CHAPTER 2

LITERATURE REVIEW

2.1 General

Many researchers have conducted numerous experimental works, analytical studies and numerical modeling to investigate the flow behavior of compound channels of both straight and meandering reaches. Study of floodplain encroachment in compound meandering channel has two aspects: i) physical modeling and experimental investigation and ii) numerical modeling and analytical analysis. In this section, as part of literature review, a brief summary of different works conducted by various researchers along with the basic theories relevant to the current study has been discussed.

2.2 Meandering Channels

The Meandering channel flow is considerably more complex than constant curvature bend flow. The flow geometry in meander channel due to continuous stream wise variation of radius of curvature is in the state of either development or decay or both. Figure 2.1 represents a simple meander reach with various characteristics that govern the behavior of flow in a meandering channel.

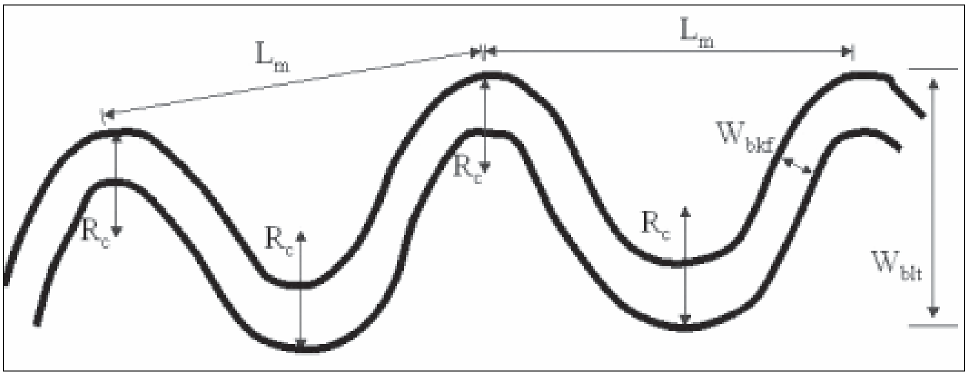

Figure 2.1: Schematic diagram of meandering channel with characteristic parameters

The figure defines various characteristic parameters, such as meander length ratio = L_m/W_{bkf} ; meander width ratio = W_{blt}/W_{bkf} and radius of curvature ratio = R_c/W_{bkf} (Harman, 2003). Some degree of sinuosity is required before a channel is called meandering. The meander ratio or sinuosity index is a means of quantifying how much a river or stream meanders. It is calculated as the length of the stream divided by the length of the valley. A perfectly straight river would have a meander ratio of 1. Sinuosity ratio more than 1.05 is classified as sinuous and meandering. As bed width is related to discharge, meander wavelength also is related to discharge. The quasi-regular alternating bend of stream meanders are described in terms of their wavelength λ_m, their radius of curvature r_m and their amplitude α_m. The following important studies are reported concerning the flow in meandering channels.

Hook (1974) measured the bed elevation contours in a meandering laboratory flume with movable sand bed for various discharges. For each discharge he measured the bed shear stress, distribution of sediment in transport and the secondary flow and found that with increasing discharge, the secondary current increased in strength.

Chang (1984a) analyzed the meander curvature and other geometric features of the channel using energy approach. It established the maximum curvature for which the river did the last work in turning, using the relations for flow continuity, sediment load, resistance to flow, bank stability and transverse circulation in channel bends. The analysis demonstrated how uniform utilization of energy and continuity of sediment load was maintained through meanders.

Imbalance in radial pressure around the bend causes the transverse velocity distribution in a meandering channel (FHWA, 2001). Figure 2.2 (a) represents a typical cross section within a bend and the velocity distribution. The radial forces that act on the shaded control volume are the centrifugal force. In addition, super elevation of the water surface, dz, results in the differential hydrostatic force γdz. Therefore, the centrifugal force is greater near the surface where the flow velocity is greater and less at the bed where the flow velocity is small. The differential hydrostatic force is constant throughout the depth of the control volume. In addition, figure 2.2 (b) explains that the combination of centrifugal force and hydrostatic force causes a secondary flow in the bend (FHWA 2001).

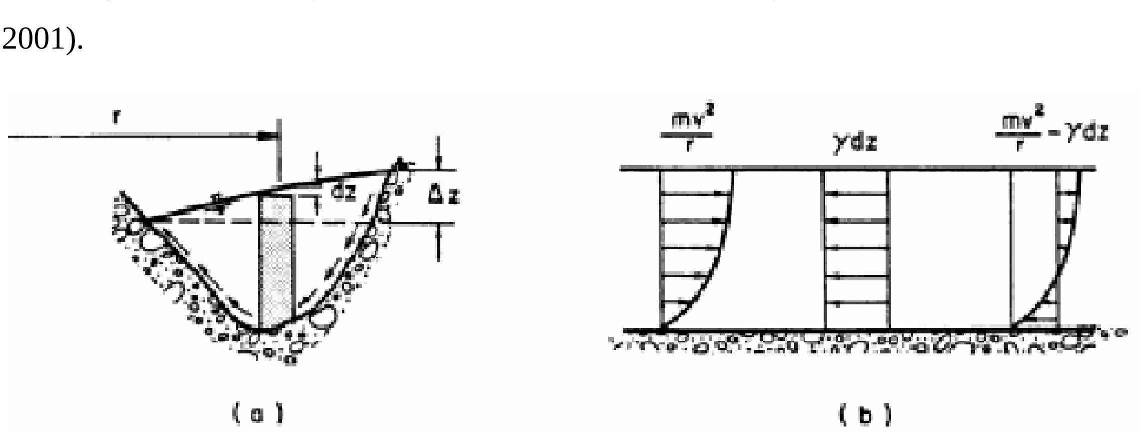

Figure 2.2: Descriptions of flow in meandering channel (Source: FHWA, 2001)

