FAULT RUPTURE PROPAGATION THROUGH ZONED EMBANKMENT DAMS

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ABSTRACT

This paper presents the results of numerical modeling of fault rupture propagation of reverse faults through a zoned embankment dam, at the end of construction. Nonlinear Finite Element Method is used to evaluate the effects of fault activity in dam foundation. The results have been verified with centrifuge physical simulations and the dependency of results on mesh density is studied. The effects of soil compaction are considered using tow typical materials for shell of the embankment which are representative of dense and loose soils. The effects of fault position are also studied in this paper. The results are presented in the form of maximum plastic strains localized in embankment and also surface displacement gradients, to evaluate rupture patterns formed in zoned embankment.

INTRODUCTION

The seismic responses of structures due to near faults are the subject of researches in the recent years. Among the structures, the dynamic analysis of embankment dams and their safeties are of great importance. Analyses of dams without considering their surrounding active faults may result in catastrophic events. The destructive effect of fault activity in dam foundations can be evaluated in two ways; the time history analyses of embankment dams due to seismic loadings and the effect of permanent quasi-static offsets on the fault under the dam foundation.Although, dam construction in the vicinity of an active fault should be avoided, however, in some cases, there is no better alternative. According to Sherard et al. (1974), in highly active seismic regions, due to existence of many faults and the fact that river channels often follow the fault direction, dams are mostly built in locations where faults are recognized or are suspected to exist. Furthermore, discovering the active faults in dam sites may not be possible unless a detailed geoseismic survey is performed or the dam foundation is excavated; whereupon the extra costs will be imposed to the project (Bray, 1990). In addition, in some seismic regions such as the High Zagros region in Iran, almost all dam sites are in the vicinity of the faults that are likely to become active anytime (Wieland *et al.*, 2008).

The phenomenon of fault rupture propagation through a horizontal soil layer has been studied primarily through field studies (Lade et al., 1984; Bray, 1990; Kelson et al., 2001; Faccioli et al., 2008), centrifuge model tests (Cole and Lade, 1984; Bray, 1990; Lazarte, 1996; Johansson and Konagai, 2006; Lin et al., 2006) and numerical analyses (Bray et al., 1994; Lazarte, 1996; Lin et al., 2006; Johansson and Konagai, 2007; Anastasopoulos et al., 2007; Loukidis et al., 2009). While, in the presence of geological structures such as valleys and hills or manmade facilities the problems become more complicated and require extra considerations.

The effects of fault displacement on earth dams was first studied by Louderback (1937) and followed by other researchers (Sherard et al., 1974; Swiger, 1978; Leps, 1989; Allen and Cluff, 2000; Wieland et al., 2008). Cheney et al. (1984) used centrifuge model tests to study strike-slip fault rupture propagation through homogenous clayey embankments. Their results demonstrated the feasibility of using centrifuge models to study the dam behavior. This work was then extended by Sohn (1987) including a reservoir to consider steady state seepage conditions during the experiments. Lazarte (1996) performed a comprehensive study on strike-slip fault rupture through earth structures using field, numerical and experimental investigations. Physical model tests were carried out in 1g environment on various model geometries such as a saturated clay embankment to investigate the effects of material properties on rupture patterns. 2D and 3Dnumerical modeling was also presented in his researches. Zania et al. (2008) presented the results of the finite element analysis of sandy embankment to evaluate the stability of the geostructure for both cases of normal and reverse fault.

This research aims to develop deeper insight into the main mechanisms of dip-slip fault rupture propagation through an embankment dam. The present study is mainly focused on the rupture patterns of the zoned embankment dam in which materials with different relative compactions are used. To have this accomplished, the numerical study is conducted for deformation of an embankment dam at the end of construction subjected to the reverse dislocation of the bedrock fault. The effects of the fault break position are also studied in this paper.

