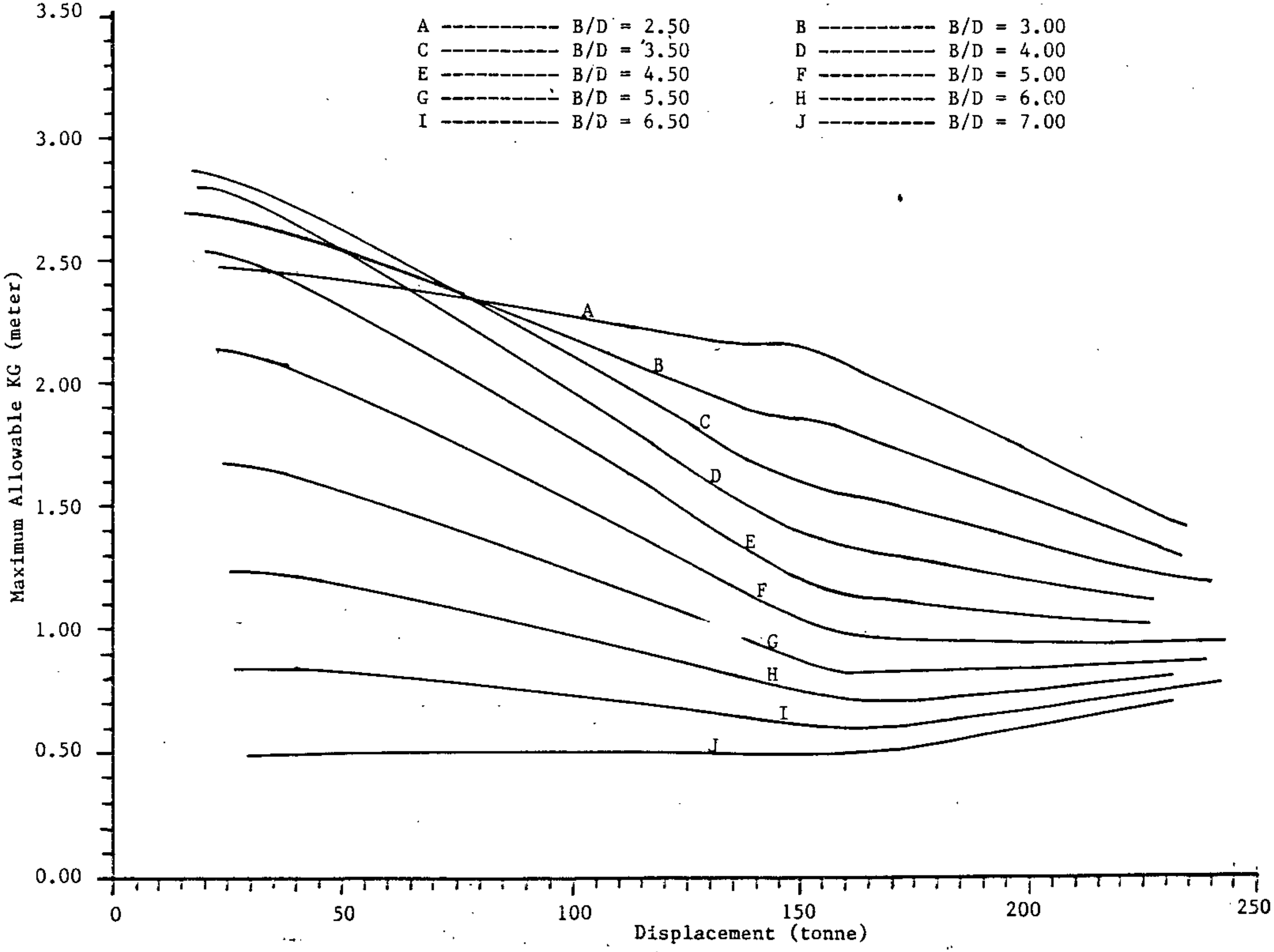

Fig. 4.3 : Variation of maximum allowable KG with displacement and B/D ratio

(Vessel No. 3)

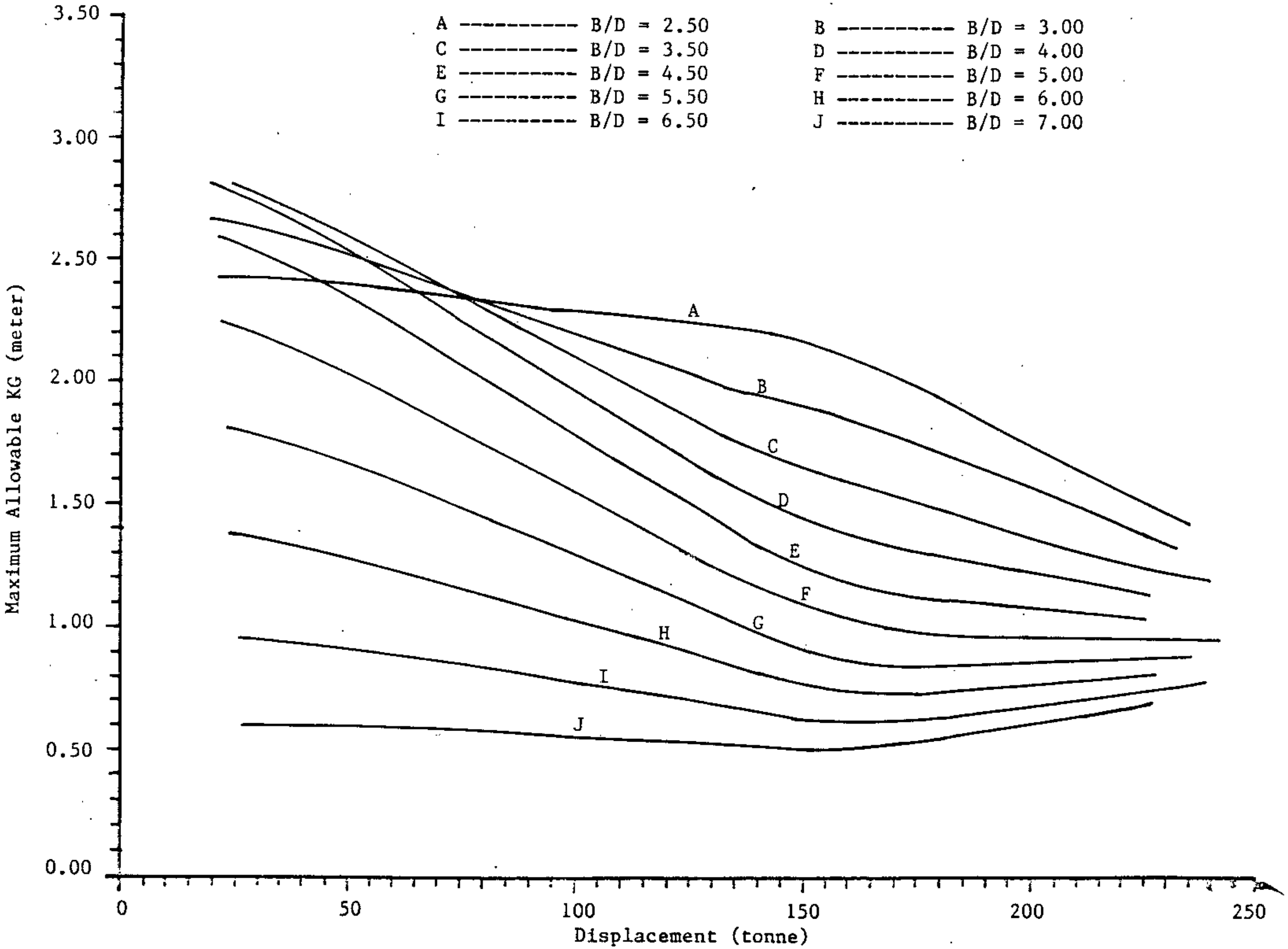

Fig. 4. 4 : Variation of maximum allowable KG with displacement and B/D ratio

(Vessel No. 4)

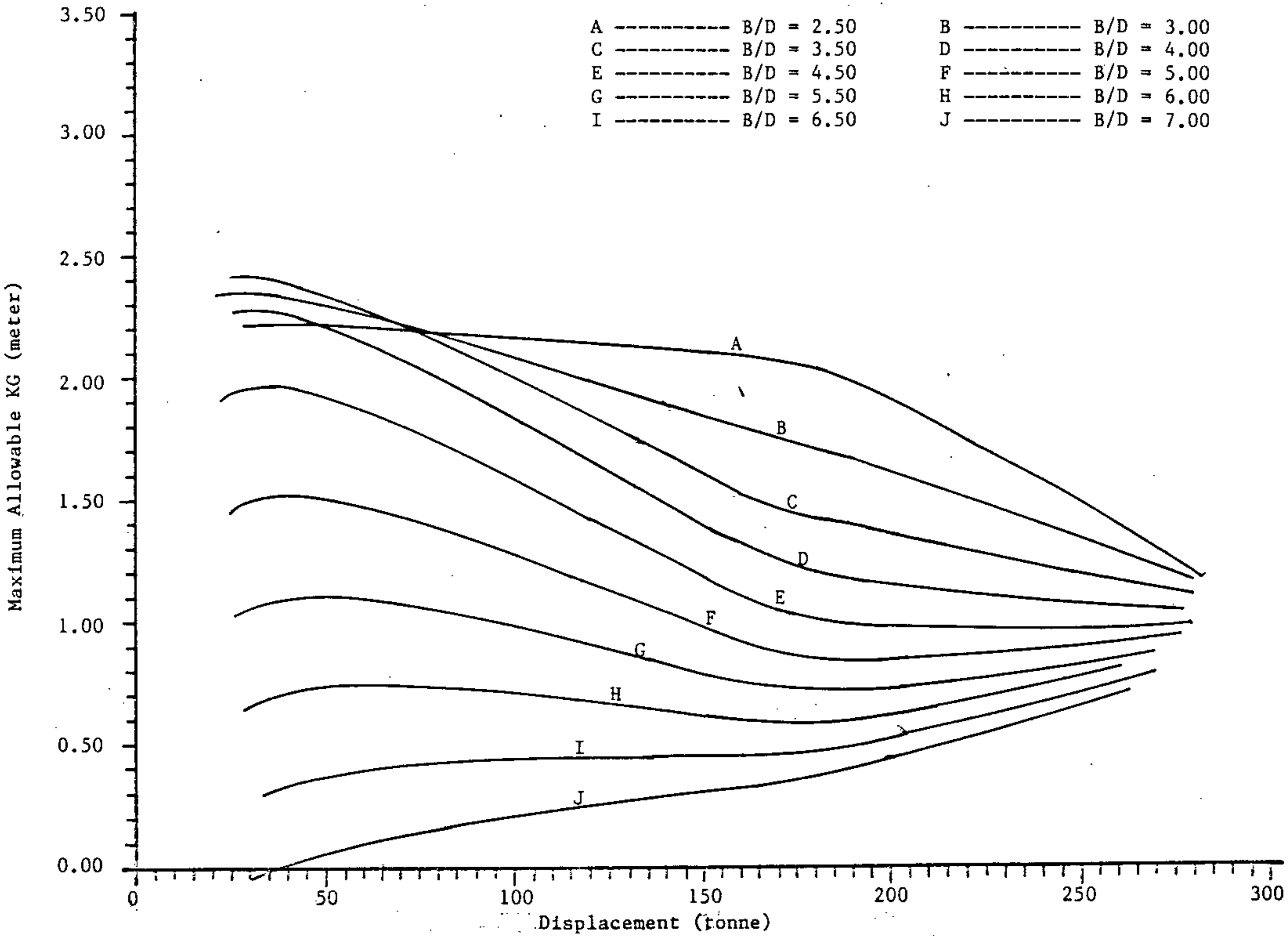

Fig. 4.5 : Variation of maximum allowable KG with displacement and B/D ratio

(Vessel No. 5)

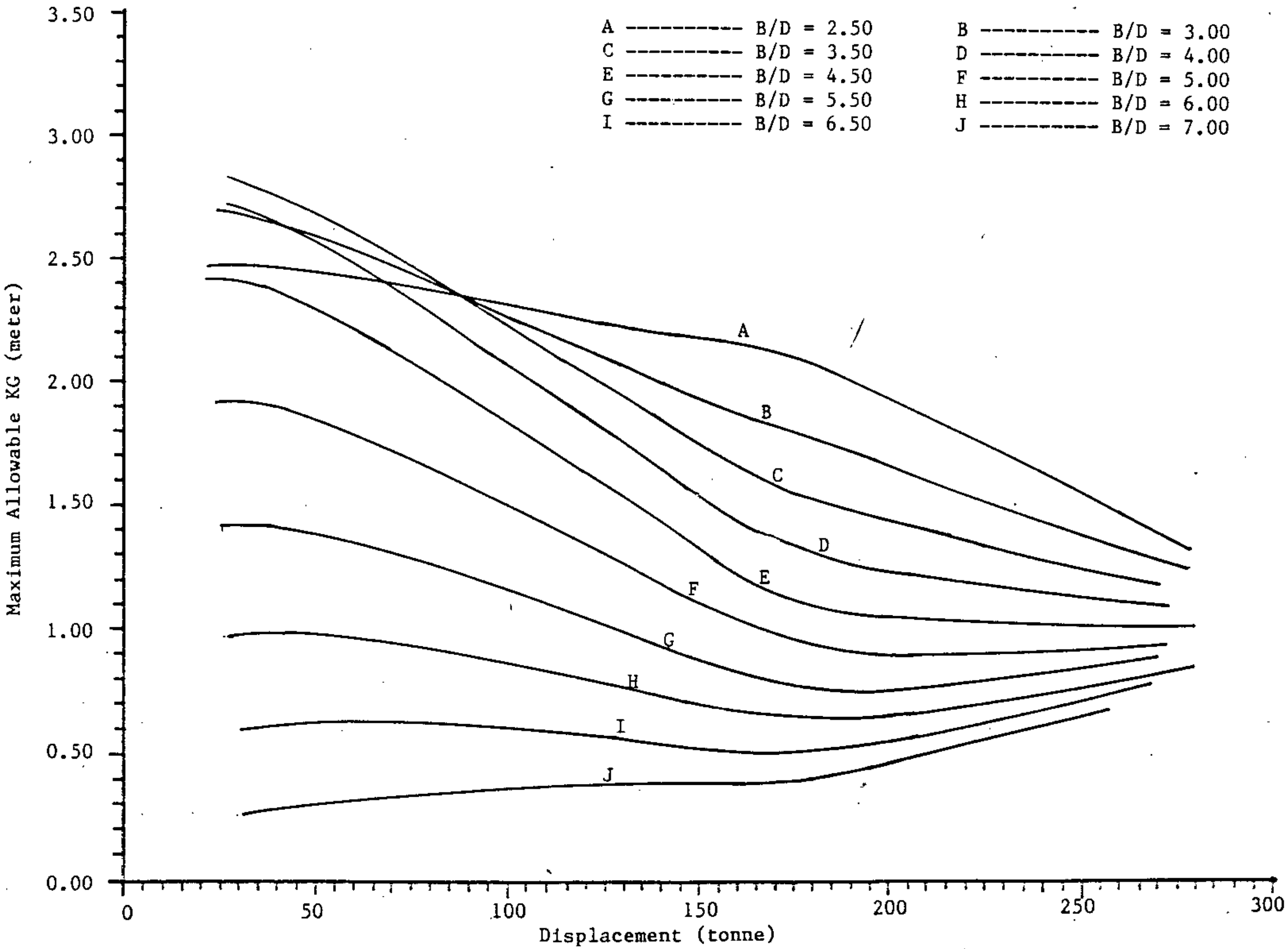

Fig. 4. 6 : Variation of maximum allowable KG with displacement and B/D ratio

(Vessel No. 6)

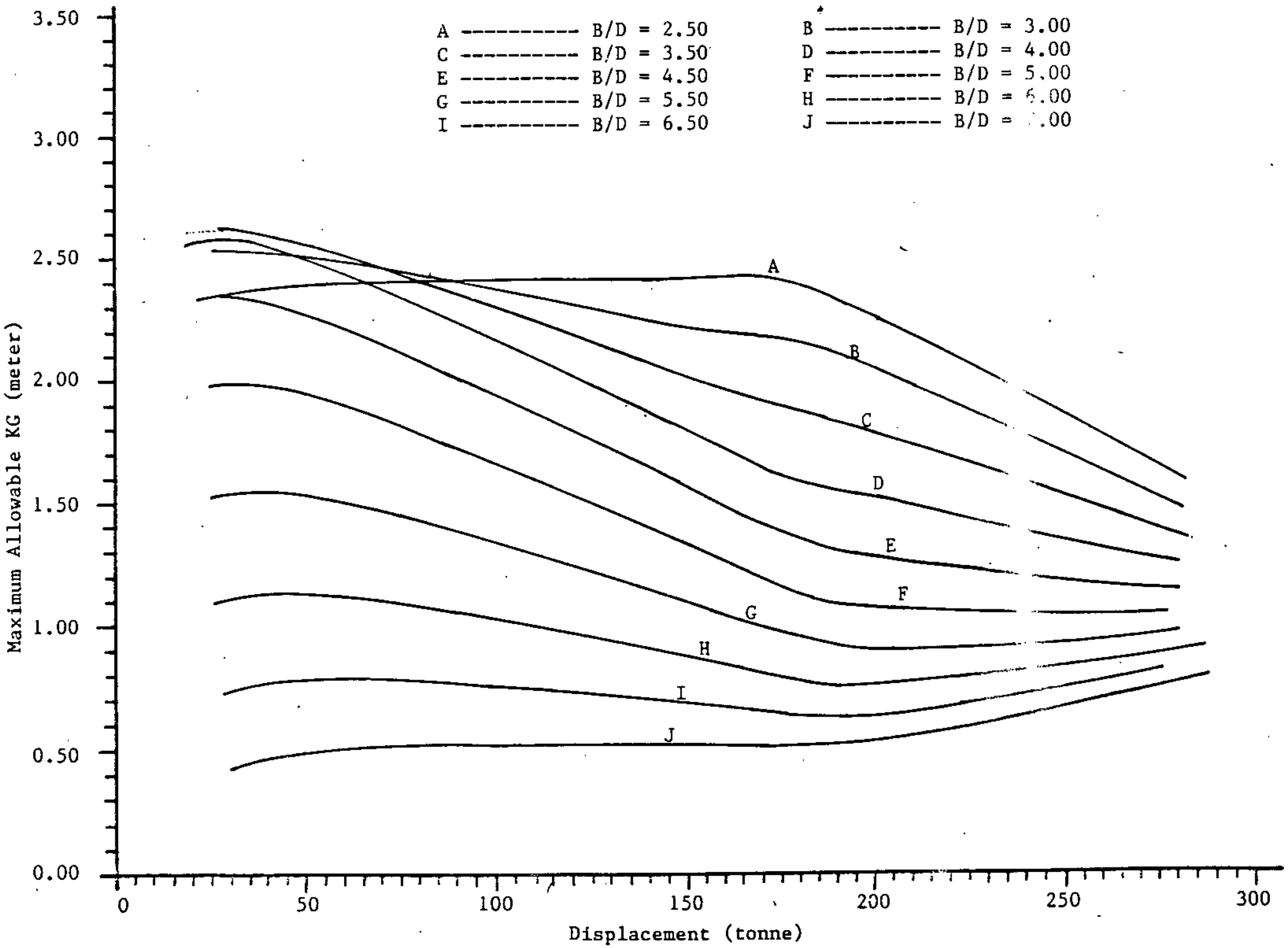

Fig. 4. 7 : Variation of maximum allowable KG with displacement and B/D ratio

(Vessel No.7)

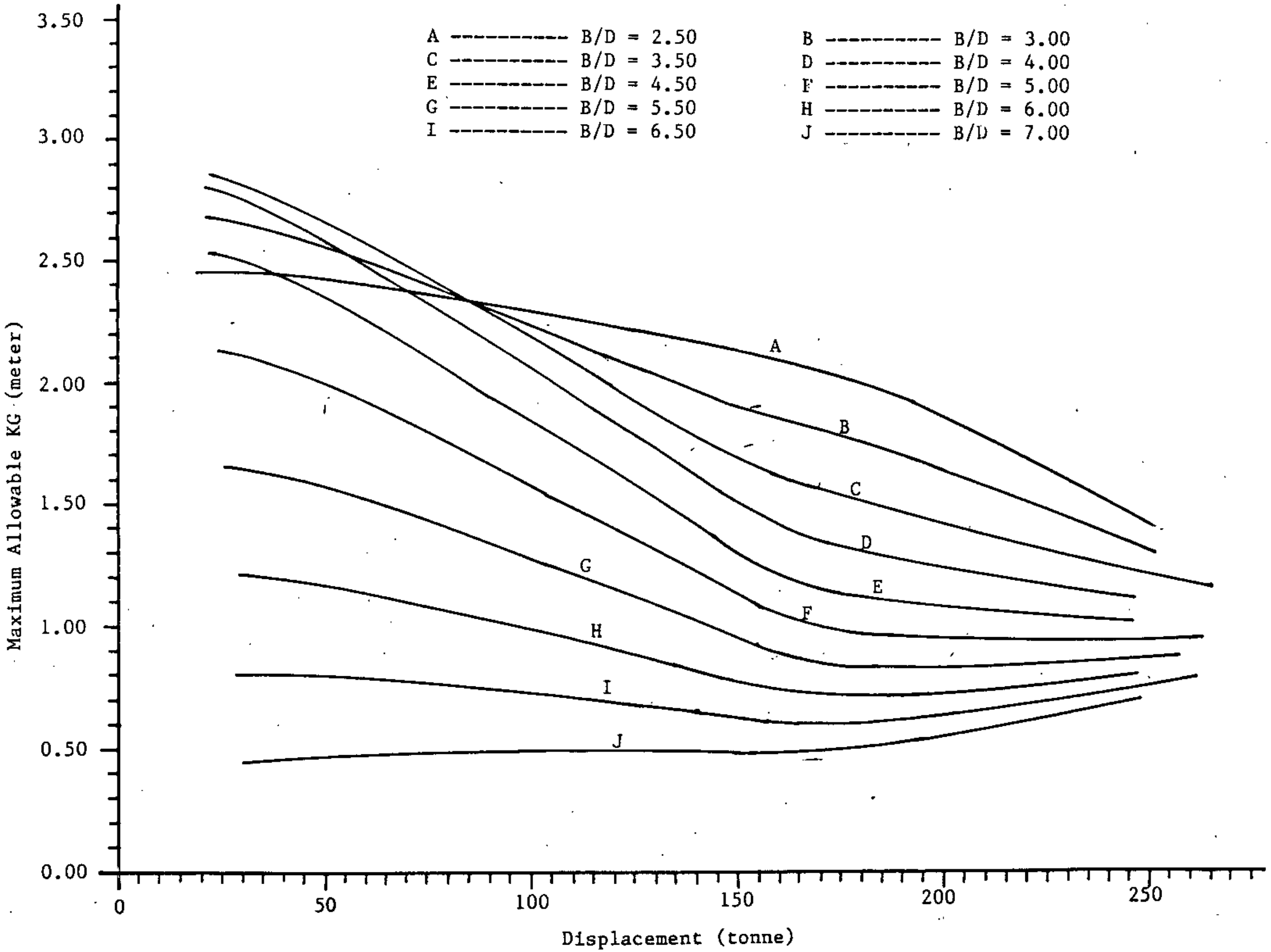

Fig. 4. 8 : Variation of maximum allowable KG with displacement and B/D ratio

(Vessel No. 8)

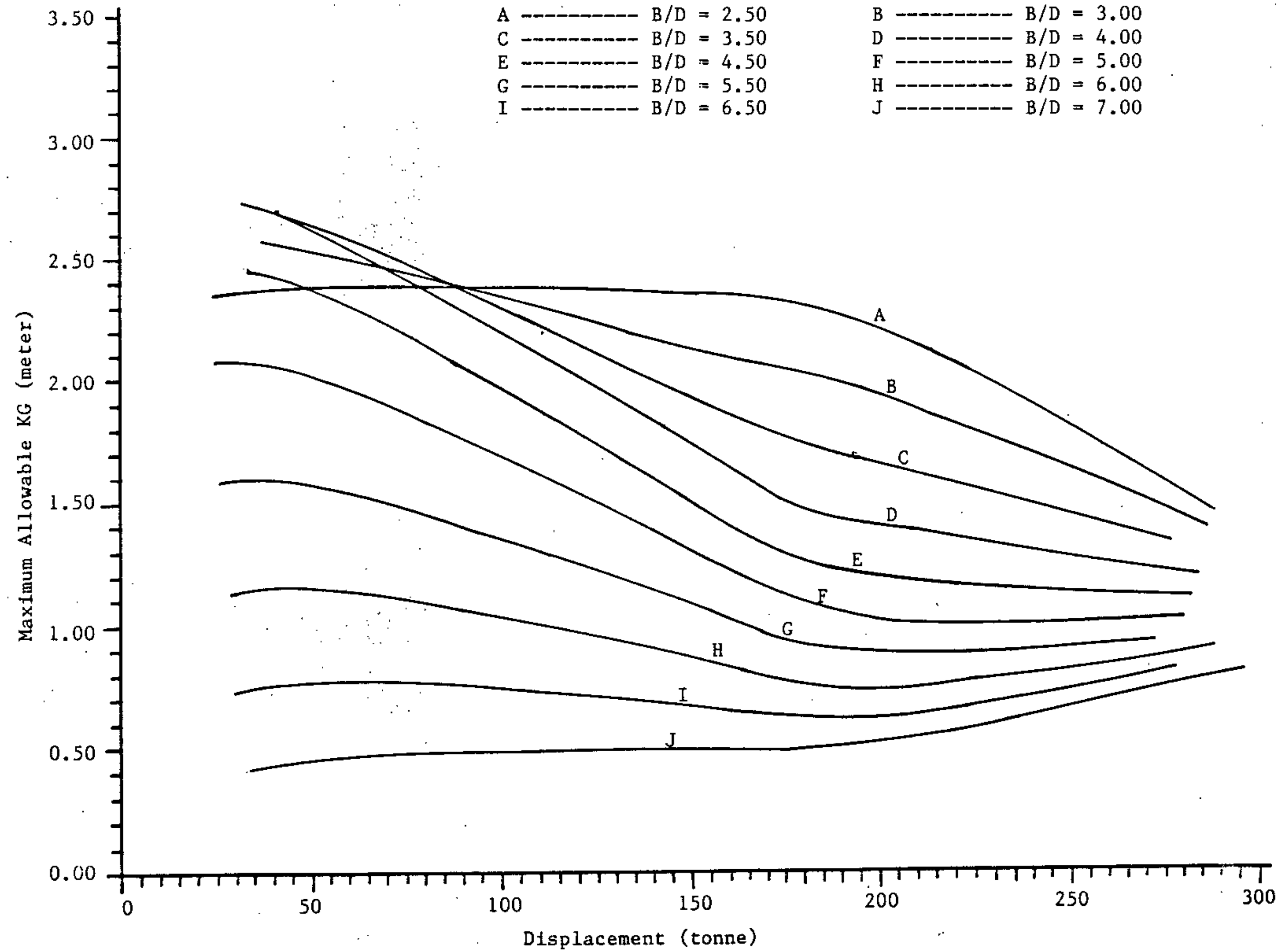

Fig. 4. 9 : Variation of maximum allowable KG with displacement and B/D ratio

(Vessel No. 9)

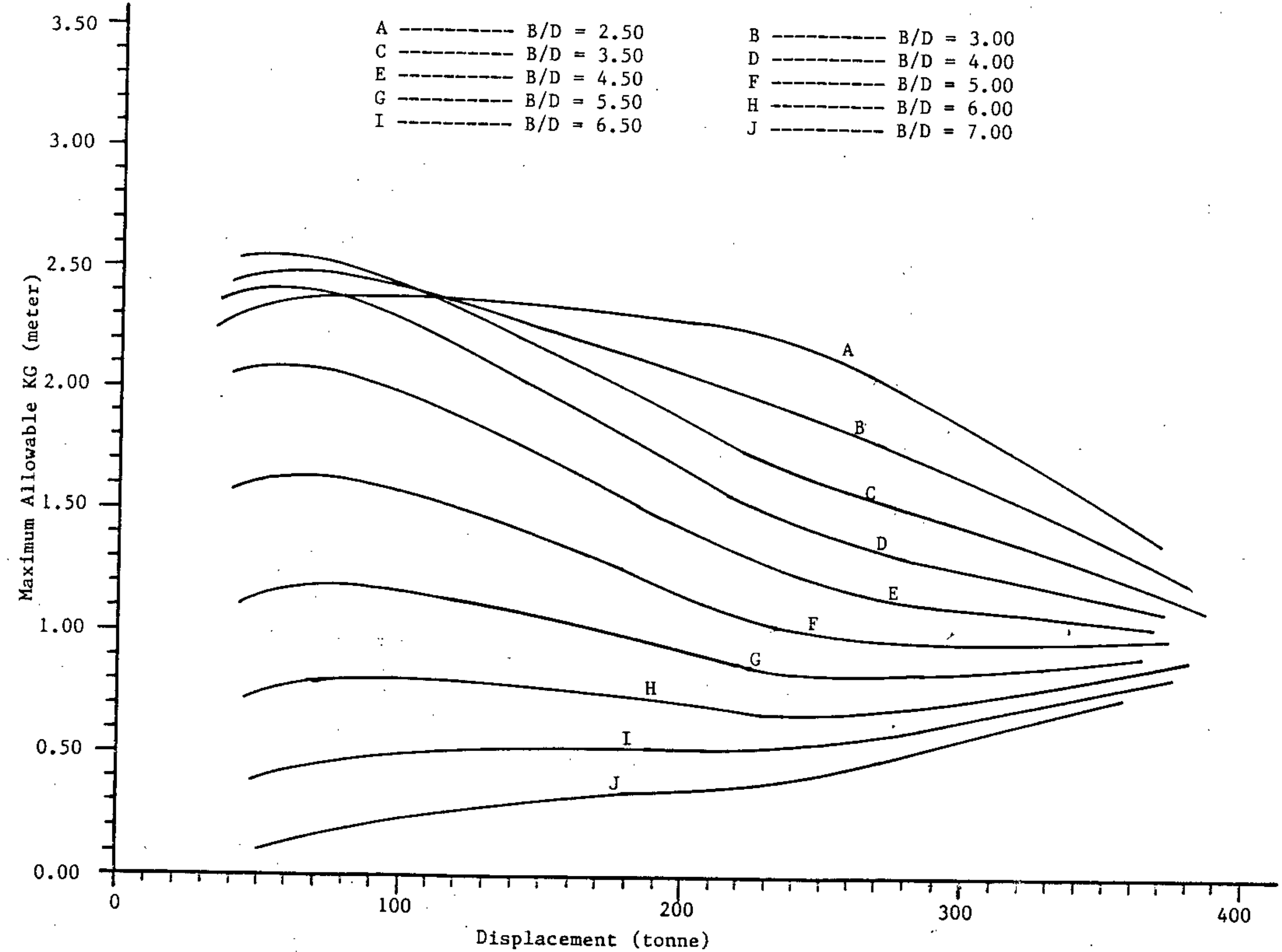

Fig. 4. 10 : Variation of maximum allowable KG with displacement and B/D ratio

(Vessel No. 10)

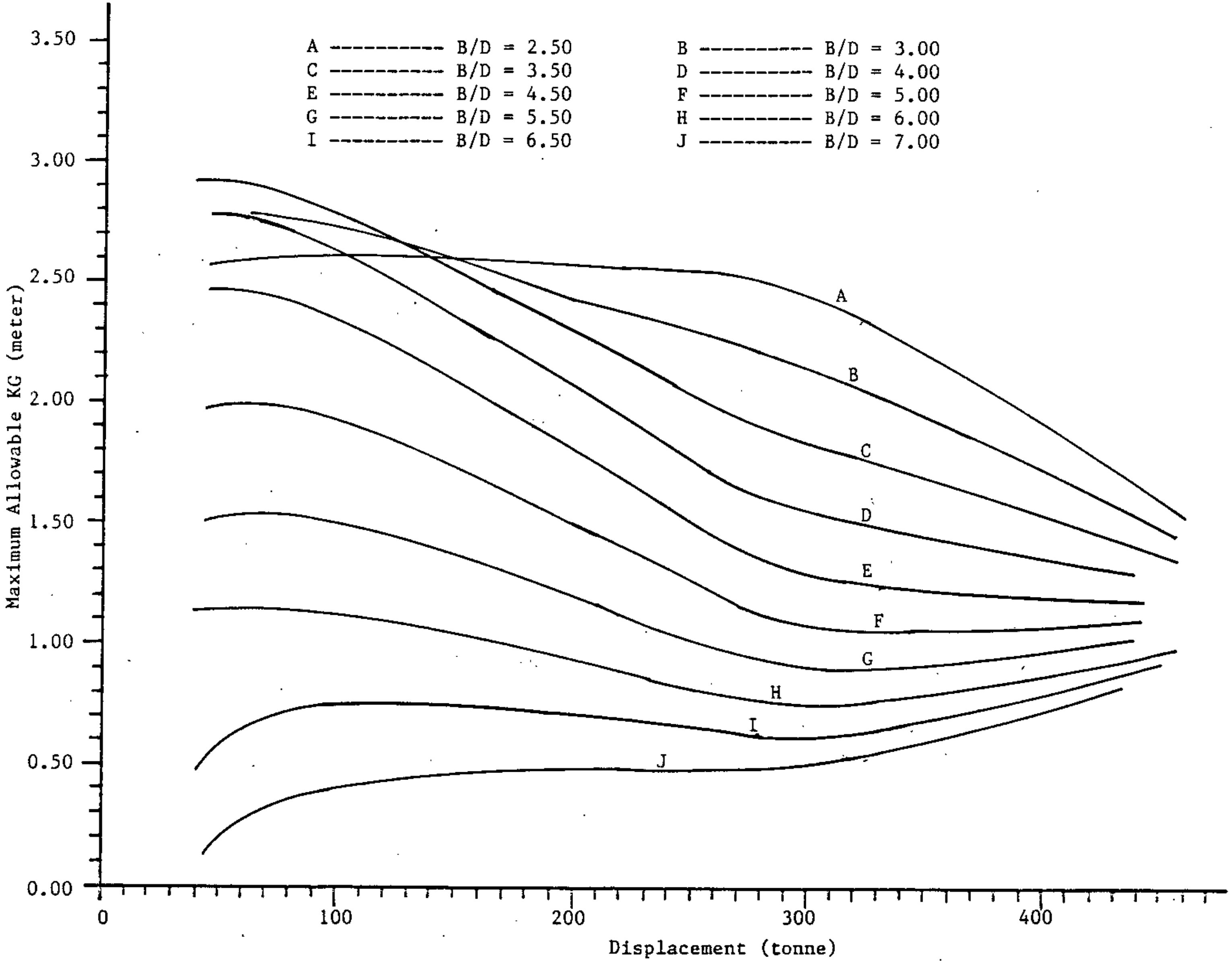

Fig. 4. 11 : Variation of maximum allowable KG with displacement and B/D ratio

(Vessel No. 11)

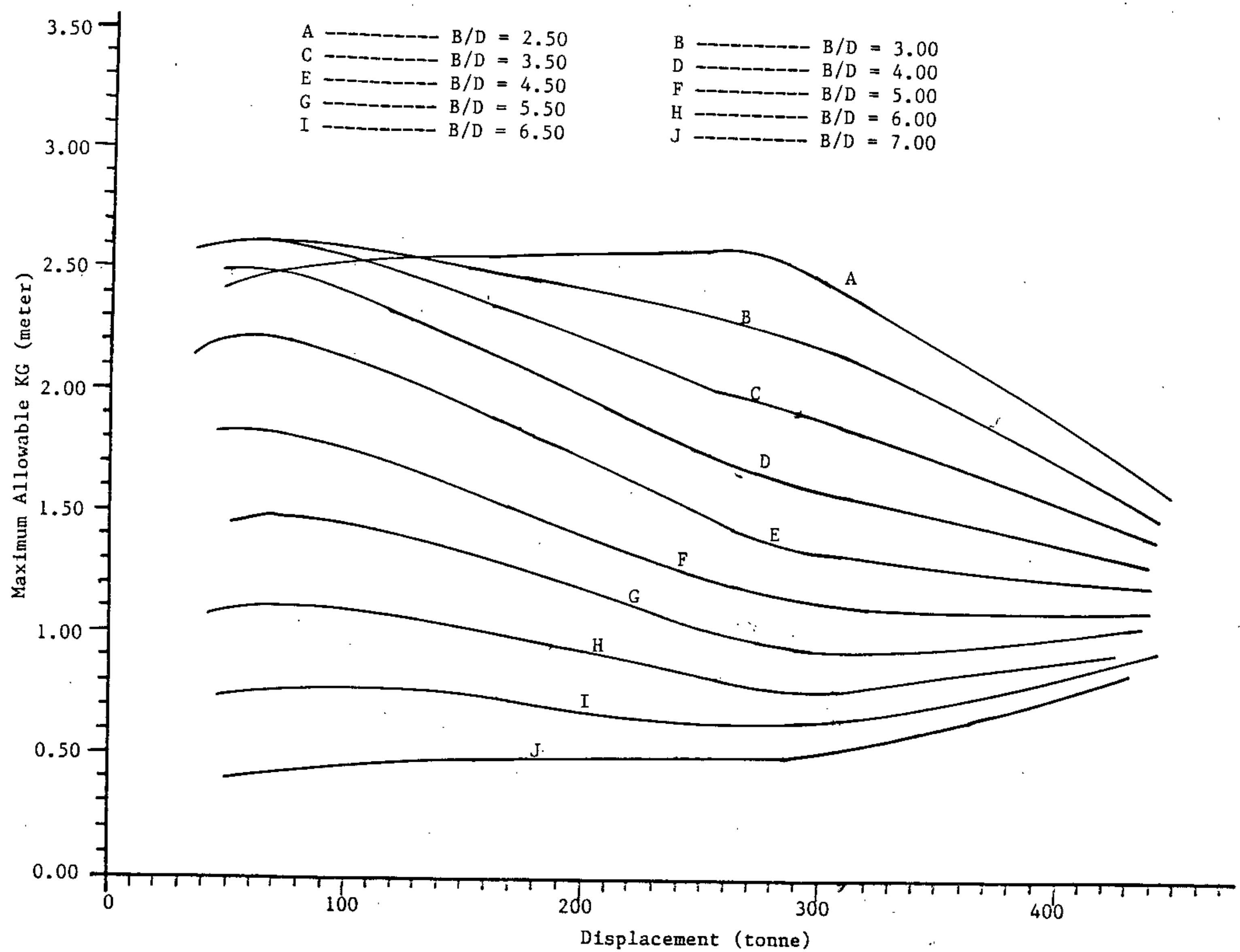

Fig. 4. 12 : Variation of maximum allowable KG with displacement and B/D ratio

(Vessel No. 12)

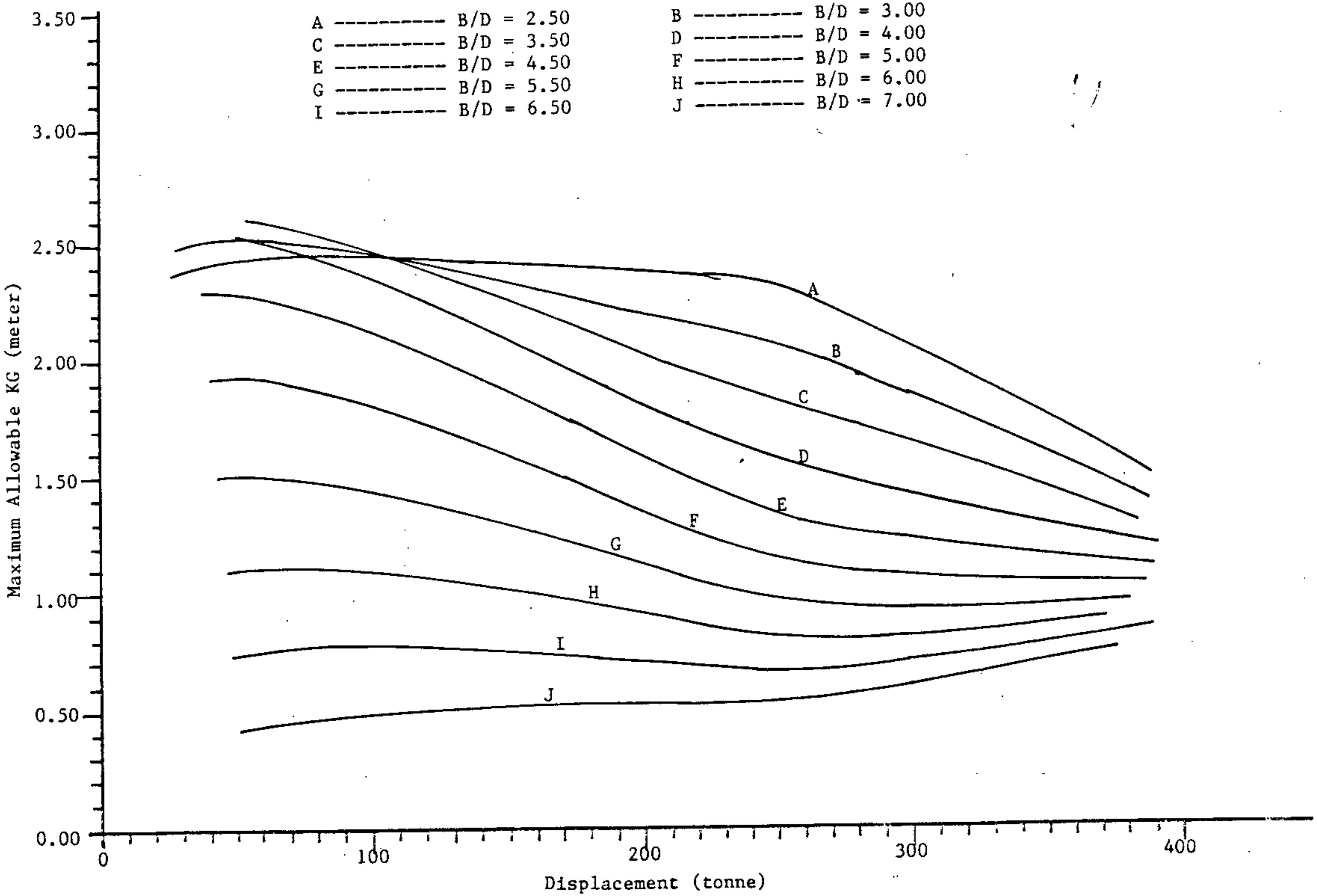

Fig. 4. 13 : Variation of maximum allowable KG with displacement and B/D ratio

(Vessel No. 13)

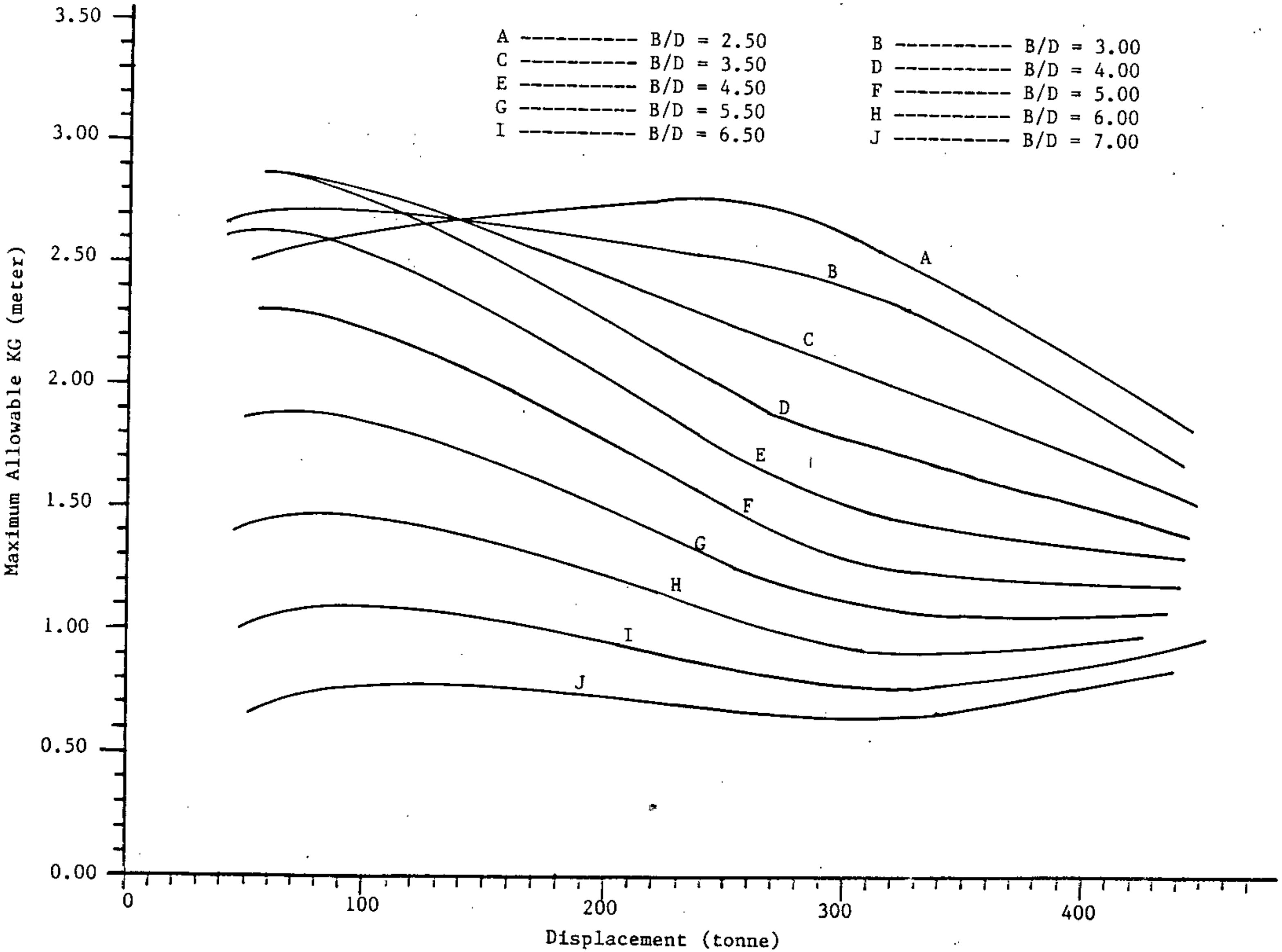

Fig. 4. 14 : Variation of maximum allowable KG with displacement and B/D ratio

(Vessel No. 14)

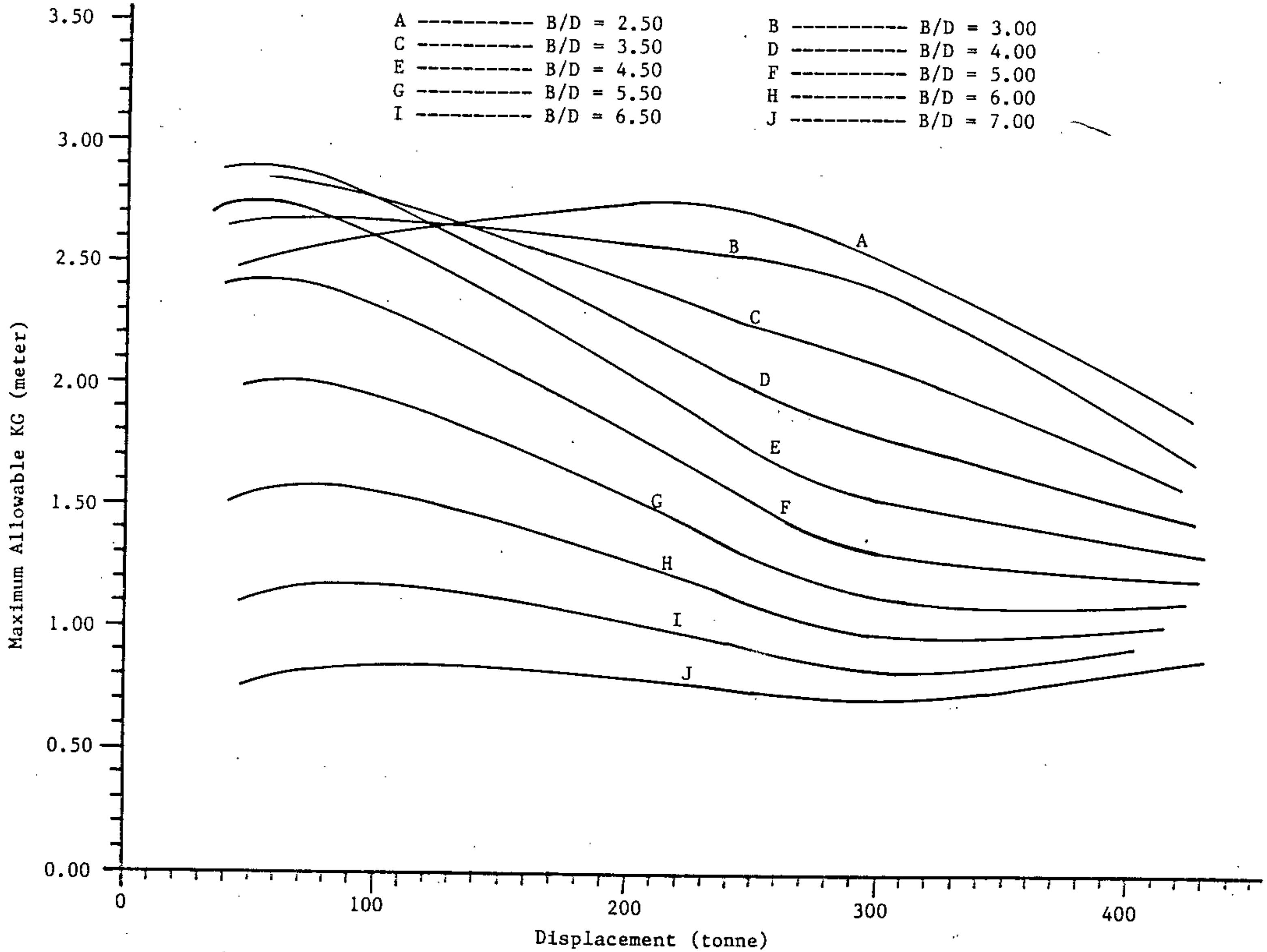

Fig. 4. 15 : Variation of maximum allowable KG with displacement and B/D ratio

(Vessel No. 15)

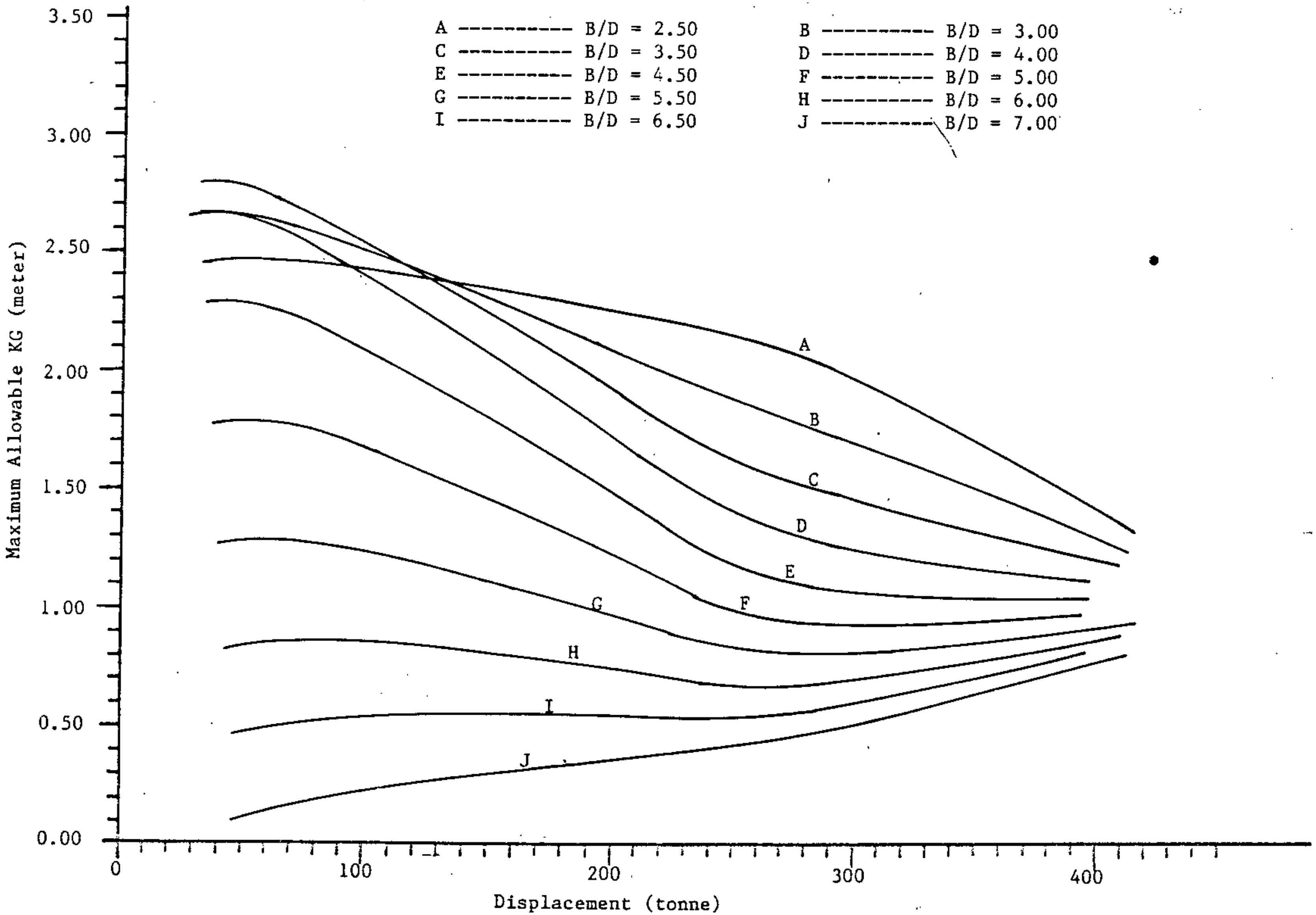

Fig. 4. 16 : Variation of maximum allowable KG with displacement and B/D ratio

(Vessel No. 16)