2.3 Encroachment at Floodplain in Compound Channels

A compound channel is usually defined as a simple main channel, which carries the normal low flows, with either one or two floodplains or berms at higher elevations on one or both sides of the main channel. The floodplains are usually dry and convey discharge only during flood conditions. Two stage or compound channels may be manmade or naturally occurring. In natural channels the first stage is the river channel and the second stage is the flood plain, which may be many times the width of the river. The second stage in manmade channels is usually termed a berm which can occur on one or both sides of the primary channel and is typically one or two times its width. The berms, which are normally exposed, are frequently grassed and may have bushes and trees growing on them.

The floodway is the channel of a river or stream and the overbank areas that must remain open to carry the deeper, faster moving water during a flood. If the remainder of the floodplain, called the floodplain fringe, is completely obstructed, the 100-year flood elevation would not increase more than one foot. Floodways are areas where fill or other development is likely to divert flow and contribute to increased water depths during a flood. Floodways may also be subject to high velocities, which can cause severe damage to structures and high risks for occupants and emergency responders. Ideally, floodways should be undeveloped areas that can accommodate flood flows with minimal risk. Any new development in the floodway generally requires an engineering analysis of the impact on flood hazards. (Figure 2.3). A driveway, road, or parking lot at grade (without any filling) would not cause an obstruction. Development of lakeshore floodplains, where there is no flow, is not considered an encroachment. An “encroachment” is any floodplain development that could obstruct flood flows, such as fill, a bridge, or a building

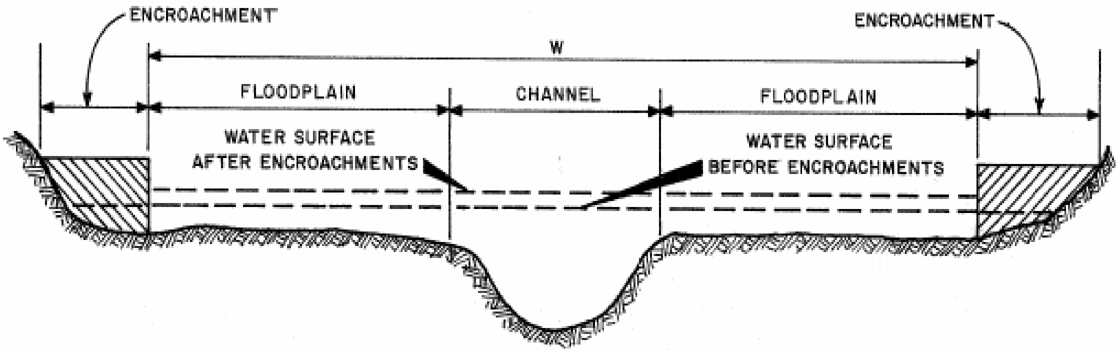

Figure 2.3: Typical floodplain encroachment in a compound channel (USACE, 1980)

The most obvious aspect of a compound channel is that the flow depths on the floodplain are often significantly smaller than the depths in the main channel, especially during small floods. The bed surface on the floodplains is often much rougher than the bed in the main channel and so the distribution of velocities and bed shear stresses are likely to be non-uniform. A number of studies have been carried out related to floodplain. A large-scale hydraulic model study of inbank and overbank river flow has been carried out in the UK Flood Channel facility operated at HR Wallingford. Some universities in UK have studied straight channels flanked on each side by floodplains and meandering channel in a straight floodplain. No detailed study on floodplain constriction and its effect on flow pattern and sediment transport have been performed. Considering the importance and scope for research, the present study was undertaken.

Floodplain encroachment modifies the innate overbank flow processes due to the presence of different types of interventions. When flow occurs in the vicinity of an encroachment, the river section varies rapidly and discontinuously. Hence, in addition to the classical turbulent interaction at the interface between the main channel and floodplain, the presence of an obstacle strongly disturbs the velocity and shear stress distribution at and near the encroached area.

The location of encroachment, i.e., whether encroachment occurs in the bends or crossover of a meandering channel, is also an important consideration of the flow dynamics of the encroached compound channels. More knowledge is needed on how velocity or shear stress varies in river bends of high curvature as well as in straight cross-over portion of the meandering channel with encroachments. Moreover, the presence of encroachment in single overbank or both overbanks is likely to have a considerable effect on the variation of these hydraulic parameters. Such conditions of ‘compound channel’ flows are quite common in the field, but a few studies have been undertaken to deal with this topic. Therefore a systematic study will be carried out from the view point of better understanding of the flow phenomena in a compound meandering channel with different encroachment conditions.

2.4 Compound Channels in Straight Reaches

While simple channel sections have been studied extensively, compound channels consisting of a deep main channel and one or more floodplains have received relatively little attention. Analysis of these channels is more complicated due to flow interaction taking place between the deep main channel and shallow floodplains. Laboratory channels provide the most effective alternative to investigate the flow processes in compound channels as it is difficult to obtain field data during over bank flow situations in natural channels. Therefore, most of the works reported are experimental in nature.

