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Evolution of Alluvial Meandering Channels: Comparison between Laboratory Experiments and Natural Channels

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Synopsis

The current study examines the evolution of alluvial meandering channels based on the laboratory experiments as well as field study. Experiments were conducted in erodible meandering channels to represent the natural scenario. Channel planform, as well as bed evolution, were analyzed. In the case of natural channels, time series satellite images were analyzed to understand the channel planform behaviour and bank erosion characteristics were analyzed through the real field data and photos. Results showed that the channel evolution characteristics vary from one alluvial meandering channel to another depending upon various channel parameters. It was found that low sinuosity channels and newly developed meander bends have higher tendency to migrate as well as undergo rapid channel adjustment. Bank protection counter-measures were effective in minimizing the bank erosion. At the same time, they tend to shift the point of erosion from one location to another.

Key Words: alluvial rivers, meandering, bank erosion, channel migration, counter-measures, groynes

1. INTRODUCTION

Natural alluvial rivers self-organize into distinct morphologies that can be considered as a continuum of patterns from incoherent (braided) to highly organized (meandering), Tal et. al. (2010). Alluvial channels are formed on the sediments that they have transported and deposited, Church (2006). Accordingly, the channel is self-formed. Banks may be composed of either cohesive or non-cohesive materials which are usually fragile and can be easily erodible by fluvial force. This fragility of the banks attributes to the self-forming characteristics of alluvial channels. Alluvial channels may take various planform shape depending on the flood discharge, bank characteristics, amount of sediment, its size and type, etc. Of the common morphological channel pattern observed in the natural alluvial channels is the meandering, about which this study is focused on. Meandering channels are one of the most studied topics in fluvial geomorphology due to its unique morpho-dynamics. However, various channel processes governing meander planform are yet to be understood fully. One of the most challenging aspects of the meandering channel research is the unpredictability of channel migration. Based on the previous studies as well as natural observation, it is generally understood that the erosion occurs at the outer bank forming deep pools and the deposition occurs at the inner bank forming a point bar. These phenomena are responsible for the channel migration. Erosion-deposition induced channel migration causes loss of hundreds of hectares of mainland floodplain, agriculture affecting the livelihood of the people. In this regard, various countermeasures are usually implemented to prevent riverbank from erosion and migration processes and hence preserve channel planform. In the analysis of river-related problems, along with the flow characteristics, channel morphological characteristics need to be equally considered. Whenever river training structures are introduced for preventing bank erosion, channel morphology is altered. Conversely, morphological change may affect the effectiveness and functionality of the river training structures itself. In this study, experimental analysis of the evolution of meandering channels of two different sinuosities with and without counter-measures is discussed. Also, based on the field study, the change in channel morphology of two alluvial meandering rivers without and with river training structures are analyzed depending.

2. OBJECTIVES OF THE STUDY

The objectives of this study are as follows,

i) To understand the morphological evolution of meandering channels of different sinuosity.
ii) To identify bank erosion and channel migration processes in natural alluvial meandering channels.
iii) To identify the effect of countermeasures on channel evolution & migration phenomenon.
iv) To suggest various factors to be considered while implementing river training works in alluvial meandering channels.

3. METHODOLOGY

The present study is based on the comparison between laboratory experiments and the natural channels cases. Laboratory experiments were conducted on meandering channels of two different sinuosities so that the single dominant channel characteristics do not influence the results. In the case of natural channels, a field study was carried out in two different alluvial meandering channels. Satellite images obtained from the Google Earth and the data collected from on-field verification, previous reports, photographs, etc. were used for the analysis and validation of real field case. Time series images of the river channel were analyzed for determining the shift in river channel centerline, bankline, bar movement, etc. Similarly, the effect of countermeasures on the river morphology was also analyzed. Images from the Google Earth were georeferenced in the ArcGIS and the channel features were drawn in the georeferenced images. On field measurements and photographs taken at the site were utilized for analyzing bank erosion characteristics. For the determination of PSD, sediment samples were collected from the respective sites and analyzed.

3.1 Laboratory Experiments

(1) Preparation of laboratory channels

The schematic layout of the experimental flume as shown in Fig.1 consists of the fixed bed inlet and outlet channel of length 50 centimetres (cm) and 100cm respectively. The main channel include 400cm (length) x 200cm (width) erodible bed filled with non-uniform (D_{mean}= 0.72mm, $\sigma = (d_{84}/d_{16})^{0.5}$ =1.38 and specific gravity=1.41) and non-cohesive sediment up to a thickness of 20cm from the fixed bottom. Particle size distribution of the sediment used for making the channel is presented in Fig.1. The sine-generated meandering channel defined by equation (1) was used to delineate the meandering channels within the erodible boundary. The main parameters determining the sine-generated curve (SGC) are channel-wise wavelength (M) and maximum deflection angle (ω).

$$\emptyset = \omega.cos(2\pi \frac{s}{M}) \qquad (1)$$

Where, s is the channel-wise length and $\emptyset$ is the local deflection angle.

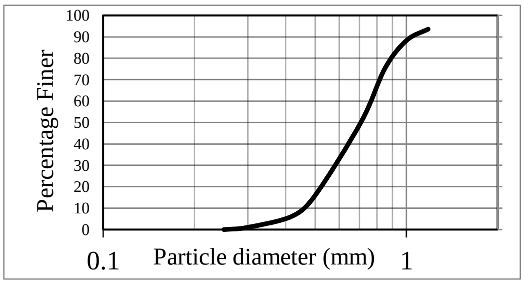

Fig.1: Particle size distribution curve of the sediment

(2) Experimental methods

In order to identify the channel planform as well as bed evolution, series of experiments were conducted. For the present analysis, four experiments

