Faulting effects on stability of embankment dams

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ABSTRACT

Many embankment dams are constructed on active faults or in their vicinity and the effect of fault rupture propagation through these dams has been studied over the past two decades. However, of crucial importance is to pay decent attention to the post-faulting stability of the dams according to their response to fault-induced unequal ground displacement. In this study, two typical homogeneous and zoned embankment dams have been studied numerically when faulting occurs in their underlying bedrock during steady state seepage conditions. Unequal ground displacement of normal and reverse dip-slip faults, with various dip angles, are applied in multiple locations of the dam’s base. The results of the numerical analyses are studied regarding the variations of pore water pressures within the embankments. Thereafter, the dam’s stability after faulting is evaluated. The results show that reverse faults may cause general increase in pore water pressure values and, consequently, reduction in slope stability safety factors; whereas normal faults have less destructive effects on the general stability of the embankment dams.

Keywords: fault rupture propagation, embankment dams, stability analyses, pore water pressure

1 INTRODUCTION

Strong ground motion of an earthquake is the main source of concern for stability of structures over a widespread area. However, unequal ground displacement cause more hazardous situation in limited zone around the fault line. Whereas evaluation of seismic safety of soil structures, as an engineering point of view, is of crucial importance, investigation of fault rupture-imposed damage on infrastructures such as pipelines, bridges and dams is critical.

For the special case of a dam in earthquake-prone areas, it is a matter of concern to find an appropriate construction site as the existence of faults in dam foundations is mostly prevalent. Originating by tectonic activities of the crust, such sites probably contain widespread active faults.

The accumulated experiences and evidence on fault movements indicate that a vigorous engineering strategy is required to tackle this issue. The possibility of surface fault breaks should, as a rule, be considered while designing dams or evaluating their safety. In cases where recent tectonic activity of a fault crossing the dam site is recognized and it is not possible to find an alternative site, a conservatively designed embankment dam (with large filter and transition zones of non-cohesive materials) offers best chances to survive the fault break effects (Wieland et al., 2008).

During strong earthquakes the most severe condition for a dam is when it is subjected to both ground shaking and movement of the faults. However, for dam engineers the primary attention is usually given to dynamic loads while the possibility of unequal ground displacements due to faulting in the dam foundation is often disregarded. Surface faulting, or more precisely, surface slip along an identified fault zone under the dam, was always understood to be the most damaging tectonic process that can affect a dam.

The fault rupture propagation through horizontal soil layers have received much attention by means of field studies, physical and numerical modelling; nevertheless, investigating the response of embankment dams to unequal ground displacements caused by faulting has received less attention. Field studies have focused on evidence from surface observations and trenches (Bray et al., 1990; Bonilla and Lienkaemper, 1990). Along with these findings, other researchers tried to model soil layer behavior due to faulting in laboratory testing (Cole and Lade, 1984; Bray et al., 1990; Lazarte, 1996; Lin et al., 2006) and in numerical simulations (Bray et al., 1994; Lazarte, 1996; Johansson and Konagai, 2007; Lin et al., 2006; Anastasopoulos et al., 2007; Loukidis et al., 2009).
2 PROBLEM DESCRIPTION

In this paper, dip-slip fault rupture propagation through homogeneous and zoned embankment dams is analyzed numerically. This study does not account for effects of dynamic loading of fault activation; in other words, it mainly focuses on the quasi-static dislocation of fault under the dam and its potential risk to the soil structure.

Two-dimensional models of dam are analyzed by a FEM-based program, Abaqus (2012), with the elastoplastic Mohr-Coulomb constitutive model. The earth dam is subjected to the fault displacement when the steady state seepage condition is established. Considering that faulting usually occurs in a short period of time, consolidated undrained conditions, CU, prevail for the soil. Coupled fluid flow-stress analyses were performed and the new regime of pore water pressure after fault activation has been obtained.

3 NUMERICAL MODELING

3.1 Geometry, Loading, and Boundary Conditions

The geometry is simplified to two-dimensional 20m-high models of typical homogeneous and zoned embankment dams lying on the base bedrock, having a potentially active fault as shown in Fig 1. It is also assumed that plane strain conditions govern the embankment geometry. The present study is limited to the case of dip-slip normal and reverse faults with the dip angle of $\alpha$. For the simulation of fault movement the right side of the embankment is assumed to be fixed (footwall) and a relative movement with angle of $\alpha$ is applied to the left boundary (hanging wall). Fig 1 shows the typical geometry and boundary conditions. For both normal and reverse faults, five dip-angles are assumed as $\alpha = 30^\circ, 45^\circ, 60^\circ, 75^\circ, 90^\circ$.

