THE RESPONSE OF UNREINFORCED HIGHWAY EMBANKMENT DUE TO UNDERLYING REVERSE FAULT RUPTURE

Eleni PETALA1, Nikolaos KLIMIS2, Emilios COMODROMOS3

ABSTRACT

A crucial issue in Earthquake Engineering is mitigation of seismic vulnerability of structures and technical projects. Seismic vulnerability of engineering projects can be affected by the phenomenon of fault rupture propagation. In this work, we study the impact of reverse fault rupture diffusion on a highway embankment. We assume that the embankment is founded on a single-layered soil. We use 2D Finite Difference software (FLAC) and perform parametric quasi-static numerical analyses to simulate this phenomenon. In this way, we examine deformations of embankment’s surface, vertical displacements of its external surface and the drop of its initial relative. In addition, we succeed to define the embankment’s damage spatial variation due to rupture spread and quantify the damage by developing of two criteria. We conclude that reverse fault rupture propagation through the embankment causes significant changes of its geometry and important drop of its initial compaction.

Keywords: embankment; reverse fault; compaction; FLAC

1. INTRODUCTION

The occurrence of a seismic event is caused by rupture of a seismic fault. This rupture can provoke two types of loading, namely: (a) dynamic oscillation and (b) permanent induced quasi-static ground deformation. In the past, it has been ascertained that constructions such as buildings, bridges, pipelines, tunnels, waste landfills and embankments have been adversely affected by permanent deformations due to rupture spread. Permanent deformations can have serious economic and social consequences and even they can threaten human life. Therefore, seismic design of construction in the vicinity of an active fault is a vital issue that Earthquake Engineering is called upon to solve. However, fault rupture propagation is a complex phenomenon dependent on various factors. Those factors are relevant to fault characteristics (type, angle and offset), geometry and properties of soil layer overlying bedrock (Bray et al., 1994a; Bray, 2001). Consequently, definition of its influence in engineering projects requires understanding of the mechanism of fault rupture propagation.

In the last few decades researchers were motivated to develop measures to mitigate or even avoid the impact of fault rupture propagation on constructions which are placed near an active fault. To investigate the mechanism of rupture spread, they used field observations, experimental studies and numerical analyses. Researchers mainly investigated the path of rupture propagation through soil, the required fault offset so that rupture reaches the ground and the location of rupture’s outcropping. In addition, they tried to define the range of a significant deformation zone. They studied vertical displacements caused on soil’s surface due to the spread of rupture (Anastasopoulos et al., 2007; Athanasopoulos et al., 2007; Bray et al., 1994a, b; Papadimitriou et al., 2007; Roth et al., 1981). On the other hand, a number of researchers studied fault rupture–soil–foundation–structure interaction (Anastasopoulos et al., 2007; Bransby et al., 2008; Fadaee et al., 2012; Moosavi et al., 2010). They have been interested not only on fault rupture pattern and vertical displacements of soil, but also on the behavior of foundations. Some issues which they examined were: contact pressure along soil-foundation interface, bending moments of structure and their distribution,

1MSc Civil Engineer, Dep. of Civil Engin., Democritus University of Thrace, Xanthi, Greece, el_petala@hotmail.com
2Assoc. Professor, Dep. of Civil Engineering, Democritus University of Thrace, Xanthi, Greece, nklimis@civil.duth.gr
3Professor, Department of Civil Engineering, University of Thessaly, Volos, Greece, ecomo@civ.uth.gr
displacements and rotation of foundations and rupture propagation’s deviation caused by foundation’s existence. Nevertheless, the effects of this phenomenon in geostructures have not yet been extensively investigated. Only few studies have been carried out about fault rupture diffusion via a geostructure, such as dams and waste landfills (e.g. Bray, 1989; Zania et al.,2008; Mortazavi Zanjani and Soroush, 2013; Soroush et al., 2015; Ejlali et al., 2015). These studies focused on rupture path, vertical displacements of a geostructure and its gradient, but without determining extend of damage caused by the rupture propagation. Furthermore, modification of pore water pressures within geostructure and its stability after fault rupture diffusion were investigated.