PROBLEM DEFINITION AND METHODOLOGY

The problem is schematically illustrated in Figure. A zoned dam with height of $H=28m$ composed of a central core, a transition zone with the same slope angle on each side of the core and the outer shell is considered. At the base of the dam, a thrust fault with angle of $\alpha=45$ makes upward vertical displacement of amplitude h. The fault displacement is imposed at the left side of the dam base, while the right side of it is fixed in both directions. The location of the fault displacement is determined by D.

The amount of fault displacement required for rupture propagation through the overlying horizontal soil layer is a controlling parameter. This amount ranges from 2 to 6% of height of the soil layer (Bray, 1990; Cole and Lade, 1984; Loukidis et al., 2009). In this research a vertical displacement of 1m which corresponds to 3.5% of the dam's height is employed throughout the analyses (i.e. h/H=3.5%).

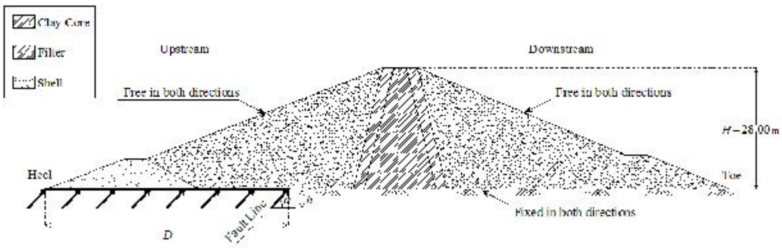


Figure 1. Schematic presentation of the 2D model used for the analyses and its boundary conditions

SOIL CONSTITUTIVE RELATIONS

A finite element base software (ABAQUS) is employed as a tool for the analyses assuming plane strain condition. The model is discretized using bilinear plane strain quadrilateral elements with an approximate size of 1m. Based upon the results of previous studies (Anastasopoulos *et al.*, 2007), the elastoplastic Mohr-Coulomb constitutive model with isotropic strain softening is incorporated in this research to predict the soil behavior. The strain softening behavoir is modeled by reduction of both the mobilized friction angle φ_{mob} and the mobilized dilation angle ψ_{mob} with the increasing of the plastic shear strain:

$$\varphi_{mob} = \begin{cases} \varphi_p - \dfrac{\varphi_p - \varphi_{res}}{\gamma_f^p}\gamma_{oct}^p, & for\ 0 \le \gamma_{oct}^p < \gamma_f^p \\ \varphi_{res} & for \quad \gamma_{oct}^p \ge \gamma_f^p \end{cases} \tag{1}$$

$$\psi_{mob} = \begin{cases} \psi_p \left[1 - \dfrac{\gamma_{oct}^p}{\gamma_f^p}\right], & for\ 0 \le \gamma_{oct}^p < \gamma_f^p \\ \psi_{res} & for \quad \gamma_{oct}^p \ge \gamma_f^p \end{cases} \tag{2}$$

Where φ_p and φ_{res} are the peak mobilized friction angle and its residual value; ψ_p is the peak dilation angle; and γ_f^p is the plastic octahedral shear strain at the end of softening response. Two typical materials are considered for shell of the embankment which are representative of the dense and loose soils. The variation of mobilized friction angle φ_{mob} and dilation ψ_{mob} with octahedral plastic shear strain for two material types are presented in Figure 2.The values assigned to the input parameters of the constitutive model are shown in Table 1.

