Soil Dynamics and Earthquake Engineering 88 (2016) 60–71

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Two-dimensional numerical modeling of fault rupture propagation through earth dams under steady state seepage

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ARTICLE INFO

Article history:
Received 25 May 2015
Received in revised form
13 May 2016
Accepted 19 May 2016

Keywords:
Fault rupture propagation
Numerical modeling
Earth dams
Rupture paths
Pore water pressures
Dam safety

ABSTRACT

This paper studies numerically the phenomenon of dip-slip faulting through homogeneous and zoned earth dams under steady state seepage conditions. Normal and reverse faults with various dip angles are included in this study. Two different materials, a clayey soil and a sand-clay mixture, for the homogeneous dam and core of the zoned dam are considered. The results show that the slope of the fault-induced rupture paths is independent of the fault orientation and its location at the base of the dam. The path of fault propagation near the dam surface could be mainly described by the conventional failure theories in the passive and active states. It is also possible to define general patterns for the propagation of rupture inside the body of the earth dams. These patterns are mainly characterized by the location, orientation and mechanism of the fault. The results indicate that reverse faults and mixed materials are responsible for comparatively higher pore water pressures. Emphasizing on engineering significance of the results, the general effects of rupture on the safety of the dams are also discussed.

1. Introduction

Although strong ground shaking is the main concern in design of structures, fault rupture hazard is considered to be an important issue in the performance of lifelines after major earthquakes [1–3]. For the case of dams, the existence of active faults in the vicinity or under the foundation is a common issue in seismotectonic active regions [4,5]. In the 1999 Chi Chi Taiwan earthquake (Mw 7.3), a dip slip fault passed through the Shin-Kang concrete dam. The most severe damage occurred near the right abutment by the vertical fault movement of several meters. In Iran, many large dams are located in the vicinity of active faults. In the 1990 Manjil earthquake (Mw 7.3), the causative fault passed near the abutment of the Sefidrud dam [6]. In the Zagros region, many large dams are located on the Karun, Dez and Karkheh rivers, adjacent to the Zagros active fault system. The issue of fault rupture hazard is also of major importance for the design of new dams, such as the Rudbar Lorestan Dam, in this region [7].

Fault rupture propagations through uniform horizontal soil layers have been studied widely. Numerous field studies [5,8], physical modeling [5,9–13] and numerical simulations [2,9,12–18] have shed light on different aspects of this phenomenon. Louderback [19] was the first who observed effects of active fault displacement in the underlying bedrock on earth dams. This topic was addressed further by [3,4,20–22]. Cheney et al. [23] studied strike-slip fault rupture via centrifuge testing on loamy (silt-clay) embankment models. Sohn [24] continued their work by adding a reservoir to study strike-slip fault rupture propagation under steady state seepage conditions, accompanied by 3D FEM simulations. Lazarte [9] performed field, numerical and 1-g model experimental studies on strike-slip fault rupture through saturated clay embankments. Mejia et al. [25] studied numerically the case of the Aviemore Dam, New Zealand and investigated the combined effects of earthquake shaking and foundation fault displacement.

A simple numerical study on 45° and 60° normal and reverse faults in a sandy embankment, for two positions of the faults in the embankment base, were carried out by Zania et al. [26]; they presented fault-induced vertical displacements on the embankment surface.

The physical and numerical studies of strike-slip fault rupture propagation through embankment dams, as introduced in the above, have limited applications for dip-slip faults, due to the fundamental differences between the slip mechanisms. Although case studies like the Aviemore Dam helped to provide a valuable insight into the earth dams' behavior during faulting, details of rupture propagation and influencing factors in earth dams have not been addressed. In addition, the impact of different geometrical and mechanical aspects of the structure was not considered in the previous numerical studies, especially for dip-slip faults.

River channels generally follow the fault line. That is, the fault trace runs perpendicular to the longitudinal axis of the dam. The

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http://dx.doi.org/10.1016/j.soildyn.2016.05.012

propagation of a fault with such orientation through an embankment dam is a fully 3D problem. However, there are actual cases reported in the literature where the fault trace runs parallel to the longitudinal axis of the dam. A clear exception to the above general rule is the Cedar Spring Dam where the fault crosses the valley almost perpendicularly. The Lower Crystal Dam is another case in which the fault is parallel to the river valley but the dam closes a gorge on the side of the valley [4]. In the cases where the fault trace runs parallel to longitudinal axis of the dam, it is possible to model the problem in 2D using plane strain assumptions.

In a research by the first two authors [27], a systematic study was carried out considering dip-slip reverse faulting through earth dams at the end of construction. In that study, simplified steps were taken; i.e., an almost fully saturated homogeneous compacted clayey embankment was modeled in undrained conditions using plane strain assumptions. Therein, the effects of different parameters, such as fault dip angle, fault location and soil characteristics were studied in depth. Moreover, some of the results of faulting under steady state seepage conditions in homogeneous dams were briefly introduced. For verification of the numerical method, a comparison was made with simulations of physical experiments on horizontal soil layers [27,28].

