

Modeling Geomorphic Features in Levee Reliability Analyses

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Abstract. It has long been understood that subsurface geology affects internal erosion potential in levee foundations. Geomorphic features associated with fluvial deposition environments are known to concentrate or block seepage, resulting in sand boils and internal erosion. However, incorporating the effects of geomorphic features into either deterministic or probabilistic analysis has remained a challenge. Based on the assumption that the preponderance of the underseepage risk to a levee reach is due to the geomorphic features along that reach, a methodology is being developed to incorporate the combined effects of these geomorphic features into reliability analyses of underseepage risk. A Response Surface-Monte Carlo (RSMC) analysis that takes into account the uncertainty in the subsurface geometry and the soil properties of the geomorphic features is used to assess the flow regime associated with each geomorphic feature. The RSMC is followed by an event-tree analysis to assess the likelihood of levee failure based on the resulting flow regime. Three-dimensional finite-element seepage analyses will be used to develop the response surface in order to take into account the inherent three-dimensional aspects of the geomorphic features. Finally, the total probability of failure of the levee reach due to underseepage will be calculated by combining the probabilities of failure for the geomorphic features located along a levee reach. In this manner, the “length effects” of a levee reach in a fluvial environment can be assessed by combining the failure probabilities of the geomorphic features located along the levee alignment.

Keywords. Levee, underseepage, reliability, geomorphic features

1. Introduction

Reliability assessments of levees founded on variable geologic conditions have often struggled with quantifying the probability of failure due to localized adverse foundation conditions. With levees, a failure at any one location along the perimeter of a protected basin often leads to failure of the entire system. As the length of the levee protecting a basin increases, the probability of encountering unfavorable subsurface conditions increases, and thus, the probability of failure increases. This phenomenon has often been referred to as length effects.

Adverse foundation conditions along a levee’s alignment are often associated with localized geomorphic features. In many cases, the locations of highest risk along a structure’s alignment can be tied to the occurrence of one or more problematic geomorphic features. By quantifying the hazard the individual geomorphic features pose to the levee and combining those hazards for the entire length of the levee, the

total probability of unsatisfactory performance for the levee can be quantitatively assessed.

Of course, not all geomorphic features of the same type will represent the same level of risk. Variation in geometric configuration and soil properties will lead to different probabilities of internal erosion due to underseepage. Thus, models for each feature type must have flexibility to account for variations in geometry, soil properties, depth, and other relevant parameters.

2. Background

Underseepage is commonly encountered in dams, levees, and other structures capable of maintaining a differential hydraulic head. In many cases, underseepage can occur without damage to the foundation or overlying structure. However, in other cases, internal erosion may begin by one of several mechanisms often leading to failure of the structure.

Two specific mechanisms are assessed in this paper: backward erosion piping (BEP) and heave. BEP describes the erosion of soil due to seepage water through a soil mass that initiates when particles of soil are dislodged from the soil matrix at an unprotected seepage exit point. Heave is the movement of mass of soil due to underlying hydraulic pressure or seepage forces.

2.1. Geomorphic Features

Geomorphic features underlying a structure often have a significant effect on the underseepage behavior and the mechanisms of internal erosion. The typical depositional environment of a meandering river is characterized by river channel deposits and flood (overbank) deposits (Brierley and Fryirs, 2005). The thickness of overbank deposits is generally greatest adjacent to the river bank, resulting in low ridges adjacent to the active channel known as natural levees (Brierley et al. 1997). Channel deposits are often referred to as the foundation layer and the overbank deposits are often referred to as the blanket layer.

In addition to the general meandering river geomorphic profile described above, a number of local geomorphic features are common within the meandering river environment including: abandoned channels, point bars, meander scrolls, and crevasse splays. Where a levee alignment crosses these features, flow concentration into the features or localized blanket thinning due to the features cutting into the blanket may occur, resulting in a significantly higher potential for internal erosion than in the surrounding areas (Glynn and Kuszmaul, 2010).

