Numerical Analysis of Stability of a Road Embankment Subjected to Floods

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Abstract

In the floodplains of the river Indus, several road embankments have failed due to the action of floods. The main motivation for this study is to analyse how much high floods a typical road embankment could sustain and to suggest remedies to prevent failure if the flood is exceptionally high. For this purpose, an 8 m high road embankment located in flood region of the Indus river was analysed for stability when subjected to 4 m and 7 m high floods. Numerical analysis was performed with finite element program PLAXIS 2D. The results showed that the road embankment was stable prior to occurrence of the flood. The road embankment became unstable when it was subjected to flood water of 4 m. This implies that the road embankment might not withstand pressure of the flood water higher than 4 m. The analysis suggested that the road embankment could fail if the flood water is 7 m high. To stabilize the road embankment when subjected to 7 m high flood, rockfill berm was utilized on the downstream side. Optimization analysis was conducted to use minimum volume of rockfill in order to reduce costs. The findings of this study could be beneficial to practicing engineers involved in maintenance of road embankments in floodplains

Keywords—Consolidation, Flood, Pore pressure, Road embankment, Safety, Stability

1 Introduction

SEVERAL infrastructure embankments of railway and roads had failed due to floods and rainfall [1-3] which resulted in monetary loss and inconvenience to the public. The infrastructure embankments in floodplains are not generally designed on the principles that are utilized for embankment dams to resist action of flood water [4]. Therefore, it is common practice that seepage protection measures are not adopted in infrastructure embankments in floodplains. The stability of such infrastructure embankments depends upon strength, degree of compaction and erodibility of the soils. Failure of such embankments may occur due to saturation, seepage, internal erosion and overtopping. During flooding, the soils of an embankment and foundation get saturated which cause increase in pore pressures. As a result, instability or failure of an embankment could occur due to decrease in shear strength of soils [5]. To date, there is lack of proper guidelines that could be utilized for safe and economical design of infrastructure embankments. In addition, rainfall induced pore pressures have triggered shallow failures of infrastructure embankments [6-7]. Gradual increase in pore water pressures in embankments may also lead to deep seated failures. It has been reported that the stability of infrastructure embankments has been affected by changes in pore water pressure due to seasonal and climatic variations [8-12]. There might have been several failures of embankments, however, a few of such incidents have been reported [13-14]. A few case studies have been carried out on numerical analysis of influence of seasonal changes of pore water pressures on stability of infra-structure embankments [15-20]. Stability issues of infrastructure embankments have received less attention as compared to that of embankment dams [see e.g., 21-24].

In Pakistan, the length of Indus river is about 1700 km. Normally, rainfall occurs from July to September [25]. However, the occurrence and intensity of rainfall is erratic. During these months, discharge of the Indus river increases and sometimes it may cause floods depending upon the intensity of rainfall and melting of

ISSN: 2523-0379 (Online), ISSN: 1605-8607 (Print)
DOI: https://doi.org/10.52584/QRJ.1902.12

Fig. 1: Failure of a local road embankment during flood in 2010

snow in glaciers located in north of the country. In this regard, earthen embankments have been constructed along both sides of the route of the Indus river to control flood water to inundate surrounding lands. These road embankments are about 7 to 8 m high. The embankments are raised using locally available alluvial soils which are generally clay, silt and sand. Flood water of the Indus river may strike with these embankments for about 1 to 1.5 months during flood season. Several road embankments located in flood region of the Indus river had failed, without being reported. Fig. 1 shows the failure of a local road embankment in flood.

With the passage of time, there is need for construction of more similar road embankments in floodplains of the Indus river to shorten the distance between various cities. There is an increased demand for safe and economical road embankments in flood plains that could sustain floods. It is, therefore, necessary to evaluate safety of existing infra-structure embankments in floodplains subjected to potential floods of different intensities to suggest protective measures in advance to prevent possible failures. In this regard, it is important to use advanced numerical tools to analyse how the shear strength, pore pressures and associated slope stability of infrastructure embankments varies when subjected to floods. This is one the first attempts in Pakistan in which stability of a road embankment subjected to floods is analysed and strengthened using optimum volume of rockfill using advanced numerical tool based on the finite element method.