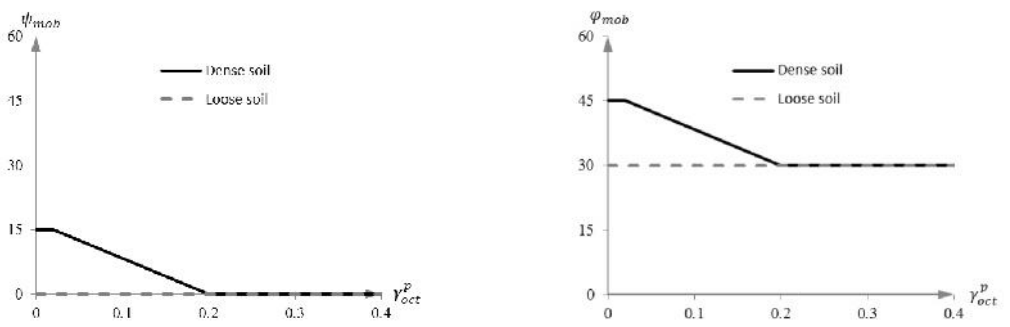


Figure 2. Variation of mobilized friction angleφ_{mob} and dilation ψ_{mob} with octahedral plastic shear strain for dense and Loose materials

Table 1. Parameters of the Mohr–Coulomb model used in the numerical simulations

Zone	Type	$\rho\ (kg/m^3)$	$E\ (Mpa)$	ν	$c\ (kpa)$	φ_p	φ_{res}	ψ_p	ψ_{res}	γ_f^p
Shell	Dense	1800	40	0.3	15	45	30	15	0	0.2
	Loose	1600	40	0.3	15	30	–	0	–	–
Core	–	1800	30	0.35	70	10	–	0	–	–
Filter	–	1600	35	0.3	15	30	–	4	–	–

MESH DEPENDENCY

The role of discretization schemes and mesh size on fault rupture propagation is of great importance in finite element based numerical analyses. By the way, according to Oda and Kazama (1998), very sharp strain gradients, noticeable volume changes and grain rotations can be observed within shear band. Localized plastic strains and also shear band are inherently formed during rupture propagation through soil media. The mesh size used in numerical analysis should be fine enough to capture narrow shear bands formed in the model. To insure the realistic description of rupture propagation, mesh independency is controlled by varying mesh densities. Figure 3 shows typical results for fault rupture of *α=45°* activated at *D=40m* in dense type shell material. The results are compared in the form of maximum plastic shear strain for three different average mesh sizes of 0.5, 1 and 2m. As observer in this figure, similar shear bands are generated in fine and medium meshes. Therefore, the mesh size of 0.5m is sufficiently accurate as well as efficient for further analyses.

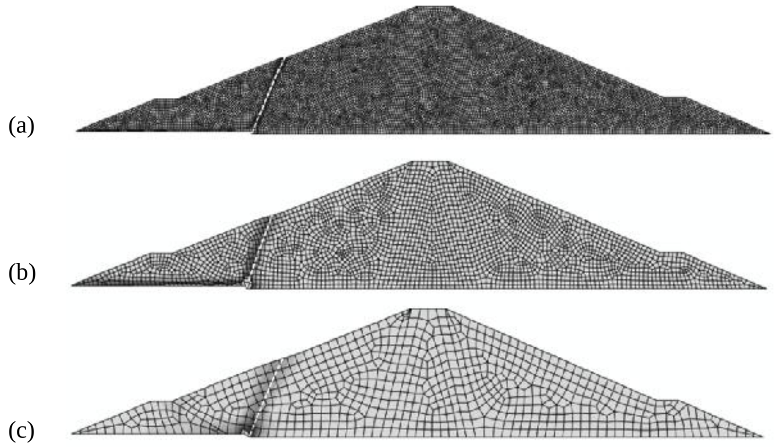


Figure 3. The effect of mesh density (contours of maximum plastic strain ranging from for 45° fault activated at D=40m) with mesh size (a) 0.5m, (b) 1m, (c) 2m

VERIFICATION

The results of numerical modelling presented in this paper are first verified by simulation of the experiments by Anastasopoulos et al. (2007) using centrifuge model test. The experimental apparatus has dimension of 68×25×20cm. The centrifuge tests were conducted at 100g centrifugal acceleration for 60° reverse fault. For the numerical predictions they reported the following mechanical soil parameters: $\varphi_p = 39^{\circ}$, $\varphi_{res}=30^{\circ}$, $\psi_p=11^{\circ}$ and $\gamma_y=0.02$. Our analysis predictions are compared with centrifuge experiment results in terms of the vertical displacement profile of the ground surface and are shown in Figure 4. Although, there is a slight difference in the tail of surface outcropping (left side of figure) at the downthrown block, the overall prediction of the surface settlement profile remains satisfactory.