In this work, we concentrate on the influence of reverse fault rupture propagating through a typical highway embankment mounted on a single-layered soil. We execute quasi-static parametric analyses using a 2D Finite Difference software. We examine deformations of the embankment’s area, displacements of its external surface and modification of its relative compaction. In this way, we attempt to map and quantify embankment’s damage. To achieve this, we define one criterion based on the variation of relative compaction of the embankment.

2. PROBLEM DEFINITION AND SIMULATION

In this work, we present and evaluate results from quasi-static numerical analyses to investigate reverse fault rupture spread via a highway embankment based on a single-layered soil. A 2D Finite Difference code, FLAC (Itasca 2011), in plane-strain mode is used to simulate the phenomenon of rupture diffusion. We assume that soil layer overlies a rigid bedrock and that both of them are horizontal. We also assume that fault rupture entirely occurs into the bedrock.

Researchers (Anastasopoulos et al. 2007; Bray et al. 1994b; Papadimitriou et al. 2007) support the idea that in order to minimize effects of lateral mesh boundaries on strain accumulation in the model central region, two conditions must be fulfilled: (a) ratio of length to height of the mesh should exceed the value 4 and (b) mesh above the fault tip and the rupture area should form a dense mesh. In this research, we consider a typical highway embankment of 15m high mounted on a soil layer 20m thick. Given the aforementioned limitations, we set model’s length equal to 180m. Moreover, we select a mesh with quadratic elements of 0.5m size at the area of the fault rupture propagation. However, dimensions of the elements outside this area are increased in the horizontal direction as well as they stand off the dislocation area towards lateral boundaries. The selected geometry of the model and the description of boundary conditions are depicted on Figure 1.

Model is separated into two parts in order to simulate fault displacement. The right part is fixed, whilst the left part is free to move. Figure 1 describes imposition of reverse fault movement. This is succeeded by quasi-static way to minimize inertial forces. Displacement is applied parallel to fault rupture plane at the bottom boundary’s left part and left lateral boundary of model.

2.1 Constitutive model and soil properties

In previous studies, many researches (Anastasopoulos et al. 2007, Papadimitriou et al. 2007) referred that the yield and the post-yield behavior of soil affect diffusion of fault rupture. Thus, they considered that a
constitutive model which simulates isotropic strain softening behavior of soil is appropriate to describe the phenomenon of rupture propagation. Taking this into account, we decided to use a Mohr-Coulomb (MC) elasto-plastic constitutive model with isotropic strain softening to simulate reverse fault rupture spread. According to this, there is a reduction of material’s cohesion, friction and dilation as functions of the deviatoric plastic strain (Itasca, 2011). In our model, we consider that the embankment consists of clayey sand with some gravels and soil layer is sand in two different conditions (DS and LS). The simulation of behavior of clayey sand and DS succeeds using Mohr-Coulomb (MC) elasto-plastic constitutive model with isotropic strain softening. Reduction of friction angle (φ) and dilation angle (ψ) is applied for both materials. Furthermore, we assume that cohesion also decreases in the case of the embankment. However, we regard that LS cannot further soften and thus, we simulate its response using Mohr-Coulomb (MC) elasto-plastic constitutive model without softening. Table 1 contains input parameters of constitutive models.

Table 1: Input parameters of constitutive models

<table>
<thead>
<tr>
<th>Constant</th>
<th>Embankment - Clayey Sand with Gravels</th>
<th>Dense Sand</th>
<th>Loose Sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>ρ (t/m³)</td>
<td>2.2</td>
<td>2.1</td>
<td>1.9</td>
</tr>
<tr>
<td>E (kPa)</td>
<td>50,000</td>
<td>1,500z+25,000</td>
<td>500z+10,000</td>
</tr>
<tr>
<td>ν</td>
<td>0.3</td>
<td>0.3</td>
<td>0.35</td>
</tr>
<tr>
<td>c (kPa)</td>
<td>8</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>cres (kPa)</td>
<td>2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>φ (°)</td>
<td>38</td>
<td>39</td>
<td>31</td>
</tr>
<tr>
<td>φres (°)</td>
<td>30</td>
<td>30</td>
<td>-</td>
</tr>
<tr>
<td>ψ (°)</td>
<td>10</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>ψres (°)</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>γf (%)</td>
<td>6</td>
<td>4</td>
<td>-</td>
</tr>
</tbody>
</table>