In the compound open channels, due to relative shallow depth, the velocity in the floodplain shows a significant difference compared with the velocity in the main channel and the flood plain induced a strong shear layer and lateral momentum transfer across the interface between partial cross section (Townsend, 1967; Wormleaton and Merrett, 1990; Ackers, 1991; Tominaga and Nezu, 1991; Bousmar and Zech, 1999). Large-scale turbulence associated with significant momentum transfer results in decreasing the total conveyance of the section (Sellin, 1964). Several attempts have been made at quantifying the interaction between the main channel and floodplain (Sellin 1964; Zheleznyakov, 1971; Yen and Overton, 1973; Myers, 1978; Rajaratnam and Ahmadi, 1981; Knight and Demetriou, 1983; Ackers, 1991; 1993). Shiono and Knight (1991) found that the velocity gradient and anisotropy of the turbulence large scale vortexes, rotating about both the vertical and horizontal axes along the main channel-floodplain interface, creates strong secondary currents and effects various hydraulic parameters (Figure 2.4).

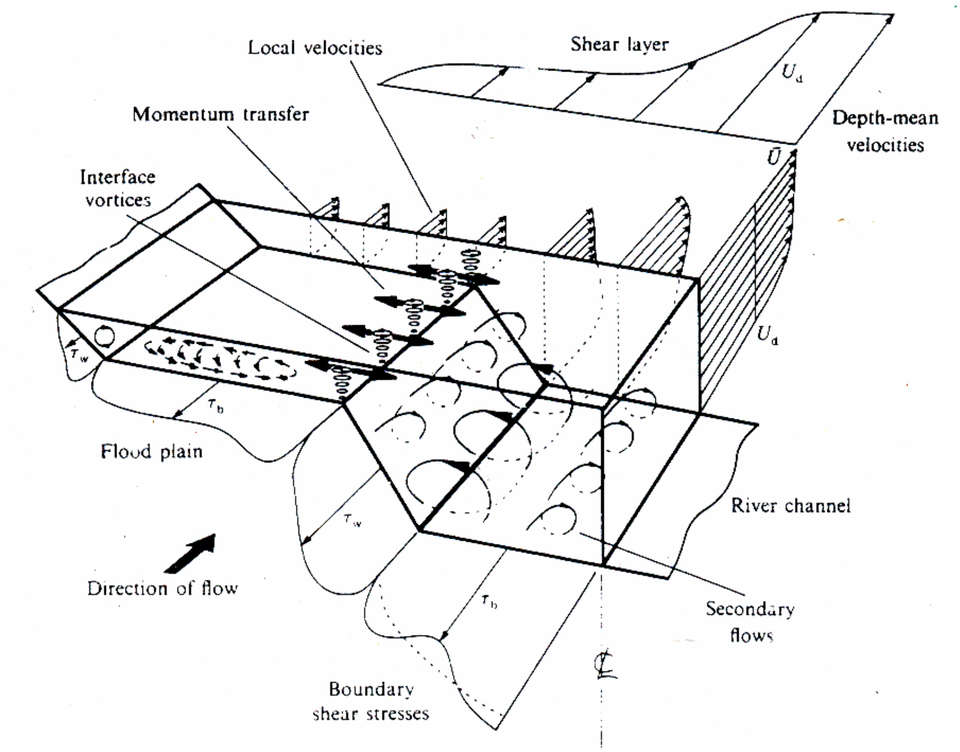

Figure 2.4: Hydraulic parameters in compound open channel (Shiono and Knight, 1991)

Few researches, less than 5%, in compound channel hydraulics were focused on critical flows (Bakhmeteff, 1932; Petryk and Grant 1978; Blalock and Sturm 1981; Konemann 1981; Schoellhamer et al., 1985; Chaudhr and Bhallamudi, 1998; Lambert and Sellin, 1996; Lee et al., 2002; Kordi, 2006; Kordi et al., 2007). In open channels, critical depth is most commonly defined as the transition between supercritical and subcritical regimes or the point of minimum specific energy/force. Several researchers have analytically and experimentally reported that there is more than one critical depth in compound open channels (Blalock and Sturm 1981; Konemann 1982; Lee et al., 2002).

Sellin (1964) confirmed the presence of the "kinematics effect" reported by Zheleznyakov (1965) after series of laboratory studies and presented photographic evidence of the presence of a series of vortices at the interface of main channel and flood plain. He studied the channel velocities and discharge under both interacting and isolated conditions by introducing a thin impermeable film at the junction. Under isolated condition, velocity in the main channel was observed to be more and under interacting condition the velocity in floodplain was less.

Rajaratnam and Ahmadi (1979) studied the flow interaction between straight main channel and symmetrical floodplain with smooth boundaries. The results demonstrated the transport of longitudinal momentum from main channel to flood plain. Due to flow interaction, the bed shear in floodplain near the junction with main channel increased considerably and that in the main channel decreased. The effect of interaction reduced as the flow depth in the floodplain increased.

Knight and Demetriou (1983) conducted experiments in straight symmetrical compound channels to understand the discharge characteristics, boundary shear stress and boundary shear force distributions in the section. They presented equations for calculating the percentage of shear force carried by floodplain and also the proportions of total flow in various sub-areas of compound section in terms of two dimensionless channel parameters. For vertical interface between main channel and floodplain the apparent shear force was found to be more for low depths of flow and for high floodplain widths. On account of interaction of flow between floodplain and main channel it was found that the division of flow between the subsections of the compound channel did not follow a simple linear proportion to their respective areas.