2 Finite Element Model of Road Embankment

A hypothetical section of a road embankment in flood plain of river Indus was selected for this study. The selected embankment is about 8 m high (Fig. 2). Computations were performed using Finite Element Program PLAXIS 2D [26]. Numerical analysis was performed on the typical embankment section subjected to flood water of different depths. The stress strain

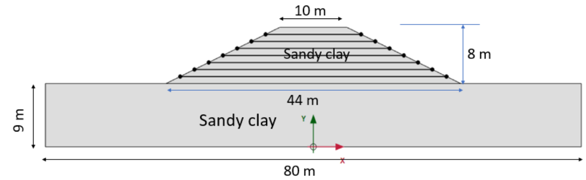

Fig. 2: Cross section of the road embankment in floodplain of the Indus river

Soil parameter	Unit	Silty soil	Rockfill
Effective cohesion	kN/m2	12	1
Effective friction angle	Deg	13	42
Young's modulus	kN/m2	7900	40000
Dilatancy angle	Deg	0	0
Poisson's ratio	-	0.4	0.35
Saturated unit weight	kN/m3	17.8	20
Unsaturated unit weight	kN/m3	16	18
Permeability in horizontal direction	m/day	7	8640
Permeability in vertical direction	m/day	7	8640

TABLE 1: Material properties of silty soil and rockfill berm used in road embankment

response of the road embankment was modelled with the Mohr Coulomb (MC) model. Input parameters of the MC model were determined from soil laboratory tests. The parameters of the MC model are shown in Tab. 1. To consider, the variation of pore pressures and associated deformations in the road embankment, coupled deformation and consolidation analyses were conducted [27]. Safety analyses were conducted using strength reduction technique to compute safety factors of the embankment [28]. At the embankment site, the ground water level was assumed to be 3 m below the natural surface level. Finite element mesh of the road embankment is shown in Fig. 3. The effect of the coarseness of the mesh was analyzed and the mesh was made so fine that the computed results did not show any significant variation with further refinement of the mesh. Numerical analysis of the stability of road embankment was performed for the following cases.

- Case I: Stability of the road embankment at the end of construction
- Case II: Stability of the road embankment subjected to flood water of 4 m depth
- Case III: Stability of the road embankment subjected to flood water of 7 m depth.

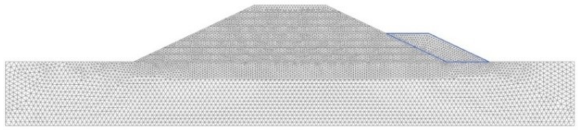

Fig. 3: Finite element model of the road embankment in floodplain of the Indus river

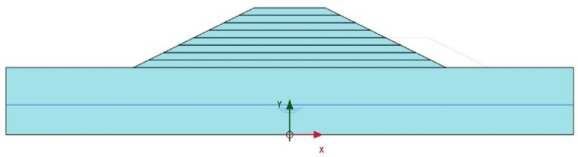

Fig. 4: Phreatic level of the road embankment at the end of construction is 3 m below the natural surface level

Initially, the raising of the road embankment was simulated in eight layers. Each layer, one-meter thick, was filled for 15 days. Safety analysis was performed for end of construction stage of the road embankment. In the numerical model, the embankment was subjected to floods of 4 m and 7 m depths for 30 days. Phreatic levels adopted in the numerical modelling of the road embankment for the above-mentioned cases I, II, and III are shown in Figs. 4, 5, and 6, respectively. Then the effect of floods on stability of the road embankment were analyzed.

3 Results

Following sections discuss the results of this study.

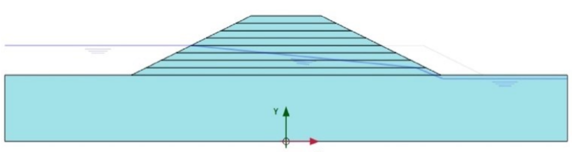

Fig. 5: Pattern of phreatic level in road embankment adopted for 4 m high flood water

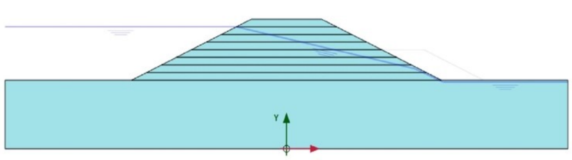

Fig. 6: Pattern of phreatic level in road embankment adopted for 7 m high flood water

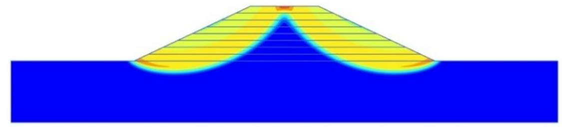

Fig. 7: Potential failure zone in the road embankment when the ground water level was at 3 m below the ground level

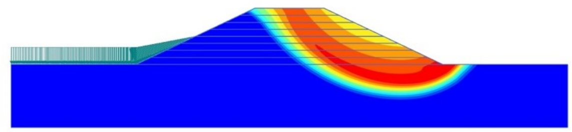

Fig. 8: Potential failure zone in the road embankment when the flood water level was 4 m above the ground level