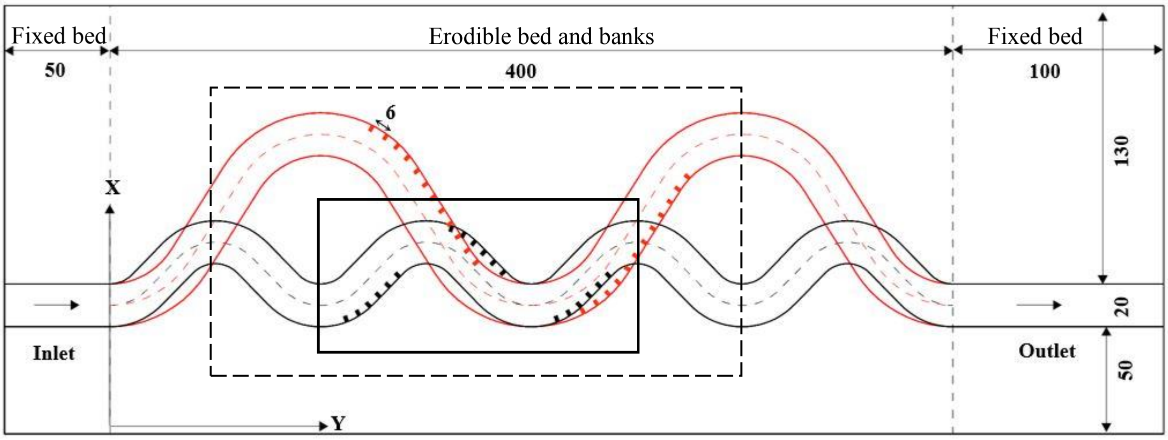

Fig. 2: Layout plan of the experimental channels (units in cm)

Table 1: Parameters of the experimental SG channels.

Parameter (cm)	Channel-LS	Channel-HS
Channel width (B)	20	20
Radius of curvature (R)	25	45
R/B ratio	1.25	2.25
Amplitude (A)	30	80
Channel-wise wavelength (M)	120	270
Valley wavelength (λ)	100	200
Sinuosity (K=M/ λ)	1.2	1.35
Angle of deflection (ω)	45^0	60^0

Table 2: Experimental flow condition.

Discharge (l/s)	0.95
Mean flow depth (cm)	2.86
Mean velocity (cm/s)	16.6
Channel slope	1:550
Shear velocity (cm/s)	1.99
Froude no.	0.31
Reynolds no.	5322

were chosen i.e. two cases for each type of the SG channel, case 1) without any groynes and case 2) with impermeable groynes. The four cases are represented as low sinuosity channel without groynes (LS-NG) and with groynes (LS-G) and high sinuosity channel without groynes (HS-NG) and with groynes (HS-G). Experimental flow condition is presented in Table 2. Experiments were conducted under clear water condition for a duration of 1 hour. In both the cases, a constant discharge of 0.95 l/s was supplied by a pump to the upstream storage tank through which water gradually entered the channel inlet. The target area for the analysis in each type of the channel is shown inside the bold and dashed rectangle in Fig.2. In the case of the experiment with groynes, the arrangement of groynes is as shown in Fig.2. Groynes were placed at 90 degrees to the bankline starting slightly from the downstream of the apex of outer-bank and were inserted well inside the banks to prevent outflanking. The length of the groynes was 3cm while the spacing between the groynes was 6cm. Channel topography was measured at every 20 minutes of the experiments.

3.2 Natural Alluvial Channels

In case of natural meandering channels, the target river reaches as shown in Photo 1 are located in the low lying southern plain areas of Nepal known as the ‘Terai’ region which begins at the border between India and Nepal in the south while the Northern part is surrounded by a range of young and fragile hills called Siwalik Hills. These hills play a major role in the supply of sediments to these rivers, Sharma (1976). The Terai also known as the food basket of Nepal, consists of fertile alluvial land which accounts for more than half of the total food production. Every year hundreds of hectares of this fertile land are lost through river erosion and deposition, thus, affecting the livelihood of thousands of people as well as the overall economy of the country. Human interventions, as well as the natural factors such as unscientific land use practice, excessive mining of river bed materials, climate change, etc. have further exacerbated the problems of river bank erosion. Despite of such problems, these areas are one of the less studied in terms of research mainly due to the limited data availability.

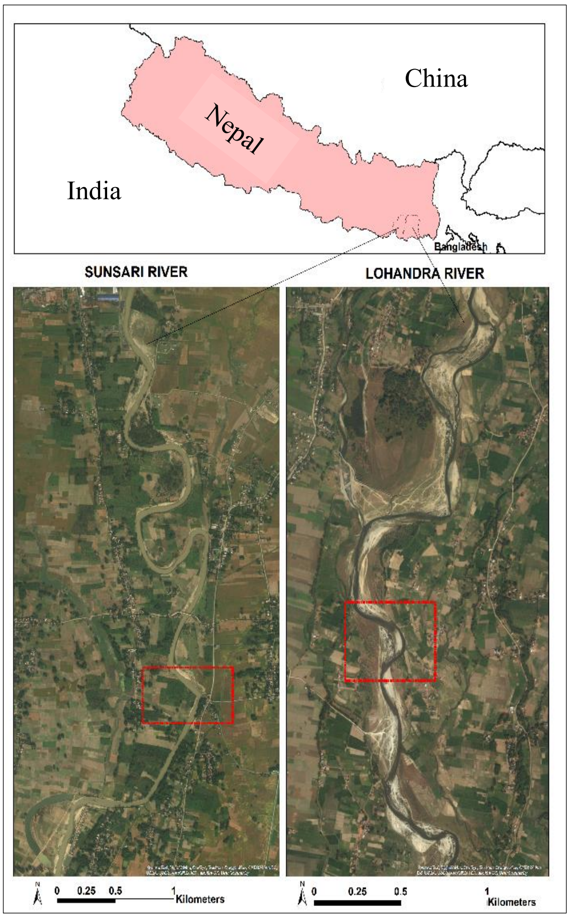

Photo 1: Location map of the study area, Google Earth, (2018)

(1) Sediment characteristics

Sediment is one of the governing factors which determine channel stability, channel shape and sinuosity, Schumm (1963). Channel morphology of an alluvial river is the result of sediment transport and sedimentation, Church (2006). Sediment properties are therefore necessary to be assessed for further understanding of the channel morphological evolution. Accordingly, the sediment samples were collected for the selected river reaches and particle size distribution (PSD) analysis was performed. Fig.3 shows the PSD curve for each of the river.

