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STABILITY ANALYSIS OF FLOOD PROTECTION EMBANKMENTS AND RIVERBANK PROTECTION WORKS

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ABSTRACT

Frequent and widespread flooding is a major problem in Assam, which is a north-eastern state of India. The problem is caused mainly by the Brahmaputra river whose erratic riverbank erosion has been leading to general widening of channels and large-scale instability of banks. In the last century, the river has widened by more than 50% in several stretches causing serious threat to nearby urban centres apart from eroding several thousand hectares of fertile agricultural land including tea gardens. As of now, the width between outer banks ranges from as low as 1.2 km at some sections to as high as 18 km at some reaches. Both the flooding and erosion in the river valley can be tackled only through an adaptive response that includes the use of structural protection systems. A practicability study was conducted for raising the height of existing flood embankments in a particular reach of the river. Stability analysis was carried out to determine safety factors under static conditions and earthquake loading. Riverbank protection works are also discussed.

INTRODUCTION

The Brahmaputra river is the main cause for flooding in the state of Assam in north-east India. The problem of flooding in the river basin is basically linked with the geomorphologic developments of Himalayan mountain building and slope erosion, which are mostly beyond human control. Further, the combination of two intense processes of tectonics and monsoon rainfall can cause vast instability of the river and therefore little predictability. This means that both the flooding and erosion in the river valley can be tackled only through an adaptive response, by managing the consequences of the ever-changing river environment in an integrated manner. While high dams are recommended for flood control, it will be necessary to continue dependence on the existing network of embankments with proper periodic maintenance.

The river originates 5300 m above sea level in the Tibetan plateau, and flows from west to east as the Tsangpo River. It then turns south through the eastern Himalayas to enter India in the state of Arunachal Pradesh as the Dihang river. As this river crosses further over to the state of Assam, it is joined by the Dibang and Luit rivers to form the Brahmaputra river. The river then flows through Assam from east to west over a length of about 650 km. Close to the western boundary of Assam, the river turns south to enter Bangladesh, where it is known as the Jamuna river. The entire length is about 2,880 km from the origin to its mouth in the Bay of Bengal. In Assam, the river lies in a well-defined valley ranging from 40 to 100 km in width. In Figure 1, the river course is shown in red color whereas the state of Assam is shown in blue color.

Fig. 1. The course of the Brahmaputra river

The Brahmaputra river basin receives heavy rainfall from the influence of South West Indian monsoon from June to September of every year. The average normal rainfall in the valley is about 2300 mm/year. The catchment area in India is around 1,95,000 sq. km. and it yields about one-third of India's total water resources. As the abundant water resources remain substantially unutilized, this imposes severe distress through frequent flooding. The development of Assam is constantly hampered by riverbank erosion and flooding, which are major and recurrent natural disasters. However, the concept of how to address them permanently is unclear.

Under low flow conditions, the river has a multi-channel character with most reaches showing a braided planform with three to six channels separated by islands and bars. The width between outer banks ranges from as low as 1.2 km at some sections to as high as 18 km at some reaches. Individual low-water channels can have widths of even up to 1 km. However, there are eight narrow and short nodal reaches along the total length, where the river is confined between resistant rock formations on both banks and the braided planform is locally suppressed.

During rising flow conditions, the islands and bars tend to get submerged, and in major floods they disappear entirely. Especially under flood conditions, the pattern of channels changes frequently, accompanied by extensive erosion of floodplain banks and deposition of new sand bars. Through more than 90 percent of the river length through Assam, the adjacent floodplains consist of deposits mainly of fine sand and silt, with very little resistance to erosion. Thus, riverbank erosion is itself the main problem hampering effective flood protection of the Brahamaputra.

This practicability study is for raising the height of flood protection embankments and upgradation of riverbank protection works in the Palasbari reach of the river along the southern bank (Figure 2). The area is located about 20 km downstream of Guwahati city, which is the capital of Assam.

Fig. 2. Location of Palasbari along the Brahmaputra river in Assam

EXISTING PROTECTION SYSTEMS

River control continues in the flood plains of the Brahmaputra river and is an important focal point for ongoing developmental efforts. Starting from the year 1951, a comprehensive policy framework for flood control has been in place, which has promoted short and long-term programs for both structural and non-structural measures.