3.1 Road Stability of the Road Embankment

Slope stability of the road embankment was computed for end of construction and for two possible floods of depths 4 m and 7 m. The factor of safety at the end of construction stage of the road embankment was computed to be 1.34. According to Federal Highway Administration [29], the recommended minimum safety factor for a road embankment is 1.25. This implies that the stability of the road embankment at the end of construction stage is satisfactory. As expected, the stability of the road embankment was decreased when the flood water was raised to 4 m and 7 m. The values of the safety factor were 1.18 and 1.07 when the flood water levels were 4 m and 7 m, respectively. The results suggest that the road embankment may start to be unstable if the flood water exceeds 4 m. The potential failure zones of the road embankment at end of construction and after subjected to floods of 4 m and 7 m are illustrated in Figs. 7, 8, and 9, respectively. The potential failure zones of the road embankment at the end of construction extended on both the upstream and down-stream slopes. Due to saturation of the road embankment with flood of 4 m and 7 m, the failure zones developed in downstream slope.

3.2 Pore Water Pressures

Besides evaluating safety factors of the road embankment at end of construction stage and for two possible floods, it is relevant to observe pore water pressures that could develop for the above-mentioned conditions. Pore water pressures in the road embankment at the end of the construction and for the two floods of 4 m and 7 m, are presented in Figs. 10, 11, and

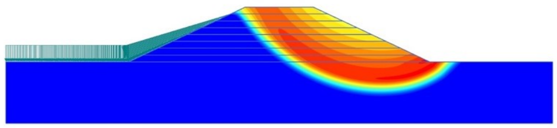

Fig. 9: Potential failure zone in the road embankment when the flood water level was 7 m above the ground level

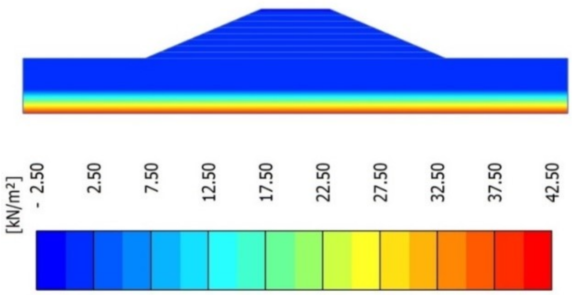

Fig. 10: Pore pressures in the road embankment after end of construction

12, respectively. The magnitude of construction pore pressures in the embankment portion of the road was about 2.5 kPa. The road embankment was saturated as the flood level was increased. As a result, there was increase in pore water pressures. It can be ob-served that the maximum pore pressures in the embankment were about 40 kPa and 60 kPa, due to floods of 4 m and 7 m, respectively. With the increase in pore water pressures, shear strength of the soil was reduced which indicates that instability of the road embankment might be initiated if the flood water exceeds 4 m.

3.3 Deformation Behaviour of the Road Embankment

Deformation behaviour of the road embankment for floods of 4 m and 7 m is presented in Figs. 13 and

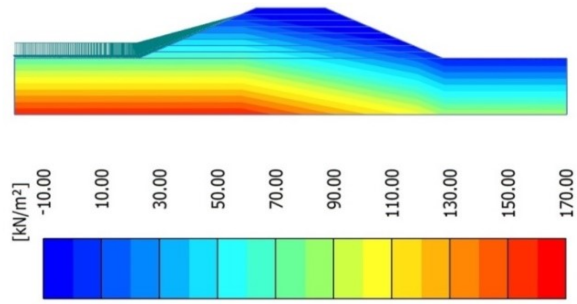

Fig. 12: Pore pressures in the road embankment when the flood water level was 7 m above ground level

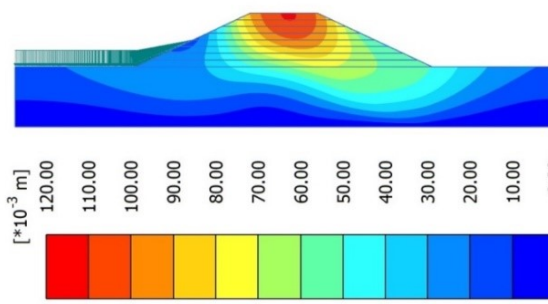

Fig. 13: Displacement in the road embankment when inundated with 4 m high flood water

14 respectively. As expected, the deformation of the embankment at the end of the construction was distributed in the central part of the embankment. For 4 m and 7 m high floods, the soil has been weakened resulting in deformations in the downstream side.