Lohandra river sediment consisted of a mixture of gravel and sand and silt, JICA (1999) whereas the Sunsari River consisted of fine sand and clay mixture. The uniformity index (UI) defined by the ratio of D_{84} to D_{16} for Lohandra River was found to be high which signified the non-uniformity in the sediment particles as compared to Sunsari River.

Table 3: Representative grain size of sediment

Representative grain size	**Lohandra River**	**Sunsari River**
D_{16} , mm	0.21	0.14
D_{50}, mm	0.89	0.26
D_{60}, mm	2.60	0.28
D_{84}, mm	19.52	0.37
D_{mean}, mm	6.87	0.26
UI	92.88	2.72

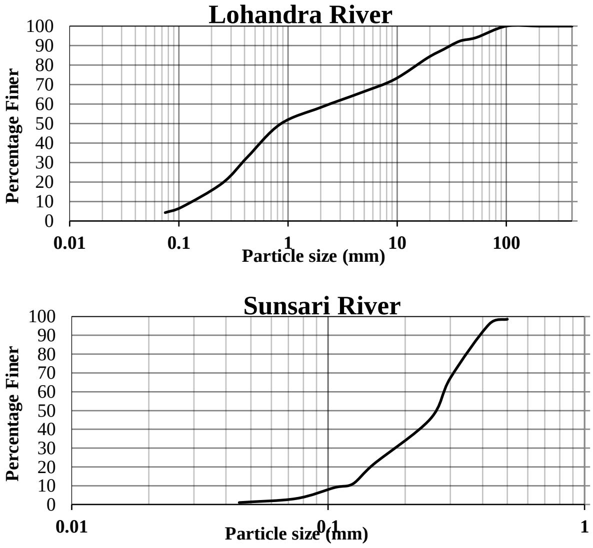

Fig.3: PSD curve for the study reach of two rivers

(2) River channel characteristics

River channel characteristics can be briefly explained based on the channel shape, width, depth, slope, in-channel morphology, etc. Sunsari River is a perennial river originating in the Siwalik Hills, JICA (2003). In the study reach about 4.5kilometers downstream of East-West Highway, it consists of a single thread sinuous channel with narrow and deep cross-section i.e. having a low width-depth ratio. The width and depth of the study reach vary between 30-40m and 3-5m respectively. The distinct meandering pattern is evident throughout the river reach. Formation of the curvature related point bar can be seen in the inner bank of the channel. These point bars are gradually armoured by the growth of vegetation which eventually develops into a mainland floodplain as seen in Photo 2. This formation has a significant implication on the channel planform evolution. Also, ox-bow Lake has been formed due to the meander cut-off at different meander bends. Most of these cut-offs are man-made for river channelization while few are naturally formed. Various kinds of cultivation can be seen on the adjacent floodplain. During monsoon, the river often overflows its bank inundating the floodplain because the river is not embanked in most of the location. Bank material is composed of a mixture of clay, silt and fine sand.

Lohandra River also originates in the Siwalik Hills. The study reach is located approximately 12 kilometres downstream from the foothills and 3.5 kilometres downstream of the Bridge at East-West Highway. The river channel is wide and braided in the upper reaches and gradually becomes narrow towards the lower reaches. Unlike Sunsari River, it has a relatively low bank with height 2-2.5m in the study reach. The main channel frequently wanders within the bankline. The average width of the main channel varied between 10-23m during the period of last 7 years from 2010-2017. However, the bank to bank width varies between 100-140m. The average channel slope of the channel for the study reach is about 1 in 250. Riverbed is composed of gravel, sand and silt while the bank materials basically constitute of sand, clay and silt mixture. Meander development, bank erosion and channel migration are very frequent phenomena. Curvature-induced point bar is dominant along the channel. During the flow recession or low flow, the formation of chute channels along the point bar can be seen.

Photo 2: River Channel in the study reach; (a and b) Sunsari River, (c and d) Lohandra River

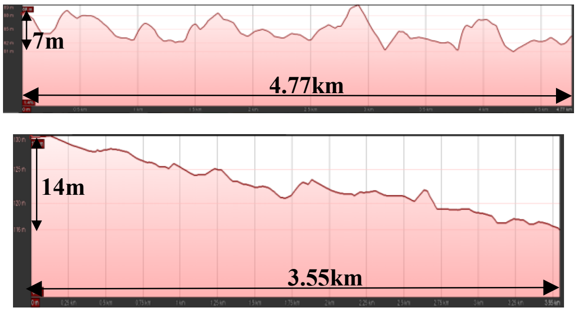

Fig.4: River Profile of the study channels (Google Earth, 2018), Sunsari River (top) and Lohandra River (bottom)

4. ANALYSES AND DISCUSSIONS

The results and analysis section is divided into two sub-sections. The first one discusses the experimental cases while the second one explains the natural channels case.