Altogether about 3,880 km length of embankments, 850 km of drainage channels, and 85 numbers of sluices have been constructed in the flood-prone areas. The embankments extend along both banks of the Brahmaputra, as well as along selected reaches of tributary rivers flowing from both the north and the south. For protection measures against erosion, more than 650 structures have been taken up in the form of spurs, revetments and porcupine fields.

The embankments were built mainly from locally available soils and were usually not constructed to very high standards. As most of the embankments are located close to the riverbanks, they are susceptible to damage due to bed scour and channel migration. Even if the embankments are initially set back some distance from the banks, they cannot be expected to remain immune to river erosion for many years. The embankments are also susceptible to erosion from rainfall. In many locations, they need repair. Where the erosion has led to breaches, the embankments have been retired or set back farther from the riverbank. The consequences are the need for land acquisition for new embankment construction, and also the impoverishment and displacement of the affected population.

Spurs are used to direct currents away from the riverbank and thereby protect the embankments. Two types have been used, namely land spurs and river spurs. Land spurs are constructed on the floodplain, perpendicular to and joined with the flood embankment. They are provided with riprap on the slope surfaces and a terminal rock apron placed in the river. Figure 3 shows various views of a land spur.

River spurs are rock-filled protrusions that extend perpendicular from the bankline well into the low-water level of the river, and are protected with aprons at their outer ends. The aprons consist of rock-filled crates dumped for a distance between 30 to 50 m in an arc shape around the spur head.

Experience with spurs has been positive, and there have been no failures. Usually, stockpiles of rock are maintained at spur sites for use whenever the spurs are threatened by erosion.

A revetment is a structure constructed at the bottom or on the banks of a river by placing a layer of material, such as rock, stones, concrete blocks, or mattresses. A porcupine is a tetrahedron-shaped concrete frame made of six concrete members each about 3 m long and connected with bolts, which are arrayed in the riverbed to retard flow and induce sedimentation. A porcupine field is shown in Figure 4.

Fig. 3. Views of a typical land spur constructed along the river

Fig. 4. Views of a typical porcupine field installed in the river

Most flood control schemes continue to deteriorate due to insufficient maintenance. After the severe floods of 2004, the state government is according high priority to rehabilitating and upgrading existing embankments that protect critical urban and rural centers with high growth potential. This will have to be accompanied by measures for effective supervision and maintenance.

INFLUENCE OF SEISMICITY

The region is subject to frequent seismic movements and periodic major earthquakes. The Assam earthquakes of 1897 and 1950, both of magnitude 8.7, have been among the largest in the history of the world. The major earthquake of 1950 caused many landslides and rockfalls in the mountains and foothills, and generated large quantities of sediment that entered the river system as a slug. This disturbed the normal regime over a period of several decades as the extra sediment worked its way downstream to the Bay of Bengal.

Another devastating consequence of major earthquakes is that landslide debris can form temporary dams on certain tributaries, which can hold back large volumes of water for periods up to even months. When these dams eventually collapse, destructive flood waves of great height and velocity can rush down the valleys. In addition, seismic action can also liquefy fine sand and silt deposits in the floodplains, leading to progressive failure of riverbanks and flood control embankments.

THE PRESENT STUDY

The selected study area is along the Brahmaputra main stem in Palasbari, as already indicated in Figure 2. Since 1955, the area had only flood embankment protection, and at the end of the 1950s, the town eroded to a great extent due to the absence of riverbank protection. Due to the erosion, the riverbank approached the embankments continuously though they were initially at some distance from the bank. Only in the middle of the 1980s, limited riverbank protection was built in this area after three decades of embankment erosion and reconstruction.

The existing flood embankments in Palasbari town do not have a uniform cross-section throughout its length. The average section has the following details:
1. Top crest width of 4.5 m
2. Height of 4 m from the ground surface
3. Side slopes assumed as 1.5H:1V on both sides

For most of the time, the embankment is exposed to no hydraulic head and remains largely unsaturated. However during flood events, the embankment has to withstand a rapid rise in water level on the riverside face, in combination with heavy rainfall. The transition from low to extreme load conditions may take only a few hours.

