Stability Analysis of Flood Bunds: A Study on Geotechnical Health Evaluation of Embankments

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Abstract. Flood constitutes one of the world’s most serious environmental hazards. Flood bunds are the earthen hydraulic structures which are constructed along the River to control the Flood water to avoid damages to the infrastructures, crops, livestock and loss of human lives. Pakistan which lies in the Indus Basin has been facing severe threats and losses from the floods since histories. About 6807 km length of flood embankment has been constructed to safeguard against the floods in the country. Punjab has been worst hit province by heavy floods and rains causing heavy loss. Geotechnical Evaluation is vital for proper functioning of such structures. In this study four flood bunds susceptible to potential embankment breaching during flood have been selected along river Chenab in district Muzaffar Garh Irrigation zone. Suite of analysis using GeoStudio software (SLOPE/W and SEEP/W for stability and seepage analysis respectively) has been performed by considering four different critical scenarios, (1) steady state at highest flood level (2) rapid drawdown from highest flood level (3) steady state at extreme condition with 3 feet free board (4) rapid drawdown from extreme condition with 3 feet free board. The safety of the flood bunds is evaluated in terms of River Embankment Breaching Vulnerability Index (REBVI), safe exit gradient and factor of safety against slope failure. Based on these calculated factors from the numerical analysis it is found that embankment at RD: 25,29 are marginally safe, whereas at RD: 147, 157 are susceptible to pipping failure. Therefore, it is recommended to make embankment impervious using cohesive material and to install cut-off walls or berms to lengthen the seepage path.

Keywords. Stability, Stability analysis, flood bunds, embankments

1. Introduction

EMBANKMENT / LEVEE / DYKE is an earthen bund extending generally in more or less parallel direction of river course and is designed to protect the area behind it on the country side from the over run of the flood water. Nature has blessed Pakistan with plenty of surface water which originates from Himalayans in the north and flows toward Arabian Sea through river Chenab and its tributaries. A number of barrages and head works have been constructed on different rivers, mostly during British rule in the Subcontinent. Major purpose of these structures was to divert the river water to the canals for irrigating the fertile lands of Chenab plane. These structures on the rivers cause the hindrance to the natural regime of the rivers which lead to the heavy floods, especially during monsoon season owing to heavy rainfall particularly in the upper Chenab basin. To control the floods and keep the river waters within limits earthen dykes have been constructed from time to time and again along the rivers in Pakistan. At present about 6803 km flood bunds are existing on different rivers in Pakistan out of which, 3332 km fall in Punjab [1]. Unfortunately, less attention has been paid to proper stability and seepage analysis based on extensive geotechnical investigations during planning and construction of
these structures due to which the failure of flood bund occurs causing heavy loss to infrastructures, crops, livestock and human lives.

Punjab has been the worst-hit province due to rains and floods, where more than 1.7 million of the population is affected [1], [2]. According to the NDMA, nearly 17,000 houses have been fully destroyed. Over 1,900 schools across the province were also damaged and remained non-operational during flood 2014 [1].

The geotechnical inspection and assessment of flood control embankments were studied by Dyer et al. [3] where they discussed that the failure was due to seasonal wetting and drying with potential cracking on the crest and side slopes. Morris et al. [4] suggested that reason of embankment failure can be broadly divided into two modes depending on where the failure generates. First mode is founding strata (settlement, sliding, seepage and piping and uplift pressure) and second mode is embankment structure (slope instability, internal seepage, erosion of outward face and toe). Mondal et al. [5] investigated the function of geotechnical, geometrical and hydraulic properties on embankment breaching of Moyna drainage basin area using a group analysis based upon vulnerability index for the indicators. Failures in embankments of Irrigation canals in Sindh were overtopping, internal erosion, structural defects and piping and those were found out during study conducted by Bhanbhro et al. [6]. The recurrent history of overtopping and stability issues in the embankments provided the motivation for developing a better understanding of the behavior of this compacted fill under different loading and wetting conditions by Mountassir et al. [7]. Flood bunds can be protected using electrical resistance tomography (ERT) methods. Protecting these vulnerable slopes requires monitoring systems capable of identifying and alerting to asset operators changes in the internal conditions that precede failure [8].