4.1 Experimental Cases

Experiments conducted on meandering channels of two different sinuosities and R/B ratio showed variations in channel characteristics. Photo 3 shows the channel morphology at the end of the experiments for different cases. First experiments were performed without groynes so that general channel evolution characteristics can be understood as well as point of maximum erosion-deposition could be

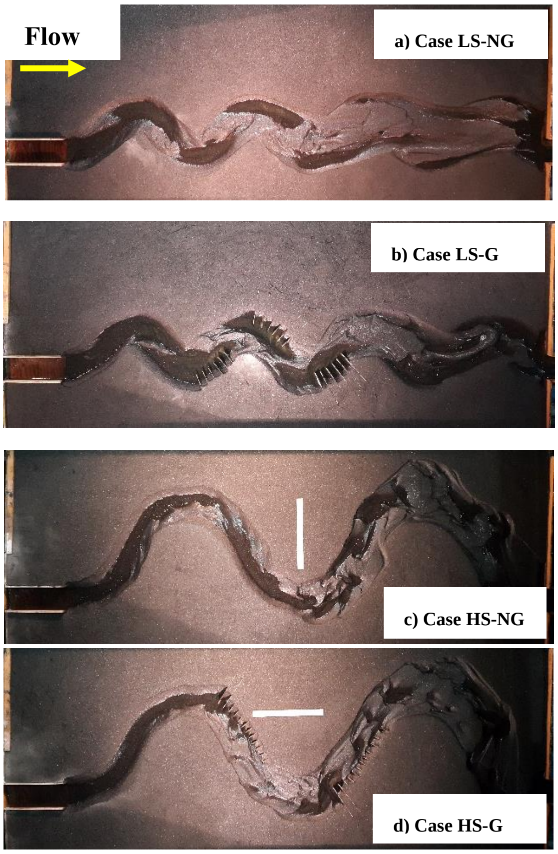

Photo 3: Channel evolution at the end of the experiments for cases with and without groyne.

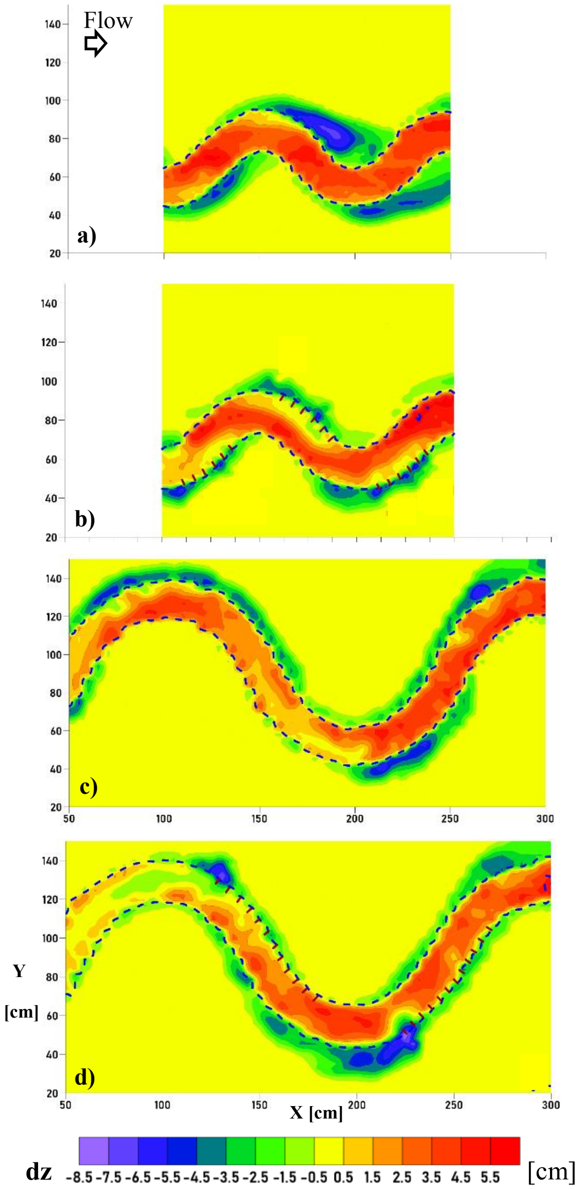

Fig. 5: Difference in channel morphology between t=0 to t=60min for case LS-NG & LS-G (a, b) and case HS-NG & HS-G (c, d) (Blue dash line show initial banks)

identified. It was seen that erosion and channel migration was higher in LS and low R/B channel. Similarly, channel width tends to increase more in LS channel. The channel expansion by erosion and migration at near the channel outlet is so high that channel tends to braid. The location of highest erosion varied in both channels. In LS channel, maximum erosion occurred near the apex of the inner bend while for HS channels, erosion was higher near the point of inflection. Similarly, the location of the formation of point bar was also different. In case of LS channel, as seen in Fig. 5 (a, c) point bar formed downstream of the inner bend apex whereas it was formed beginning from slightly upstream of the apex in HS channel. This signifies that the formation and growth of point bar are influenced by channel sinuosity and R/B ratio. The growth of the point bar pushed the flow further towards the outer bank, thereby enhancing bank erosion. The channel showed the tendency to migrate downstream. Compared to HS channels, LS channel was characterized by distinct point bar and pool-riffles sequences. Although few blocks or slump failure were observed at the start of the experiment, bank erosion mostly occurred by fluvial erosion of the bank materials due to high velocity around the outer banks just downstream of the groynes. It is mainly due to the non-cohesive sediment. However, in the natural channels, cohesion exists in the bank materials so the bank erosion phenomenon may be different.

After identifying the channel evolution characteristics for without counter-measures, experiments were performed with groynes as a bank protection counter-measures. It can be seen from Fig.5 (b,d) that the presence of groynes significantly reduce the bank erosion and thus prevent the overall channel migration. It also tends to reduce the growth of the point bar. However, erosion still continued in the embayment between the groynes. Despite the protection of outer bank by groynes, some adverse effect was observed. Bank erosion was protected at one location but erosion was shifted to the other location. Comparing between with and without groynes cases, it can be seen from Fig. 5 (d) that higher erosion occurred near the right outer bank apex (at X=200cm) and also on the right bank between X=100-200cm. This signifies that the groynes can cause a negative effect on the opposite bank.