Subsoil exploratory work was carried out in the flood plain area accompanied by laboratory testing. Appropriate soil parameters have been defined based on the site investigation and laboratory analysis.

A knowledge about the type of fill material used to construct flood embankments and the method of construction allows the performance of the embankment to be analysed using principles of soil mechanics. The usual method for construction has been to excavate soil from adjacent ground in the countryside of the embankment. The excavated soil would mainly be a fluvial deposit from a flood plain that was composed of fine silt and clay sized particles. The excavated soil would be placed in layers using light compaction equipment without necessarily complying with engineering specifications to achieve a target density or permeability.

For raising the height of the flood embankments, alternative design sections need to be studied. They should be checked for geotechnical stability against hydraulic and other loads. The possibility of occurrence of major earthquakes during the flood season is expected to be the critical load combination. Thus, the conditions that need to be considered are:
1. Full water level during the flood season,
2. Scouring at the toe of the embankment, and
3. Earthquake loads.

The average reduced level (RL) of the ground is 103.4 m. The high flood level provided is 108.4 m RL, at 5 m elevation from the ground. If a free board of 1.5 m is to be adopted, the crest level of the proposed raised embankment will be at 109.9 m RL, with the full height of the embankment from ground level equal to 6.5 m.

With top width 4.5 m, elevation from ground 4.0 m, and side slopes 1.5H:1V, the average base width of the existing embankment works out to be 16.5 m. Keeping the top width and height of the raised embankment as 4.5 m and 6.5 m respectively, stability analysis is required for different cross-sections having different base widths and side slopes.

Some stretches of embankments just next to the riverbank can be seen from photographs presented in Figure 5.

Fig.5. Views of existing embankments at Palasbari next to the Brahmaputra river

Embankment geometry can vary according to type of materials used and construction history. Preferably, an embankment should have a crest width greater than 2.5 m to allow access for maintenance vehicles. Poor maintenance activities can result in steepening of the slope through excessive removal of soil when cutting vegetation. Changing the slope of an embankment affects the way in which water waves run up the face and overtop the embankment.

ANALYSIS OF FLOOD EMBANKMENTS

In this practicability study for raising the height of the existing embankments, three different sections have been considered:

Section I. Widening of base width is possible both on the countryside and the riverside. The final embankment section has height of 6.5 m and base width of 24 m.

Section II. Widening of base width is not possible on the countryside due to thick population. This embankment section has final height of 6.5 m and base width of 20.25 m.

Section III. Widening of base width is not possible on both sides. The embankment section has height of 6.5 m and base width of 16.5 m.

Separate analysis and design for each section type is necessary. The analysis should include static analysis and severe earthquake conditions with water at high flood level.

Static Analysis

For static slope stability analysis, Simplified Bishop method, Simplified Janbu method, and Morgenstern and Price method have been used (Duncan & Wright, 2005). In these methods, the embankment soil mass is divided into a number of slices, and equilibrium equations are written and solved for each slice. Simplified Bishop method considers interslice normal forces, ignores interslice shear forces, and satisfies overall moment equilibrium but not overall horizontal force equilibrium. Simplified Janbu method also considers only interslice normal forces while ignoring interslice shear forces, and satisfies overall horizontal force equilibrium but not overall moment equilibrium. Morgenstern and Price method considers both shear and normal interslice forces, and also satisfies both moment and horizontal force equilibrium.

For any particular cross-section, the analysis involves trial and error, and many trials are required to locate the critical slip surface having the minimum factor of safety. Manual calculation is impractical, and hence Geo-Slope (2008) software has been used. The properties of the embankment soil are: unit weight = 20 kN/m^3, cohesion = 18 kN/m^2, and angle of internal friction = 24°. The water level in the riverside corresponds to high flood level of 5 m elevation above the surrounding ground. The countryside is considered to be dry.

Under static conditions, the factors of safety determined for different methods of slope stability analysis are presented in Table 1. The critical slip surfaces of the three embankment sections obtained by using the Morgenstern and Price method are depicted serially in Figure 6.