Knight and Hamed (1984) extended the work of Knight and Demetriou (1983) to rough floodplains. The floodplains were roughened progressively in six steps to study the influence of different roughness between floodplain and main channel to the process of lateral momentum transfer. Using four dimensionless channel parameters, they presented equations for the shear force percentages carried by floodplains and the apparent shear force in vertical, horizontal diagonal and bisector interface plains. The apparent shear force results and discharge data provided the weakness of these four commonly adopted design methods used to predict the discharge capacity of the compound channel.

Prinos et. al. (1985) examined the structure of turbulence in compound channel flows from laboratory experiments. The experiments were performed in a specially designed, 12.2 m long, symmetrical compound channel, having a trapezoidal main section and two shallow flood plain zones. The experiments were started satisfying “narrow channel” condition and extended subsequently to “wide channel” condition. Mean velocity measurements were made with a commercial Pitot-static tube connected to a differential pressure transducer. Local boundary shear stress was calculated from measured differential pressure using the Preston-tube technique. Average boundary shear stresses for the main channel and flood plain subsections were found by integrating local shear stresses over the respective wetted perimeters. Turbulence intensities and shear stresses were measured using a hot-film cross-sensor probe, connected to two constant-temperatures anemometers. The study examined the nature of turbulence in the mixing regions of compound channel flows and following were the main conclusions:

1) Both longitudinal and vertical turbulence intensities were significantly higher in the mixing regions than their respective values in the central region of the main channel flow. The increase in turbulence intensities is the result of intense shear action along the interface planes separating the deep and shallow zones.

2) In general, the mixing zone’s longitudinal and vertical turbulence intensities were found to increase with an increase in the relative boundary roughness parameter for the compound section. They were also found to increase with a decrease in the relative depth parameter.

3) Large eddy transport of shear stress in the mixing regions can produce negative shear stress values there even though no negative velocity gradients occur in these regions.

4) The numerical modeling of the shear stress in the mixing regions should be based on all the contributing physical processes, i.e. advection, diffusive transport, turbulence production, viscous dissipation, etc.

5) Direct measurement of apparent shear stress using a cross-type hot film probe, compared favorably with values based on momentum balance considerations.

2.5 Compound Meandering Channels

Bankfull flow in a meandering channel is characterized by centrifugal circulation generated around the bends, which dies out and reverses direction alternately between bends. However, if the channel flows out of bank into a predominantly straight floodplain, there will be interference between the main channel and floodplain flows, particularly in the region of the crossover points. This interference will create a secondary circulation in the main channel, which will reinforce the centrifugal circulation created around the upstream meander bend. However, as the flow proceeds into the next bend, the centrifugal circulation will change polarity. Thus the two circulation cells will tend to counteract each other. The flow patterns in a meandering channel with overbank flow are thus largely determined by the relative strength of these secondary cells, generated by channel/floodplain interaction at the crossover and centrifugal forces around the apex. If the floodplain velocities are relatively high, typically with smooth floodplains and/or higher depths, then the circulation at the crossover may be strong enough to be carried well into or through the downstream apex as observed by Sellin et al. (1993) and shown in Figure 2.5 (a). On the other hand with lower floodplain velocities the centrifugal circulation will predominate through the apex as shown in Figure 2.5 (b). Large scale laboratory experiments with rigid boundary overbank meandering channels (Loveless et al. 1999, 2000; O’Sullivan 1999) have shown how this interaction between floodplain and channel flows profoundly affects primary velocities, secondary circulation, and boundary shear stress distributions within the main channel. They also highlight the potential impact of this interaction on flood levels and conveyance.

