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Research Paper

Assessment of remedial measures to reduce exceedance probability of performance limit states in embankment dams

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ABSTRACT

Results of a series of numerical analyses, simulating three remedial measures applied to an embankment dam, are used to investigate the extent of lessening the severity of the distress level under flood loading. Conceptually, the three remedial measures are increasing the mean effective stress, adding a low permeability curtain to limit seepage, and improving drainage to lower pore water pressure magnitudes at key locations. The results are presented in the context of exceeding predefined limit states in terms of toe deformation and hydraulic gradient. Constructing a downstream berm has a significant impact on the exceedance probabilities of the deformation limit states at the toe, but a small impact on the toe gradient values. Adding a low permeability curtain below the dam crest considerably reduces both deformation and gradient magnitudes in relation to the predefined limit states. This occurs due to an increased seepage path leading to a higher drop of pressure head and lower phreatic surface level; these two effects result in lower shear strains and less deformations at the toe. Improvement was observed by adding the toe drainage system with a hydraulic conductivity that is 4–20 times higher than the hydraulic conductivity of the embankment material. In this case, the exceedance probabilities of deformation limit states decrease and the impact is higher for a higher hydraulic conductivity of the drainage system compared to the embankment soil. Given the analyses configurations and parameters, constructing a berm at the toe leads to the lowest exceedance probabilities, in terms of deformation limit state, and thus seems to be the most effective approach among the three analyzed remedial measures.

1. Introduction

The application of probabilistic analysis in the geotechnical engineering has gained acceptance over the years as a supplemental approach providing insight into performance under a design event and potential associated risk [16,29]. The assessment of risk including the uncertainty in the hazardous event is fundamental for assessment of structure's vulnerability, and uncertainty in exposure, especially for aging embankment dams. Zimmerman et al. [8] stated that out of over 1970 dams in the state of New York, the mean age of 375 dams classified as "high hazard" is 81 years with a mode of 97 years and range of 209 to 8 years. In such cases, remedial and rehabilitation measures are required to upgrade the dam conditions, and downgrade the level of progressive failure and perhaps alter a potential failure mechanism to a less critical one. Facilitating the incorporation of probabilistic condition assessment is therefore of paramount importance to allow cost effective specification and implementation of rehabilitation measures and improved communication of the risk level to the public. To this end, the concept of deformation-based limit states (LS) for protective earth structures is introduced by Khalilzad and Gabr [32] and provides a graded measure (versus the binary classification of safe/unsafe) of the safety margin under a specified storm loading. Such an approach provides a rational basis for condition assessment of the structure as it is progressively loaded over time with multiple storms as well as the efficacy of remedial actions.

Using traditional deterministic analysis with the single values for strength, stiffness and hydraulic properties have led to several failures, even though, the design has been performed according to the engineering codes (e.g. [20,23]).

The specification of a remedial approach starts with evaluating the existing conditions to estimate the severity of the problem and assess potential factors leading to deterioration of the distress level. In some cases, such an evaluation is accompanied with a monitoring program to assess the response before and after remedial measures [9,15]. This is especially advantageous nowadays

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with the advancement of computer technology, data management programs, and intelligent instruments to assess real time response of a dam or a levee under various loading condition. However, and in associate with a monitoring program, there is a need to establish base line limit states and benchmark the measured quantities with those predefined limits. Additionally, by incorporating these limit states into the analysis, the probabilities of exceeding each limit state can be estimated as well.

The objective of this study is to investigate the effects of remedial measures on decreasing the probability of exceeding established performance limit states of earth embankments forming levees and dams. An embankment dam in a marginal stability condition is analyzed using finite element approach and three remedial measures are implemented. These are constructing a downstream berm, adding a downstream drainage system, and installing a low permeability layer (cutoff wall). The results of numerical modeling are incorporated into a simple deformation-based probabilistic analysis and the impact of the remedial measures on the probabilities of exceeding limit states are presented. Performance-based aspects of the remedial measures are discussed.