2.2. Analysis of Internal Erosion

Simplified theoretical equations such as those in the “blanket theory” developed by the US Army Corps of Engineers (USACE, 1956, 2000) assume two soil layers in the levee foundation with constant thickness and horizontal boundaries (the blanket and foundation layers described above). The main limitation of the “blanket theory” is that the subsurface geometry is restricted to two homogenous layers of constant thickness.

Probabilistic methods for assessing underseepage have been developed by coupling the deterministic methods discussed above with probability models. One common approach that is well documented by the USACE consists of using the “blanket theory” equations as the performance function and the first order-second moment Taylor series method as the probability model (Wolff, 2008). This methodology is subject to the same simple-profile limitations as the blanket theory and cannot model complex subsurface conditions and three-dimensional aspects often associated with discrete geomorphic features.

2.3. Basin Behavior and Length Effects

Levees pose a challenge in terms of evaluating the overall reliability of the system. Failure at any point of the structure often represents failure of the entire system. In current practice, the reliability of these structures is typically evaluated by dividing the structure into reaches and evaluating the reliability of the individual reaches using a characteristic subsurface profile representing generic conditions within the reach. It is recognized that within this reach there are perturbations away from the generic conditions and that failure will have the highest probability of occurrence where these perturbations create conditions most susceptible to one or several modes of failure (Wolff, 2008; Vrouwenvelder et al. 2010). It is also recognized that the longer reaches will have greater the likelihood that the perturbations create a condition susceptible to failure; a phenomenon generally referred to as length effects.

3. Methodology

The methodology presented herein is based on the concept that the majority of the underseepage hazard along a levee comes from geomorphic features that interrupt the characteristic profile, providing locations for concentration of seepage and/or buildup of hydraulic pressure. The interactive hydraulic behavior between these features, the structure, and the surrounding characteristic subsurface profile is definitely three-dimensional, concentrating seepage flow

into the geomorphic feature and decreasing flow in the surrounding area. Thus, by identifying and analyzing the geomorphic features along the alignment of a structure, the majority of the underseepage hazard can be evaluated.

The steps for calculating the failure probability of a levee-protected basin using the proposed methodology are defined below. This paper describes the methodology for Step 2 in detail while the remaining steps, which are the subject of further research and implementation, are briefly described to provide a context for how the Step 2 results will ultimately be used.

3.1. Step 1: Identify Geomorphic Features

This will generally be accomplished using existing geologic information such as maps prepared along the Sacramento River Levee System (William Lettis and Associates, 2008).

3.2. Step 2: CADFs for Geomorphic Features

The assessment of the hazard that each geomorphic feature poses to the levee system begins with developing a cumulative ascending distribution function (CADF) for either the exit gradient or uplift pressure of each geomorphic feature. A CADF is a plot of increasing values of the exit gradient or uplift pressure versus the probability of being less than that value for a given river level (say the 100-year flood). The probability of exceeding a limit value of the exit gradient or uplift pressure can be obtained directly from the CADF, such as the anticipated gradient at which erosion will initiate (i.e., at a factor of safety of 1.0). However, this probability is not the probability of levee failure because other factors will need to be considered in the assessment of the probability of the internal erosion progressing to a levee failure. These additional factors will be included using the event tree analysis presented as Step 5.

The CADFs will be evaluated for each of the mapped geomorphic features using a probabilistic assessment of hydraulic conditions model developed using a Response Surface-Monte Carlo (RSMC) simulation methodology. Rice and Polanco (2012) have developed two-dimensional models for assessing hydraulic conditions in geometrically complex levee

profiles that uses multiple finite element method (FEM) analyses to develop a relationship between the key input parameters (hydraulic conductivity of the soil layers and subsurface geometry) and the probability of reaching critical hydraulic conditions (uplift pressures or hydraulic exit gradients). This relationship, generally called a Response Surface (Low, 2008), is used to perform a Monte Carlo simulation that results in the CADF. The probability distributions for each soil or geometric parameters are represented using a probability density function (PDF). For this study the RSMC methodology has been expanded using three-dimensional FEM analyses to account for the three-dimensional seepage aspects of the individual geomorphic features.