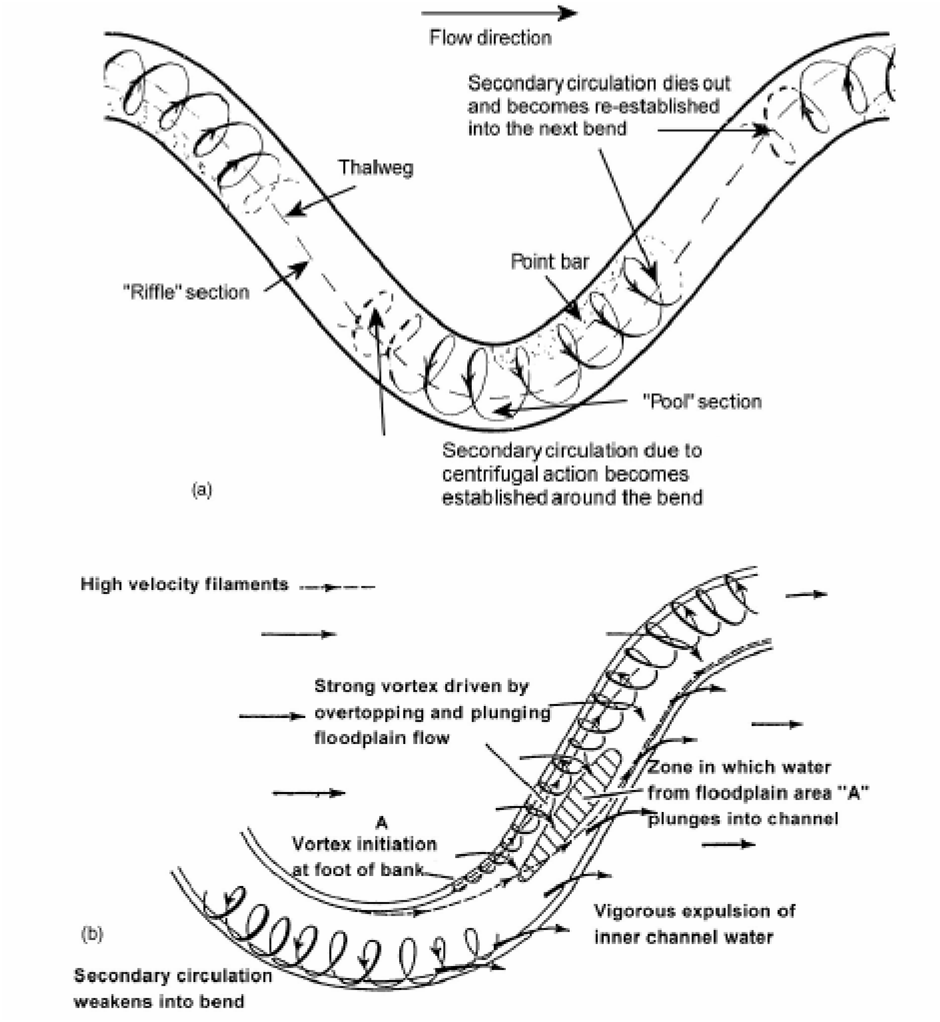

Figure 2.5: Flow pattern in meandering channel with floodplain (a) inbank (b) overbank (Source: Sellin et al. 1993)

The flow in compound meandering channel is influenced by several kinds of forces and shear stresses generated by momentum transfer between the main channel and the floodplain. Khan (1999) developed a simplified equation to calculate flow velocity distribution in a straight compound channel. Mekeogh and Kiely (1989) found that the conveyance of a meandering channel floodplain is greater than that of a straight channels' floodplain and boundary shear is higher in meandering flood flow than that of straight channel flood flow. Patra et al. (2004) observed that the flow and velocity distributions in meandering compound channels are strongly governed by turbulent interaction between the main channel and adjoining floodplain. After performing a series of laboratory tests, Rajaratnam and Ahamadi (1981) and Wormleaton et al. (1982) concluded that because of the interaction the bed shear stress increases in the floodplain while decreases in the main channel. Parvin (2012) described that the placement of artificial roughness strip in the floodplains increases the floodplain shear stress.

Toebes and Sooky (1967) were probably the first to investigate under laboratory conditions the hydraulics of meandering rivers with floodplains. They attempted to relate the energy loss of the observed internal flow structure associated with interaction between channel and floodplain flows. The significance of helicoidal channel flow and shear at the horizontal interface between main channel and floodplain flows were investigated. The energy loss per unit length for meandering channel was up to 2.5 times as large as those for a uniform channel of same width and for the same hydraulic radius and discharge. It was also found that energy loss in the compound meandering channel was more than the sum of simple meandering channel and uniform channel carrying the same total discharge and same wetted perimeter. The interaction loss increased with decreasing mean velocities and exhibited a maximum when the depth of flow over the floodplain was less. For the purpose of analysis, a horizontal fluid boundary located at the level of main channel bank full stage was proposed as the best alternative to divide the compound channel into hydraulic homogeneous sections. Hellicoidal currents in meander floodplain geometry were observed to be different and more pronounced than those occurring in a meander channel carrying in bank flow. Reynold's number (R) and Froude number (F) had significant influence on the meandering channel flow.

Ghosh and Kar (1975) reported the evaluation of interaction effect and the distribution of boundary shear stress in meander channel with floodplain. Using the relationship proposed by Toebes and Sooky (1967) they evaluated the interaction effect by a parameter (W). The interaction loss increased up to a certain floodplain depth and there after it decreased. They concluded that channel geometry and roughness distribution did not have any influence on the interaction loss.

Stein and Rouve (1988) has investigated the detailed flow structures present over one meander wavelength for over bank flow conditions. Sophisticated laser Doppler anemometry was used to measure all three point velocity components within the flow for one water level and discharge. The meandering channel was constructed in a flume 15.0 m long by 3.0 m wide. The main channel was rectangular with a width of 0.4 m and a bank full depth of 0.1 m. The preliminary results presented allowed the following conclusions to be drawn:

1) Secondary currents in the main channel rotate in the opposite direction to those for in bank flow.

2) Fluid swelling out of' the main channel slows the discharge on the flood plain.

3) A horizontal shear layer exists between the lower and upper parts of the main channel.

Ervine, Willetts, Sellin and Lorena (1993) reported the influence of parameters like sinuosity, boundary roughness, main channel aspect ratio, and width of meander belt, flow depth above bank full level and cross sectional shape of main channel affecting the conveyance in the meandering channel. They quantified the effect of each parameter through a non-dimensional discharge coefficient F* and reported the possible scale effects in modeling such flows.

Patra and Kar (2000) reported the test results concerning the boundary shear stress, shear force, and discharge characteristics of compound meandering river sections composed of a rectangular main channel and one or two floodplains disposed off to its sides. They used five dimensionless channel parameters to form equations representing the total shear force percentage carried by floodplains. A set of smooth and rough sections is studied with an aspect ratio varying from 2 to 5. Apparent shear forces on the assumed vertical, diagonal, and horizontal interface plains are found to be different from zero at low depths of flow and change sign with an increase in depth over the floodplain. A variable-inclined interface is proposed for which apparent shear force is calculated as zero. Equations are presented giving proportion of discharge carried by the main channel and floodplain. The equations agreed well with experimental and river discharge data.