Table 1. Static factors of slope safety for different embankment sections

Method	Section I	Section II	Section III
Simplified Bishop method	1.757	1.482	1.467
Simplified Janbu method	1.645	1.469	1.456
Morgenstern & Price method	1.754	1.481	1.467

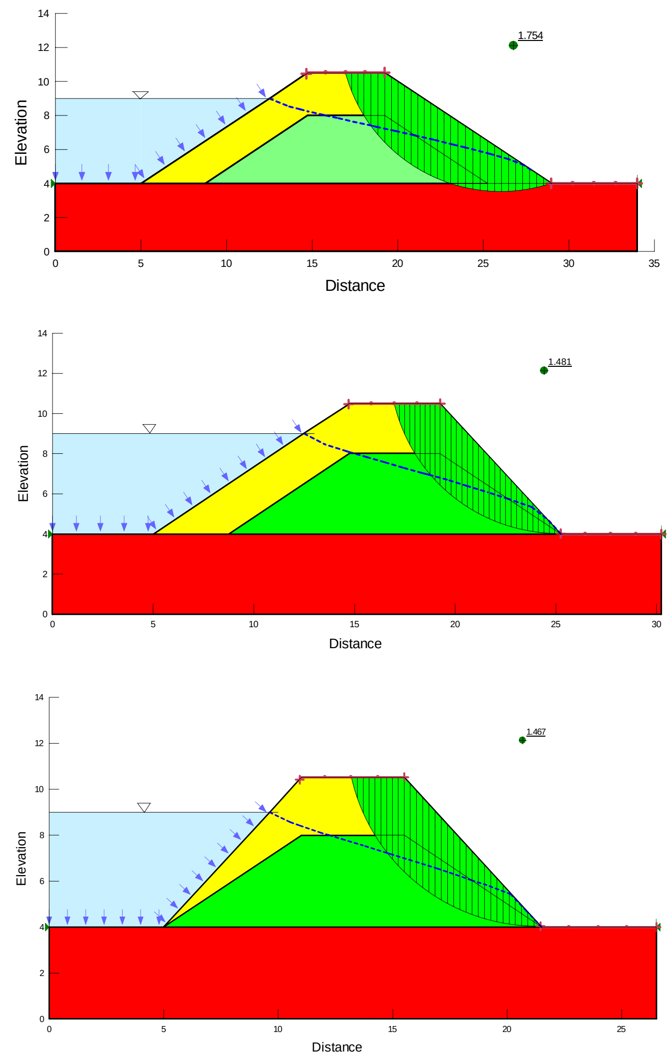

Fig. 6. Critical slip surfaces of different embankment sections under static conditions determined with Morgenstern and Price method

Dynamic Analysis

During earthquakes, the embankment sections may not completely collapse, but there may be unacceptable permanent deformation. In dynamic analysis, it is therefore necessary to estimate permanent deformations that can occur as a result of inertial forces associated with an earthquake. For this, the first step is to determine the in-situ state of stress in the ground which exists before the earthquake occurs and then shakes the ground. Initial stress contour plots of the three final embankment sections are shown in Figure 7.

In the next step, the embankments are subjected to an earthquake acceleration-time history of 44.3 sec duration, as shown in Figure 8. The data for this record has a constant time interval of 0.02 sec. A procedure similar to Newmark method of analysis has been used to examine the stability and determine the permanent deformation during the earthquake.

For each trial slip surface of an embankment section, the initial in-situ stress condition is used to establish the static strength of the slope. During the shaking, constant undrained strength behavior is considered. Then, the dynamic shear stresses are computed at all time steps during the shaking process. Thus, the factor of safety at every time step can be computed. At any time step, the average acceleration of the total sliding mass can be obtained. For this, the total mobilized shear due to the dynamic inertial forces is determined first. This is then divided by the total sliding mass.