Selecting proper vertical base displacements for development of rupture paths within the soil body requires careful considerations. In the case of earth dams, regarding the trapezoidal geometry, sensitivity analyses showed that vertical base displacements of 2 and 4 percent of the height of the dam (i.e., 40 and 80 cm for this study) are adequate for development of normal and reverse fault rupture paths, respectively.

The model domains are discretized with quadrilateral elements and with biquadratic and bilinear shape functions for displacement field and pore water pressure, respectively. Effects of mesh size on fault rupture propagation have been studied through varying mesh densities by Mortazavi Zanjani and Soroush (2013) and the approximate mesh size of 2.5 percent of the model height was deemed both sufficiently accurate and computationally efficient for numerical analyses.

3.2 Soils Characteristics

The homogeneous dam and the core of the zoned dam are made of cohesive materials, named ST40 which is a mixture of clay (40%) and granular materials (60%). Also, typical granular materials are selected for filter and shell of the zoned dam. The cyclic and post-cyclic behavior of ST40 has been studied by Soroush and Soltani Jighe (2009) and they showed that it does not behave strain softening considering its

![Figure 1. Homogeneous and zoned earth dams (a) steady state seepage conditions (b) geometry and boundary conditions of the dams (c) discretization of models](image-url)
post-peak behavior. However, it is conceivable that dense granular non-cohesive materials usually behave strain softening; therefore, a modified Mohr-Coulomb constitutive model with strain softening has been used to model filter and shell (Mortazavi Zanjani and Soroush, 2014). The physical mechanical parameters of the materials are introduced in Table 1.

The elastic modulus of soils are considered as a linear function of effective confining stress, \( \sigma_{\text{eff}} \), for the granular soils and a function of square root of \( \sigma_{\text{eff}} \) for the cohesive soil (Loukidis et al., 2009). Fig. 2 demonstrates these functions for ST40, filter and shell materials, where \( Z \), the height of soil above any specific element of the embankment, represents the effective confining stress. The mechanical parameters of ST40 are adopted from numerical back-analysis (Sasanian et al., 2011) of the triaxial tests on ST40 samples performed by Soltani and Soroush (2009).

Table 1. Physical and mechanical parameters of the materials

| MAT    | \( \gamma \) (kN/m³) | \( E \) (MPa) | \( \nu' \) (kPa) | \( c' \) (°) | \( \varphi' \) (°) | \( K \) (m/sec) | \( e_0 \) |
|--------|----------------------|--------------|---------------|-------------|--------------|---------------|--------|
| ST40   | 20 \( aZ + b \) 0.3 | 25           | 26            | 0           | 6.76x10^{-9} | 0.4           |
| SHELL  | 20 \( aZ + b \) 0.28 | 1            | 36            | 6           | 1x10^{-6}   | 0.7           |
| FILTER | 18 \( a\sqrt{Z} + b \) 0.3 | 5        | 34            | 4           | 1x10^{-6}   | 0.6           |

ST40 used as impermeable core of the zoned dam and the body of the homogeneous dam.

4 RESULTS

4.1 Faulting-induced pore water pressure

Pore water pressure distribution is changed after fault activation. Contours of pore water pressure during steady state seepage conditions, i.e. before faulting, are shown in Fig. 3. Post-faulting contours for normal and reverse faults activated under various dip-angles are presented in Figs. 3 and 4 for homogeneous and zoned embankment dams, respectively.

In normal faults, the relative downward movement of the hanging wall produces extensional state on the hanging wall side and compression state on the footwall side (Figs. 3f to 3j and 4f to 4j). This is especially bold near the fault application point. Therefore, due to the tendency for volumetric changes and undrained loading conditions, the areas in the hanging wall side (left side of the fault activation point) may experience a decrease in the pore water pressure values, while the areas in the right side may experience an increase in the pore water pressure values. Furthermore, there is a low-pressure wedge shape area just up to the fault line on the hanging wall side. This area spreads to upstream slope boundaries and the most recognizable wedge is induced for \( \alpha=30^\circ \).