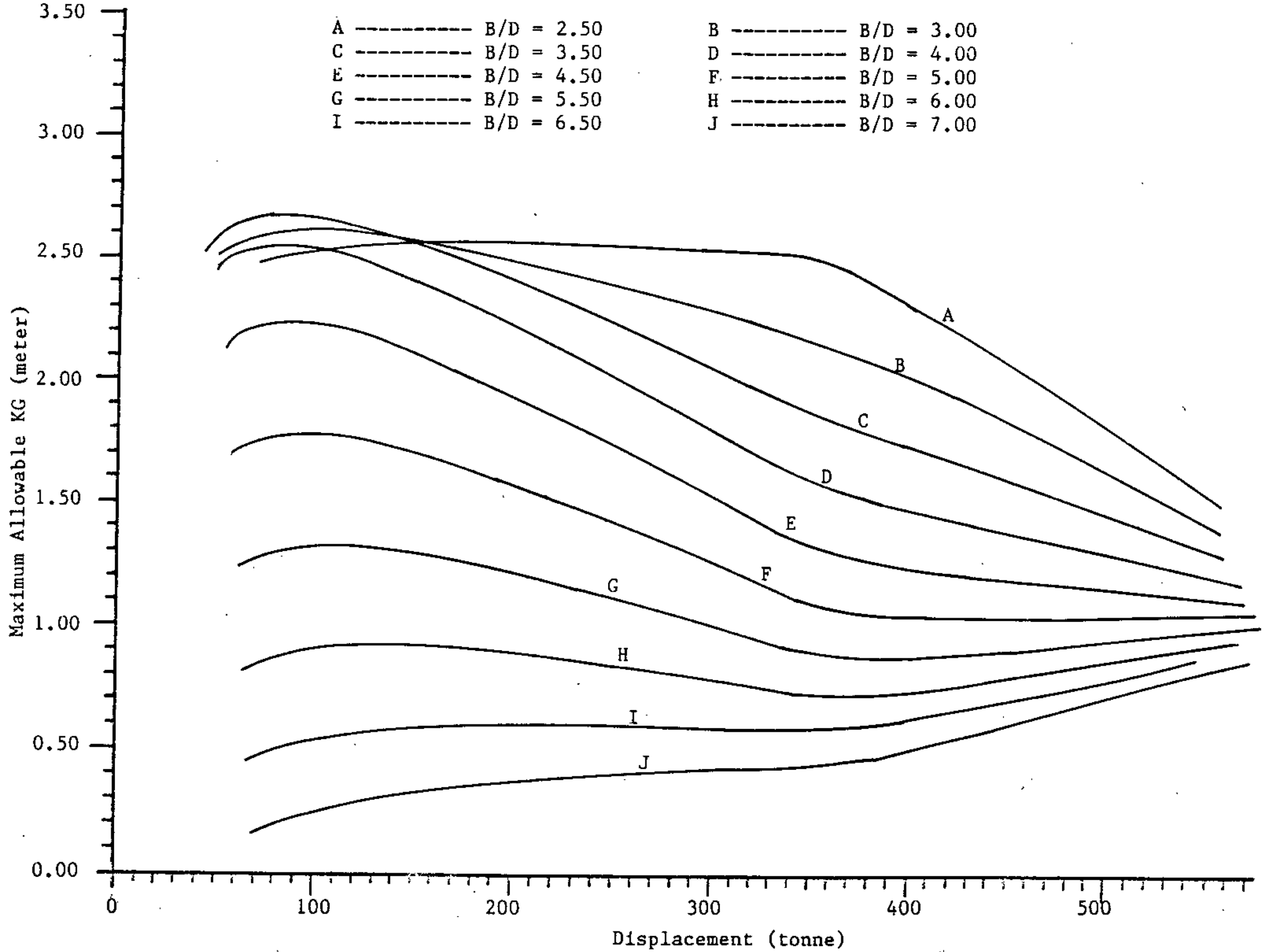

Fig. 4.17 : Variation of maximum allowable KG with displacement and B/D ratio

(Vessel No. 17)

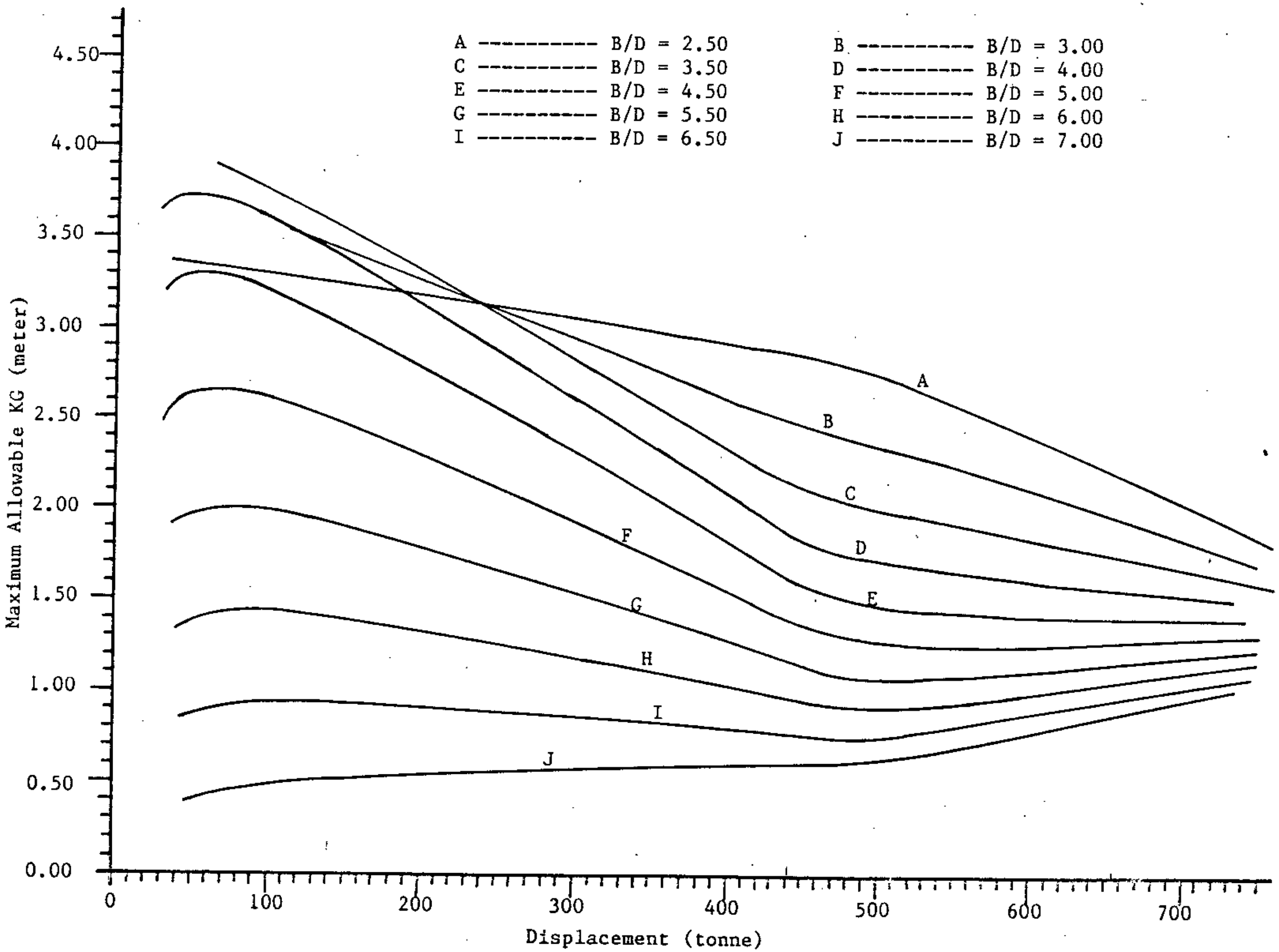

Fig. 4. 18 : Variation of maximum allowable KG with displacement and B/D ratio

(Vessel No. 18)

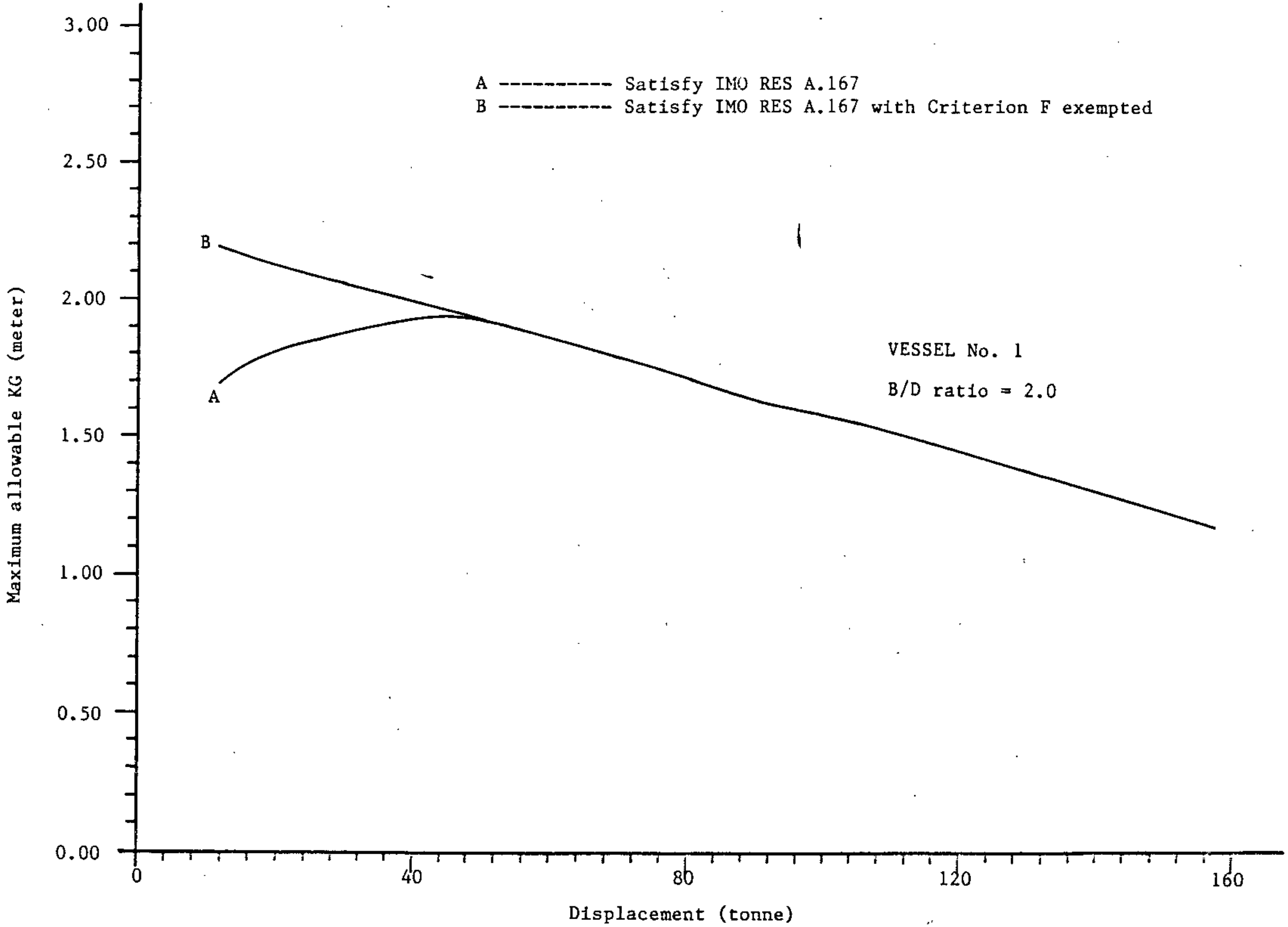

Fig 4. 19 : Variation of maximum allowable KG with criterion F exempted
VESSEL No. 1

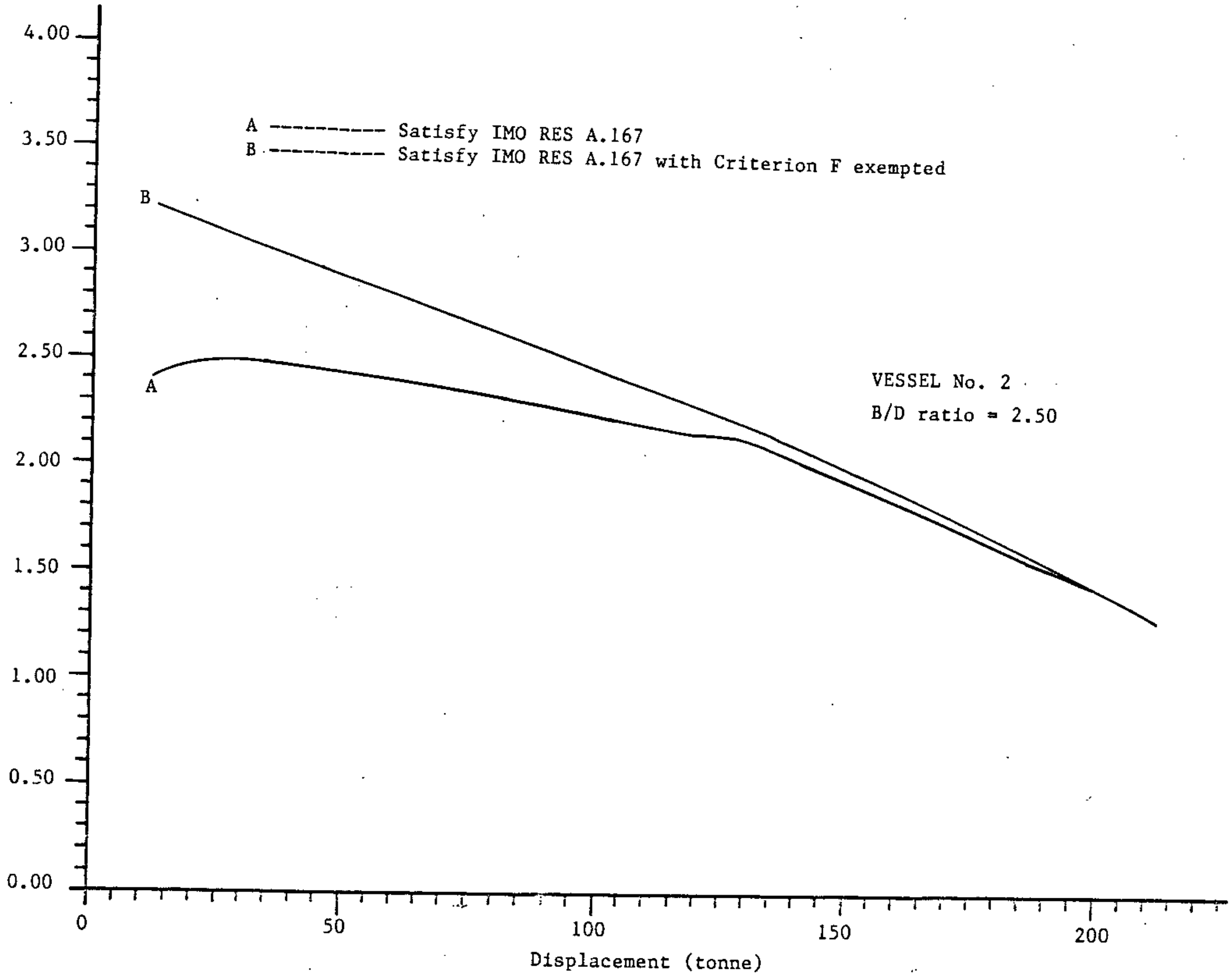

Fig 4. 20 : Variation of maximum allowable KG with criterion F exempted

(VESSEL No. 2)

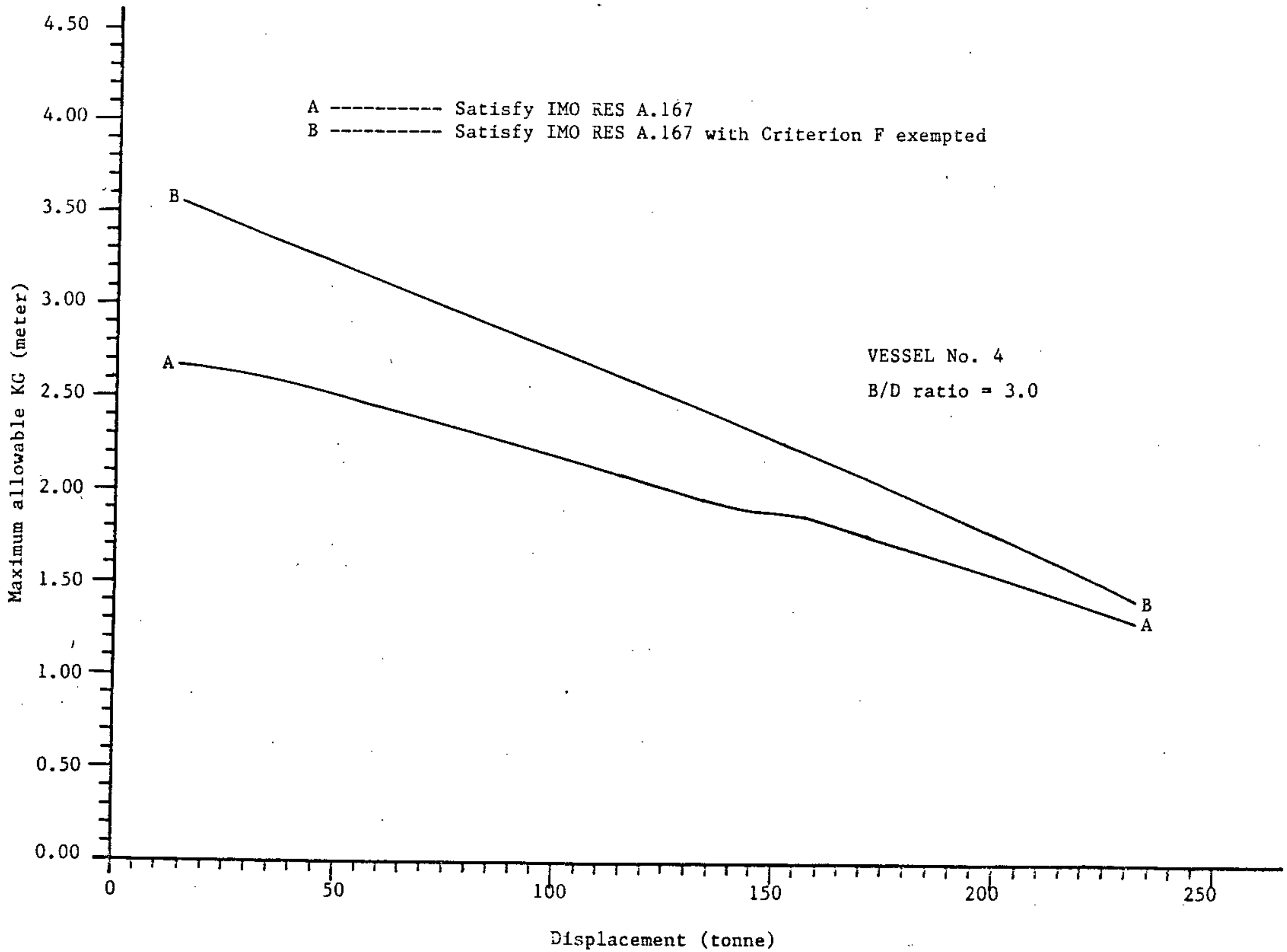

Fig 4.21 : Variation of maximum allowable KG with criterion F exempted

VESSEL No. 4

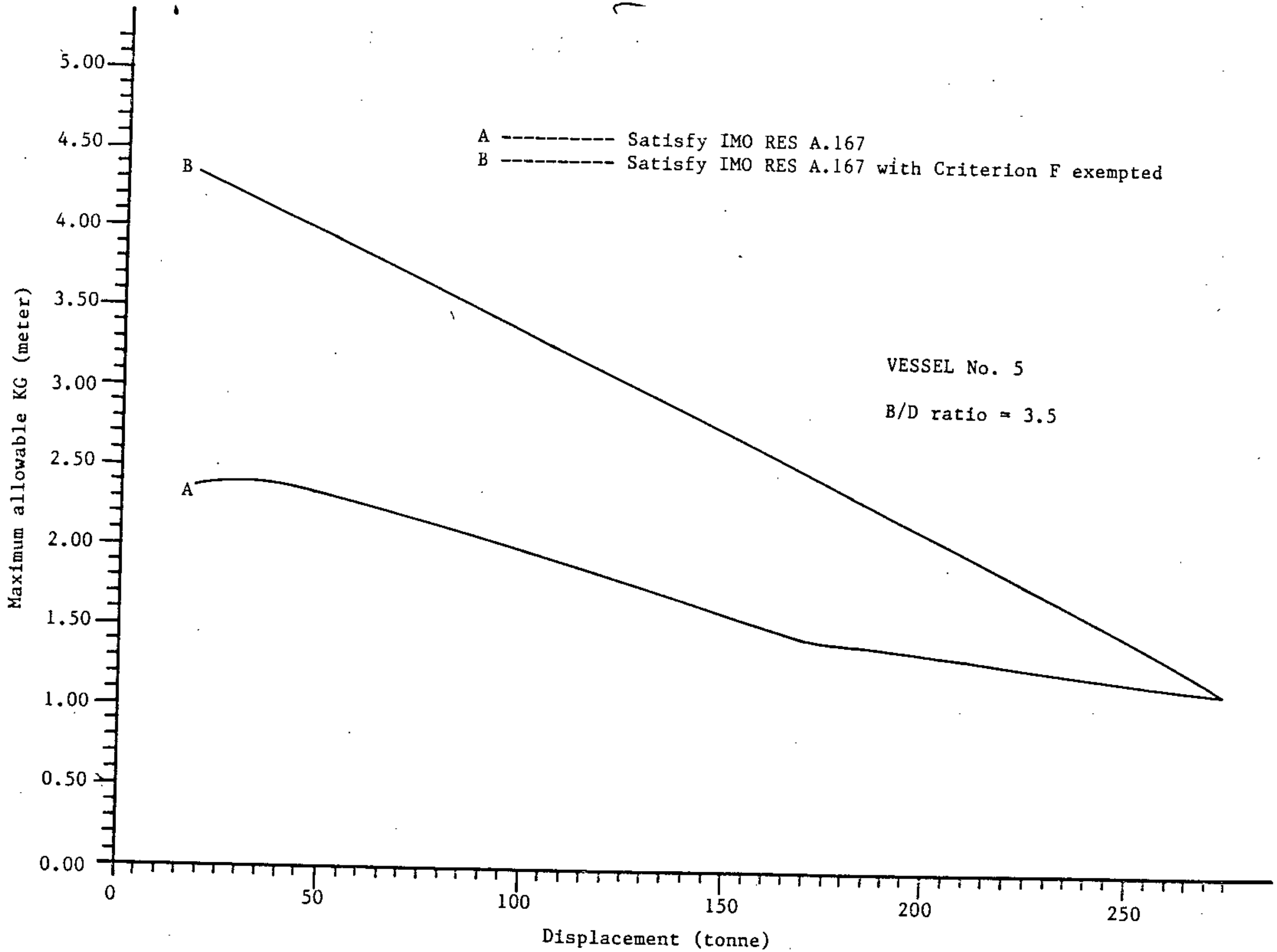

Fig 4. 2.2 : Variation of maximum allowable KG with criterion F exempted
VESSEL No. 5

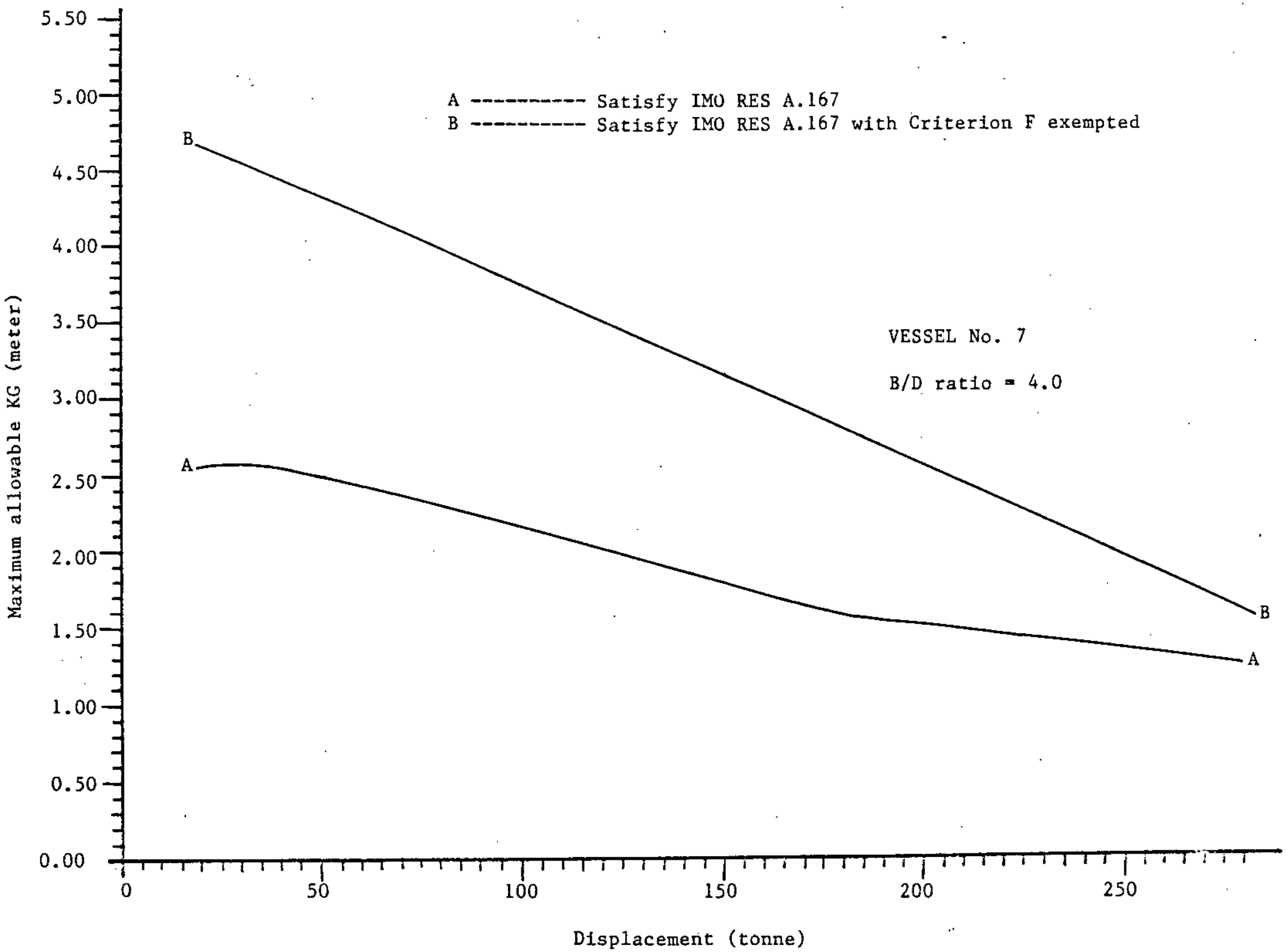

Fig 4.23 : Variation of maximum allowable KG with criterion F exempted
VESSEL No. 7

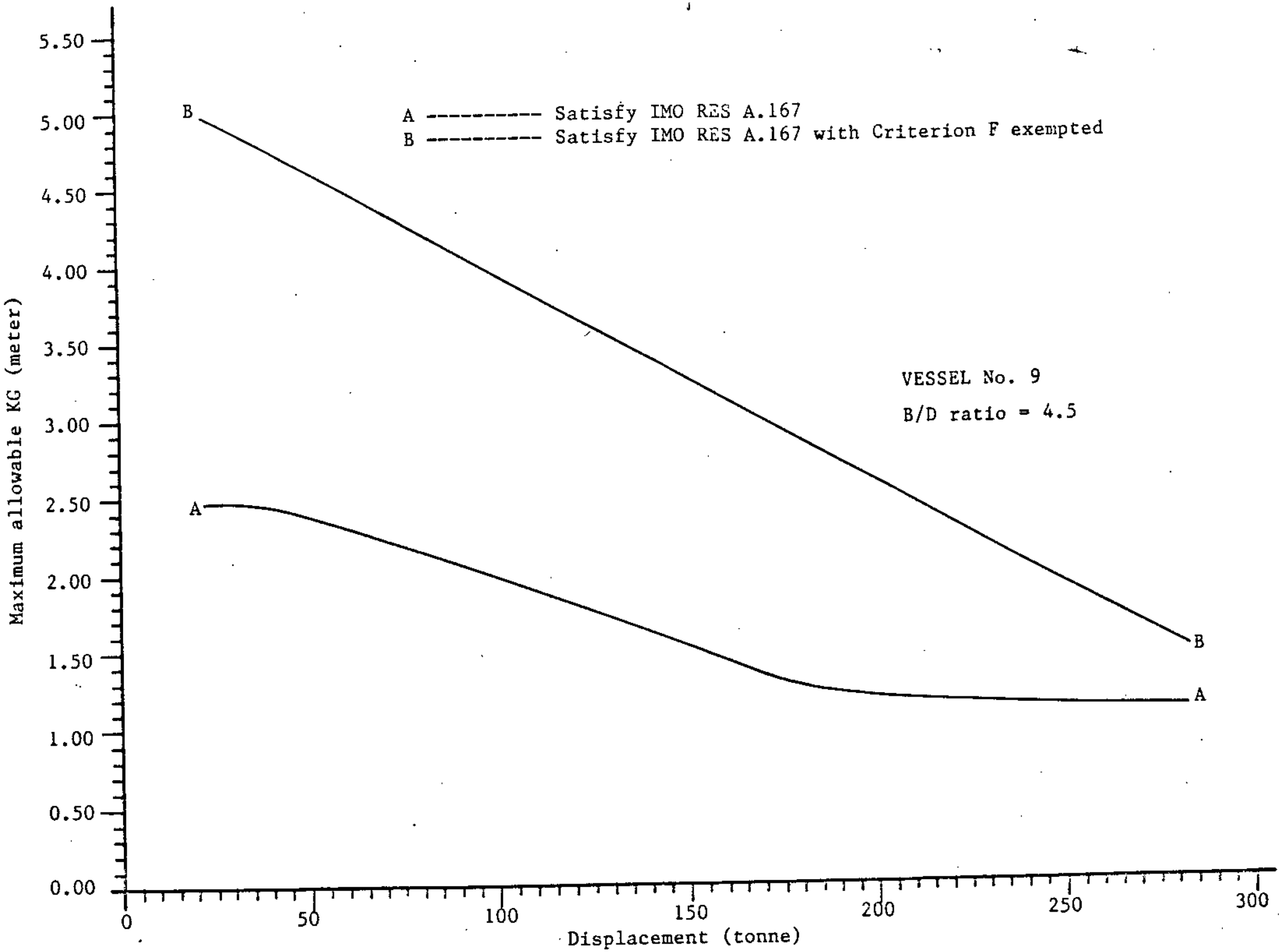

Fig 4.2.4 : Variation of maximum allowable KG with criterion F exempted
VESSEL No. 9

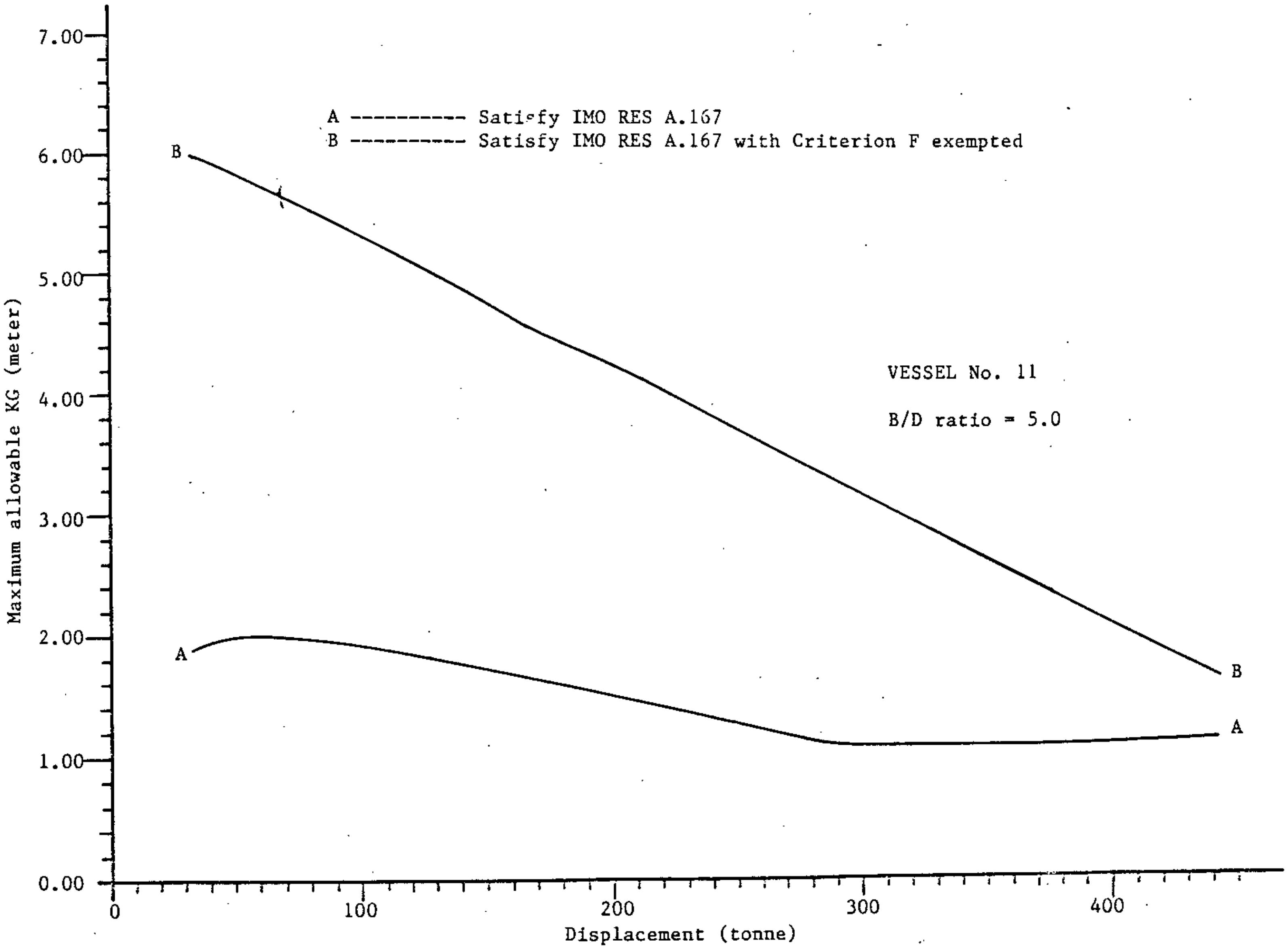

Fig 4.25 : Variation of maximum allowable KG with criterion F exempted
VESSEL No. 11

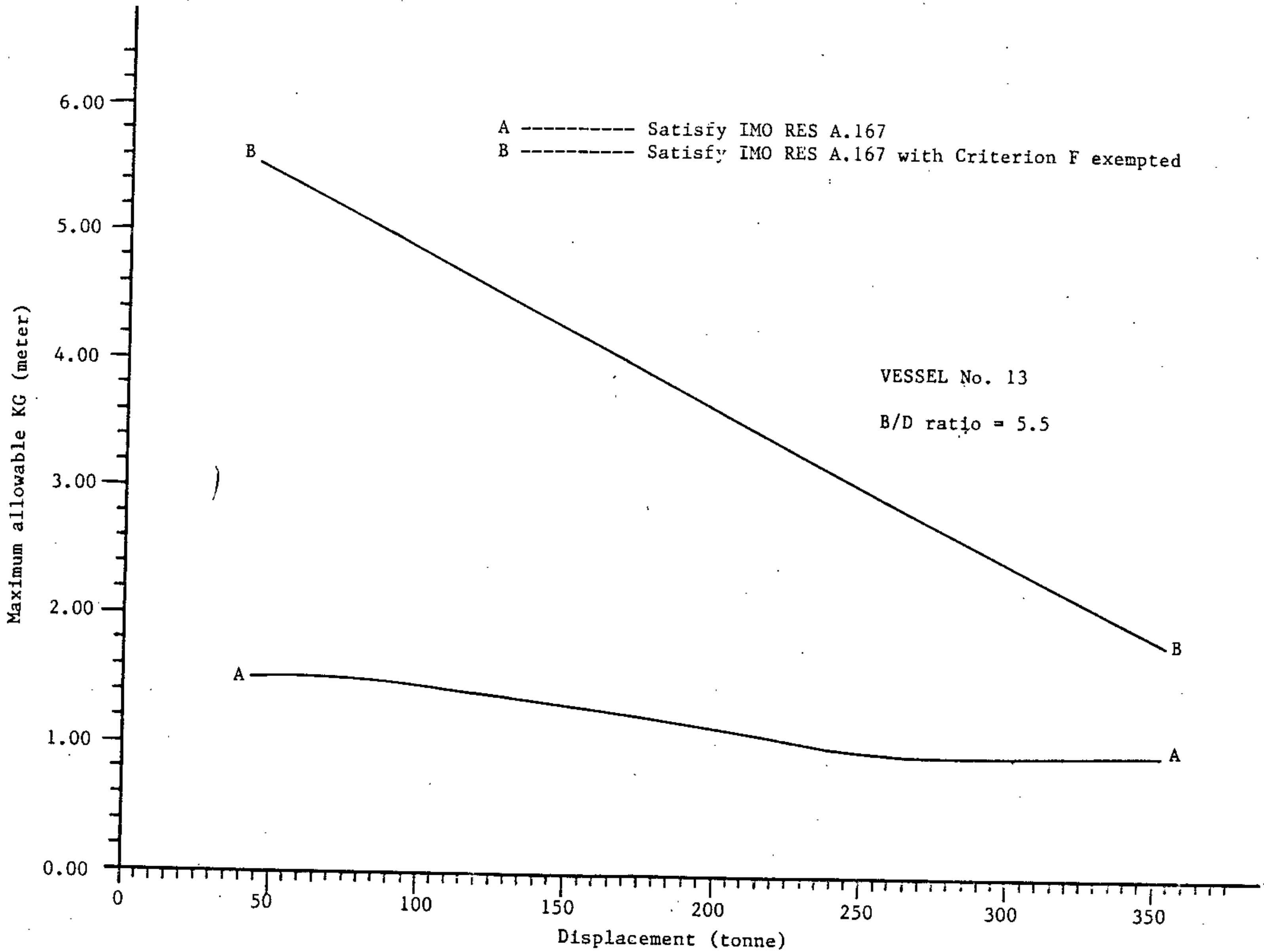

Fig 4.26 : Variation of maximum allowable KG with criterion F exempted

VESSEL No. 13

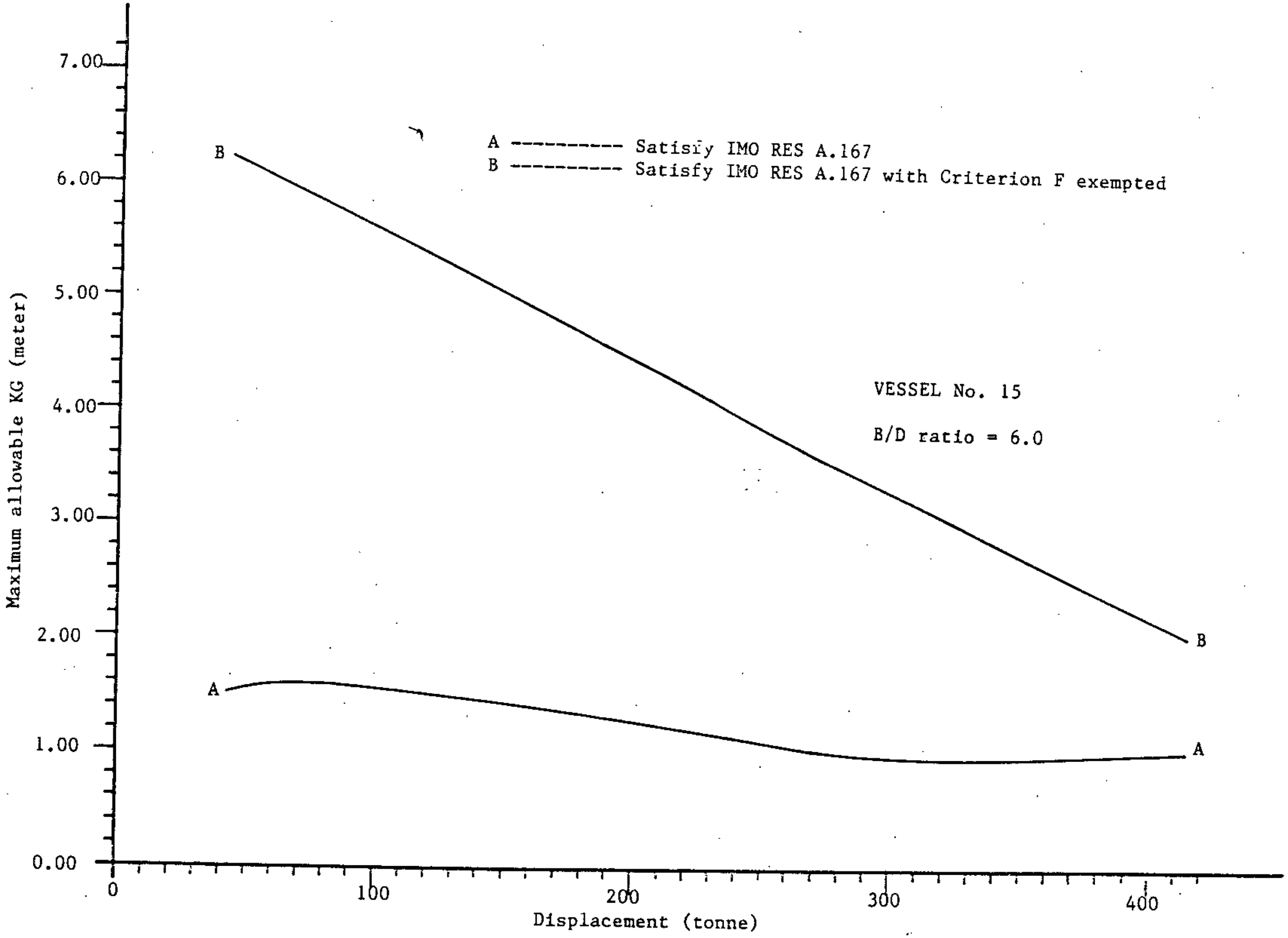

Fig 4.27 : Variation of maximum allowable KG with criterion F exempted
VESSEL No. 15