3.4 Stabilization of the Road Embankment with Rockfill Berm

It is concluded from the previous discussion that the road embankment was not capable of sustaining 7 m high flood. It is to be emphasized that the potential

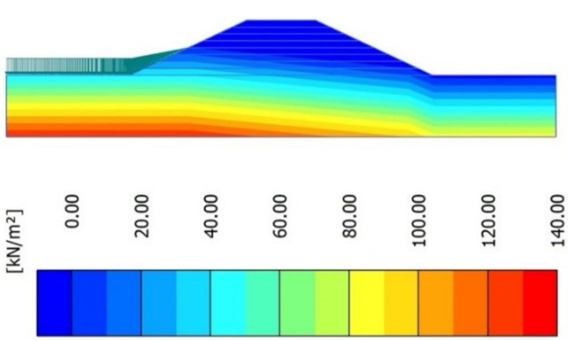

Fig. 11: Pore pressures in the road embankment when the flood water level was 4 m above ground level

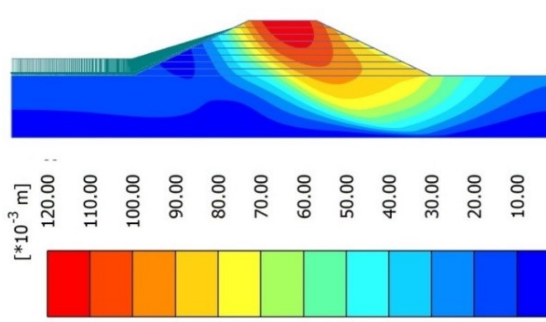

Fig. 14: Displacement in the road embankment when inundated with 7 m high flood water

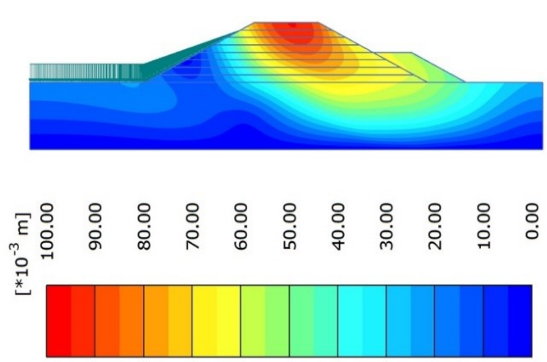

Fig. 15: Displacement in the road embankment stabilized with rock-fill berm when inundated with 7 m high flood water

failure zone of the road embankment when subjected to floods of 4 m and 7 m developed on the downstream side. It is to be noted that the 7 m flood is considered as a maximum possible flood that may occur in the studied region. To make the road embankment stable against 7 m high flood, one of the feasible options is to use rockfill berm as a support to the embankment. Since the length of the embankment is long. Optimization analysis was performed to optimize the volume of rockfill berms to save time and money. This was done by gradually increasing the width and depth of the rockfill berm on the downstream side of the embankment. The criteria adopted was to obtain allowable safety factor of 1.25. Finally, the rockfill berm of dimensions 6 × 4 m (width × depth) was used on the downstream side as a sup-port to the road embankment. Displacement in the road embankment stabilized with rockfill berm is shown in Fig. 15. The magnitude of deformation was reduced with the rockfill stabilization as compared to the embankment without the rockfill berm. With the addition of the rockfill berm, the safety factor was increased to 1.25 as compared to the previously computed value of 1.07 when no rockfill berm was used. The potential failure zone of the road embankment after rockfill stabilization is shown in Fig. 16. As expected, with the addition of rockfill berm, both the length and depth of the failure zone was extended. As a result, more resisting moment was developed and in turn safety factor of the road embankment was increased to an acceptable value.

4 Discussion

As flood water level was increased, more portion of the embankment was saturated. As a result the magnitude of excess pore pressures increased and stability of the embankment was reduced. In order to counteract the

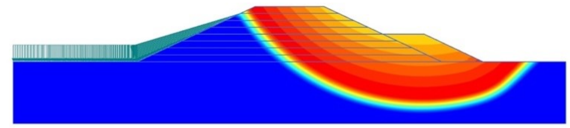

Fig. 16: Potential failure zone in the road embankment stabilized with rockfill berm when subjected to 7 m flood water

potential failure zone that developed due to saturation of flood water, rockfill berms were provided to strengthen the embankment on downstream side of the road. The optimization analysis are needed to quantify the necessary volume of rockfill. Such type of analysis could be useful for strengthening of existing road embankments so that they could be stable to mitigate the effects of flood waters.

5 Conclusion

Presented in this study are the results of numerical analysis on stability of road embankment inundated with different floods. Main conclusions of this study are summarized below. Stability of the road embankment was satisfactory in non-flood conditions. However, the stability of the embankment was gradually reduced with subsequent flood water levels higher than 4 m. The stability of the embankment may not be satisfactory if the flood water level is more than 4 m. To make the road embankment stable against a 7 m high flood, the downstream side of the embankment was stabilized with rockfill berm. The dimensions of the rockfill berm were optimized based on acceptable factor of safety. Practicing engineers involved in the maintenance of road embankments in floodplains could find this study helpful.

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