Further, extensive literature regarding the flood bunds have been presented [9], [10]. In this paper, embankment stability is evaluated as a case study for the four embankment selected along Chenab river in district Muzzafar Garh, Punjab, Pakistan. Potential to embankment breaching is calculated in term of River Embankment Breaching Vulnerability Index (REBVI) suggested by Mondal et al. [5] and safe exit gradient using limit equilibrium program SEEP/W while factor against failure is evaluated using SLOPE/W (Geo Studio 2012) [11]. Remedial measures are recommended to avoid the embankment failure due to seepage.

2. SELECTION OF FLOOD BUNDS AND DESK STUDY FOR THE SELECTED SITES

2.1 Study Area
A study on four flood bunds of Chenab river was carried out to evaluate the health of flood bunds by investigating their geotechnical, geometrical and hydraulic properties to ascertain their strength against breaching during floods. The location map for selected flood bunds is given in Figure 1.

2.2 Field Survey and Subsurface investigations
For study purpose, four sites were selected on Chenab river which have potential for breaching, as shown in Figure 1. On two sites (RD 147+000 and RD 157 + 000) natural breaching was occurred during Flood 2014, while the other two sites (RD25+ 000 and RD29 +000) were remain safe in the vicinity of that breaching Flood Bunds.
Geotechnical investigations (SPTs and field permeability tests) were carried out. Disturbed and undisturbed soil samples were collected for laboratory testing. Based on direct shear, unconfined compression, atterberg limit, modified proctor and laboratory permeability (constant and falling head) tests the soil properties selected for embankment as well as foundation are shown in Figure 2.

Figure 1. Location Plan of selected bund sites along Chenab river

Figure 2. Selected embankment dimension and soil properties at R.D a) 25 b)29 c)147 d)157
3. Methodology Adopted for Health Evaluation of Selected Flood Bunds

3.1. Evaluation of River Embankment Breaching Vulnerability Index (REBVI)

A River Embankment Breaching Vulnerability Index (REBVI) was derived based on weightings of bank material to delineate the risk of vulnerability of the embankment. Transformation of absolute values into weighted values (W) for sites of flood bund is shown in Table 1.

| Bank Materials and Geotechnical Analysis | Embankments Structure | Hydraulic pressure |
|-----------------------------------------|------------------------|--------------------|
| Transformative Absolute values into Weighted value (W) | Top height (Bank Height) | Base Width (m) | Bank Slope | Water height (m) |
| Weight value | Soil texture | Bulk density (g/cm³) | Plasticity Index PI = LL-PL | Compressive strength (kg/cm²) | Safety Factor | Rank value |
|-----------------|--------------|-------------------|-----------------------------|-----------------------------|------------------|-----------|
| 0 | loam | <1.3 | >40 (very high) | >4 (hard) | 0.2 | >9 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 1 |
| 1 | Sandy clay | 1.3-1.4 | 20-40 (high) | 2-4 (very stiff) | 0.2-0.4 | 8-9 | 15-20 | 30-35 | 4-5 |
| 2 | Clay loam | 1.4-1.5 | 10-20 medium | 1-2 (stiff) | 0.4-0.6 | 7-8 | 10-15 | 35-40 | 5-6 |
| 3 | Silt loam | 1.5-1.6 | 5-10 (low) | 0.5-1 (medium) | 0.6-0.8 | 6-7 | 5-10 | 40-45 | 6-7 |
| 4 | Sandy loam | >1.6 | <5 very low | <0.5 soft | >0.8 | >8 | <6 | <5 | >45 | >7 |

Table 1: Methodological approach of River embankment breaching vulnerability index [5]

i. Ranking of different parameters. (1-7): 1 means highly ranked and 7 means lowest ranked

ii. Weighting of values within parameter. (0-6): 0 means very less vulnerable and 6 means very highly vulnerable.

After deriving the normal weights and ranks of all individual parameters, they were integrated with one another in a linear model to demarcate REBVI in the study area. The equation of REBVI is as follows:

\[ \text{REBVI} = (R_x \times W_x) + (R_y \times W_y) + (R_z \times W_z) + (R_p \times W_p) + (R_u \times W_u) + (R_v \times W_v) + (R_w \times W_w) \]  

where R= Rank Value, W= Weight Value, ST = Soil Texture, C= Compaction, X = Cross Section, PI = Plasticity Index, p= Permeability, UCS= Unconfined Compressive Strength, \( \phi \) = Angle of internal Friction