4.2 Natural Channels Case

(1) Bank erosion processes

Alluvial meandering channels are morpho-dynamically active in a sense that they frequently keep changing their planform as well as bed morphology even with a single flood event. These channels quickly respond to the change in channel discharge, sediment supply, bank properties, etc. by changing their morphology through erosion- deposition.

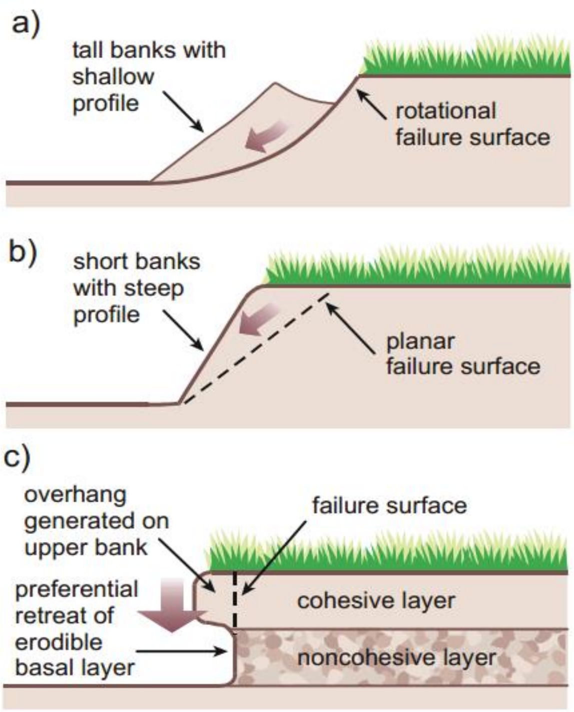

Fig.6: Different mechanisms of bank failure, Langendoen (2000): a) rotational failure b) planar failure c) cantilever failure.

In this context, bank erosion is one of the most common problems associated with alluvial rivers. The problem gets even more complicated in the case of meandering channels. The self-adjusting nature of alluvial meandering channels increases the risk of bank erosion in these rivers. This sub-section discusses about the different modes of bank erosion in alluvial channels and relate those with the study channels. Similarly, it also talks about the role of counter-measures in bank erosion mitigation with respect to the study channels.

In general, two modes are attributed to the failure of a riverbank, Langendoen (2000); 1) Hydraulic or fluvial force that detaches and entrains surface particles from bank and bed, 2) geotechnical instabilities of soil mass leading to the mass failure. However, in most of the cases, the combination of both of these modes are prevalent (your.kingcounty.gov). Hydraulic or fluvial force leads to the erosion of riverbank whenever the local boundary shear stress exerted by the flow near the bank exceeds the critical value, Langendoen (2000). Similarly, the geotechnical stability of the soil mass with respect to mass failure depends on the balance between the driving forces of gravity that tends to drive the soil mass downward and the resisting force of friction and cohesion that tend to resist the downward movement. In view of these different bank failure modes and mechanisms, the study channels were analyzed.

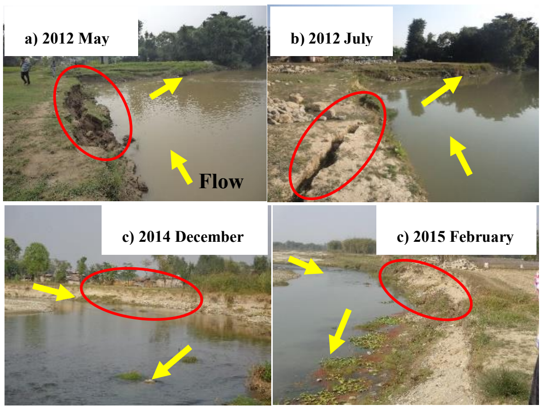

Photo 4: Bank erosion in the study reach; (a & b) Sunsari River and (c & d) Lohandra River

Photo 4 (a-d) shows the bank failure along the study channels. It was seen that in case of Sunsari River, the mass failure mode was dominant while fluvial erosion was principal mode of bank erosion in Lohandra River channel. High and steep banks with deep channels in Sunsari River resulted in the instability of the bank. Consequently, failure of the bank as a mass of soil was observed (see Photo 4a). Similarly, due to the undermining of the lower bank layer, cantilever or overhang bank was formed. As a result, tension crack was observed in the upper bank layer as can be seen in Photo 4b which ultimately resulted in the mass failure. The arrow in the photo represents the flow direction. Unlike in Sunsari River, in case of the Lohandra River, as it can be seen in Photo 4(c,d), mass failure is not the active mode of bank failure although some failed materials can be seen near the bank. It suggests that the erosion of bank toe caused some of the bank materials to fail. As a response, the bank readjusted to the stable slope by the failure of some materials. During the low flow, the failed bank materials tend to get armoured by the growth of vegetation which during the next flood period resist the bank erosion to some extent. In order to control the bank erosion process, different counter-measures were implemented along the study reaches of both the Rivers. The next sub-section discusses the performance of such counter-measures against bank erosion process and its effect on the channel evolution.

(2) Application of bank erosion counter-measures

Different measures are adopted in order to mitigate bank erosion and thus protect adjacent land and the floodplain from the losses due to erosion. In this context, groynes are widely implemented counter-measures in the study area to protect the banks from erosion. Groynes are linear structures projecting perpendicular or at a certain inclination from bank towards the river. The major function of groynes is to deflect the high-velocity flow from the near bank region to the river center, thereby inducing deposition in the near bank region thereby protecting the river bank.

A conceptual orientation of groynes in a channel bend is shown in Fig.7. In general, groynes are placed at the outer bank where the erosion is severe. In this regard, impermeable groynes made up of galvanized iron (GI) gabion wire and boulders were constructed in the study reach as shown in Photo 5.