The RSMC analyses will produce CADFs of key hydraulic conditions for each geomorphic feature mapped along the levee alignment in Step 1. The development of the various response surfaces that are needed is not trivial. The PDF distributions for each parameter are discretized into five or six values (or more if needed) that represent the range of values in the PDFs. FEM seepage analyses are then run for every combination of values for each variable using a 3-D FEM model (for instance SoilVision Systems Ltd. – SVFlux, 2009) representing the respective geomorphic feature. The results of the FEM analyses are plotted to develop surfaces describing the relationship between the variables and the hydraulic conditions, the response surface.

While there are many soil and geometry parameters that may affect the results of the FEM analysis, part of the challenge of performing the RSMC analysis is reducing the number of parameters to those that have a significant effect on the analysis outcome when varied over the parameter's possible range of values.

For example, consider the crevasse splay deposit model depicted on Figure 1 that is modeled using a FEM model similar to that presented on Figure 2. The parameters that may be considered for this feature include the dimensions of the crevasse channel and splay, the depth that the deposit is buried in the blanket, the hydraulic conductivities of the various components of the deposits, and the unit weight of the blanket. If nine variables are considered in the above analysis with the potential range of

each represented by five discretized values, the total number of FEM analyses run will be at least 5^9 or nearly 2 million runs; an impossible number to complete.

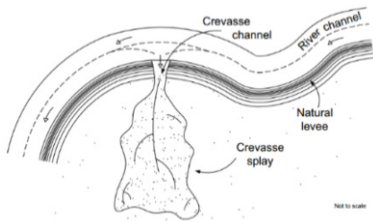


Figure 1. Schematic illustration of a crevasse-splay deposit

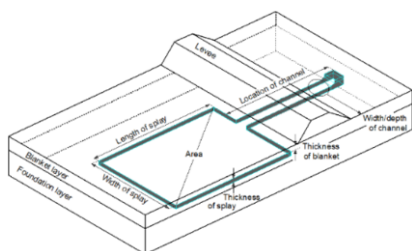


Figure 2. 3D-FE model of a crevasse-splay deposit

Therefore, it is necessary to reduce the number of parameters defining the response surface by identifying parameters that have insignificant effect on the outcome of the analysis and combining the remaining parameters. The process of combining parameters is illustrated in the example presented in the following section of this paper. The simplified model is then used to create a response surface for each type of geomorphic feature encountered along the levee alignment.

Once the response surface has been developed, a CADF is produced for each geomorphic feature with a Monte Carlo simulation (enhanced with Latin Hypercube sampling) using the response surface and the computer program @Risk (Palisade, 2013). PDFs for the input variables that are specific to each mapped geomorphic feature based on the mapped size, subsurface information, and knowledge of the depositional processes are input into the analysis. Although some of the input parameters have been combined for the response surface development, individual PDFs for each of the combined parameters will be input into the analysis.

3.3. Step 3: Assess Interdependence of Features and Levee Alignment

If adjacent geomorphic features are located close enough to each other they have potential to affect the seepage regime of each other. This step will assess the effects of distance between adjacent features using three-dimensional seepage analyses modeling multiple features in one model.

3.4. Step 4: Event Tree Analysis

The probabilities of achieving the uplift pressure or exit gradient levels calculated in Steps 2 and 3 are contingent on the water level rising to a specified level (such as the 100 year flood). Several other conditions are necessary for the initiation condition to propagate into failure which will be assessed by an event tree analysis.