2.2 Constitutive model validation

Prior to performing numerical analyses, we need to confirm the ability of the chosen constitutive model to simulate soil’s response. Thus, we contrast outputs from FD analyses with results of centrifuge tests which were described by Anastasopoulos et al. (2007). Results of comparisons refer to vertical displacements of single-layered soil’s surface (Figure 2). As Anastasopoulos et al. (2007) refer, there were some problems in measuring displacements during the tests that affected the quality of certain measurements. Thus, we thought it is required to correct experimental results before using them in validation of our constitutive model. The corrected experimental results are presented with the square shapes. Figure 2a displays displacements when fault ruptures at an angle of 60° and offset of 1.13m and it spreads via soil layer of DS. On the other hand, the comparison for rupture at an angle of 60° and offset of 1.24m via loose sandy soil is shown in Figure 2b. As we can see, the curve which corresponds to our analyses outputs approaches fair enough, centrifuge tests data, for both DS and LS. Thus, it is obvious that our constitutive model is capable to describe with sufficient precision fault outcrop position and ground surface distortion.
2.3 Parametric analyses

Factors related to fault rupture propagation are: characteristics of fault (type, angle and offset), geometry and properties of overlying soil (Bray et al. 1994a; Bray 2001). Our aspiration is to investigate how variation of those factors influences the impact of rupture propagation in the embankment. To achieve this, we performed in total, 48 parametric analyses. We assume that single-layered soil appears in two different conditions, namely: dense sand and loose sand. We select to study reverse fault rupture with angles of $\beta=45^\circ/60^\circ$ and vertical dislocation of $h=0.5m/1m/1.5m/2m$. The description of fault parameters is shown in Figure 1. Given that fault may break at any position along the base of embankment, we choose three potential fault tip locations. Those are placed at: (a) embankment’s left toe, (b) a distance of 15m from the left toe and (c) embankment’s axis of symmetry (Figure 3).

Figure 3. Fault tip locations at the base of the model.

3. RESULTS

Last few years, many researchers have focused their interest in study of fault rupture propagation via uniform single-layered soil and its interaction with a structure/ foundation. They succeeded to define the general behavior of fault pattern. However, the influence of this phenomenon on a geostructure such as a highway embankment has not yet been explored in depth. In the present work, we perform a number of FD numerical analyses in order to investigate the impact of reverse fault dislocation diffusion on a highway embankment founded on a single-layered soil. Figure 4 shows the change of embankment’s initial geometry and creation of a shear zone within its body for fault rupture at an angle of $45^\circ$ and an offset 2m via a soil layer of DS. When fault disrupts under the left toe of the embankment (Figure 4a and 4d), we observe that a main shear zone is formed and reaches the area of the left toe. This leads to the uplift of this area. On the other hand, when fault tip is located at $S_2$ and $S_3$, we remark that main fault path diverts at a certain depth below the embankment and it emerges right after the right foot of the embankment. In these cases, almost the whole embankment’s body is deformed. For a fault tip at $S_2$ location (Figure 4b and 4e), a sliding surface is created under the left slope. Finally, for three tip locations, shear surfaces are formed along at bedrock-soil interface and at the right toe. As per the total number of analyses, we conclude that for fault tip at $S_1$, main fault zone reaches close to the left toe for all cases. When fault disrupts at $S_1$ with $\beta=45^\circ$, the main shear band emerges
just immediate after the right foot. However, for tip fault at $S_3$ and $\beta=60^\circ$, the main fault surface inserts within embankment and no diversion is observed. Finally, when dislocation takes place at $S_2$, conclusions are partly convergent with those for $S_1$ location and partly for $S_3$ location.