2. Background

Wahlstrom and Nichols [28] presented the remedial measures undertaken during the construction of Dillon Dam in Colorado where movements were observed during excavating the toe. In this case, a landslide was having the potential of engulfing the intake structure. To address the issue of increased deformations, a large volume of the landslide material was excavated and a gravel-fill dike was constructed on bedrock at the toe. In the study of the Gold Tailings dam in South Africa, Sully [24] reported a minor failure which raised concerns about the future stability of the dam under high water condition. The situation necessitated the control of the phreatic surface to reduce the risk of seepage and stability issues. At first, installation of elevated drains within the body of the dam was recommended as a remedial measure, but later, more comprehensive seepage analysis of the dam provided results indicating that less costly remedial measures including the construction of a buttress at the toe could be implemented instead. Mann and Snow [14] presented a remedial design to stabilize the upstream slope of a 13.7 m high dam in Ohio where a crack was observed along the crest prior to filling the dam. Subsurface explorations and testing revealed that either significant excess pore pressure along the failure surface or creep movements could be the reason for developing the crack. The main course of action in this case included the construction of a buttress on the upstream slope, repairing the crack by reconstructing the upper 3–4.5 m layer, and additional seepage control measures. Twenty years later, Mann et al. [15] studied the 1993 remedial design using numerical analysis, and with the aid of performance monitoring data. The authors showed that the creep movements continued to occur over time but at a decreasing rate. Mann et al. [15] concluded that limit equilibrium analysis is not a robust measure of dam performance. Richards and Reddy [19] used both numerical and analytical approaches to model a failure occurred in an embankment dam and concluded that the limit equilibrium approach could lead to a more conservative design for a given shear strength.

Ref. [17] reported seepage problems in an embankment dam in Jordan, where a plan to raise the crest of the dam to increase its storage capacity was proposed. Due to the presence of alluvial material under the foundation, the remedial actions suggested for controlling the seepage problems were constructing an upstream blanket, increasing the capacity of downstream relief wells and grouting in the likely seepage areas. Ref. [26] studied the case of a hydroelectric power dam where failure occurred following the emergence of major sinkholes within the embankment. They concluded that the failure happened due to several factors including shortened critical seepage path, inadequate filter protection, as well as design and construction quality control deficiencies. Remedial action was undertaken to return the dam to operational condition by excavating the embankment containing loose and free-draining material, placing granular backfill with controlled quality, and installing sand filters and drains.

On the other hand, probabilistic analysis has been widely developed in the geotechnical literature (e.g. [2,3,5,25,30,31]). A combination of random field simulation, seepage analysis, and slope stability analysis was employed by Gui et al. [10] to study the effects of stochastic hydraulic conductivity on the slope stability of an embankment dam and concluded that the reliability index is very sensitive to the uncertainty of saturated hydraulic conductivity. Srivastava et al. [33] also investigated the effect of permeability parameter on the seepage and embankment stability using the finite difference approach. They assumed the permeability as a random variable with a lognormal distribution and reported that a lower value of correlation distance and coefficient of variation in the permeability parameter provides higher factor of safety values. Ahmed [1] analyzed the free surface flow through earth dams using a probabilistic method, also with the assumption of a lognormal distribution for the permeability values. The conclusion was that numerical models over predict the amount of seepage flow through a homogenous dam formation. In summary, the application of probabilistic approach in embankment dams provides a novel understanding of the variability in the safety level. The limited use of probabilistic approaches in earth embankments has not only been due to the lack of databases with sufficient level of information to provide spatial variability in properties, but also due to the difficulty of modeling various uncertainties, and unfamiliarity of the practicing professionals with the probabilistic techniques.

3. Study model

An embankment dam is modeled using the finite element program Plaxis [18]. The modeled dam geometry is obtained from the US Army Corps of Engineers technical manuals [27] and it represents an earth dam section with geological profile representative of the lower Mississippi valley where a three layer soil system including a shale layer at the bottom is overlain by a layer of alluvial soil with a relatively high hydraulic conductivity. Above the alluvial soil, a low permeability soil forms the top foundation layer and the body of the embankment dam. The side slopes are 4H:1V on both upstream and downstream sides of the embankment dam. The landside ground surface slopes at 50:1 and the river side slopes at 30:1. In this paper, a model with a scale factor of 0.5 (i.e. scaling down the original geometry by 50%) has been used as the base case with the soil properties adjusted such that the dam is in a marginal stability condition. To obtain the soil properties corresponding to this condition, the dam is modeled in Slope/W (a limit equilibrium program) and the material strength is reduced until a factor of safety of 1.05 is reached. This factor of safety value is selected to represent the near-failure condition while preventing the numerical convergence issues. The geometry and meshing of the model are shown in Fig. 1. The finite element mesh consists of approximately 47,000 nodes and 5800 elements. The 15-node triangular plane strain elements are utilized to capture a better resolution of stress and deformation magnitudes.

The soil properties of the embankment and foundation layers are presented in Table 1. As mentioned earlier, the soil strength parameters originally reported in USACE [27] have been reduced by a factor of 1.55 in order to reach a safety factor of 1.05 in the model. This is consistent with the soil strength reduction method