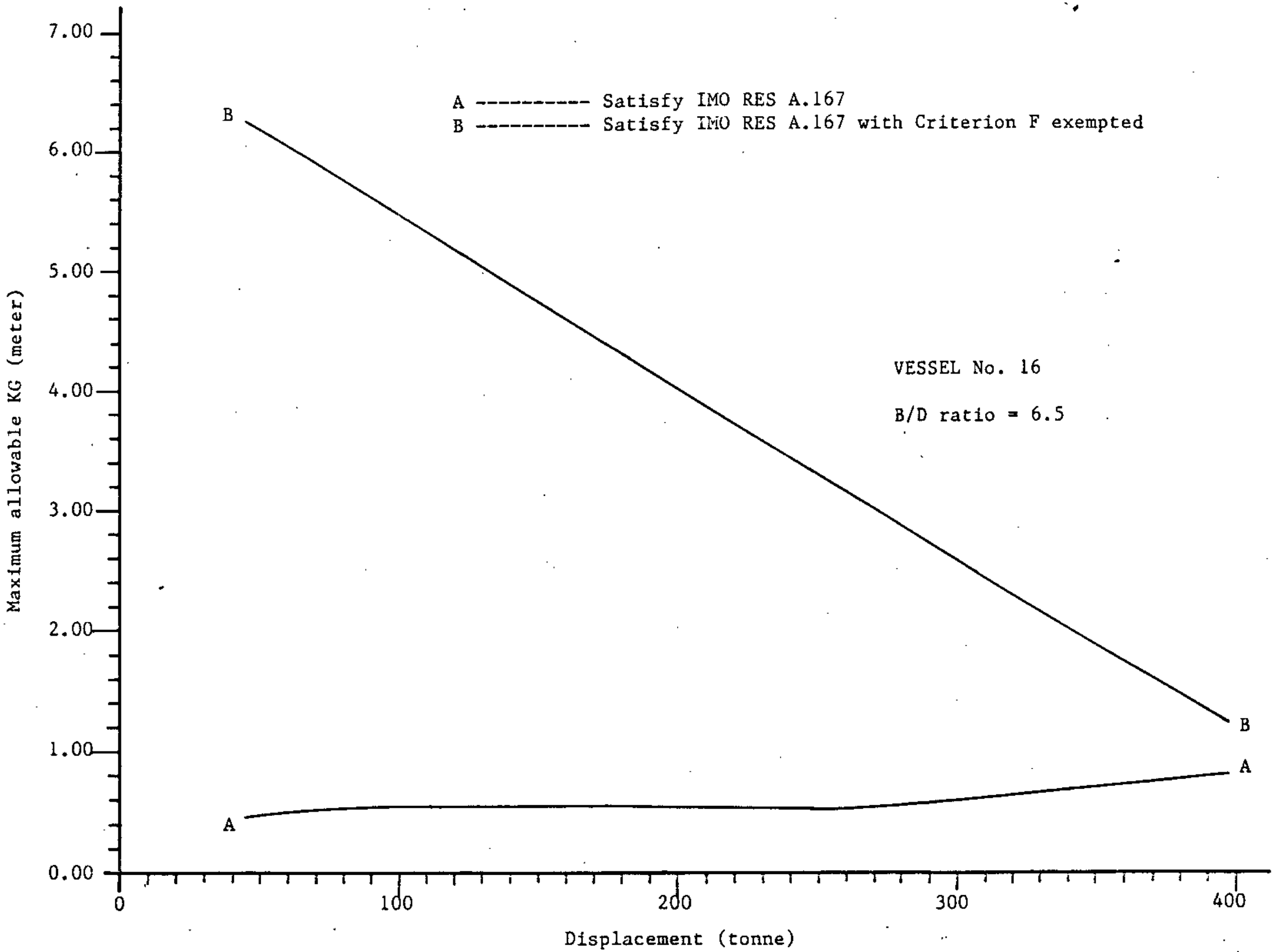

Fig 4. 28 : Variation of maximum allowable KG with criterion F exempted

VESSEL No. 16

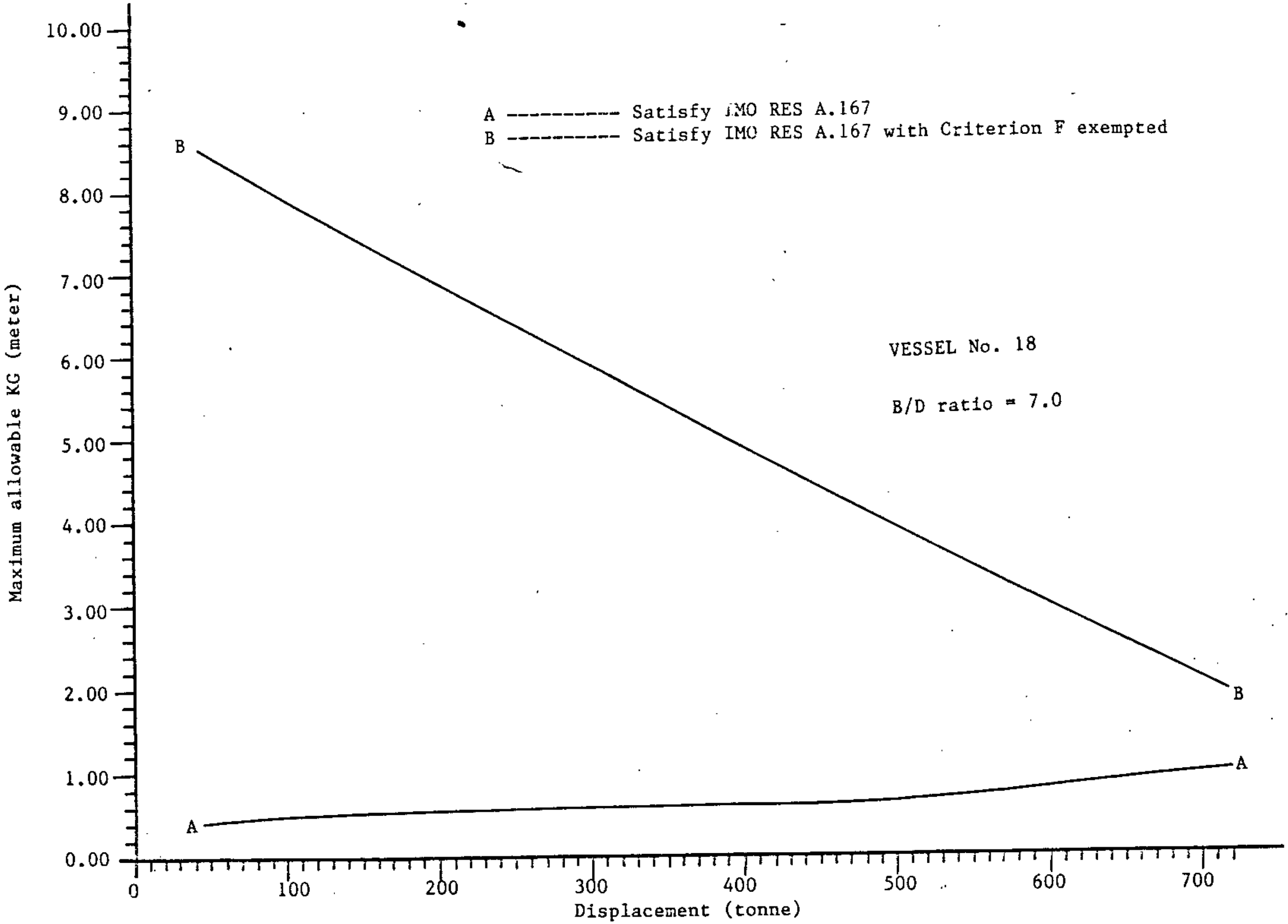

Fig 4.29 : Variation of maximum allowable KG with criterion F exempted

VESSEL No. 18

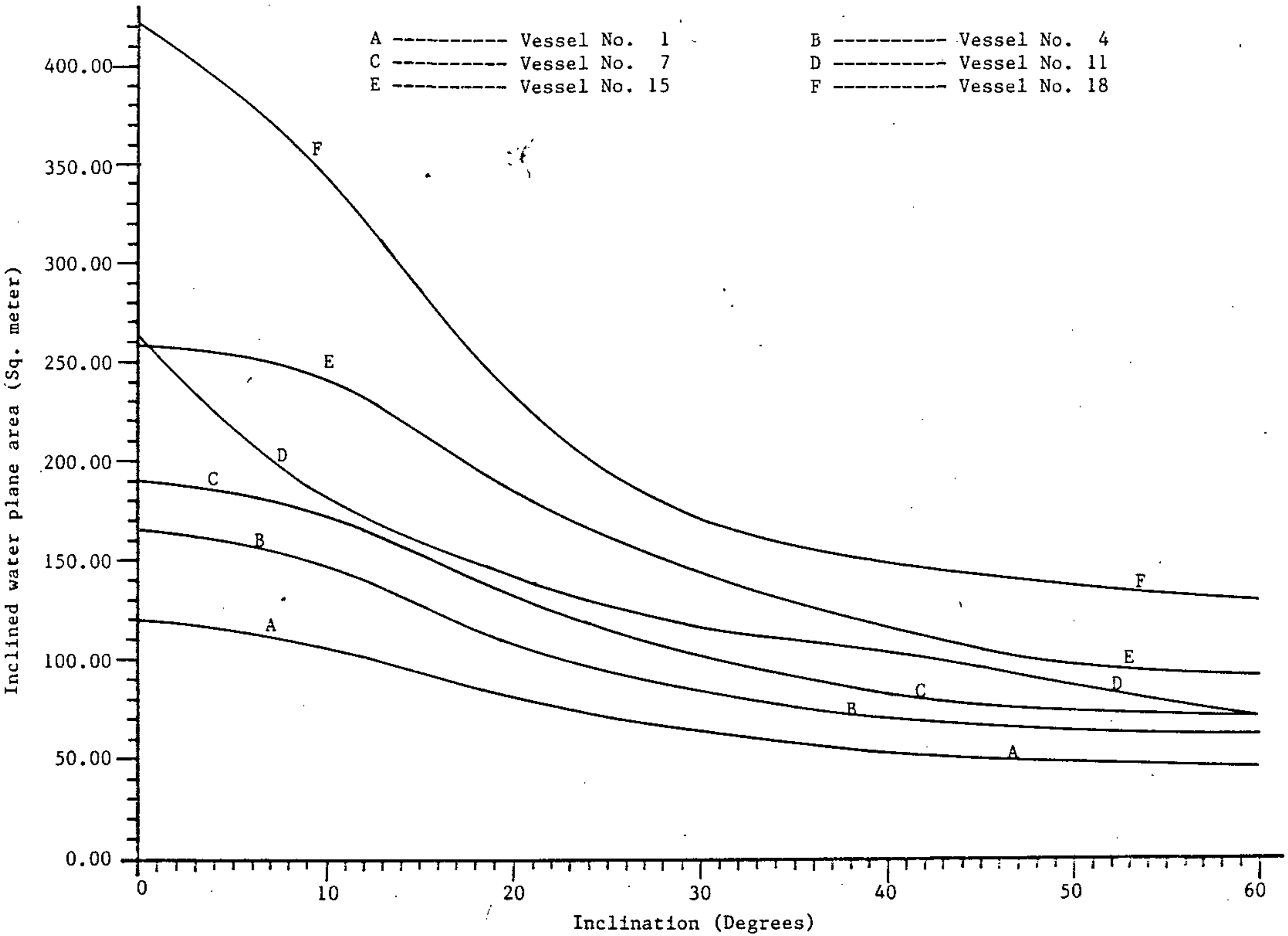

Fig 4.30 : Reduction of water plane are with inclination

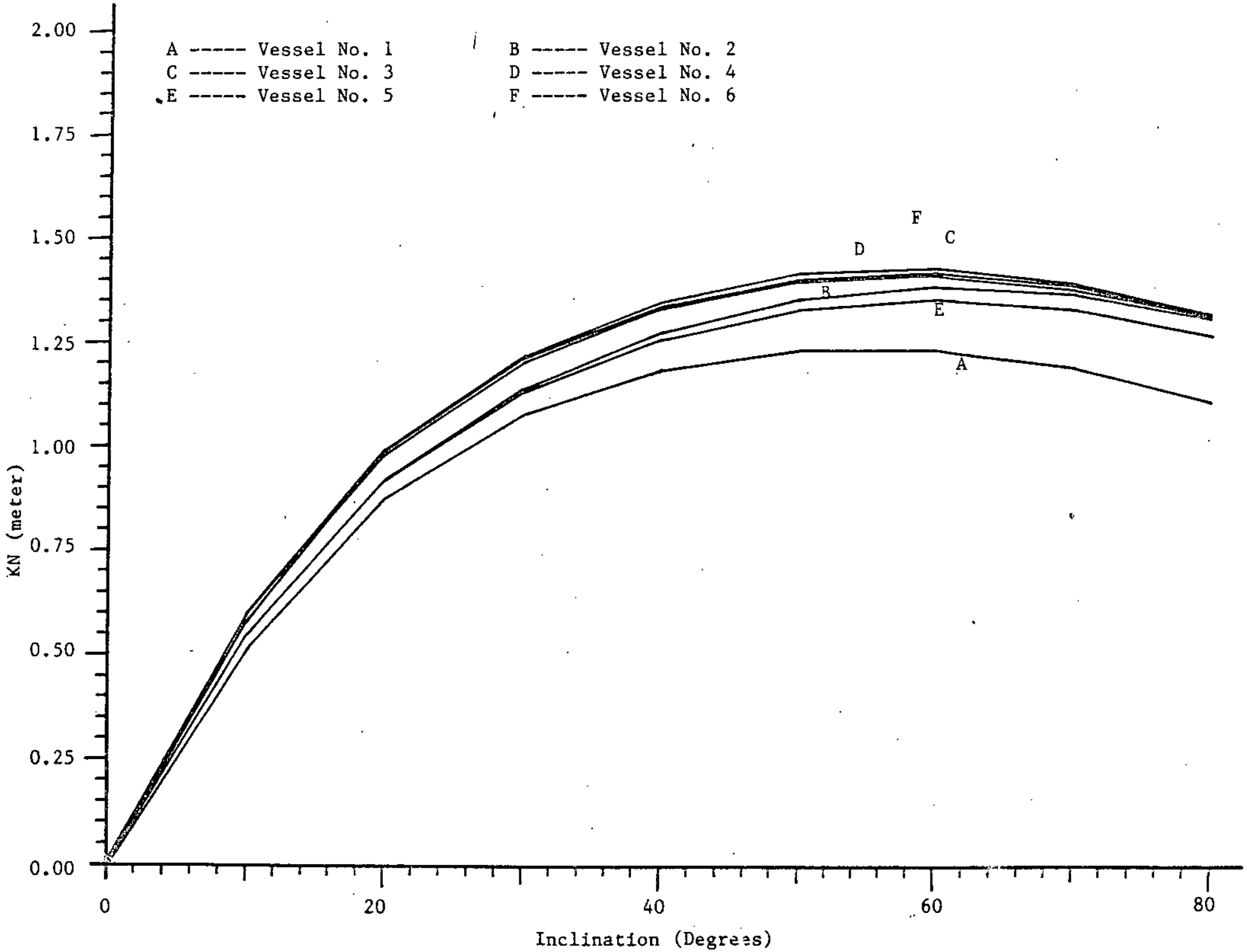

Fig. 4.31 : KN curves of Vessels No. 1 to 6

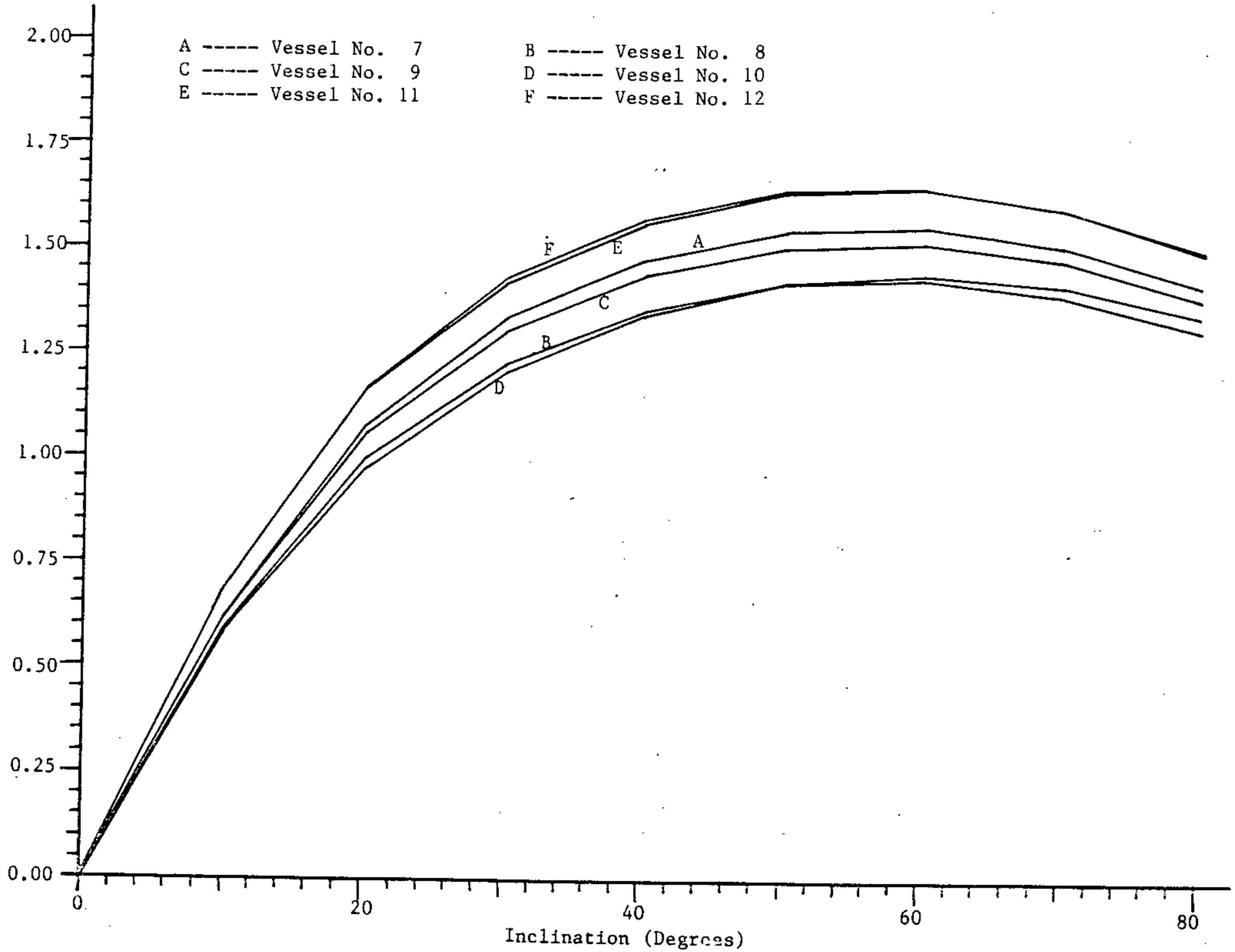

Fig. 4.32 : KN curves of Veseels No. 7 to 12

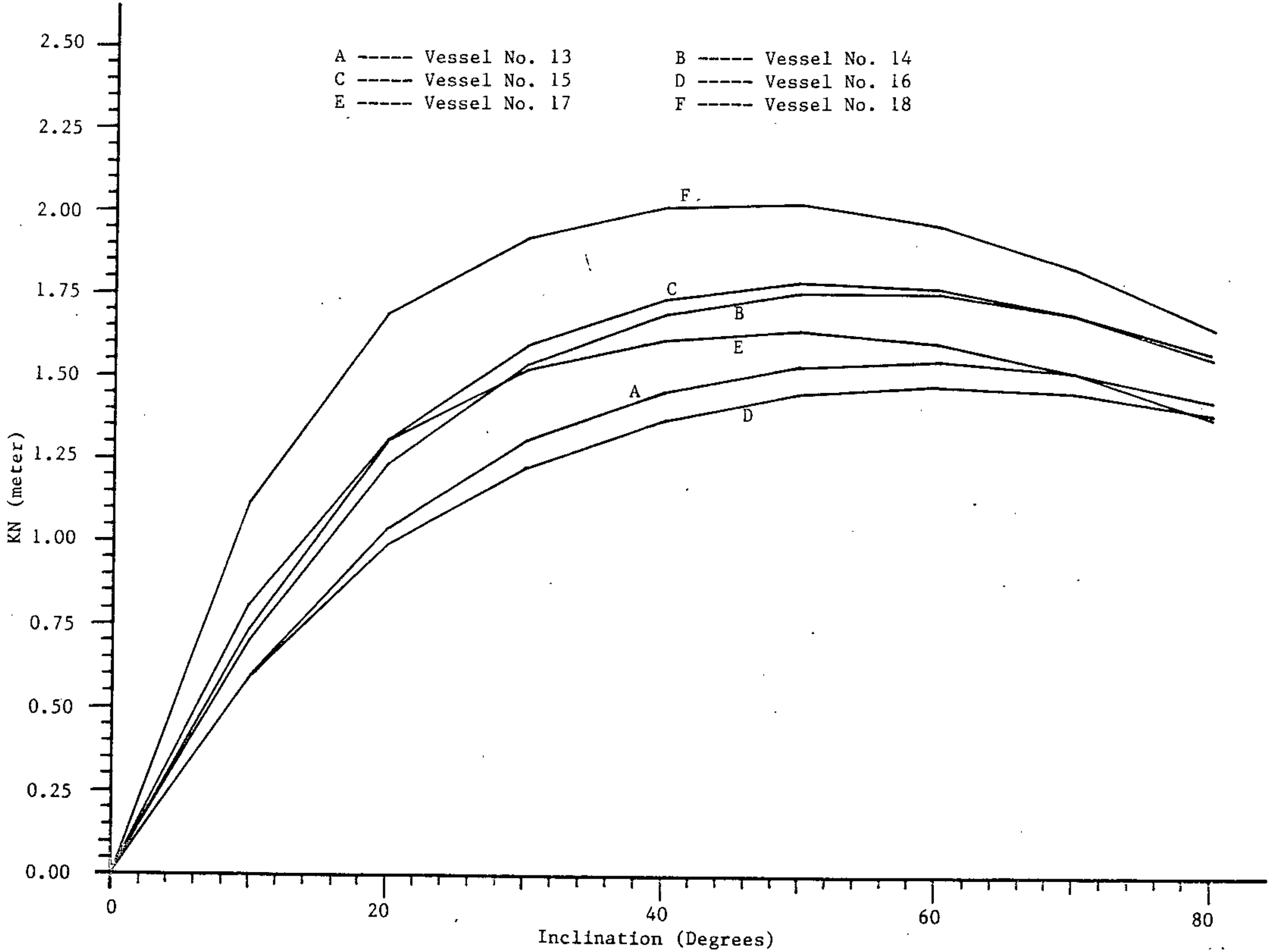

Fig. 4.33 : KN curves of Vessels No. 13 to 18

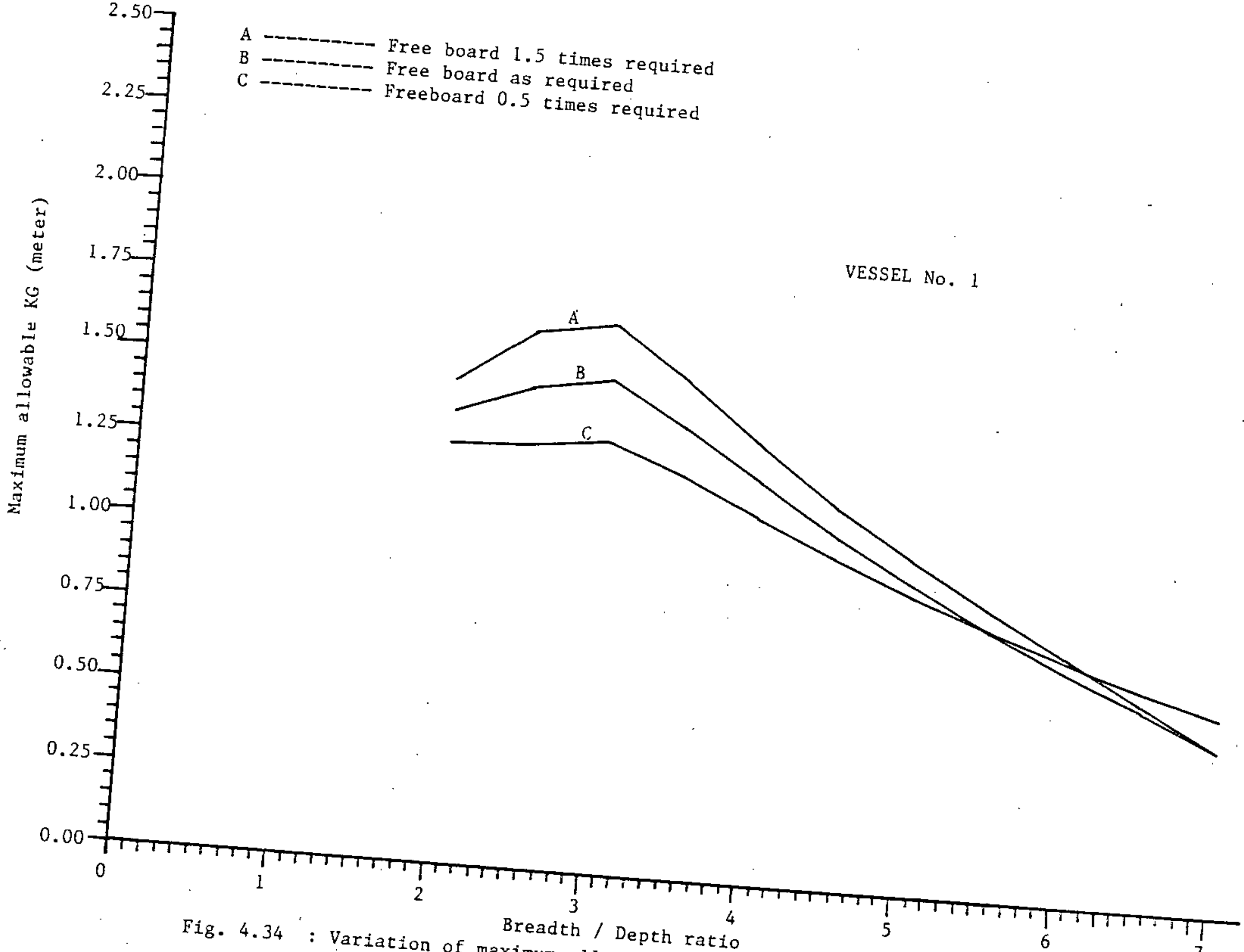

Fig. 4.34 : Variation of maximum allowable KG with B/D ratio at and around f_{min} displacement

VESSEL No. 1

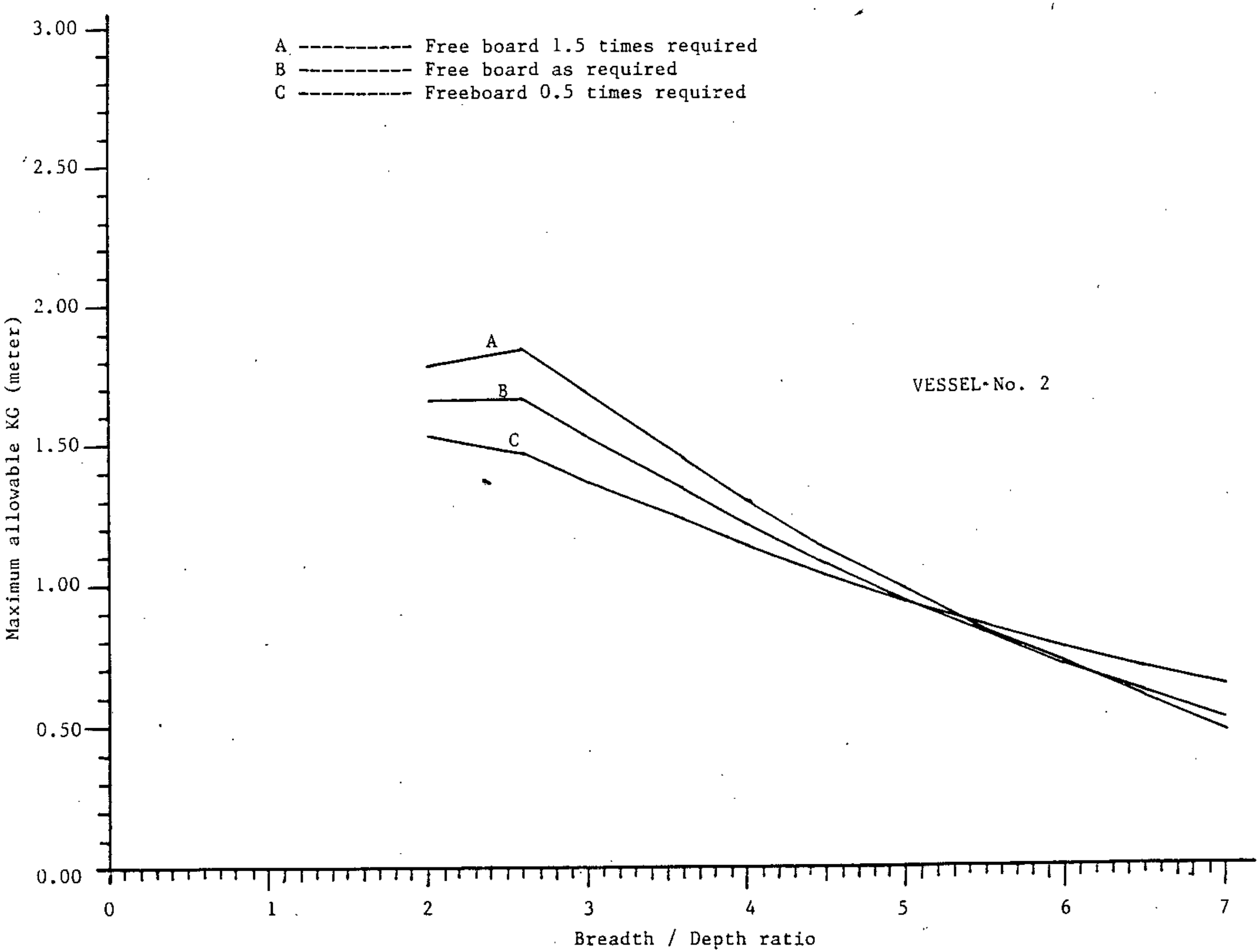

Fig. 4. 35 : Variation of maximum allowable KG with B/D ratio at and around f_{min} displacement.
VESSEL No. 2

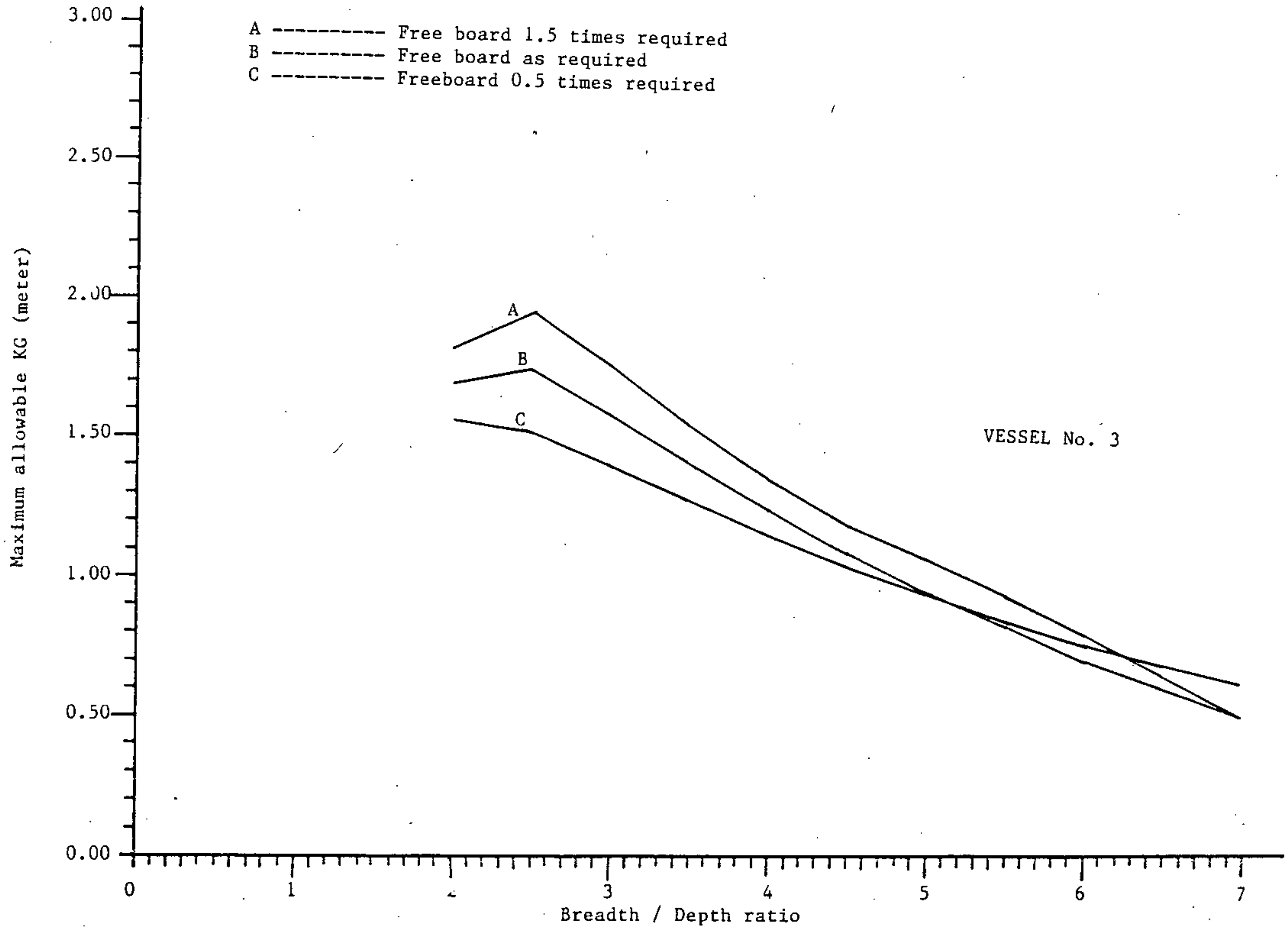

Fig. 4.36 : Variation of maximum allowable KG with B/D ratio at and around f_{min} displacement.
VESSEL No. 3

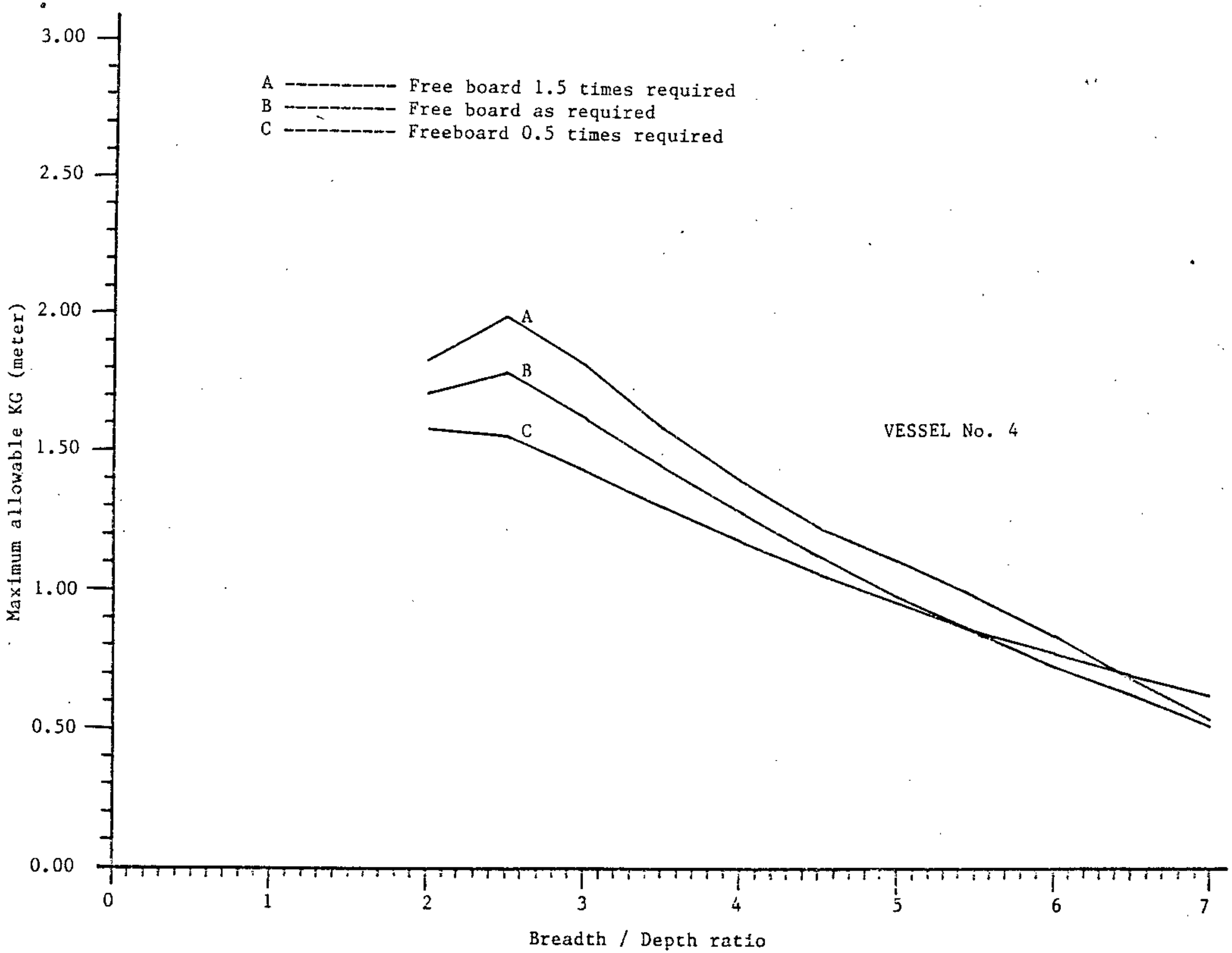

Fig. 4.37 : Variation of maximum allowable KG with B/D ratio at and around f_{min} displacement.
VESSEL No. 4

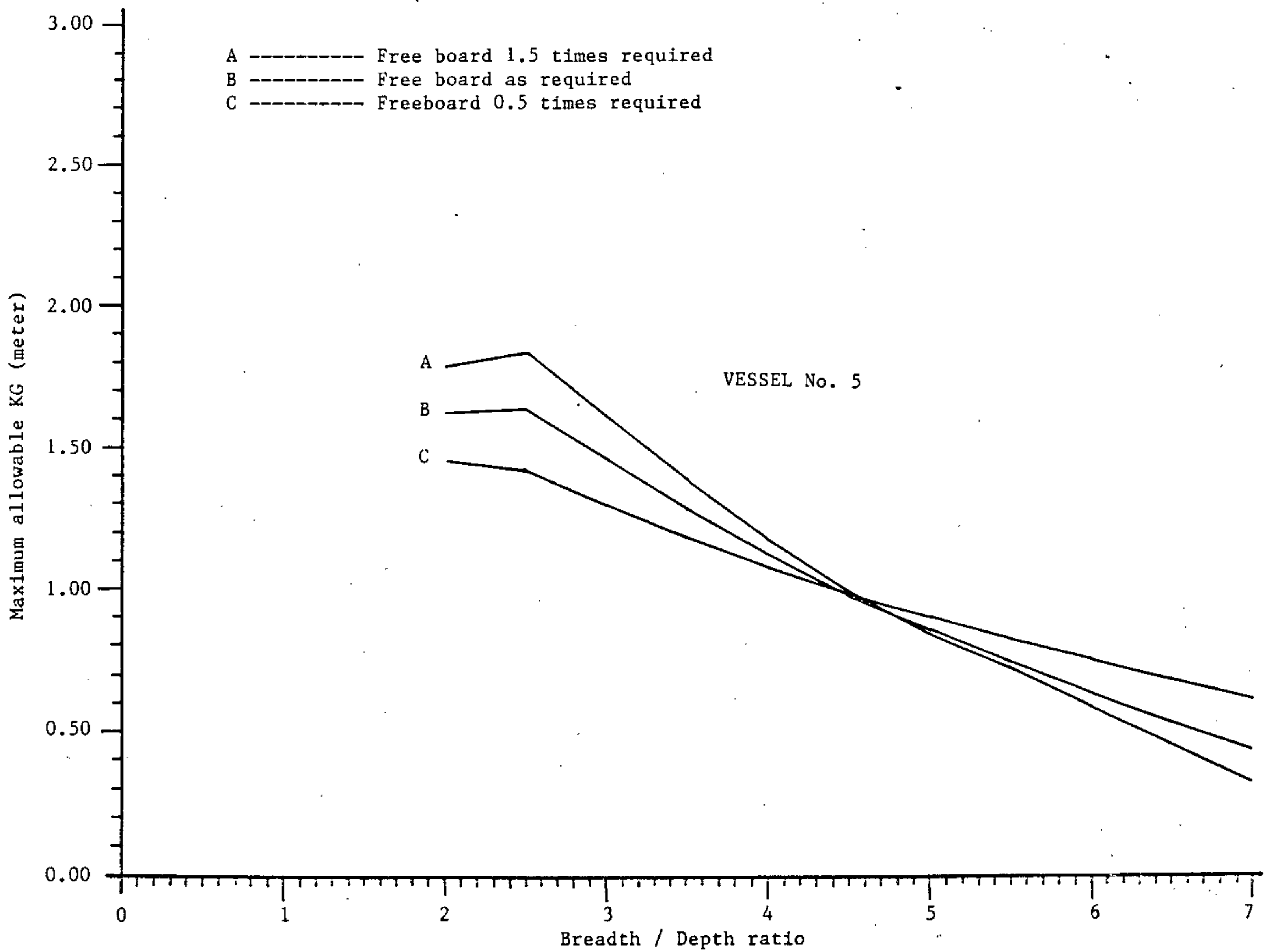

Fig. 4.38 : Variation of maximum allowable KG with B/D ratio at and around f_{min} displacement.

VESSEL No. 5

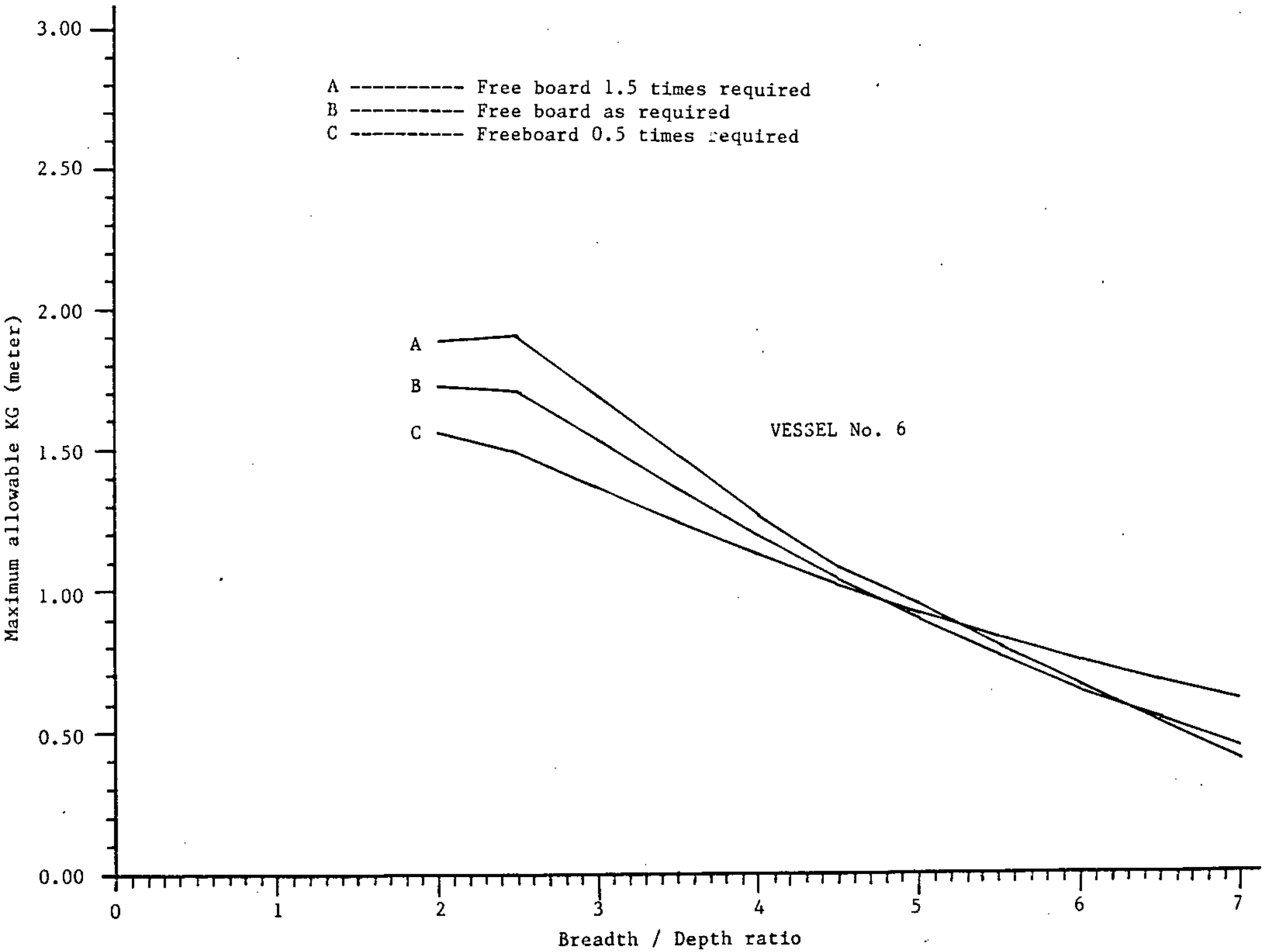

Fig. 4.39 : Variation of maximum ailowable KG with B/D ratio at and around f_{min} displacement.
VESSEL No. 6

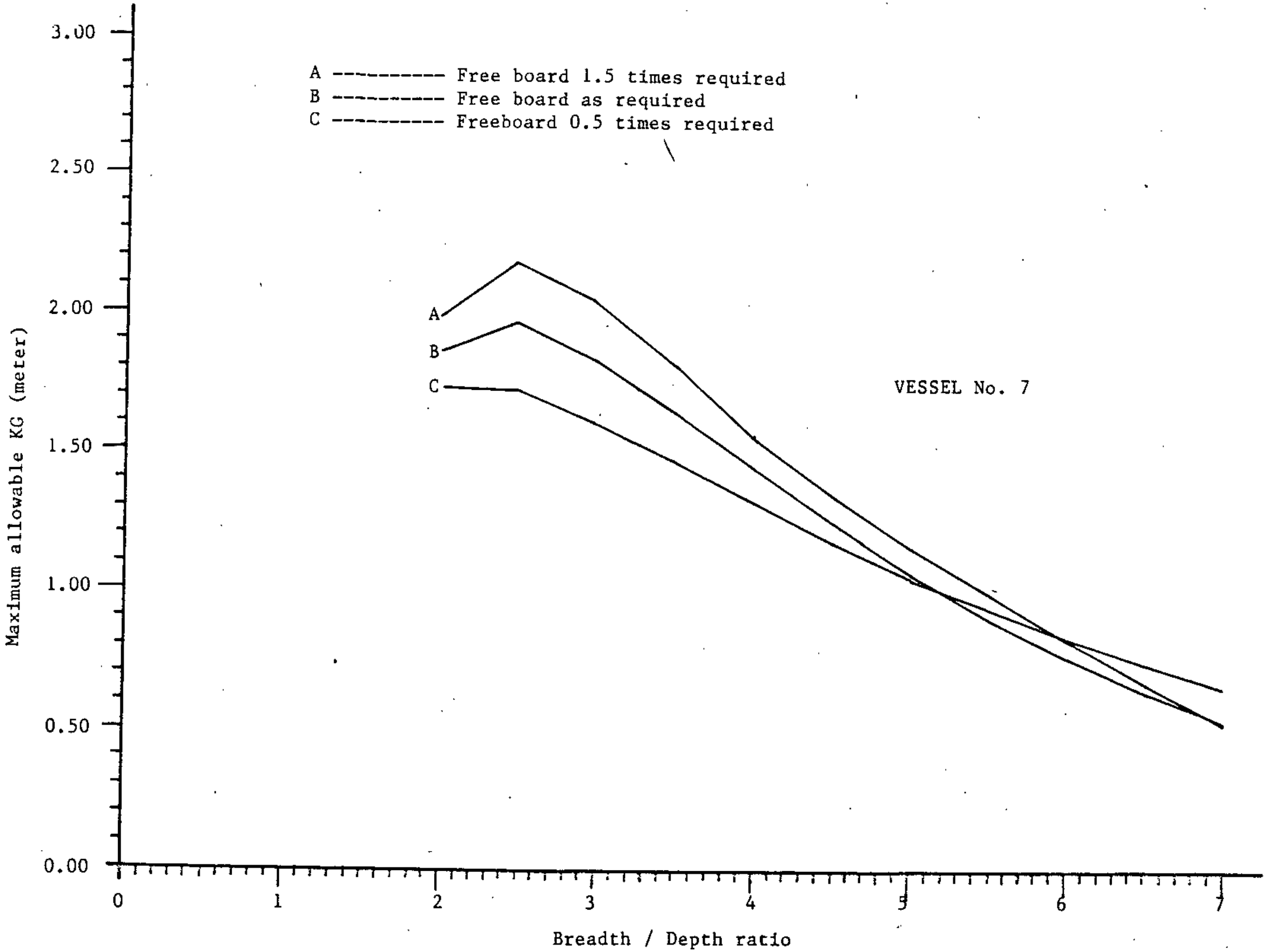

Fig. 4.40 : Variation of maximum allowable KG with B/D ratio at and around f_{min} displacement.

VESSEL No. 7

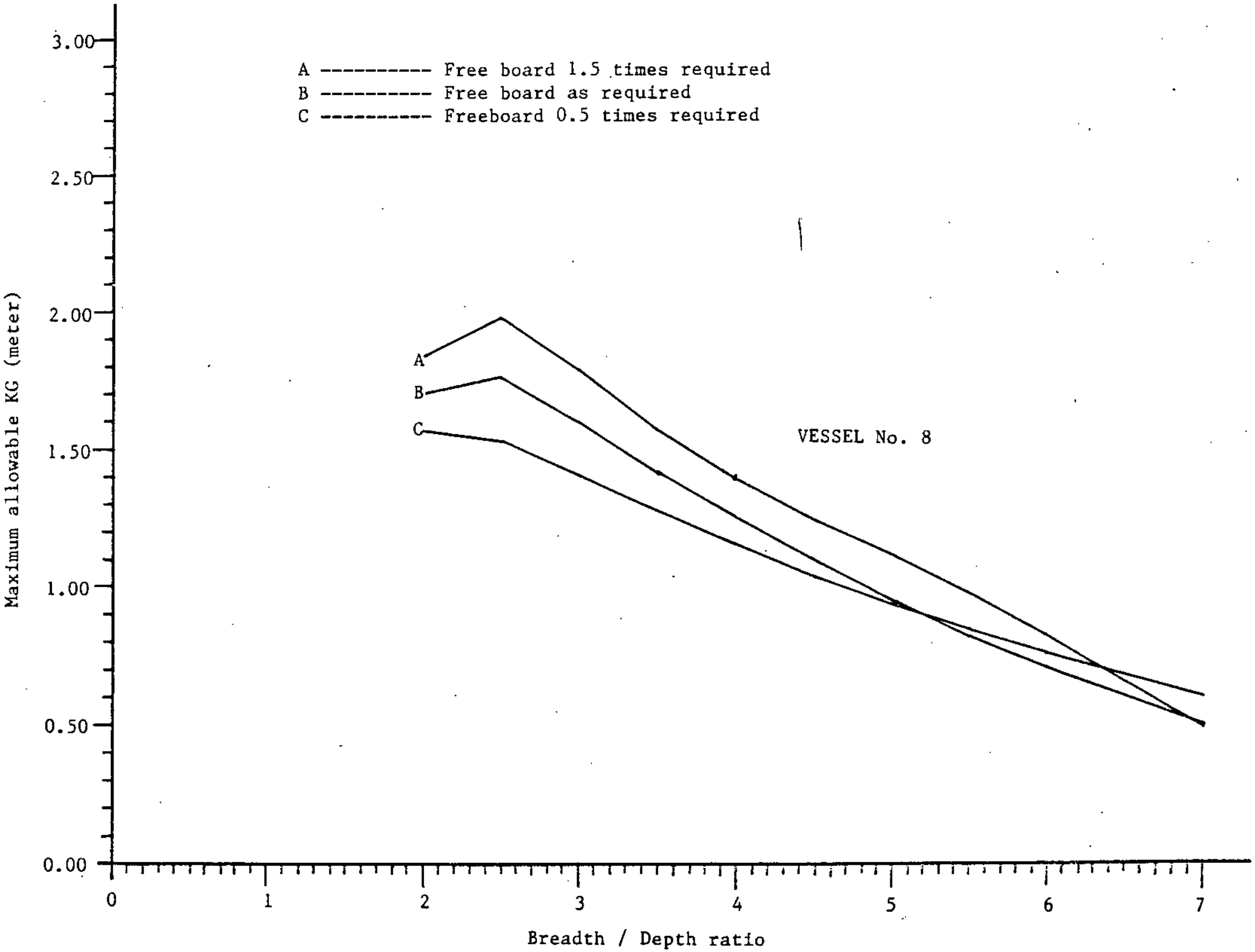

Fig. 4.41 : Variation of maximum allowable KG with B/D ratio at and around f_{min} displacement.
VESSEL No. 8

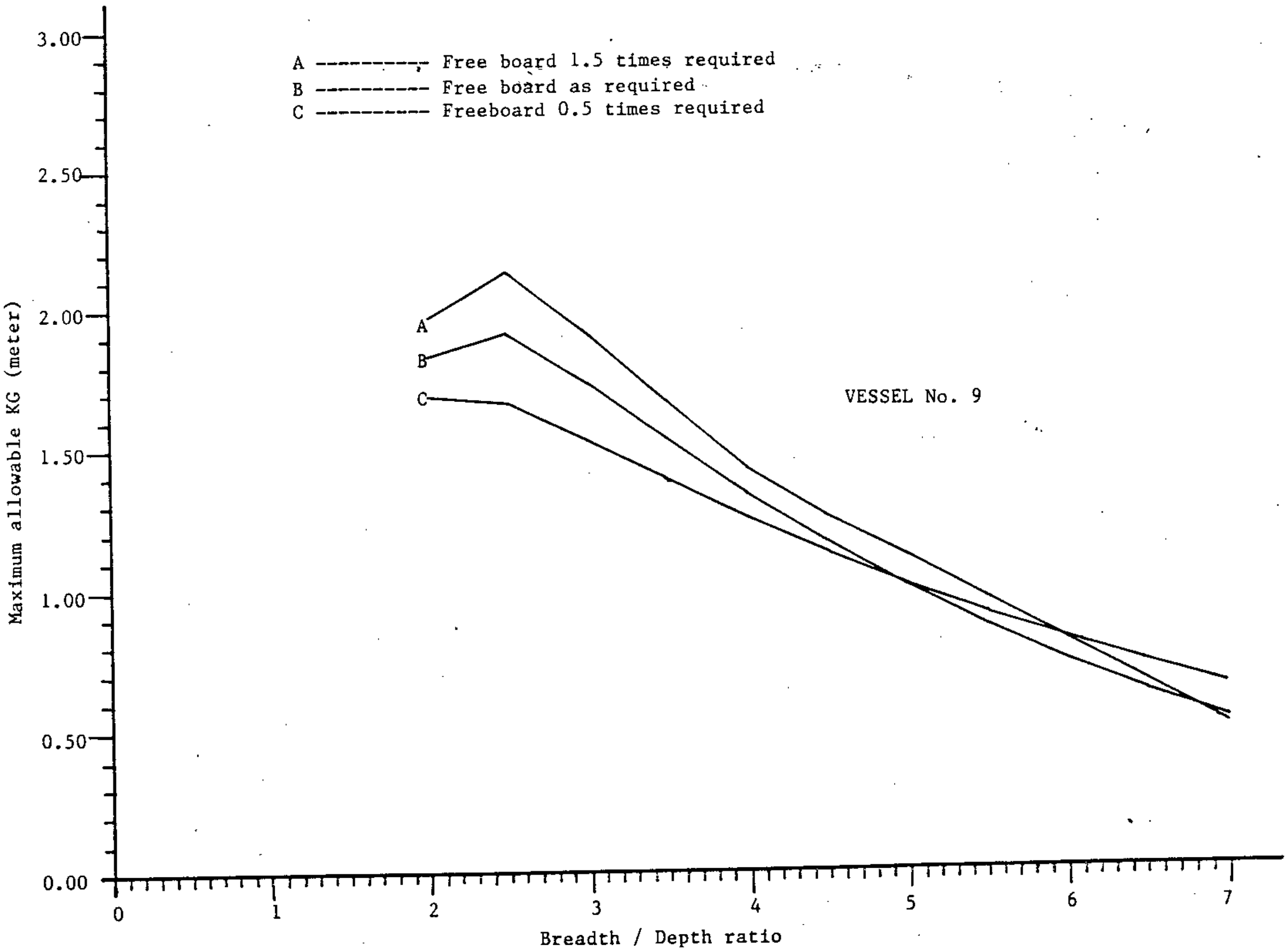

Fig. 4.42 : Variation of maximum allowable KG with B/D ratio at and around f_{min} displacement.

VESSEL No. 9

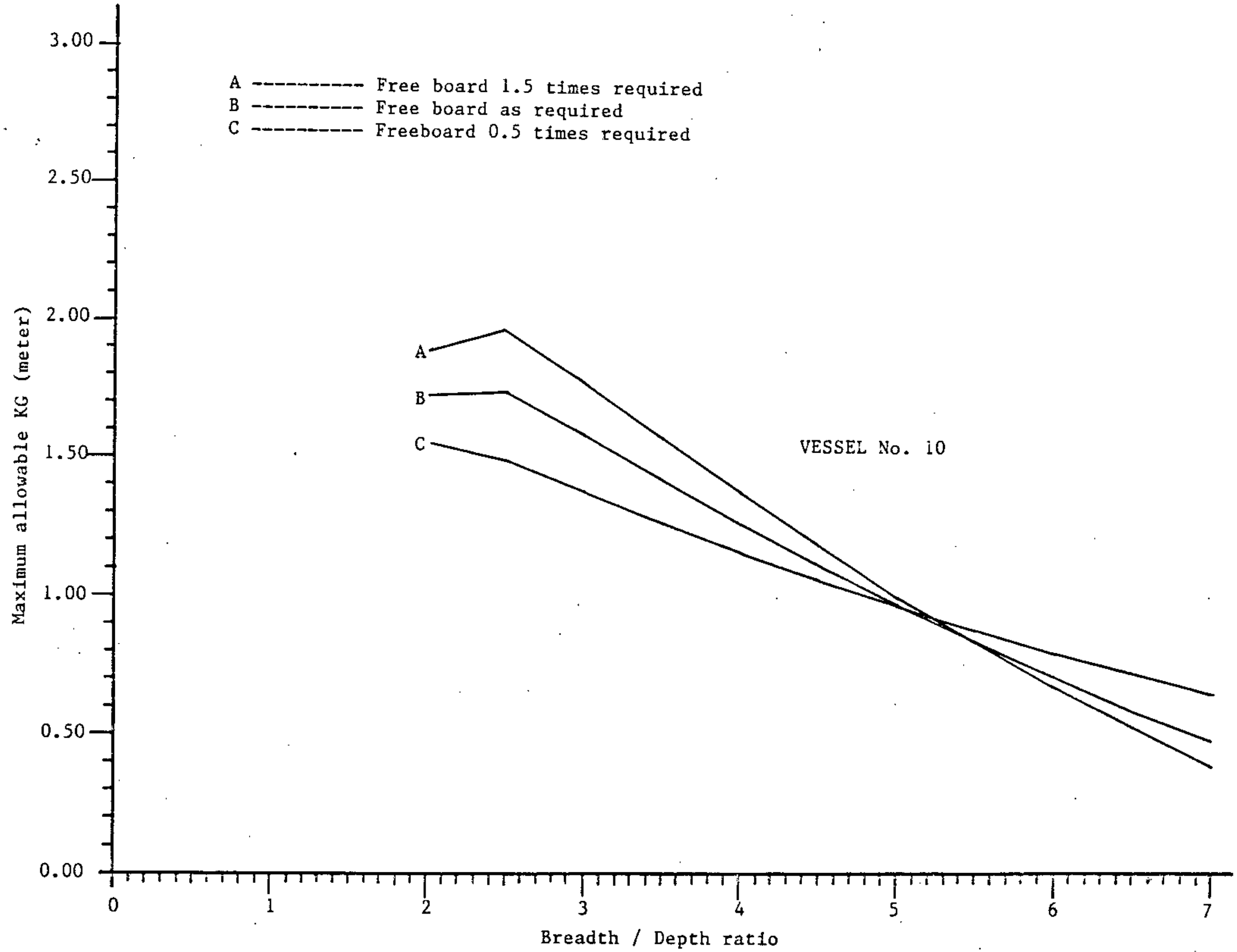

Fig. 4.43 : Variation of maximum allowable KG with B/D ratio at and around f_{min} displacement.