Another considerable effect of rupture spread which should be examined is settlement of embankment’s external surface. For this purpose, in Figures 5 and 6, diagrams of vertical displacements ($\delta_y$) versus initial horizontal coordinates (x) of the embankment’s external surface are depicted. In every diagram, there are three curves which refer to a tip location $S_1$, $S_2$ and $S_3$, respectively. The vertical dotted lines represent locations of the crest edges, the middle of slopes and the embankment’s toes. For fault dislocation under dense sandy soil with $\beta=45^\circ/60^\circ$ and $h=1m$, $\delta_y$ values are shown in Figure 5. It becomes obvious that, for both fault angles, as fault trace location moves to right (from $S_1$ to $S_3$), an increasing part of the embankment shifts to the hanging wall, whilst maximum vertical displacements ($\delta_{y,\text{max}}$) gets smaller values. Comparing Figures 5a and 5b, it results that values of $\delta_{y,\text{max}}$ are greater for $\beta=45^\circ$. However, when fault disrupts at $S_2$ and $S_3$, we see that the right toe uplifts. This is because of a shear zone development in the area of the right toe.

Figure 5. Vertical displacement of external surface of the embankment founded on soil layer of DS for three different tip locations: (a) fault ruptures with $\beta=45^\circ$ and $h=1m$ and (b) fault ruptures with $\beta=60^\circ$ and $h=1m$.

Figure 6 depicts $\delta_y$ values of embankment’s external surface for the case of LS. It seems that for both dip angles the shift of fault tip to right provokes more intense deformations on the embankment. When $\beta=45^\circ$ (Figure 6a), $\delta_{y,\text{max}}$ gets smaller values as trace moves from $S_1$ to $S_3$. However, when $\beta=60^\circ$ (Figure 6b), $\delta_{y,\text{max}}$ appears for fault disruption at $S_2$. Comparing $\delta_{y,\text{max}}$ values for both fault angles, it results that $\delta_{y,\text{max}}$ gets bigger values for $\beta=45^\circ$. In addition, when fault trace is located at $S_2$ and $S_3$, the right toe of the embankment
uplifts due to the creation of shear bands. The above observations stand almost for the entity of analyses in the case of LS.

![Displacement of the Embankment's External Surface](image)

Figure 6. Vertical displacement of external surface of the embankment founded on soil layer of LS for three different tip locations: (a) fault ruptures with $\beta=45^\circ$ and $h=1m$ and (b) fault ruptures with $\beta=60^\circ$ and $h=1m$.

Next, we investigate the influence of sandy soil conditions on the external embankment’s surface (Figure 5 and 6). We deduce that when fault ruptures under the left foot of the embankment, $\delta y_{\text{max}}$ gets larger value for sandy soil in dense condition. The opposite is true for fault tip at $S_2$ and $S_3$ locations. Moreover, it seems that fault path deviates when single-layered soil consists of DS. Those findings confirm conclusions of all analyses. At the end, as per $\delta y_{\text{max}}$ values, it should be mentioned that the worst-case scenario refers to the case of fault dislocation under layer of DS at location $S_2$ with $\beta=45^\circ$ and $h=2m$.

The main goal of this work is to evaluate and quantify embankment’s damage due to reverse fault rupture propagation. For this purpose, we developed one criterion based on variation of embankment’s compaction degree which is an indicator of evaluating its safety and its serviceability. Yi (2012) described a relation between initial and final relative compaction (RC) of a geomaterial, as given by Equation 1.

$$\Delta \varepsilon_v = \frac{\text{RC}_1 - \text{RC}_2}{\text{RC}_2}$$

where $\Delta \varepsilon_v$ is modification of the volumetric strain

$\text{RC}_1$ and $\text{RC}_2$ represent respectively the initial and ultimate relative compaction geomaterial

In order to map and quantify the embankment’s damage, we apply Equation 1 to estimate values of $\text{RC}_2$ of the entire embankment after rupture spread. To achieve this, we regard that $\text{RC}_1$ is equal to 95%. This value corresponds to the initial compaction degree of a highway embankment in Greece. In this way, we create diagrams presenting the distribution of $\text{RC}_2$ within embankment’s body.