Patra and Kar (2004) reported the test results concerning the velocity distribution of compound meandering river sections composed of a rectangular main channel and one or two floodplains disposed off to its sides. They used dimensionless channel parameters to form equations representing the percentage of flow carried by floodplains and main channel sub sections.

Shiono, Romaih and Knight (2004) carried out discharge measurements for over bank flow in a two-stage meandering channel with various bed slopes, sinuosities, and water depths. The effect of bed slope and sinuosity on discharge was found to be significant. A simple design equation for the conveyance capacity based on dimensional analysis is proposed. This equation may be used to estimate the stage-discharge curve in a meandering channel with over bank flow. Predictions of discharge using existing methods and the proposed method are compared and tested against the new measured discharge data and other available over bank data. The strengths and weaknesses of the various methods are discussed.

Wormleaton et al. (2005), measured velocity distributions, depth variation, and sediment transport under bankfull and overbank flow conditions in meandering channels with a graded sand bed, using the large-scale U.K. Flood Channel Facility. They concluded that the influence of overbank flow on the morphology of the bend depended upon the roughness of the floodplain, which determined the intensity of the interaction circulation generated around the crossover. This counteracted the centrifugal circulation around the bend, which in the case of both smooth and rough floodplains led to erosion of the inner point bar. However, in the case of the smooth floodplain the interaction circulation was strong enough through the bend to cause deposition around the outside bank. With the rough floodplain, the net circulation around the bend was not strong enough either to maintain the point bar or cause deposition around the outside of the bend. This led to increased net erosion of bed material around the apex which was deposited downstream to form an enhanced point bar.

The effect of channel sinuosity on flow pattern in meandering streams was investigated by Silva et al. (2006). The centerlines of the idealized meandering streams under consideration follow sine-generated curves, and the banks are rigid; the flow is turbulent and subcritical. This study focuses on the vertically averaged flow over a flat horizontal at any cross section bed formed by a granular material. The “flat bed” is viewed as the initial surface of a moveable bed at the beginning of an experiment at time t =0. A series of laboratory flow measurements involving the systematic variation of the deflection angle θ_o from 30° to 110° is used. It is found that every different sinuosity (every different θ_o) has its own convective flow pattern, i.e. its own distribution in plan of (the L / 2 long) convergence– divergence zones of flow. As θo increases, a gradual change in flow pattern was observed. Two expressions defining the observed variation of the convective flow pattern were introduced.

2.6 Shear Stress Distribution in Compound Meandering Channel

Boundary shear stress distribution information in a flowing stream is necessary for many reasons: to give a basic understanding of the resistance relationship, to understand the mechanism of sediment transportation, to design stable channels and to design revetments for channels where meandering phenomena are predominant (Ghosh and Jena, 1971). Flood-routing methods assume a simple cross-section for the purpose of calculating stage-discharge characteristics of rivers. These methods, therefore, ignore the transformation of momentum that results between the main channel and its floodplains (Al-Abaza, Al-Khatib and Dmadi, 1999). Boundary shear stress distribution and flow resistance in compound cross-section channels have been investigated by several authors (Al-Khatib and Dmadi, 1999; Knight and Cao, 1994; Rhodos and Knight, 1994; Rhodos and Lamb, 1991; Myers and Brennan, 1990; Lai and Knight, 1988; Lai, 1986). Al-Khatib and Dmadi (1999) described the effect of the interaction mechanism on shear stress distribution in a channel of compound cross-section. Specifically, the effect of the main channel width and step height on the variation of shear stress distribution has been investigated in both the main channel and its floodplains for constant flow discharges. None of the above mentioned studies had generalized the shear stress distribution in compound cross-section channels.

Yang (2010) derived equations of the depth averaged shear stress in typical open channels based on a theoretical relation between the depth-averaged shear stress (or depth-averaged shear stress) and boundary shear stress. Equation of depth mean velocity in a rough channel is also obtained and the effects of water surface (or dip phenomenon) and roughness are included. Experimental data available in the literature have been used for verification which shows that the model reasonably agrees with the measured data. The equation for rough channels, the depth-averaged velocity can be derived as

$$\frac{\bar{u}}{u_*} = \frac{1}{\kappa}\left[ln\left(f\frac{30h}{k_s}\right) - 1 - \alpha_1\right] \tag{2.1}$$

Where u = depth-averaged velocity. Yang et al. (2004a) obtained the following empirical equation by analyzing the location of ymax/h,

$$\alpha_1 = \alpha_0 exp\left(-\frac{z}{h}\right) \tag{2.2}$$

Where α_0 is a coefficient and for smooth rectangular channels. Yang et al. (2004) obtained α_0 = 1.3 and this value is valid in smooth channel flows. Afzalimeh and Singh (2009) carried out field experiments on five reaches of the meandering cobble-bed Beheshtabad River in central Iran and showed that the position of the maximum velocity was independent of the relative submergence h / d where h is the flow depth, and relative curvature R / W, d is the median diameter of sediment, R is the radius of curvature, and

W is the river width. A new method, called the boundary-layer characteristic method, was employed for the determination of shear velocity.

Shiono and Muto (1998) measured boundary shear stress in meandering channels for overbank flow using a Preston tube and a heated thin-film sensor. Measurements of secondary flow were also carried out using a laser Doppler anemometer. The distributions of the boundary stress and secondary flow along the meandering channels for over bank flow show that locations of peak and dip on the boundary shear stress distribution well correspond to those of the secondary flow downwards and upwards motion respectively. The dominant secondary flow generation mechanism is shown in figure 2.6 together with the main contributions to turbulence energy production in the cross-over region.