VESSEL No. 10

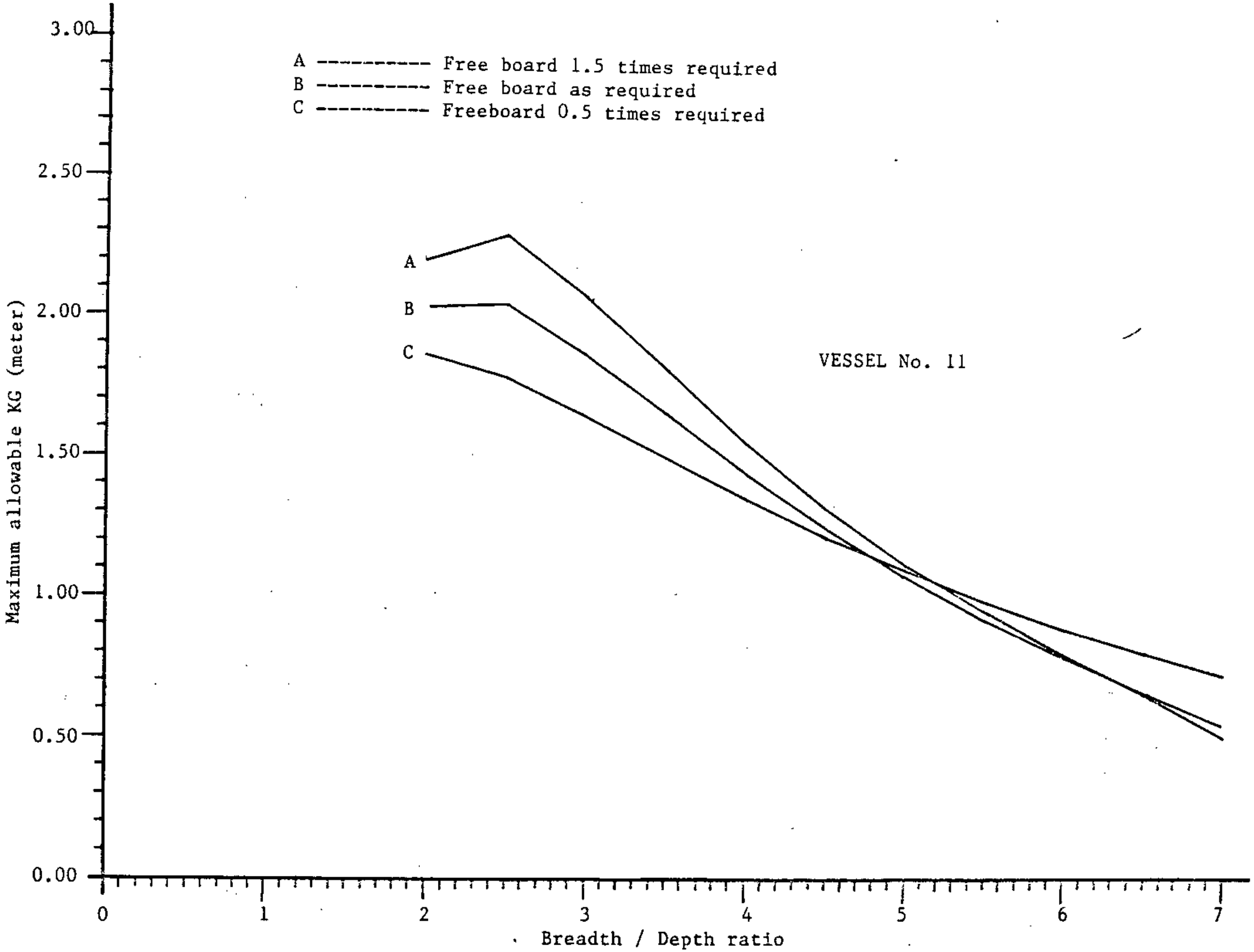

Fig. 4.44 : Variation of maximum allowable KG with B/D ratio at and around f_{min} displacement.
VESSEL No. 11

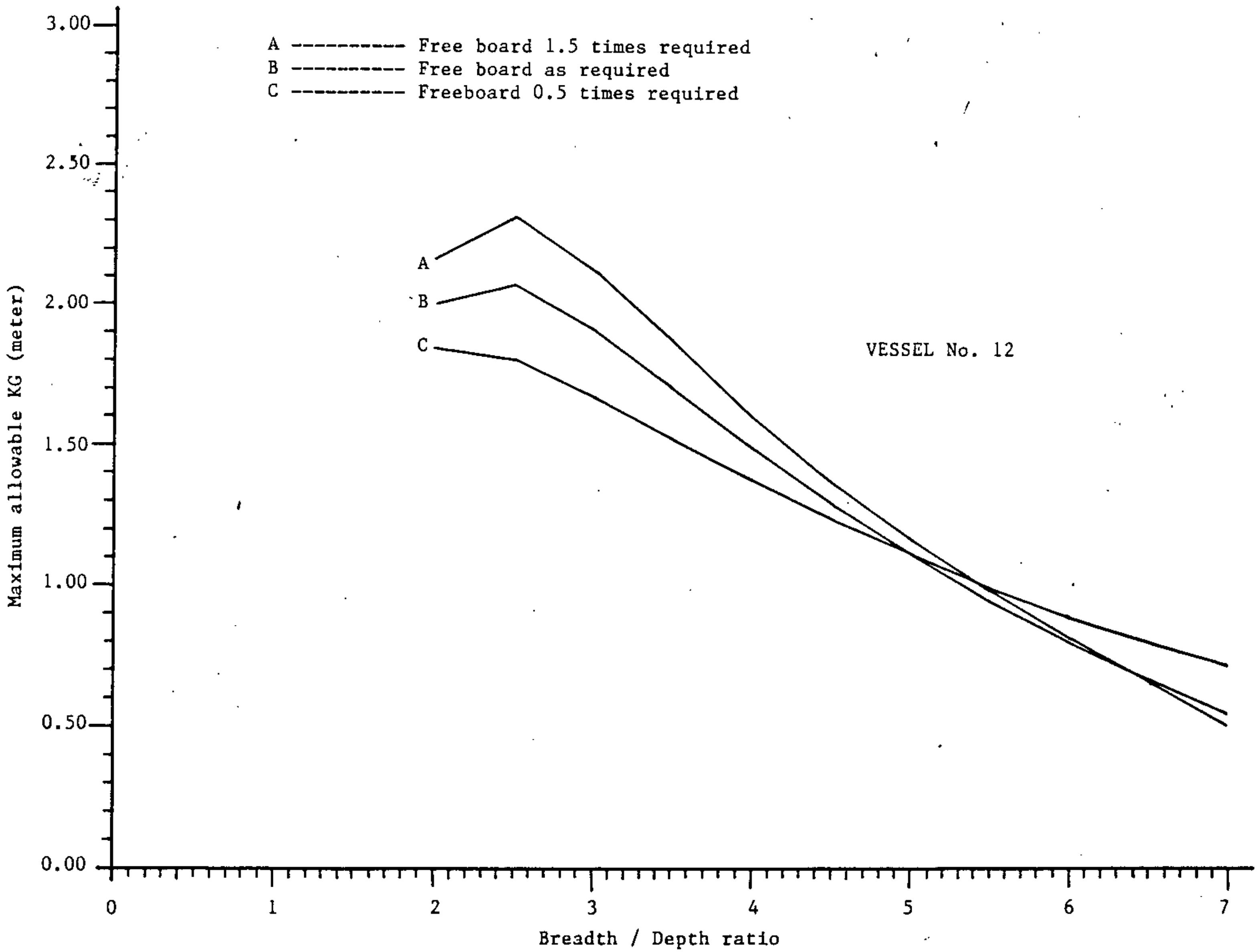

Fig. 4.45 : Variation of maximum allowable KG with B/D ratio at and around f_{min} displacement.
VESSEL No. 12

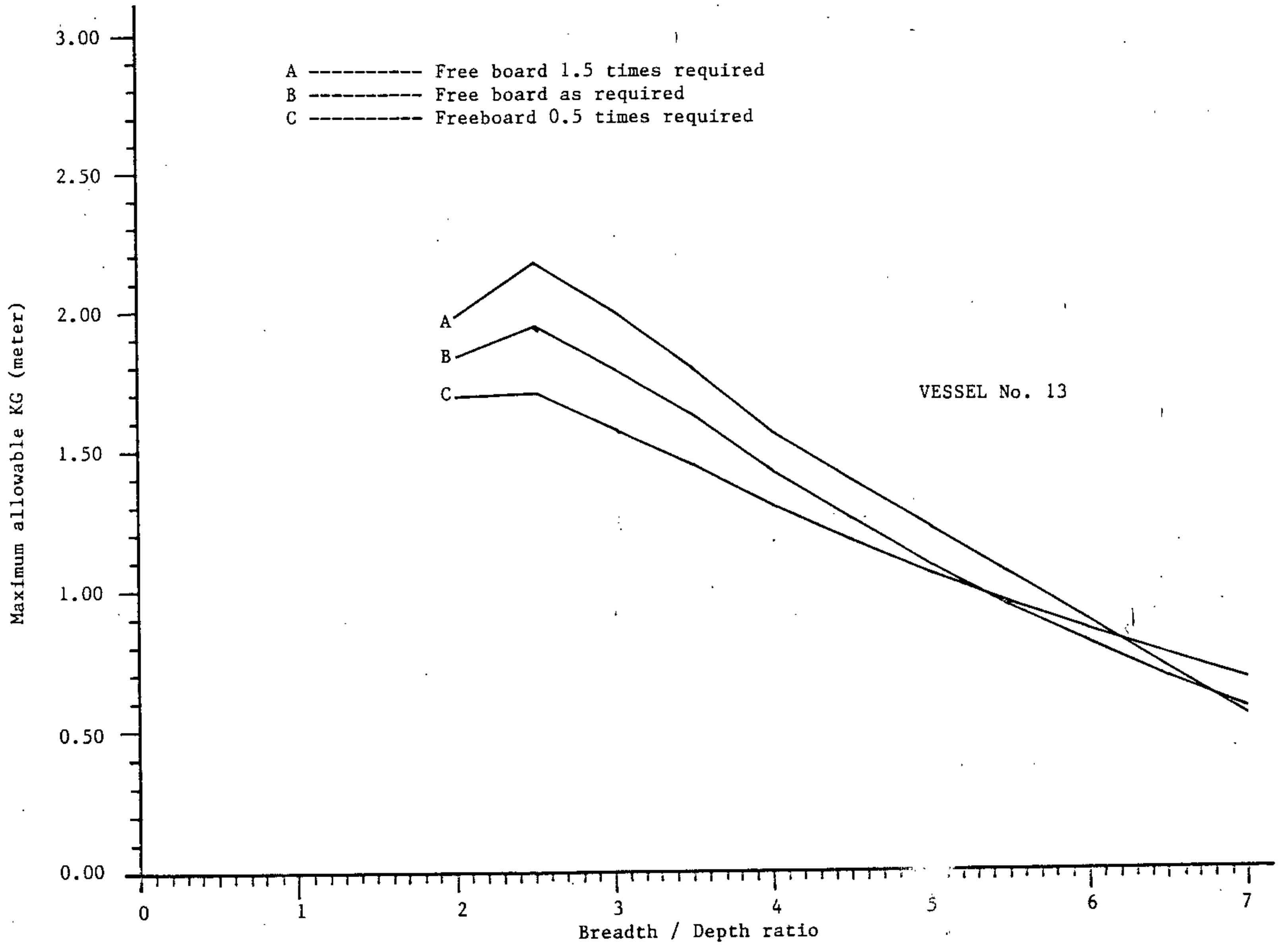

Fig. 4.46 : Variation of maximum allowable KG with B/D ratio at and around f_{min} displacement.

VESSEL No. 13

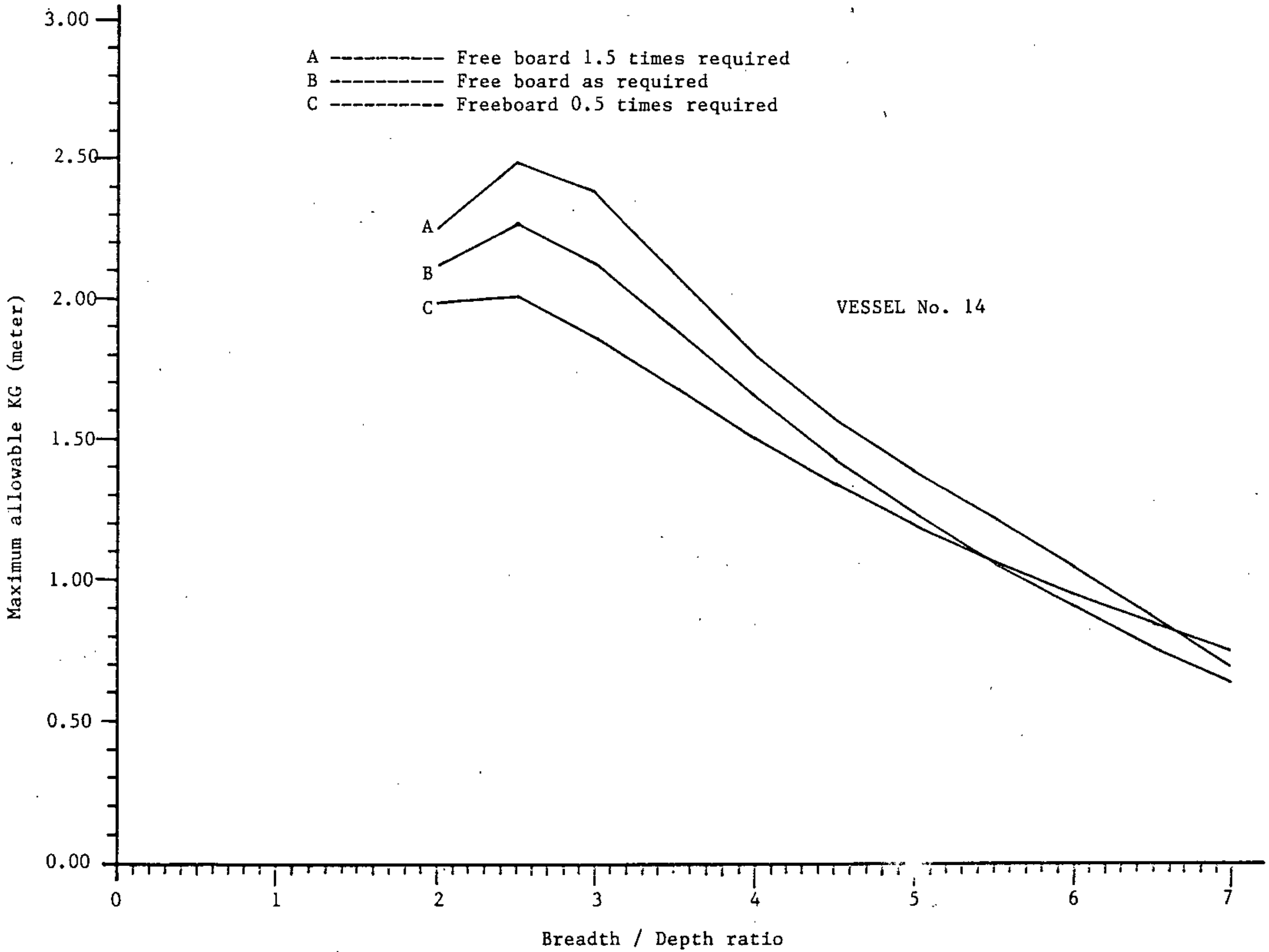

Fig. 4.47 : Variation of maximum allowable KG with B/D ratio at and around f_{min} displacement.

VESSEL No. 14

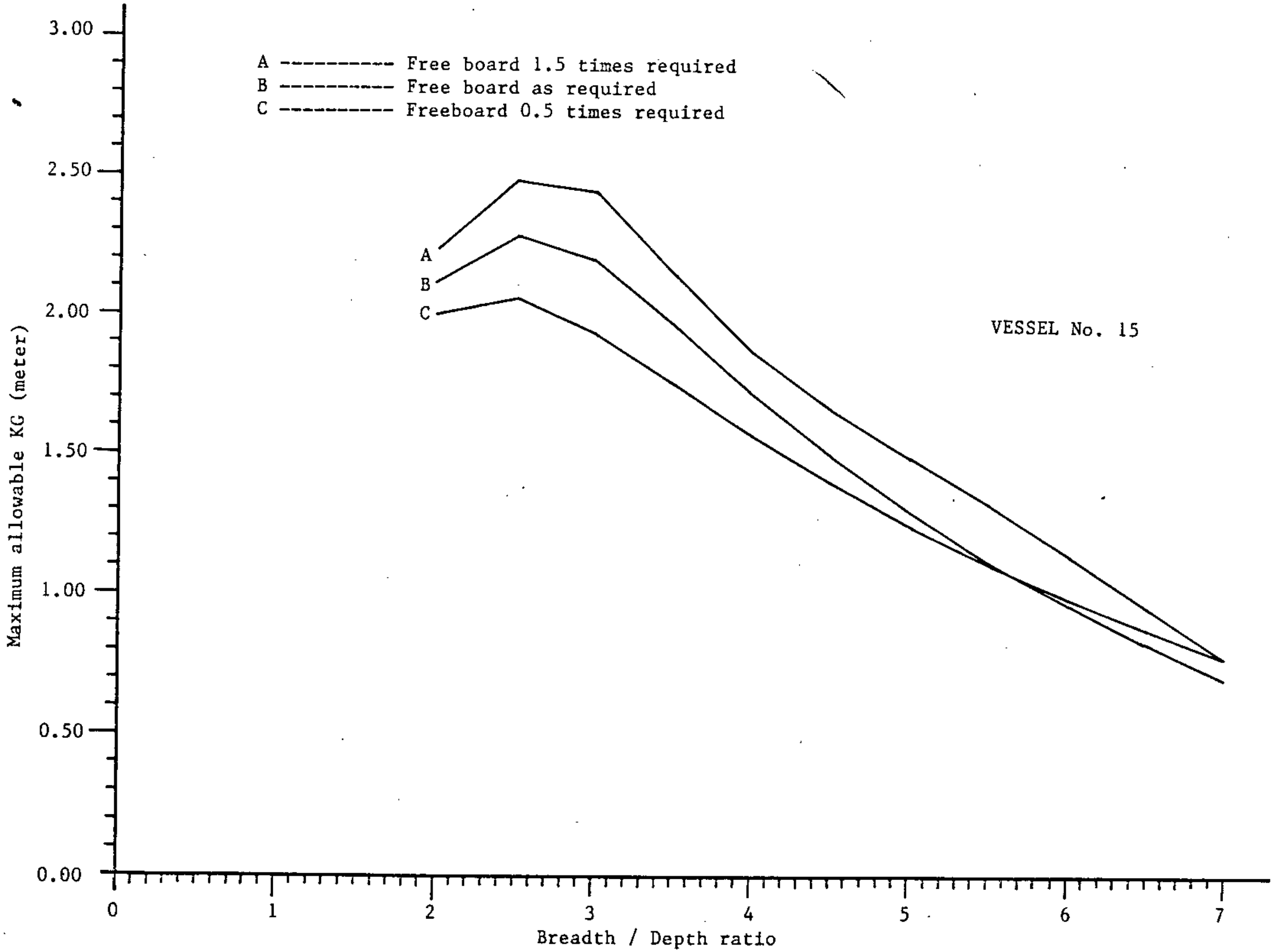

Fig. 4.48 : Variation of maximum allowable KG with B/D ratio at and around f_{min} displacement.

VESSEL No. 15

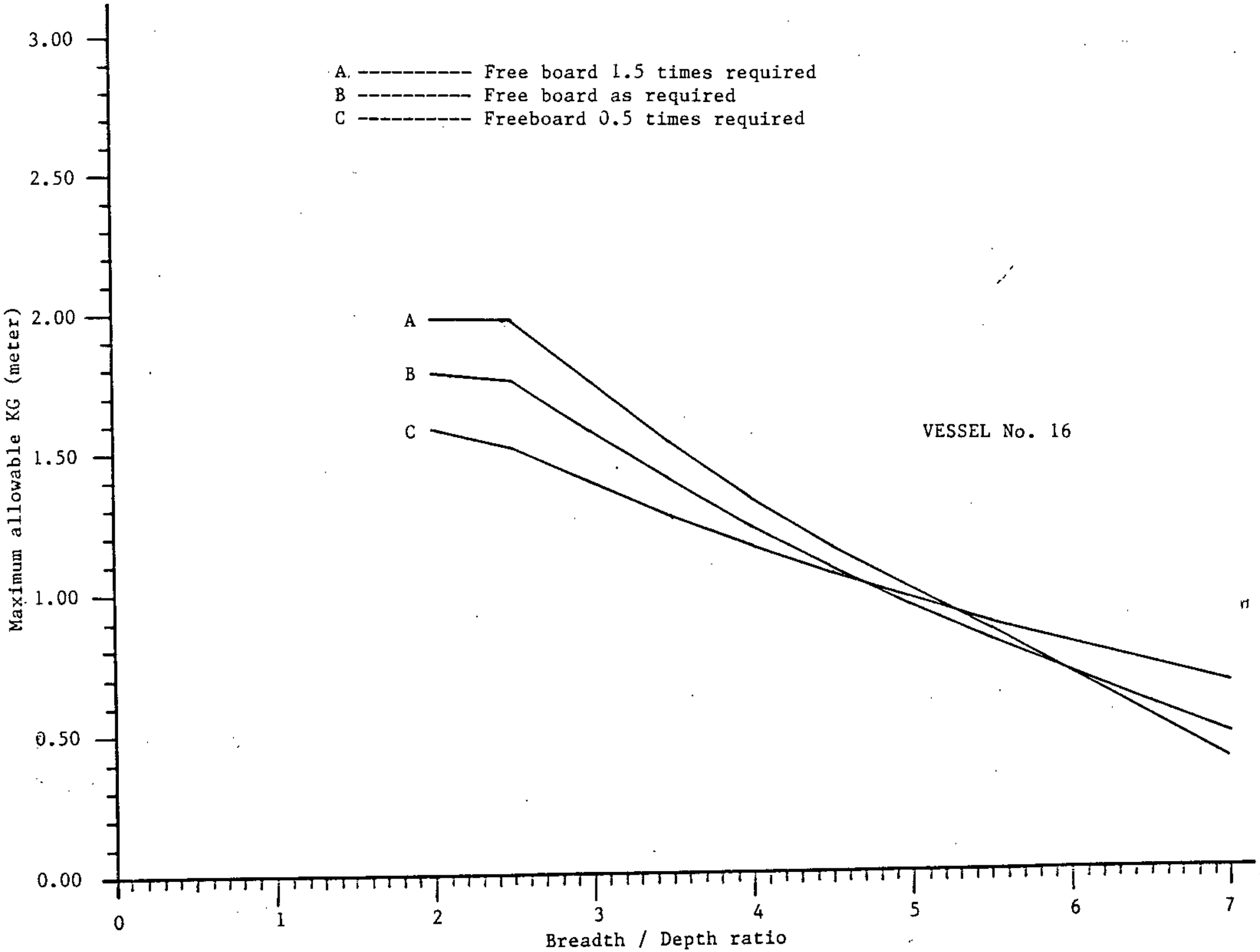

Fig. 4.49 : Variation of maximum allowable KG with B/D ratio at and around f_{min} displacement.
VESSEL No. 16

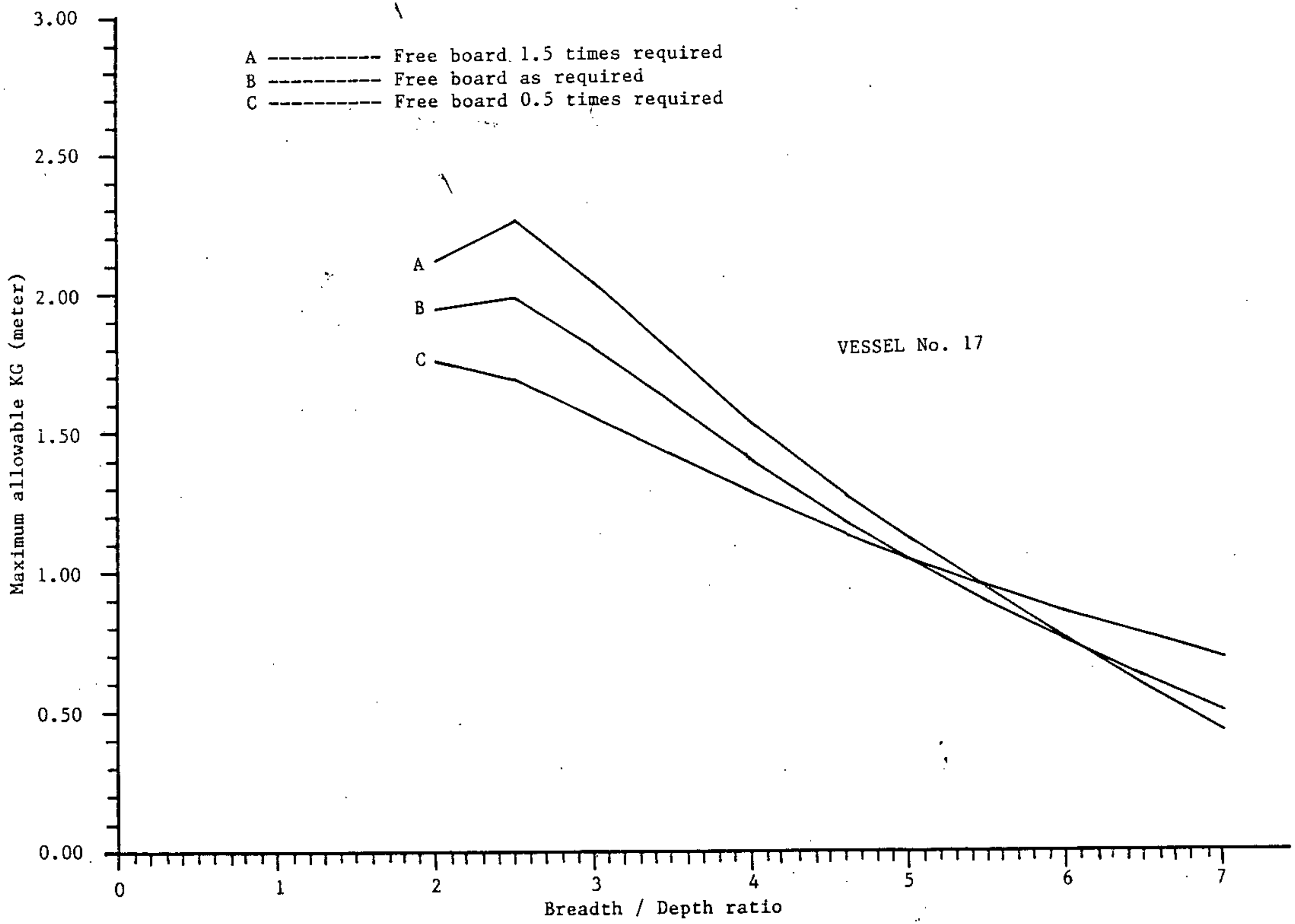

Fig. 4.50 : Variation of maximum allowable KG with B/D ratio at and around f_{min} displacement.
VESSEL No. 17

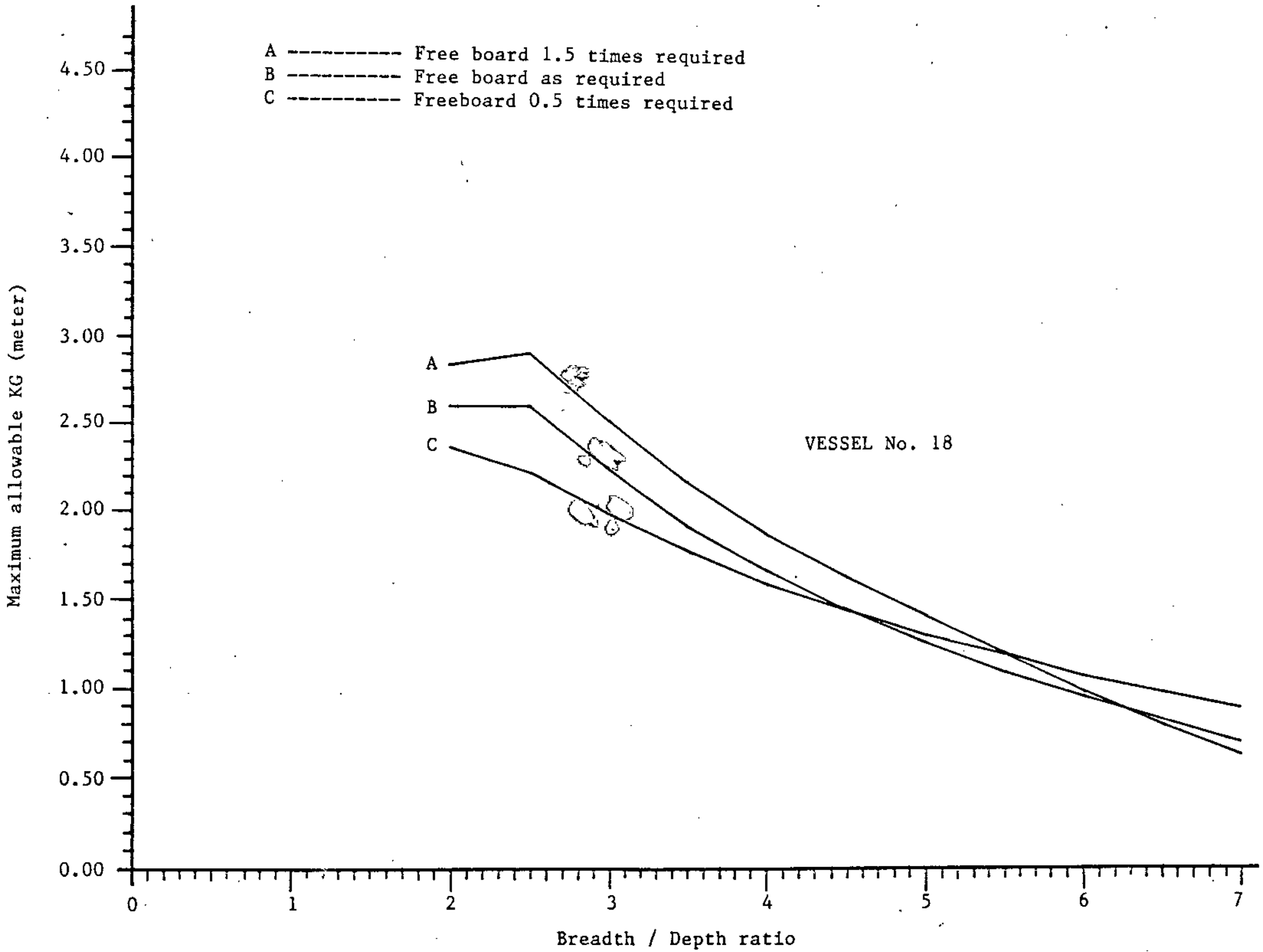

Fig. 4.51 : Variation of maximum allowable KG with B/D ratio at and around f_{min} displacement.
VESSEL No. 18

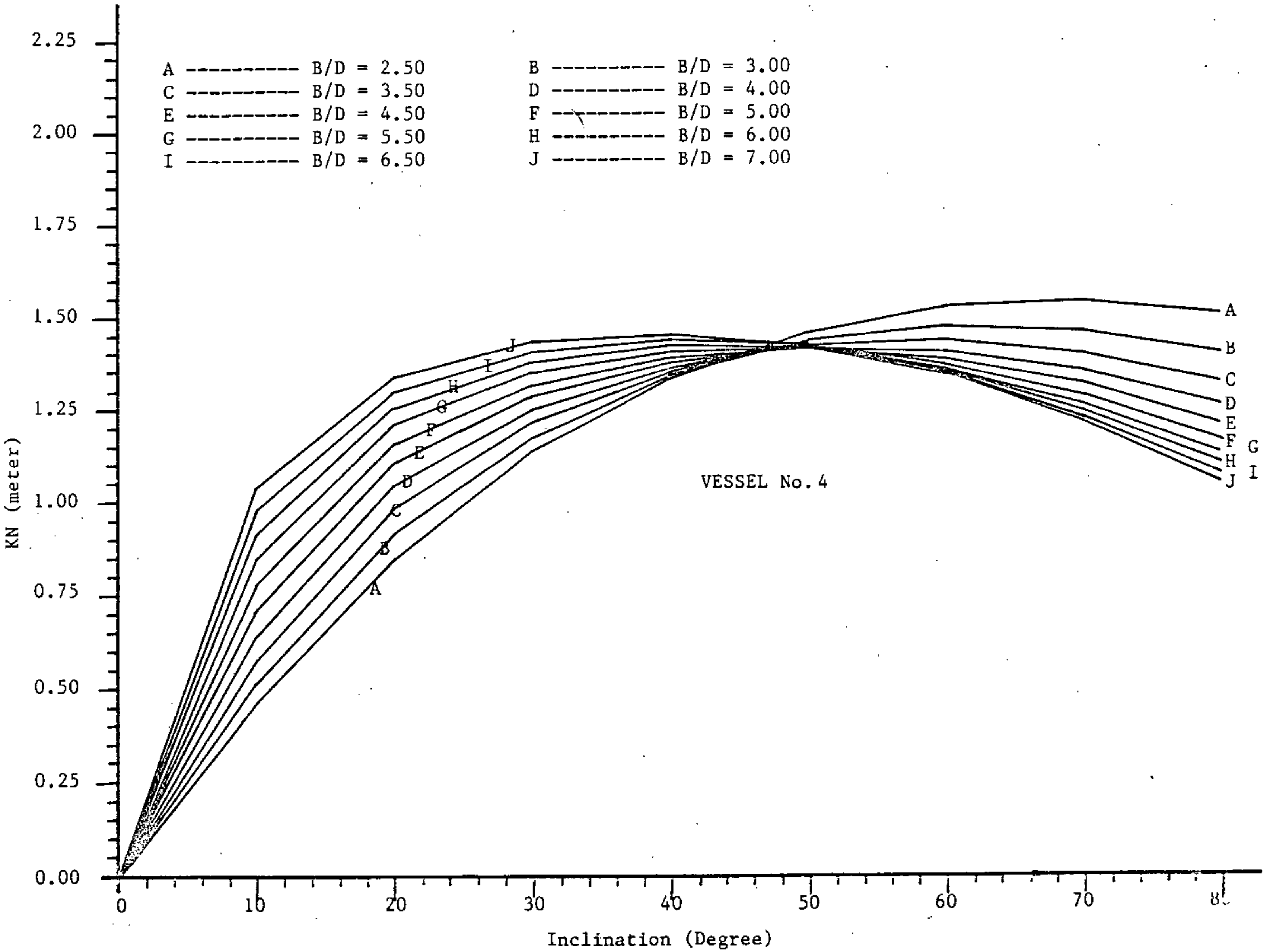

Fig. 4.52 : KN diagrams at different Breadth / Depth ratios.
VESSEL No. 4

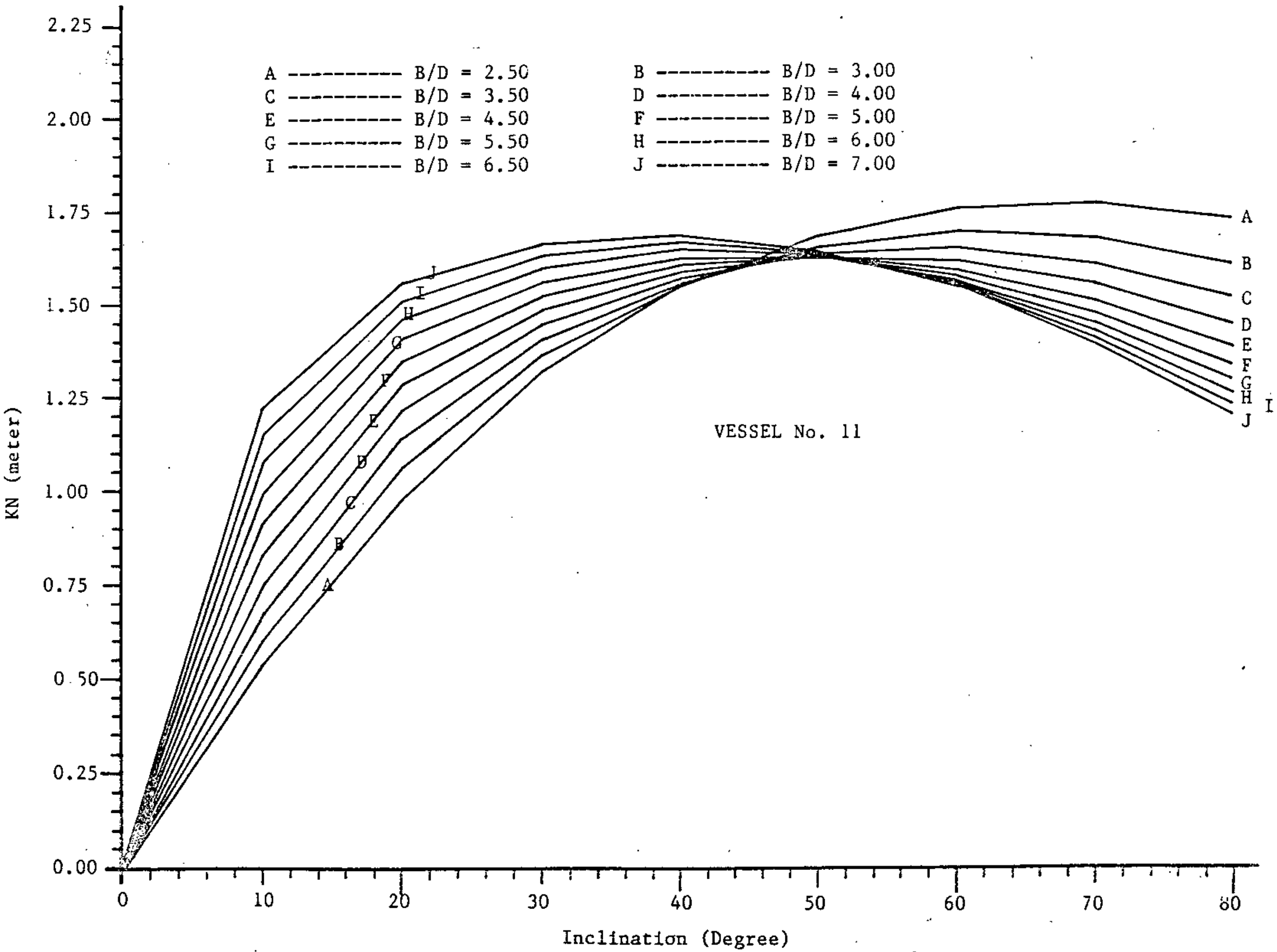

Fig. 4.53 : KN diagrams at different Breadth / Depth ratios.
VESSEL No. 11

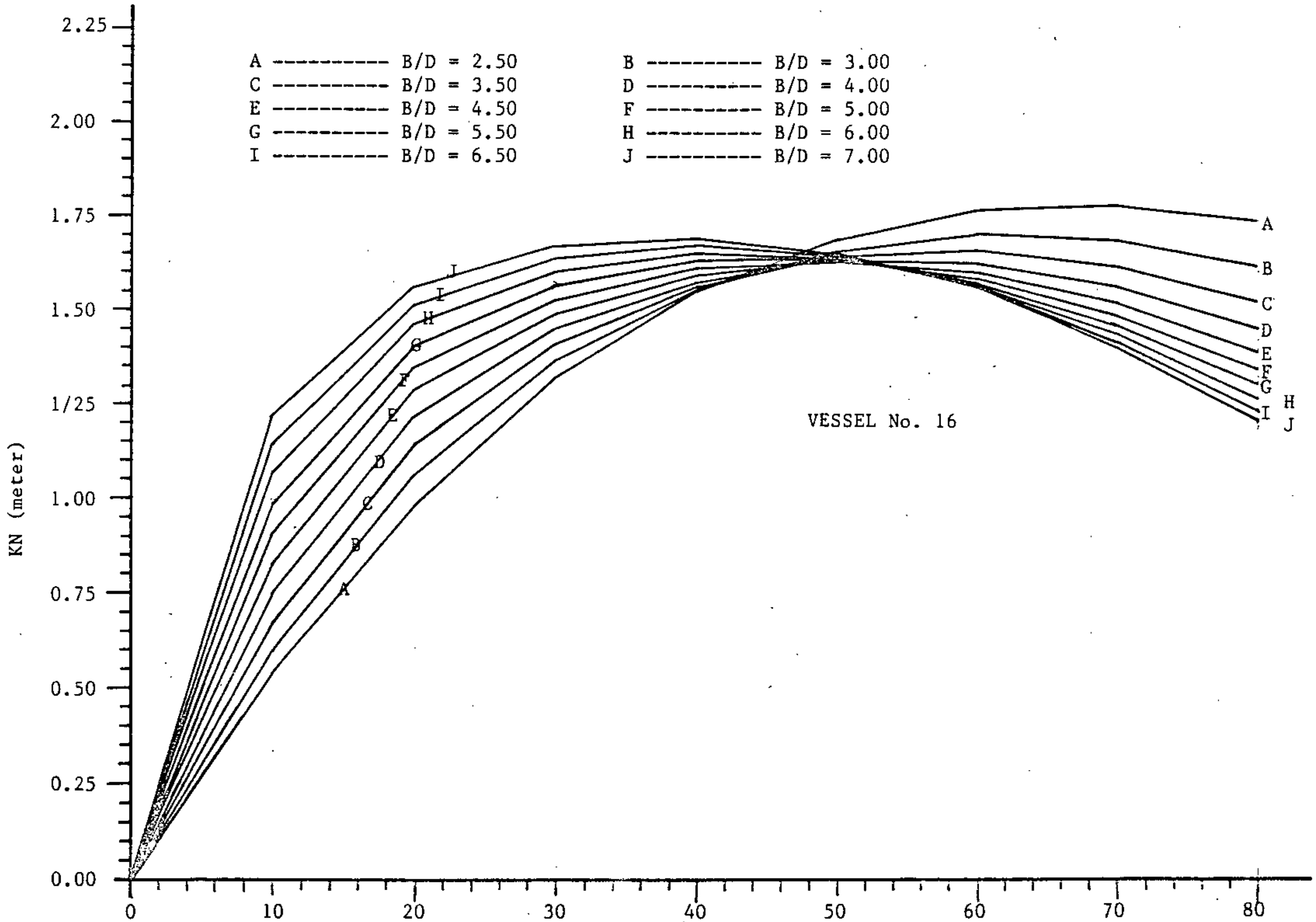

Fig. 4.54 : KN diagrams at different Breadth / Depth ratios.

VESSEL No. 16

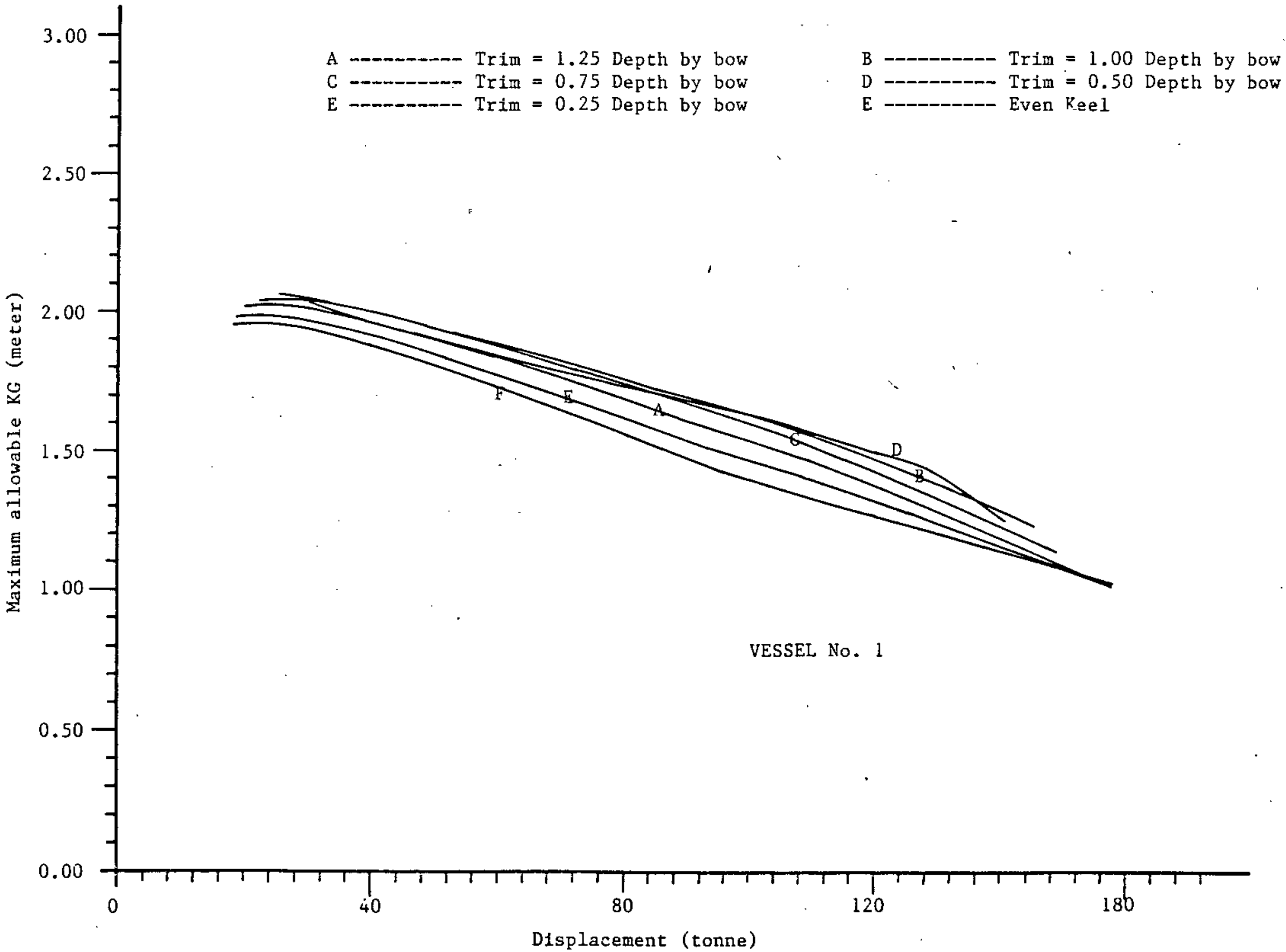

Fig. 4.55 : Variation of maximum allowable KG with displacement and trim by bow.
VESSEL No. 1

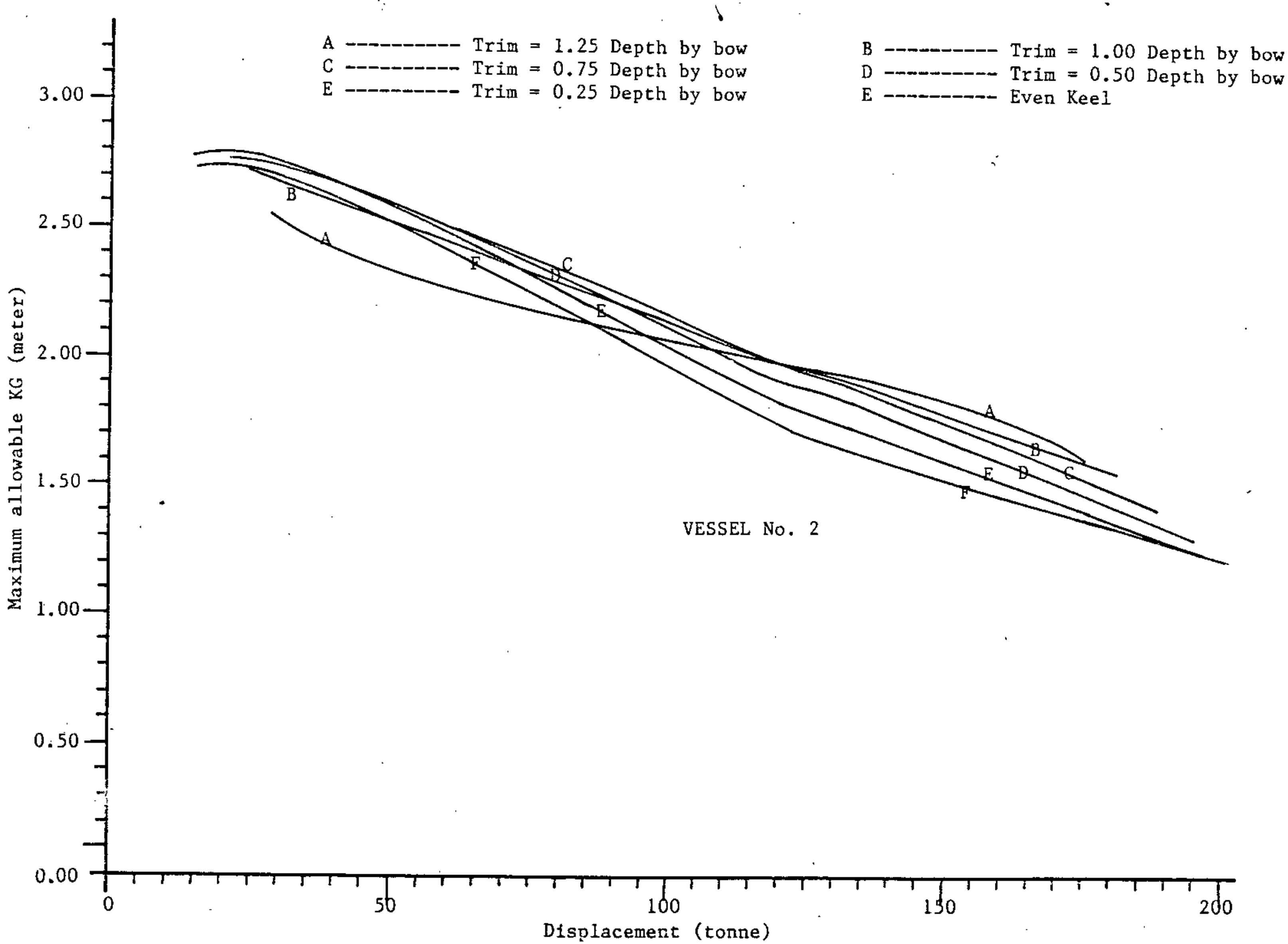

Fig. 4.56 : Variation of maximum allowable KG with displacement and trim by bow.