3.5. Step 5: Combine the Probabilities of Failure

Once the probabilities of underseepage failure for the mapped geomorphic features and the background hazard have been assessed in Steps 2 through 4, these probabilities must be combined to calculate the probability of failure for the entire levee system considering a “common cause effect” correction due to the interdependence of the hazard sources (e.g., Bowles et al. 2012).

4. Example – Crevasse Splay Deposit

This section presents the development of a response surface for the crevasse splay feature. The response surface is then used to produce two CADFs for a hypothetical crevasse splay deposit; one to represent the probability of exceeding critical values of hydraulic gradient and one to represent the probability of exceeding values of the factor of safety against blanket heave.

4.1. Model Description

The FEM seepage model is based on the crevasse-splay model presented in Figure 2. It consists of 1) a crevasse channel leading from the river to the splay, 2) a splay area, and 3) a

low-permeably blanket above the splay. The geometry and characteristics for the feature are represented by the 10 parameters listed in Table 1.

Table 1. Parameters describing the geometry and seepage characteristics of the crevasse-splay model

Parameter	Description
W_{ch}	Width of the crevasse channel
L_{ch}	Length of the crevasse channel
t_{ch}	Thickness of the crevasse channel
K_{ch}	Hydraulic conductivity of the channel
W_s	Width of the splay area
L_s	Length of the splay area
t_s	Thickness of the splay
K_s	Hydraulic conductivity of the splay
t_b	Thickness of blanket above the splay
K_b	Hydraulic conductivity of the blanket

The range and probability distributions for the 10 parameters can be represented using probability density functions (PDF). However, as previously discussed, the 10 parameters are combined into three parameters that adequately describe the flow regime in the deposit. The conductance of the crevasse channel, $C_{channel}$, describes the resistance to flow in the channel. The transmissivity of the splay, T_s , describes how easily flow is distributed throughout the splay. The conductance of the blanket, $C_{blanket}$, defines how easily pressures in the splay are dissipated through the blanket. The combined parameters are calculated using the following equations:

$$C_{channel} = \frac{K_{ch}W_{ch}t_{ch}}{L_{ch}} \quad (1)$$

$$T_s = K_s t_s \quad (2)$$

$$C_{blanket} = \frac{K_b W_s L_s}{t_b} \quad (3)$$

4.2. Verification of the Simplified Model

Parametric analyses are performed to confirm the validity of the simplified model. FEM analyses are performed on the model by varying individual parameters while keeping the values of $C_{channel}$, T_s , and $C_{blanket}$ constant. The analysis resulted in maximum variation from using the simplified model of less than one foot of total head from the model using all parameters. Therefore, it can be concluded that the

simplification of the model does not impose significant errors to the results.

4.3. Developing the Response Surface

Using the parameters T_s , $C_{blanket}$, and $C_{channel}$, the response surface was generated for the crevasse-splay feature using multiple runs of a 3-D FEM analysis. The response surface was generated over ranges of values for the three combined parameters that cover all of the possible values resulting from variation of the 10 original model parameters. The range of each combined parameter was discretized into six to eight discretized values to represent the variation of the parameter. FEM analyses were then performed on every possible combination of the discretized values. The results of the analyses were plotted on a “family of curves” presented in Figure 3 that together represent a three-dimensional surface defining the relationship between the three combined parameters and the maximum total head in the splay. Thus, given values of each of the combined parameters, the maximum total head in the splay can be calculated. Equations were developed through regression analysis to fit the curves to facilitate computer coding the response surface into a spreadsheet which runs the Monte Carlo Simulation.

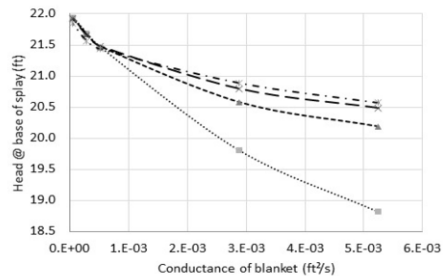


Figure 3. Family of curves for the crevasse-splay model for one constant $C_{channel}$ and different ranges of T_s and $C_{blanket}$.