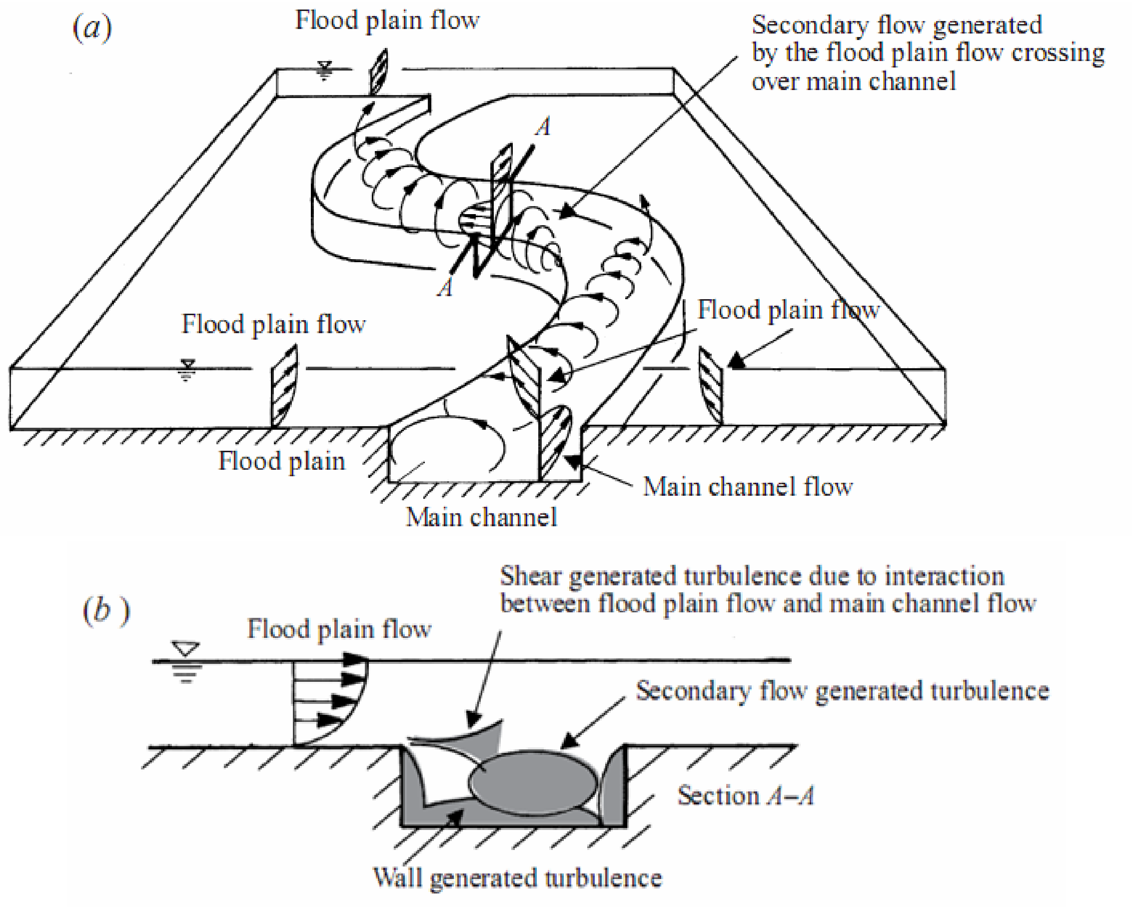

Figure 2.6: Effect of secondary flow on boundary shear stress (Shiono and Muto, 1998)

Experimental testing of 5 deferent types of boundary shear stress distribution in a symmetrical rectangular compound section channel was conducted by Al-Abaza, Al-Khatib and Dmadi (2002). Shear stress distributions in the main channel and floodplains of 6 deferent rectangular compound cross-sections are presented. A generalized multiple-variable regression model has been derived to predict each of the 5 experimentally measured shear stresses as a function of 3 dimensionless parameters. These 3 dimensionless parameters combine both the depth and horizontal dimensions of the constructed cross-sections. All obtained regression statistics indicate the high reliability of the derived regression model in estimating presented shear stress types in an open channel of a rectangular compound cross-section. A single multi-variable regression model for estimating mean shear stress at the bottom of a rectangular compound cross-section has been formulated using average values of obtained regression coefficients of the multiple-variable regression model.

Knight et al. (1979) and Ishigaki et al. (1996) measured the boundary shear stress using a Preston tube and investigated its distribution with respect to an aspect ratio in straight open channels. Knight et al. (1984) measured the boundary shear stress in strong secondary flow regions in a relatively large meandering channel. Their results indicate that an undulation of the boundary shear stress distribution is closely related to the secondary flow structure. The downwards motion of secondary flow is generally related to larger boundary shear stress, on the other hand, the upwards motion is related to smaller boundary shear stress. Khatua and Patra (2007) investigated the distribution of shear stress in the main channel and floodplain of meandering and straight compound channels. Based on the experimental results of boundary shear, they predict the distribution of boundary shear carried by main channel and floodplain sub sections. Five dimensionless parameters are used to form equations representing the total shear force percentage carried by floodplains. A set of smooth and rough sections was studied with aspect ratio varying from 2 to 5.

2.7 Shear Stress Distribution around Encroachment or Vertical Wall

Knowledge on the shear stress distribution around encroachments is based on a few past experimental and numerical site of investigating flow around dikes. Dikes can be viewed as very thin rectangular vertical wall abutments.