RESULTS

To study the effects of material type on rupture propagation through the embankment, the results are analysed from two points of view: “Path and shape of rupture within the embankment” and “surface displacement gradient caused by rupture propagation”. According to different researches suggestions, contours of maximum plastic shear strains are used to describe fault rupture paths.

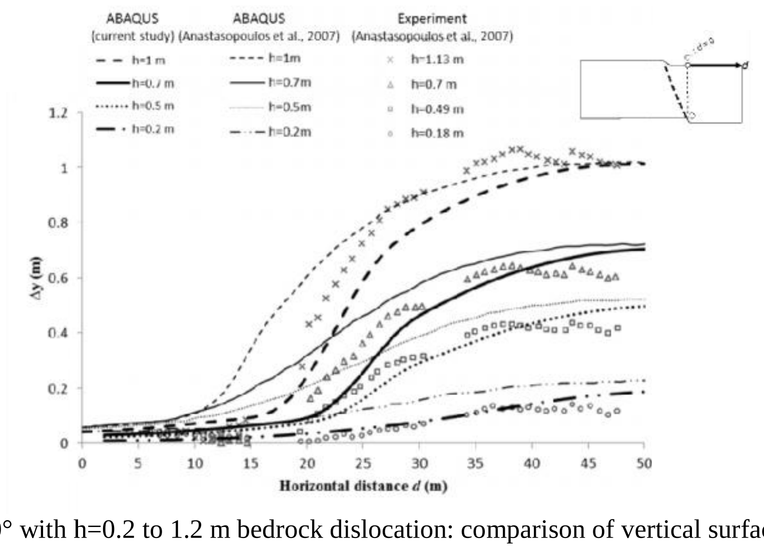


Figure 4. Reverse faulting at 60° with h=0.2 to 1.2 m bedrock dislocation: comparison of vertical surface displacement in numerical simulation of this study with experimental and numerical results of Anastasopoulos et al.

RUPTURE PATHS IN EMBANKMENT

The rupture paths developed in the embankment are compared for two typical materials of shell and presented in figs5 and 6. In Figure 5 the results of 45 fault activation in upstream base of the dam are showed for three selections of D=20, 40 and 60m. As seen in Figure 5 the rupture paths divide in two branches, a vertical path and a horizontal path. The vertical path creates a convex curvature looking from the heel and the horizontal path has a concave upward curvature which cuts the slope surface at the embankment heel. Results show that in the dense soils (figs 5- a, b and c) the orientation of the rupture tends to bend more compared to that in the loose materials (figs d, e and f). Furthermore, the maximum shear strains for dense soils are concentrated in narrower parts rather than that of the loose soil. Figure 5 can be representative of the response of the dam to fault displacement when fault tip is located at upstream of the embankment.