Figure 9 describes the variations of factor of safety with time for the three embankment sections. It can be noted that the factor of safety goes up when the shaking is towards the riverside. As there is a wide variation in the factors of safety during the earthquake, it is difficult to state anything meaningful about the stability of the embankments. During the shaking period, there are short time moments when the initial static forces plus the inertial forces exceed the available shear resistance. During these times, there is a temporary loss of stability that leads to unrecoverable deformations. These deformations accumulate and result as permanent deformation after the shaking is over.

For every trial slip surface, an estimate of the resulting deformation can be determined in steps as follows. First, a plot of factor of safety with average acceleration is made so as to determine the yield acceleration, which is defined as the average acceleration corresponding to a factor of safety of 1.0. Second, the average acceleration is plotted with time. Third, the area in this plot that is greater than the yield acceleration is integrated twice so as to obtain the accumulated deformation.

It is then possible to identify the particular slip surface on which the largest computed deformation occurs. These specific critical slip surfaces for the three embankment sections are presented in Figure 10.

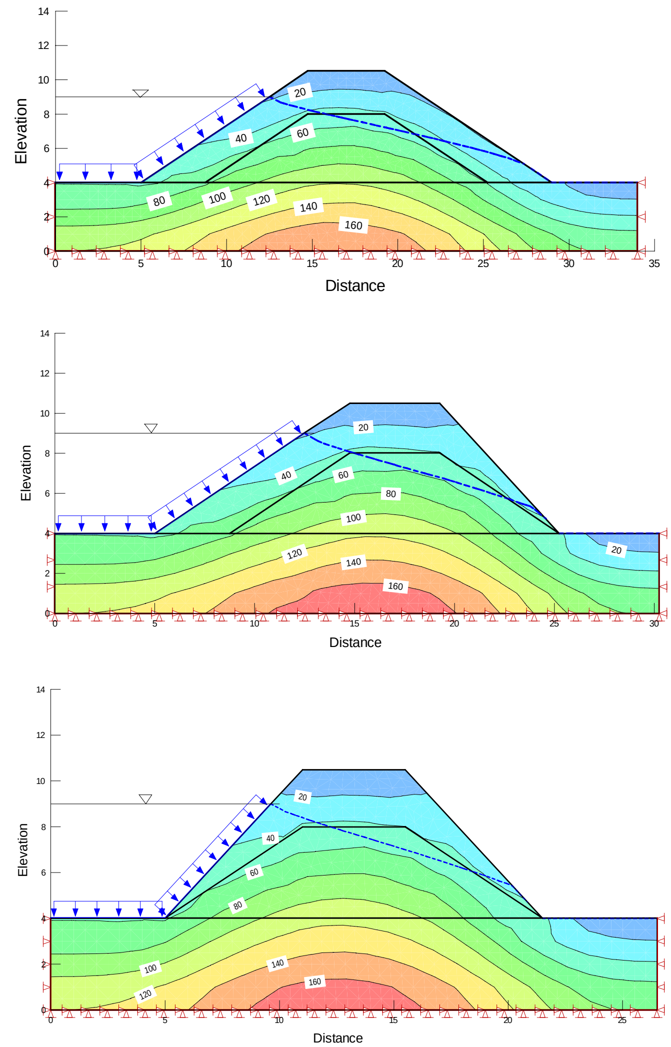

Fig. 7. Initial static stress contours of embankment sections

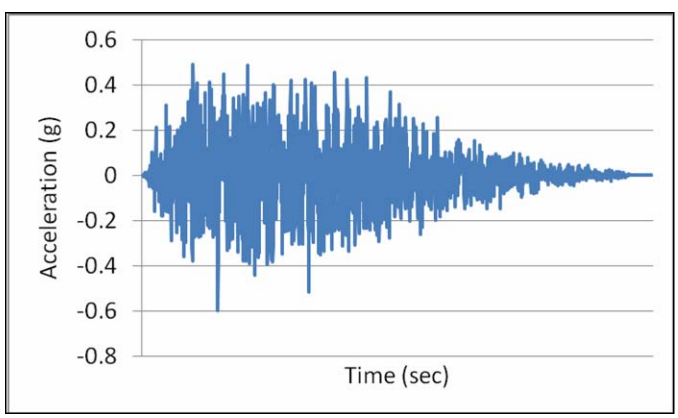

Fig. 8. Typical acceleration-time history

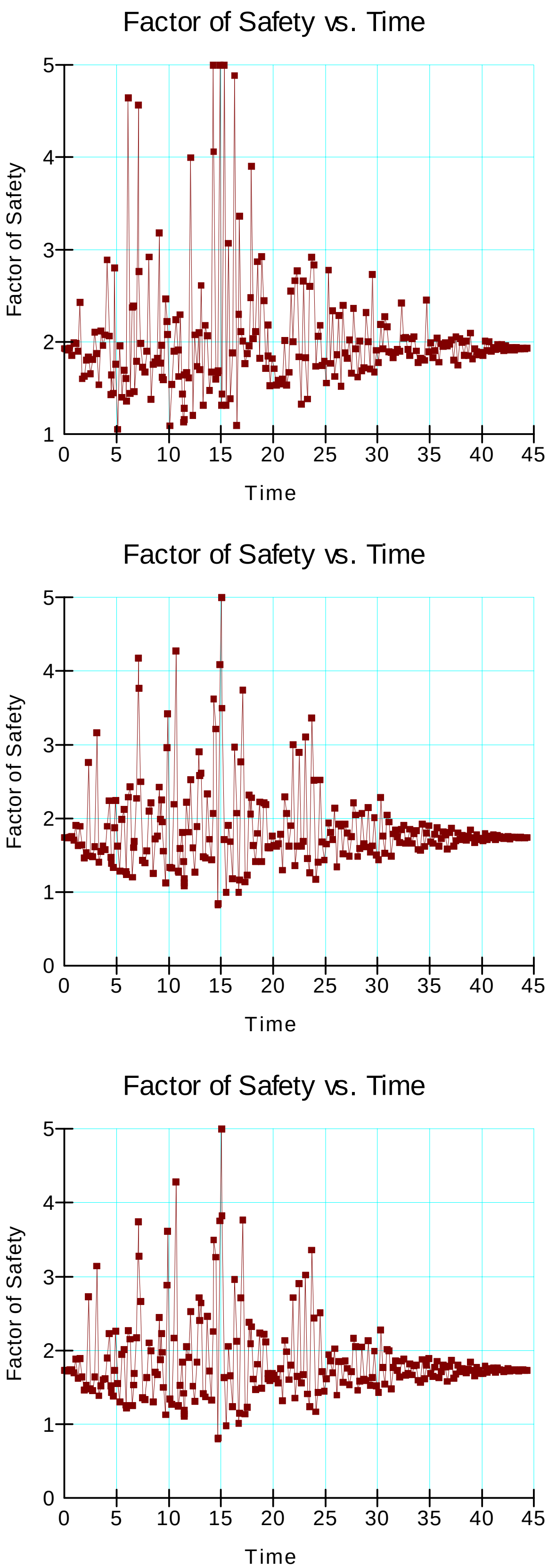

Fig. 9. Variations of factor of safety with time of the embankment sections under dynamic loading