4.4. RSMC Analysis

A Monte Carlo simulation was performed using a program written in an Excel spreadsheet and linked with the computer program @Risk. PDFs for each of the 10 original model parameters plus (the unit weight of the blanket, γ_b are input into the program. For each iteration of the Monte

Carlo analysis, two parameters that are useful for estimating the potential for levee failure, the gradient through the blanket, i_{blanket} , and the factor of safety against heave, F_{heave} , are calculated using the following sequence:

- Values of each of the 10 parameters are randomly selected based on the PDFs.
- The three combined parameters are calculated using Equations 1 through 3.
- The response surface an with the to calculate the maximum total head in the splay h_{max} .
- Using h_{max} the gradient through the blanket and the factor of safety against heave are calculated using Equations 4 and 5:

$$i_{\text{blanket}} = \frac{\Delta h}{t_b} = \frac{h_{\text{max}}}{t_b} \quad (4)$$

$$F_{\text{heave}} = \frac{t_b \gamma_b}{u_{\text{splay}}} = \frac{t_b (\gamma_b)}{(h_{\text{max}} + t_b) \gamma_w} \quad (5)$$

The sequence above was repeated for 10,000 iterations to produce the CADFs (Figures 4 and 5) representing the probability of various values of i_{blanket} (85.1% larger than 1 in Figure 4) and F_{heave} (91.7% smaller than 1 in Figure 5). The CADFs can also be used to calculate the probabilities of exceeding lesser or greater values of these parameters that may indicate greater or lesser probabilities of initiating an erosion. Thus, the CADFs may be used in conjunction with the event tree analyses described in the previous section to assess the likelihood of levee failure due to an individual geomorphic feature. The procedure could be repeated for all of the geomorphic features located along the levee alignment and the probabilities of failure for each feature combined to produce the total probability of failure for the entire levee.

The hydraulic exit gradients and pore pressures calculated for this crevasse splay model are generally higher than those computed by a two-dimensional or blanket theory model, illustrating the three-dimensional concentration effect that this geomorphic feature has on the seepage flow. These results represent a condition that may initiate internal erosion and assessing the probability of failure will require further assessment though the event tree analyses.

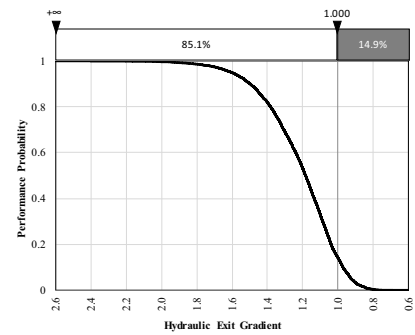


Figure 4. CADF for gradient through the blanket, i_{blanket} .

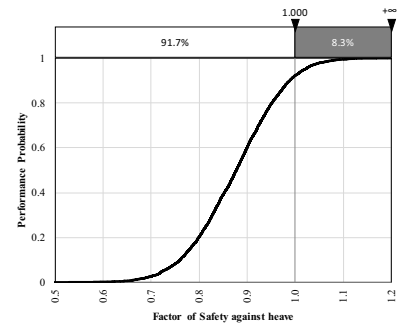


Figure 5. CADF for factor of safety against heave, F_{heave} .

5. Conclusion

A methodology for calculating the probability of failure of a reach of levee by calculating the individual failure probabilities due to geomorphic features that intersect the levee alignment is presented. The total procedure includes identifying the geomorphic features, producing CADFs for the probabilities of various heave or BEP initiation, calculating the interaction between geomorphic features, calculating failure probabilities using event tree analyses, and calculating the total probability of failure to a levee reach by combining the probabilities from all of the geomorphic features.

Details of the RSMC procedure for producing CADFs for the geomorphic features are presented. An example is presented where CADFs for heave and exit gradient are calculated for a crevasse splay deposit.

6. Acknowledgments

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