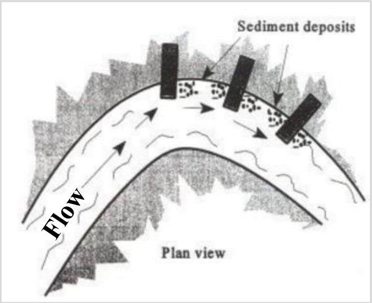

Fig.7: Conceptual positioning of groynes in a channel bend, CWC, India (2012)

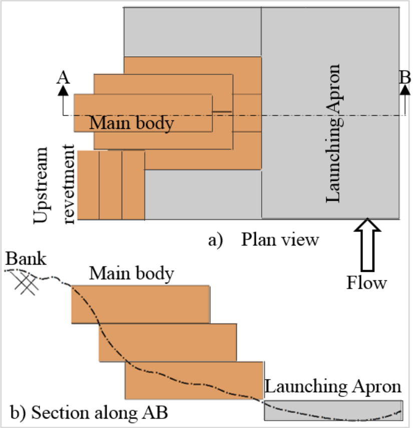

Fig.8: Layout plan and section of groynes implemented in study channel (Figure not to scale)

The layout plan and sectional view of the implemented groyne is shown in Fig.8. It consists of the main body of three layers each of height 0.75m and length 9m and slightly inserted inside the bank. Similarly, the protection of the main body from possible scour is done by the launching apron of height 0.45m provided at the nose as well as at the upstream and downstream of the main body. At the upstream bank, a revetment wall having the same height as the body of the groyne is provided to prevent the outflanking. Two straight type impermeable groynes were implemented just below the apex of the meander bend on the outer bank of Lohandra River in February 2015 as shown in Photo 5 (a-c). The length of the main body of groynes was 9m while the spacing between the two groynes was 30m. The total height of the groynes was 2.25m from the channel bed up to the bank top. The upstream bank of both the groynes was protected by revetment wall so as to prevent the outflanking. Similarly, in order to prevent excessive scour at the nose (the front or head portion) of the groynes, launching apron was provided.

Before the implementation of groynes, it can be clearly seen from Photo 5(a-c) that the flow is concentrated on the outer bank. Also, the point bar located on the opposite bank tend to push the flow further towards the outer bank. However, after the implementation of groynes, it had a significant influence on the flow and the bed morphology as seen in Photo 5d. Due to the effect of groynes, the point bar on the opposite side has been reduced and the main flow is now shifted towards the opposite banks. A significant amount of deposition has occurred in the space between the groynes as well as at the immediate downstream. In fact, the deposition is nearly upto the crest of groynes. Also, the growth of vegetation further strengthened the deposited sediments. Although it seemed that the purpose of implementing groynes was achieved, there are certain factors that need to be taken care of. As the flow is now shifted towards the opposite bank, there are high chances of erosion along that bank. Similarly, along the groynes implemented bank, the erosion shifted downstream. So it needs to be protected as well. This suggests that the phenomena of erosion and channel adjustment are complicated in a meandering channels. Therefore in case of meandering channel, the analysis of the problem needs

Photo 5: Implementation of groynes in Lohandra River.

Photo 6: Implementation of Groynes for bank protection and its effect in Sunsari River.

to be done in a multidimensional way, i.e. not just focus on one aspect of bank erosion.

In case of Sunsari River, as seen in Photo 6a, one straight type impermeable groynes, as well as a revetment, were implemented in the year August 2012 on the outer bank to check the bank erosion. The length of the groyne was 9m the top-level of which coincide with the level of the bank and slightly sloping towards the channel. The other configuration was similar to the groynes of Lohandra River with launching apron at the nose and at upstream and downstream of the main body. About 30m downstream of the groyne, a revetment wall of length 9m and height 1.5m was also installed.

Before the implementation of groynes, as discussed in subsection 5.1 and shown in Photo 4 (a & b), the mass failure of bank materials along the outer bank was very active due to the concentration of flow along the outer bank. However, the implementation of counter-measures resulted in a massive evolution of channel alignment as well as morphology. As it can be clearly seen from Photo 6 (c, d) that a considerable amount of land has been reclaimed as a result of the deposition induced by the implementation of the counter-measures. This deposited land has eventually turned into a mainland floodplain. However, the risk of erosion is now shifted to downstream and hence bank protection is required in that portion. This had a positive impact on the outer bank but the opposite bank has been eroded significantly due to the shifting of the channel towards it. As a result, almost the same amount of area deposited on the outer bank has been lost to erosion from the opposite bank. The main reason behind this impact on the opposite bank is the narrow width of the channel. Whether or not the groynes should have been implemented remains a topic of debate. But what can be said for sure is that the length of the groynes should be decided carefully in narrow channels or even opt for alternative means of bank protection.

From the analysis of bank erosion and effect of the implementation of counter-measures, it can be said that the erosion-deposition is a natural phenomenon and will continue to occur under whatever condition is implied in the river channel. Even with the implementation of counter-measures, erosion will shift from one point to the other or from one bank to the other. This suggests that rather than focusing on the counter-measures alone, the overall phenomena of channel evolution over the past should be analyzed. At the same time, different alternative counter-measures should be discussed before coming to any conclusion on the choice of appropriate measures for a given reach of the channel.

(3) Meander migration

Meandering channels often change their planform characteristics by shifting their position within the floodplain. The migration of meandering rivers results from interactions among flow, sediment transport, and channel form that create complicated sedimentary structures and lead to the evolution of channel planform over time, Guneralp et. al. (2012). The change in channel planform and its shifting has a