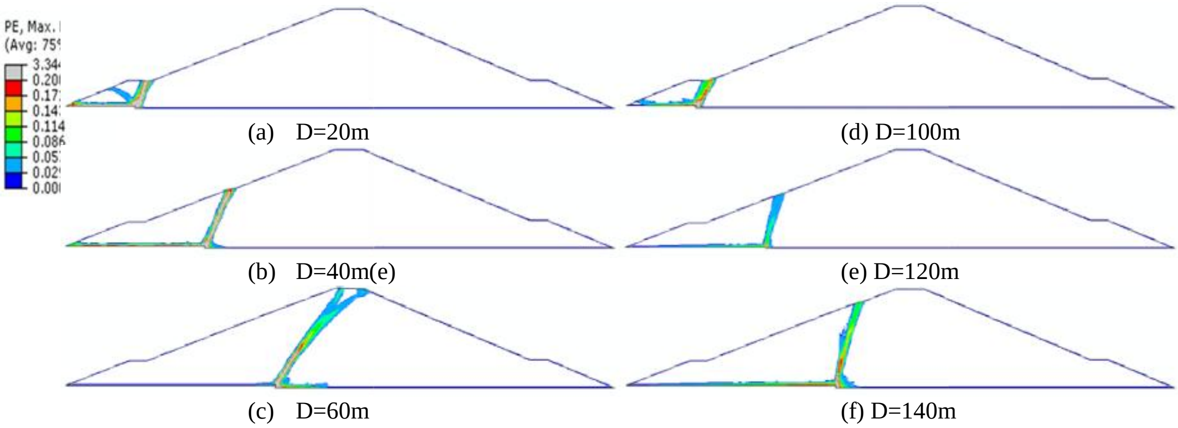


Figure 5. Rupture propagation of 45° reverse fault in dense soil (a to c) and loose soil (d to f); 'D' represents the location of fault in base

In

Figure 6 the results of 45 fault activation in downstream base of the dam are showed for three selections of D=100, 120 and 140m. In this case the horizontal branch of rupture path is toward the toe of the dam. As the location of fault activation moves downstream the horizontal branch fades gradually. It is observed that the horizontal branch has not formed for the case that shell material is loose soil (figs 6- d, e and f). The same results aforementioned above are seen for this case.

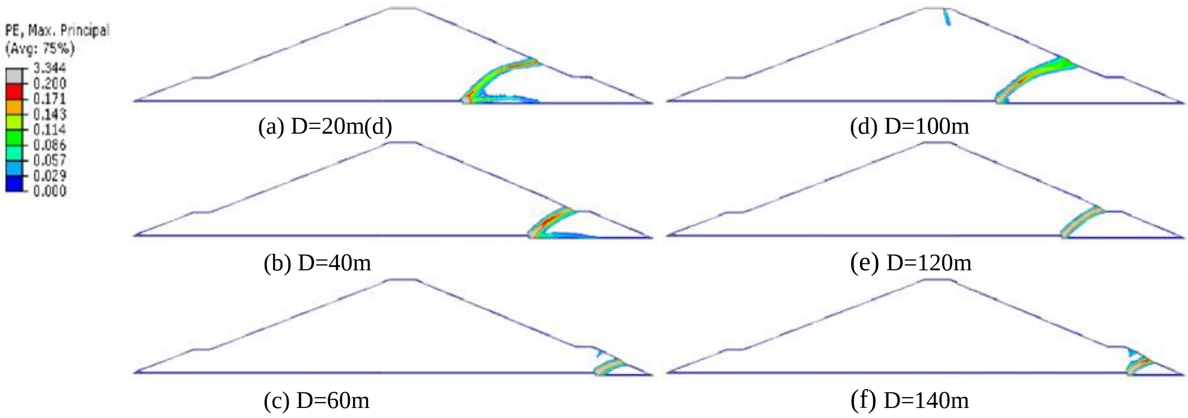


Figure 6. Rupture propagation of 45° reverse fault in dense soil (a to c) and loose soil (d to f); 'D' represents the location of fault in base

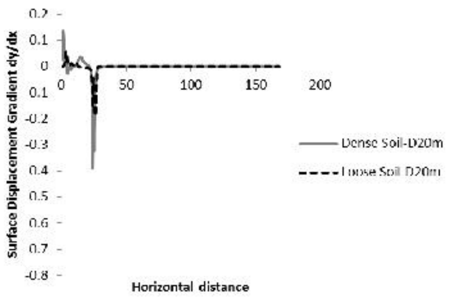
SURFACE DISPLACEMENT GRADIENT

Figure 7 presents surface displacement gradients for tow typical materials of the shell and for 6 locations of fault tip at the base of the embankment dam. It is observed that the location of the emergence of rupture at the surface is different for dense soil and loose soil. In the other word as fault tip moves from heel toward toe of the dam, its location on the surface is similar for both materials at first and then gets far for dense soil in the middle part of the dam and again coincides at downstream part. Moreover, graphs show that the amount of surface displacement gradient is much more for dense soil in comparison with loose soil. It can be interpreted as that loose soils can disperse the rupture through the embankment. Furthermore, surface displacement amounts in upstream (figs 7- a to c) are less in comparison with its amount in downstream (figs7 d to f). So it can be resulted that the orientation of rupture path relative to the embankment slope is another effective parameter to evaluate the rupture propagation through earth dams.