VESSEL No. 2

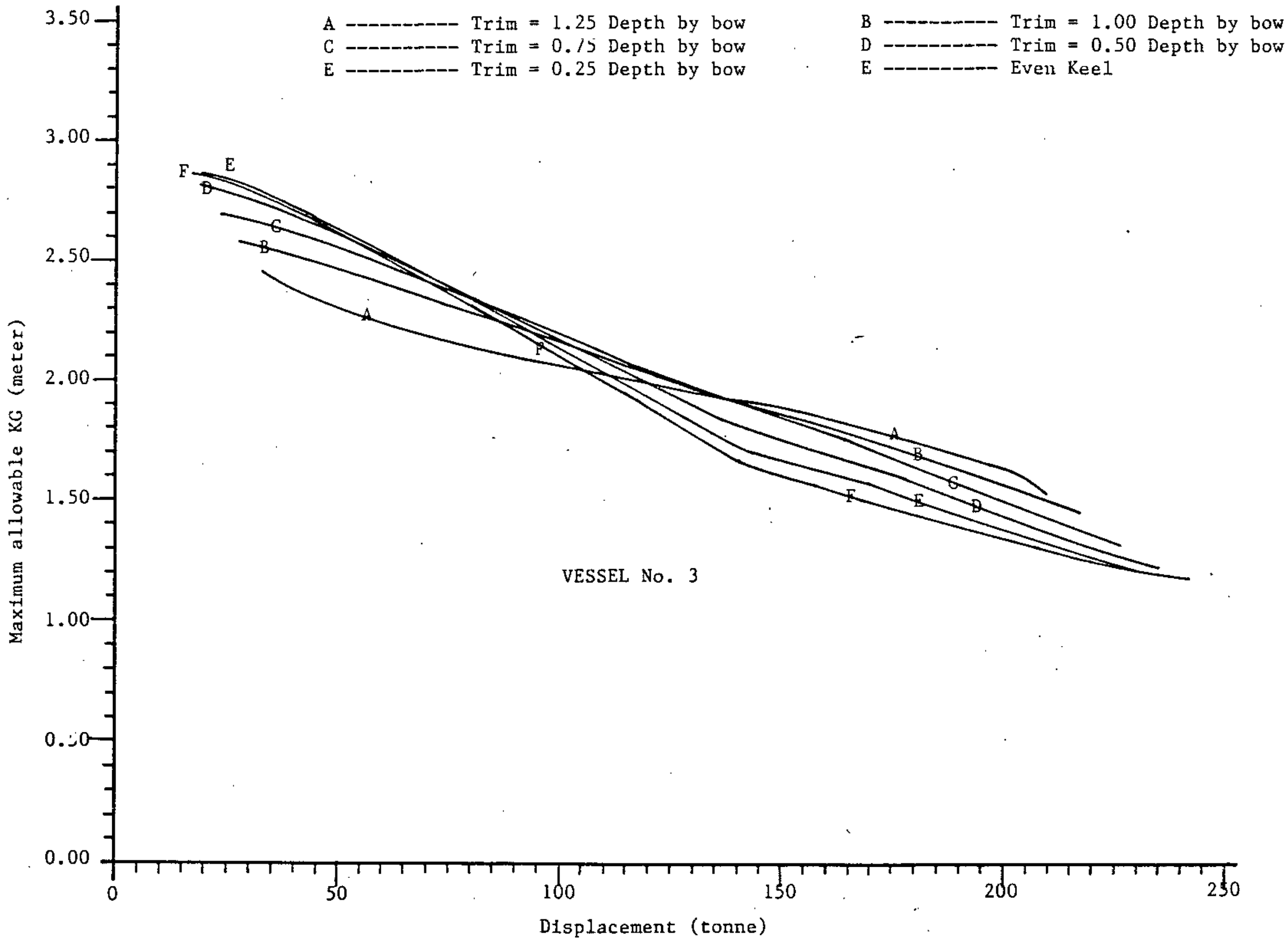

Fig. 4.57 : Variation of maximum allowable KG with displacement and trim by bow.
VESSEL No. 3

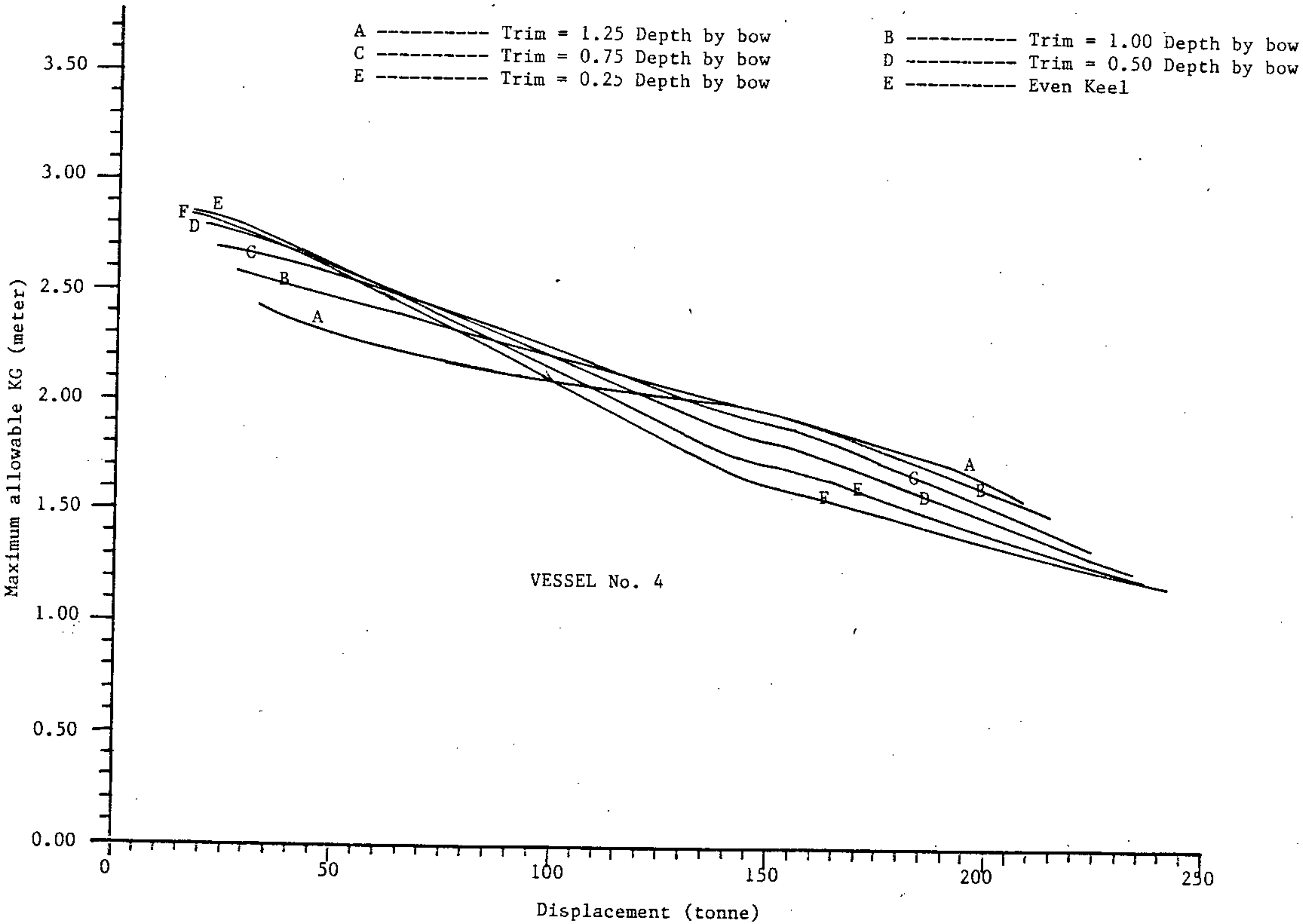

Fig. 4.58 : Variation of maximum allowable KG with displacement and trim by bow.
VESSEL No. 4

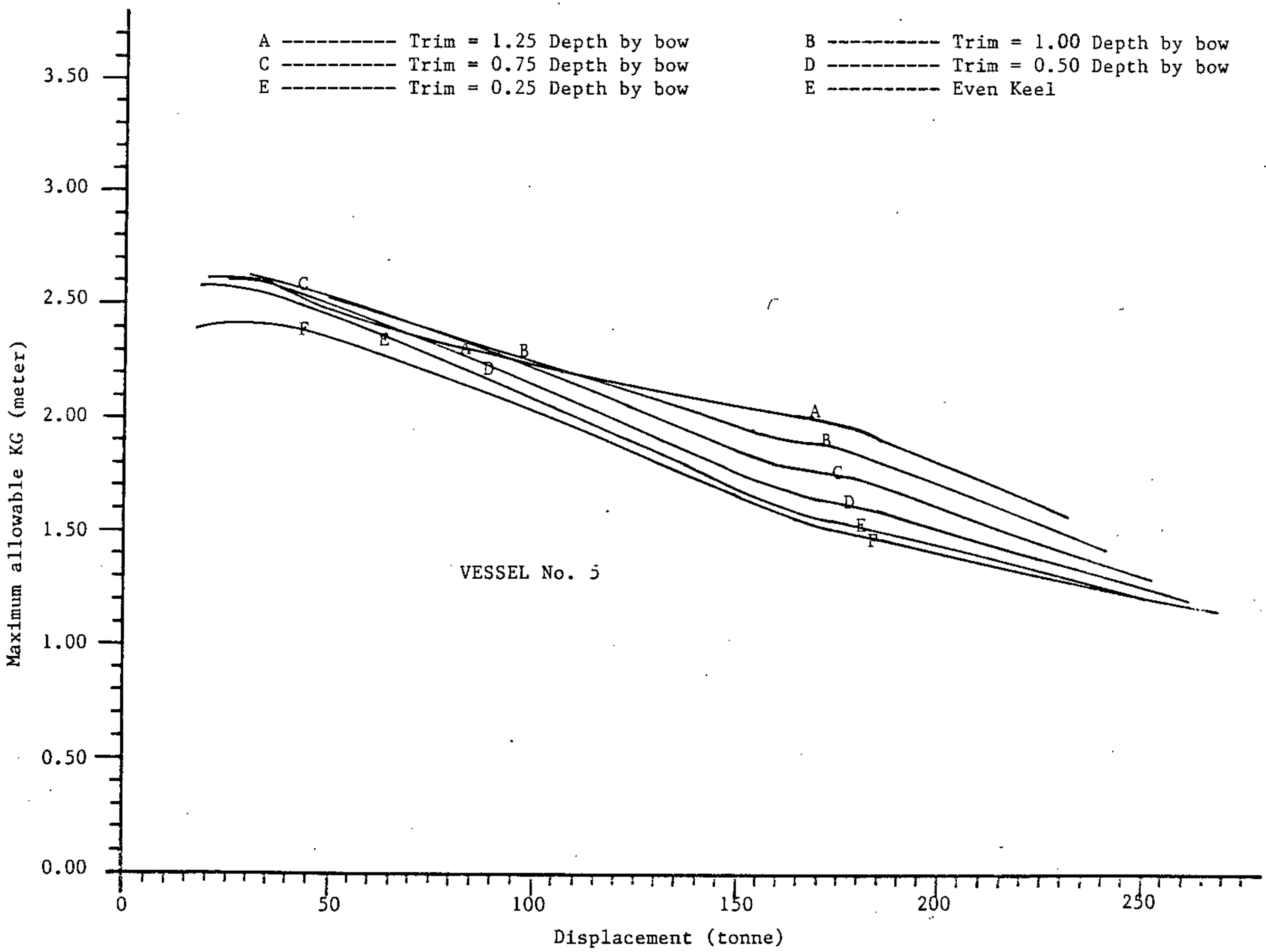

Fig. 4.59 : Variation of maximum allowable KG with displacement and trim by bow.

VESSEL No. 5

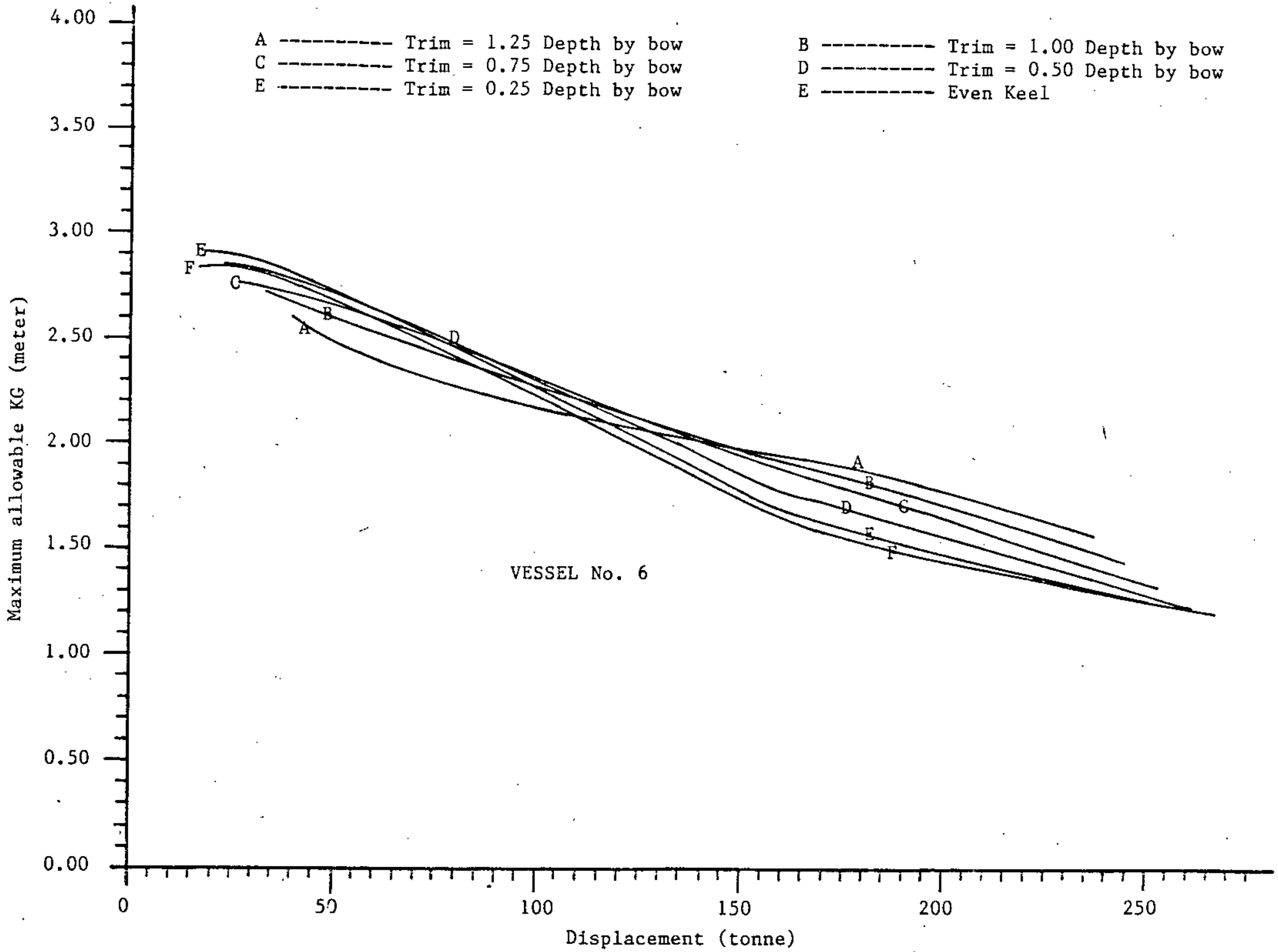

Fig. 4.60 : Variation of maximum allowable KG with displacement and trim by bow.

VESSEL No. 6

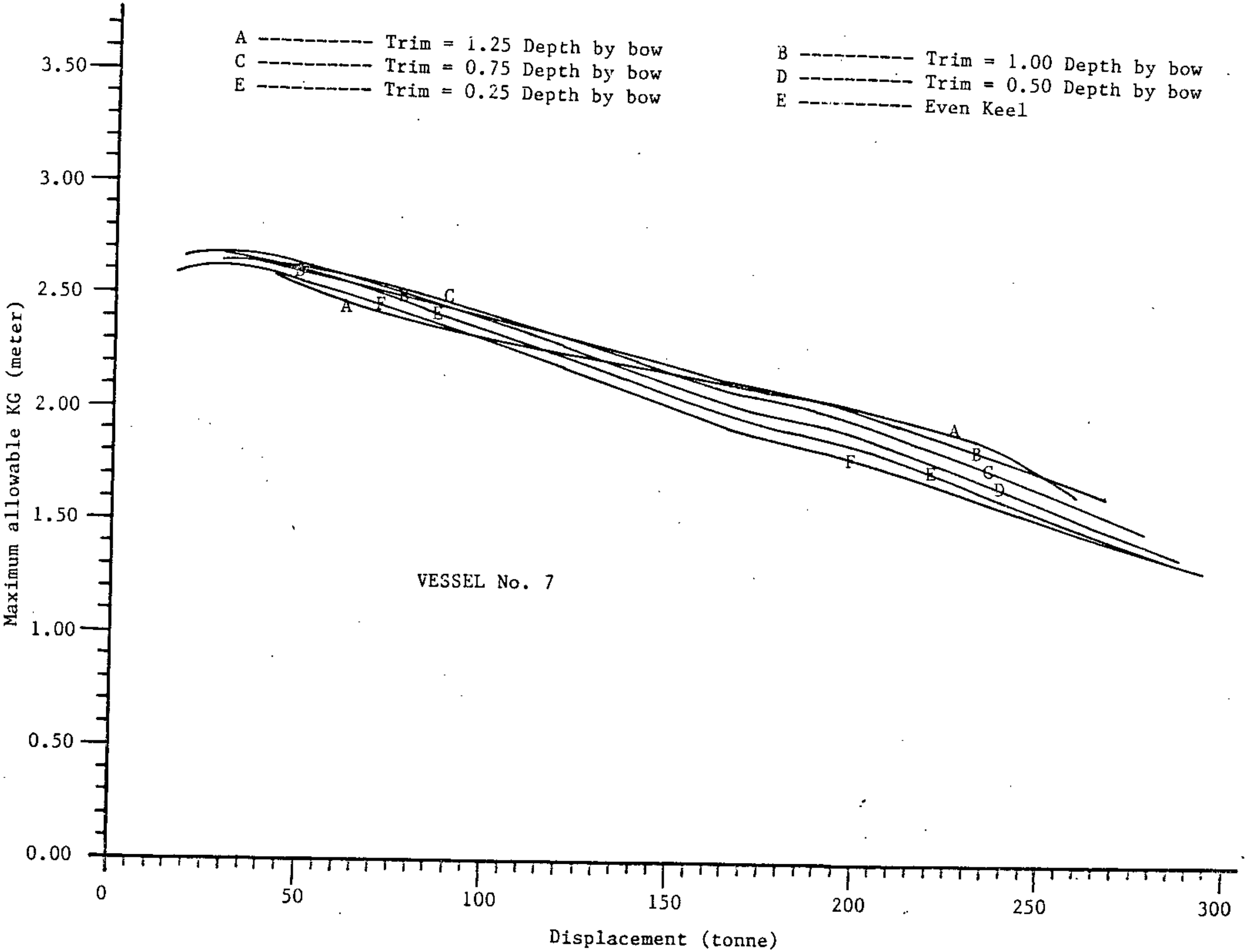

Fig. 4.61 : Variation of maximum allowable KG with displacement and trim by bow.
VESSEL No. 7

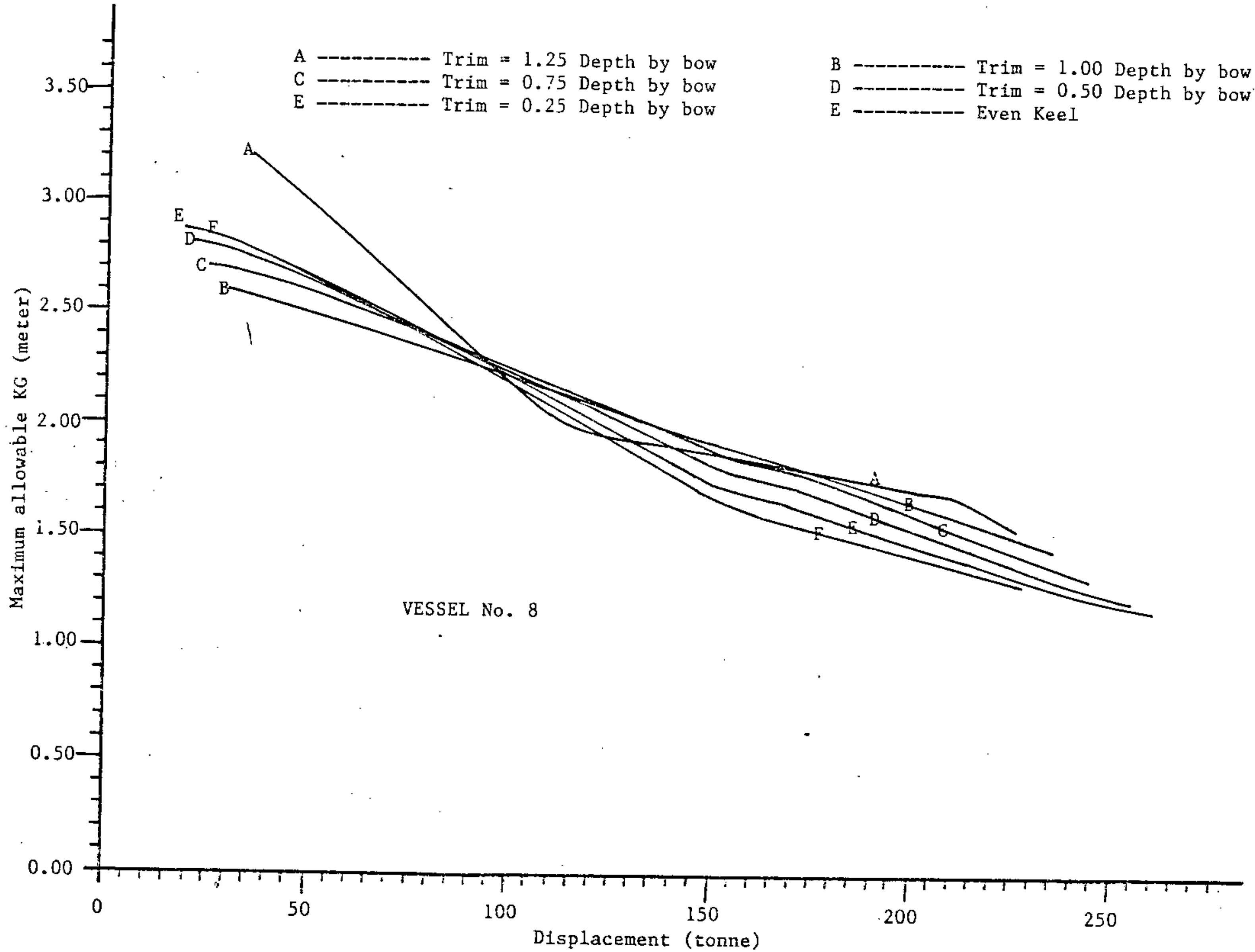

Fig. 4.62 : Variation of maximum allowable KG with displacement and trim by bow.
VESSEL No. 8

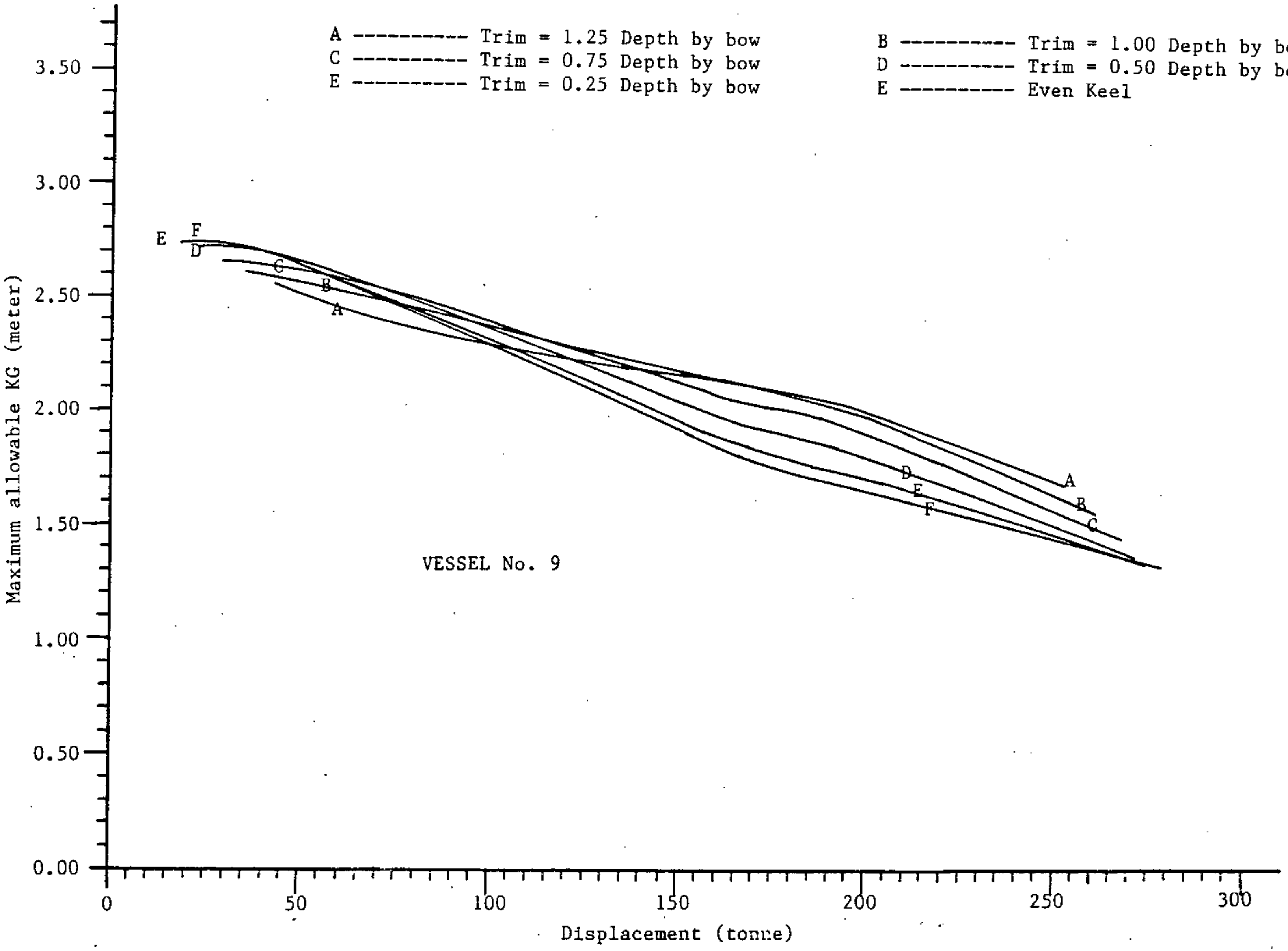

Fig. 4.63 : Variation of maximum allowable KG with displacement and trim by bow.
VESSEL No. 9

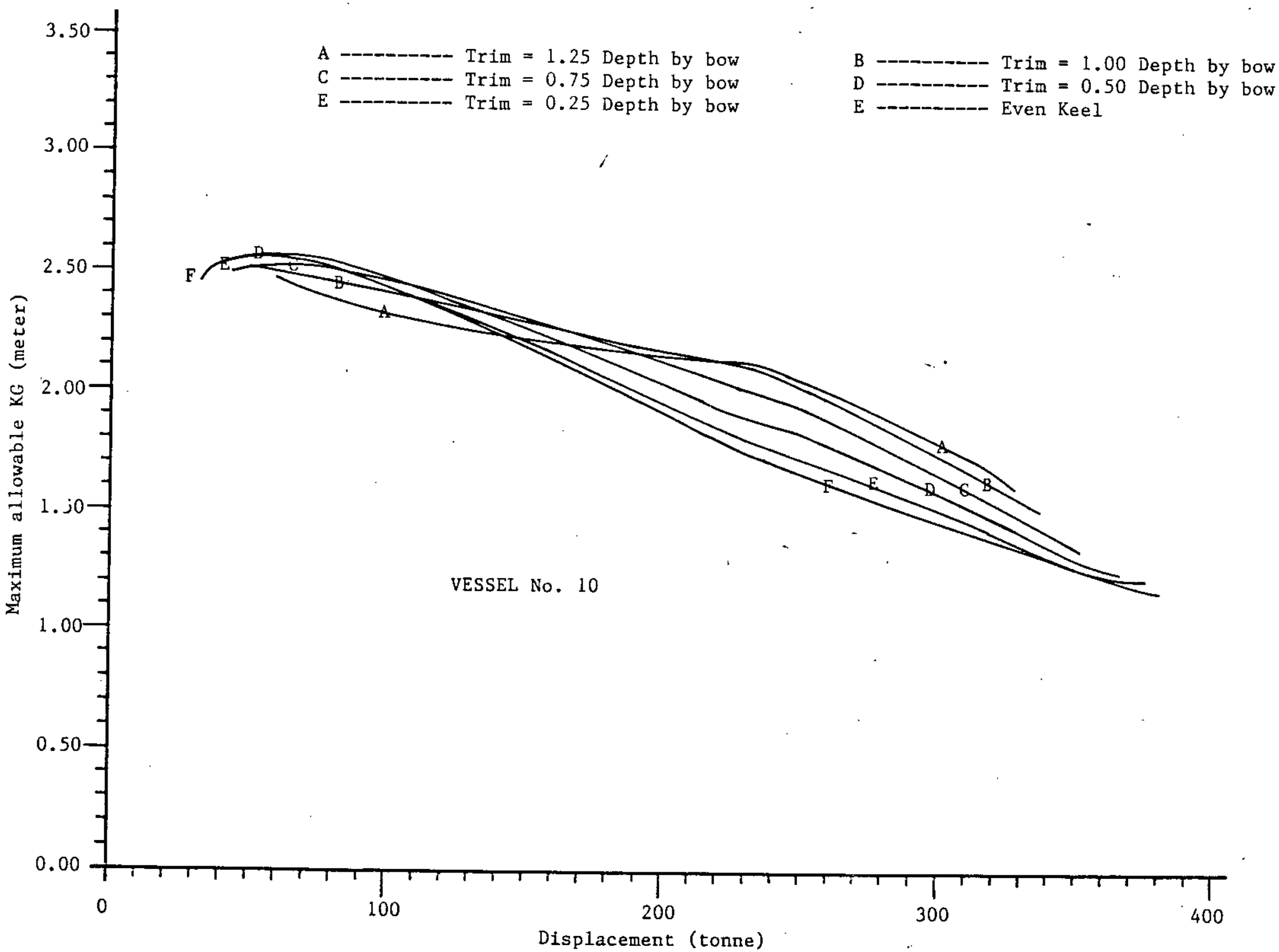

Fig. 4.64 : Variation of maximum allowable KG with displacement and trim by bow.
VESSEL No. 10

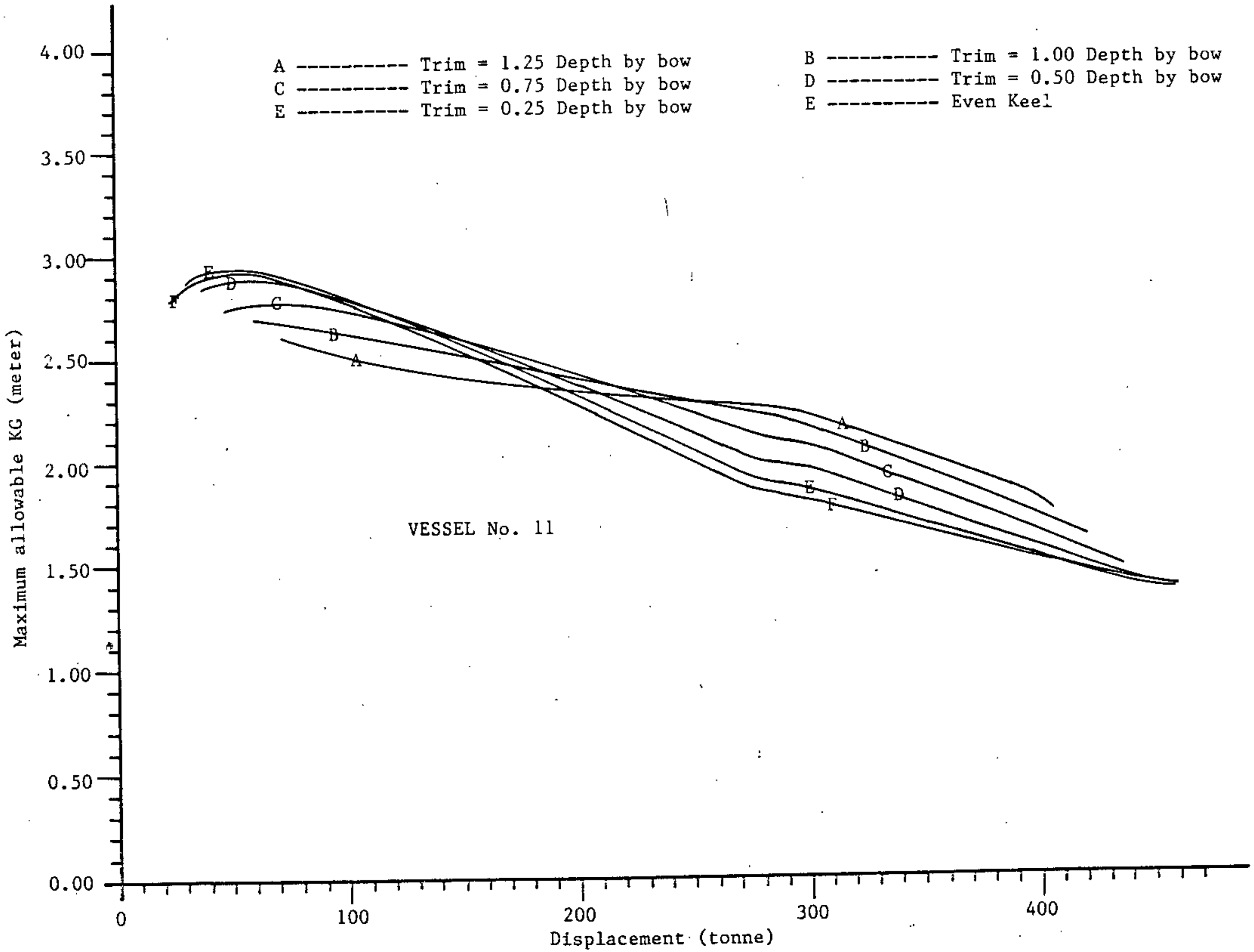

Fig. 4.65 : Variation of maximum allowable KG with displacement and trim by bow.
VESSEL No. 11

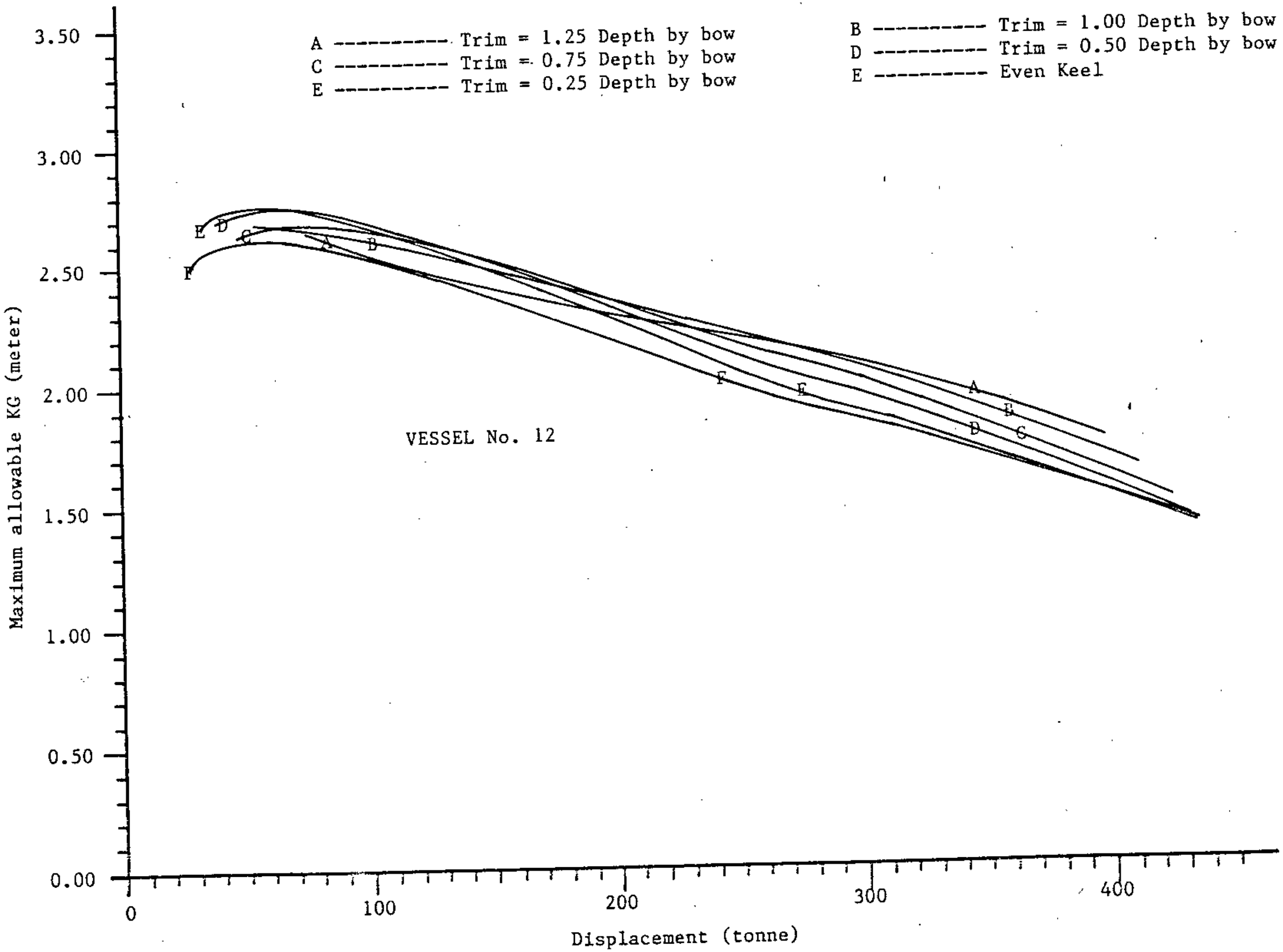

Fig. 4.66 : Variation of maximum allowable KG with displacement and trim by bow.
VESSEL No. 12

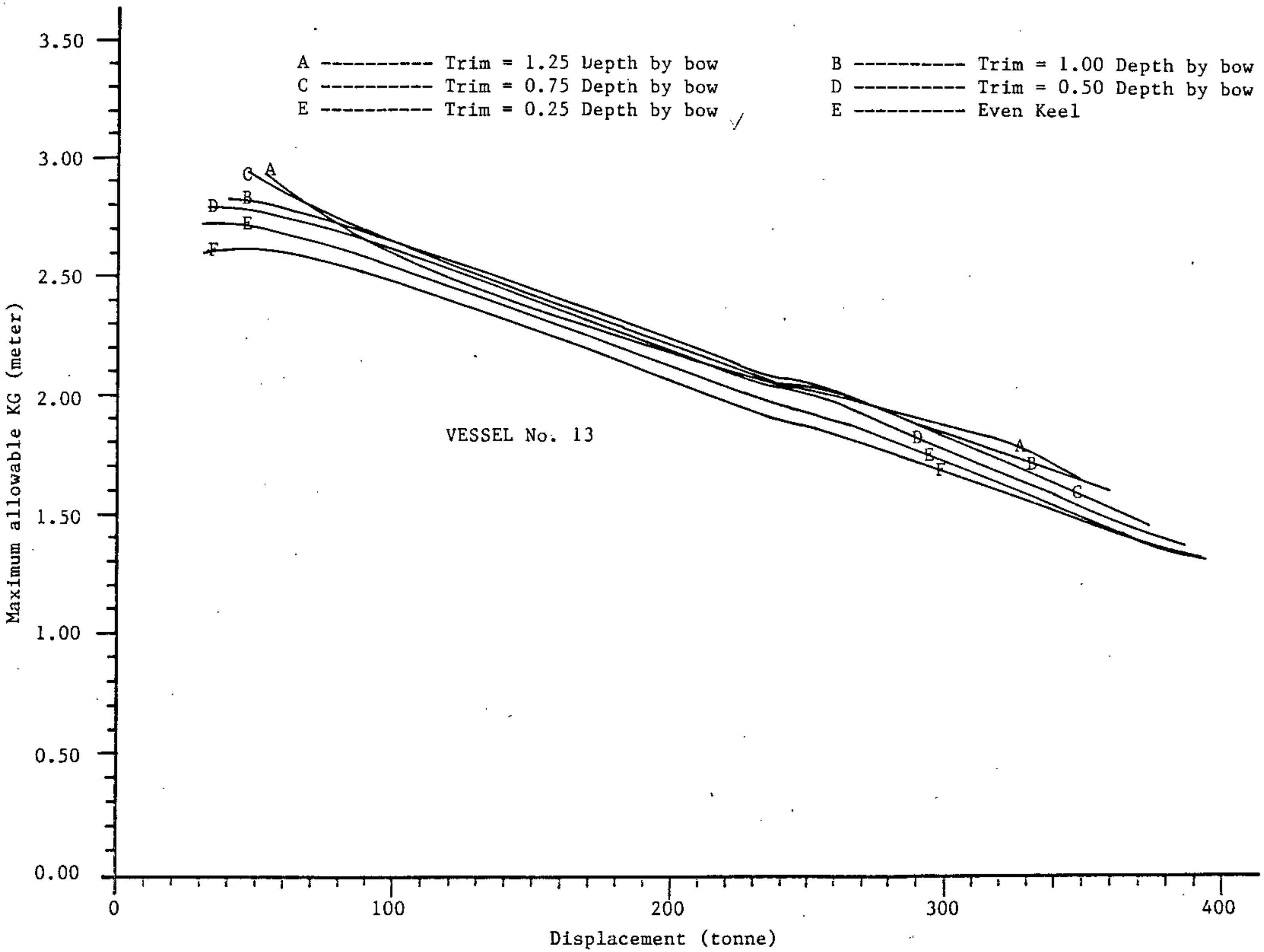

Fig. 4.67 : Variation of maximum allowable KG with displacement and trim by bow.
VESSEL No. 13

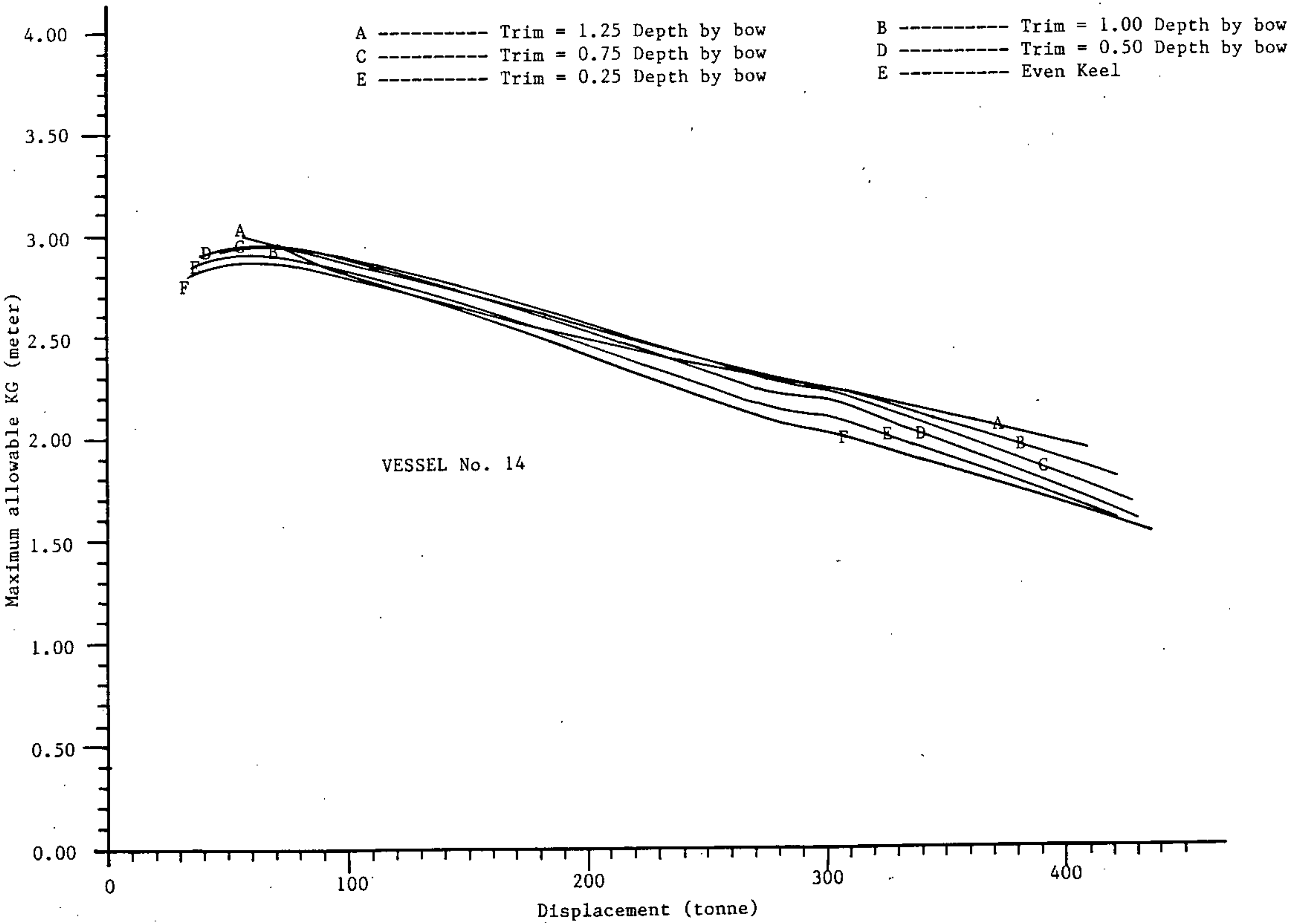

Fig. 4.68 : Variation of maximum allowable KG with displacement and trim by bow.

VESSEL No. 14

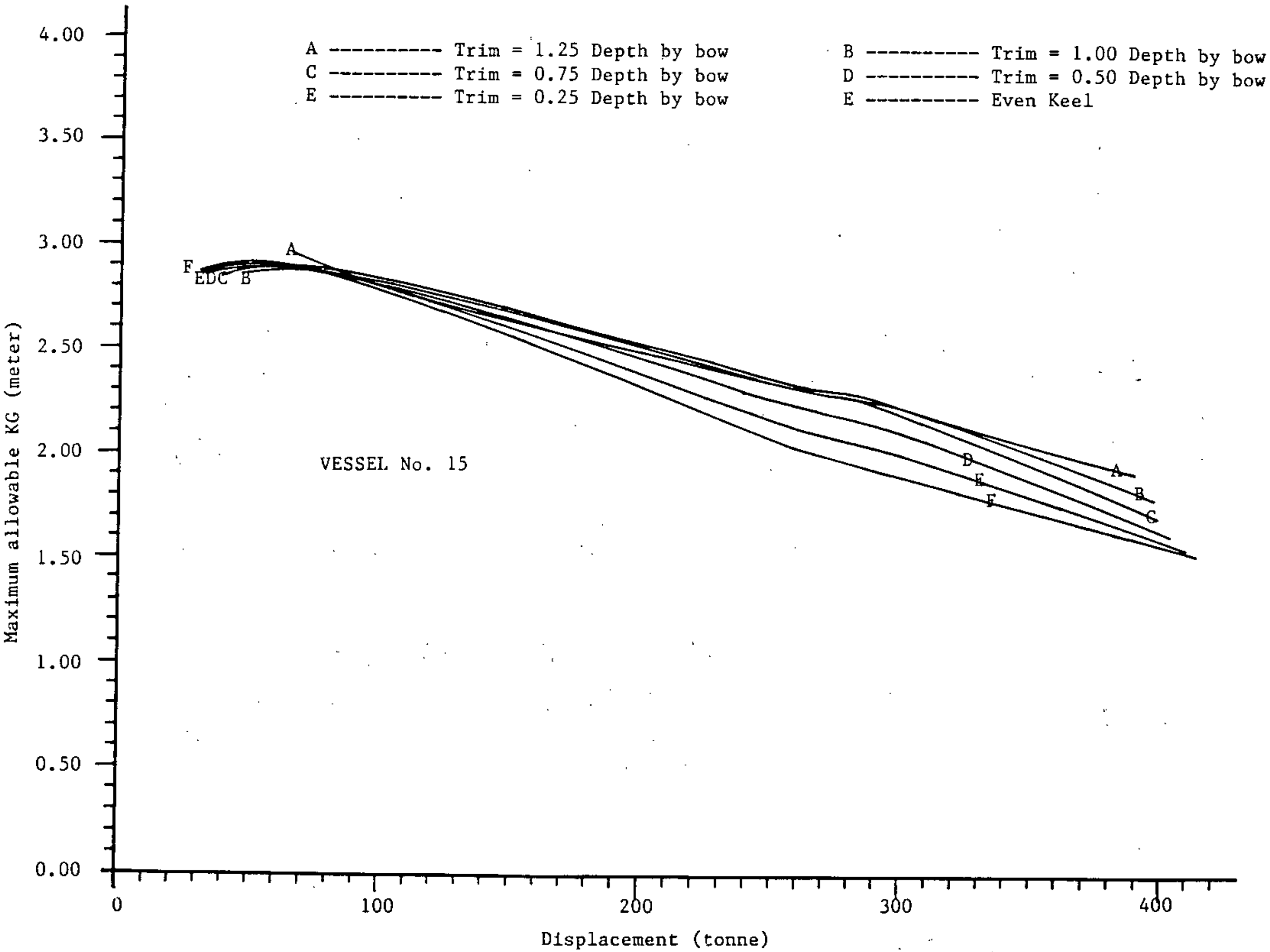

Fig. 4.69 : Variation of maximum allowable KG with displacement and trim by bow.

VESSEL No. 15

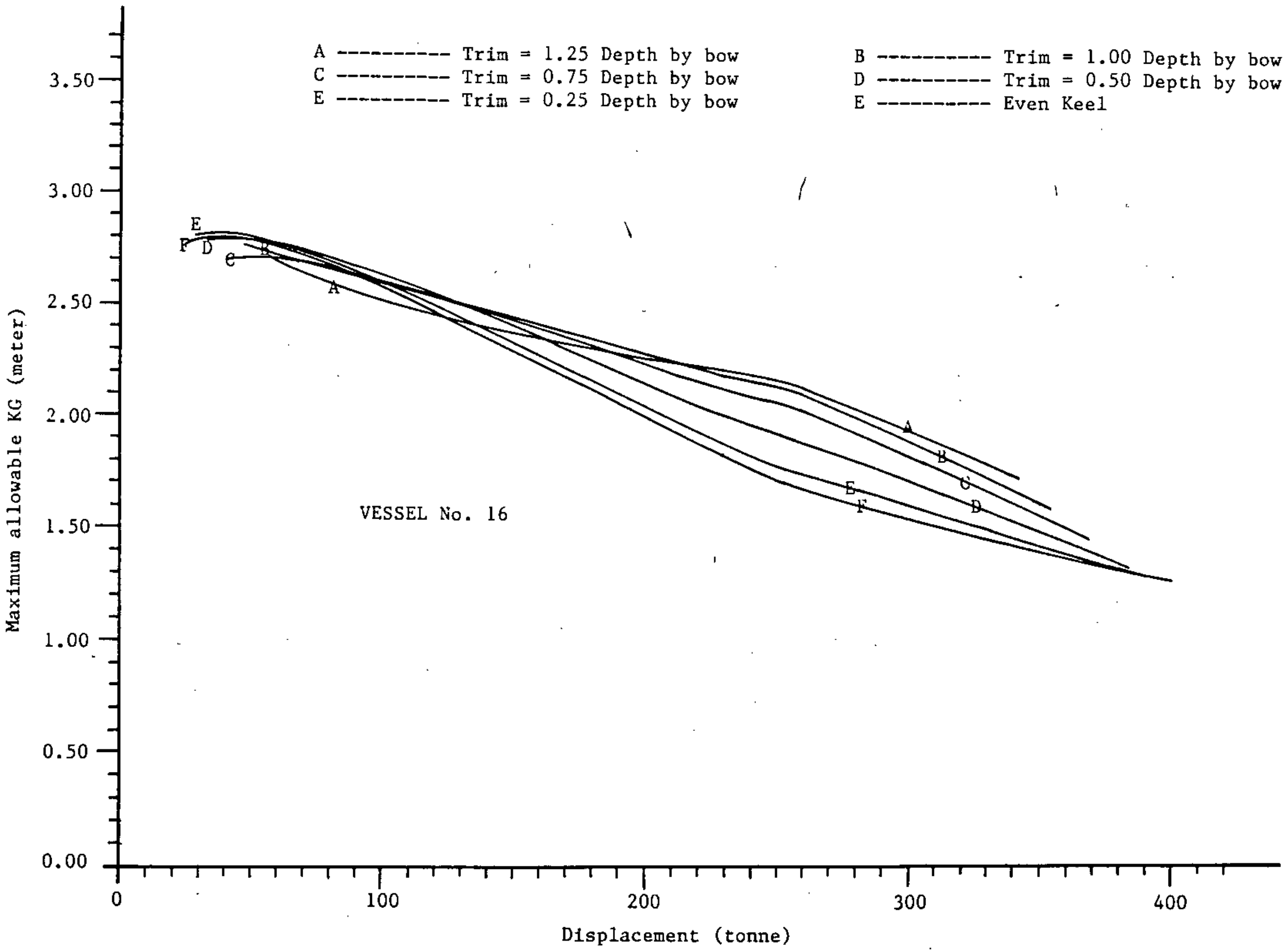

Fig. 4.70 : Variation of maximum allowable KG with displacement and trim by bow.
VESSEL No. 16

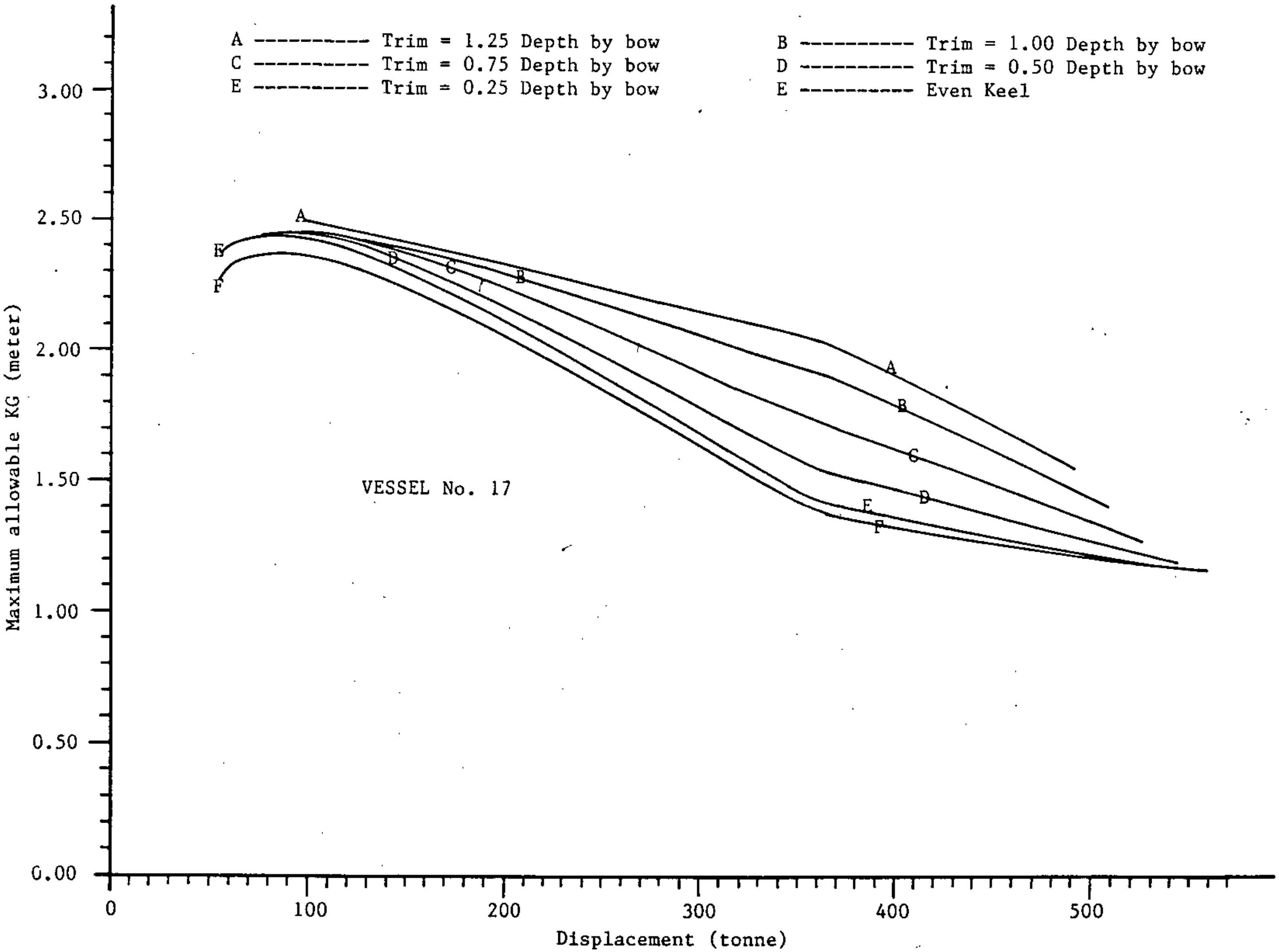

Fig. 4.71 : Variation of maximum allowable KG with displacement and trim by bow.