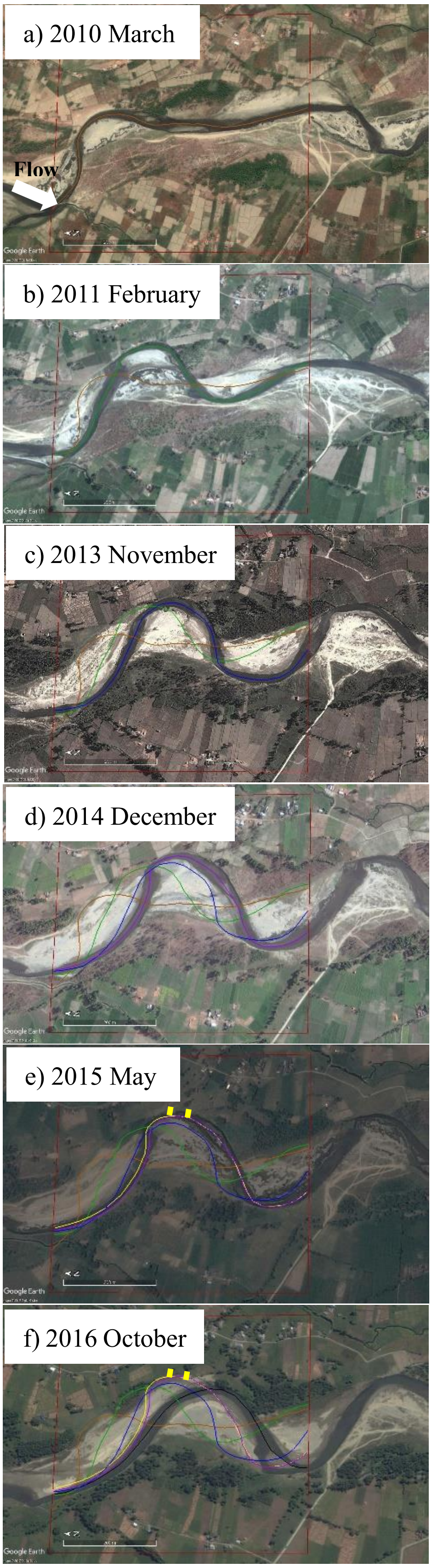

Photo 7: Time series images of meander migration of Lohandra River (small yellow rectangle represent the groynes), Google Earth (2018)

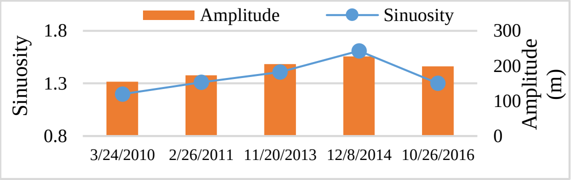

Fig. 9: Temporal change in channel sinuosity and amplitude of Lohandra River.

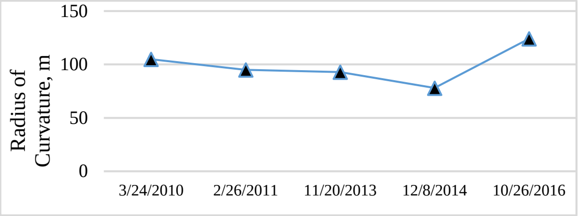

Fig. 10: Temporal change in the radius of curvature of channel centerline of Lohandra River.

tremendous impact on the riparian activities and structures, Hooke (2013). It is, therefore, necessary to understand the process of meander migration with regard to various issues of river engineering and management like flood control, navigation, bank erosion and protection of land and infrastructures.

In order to learn how the channel has evolved over the years and to analyze its potential impact on the channel stability, channel migration characteristics were studied. The available time-series images of the study reach of both Lohandra and Sunsari River were obtained from google earth engine, 2018 which is presented in Photo 7 and Photo 8 respectively. The colored lines along the channels in Photo 7 & 8 represent the approximate channel centerline. In case of Lohandra River, distinct meander planform has been evolved from the initial low sinuous planform. Before the implementation of groynes in Photo 7 (a-e), due to the erosion of outer bank near the apex and further downstream, the channel centerline continuously shifted downstream. Similar phenomenon was observed in the experimental case where the channel erosion occurred around the same locations. It can be seen from Photo 7 (a-e) and Fig. 9 that the amplitude, as well as the sinuosity of the channel, increased consistently from the year 2010 to 2015. In experimental case, the high sinuosity channel showed similar phenomenon while in case of low sinuosity channel, channel couldn't preserve the meandering pattern and tend to be braided due to high rate of erosion of outer banks. But after the implementation of groynes in the year 2015, both these parameters decreased as shown in Photo 7 (f) and Fig. 9. The radius of curvature which signifies the sharpness of the meander bend has also decreased during the period 2010 to 2015 before the placement of groynes. However, the radius of curvature was found to be increased after the groynes installation as shown in Fig. 10. The lower radius of curvature increases the sharpness of bend which in turn enhances channel migration or the overall instability of the channel. The implementation of groynes protected the bank erosion by inducing deposition and shifting the flow away from the bank. However, the erosion has now shifted to the downstream portion as well as the opposite bank. It can be clearly seen from the shift in the channel centerline that the channel has the overall tendency to migrate downstream. Another important aspect to be analyzed is the formation and movement of point bars in the meandering channel as they have a significant effect on the overall channel development. Bar formation and growth signifies that the channel migration is active in the channel. Accordingly, it was seen that the point bar has grown in size which is basically due to the deposition of eroded sediments from the opposite bank. As the flow was shifted more towards the channel center due to the effect of groynes, the size of the point bar on the opposite bank was reduced to some extent.