Awazu (1967) studied the shear stress distribution around dikes experimentally in a small scale laboratory flume. In Awazu’s experiments, the protrusion ratio (ratio between the perpendicular lengths of the dike protruding into flow to the overall channel width) varied between 0.1 and 0.4. The froude number of the approach flow were 0.49, 0.51 and 0.53. A total of 12 experiments with different protrusion ratios and froude number of combinations were conducted. Awazu estimate the value of bed shear stress around spur dikes using gradually varied flow relationships and developed an expression to estimate the bed shear stress amplification (ratio of bed shear stress to unconstricted shear stress) around a spur dikes. Since the froude number in Awazu's experiment was keep constant(approximately 0.5), this relationship does not reflected change in shear stress amplification due to approach flow conditions.

The construction of groynes or encroachment leads to increased flow velocities and therefore to increased erosion processes in the main channel of the river. This is the reason why the planned crown elevation does not always correspond to the final water surface elevation which means that the crown elevation varies from reach to reach. An important feature of the flow field in groin fields is the transition region between the dead-water zone and the main stream called mixing layer. It is characterized by a time averaged velocity profile shown in (Figure 2.7) with the typical negative flow velocities close to the channel bank due to the recirculating movements. In rivers the flow is usually very shallow which means, that the horizontal dimension of the flow is much larger than the water depth. This shallowness of the flow is the reason for the development of large coherent structures within the mixing layer. These flow structures emerge because of separation effects at the upstream groin heads and travel downstream within the mixing layer. During their travel they grow predominantly in horizontal direction and reach a final extension which is again much larger than the water depth (figure 2.5, ii). These structures are traveling into the dead-zone or remain in the main stream and therefore play an important role in terms of exchange processes between the main stream and the dead-zone.

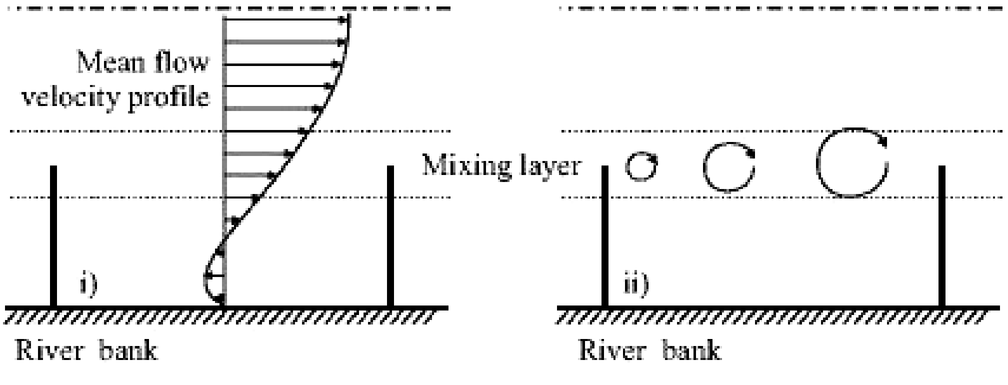

Figure 2.7: Schematic sketch of velocity profile and large coherent motions that emerge at the groin heads and grow during their travel downstream.

Zaghloul and McCor(1973) and Zaghlou(1974) stated that the bed shear stress in a dike's vicinity depends on the local velocity, vorticity and turbulence. Zaghlou(1974) solved the depth integrated two dimensional (2D) equation numerically and compared this value with empirical formula. Tingsanchali and Maheswaran (1990) used a 2D depth average k-ε turbulence model corrected to solve governing equation near groin structures. The roughness coefficient is corrected at the nose region for the 3D effects. Tingsanchali and Maheswaran calibrated their numerical model result to compute shear distribution at the nose region of groins using Rajaratnam and Nwachukwu experiment.

Rajaratnam and Nwachukwu (1983) measured bed shear stress experimentally around spur dikes (simulated by a rectangular thin plate) using a preston tube and a three dimensional (3D) pitot tube for different protrusion ratio (0.08 and 0.16) and froude numbers. The range of froude numbers considered in the 13 experiments presented by a Rajaratnam and Nwachukwu are limited to low froude numbers (0.17 to 0.29) .These experiment indicate considerable increase in bed shear stress near upstream nose and in the immediate neighborhood of the dike (an amplification of up to five times the approach bed shear).

Shear stress distribution around vertical wall abutments is studied experimentally, and maximum shear stresses that occur at the upstream corner of vertical wall abutments are determined. Shear stress distributions are presented for Froude numbers ranging from 0.30 to 0.90 and for protrusion ratios (ratio of protrusion length perpendicular to direction of flow to total channel width) of 0.1, 0.2, and 0.3. Shear stress at the nose region of an abutment can be expressed as the sum of stresses due to contraction and the abutment structure alone. An expression for the nose shear amplification factor, Λnose, defined as the ratio of the bottom shear stress at the nose region to the approach flow shear stress, is derived. This amplification is due to the contraction and to the presence of a protrusion. Shear stresses around vertical wall abutments are amplified up to a factor of 10 and velocities are increased by up to 50% depending upon flow conditions and abutment protrusion ratios. Results are compared with previous experimental and numerical studies for shear stress distribution around groins and spur dikes. By quantifying the shear amplification and by identifying regions of shear concentration, the method developed can be used to determine sediment sizes needed to protect structures against local scour (Albert Molinas, 1999).