3.2. Numerical Analyses

The selected flood bunds are modelled under different critical condition in SEEP/W and SLOPE/W to study the failure of flood bunds under seepage pressure and safety against slope failure. Following four (04) critical Scenarios were selected, (i) Steady state at highest Flood Level (ii) Rapid drawdown from highest Flood Level (iii) Steady state at extreme condition with 3ft free board and (iv) Rapid drawdown from extreme condition with 3ft free board. The constitutive behaviour of both embankment and foundation were simulated using the elastic-perfectly plastic assumption of Mohr-Coulm model. The boundary conditions in numerical model were applied such that vertical face is fixed in horizontal direction and base is fixed in both horizontal and vertical directions.
4. Results and Discussions

The result of the REBVI showed that the highest score is less potential to prevent from embankment breaching or bank erosion. Lowest score is more potential to prevent from embankment breaching or bank erosion. Calculated REBVI values at RD 25, 29, 147, 157 are 45, 47, 55 and 66 respectively. Based on the results of SEEP/W, seepage analysis the values of exit gradient for four critical conditions is more than the safe exit gradient (0.3) at RD-147 & 157, which concludes that bund structure was failed due to piping. While the values of exit gradient at RD-25 & 29 were lesser than safe exit gradient and remain safe. SEEP/W results of are shown in Figure 3-6.

Based on FoS calculated from SLOPE/W, stability analysis, stability of bund structures is not the key issue. As the values of FoS for slope stability are more than the critical FoS against sliding.

| RD     | Water Level (ft) | States | Seepage Analysis | Slope Analysis | Remarks       |
|--------|-----------------|--------|------------------|----------------|---------------|
|        |                 |        | Safe Exit Gradient | Exit Gradient Obtained | Phreatic line | Safe FoS | Obtained FoS |
|        | RD              |        |                  |                 |               |           |               |
| 147+000| HFL             | SS     | 0.3              | 0.34            | exposed       | 1.5       | 1.21          |
|        |                 | RDD    | 0.3              | 0.13            | Within toe    | 1.3       | 1.11          |
|        | Extreme Condition | SS    | 0.3              | 0.41            | Exposed       | 1.4       | 1.06          |
|        |                 | RDD    | 0.3              | 0.22            | Exposed       | 1.1       | 1.00          |
| 157+000| HFL             | SS     | 0.3              | 0.33            | exposed       | 1.5       | 1.25          |
|        |                 | RDD    | 0.3              | 0.20            | Within toe    | 1.3       | 1.25          |
|        | Extreme Condition | SS    | 0.3              | 0.38            | Exposed       | 1.4       | 1.15          |
|        |                 | RDD    | 0.3              | 0.30            | exposed       | 1.1       | 1.072         |
| 25+000 | HFL             | SS     | 0.3              | 0.18            | Within toe    | 1.5       | 1.5           |
|        |                 | RDD    | 0.3              | 0.056           | Within toe    | 1.3       | 1.8           |
|        | Extreme Condition | SS    | 0.3              | 0.26            | Within toe    | 1.4       | 1.4           |
|        |                 | RD     | 0.3              | 0.072           | Within toe    | 1.1       | 1.8           |
| 29+000 | HFL             | SS     | 0.3              | 0.17            | Within toe    | 1.5       | 1.53          |
|        |                 | RDD    | 0.3              | 0.002           | Within toe    | 1.3       | 2.12          |
|        | Extreme Condition | SS    | 0.3              | 0.23            | Within toe    | 1.4       | 1.48          |
|        |                 | RDD    | 0.3              | 0.003           | Within toe    | 1.1       | 2.08          |

SS-Steady state, RDD-Rapid draw down
Figure 3. Seepage analysis results for various cases of RD-25

Figure 4. Seepage analysis results for various cases of RD-29

Figure 5. Seepage analysis results for various cases of RD-147
5. Conclusions
In this paper the health of flood bund for the four selected sites along the Chenab river in the Muzzafer Garh district, Punjab is evaluated in term of REBVI, safe exit gradient and safety factor against slope failure. Soil parameters for the embankment and foundation of bund were selected based on the extensive laboratory tests performed on collected soil samples from in-situ testing. Based on REBVI the calculated value RD-147 & 157 are shown to be susceptible to failure whereas RD-25 & 29 are found to be safe. The selected flood bunds are also numerically simulated using SEEP/W and SLOPE/W under different critical conditions to calculate the seepage and stability FoS respectively. The FoS against the seepage shows that the RD-147 & 157 are unsafe while RD-25-29 are safe against the seepage. The stability of flood bunds can be improved by using clayey material to make flood bunds impervious. As most of the flood bunds are susceptible to piping, it is suggested to install cut-off walls or berms to lengthen the seepage path.

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