This paper addresses rupture propagation in homogeneous and zoned dams under steady state seepage conditions. Herein, coupled pore water pressure-stress analyses have been carried out using effective stress soil parameters. The fault is dip-slip, and for all of the analyses the fault trace is assumed to run parallel to the longitudinal axis of the dam; the numerical analyses are performed utilizing the Finite Element Method adopted in the Abaqus software [29]. Localized shear strains and variations of pore water pressure after the application of fault displacement are studied.

This study covers both normal and reverse faults with different orientations applied in different locations of the dams' base. Moreover, two different materials are considered for the homogeneous dam and core of the zoned dam: *mixture of sand and clay* and *pure clay*. In the present study the effects of the strong ground motion on the structures are not considered; i.e. the study deals only with the quasi-static dislocation of the faults under the dams.

2. Fault displacement

In fault rupture analyses, usually a threshold value of fault displacement is required for the rupture to reach the ground surface. Smaller displacements are absorbed through the soil and the rupture will not impose any threat to the integrity or stability of the dam [18]. For displacements sufficiently larger than the threshold value, drastic surface damages are anticipated. Moreover, the effects of normal faults and reverse faults on their overlying structures differ. Reverse faults impose compressional forces on the structure, similar to the passive state of soils in retaining walls; whereas normal faults impose extensional forces which is analogous to the soils active state. Therefore, comparatively larger base displacements are required for reverse faults to lead the overlying soil to failure.

Table 1 summarizes the suggested normalized, to the overlying soil structure height, base displacements of reverse and normal faults for the rupture to reach the surface of a horizontal soil layer. In this regard and for trapezoidal geometry of the earth dams, sensitivity analyses showed that 4% and 2% normalized base displacements are sufficient for reverse and normal faults, respectively.

In addition, displacement magnitude of a potential fault may be known from site investigations. Otherwise, empirical correlations between the earthquake magnitude and fault-induced surface displacement can provide an insight into the scale of fault rupture.

Table 1
Normalized base displacements required for normal and reverse fault ruptures to reach surface of a horizontal soil layer.

Normalized base displacement (%)		Soil type	Study type	Reference
Normal fault	Reverse fault			
11–13	10 – 16	Soft saturated clay	Experimental	[5]
3	3 – 5	Sand	Numerical	[5]
1.1 – 3.3	2.2 – 4.4	Sand	Experimental	[10]
0.75 – 1	2.5 – 4	Sand	Experimental	[2]
0.2 – 0.4	1 – 2.4	Sand-clay	Numerical	[18]

Table 2
Maximum surface displacement in normal, reverse and strike slip faults correlated to earthquake magnitudes [30].

Magnitude of earthquake	**Maximum displacement (m)**		
	Reverse	Normal	Strike slip
5.6	0.61	0.12	0.05
5.8	0.70	0.18	0.09
6	0.79	0.28	0.14
6.2	0.91	0.41	0.23
6.4	1.04	0.63	0.36
6.6	1.19	0.94	0.59
6.8	1.36	1.42	0.94
7	1.55	2.14	1.51
7.2	1.77	3.22	2.43

Table 2 presents correlations between maximum displacements in normal, reverse and strike slip faults and magnitudes of earthquakes [30]. The data of Table 2 could be used as approximate values of the magnitude of rupture during large earthquakes.

The rate of loading of a fault is controlled by introducing a time period, known technically as the slip duration. The slip duration increases near the earth's surface, compared to that in the vicinity of the earthquake hypocenter, deep (kilometers) in the crust, mainly because of the softer deposits on the bedrock. However, assuming that the dam overlies immediately the bedrock (Section 3.1), the slip duration is selected based on the stochastic approach of Somerville et al. [31] for crustal (shallow) earthquakes. Therein, the slip durations of the earthquakes vary in the range of 0.3–2.5 s with an average of 1.1 s In the present study, the displacement time is selected as 1 s.

3. Problem description

3.1. Geometry and faults characteristics

The earth dams of this study are assumed to overly immediately the horizontal bedrock Therefore, the local soil conditions (alluvium foundation) are not studied in this research. Considering the local soil conditions requires a separate, thorough study which is beyond the scope of this paper. The fault intersects the bedrock-soil interface at different points of the dams' base. Two distinct cases were considered where hanging walls of the faults are located in the upstream and downstream of the dams. Figs. 1 and 2 present plane strain geometries, boundary conditions (when the hanging wall is on the upstream side) and FE idealizations of the homogeneous and zoned dams, respectively.

The geometrical properties of the dams are introduced in Table 3. The model domains are discretized with 8 noded quadrilateral elements and with biquadratic and bilinear shape functions for displacements and pore water pressures, respectively.