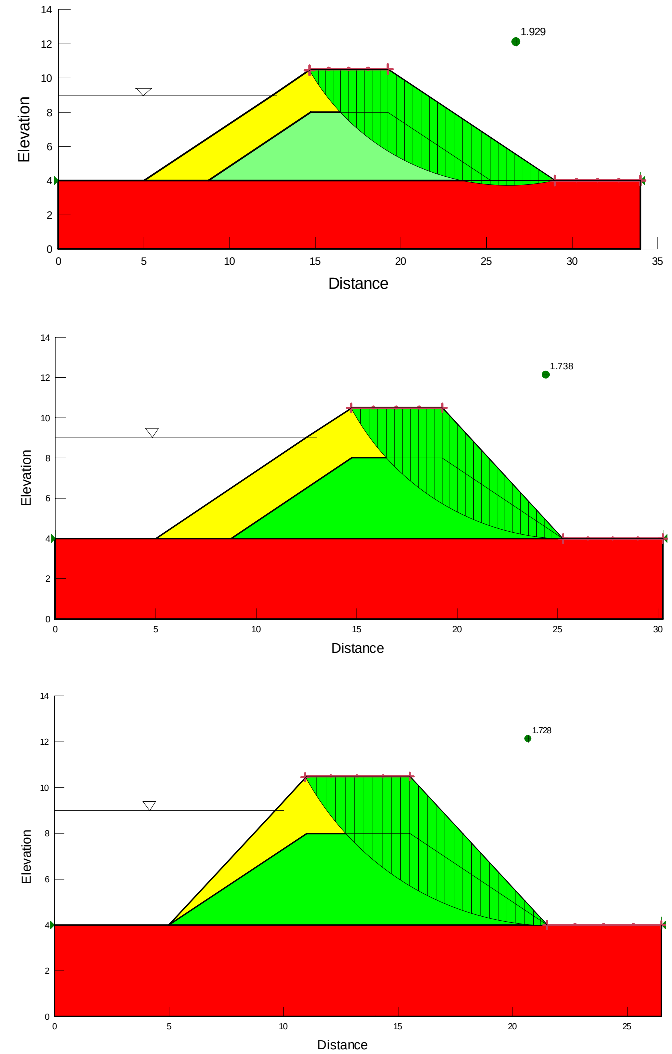

Fig. 10. Critical slip surfaces with the largest deformations of the embankment sections under dynamic loading

The corresponding factors of safety and the permanent deformations for these particular slip surfaces are tabulated in Table 2. It can be observed that there is no permanent deformation for Section I, in which the embankment is widened in both the sides. All the three sections are safe but the steep side slopes should be stabilized immediately after construction so as to prevent gulley and rut formation. Therefore, the new embankment slopes should be vegetated as soon as possible.

Table 2. Comparison of factors of safety and deformation of the embankment sections

	Section I	Section II	Section III
Factor of safety	1.928	1.738	1.728
Permanent deformation (mm)	0	12.1	15.6

RIVERBANK PROTECTION WORKS

The riverbank has eroded severely in several portions at Palasbari as observed from photographs shown in Figure 11.

Fig. 11. Some views of riverbank erosion at Palasbari

The riverbank revetment protection measures that exist only at certain portions along the Palasbari reach can be seen from photographs depicted in Figure 12.

The revetment protection needs to be extended throughout the entire length of the riverbank in Palasbari above the low-water level of the river. However, prior to the construction of the revetments, for prevention of long-term erosion of the riverbank slopes, it is proposed to protect first below the low-water level with sand-filled geobags (geotextile bags) as an alternative solution. To start the installation, a launching apron made of geobags is to be placed first above the toe of the riverbank slope below the low-water level. The slope angle under this immediate protection will be relatively steep as the bags are placed on the natural slope along the eroding bank.

In the first place, this will provide immediate protection from acute riverbank erosion. During further scouring, the toe of the launching apron gets undercut, and this will cause the geobags to unfold and then slide down the slope.

Fig. 12. Existing revetment riverbank protection at Palasbari

In the process, they will cover the newly exposed slope above the toe. If scouring and bank erosion continue, the slope becomes smoother. The final inclination will stabilize around 2H:1V, as the flexible geobags rearrange individually on the new stable slope. At the end of this process after end of scouring, more layers of bags will have to be placed over the launched layer. The final protection will consist of multiple layers of geobags, which will be installed in front of the toe.

During the above installation phases, there will be some geotechnical uncertainties, as the protection starts once the unstable situation has arisen, which is the condition for the bags to launch. It is on the basis of the subsequent geotechnical conditions till stability that the mechanism for the riverbank protection works gets established finally.

CONCLUDING REMARKS

The existing situation in Palasbari demonstrates that any delay of the investment into embankment and riverbank protection does not pay off. It is necessary to address riverbank erosion of the Brahmaputra river to sustain flood protection and to reduce the risk level for investment into economic development. One major consequence of the widening of the river is that private land predominantly held by poor households is getting lost systematically.

The practicability study for Palasbari area is intended to strengthen the existing embankment network, and to mitigate the risk of erosion through measures with the long-term target of providing a more stable river environment. The visualized combination of flood and erosion protection is expected to be valuable in tackling this problem.

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