VESSEL No. 17

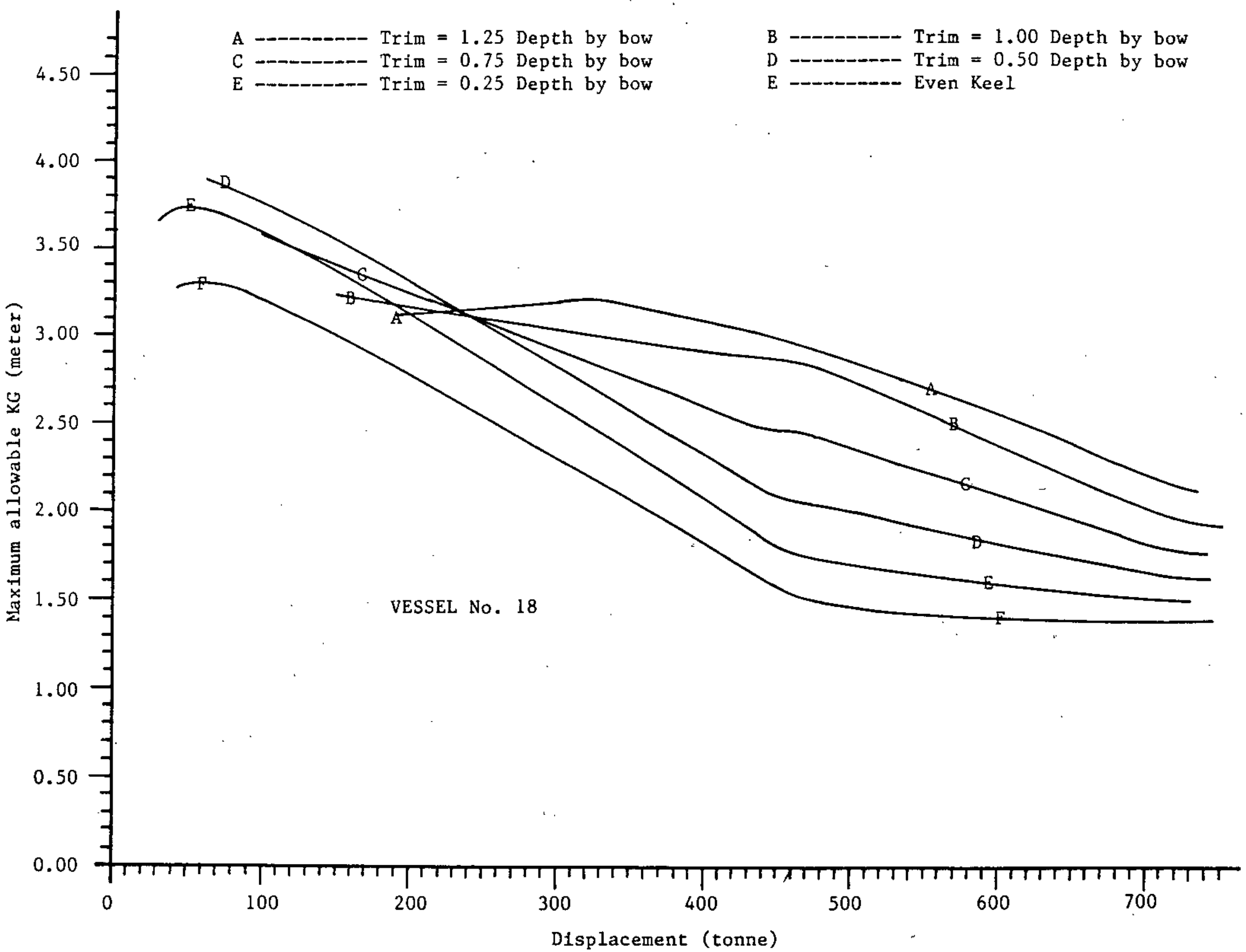

Fig. 4.72 : Variation of maximum allowable KG with displacement and trim by bow.
VESSEL No. 18

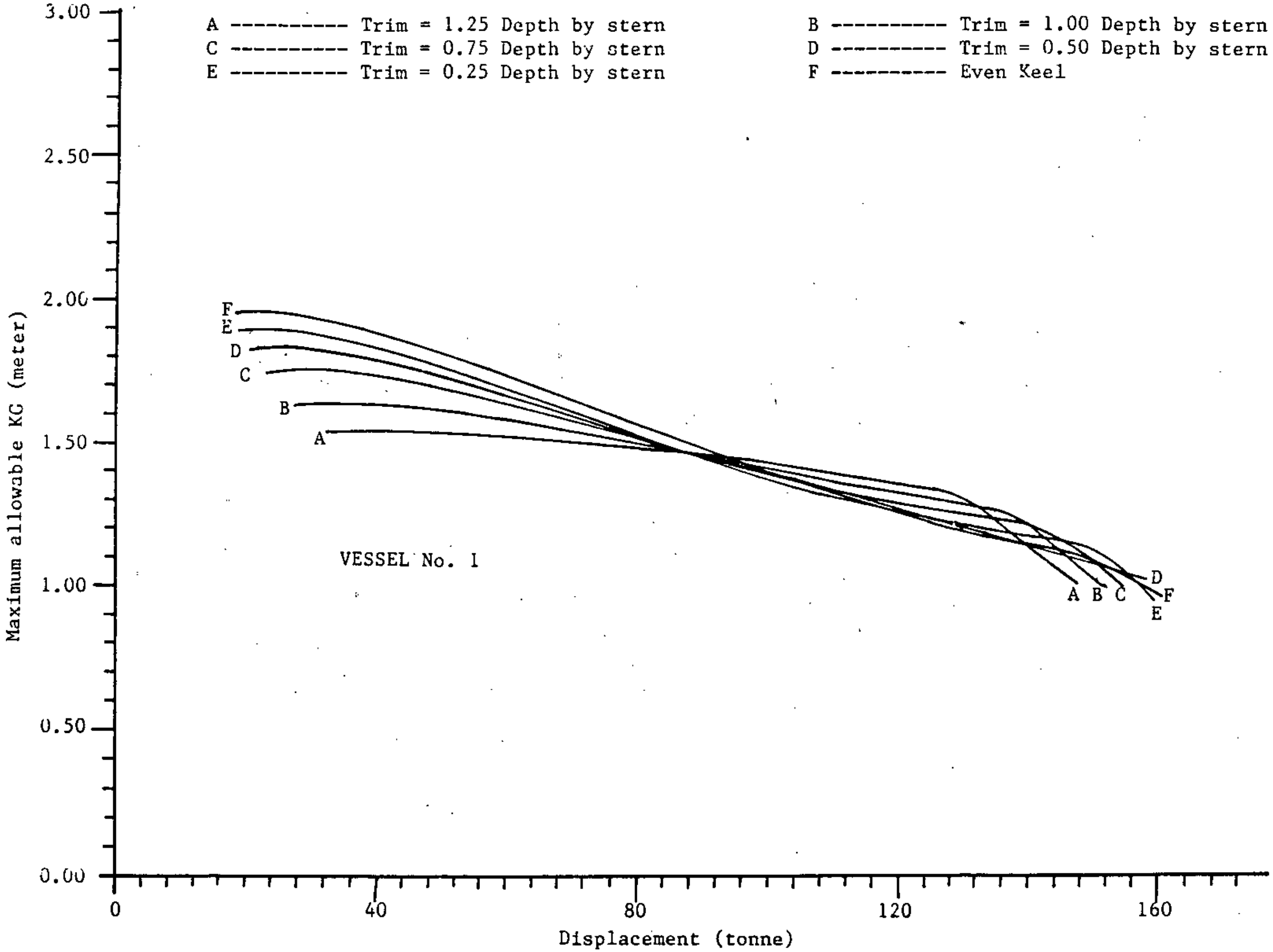

Fig. 4.73 : Variation of maximum allowable KG with displacement and trim by stern.

VESSEL No. 1

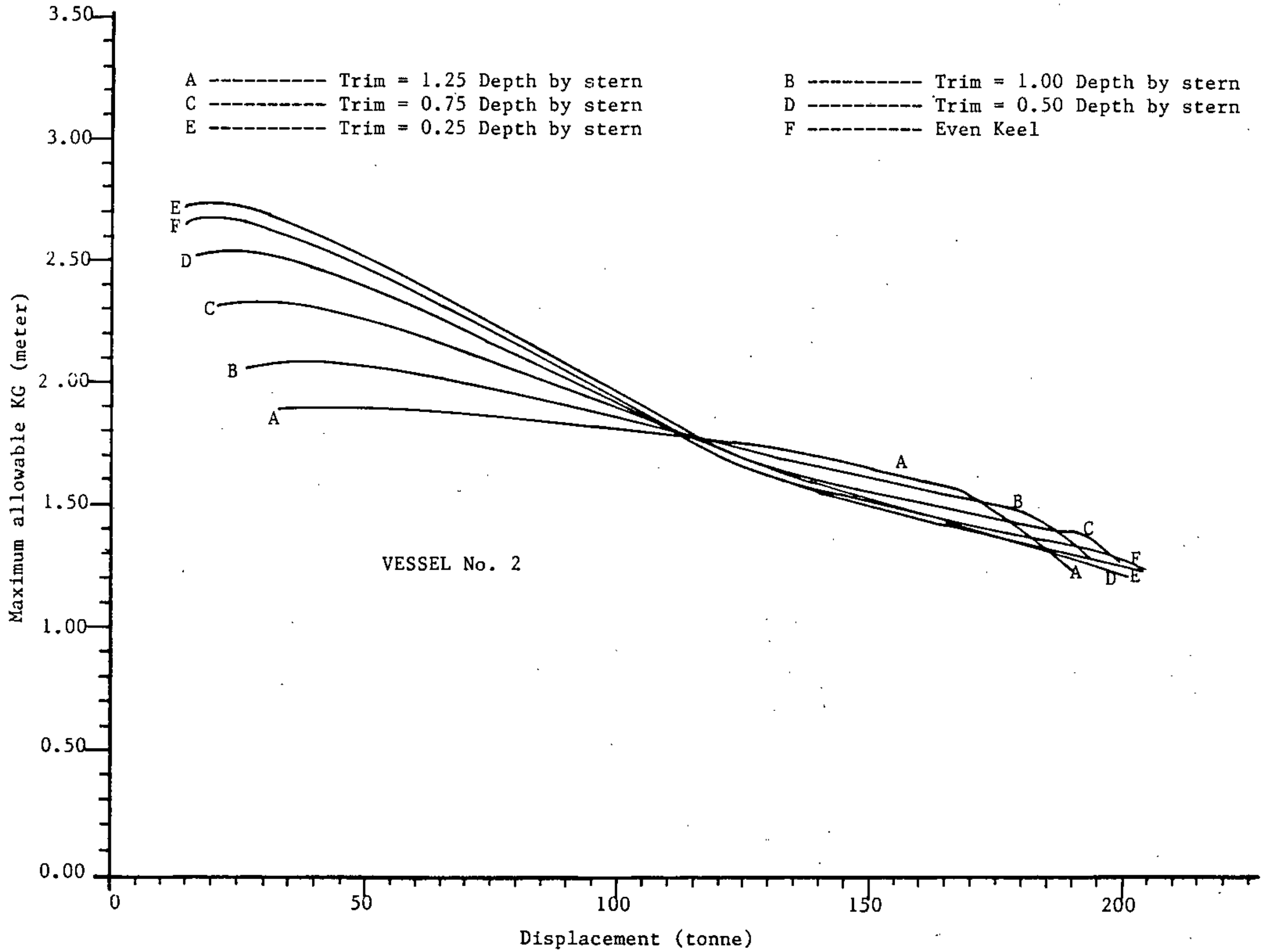

Fig. 4.74 : Variation of maximum allowable KG with displacement and trim by stern.
VESSEL No. 2

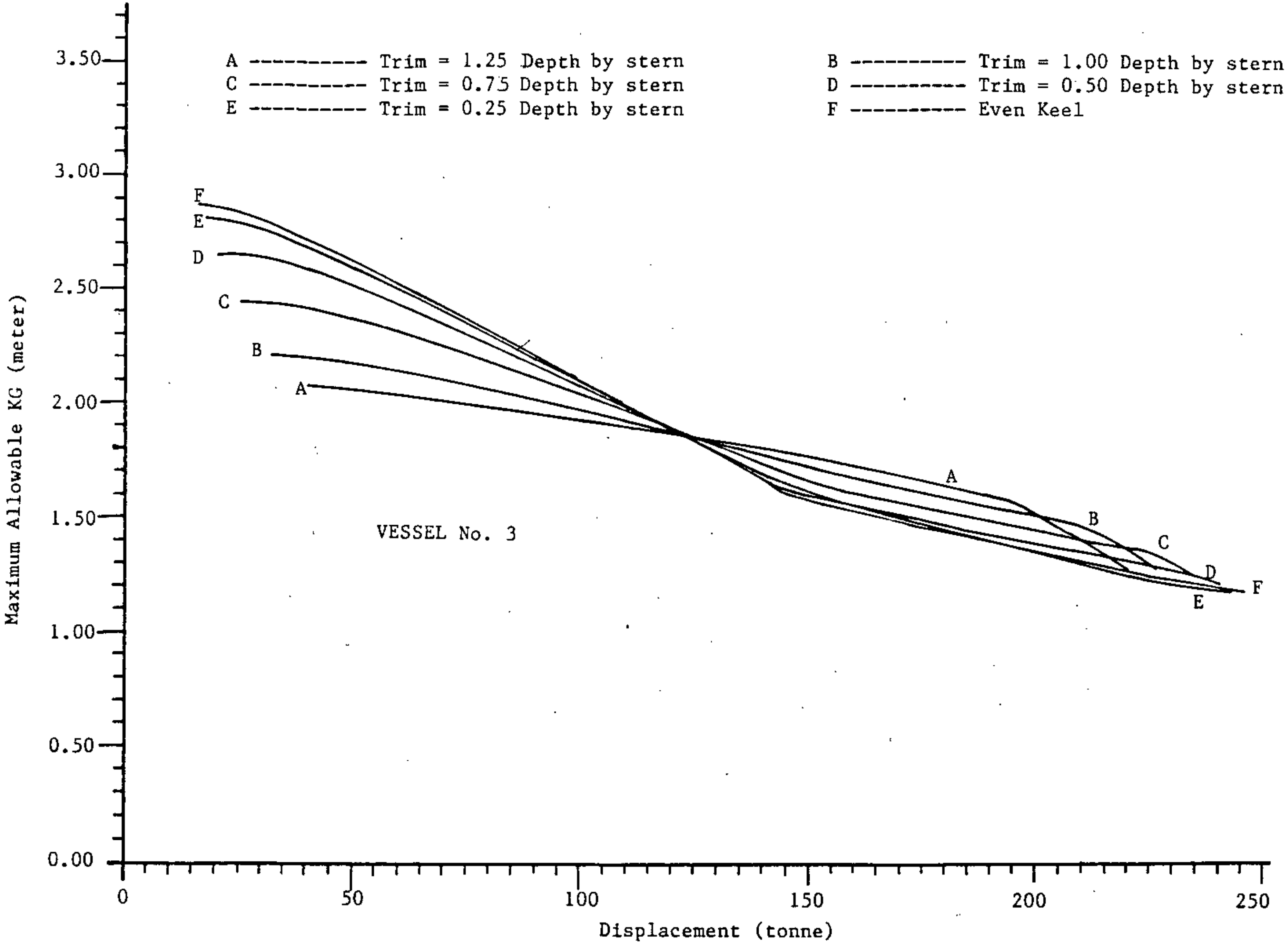

Fig. 4.75 : Variation of maximum allowable KG with displacement and trim by stern.
VESSEL No. 3

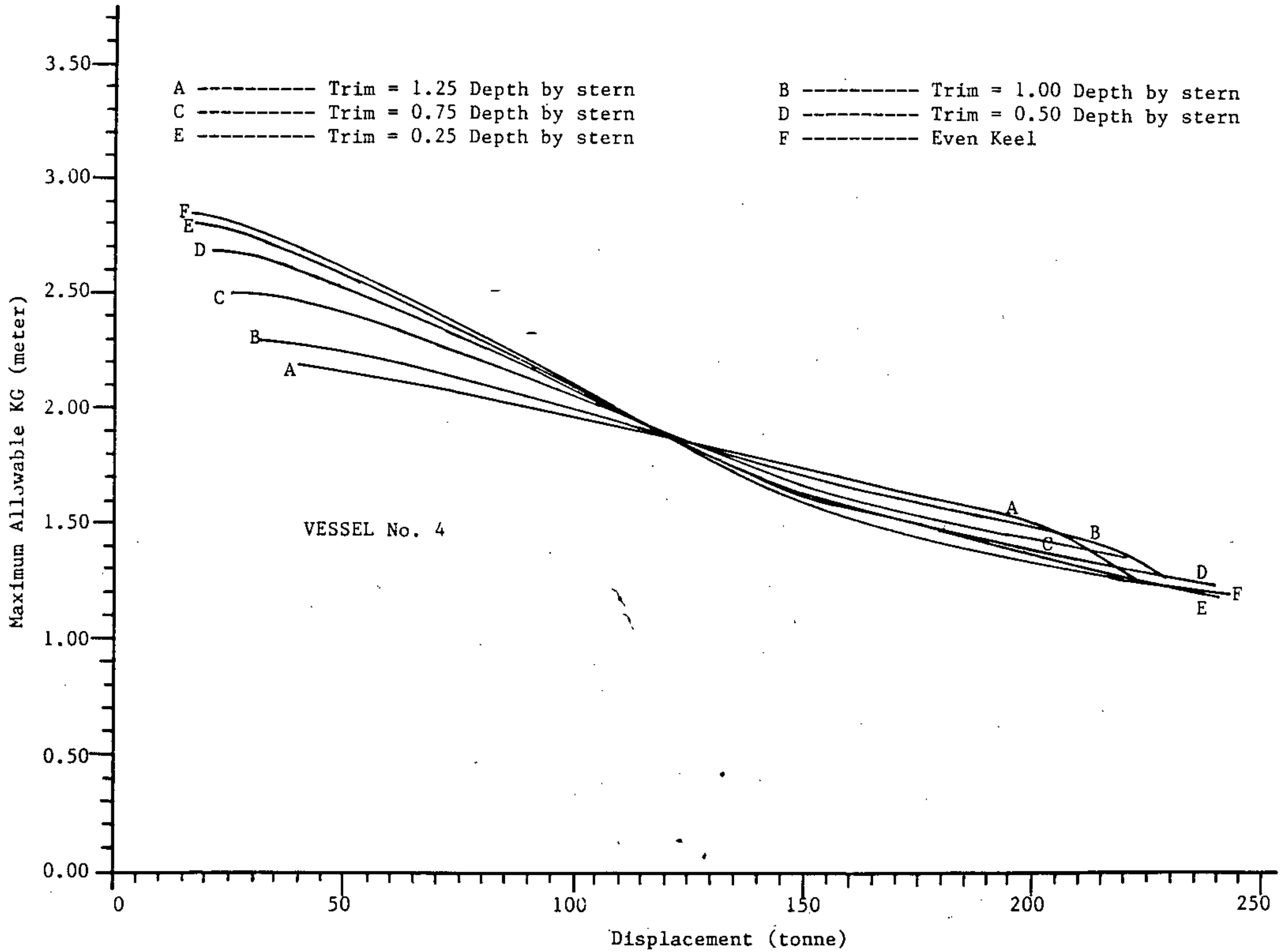

Fig. 4.76 : Variation of maximum allowable KG with displacement and trim by stern.
VESSEL No. 4

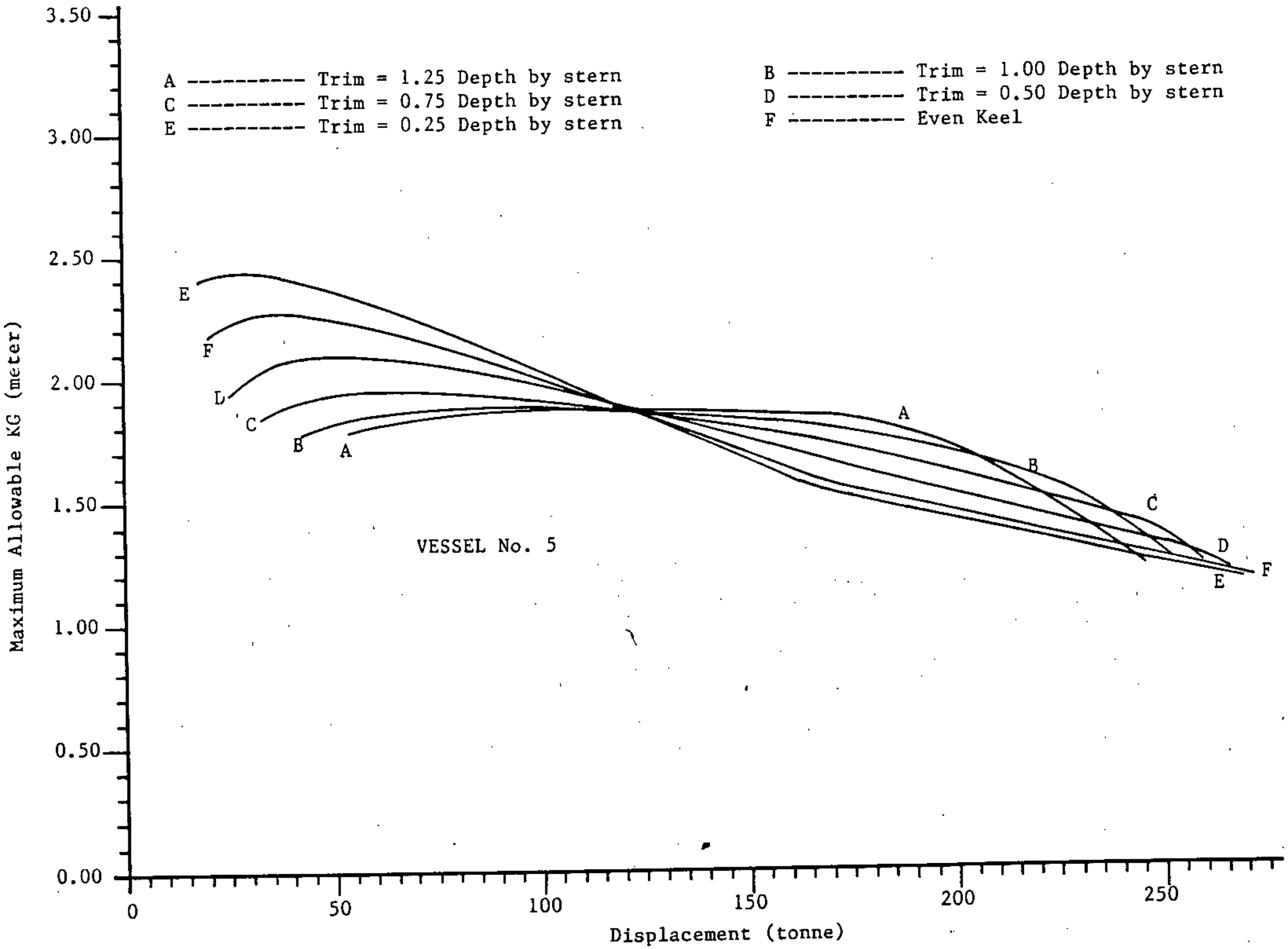

Fig. 4.77 : Variation of maximum allowable KG with displacement and trim by stern.
VESSEL No. 5

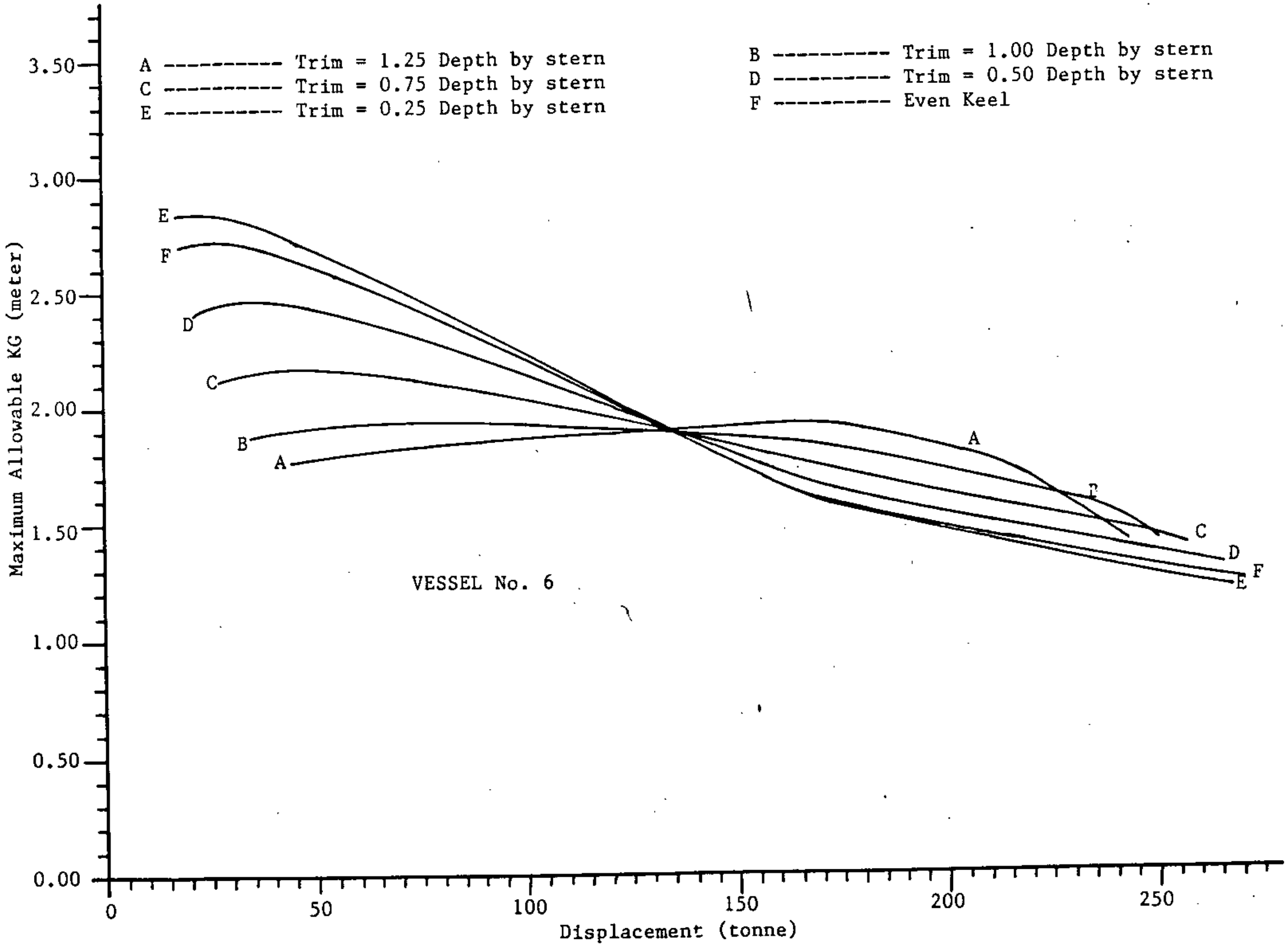

Fig. 4.78 : Variation of maximum allowable KG with displacement and trim by stern.

VESSEL No. 6

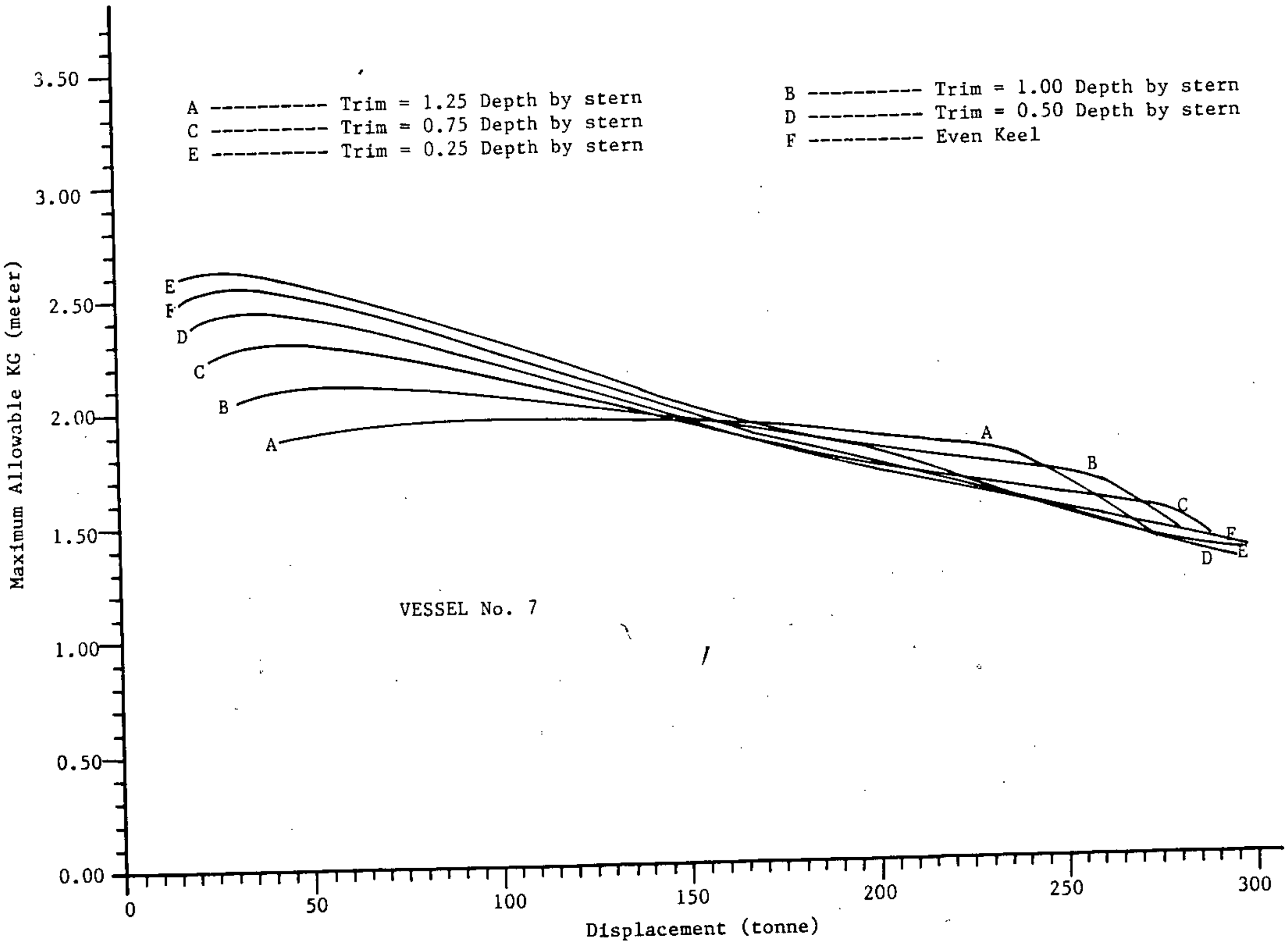

Fig. 4.79 : Variation of maximum allowable KG with displacement and trim by stern.

VESSEL No. 7

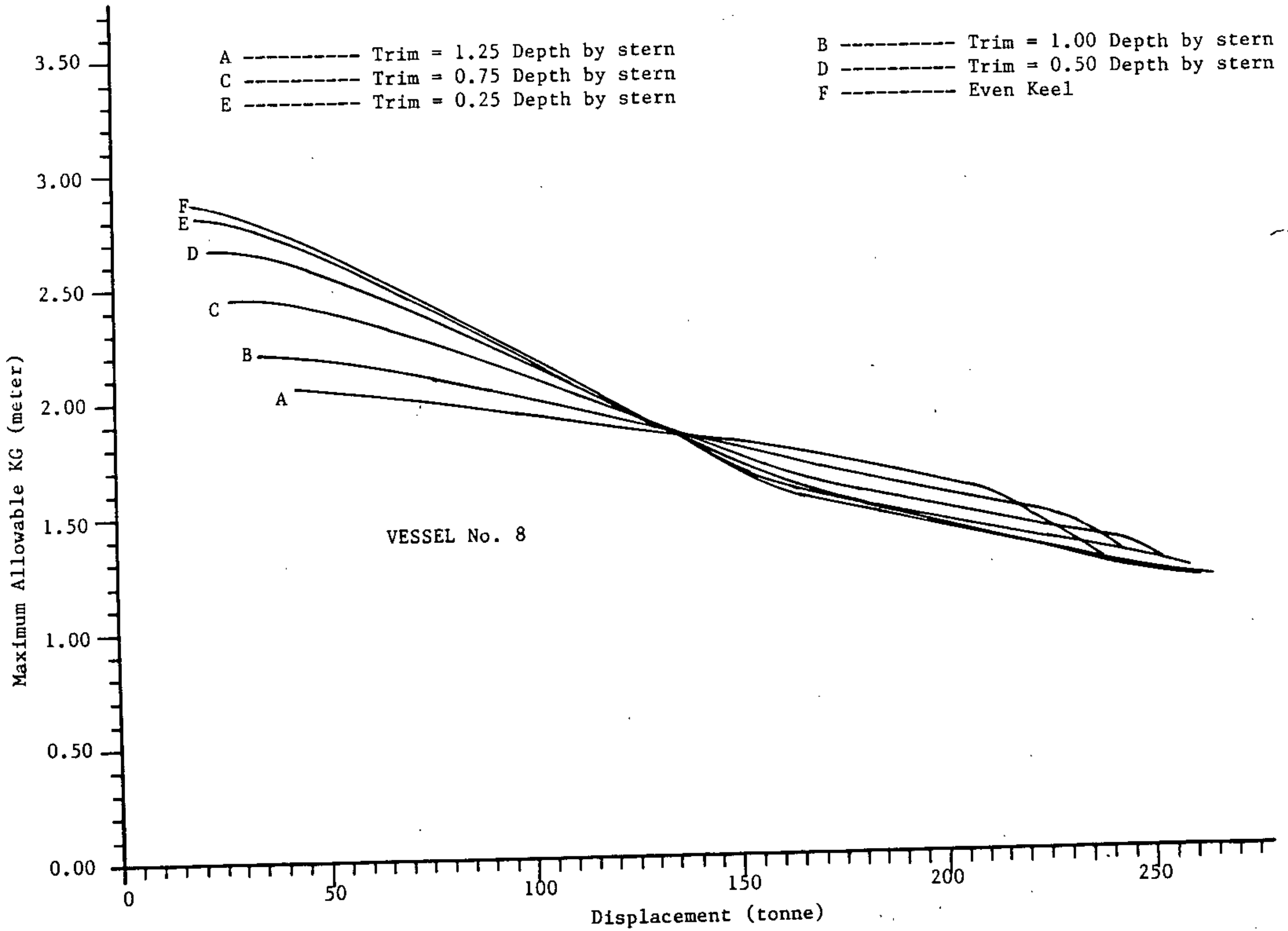

Fig. 4.80 : Variation of maximum allowable KG with displacement and trim by stern.
VESSEL No. 8

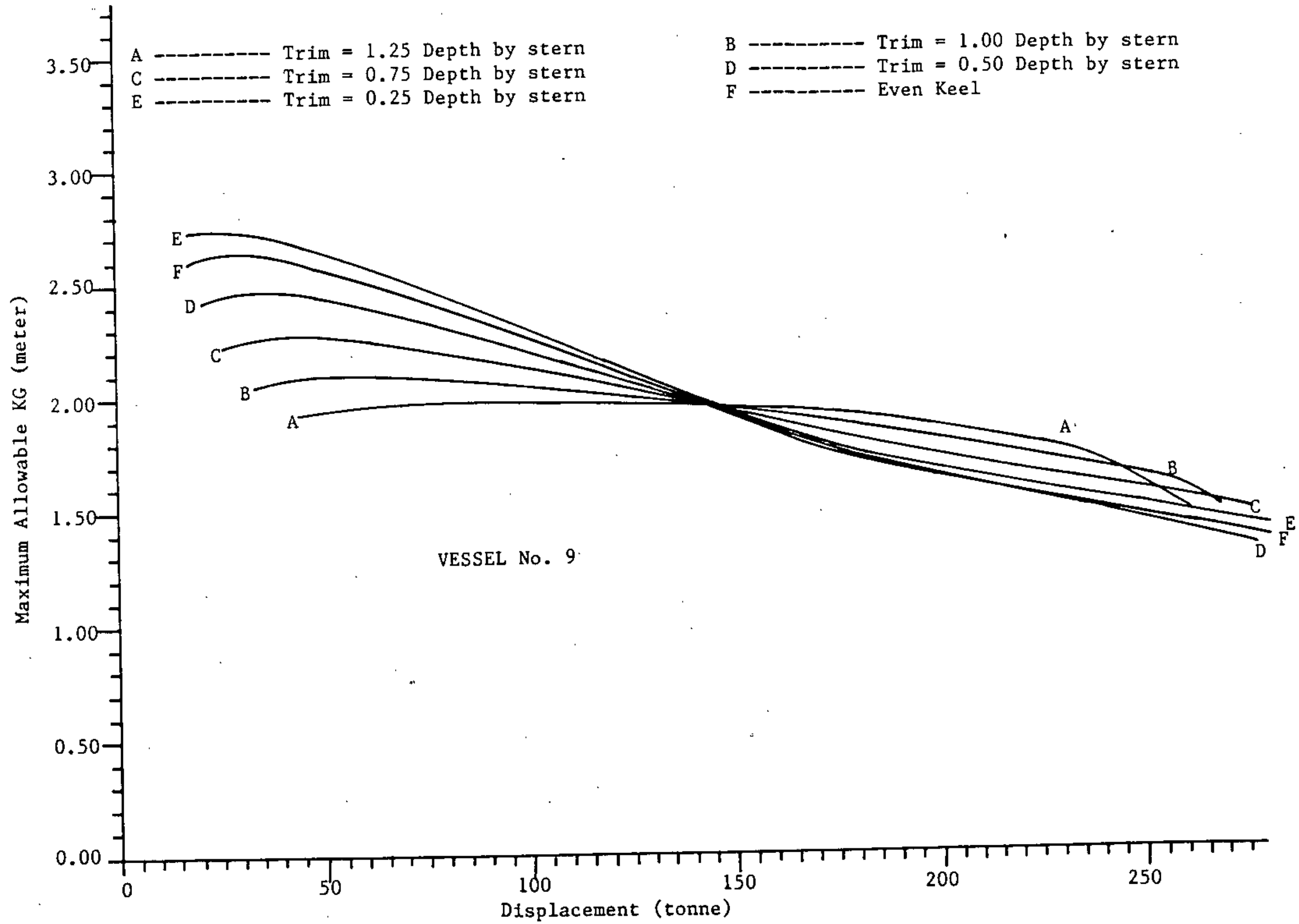

Fig. 4.81 : Variation of maximum allowable KG with displacement and trim by stern.

VESSEL No. 9

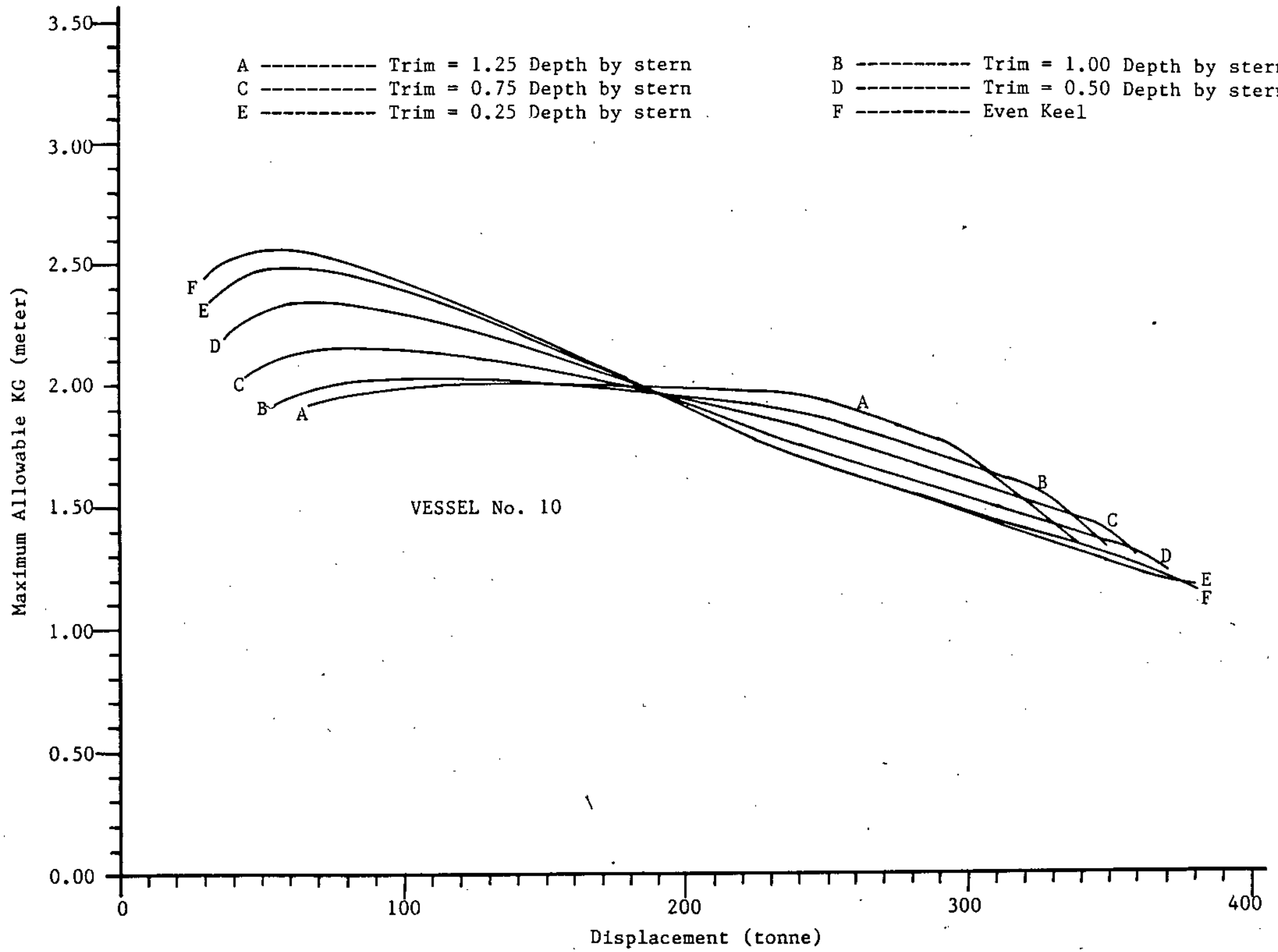

Fig. 4.82 : Variation of maximum allowable KG with displacement and trim by stern.
VESSEL No. 10

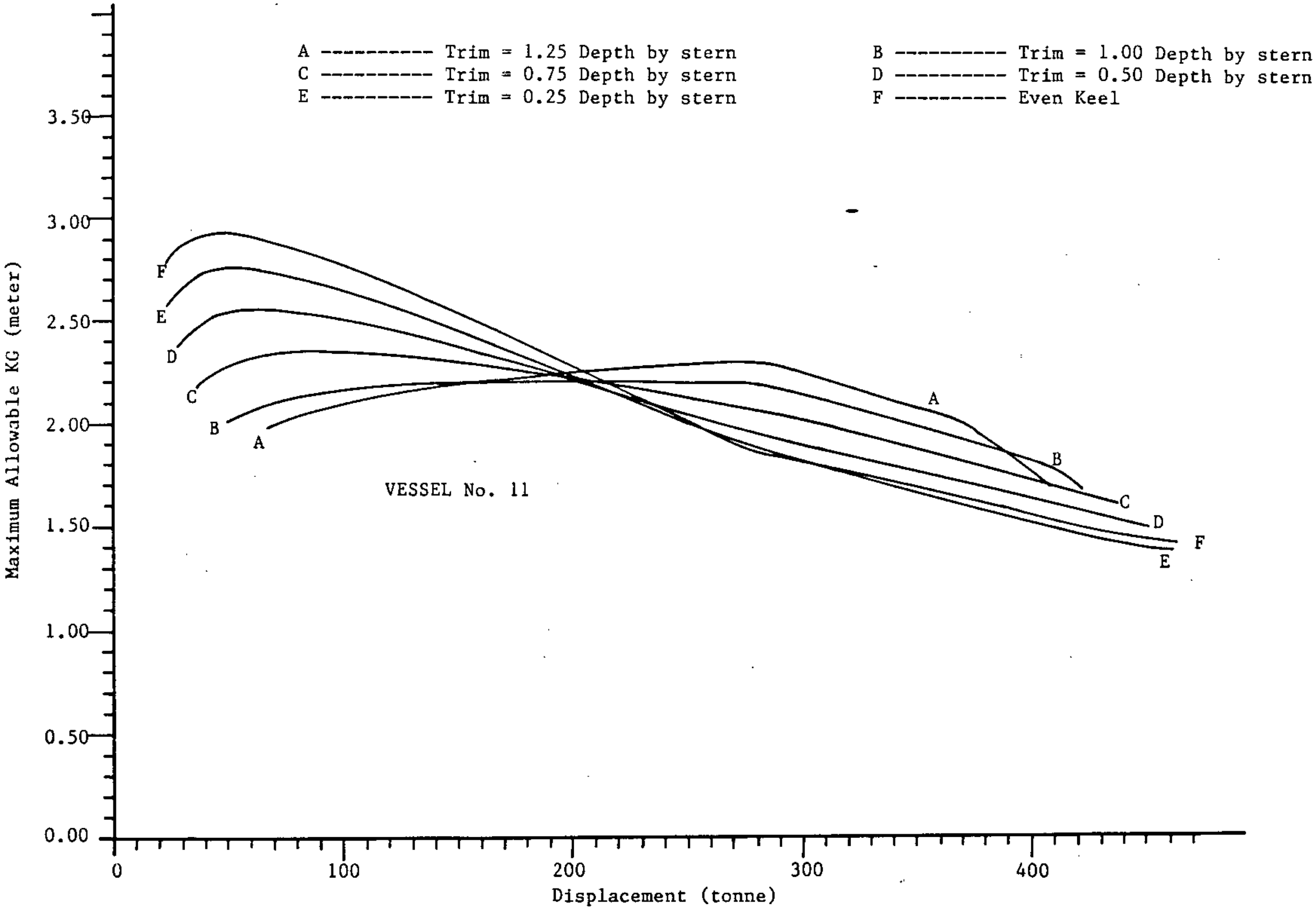

Fig. 4.83 : Variation of maximum allowable KG with displacement and trim by stern.

VESSEL No.11

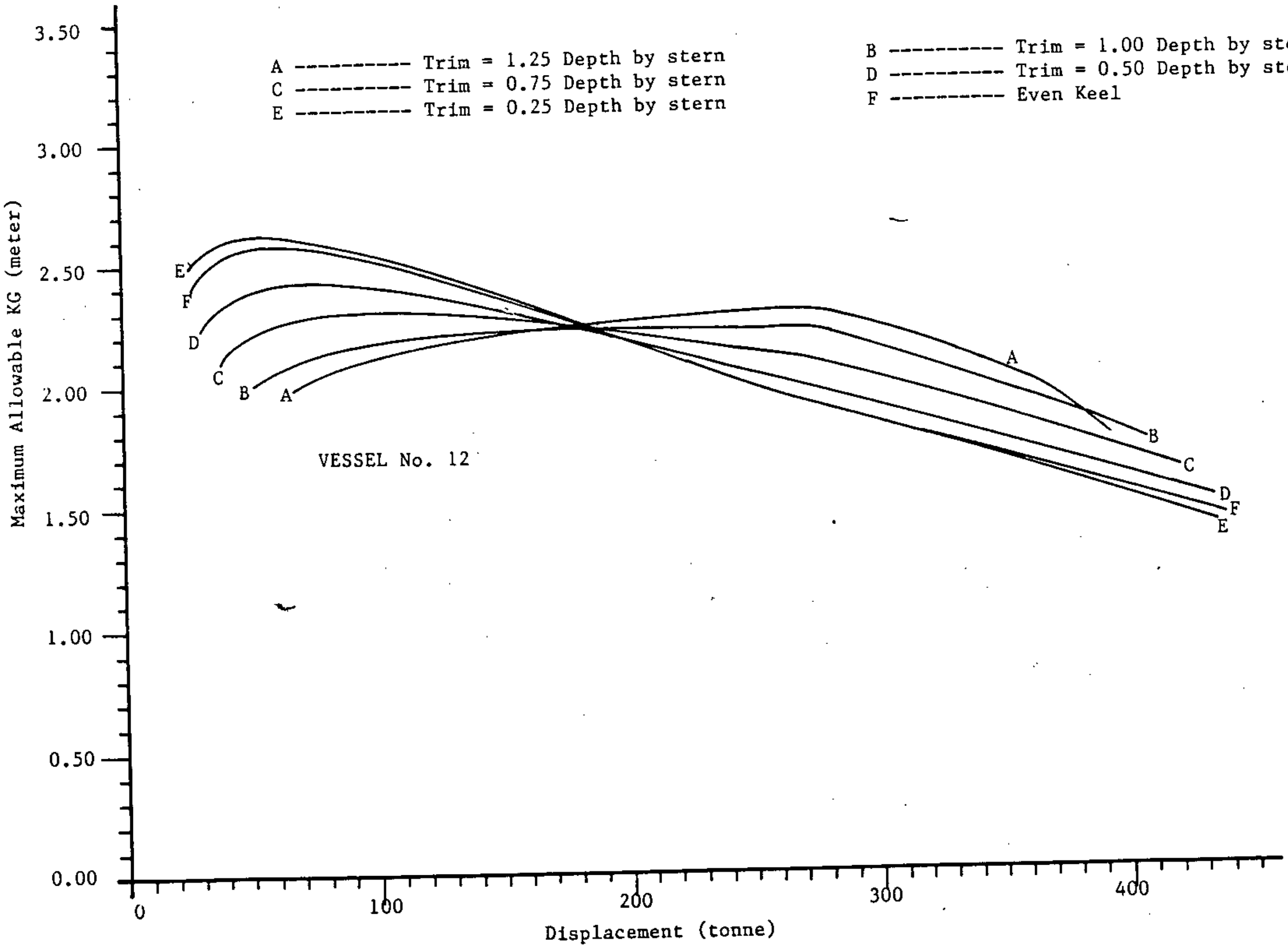

Fig. 4.84 : Variation of maximum allowable KG with displacement and trim by stern.