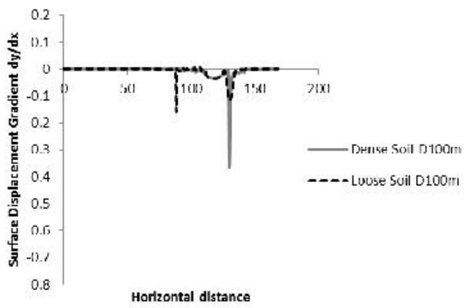
CONCLUSIONS

In this paper the mechanism of fault rupture propagation through an embankment dam at the end of construction was investigated. The numerical method was verified successfully with centrifuge physical simulations. Two aspects of fault rupture propagation were studied: “Path and shape of rupture within the embankment” and “surface displacement gradient caused by rupture propagation”.

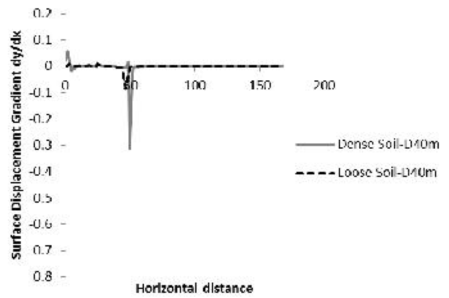
The results showed that in the dense soils the orientation of the rupture tends to bend more compared to that in the loose materials. This different behaviour may be attributed to the fact that the stiffer materials behave more brittle during rupturing and therefore the rupture paths leans more to follow straight lines. Moreover, it was observed that the amount of surface displacement gradient is much more for dense soil in comparison with loose soil. The orientation of rupture path relative to the embankment slope was another effective parameter to evaluate the rupture propagation through earth dams.



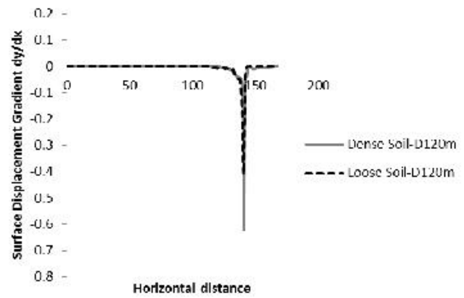
(a) D=20m



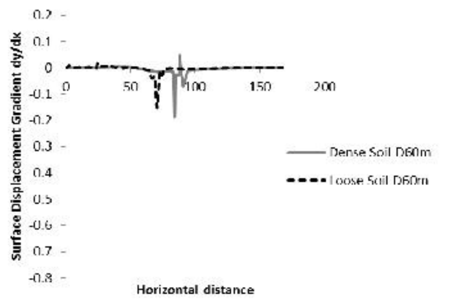
(d) D=100m



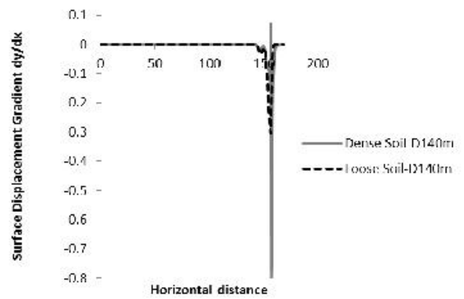
(b) D=40m



(e) D=120m



(c) D=60m



(f) D=140m

Figure 7. Surface displacement gradient of 45° reverse fault in dense and loose soil; ‘D’ represents the location of fault in base

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