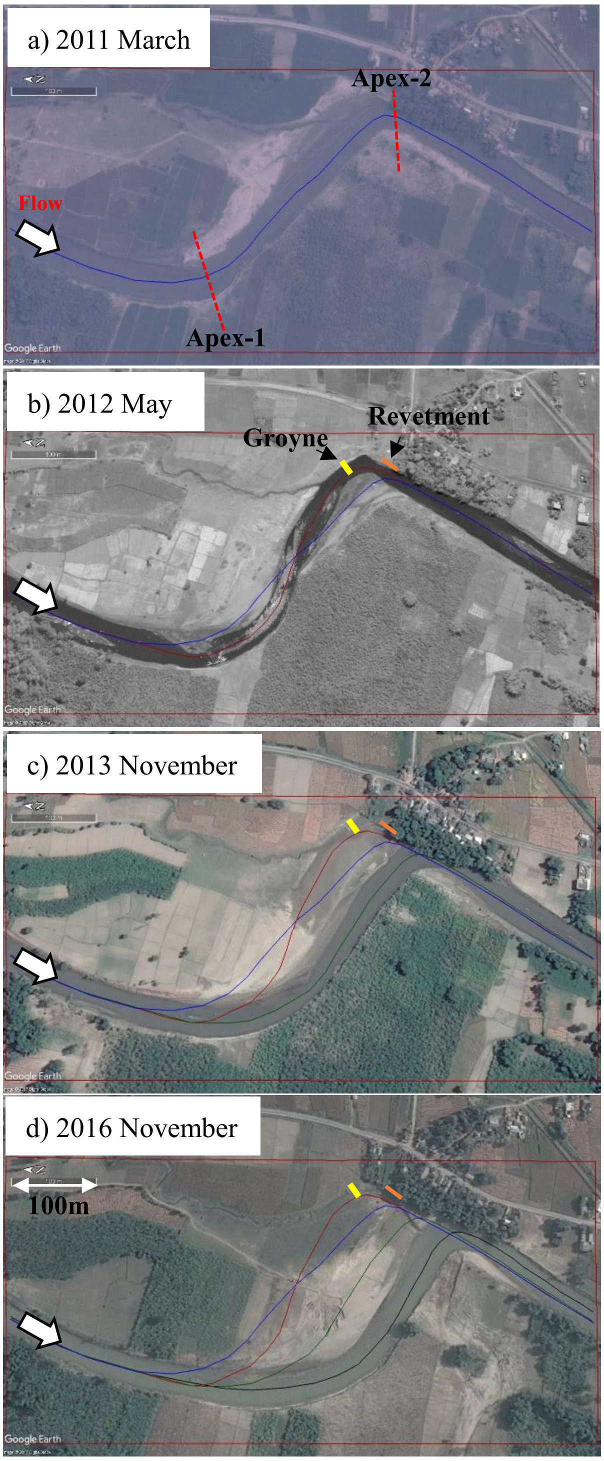

Photo 8: Time series of meander migration of Sunsari River (small yellow rectangle represent the groyne), Google Earth (2018)

In case of Sunsari River, as shown in Photo 8 the channel planform can be regarded as a sharp bend rather than a fully developed meander compared to the previous case of Lohandra River. As a result, the channel planform evolution is very much drastic and uncertain. In Photo 8a of 2011, downstream of the apex-1, it seems as the right bank behaves as an outer bank but in Photo 8b of 2012, the left bank upstream of the apex-2 acts as an outer bank. Accordingly, the groyne was installed in the year 2012 on the left bank upstream of the apex-2 which is shown by a small yellow rectangle in Photo 8b. However, it seemed that the channel planform of 2012 May was just a temporary adjustment and not a fully formed meander bend. Implementation of groyne resulted in a drastic change in the channel planform and morphology as seen in Photo 8 (c & d). The major changes occurred in the region between the two apices; deposition on the left bank and erosion on the right bank. In the left bank where the groyne was implemented, a major deposition occurred which consequently pushed the flow towards the opposite right bank. As a result of this, a consistent erosion and shifting of the channel towards the right bank occurred. The implemented groyne as seen in Photo 6 (b-d) has been completely filled with the sediment and is about 100m away from new bankline. The deposited portion of land on the left bank has been reclaimed but the almost same amount of land has been lost to erosion on the opposite bank. The major factor that can be attributed to this evolution of channel pattern is the location of the apex-2. At first, the implementation of groyne pushed the flow towards the channel center. As it can be seen that the apex-2 has a very sharp bend almost 90^0. Also, the bank just downstream of apex-2 is protected by the revetment as well as there is plenty of vegetation which further strengthened the bank against erosion. Due to this reason, the outer bank couldn't be eroded. This factor along with the groyne implementation behaved as an external forcing to the channel. Consequently, the channel tends to adjust to this external factor by eroding the bank that is weak and easy to erode. The consistent shifting of the channel centerline between the apices from left bank to the right bank clearly justifies the above discussion.

5. CONCLUSION & RECOMMENDATION

In this case study, bank erosion, channel migration and the effect of the implementation of the countermeasures were analyzed based on the laboratory experiments as well as two natural alluvial meandering channels. It was observed that the bank erosion in alluvial meandering channels is very common and active phenomenon. In case of experiments, fluvial erosion was dominant due to non-cohesive sediment whereas both the fluvial erosion and the mass failure mode of erosion can be attributed to the cause of failure in natural channels. Also, the erosion of bank shouldn't be viewed as a single or an isolated problem. Rather it should be regarded as a part of the channel formation or overall channel evolution process and the counter-measures should be implemented keeping in view of these overall channel development processes. Both experiments and natural channels, in general, showed a tendency to migrate downstream. Implementation of counter-measures has a significant effect on the control of bank erosion as well as channel migration. However, at the same time, these counter-measures have an adverse effect on the opposite banks if not implemented carefully. The implementation of countermeasures may have a tremendous impact on the overall channel planform and morphological evolution. In the short term, the countermeasures like groynes tend to look effective in the control of bank erosion but may have a negative impact on the long run, for example, by shifting the point of erosion to another point or another bank. It is thus suggested to analyze the different alternative before the implementation of any countermeasures. Similarly, it is also recommended to implement the groynes in a series to achieve maximum functionality. The analysis of the channel migration characteristics showed that the meandering channels, in general, have a tendency to migrate in a downstream direction. Alluvial meandering channels very frequently modify the channel planform depending upon the change in any flow, sediment or river structures. It was also found that the groynes tend to stabilize the channel migration and meander development processes to some extent. It is thus strongly recommended that the long-term evolution of channel planform be analyzed before coming to any conclusion on the choice of type and location of the installation of any countermeasures.

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