VESSEL No. 12

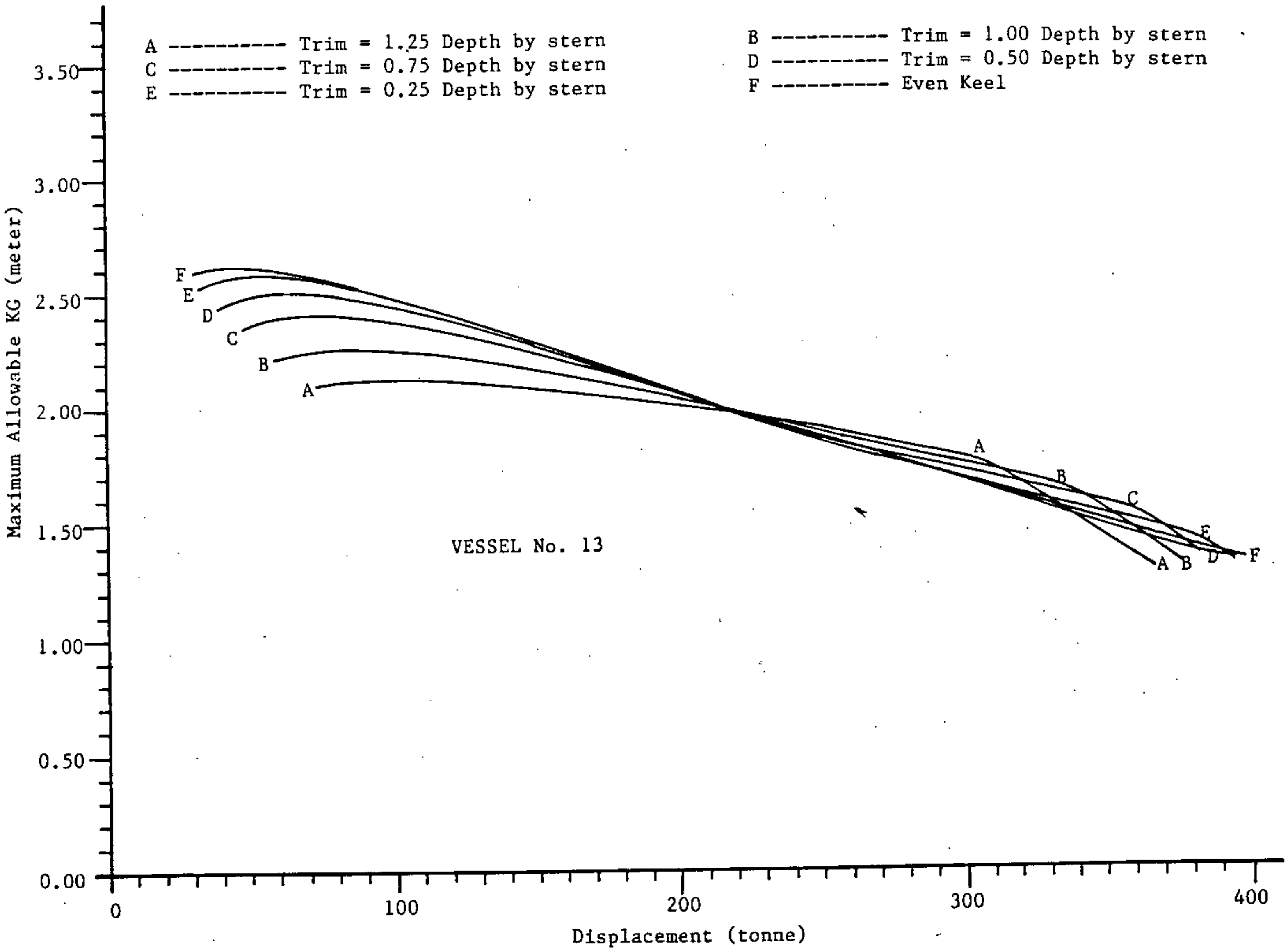

Fig. 4.85 : Variation of maximum allowable KG with displacement and trim by stern.
VESSEL No. 13

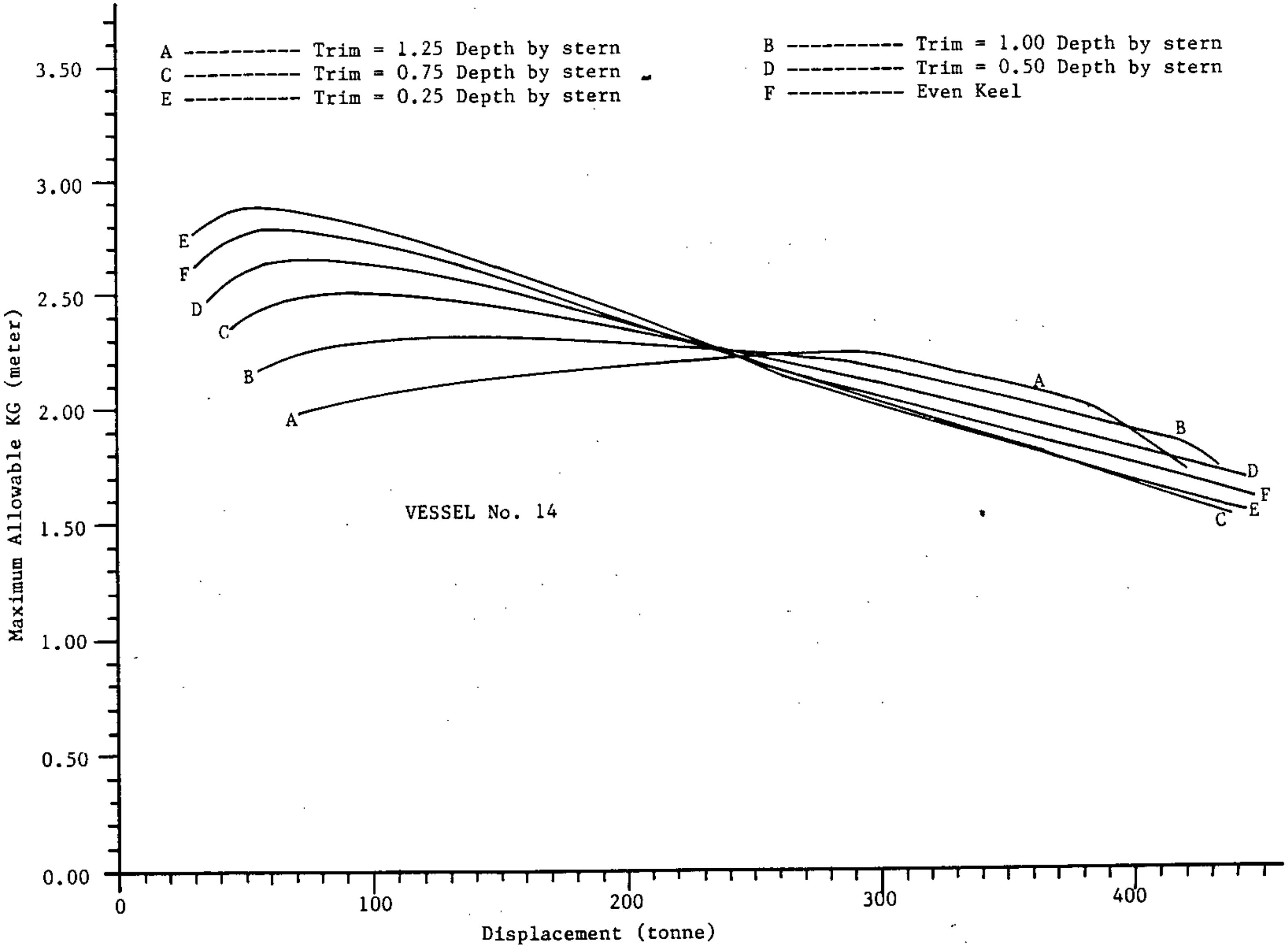

Fig. 4.86 : Variation of maximum allowable KG with displacement and trim by stern.
VESSEL No. 14

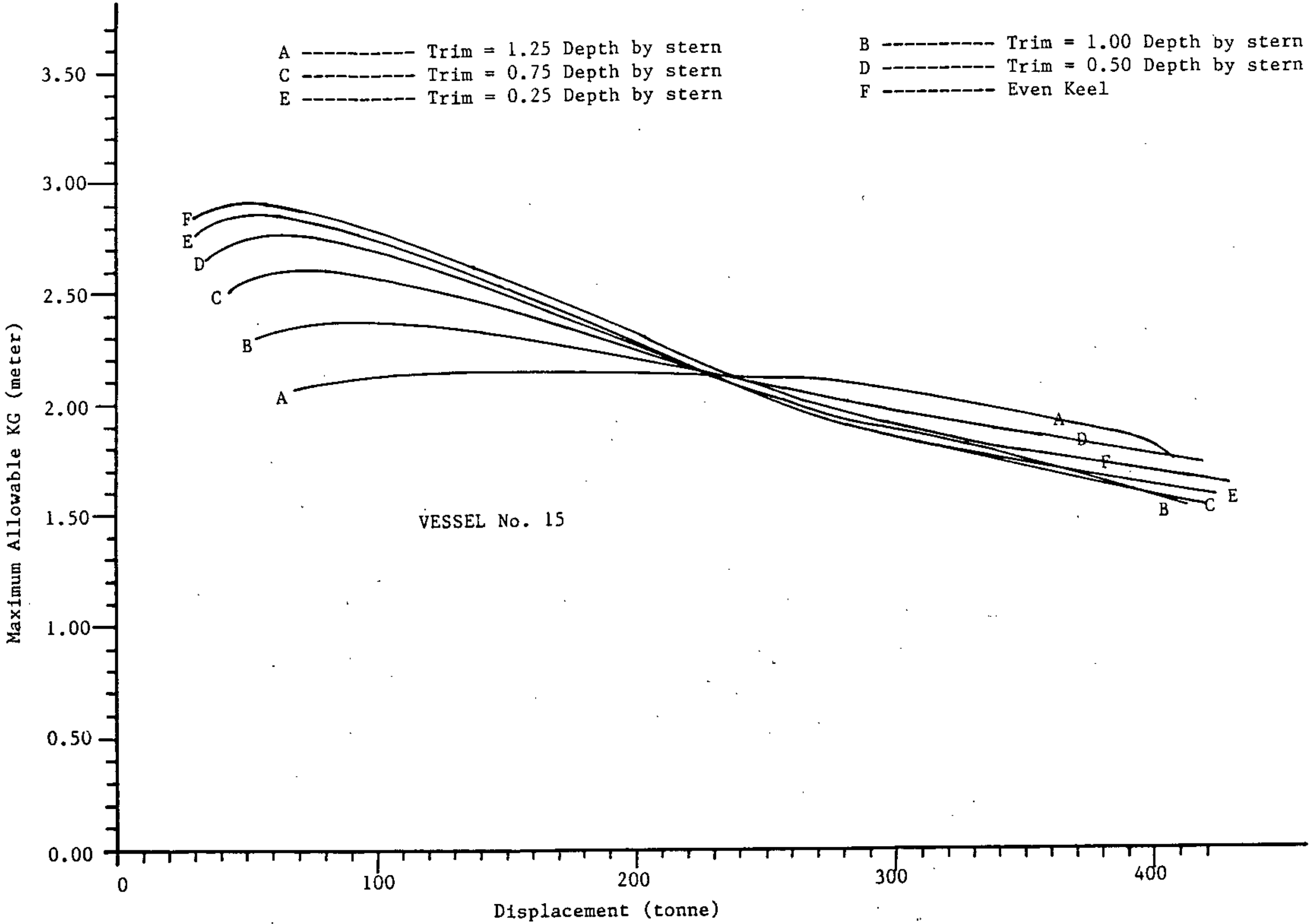

Fig. 4.87 : Variation of maximum allowable KG with displacement and trim by stern.
VESSEL No. 15

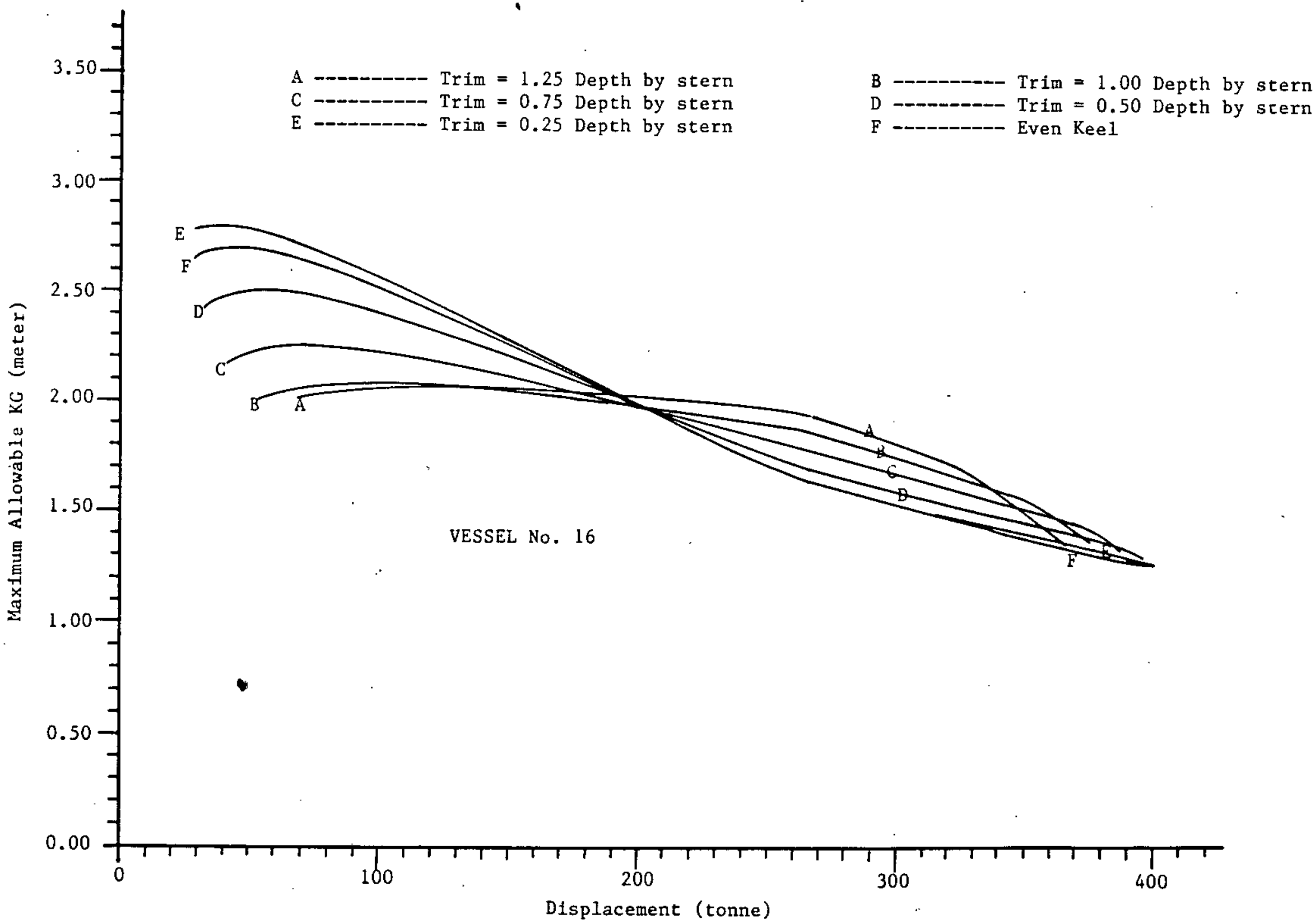

Fig. 4.88 : Variation of maximum allowable KG with displacement and trim by stern.
VESSEL No. 16

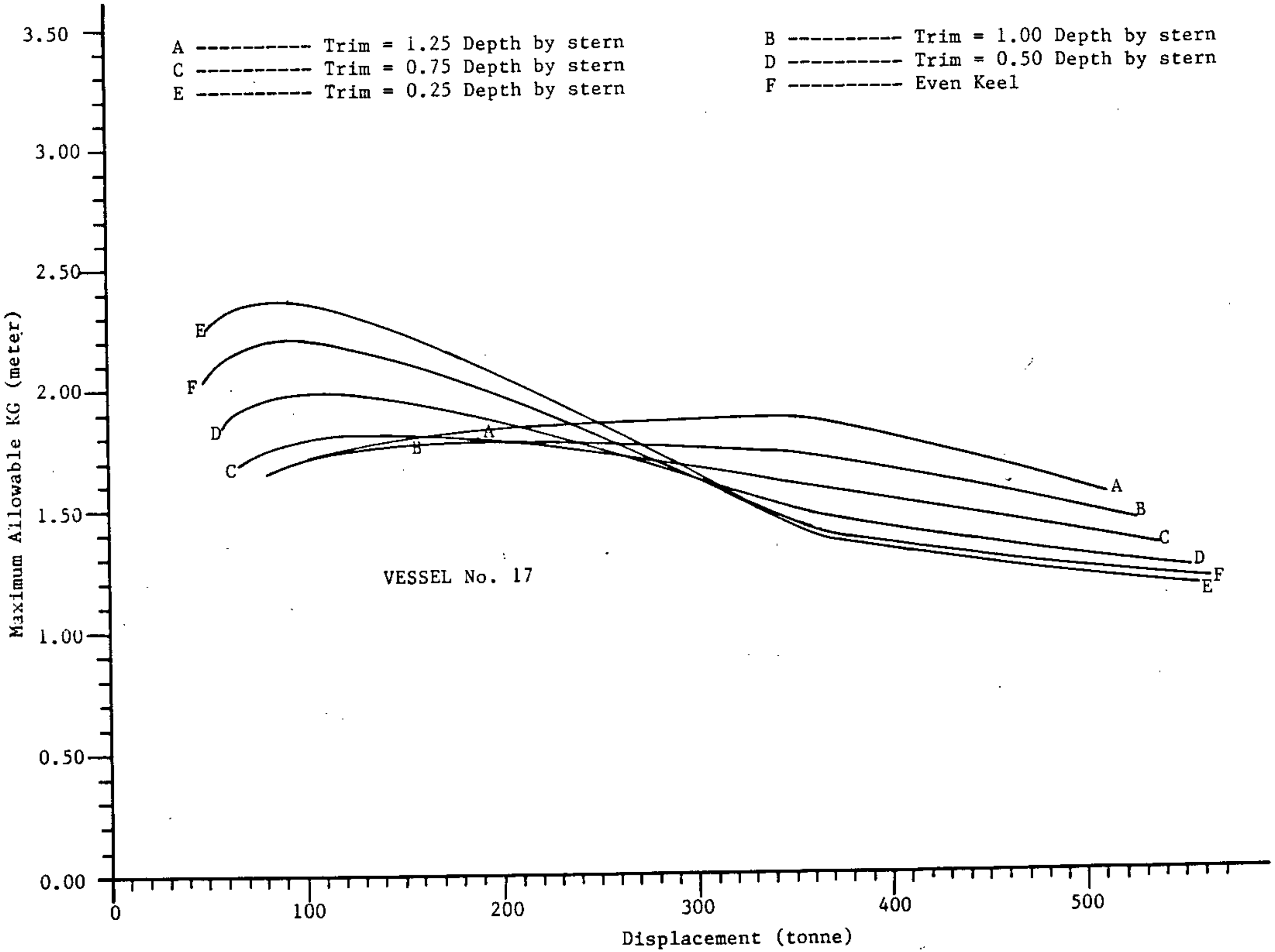

Fig. 4.89 : Variation of maximum allowable KG with displacement and trim by stern.
VESSEL No. 17

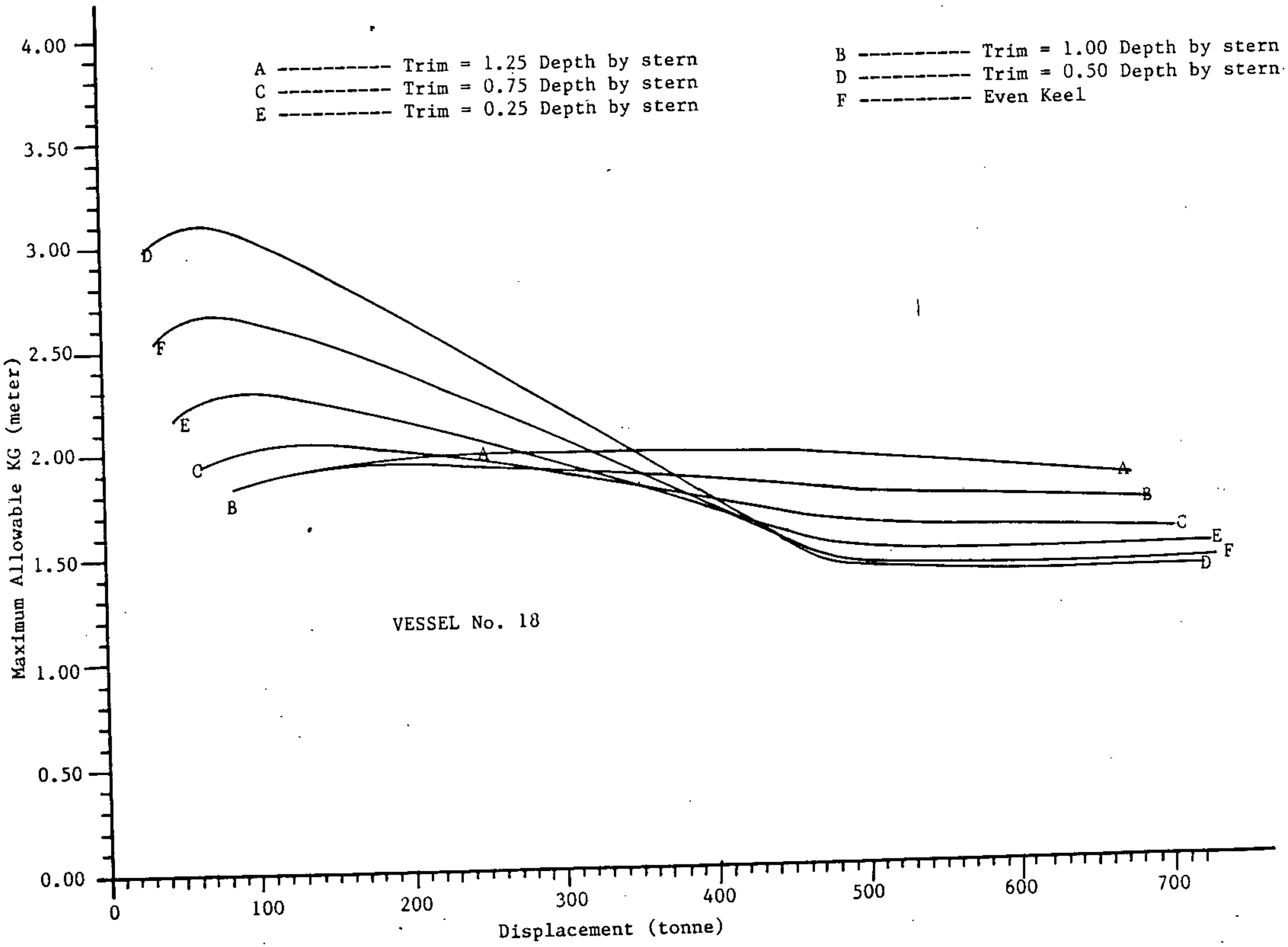

Fig. 4.90 : Variation of maximum allowable KG with displacement and trim by stern.
VESSEL No. 18

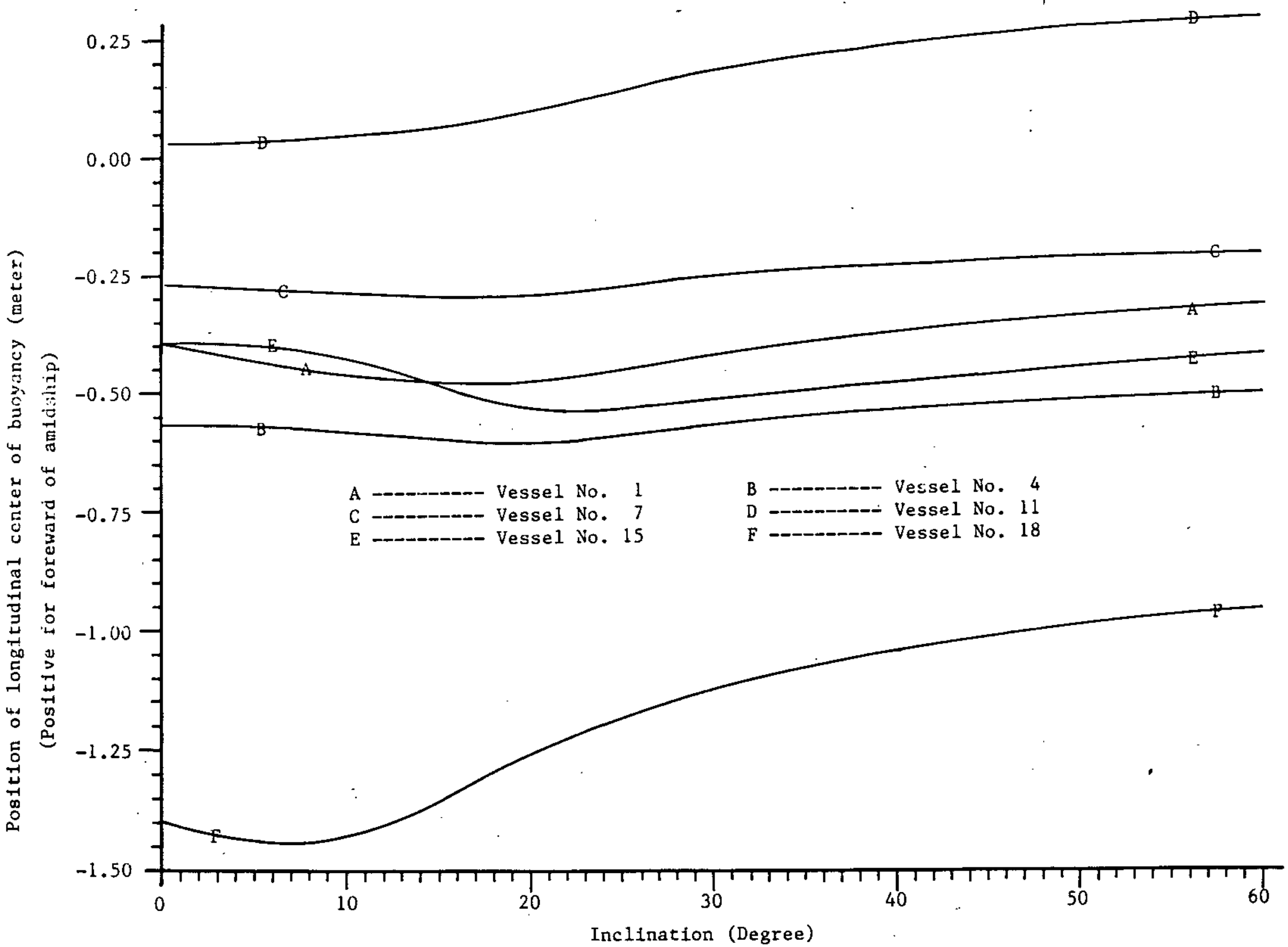

Fig. 4.91 : Shift of longitudinal center of buoyancy with inclination.

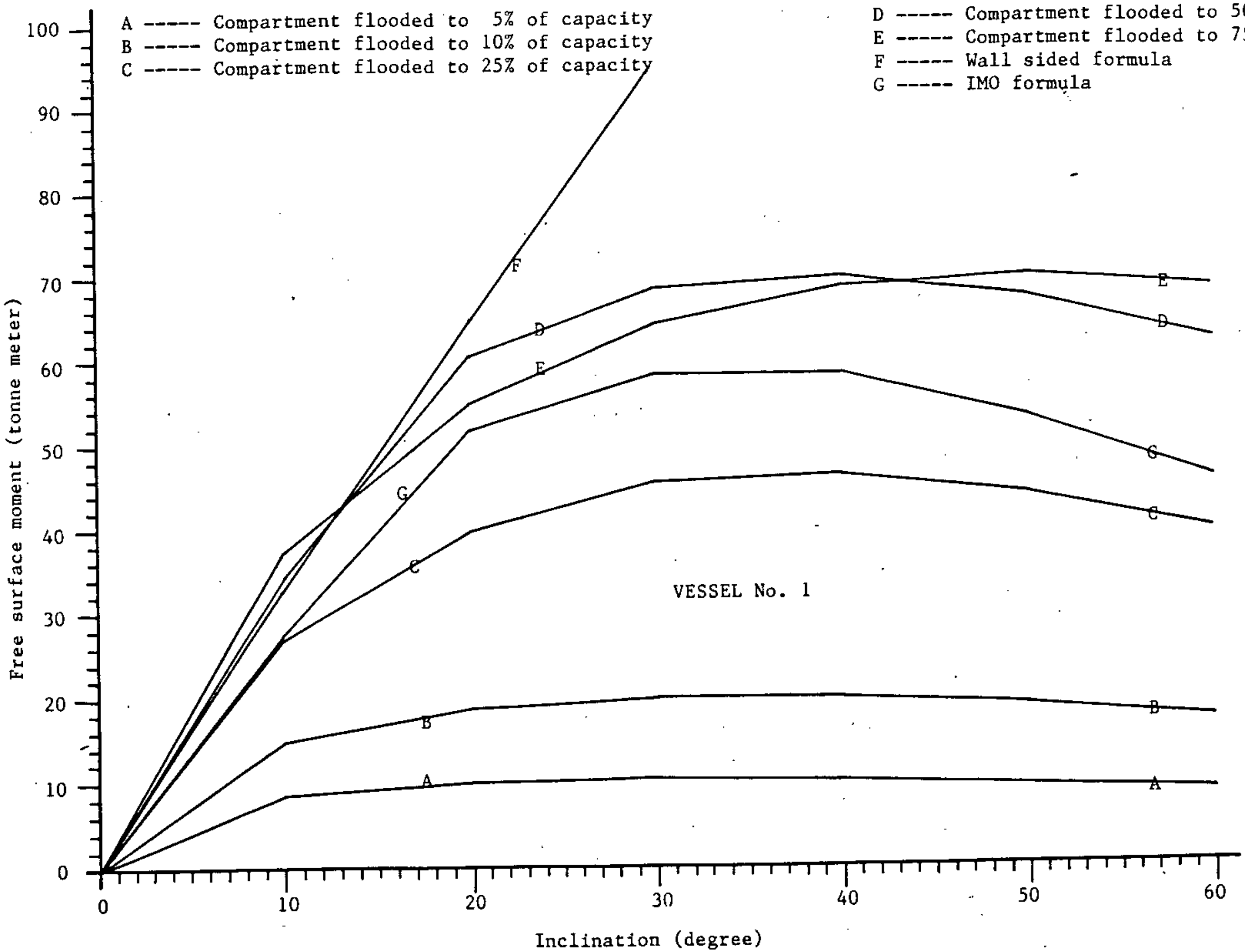

Fig. 4.92 : Estimation of free surface moment for flooding of central compartment.
VESSEL No. 1

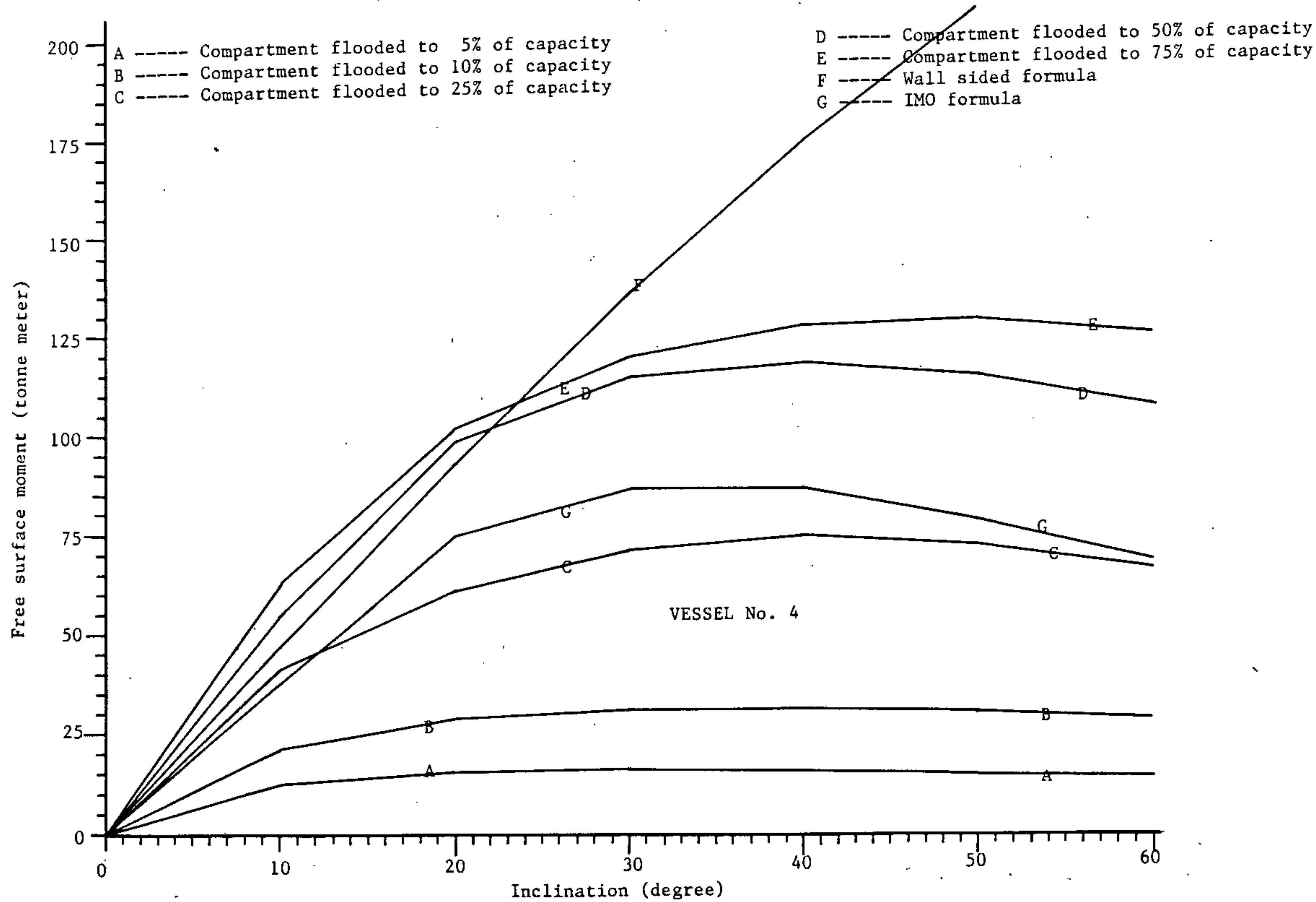

Fig. 4.93 : Estimation of free surface moment for flooding of central compartment.

VESSEL No. 4

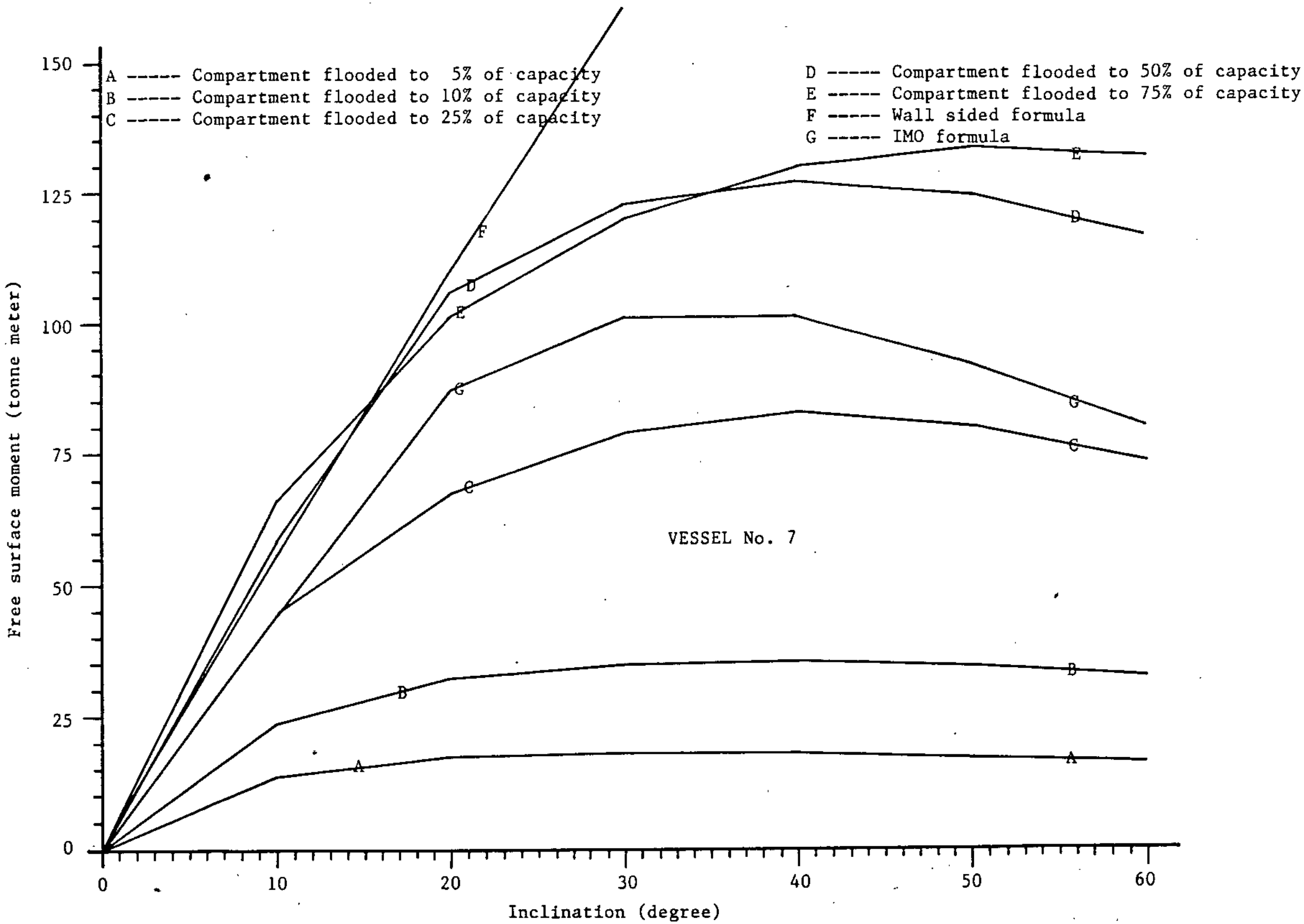

Fig. 4.94 : Estimation of free surface moment for flooding of central compartment.

VESSEL No. 7

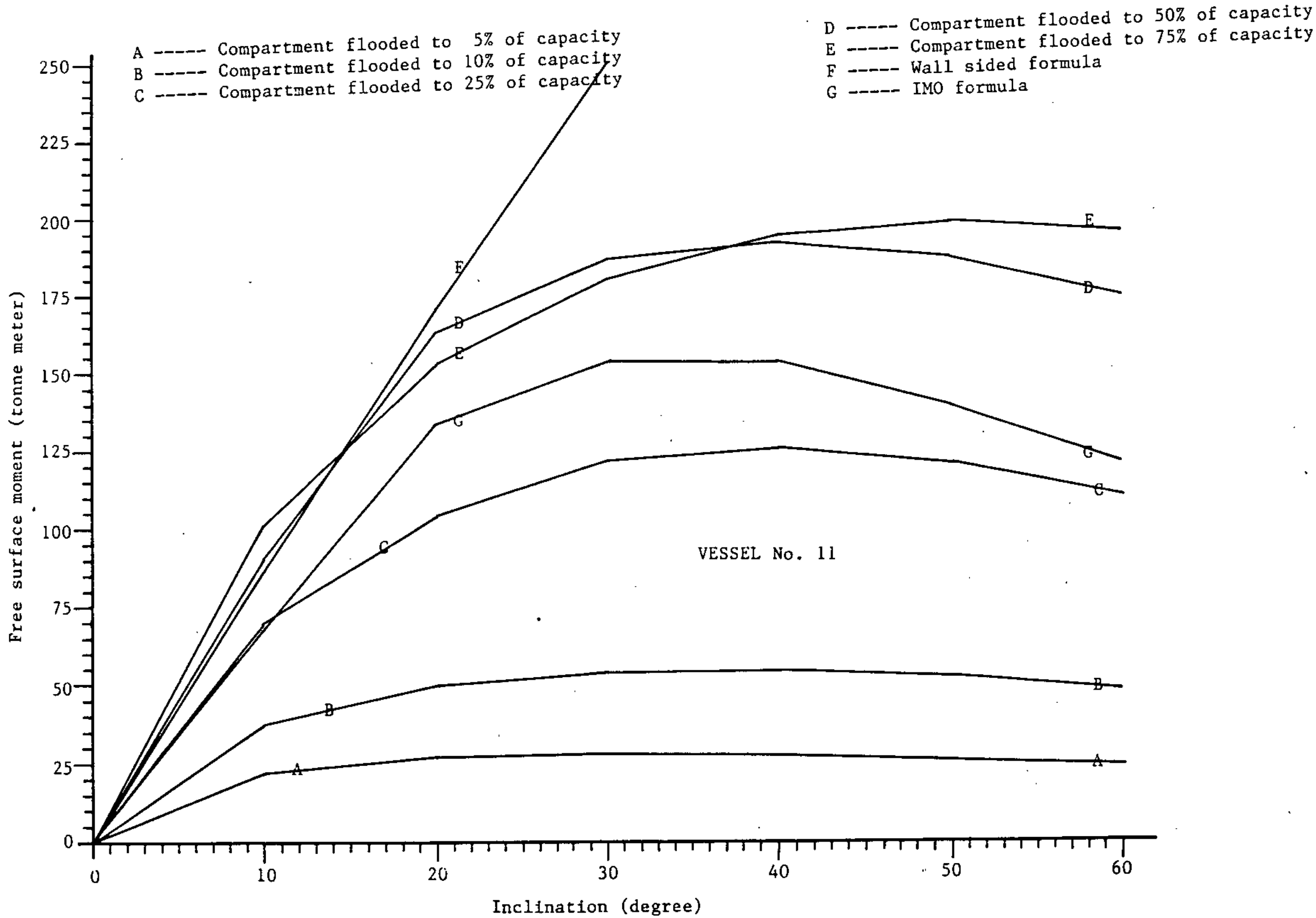

Fig. 4.95 : Estimation of free surface moment for flooding of central compartment.
VESSEL No. 11

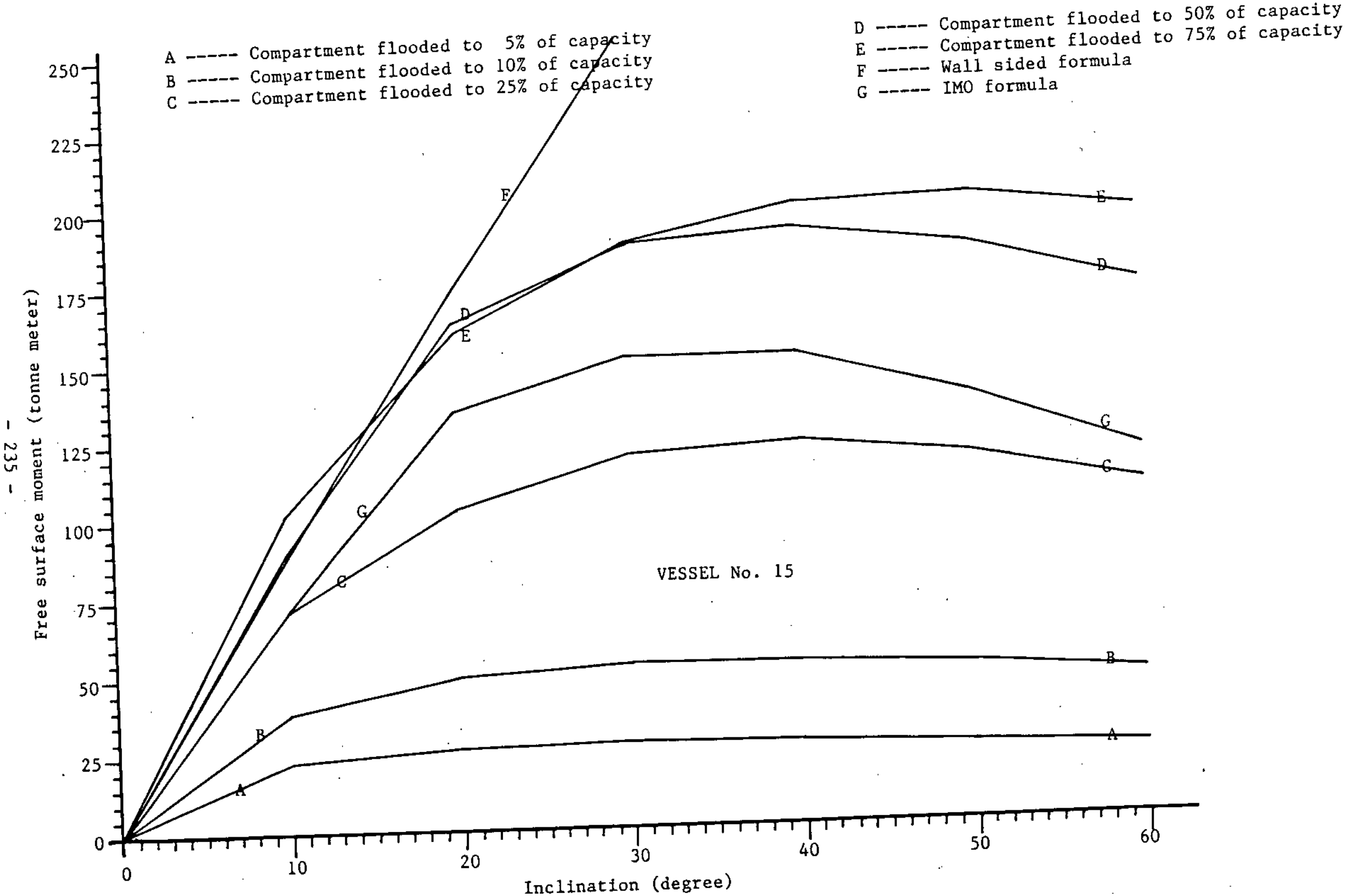

Fig. 4.96 : Estimation of free surface moment for flooding of central compartment.
VESSEL No. 15

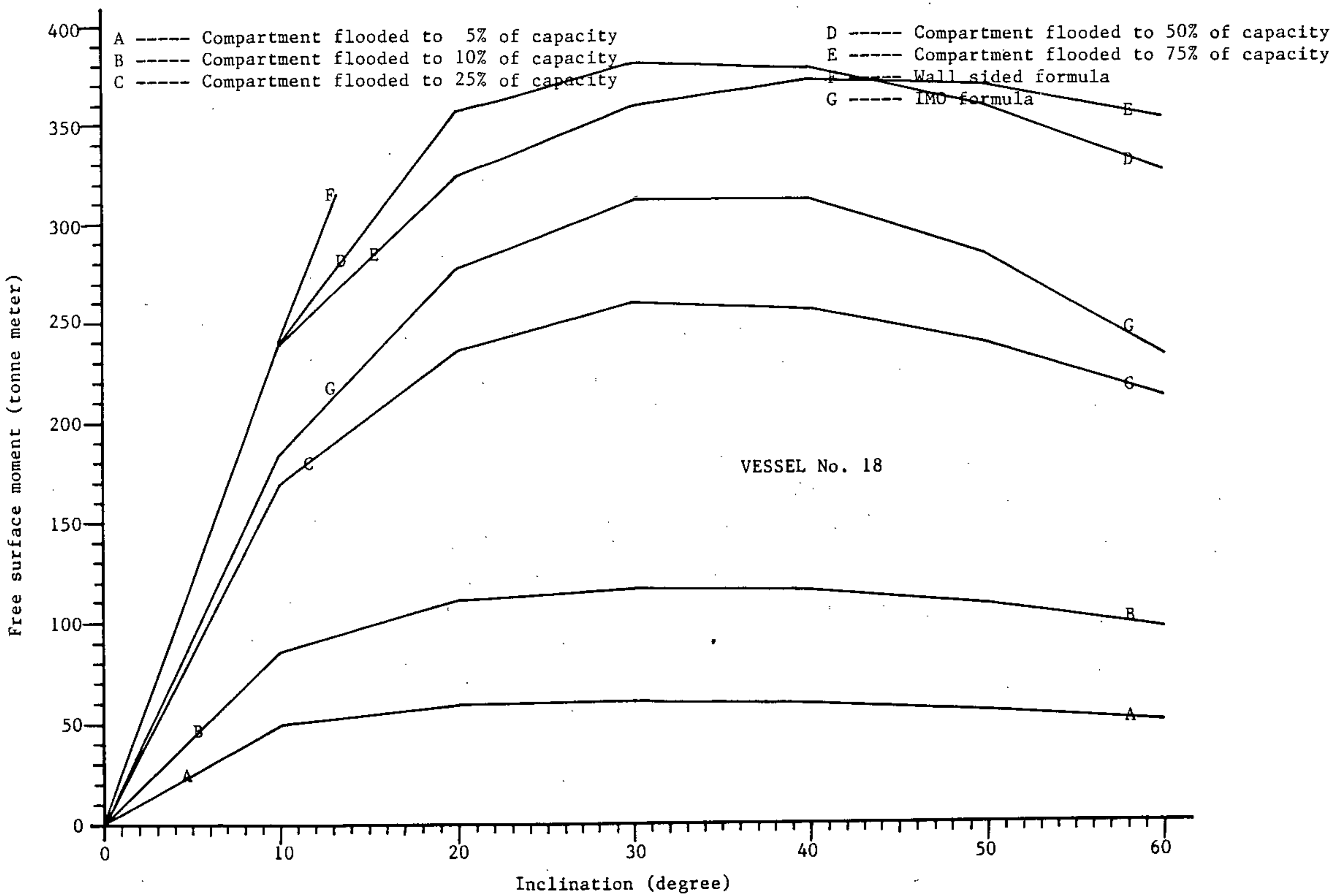

Fig. 4.97 : Estimation of free surface moment for flooding of central compartment.

VESSEL No. 18

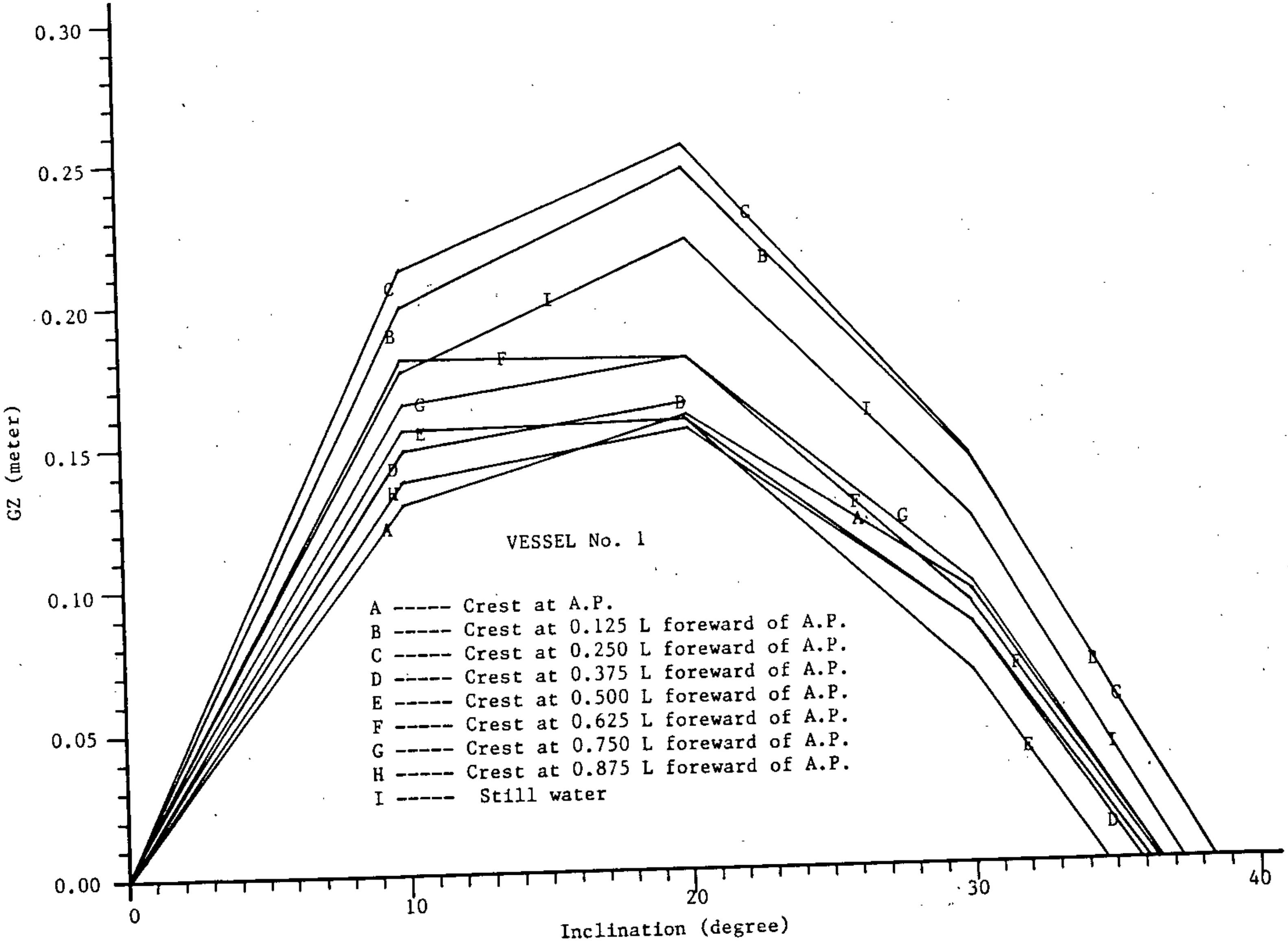

Fig. 4.98 : GZ curve in still water and in wave.