Modification of RC values of the embankment, mounted on a dense sandy soil is presented in Figure 7. It depicts the damage distribution due to fault rupture at $\beta=45^\circ/60^\circ$ and $h=1.5m$. For all fault tip locations, it is observed that there is a reduction of RC values due to rupture spread. For an area that covers about 1% of the total surface of the embankment, it seems that RC maintains its original value (RC=95%). Nevertheless, within the greater part of the embankment's body, drop of RC is slight (e.g. RC=94%). When the fault tip is located at $S_1$ (Figures 7a & 7d), values of RC ranging between 80% and 94% are concentrated at the area of left embankment’s foot for both fault angles. For fault breakage at $S_2$ location with $\beta=45^0$ (Figure 7b), we remark that RC values less than 94% cover the upper part of the left slope and the right part of the embankment. Values of RC less than 80% scarcely appear and they are located at the embankment’s right toe and the left edge of the crest. However, when $\beta=60^0$ (Figure 7c), RC<94% appears mainly along the whole height of the embankment’s left part. On the opposite, when fault rupture occurs at $S_3$ (Figures 7c & 7f), values of RC inferior to 94% are detected at the central part and at the right toe of the embankment. In all the above cases, it is confirmed that the most intense reduction of the embankment’s RC is stated in the vicinity of shear zones. Therefore, we propose that the percentage of the total embankment area where RC is
less than 94% could be used as a quantified measure of the damage, and could be symbolized as $RC_{94}$. Table 2 contains percentages of $RC_{94}$. Comparing values reported in the case of DS, we conclude that as fault tip moves to the right edge of the embankment, the percentage of $RC_{94}$ increases. When fault dislocation takes place at $S_1$ and $S_2$ locations, we observe that $RC_{94}$ obtains higher values for $\beta=45^\circ$. It denotes that $RC<94\%$ is localized at larger part of the embankment, when $\beta=45^\circ$. This observation is not confirmed for tip location of $S_3$. Aforementioned results are valid for all parametric analyses for DS, except very few cases.

Table 2. Percentages of $RC_{94}$ of the embankment founded on a soil layer of 20m thick with reverse fault rupture with vertical offset of 1.5m.

<table>
<thead>
<tr>
<th>Location of tip fault</th>
<th>$\beta=45^\circ$</th>
<th>$\beta=60^\circ$</th>
<th>$\beta=45^\circ$</th>
<th>$\beta=60^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_1$</td>
<td>3%</td>
<td>1.8%</td>
<td>2.2%</td>
<td>0.9%</td>
</tr>
<tr>
<td>$S_2$</td>
<td>8.1%</td>
<td>6.1%</td>
<td>5.1%</td>
<td>6.3%</td>
</tr>
<tr>
<td>$S_3$</td>
<td>13%</td>
<td>14.5%</td>
<td>9.3%</td>
<td>7.3%</td>
</tr>
</tbody>
</table>

Figure 7. Modification of RC of the embankment founded on a DS layer, with reverse fault rupture with vertical fault offset of 1.5m: (a) fault rupture at $S_1$ location at $\beta=45^\circ$, (b) fault rupture at $S_2$ location at $\beta=45^\circ$, (c) fault rupture at $S_3$ location at $\beta=45^\circ$, (d) fault rupture at $S_1$ location at $\beta=60^\circ$, (e) fault rupture at $S_2$ location at $\beta=60^\circ$, (f) fault rupture at $S_3$ location at $\beta=60^\circ$.

Table 2. Percentages of $RC_{94}$ of the embankment founded on a soil layer of 20m thick with reverse fault rupture with vertical offset of 1.5m.