In order to support the aforementioned idea quantitatively, pore water pressure ratios, \( R_u \) (i.e., ratio...
of pore water pressure to total vertical stress), after fault activation are compared to the corresponding values before faulting in Fig. 5. This figure shows these ratios in the elevation of 4m above base of the homogeneous dam, when normal and reverse faults are activated in the center of the dam base and with various dip angles. The pre-faulting ratio is shown as a solid line smoothly declined over horizontal distance.

It can be seen that apart from the fluctuated trend, the difference between the pre and post-faulting values of $R_u$ is relatively more dominant in the case of reverse faults. For normal faults, differences between pre and post-faulting ratios are marginal for all fault angles. Moreover, the low-pressure wedge shape area, introduced earlier, can be seen by the lower values of $R_u$ above the fault location. There are, however, some alarming increases in cases of greater dip-angles ($\alpha=75^\circ$ and $90^\circ$). The same discussion applies to the variations of pore water pressure in the zoned dam, except that the phreatic surface drops comparatively closer to the downstream filter.

4.2 Stability of slopes

Being totally changed after new pore water pressure distribution, Stability safety factors of the embankment slopes should be re-evaluated after faulting. The dams’ stability has been studied using the Limit Equilibrium Method (LEM). In order to consider highly irregular pore water pressure conditions after faulting, the Morgenstern-Price Method has been employed, where shear and normal inter-slice forces are taken into consideration. Using the FEM-based code, the pore water pressures due to faulting have been obtained. Then these pore water pressures were introduced by a spatial function to LEM.

![Fig. 5 Pore water pressure ratios, $R_u$, in the elevation of 4m above base of the homogeneous dam for (a) normal and (b) reverse faults activated in center of the base](image)

![Fig. 6 Normalized stability safety factors for (a) and (b) upstream and (c) and (d) downstream slope of the homogeneous dam subjected to five angles of normal and reverse faults at five different locations of the dam base](image)

Figure 6. Normalized stability safety factors for (a) and (b) upstream and (c) and (d) downstream slope of the homogeneous dam subjected to five angles of normal and reverse faults at five different locations of the dam base
factors are normalized to their before-faulting values. The results show that, generally, activation of normal fault has little effects on the safety factors, whereas reverse faulting decreases safety factors substantially. Fig. 6 suggests that when the fault activation point is on the downstream, the stability of upstream slope is less affected. Likewise, when the fault activation point is on the upstream, the stability of downstream slope remains unchanged approximately.

In the case of normal faults (Figs. 6a and 6c), apart from some fluctuations, it seems that fault inclination does not affect the safety factors seriously. Whilst in reverse fault activation, reduction of safety factor seems to be more dependent on the fault inclination in many cases (Fig 6 b).

While the reduction of safety factors are marginal for normal faulting (it fluctuates between +5 to −10 percent), reverse faulting imposes severe conditions on slopes. Upstream slope safety factor declines up to 40 percent and the downstream one decreases by 20 percent. The most hazardous condition is observed for the upstream slope at 30° reverse fault activated near upstream (the green line), Fig. 6-b. For reverse faults, safety factors are dependent on dip angle.

Fig. 7 presents normalized safety factors for the zoned dam for five dip-angles and three fault locations in the dam base, upstream edge, center, and downstream edge of the core. In this case, the stability analyses were limited to only the upstream slope and reverse faults as the pore water pressure analyses showed them to be the crucial cases.

This figure suggests that after-faulting stability of the zoned dam is substantially affected by the location and angle of the fault. The safety factors decreases up to 35 percent for two fault locations and for the third one (downstream edge of the core, the red line) increases about 20 percent.

Prominent results may be summarized as below:

In the case of normal faults, the hanging wall and footwall surrounding areas may experience a decrease and increase in pore water pressure, respectively. On the contrary, in the case of reverse faults, increase and decrease of pore water pressures can be detected on the hanging wall and footwall side, respectively.

As a quantitative way to describe pore water pressure changes, the variations of \( R_u \) were evaluated for both homogeneous and zoned embankment dams. In the case of reverse faults, the values of \( R_u \) are relatively more affected by faulting.

After faulting, when pore water pressures within the dam body change, a more critical slip surface prevails; therefore, stability of the earth dam should be re-evaluated. The results show that reverse faults activation can reduce safety factors of the slopes to a large extent whereas normal faulting has less destructive effects on dam stability.

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5 CONCLUSIONS

This article studied numerically the behavior of two typical homogeneous and zoned embankment dams subjected to dip-slip normal and reverse faulting.

Fig. 7. Normalized upstream slope stability safety factors of zoned dam for three reverse fault locations in dam base
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