VESSEL No. 1

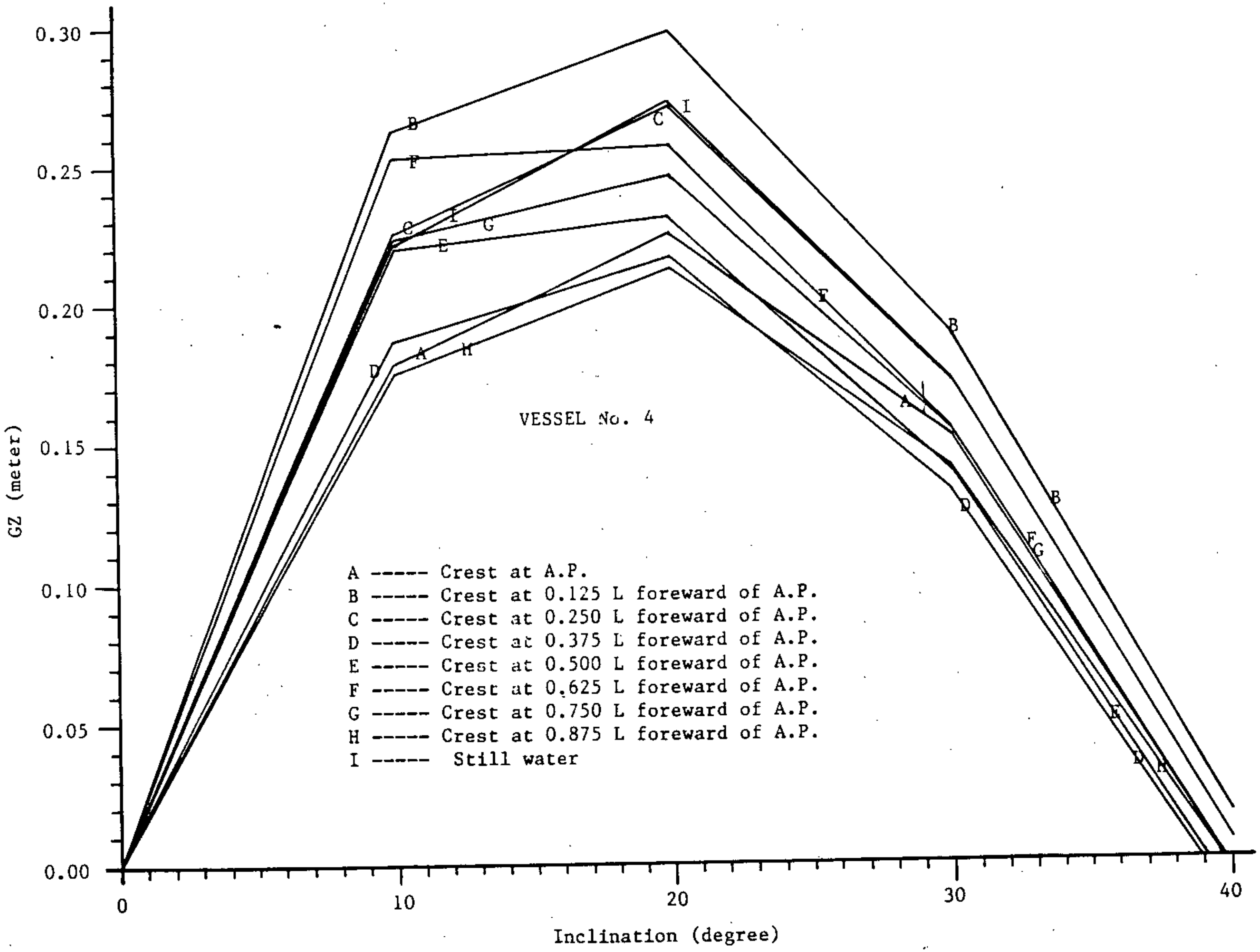

Fig. 4.99 : GZ curve in still water and in wave.
VESSEL No. 4

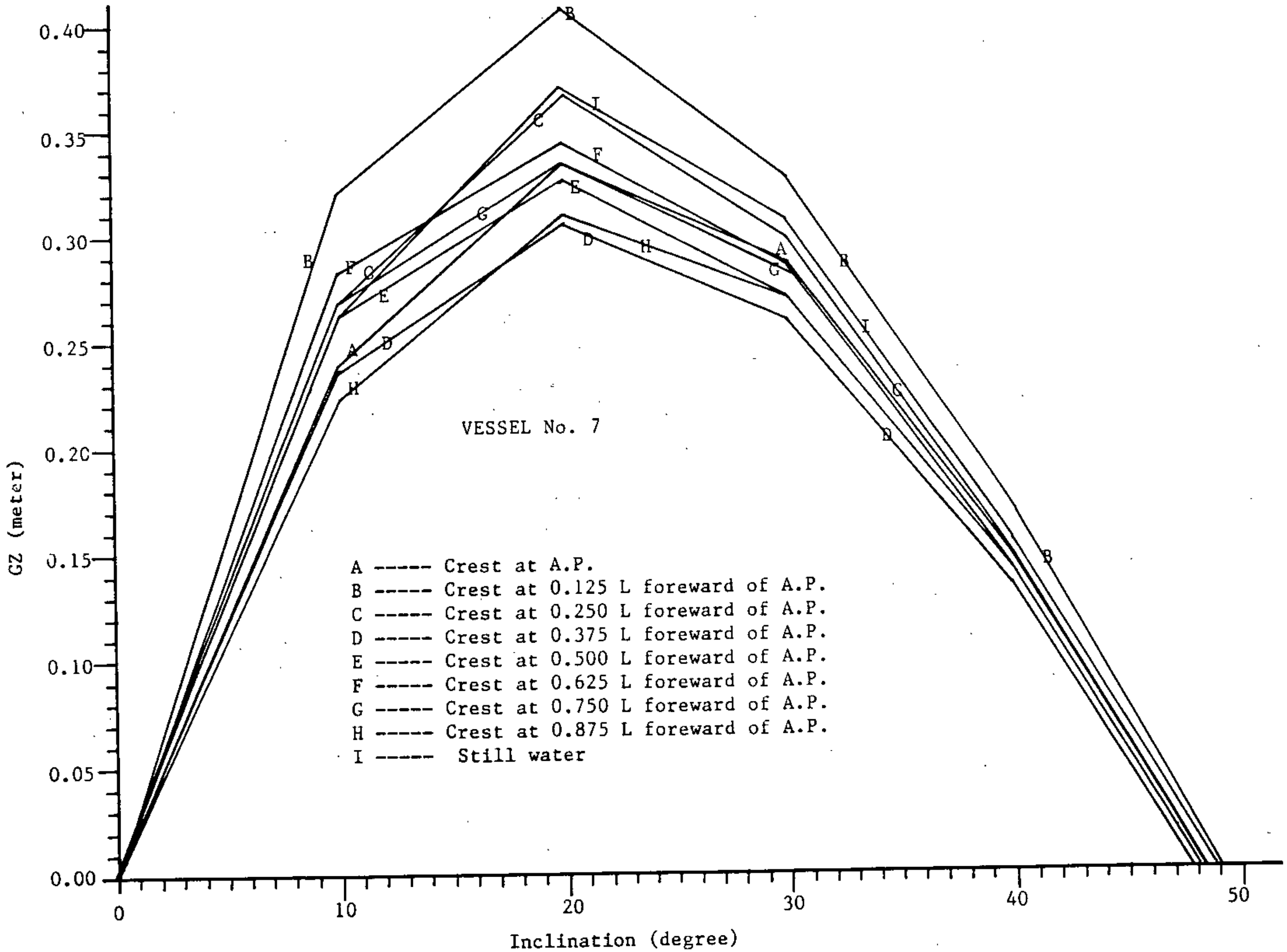

Fig. 4.100 : GZ curve in still water and in wave.
VESSEL No. 7

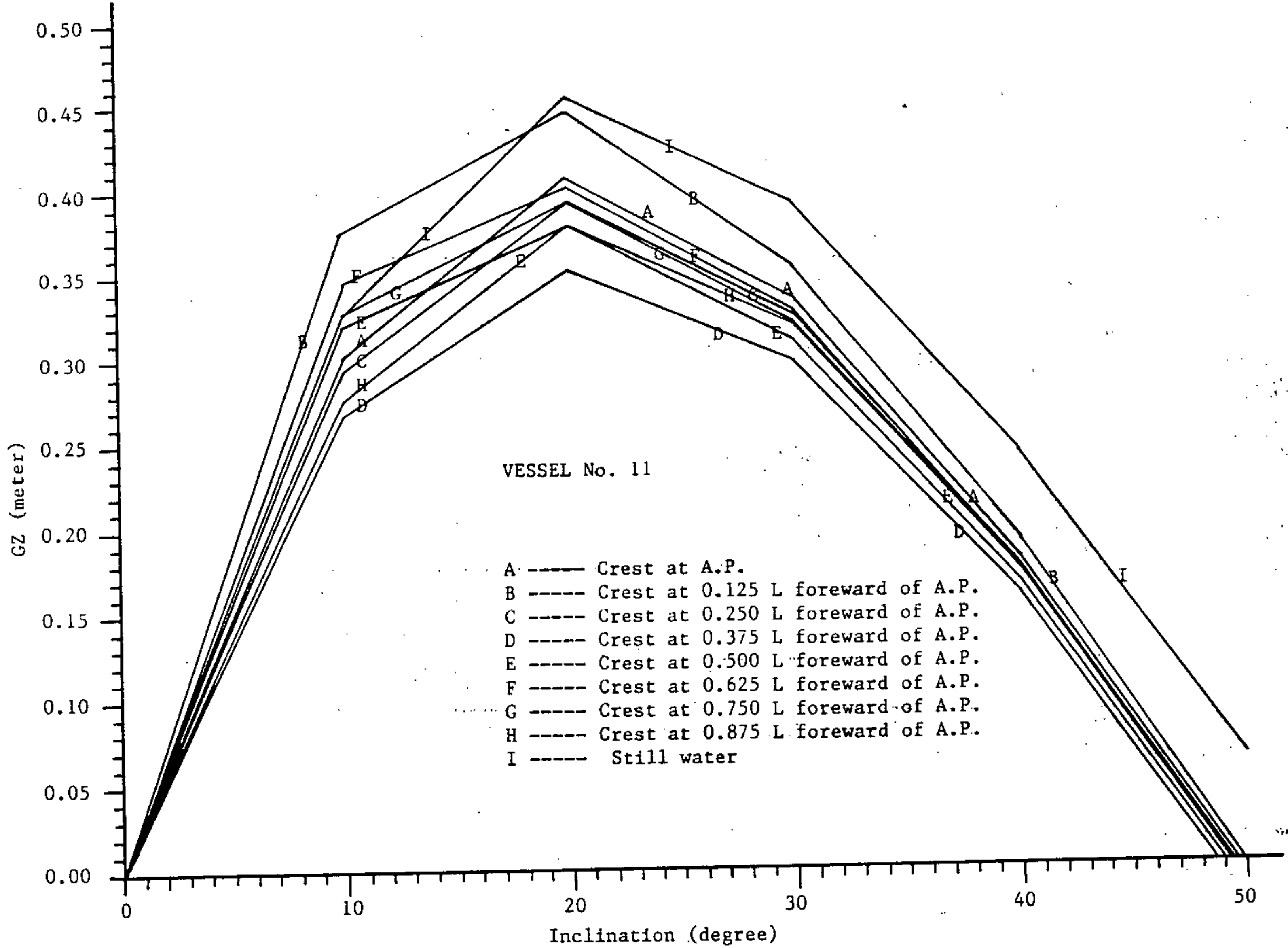

Fig. 4.101 : GZ curve in still water and in wave.

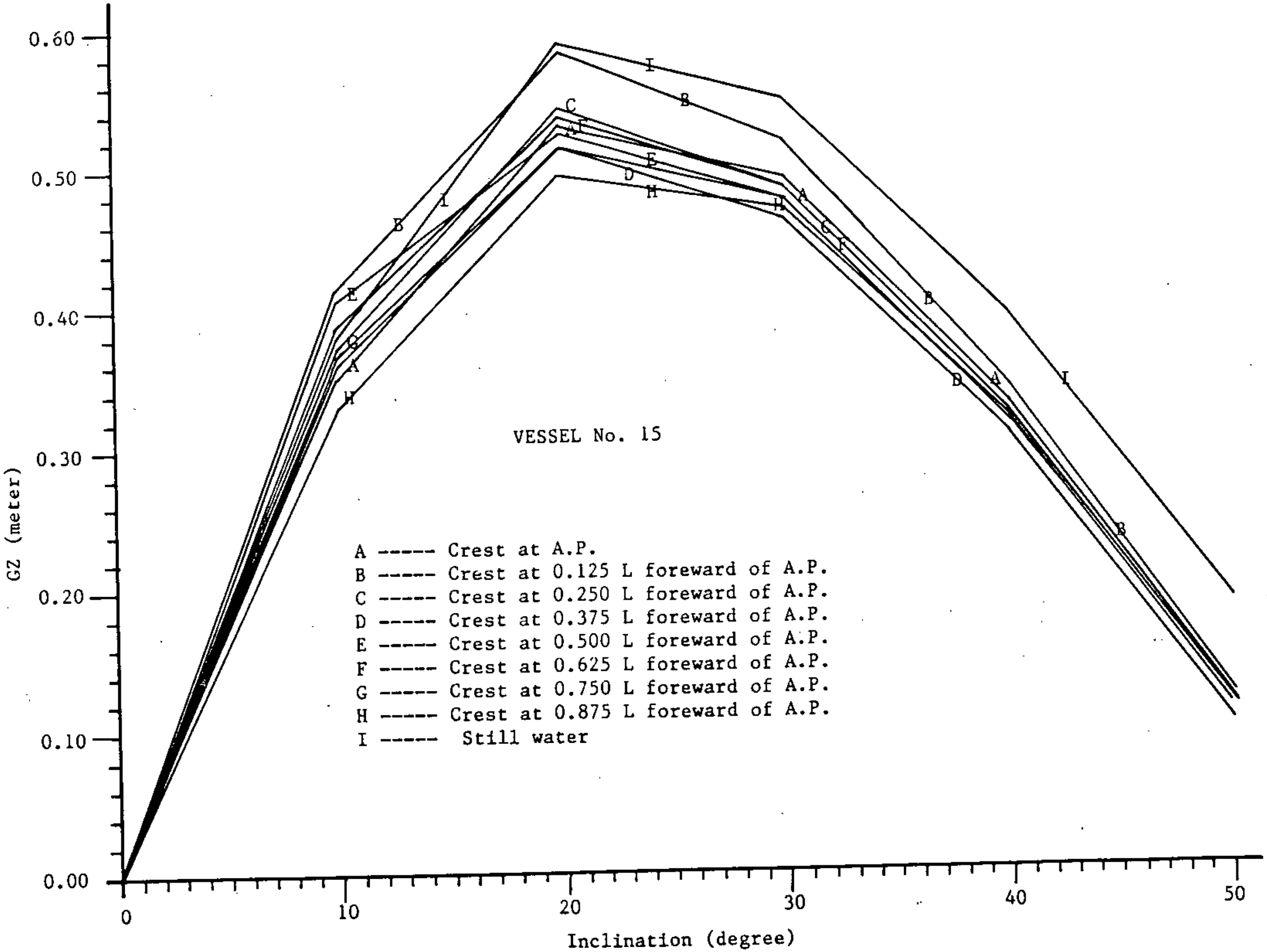

Fig. 4.102 : GZ curve in still water and in wave.

VESSEL No. 15

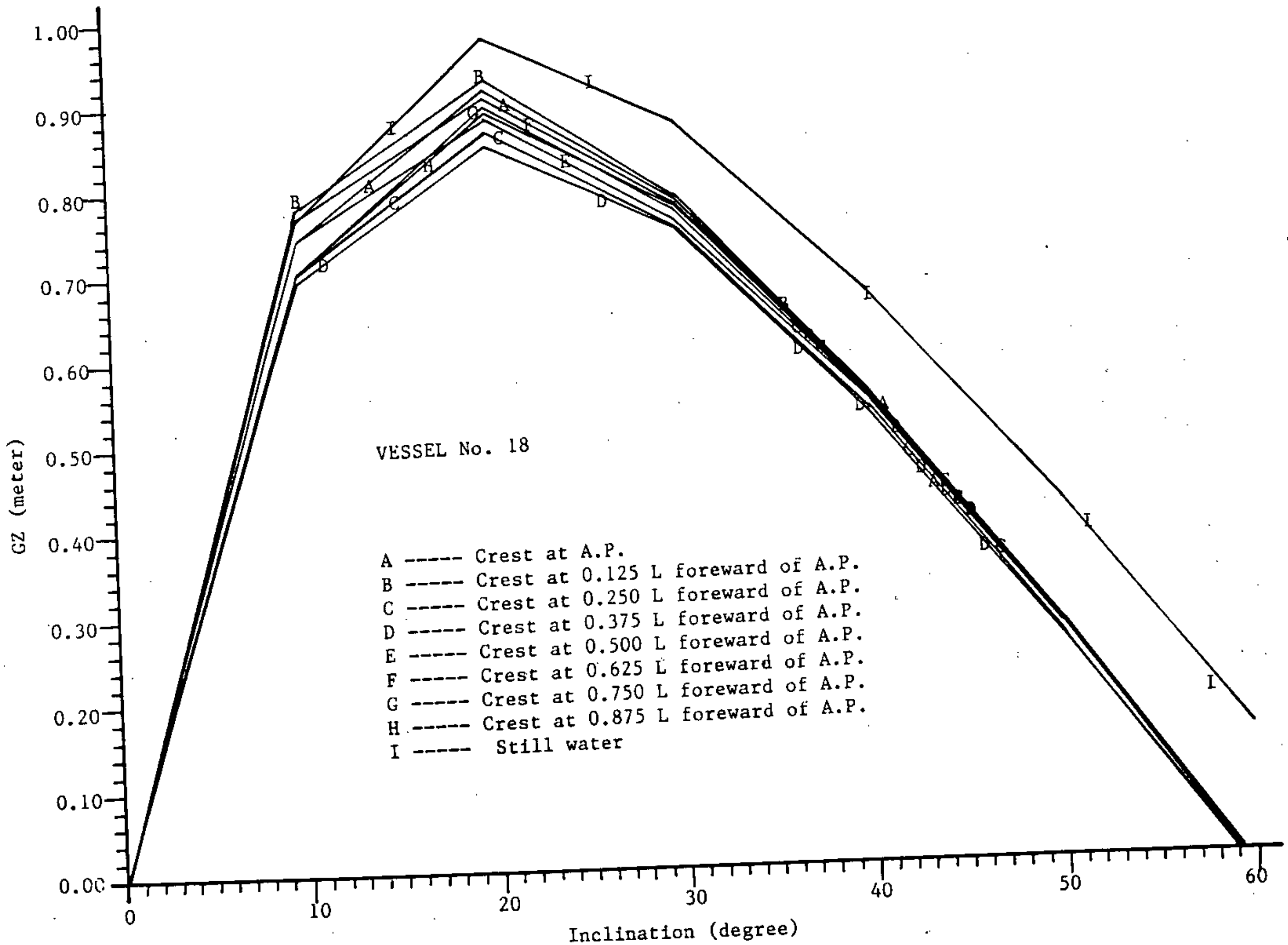

Fig. 4.103 : GZ curve in still water and in wave.
VESSEL No. 18

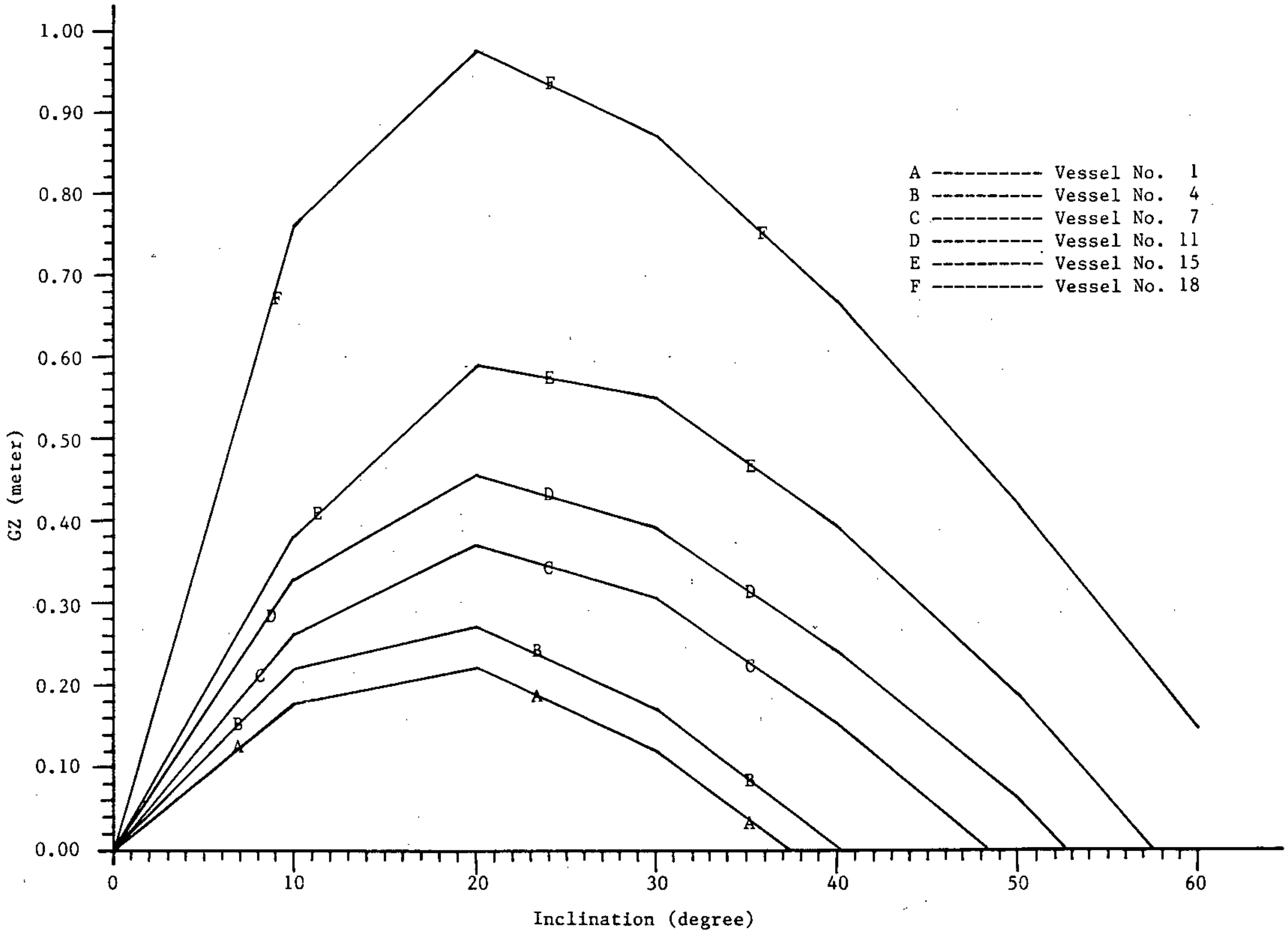

Fig. 5.1 : GZ curves of vessels 1, 4, 7, 11, 15 and 18

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SYMBOLS USED IN APPENDICES A, B AND C

A_{vp}	Area of the vertical profile area upto load water line.
A_{wvp}	Area of the whole vertical profile area.
D_p	Propeller diameter.
Disk	Fraction of the propeller disk area blanketed by rudder turned to 45^0.
f_{min}	Minimum freeboard.
H_{fcle}	Height of the forecastle.
H_p	Height of the propeller above base line.
H_{poop}	Height of the poop deck.
H_{vp}	Height of the centriod of the vertical centre plane area upto water line.
L_{fcle}	Length of forecastle.
L_{poop}	Length of poop.
L_{IMCO}	Length of the vessel as defined by IMCO (presently IMO).
M_{vp}	Moment of the vertical profile area about baseline.
M_{wvp}	Moment of the whole Profile area about baseline.
N_p	Number of propellers.
θGZ_{max}	Inclination corresponding to maximum GZ.

APPENDIX A

STABILITY CRITERIA IMO RES A.167

As this vessel is required to be in compliance with IMO Resolution A167 concerning minimum stability requirements, it is most important to ensure that in any sailing condition the stability at least complies with the following minimum criteria:

A. Area under curve upto 30 degrees to be not less than 0.055 m-radians

B. Area under curve upto θf degrees to be not less than 0.09 m-radian.

C. Area between 30 degrees and θ_f degrees to be not less than 0.03 m-radians

D. GZ to be at least 0.20 m at an angle between 30 degrees and θ_f degrees

E. Initial GM to be not less than (i) 0.15 m for L >= 70 m
(ii) 0.35 m for L < 70 m

F. Maximum GZ should occur at an angle preferably greater than 30 degrees, but in no condition less than 25 degrees.

θ_f = 40 degrees or any lesser angle at which the lower edges of any opening in the hull, superstructure or deckhouse which may lead to below deck and can not be closed watertight, would be immersed. However, small openings through which progressive floodings can not take place are to be ignored.

APPENDIX - B

Stability Criteria Under Practice : Static Stability

1. Argyriadis formula for towing vessels:

GM be at least { shp x (H_T - H_{vp})/(f_{min} / B) }

2. Japanese Fishing Boat:

For Seiners GM be at least { B/23.0 + 0.8853 } or { L_{IMCO} /120 + 0.8853 } whichever is greater.

For other fishing vessels :

For Breadth less that 22.966 ft.

GM be at least { B/25 + 0.3937 } or { L_{IMCO} /150 + 0.3937 } whichever is greater.

For Breadth greater than or equal to 22.966 ft

GM be at least [{(B/3.2808-7.0)/12.0+0.40} x 3.28083 or [{(L_{IMCO}/3.2808-4.2)/72.0+0.40} x 3.28083 whichever is greater

3. Murphy's proposal for towing vessel.

GM be at least X/Y

Where X = N_p x (shp x D_p)0.667 x Disk x (H_T - H_p)

Y = 76.0 x Displacement x f_{min} / B

4. Proposed Norwegian Criterion (Towing vessel).

GM be at least $\{(H_T - D/2) \times 3.2808 \}/(5.0 \times f_{min})$

5. Polish simplified criterion.

GM be at least $D \times (0.105 - 0.706 \times (f_{min} / B)+0.083*B/D)$

6. Polish not so simplified criterion

GM be at least $1.3123 - 2.0 \times B \ / \ (A_1 + A_2)$

Where $A_1 = -0.061 + 0.376 \times (f_{min}/B) - 0.831 \times (f_{min}/B)2$

$A_2 = 0.007 \times B/D + 0.028 \{L_{fcle} \times H_{fcle} + L_{poop} \times H_{poop}\} / L_{IMCO}$

7. Rooch formula for towing vessels.

GM be at least

$BHP \times 15.0 \{H_T - H_{VP}\} / [Displacement \{f_{min} / B\} \times 2240]$

8. Roorda formula.

GM be at least $0.6 \times B$

9. IMO simplified criterion.

GM be at least $1.7388 + 2.0 \times B \ (GM_1 + GM_2)$

Where $GM_1 = 0.075 - 0.37 \{f_{min}/B\} + 0.82 \{f_{min}/B\}2$

$GM_2 = - 0.014\ B/D - 0.032 \{L_{fcle} \times H_{fcle} + L_{poop} \times H_{poop}\} / LWL$

10. Soviet simplified criterion.

GM be at least equal to $D\{-0.47 - 0.35\, f_{min}/B + 0.35\, B/D\}$

11. Townsend formula.

GM be at least $0.08 \times B_2 / \{12 \times fmin\}$

12. US Coast Guard towing vessel criterion.

GM be at least X/Y

Where $X = N_p \times (shp \times P_D/N_p)0.6667 \times Disk \times (H_T - H_P)$

$Y = 38.0 \times Displacement \times f_{min} / B$

13. Wind heel criterion.

GM be at least $X_p\, h\, (A_{wvp} - A_{vp}) / (Displacement \times f_{min}/B)$

where $X_p = 0.005 + (L_{BP} / 14200)2$

$h = [\{M_{wvp} - M_{vp}\}/\{A_{wvp} - A_{vp}\}]/H_{vp}$

but f_{min}/B is not to be taken greater than 0.24933

14. Wood formula.

GM be at least

$[\{SHP \times P_D\}/N_P]0.667x(H_T - H_P) \times Displacement$

$\times f_{min}/\{B \times 24\}$

Criteria mentioned in the text are not repeated.

APPENDIX - C

Stability Criteria Under Practice : Dynamic Stability

1. German Democratic Republic stability criteria.

   (i) GZ at 30^0 be at least 0.82 ft

   (ii) GZ at 60^0 be at least zero.

2. Leatherd formula.

   (i) GM be at least { $1.0 + 0.02 \times L_{IMCO}$ }

   (ii) GZ_{MAX} be at least $0.0833 \times L_{IMCO} + 0.25$

   (iii) GZ at 60^0 be at least zero.

   (iv) f_{min} be at least $0.02 \times L_{IMCO} + 0.50$

   (v) f_{min} / {B/2} be at least 0.1763

3. Polish dynamic criteria.

   (i) GZ at 30^0 be at least 0.656 ft

   (ii) GZ at 60^0 be at least zero

   (iii) GM be at least zero

4. Soviet Union dynamic stability criteria:

   (i) GZ_{max} be at least 0.82 ft

   (ii) θGZ_{max} be at least 30^0

   (iii) GZ at 60^0 be at least zero.

5. US dynamic Stability criteria for towing vessel.

(i) H_a at the flooding angle must be greater than righting arm

where $H_a = 2 \times N_P \times Disk \times \{ H_T - H_{VP} \} \times Cos\ \theta$

$\times \{(SHP \times D_P)/N_P\}0.667\ /(38.0 \times Displacement)$

(where θ is the angle of heel)

(ii) The area between the GZ curve and the Ha curve upto maximum righting arm, 40 degrees or the angle of the downflooding, whichever is least must be at least 2 ft-degrees.

Criteria mentioned in the text are not repeated.

APPENDIX D

STRATHCLYDE METHOD

This proposal for stability assessment is a result of studies carried out under the SAFESHIP Project of the UK government. The project is aimed at finding out means to ensure safety of ships. The University of Strathclyde at Glasgow was a major participant in the project. Research started in 1973 and it took several years to come out with such a proposition. In this method a balance is drawn between all restoring and excitation energies; to be safe, restoring energy must be more than excitation one. This is much like the method presented in references 43 and 44, the difference being that it is a quasistatic approach, and effects of incident wave, encounter frequency, roll damping, wind heeling etc. are all taken into account. The steps are as follows:

The vessel is assumed to be floating in regular waves of length generally equal to that of the vessel and frequency of encounter derived from vessels service speed. The vessel rolls between a windward angle θ_1 derived from weather criterion as in references 43 and 44. The extreme leeward angle θ_2 is taken minimum of 50^0, flooding angle and the second angle of intersection of heeling arm and righting arm curves. A rolling from θ_1 to θ_2 and back will complete a rolling cycle. As the vessel passes over the regular wave oscillating between θ_1 and θ_2 with frequency equal to that of encounter, the resulting GZ will be a function of not only inclination but also of time. This is because as the vessel proceeds the position of the crest, or say trough, of the wave along the ships length will be changing causing a shift in the GZ curve. As a general rule, the GZ curve shift upward from that in calm water when the trough is at the midship and the downward when crest at amidship. As the vessel rolls and advances along the wave, the righting arm (GZ) curve will depend on at what positioning of the wave along the ship's hull the rolling had started. The curve for rolling from θ_1 to θ_2 will be different from that of θ_2 to θ_1. The first half cycle of the rolling i.e., from θ_1 to θ_2 comes under investigation. Critical roll cycle (half cycle from θ_1 to θ_2) is the one during which the area under the GZ curve is minimum i.e. in other words minimum restoring energy. This GZ curve, instead of the calm water curves is used for investigation of the stability.

In addition to the righting arm (GZ) other forces affecting the motion such as beam wind, unsymmetric loading, roll damping etc. are taken care of. At different inclinations effects of each individual force in terms of moment lever are computed and superimposed on the GZ curve. The vessel starts rolling from a windward angle θ_1 to the leeward direction due to an excitation by an exciting force. Excitation energy starts accumulating with rolling. Since the vessel is moving toward upright position the righting arm GZ itself will contribute to accumulation of this excitation energy. This accumulation of excitation energy will continue till restoring forces appear, which will happen after exceeding the angle of heeling to be determined by the GZ curve, wind heeling arm curve, motion damping curve and effects of other forces. However, the vessel will be rolling to an angle θ_2 in the leeward direction. But after exceeding the heeling angle the vessel will tend to get upright and this will be resisted at the expenses of accumulated excitation energy. If this excitation energy is not exhausted before the vessel rolls to the extreme leeward angle θ_2 it will be termed 'unsafe'. This is because the excitation energy appears to be predominant over the restoring one. A safe vessel will have more restoring energy than that of excitation. The above process is summarized in figure-3.10.

APPENDIX E

LYAPUNOV METHOD

This method developed by the BMT is also a result of researches under the 'SAFESHIP' project[92]. The method is derived through a rigorous analytical treatment using a mathematical technique developed by Lyapunov. It was meant for estimating whether, under a certain environment, the energy of the system would decrease after a disturbance. If so, the system can be said to be stable.

The rolling motion of a vessel obeys the following second order differential equation : -

$$\ddot{\theta} + f(\theta)\,\dot{\theta} + g(\theta) = e(t) \qquad \text{.................(E.1)}$$

where θ = angle of heeling

$\dot{\theta}$ = speed of rolling motion

$\ddot{\theta}$ = accelaration of rolling motion

$f(\theta)$ = the linearized damping function

$g(\theta)$ = the restoring function

$e(t)$ = the excitation function

But Lyapunov method does not attempt to solve the above differential equation, since apart from being anything else this cannot result in a usable stability criteria. The investigation is centered around the energy contained in a rolling ship. At an inclination the total energy is:

$$0.5 \times [\dot{\theta} + F(\theta)]^2 + G(\theta) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (E.2)$$

$$\text{where} \quad F(\theta) = \int_0^\theta f(\theta)\, d\theta \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (E.3)$$

$$G(\theta) = \int_0^\theta g(\theta)\, d\theta \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (E.4)$$

Now it is necessary to differentiate the expression. If the derivative is negative in a certain environment, the vessel is stable. But this analytic operation is not so simple, specially if a simple usable criteria has to be found. A detailed analysis has be carried out by Saraiva[70].

However, a summary of the analysis is given below without going into details.

The substantial derivative of the expressions for total energy U (Equation E.2) becomes:

$$\frac{dU}{dt} = e\dot{\theta} + F(e - g) \quad \text{.....................(E.5)}$$

For an excitation that switches sign in time, the sign of U will be indeterminate. To avoid such a situation the Lyapunov function is taken of the form:

$$V(\theta, \dot{\theta}) = 0.5 \times [\dot{\theta} + F(\theta) - h(\theta)]^2 + G(\theta) \quad \text{........(E.6)}$$

Where h(θ) is an arbitrary functions satisfying certain conditions which will be discussed later.

The restoring function 'g' (GZ curve) should satisfy the following conditions:

(i) $g(x) = - g(-x)$

(ii) $g(-\theta_v) = g(0) = g(\theta_v) = 0$ ....(E.7)

(iii) $g(x) > 0$ for $0 < x < \theta_v$

θ_v is the angle of vanishing stability

The roll damping function f(x) should satisfy the following condition.

$$f(x) = - f(-x) \quad -\theta_v < x < \theta_v \quad \text{............(E.8)}$$

Conditions E.7(i) and E.8 are not essential but will make further analysis simple.

If the arbitrary function $h(\theta)$ satisfy the following conditions, the Lyapunov function V will remain representative of the vessel.

(i) $h(0) = F(0)$

(ii) $h(\theta_v) = F(\theta_v)$, $h(-\theta_v) = F(-\theta_v)$

(iii) $F(0) < h(\theta) < F(\theta) \qquad 0 < \theta < \theta_v$

$F(0) > h(\theta) > F(\theta) \qquad -a < \theta < \theta_v$

iv) There is a $c > 0$ such that

$$h'(\theta) >= c \quad \text{for } -\theta_v < \theta < \theta_v$$

v) for any $\alpha > 0$ ..(E.9)

$$h'(\theta) < \frac{\alpha \quad g(\theta)}{F(\theta) - h(\theta)}$$

The derivative of the function V takes the form

$$V(\theta, \dot{\theta}, e) = -h(\theta)\dot{\theta}^2 + [e - h'(\theta)(F(\theta) - h(\theta))]\dot{\theta}$$

$$+ (F(\theta) - h(\theta))(e - g(\theta)) \quad ....(E.10)$$

Since all concerned functions are either symmetric or antisymmetric and positive excitations generally create the most critical condition, the positive quadrant will only be considered in the rest of this analysis.

Equation E.10 is a quadratic in θ. The discriminant is of the form:

$$D(\theta, e) = [e - h'(F-h)]^2 + 4 h' (F-h) (e-g) \quad \text{........(E.11)}$$

The quadratic reduces to zero when

$$e = PSI1(\theta) = [h'(F-h)]^{0.5} \; [2 g^{0.5} - \{h'(F-h)\}^{0.5}] \quad \text{......(E.12)}$$

$$\text{or } e = PSI2(\theta) = [h'(F-h)]^{0.5} \; [2 g^{0.5} + \{h'(F-h)\}^{0.5}] \quad \text{......(E.13)}$$

If the value of α is taken equal to 4.0 conditions E.9(iii). E.9(iv), E.9(v) will ensure that both PSI1(θ) and PSI2(θ) exists and the earlier will always be positive and the latter negative.

A study of the equations E.11, E.12, and E.13 will reveal that if $e <$ PSI1(θ) $\dot{V}$ will be negative. But if $e >=$ PSI1(θ) $\dot{V}$ may have either positive or negative sign. Since $\dot{V}$ negative simply indicate stable motion of the vessel, the aim is to exclude the domain where V is positive. So the region of $e >=$ PSI1(θ) is to be investigated only. In this region exists the roots of the equation E.11 which are

$$\theta = PHI1(\theta,e) = [e - h'(F-h) - D^{0.5}] \,/\, 2 h' \quad \text{......(E.14)}$$

$$\theta = PHI2(\theta,e) = [e - h'(F-h) + D^{0.5}] \,/\, 2 h' \quad \text{......(E.15)}$$

Since the coefficients of θ^2 in equation E.11 is negative, $\dot{V}$ will be negative for $|\theta|$ large.

So the $\dot{V}$ positive region reduces to PSI1(θ) <= e

and PHI1 < θ < PHI2 or PHI2 < θ <PHI1.

Finally it has been shown that a stable motion of a vessel

(i) can not start from

(ii) The Lyapunov function can not be more than the maximum in;

the $\dot{V}$ positive region.

The analysis results in the plotting of the domain of stability in terms of θ and θ of a vessel subjected to a certain excitation. For example, Figure 3.7 reproduced from Saraiva's[70] work is for a fishing vessel excited to an accelaration of 2.73 deg/s^2. A motion starting within this domain will be stable, i.e., the vessel will eventually become upright. Figure 3.7 also shows that the maximum allowable angle of inclination is 60^o and at upright condition it can withstand a roll speed of 30^o/sec.

In addition to steady winds, it can take account of gusts acting for a short period of time with high intensity. If the resulting motion crosses the domain, the vessel will capsize.

Phillips[80] has proposed a slightly different method for assessing roll stability of a vessel. This is easier for adoption, of course, subject to validation. It consists of plotting the PSI1 curve versus inclination.

$$PSI1(\theta) = \{h'(F-h)\}^{0.5} \; [2 \times g^{0.5} - \{h'(F-h)\}^{0.5}] \; ....(E.16)$$

Where 'h' is an arbitrary function introduced by Saraiva[70] satisfying the above mentioned preconditions (Equation E.9). Phillips also introduced certain simplifications. The excitation lever is taken constant and independent of inclination. The excitation lever is superimposed on PSI1 curve (see Figure-3.8). The ratio of the area AC to the area under the PSI1 curve may form the requirement of a criterion, limiting values to be determined after studying the disaster cases. A number of vessels have been investigated using computer softwares developed by BMT and reported in reference 80.

In course of the analysis the aim is to search the most optimum function which will maximize the 'span of intersection' between the excitation lever and the PSI1 curve. Absence of any 'span of intersection' will indicate absence of any domain of stability. In other words, the vessel will capsize if subject to an excitation of such intensity. No indication of the nature of the function is available. But researchers have been experimenting with an equation of the form:

$$h = a\,\theta + b\,\theta^3 \; ....(E.17)$$

where 'a' and 'b' are constants depending on hull parameters and the excitations. Phillips[80] have reported some uniformity in the values of 'a' and 'b', which is discussed in detail in the thesis.

TABLE 4.1

PARTICULARS OF SUBJECTS VESSELS:

	Length (m)	Breadth (m)	Depth (m)	Free board (m)	Draft (m)	D_{FW} (tonne)	D_{SW} (tonne)	AWP (m^2)	LCB* (m)	LCF* (m)
Vessel No. 1	23.500	6.100	1.600	.300	1.300	122.193	125.248	119.874	-.392	-.929
Vessel No. 2	24.400	6.700	1.975	.300	1.675	170.131	174.384	139.108	-.488	-1.004
Vessel No. 3	29.000	6.710	1.910	.331	1.579	188.768	193.488	166.038	-.555	-.956
Vessel No. 4	29.000	6.710	1.910	.331	1.579	187.292	191.974	165.174	-.566	-.958
Vessel No. 5	30.120	6.706	1.981	.339	1.642	224.632	230.247	171.569	-1.263	-1.086
Vessel No. 6	30.250	6.860	1.980	.340	1.640	220.091	225.594	182.988	-.376	-.932
Vessel No. 7	31.400	7.000	2.000	.349	1.651	227.606	233.295	190.254	-.268	-1.059
Vessel No. 8	31.440	6.710	1.910	.349	1.561	200.702	205.719	179.513	.407	-.043
Vessel No. 9	31.500	6.950	1.988	.350	1.638	227.745	233.439	188.471	-.300	-1.011
Vessel No. 10	34.500	7.310	2.133	.373	1.760	306.237	313.893	219.455	-.607	-1.090
Vessel No. 11	37.034	7.920	2.218	.392	1.826	363.377	372.460	264.280	.031	-.848
Vessel No. 12	37.060	7.848	2.178	.393	1.785	353.352	362.186	257.396	.151	-.612
Vessel No. 13	37.425	7.100	2.100	.395	1.705	305.501	313.139	227.546	-.968	-1.269
Vessel No. 14	38.000	7.830	2.175	.400	1.775	352.919	361.742	259.363	-.402	-1.237
Vessel No. 15	38.000	7.930	2.075	.400	1.675	328.878	337.100	258.336	-.394	-1.172
Vessel No. 16	38.558	7.334	2.199	.404	1.795	328.144	336.347	239.129	-.917	-1.729
Vessel No. 17	42.800	8.840	2.050	.437	1.613	431.264	442.045	330.271	-.311	-1.286
Vessel No. 18	47.000	10.660	2.280	.490	1.790	547.597	561.286	422.557	-1.399	-2.079

* Positive for foreward of midship.

TABLE 4.1 (CONTD.2)

PARTICULARS OF SUBJECTS VESSELS:

	L/B	B/D	D/d	C_b	C_m	C_{wp}	C_p	C_{vp}
Vessel No. 1	3.8525	3.8125	1.2308	.6557	.9236	.8362	.7100	.7841
Vessel No. 2	3.6418	3.3924	1.1791	.6213	.9236	.8509	.6727	.7302
Vessel No. 3	4.3219	3.5131	1.2094	.6143	.8966	.8533	.6851	.7199
Vessel No. 4	4.3219	3.5131	1.2094	.6095	.8971	.8488	.6794	.7180
Vessel No. 5	4.4915	3.3852	1.2067	.6774	.9044	.8494	.7490	.7975
Vessel No. 6	4.4096	3.4646	1.2076	.6468	.8942	.8818	.7234	.7335
Vessel No. 7	4.4857	3.5000	1.2115	.6273	.8875	.8656	.7068	.7247
Vessel No. 8	4.6855	3.5131	1.2239	.6096	.8895	.8509	.6854	.7164
Vessel No. 9	4.5324	3.4960	1.2136	.6351	.8877	.8609	.7154	.7377
Vessel No. 10	4.7196	3.4271	1.2119	.6899	.9478	.8702	.7279	.7928
Vessel No. 11	4.6760	3.5708	1.2150	.6786	.8836	.9010	.7680	.7532
Vessel No. 12	4.7222	3.6033	1.2199	.6805	.8958	.8850	.7596	.7689
Vessel No. 13	5.2711	3.3810	1.2320	.6745	.9079	.8563	.7429	.7876
Vessel No. 14	4.8531	3.6000	1.2252	.6682	.9233	.8717	.7237	.7665
Vessel No. 15	4.7919	3.8217	1.2387	.6515	.9055	.8573	.7195	.7600
Vessel No. 16	5.2574	3.3352	1.2252	.6465	.9050	.8456	.7144	.7645
Vessel No. 17	4.8416	4.3122	1.2707	.7065	.9337	.8729	.7567	.8094
Vessel No. 18	4.4090	4.6754	1.2738	.6106	.8664	.8434	.7048	.7240

TABLE 4.1 (CONTD.3)

PARTICULARS OF SUBJECTS VESSELS:

	KMT	KML	KB	S. Area	MCT1M	D 1 M T	A_{mid}
Vessel No. 1	3.256	36.016	.734	131.865	183.452	-4.738	7.324
Vessel No. 2	3.632	32.479	.978	157.109	219.645	-5.724	10.365
Vessel No. 3	3.730	49.918	.930	183.143	318.872	-5.470	9.501
Vessel No. 4	3.712	49.954	.931	182.692	316.598	-5.455	9.506
Vessel No. 5	3.464	45.473	.947	198.461	332.097	-6.187	9.957
Vessel No. 6	3.898	52.378	.963	199.931	374.072	-5.640	10.058
Vessel No. 7	3.378	57.386	.977	210.669	408.865	-6.413	10.256
Vessel No. 8	3.755	59.422	.920	197.085	373.394	-5.952	9.314
Vessel No. 9	3.842	55.691	.964	209.097	395.711	-6.050	10.106
Vessel No. 10	3.810	58.061	.991	249.973	506.707	-6.937	12.194
Vessel No. 11	4.428	72.944	1.067	288.657	705.294	-6.055	12.776
Vessel No. 12	4.299	72.214	1.034	284.669	678.734	-4.252	12.552
Vessel No. 13	3.722	68.698	.967	262.236	552.898	-7.715	10.988
Vessel No. 14	4.340	72.151	1.017	287.777	660.681	-8.445	12.833
Vessel No. 15	4.555	75.515	.961	278.359	645.376	-7.968	12.028
Vessel No. 16	3.866	70.758	1.031	270.833	593.485	-10.720	11.913
Vessel No. 17	5.355	94.206	.899	331.993	940.195	-9.923	13.315
Vessel No. 18	7.452	109.261	1.061	392.505	260.723	-18.692	16.532

TABLE 4.2

ESTIMATION OF WAVE HEIGHT FROM WAVELENGTH

Length (m)	10.0	20.0	30.0	40.0	50.0
Height (m) Equation 4.1	1.805	2.881	3.597	4.107	4.488
Height (m) Equation 4.2	1.920	2.715	3.325	3.839	4.292
Height (m) Equation 4.2	0.954	1.818	2.609	3.333	4.000
Mean of 4.1, 4.2 and 4.3	1.560	2.471	3.177	3.760	4.260

TABLE 4.3

ESTIMATION OF WAVE HEIGHT FROM WIND SPEED

Wind Speed Knots	10.0	20.0	30.0	40.0	50.0	60.0	70.0
Wave Height meter	0.568	2.272	5.112	9.088	14.20	20.45	27.832

TABLE 5.1

STABILITY INPUT PARTICULARS OF SUBJECT VESSELS

Item	Vessel No 1	Vessel No 4	Vessel No 7	Vessel No 11	Vessel No 15	Vessel No 18
Displacement						
Loaded	122.19	187.29	227.61	363.38	328.88	547.60
Light	45.21	63.93	81.55	95.77	112.52	195.43
Capacity						
Cargo (Tonne)	60.53	101.22	121.06	234.04	187.06	295.03
Passenger* (no.)	230	310	350	470	410	800
KG Loaded (m)	1.915	2.093	2.055	2.051	2.091	2.098
Windage area (m^2)	101.5	128.3	140.2	183.2	185.4	236.4
Windage area lever (m)	3.075	3.413	3.336	3.772	3.651	3.950
Passenger movement lever (m)	1.525	1.678	1.750	1.980	1.983	2.665
Passenger moment (t x m)	25.05	37.16	43.75	66.47	58.07	152.29

* Passengers weighing 160 pounds (72.72 Kg) on an average.

TABLE 5.2

INTACT STABILITY CRITERIA IMO RES A 167

Item	Limit	Vessel No 1	Vessel No 4	Vessel No 7	Vessel No 11	Vessel No 15	Vessel No 18
GM	0.15	1.3410	1.6190	1.8230	2.3770	2.4640	5.3540
A_{30}	0.055	0.0860	0.1076	0.1438	0.1790	0.2253	0.3992
A_{40}	0.090	0.0936	0.1238	0.1852	0.2353	0.3089	0.5346
A_{30-40}	0.030	0.0075	0.0162	0.0413	0.0563	0.0836	0.1353
GZ_{30}	0.20	0.1205	0.1705	0.3055	0.3895	0.5475	0.8690
θ_{max}	25.0	18.5	18.25	21.5	22.0	23.75	19.0
GZ_{max}	None	0.2230	0.2742	0.3705	0.4559	0.6018	0.9770
θ_v	None	37.75	40.5	48.75	53.5	58.5	65.25

TABLE 5.3

STABILITY AGAINST BEAM WIND: US COAST GUARD REQUIREMENT

	Limit	Vessel No 1	Vessel No 4	Vessel No 7	Vessel No 11	Vessel No 15	Vessel No 18
Heeling Lever Coefficient*	None	0.0407	0.0343	0.0226	0.0190	0.0206	0.0170
θ_o	None	2.8	2.0	1.6	1.2	1.2	0.8
θ_2	None	35.6	38.8	47.6	50.0	50.0	50.0
Maximum Win-ward angle θ_1	None	22.2	23.0	23.4	23.8	23.8	24.2
GZ_s	None	0.0631	0.0573	0.0523	0.0500	0.0546	0.0811
GZ_s/GZ_{max}	Max^m 0.60	0.2832	0.2090	0.1413	0.1097	0.0908	0.0830
Area A_1	None	0.0719	0.1037	0.1816	0.2492	0.3460	0.6178
Area A_2	None	0.0779	0.0940	0.1130	0.1401	0.1702	0.3118
A_1/A_2	1.40	0.9239	1.1031	1.6070	1.7776	2.0329	1.9811

(*) Heeling arm = Heeling arm coefficient x $\cos^2 \theta$

TABLE 5.4

STABILITY AGAINST BEAM WIND: IMO CRITERIA

	Limit	Vessel No 1	Vessel No 4	Vessel No 7	Vessel No 11	Vessel No 15	Vessel No 18
Heeling Arm	None	0.0959	0.0880	0.0774	0.0718	0.0777	0.0643
θ_o	None	4.8	3.2	2.8	2.0	2.0	0.8
θ_2	None	32.0	35.6	44.4	49.6	50.0	50.0
GZ_s	None	0.1019	0.0885	0.0890	0.0817	0.0897	0.0811
GZ_s/GZ_{max}	None	0.4568	0.3227	0.2403	0.1793	0.1491	0.0830
Area A_1	None	0.0397	0.0679	0.1357	0.2007	0.2935	0.5739
Maximum windward angle θ_1 (20)	None	16.8	17.6	18.4	18.8	18.8	19.2
Area A_2 (20^o)	None	0.0734	0.0848	0.0987	0.1178	0.1370	0.2421
A_1/A_2 (20^o)	1.0	0.5414	0.8012	1.3748	1.7037	2.1413	2.3701
Maximum windward angle θ_1 (25)	None	21.8	22.6	23.4	23.8	23.8	24.2
Area A_2 (25^o)	None	0.1099	0.1195	0.1303	0.1476	0.1693	0.2693
A_1/A_2 (25^o)	1.0	0.3616	0.5684	1.0411	1.3596	1.7331	2.1308

TABLE 5.5

STABILITY AGAINST PASSENGER CROWDING: US COAST GUARD REQUIREMENT

	Limit	Vessel No 1	Vessel No 4	Vessel No 7	Vessel No 11	Vessel No 15	Vessel No 18
Heeling Arm Coefficient	None	0.1848	0.1714	0.1453	0.1252	0.1137	0.1787
θ_o	15	12.8	8.8	6.8	4.8	4.4	3.2
θ_2	None	25.6	30.0	40.8	46.8	53.0	63.60
GZ_s	None	0.2031	0.2021	0.1951	0.1826	0.1883	0.3035
Gz_s/GZ_{max}	0.60	0.9108	0.7368	0.5267	0.4005	0.3129	0.3107
Area A_1	None	0.0945	0.1239	0.1969	0.2642	0.3740	0.6857
Area A_2	None	0.0085	0.0309	0.0972	0.1683	0.2743	0.4941
A_2/A_1	0.40	0.0905	0.2498	0.4938	0.6371	0.7335	0.7207

TABLE 5.6

VALUES OF ANGLE Ø AND Ø' IN KANSAI SOCIETY'S METHOD FOR

STABILITY AGAINST PASSENGER CROWDING

Vessel No	1	4	7	11	15	18
Ø (deg)	5.62	5.63	5.69	5.65	5.76	5.25
Ø' (deg)	4.50	4.51	4.56	4.53	4.61	4.21

TABLE 5.7

STABILITY ASSESSMENT BY STRATHCLYDE METHOD

Vessel No	θ_1 (Deg)	θ_0 (Deg)	θ_2 (Deg)	A_1 (m-rad)	A_2 (m-rad)	A_1/A_2	$\theta_{r,max}$ (Deg)
1	-22.25	2.75	33.00	0.0414	0.0944	0,4368	15.00
4	-22.75	2.25	37.50	0.0728	0.1108	0.6570	18.50
7	-23.25	1.75	47.25	0.1434	0.1361	1.0536	26.00
11	-23.50	1.50	48.50	0.1708	0.1492	1.1447	27.75
15	-23.75	1.25	50.00	0.2776	0.1830	1.5169	35.25
18	-24.25	0.75	50.00	0.5024	0.3020	1.6636	42.25

TABLE 5.8

STABILITY ASSESSMENT BY LYAPUNOV METHOD

			Wind Load And Passenger Crowding Combined				
Vessel No	a	b	θ_0 (Deg)	θ_2 (Deg)	A_1 (m.rad)	A_2 (m.rad)	A_2/A_1(%)
1	0.01067	5.5E-7			No bound exists		
4	0.01165	5.5E-7			No bound exists		
7	0.01185	5.5E-7			No bound exists		
11	0.01626	5.5E-7			No bound Exists		
15	0.01067	5.5E-7	12.75	31.0	13.192	0.306	2.320
18	0.03059	5.5E-7	6.50	43.25	24.691	4.193	16.982