Figure 8 depicts corresponding results of Figure 7 for the case loose sandy soil. We observe that in all cases values of RC are decreased. Only in a small area of the embankment’s body (up to 2%) RC remains invariable ($RC=95\%$). We detect that for fault dislocation at $S_1$ (Figures 8a & 8d), RC values in between 80% and 94%, are localized close to the left embankment’s foot. For rupture at $S_2$ location (Figures 8b and 8d), significant reduction of RC values takes place along the whole height of the embankment’s left part and under its right slope. Finally, RC values range from 80% to 94% at the upper half of the embankment and in the vicinity of embankment's right toe, when rupture occurs at $S_3$ location (Figures 8c & 8f). Percentages of $RC_{94}$ for previous cases are included in Table 2. We realize that as tip location moves from $S_1$ to $S_3$ values of $RC_{94}$ increase. For fault disruption at $S_1$ and $S_3$, it seems that values of $RC_{94}$ obtain higher values for fault angle of 45°. In the case of rupture taking place at $S_2$ location, the opposite is true. The above are confirmed for all analyses referring to loose sandy soil. Nevertheless, the influence of fault angle in values of $RC_{94}$ is not clear for tip location at $S_2$ and $S_3$.

In this section, we investigate how soil’s condition affects modification of $RC_{94}$ values. Comparing values reported in Table 2, we deduce that $RC_{94}$ gets higher values when fault rupture underlies a dense sandy soil.
This observation is not confirmed when disruption takes place at S₂ location with an angle of 60°. Finally, based on results of the rest parametric analyses, we conclude that RC₉₄ gets higher values for soil layer of DS.

Figure 8. Modification of RC of the embankment founded on a LS layer, with reverse fault rupture with vertical fault offset of 1.5m: (a) fault rupture at S₁ location at β=45°, (b) fault rupture at S₂ location at β=45°, (c) fault rupture at S₃ location at β=45°, (d) fault rupture at S₁ location at β=60°, (e) fault rupture at S₂ location at β=60°, (f) fault rupture at S₃ location at β=60°.

Eventually, we consider that it is appropriate to mention the worst-case scenario. Bearing in mind results of the total parametric analyses, we conclude that a fault rupture with an angle of 45° and an offset of 2m below dense sandy soil corresponds to the worst-case scenario, regarding values of RC₉₄. In this case, RC₉₄ values are equal to 21.9%.

4. CONCLUSIONS

In this work, the impact of a reverse fault rupture propagation on a highway embankment resting on a single-layered soil is investigated. The scope of this paper is to assess and quantify the damage of the embankment induced by disruption spread. For this purpose, we use a 2D finite difference code to perform numerical parametric analyses. Deformation and vertical displacement of the embankment’s external surface, as well as, the modification of its initial RC is studied. The main conclusions are as follows:

- Fault disruption affects an increasing part of the embankment, as fault tip gets closer to the embankment’s axis of symmetry.
- As per δᵧₘₐₓ values, it is concluded that they decrease, as fault trace moves from S₁ to S₃. Nevertheless, when rupture spreads through LS with β=60°, δᵧₘₐₓ values appear for rupture at S₂. Comparing values of δᵧₘₐₓ for both soil conditions, we regard that when fault dislocation occurs below the left foot of the embankment, δᵧₘₐₓ is observed for a dense sandy layer. The opposite is valid for fault tip at S₂ and S₃.
- Significant decrease of the embankment’s initial relative compaction is provoked by rupture diffusion through its body. RC values remain invariable (RC=95%) only in a very small part of the embankment which does not exceed 2% of its total area.
- Finally, as fault trace shifts from S₁ to S₃ location, values of RC₉₄ are heightened. This states that values of RC less than 94% cover greater part of the embankment. In most cases, RC₉₄ gets higher values for sandy soil in dense condition.

Conclusions of this work contribute to assessment and quantification of embankment’s damage caused by reverse fault rupture propagation. The implementation of the criterion of RC modification is considered to be a reliable way to map and quantify rupture diffusion impact on the embankment. On the other hand, in order to use this criterion, it is necessary to know the characteristics of the reverse fault and of the overlying...
single-layer soil.

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