Effects of earthquake fault rupture propagation on nearby structures

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Abstract

The FEM was used to analyze the pattern of ground deformations caused by the potential slip of a known normal fault crossing a populated area of the city of Patras, Greece. The analyses were based on geological-geotechnical data of the area which were found in the literature. The results of the analyses showed that the maximum values of differential settlements were developed on the footwall of the fault. By assuming a safe limit of $\beta = 1/500$ for the angular distortion of the buildings of the area, a critical zone was defined (based on the criterion $\beta > 1/500$) having a width of 150 m, within which the buildings (and possibly other structures) run the risk of undergoing various degrees of damage, in case the fault is activated. The approach used herein may be applied to other situations of known dip-slip faults crossing populated areas.

1 Introduction

Much attention has been devoted in the past to the effects of local soil conditions on seismic ground response and significant progress has been made toward developing analytical models utilizing non-linear inelastic soil behaviour. The results of such seismic soil response studies are particularly useful for assessments of design ground motions when designing earthquake resistant structures. Very little effort has been devoted, however, to the study of fault rupture propagation through soil and its effects on the pattern of ground deformation in the vicinity of the fault. Such an intense deformation could cause serious, or even catastrophic, damages to structures lying in the immediate vicinity of the trace of the fault. Therefore, a study of this aspect of earthquake effects, would assist engineers in either siting structures outside an appropriately defined critical zone, or-when this becomes impossible (e.g. lifeline facilities) - designing measures to mitigate the damaging effects.2,6

During the last few years the pattern of soil deformations developing as
a result of a fault rupture in the underlying bedrock, has become the subject of several investigations. The results of these investigations are briefly summarized in the next section whereas in the rest of the paper the results are presented of a preliminary study regarding the expected ground movements in the vicinity of a normal fault crossing a populated area of the city of Patras, Greece.

2 Review of Previous Work

Although the propagation of fault rupture through soil is a quite complex phenomenon the systematic study of field case histories has revealed the typical characteristics of the deformation patterns which are summarized in Fig. 1,

Figure 1: Path of normal fault rupture through soil: (a) Stiff earth materials, steep dip; (b) Stiff earth materials, shallow dip; (c) Ductile earth materials
Fig. 2 and Fig. 3 for the cases of normal, reverse and strike-slip faults, respectively. The effects of the three most important variables - type of fault, inclination of fault plane and nature of overlying soil - are shown in these figures: Reverse faults tend to gradually decrease in dip near the ground surface, whereas normal faults tend to refract at the soil - bedrock contact and to increase in dip as they approach the ground surface. Strike-slip faults, on the other hand, tend to follow the almost vertical orientation of the underlying bedrock fault - although the rupture zone may spread (or "flower") near the ground surface.

Results of small scale physical model studies on fault rupture propagation are also available in the literature and have helped to gain insight into several aspects of the phenomenon. The study of well-documented problems displaying behaviour analogous to the fault rupture propagation problem has also been employed in an attempt to overcome the variability inherent in the
field case studies and the limited number of physical model studies. The anchor pullout problem proved to be a very good analogy in this respect and pertinent studies have provided valuable insight regarding the effects of basal boundary deformations on overlying particulate media\(^2\)\(^,\)\(^4\).

Besides the field case studies and the small scale physical model studies, the fault rupture propagation through soil material has also been investigated by numerical model studies. The results of numerical analyses suggest that the Finite Element Method can be applied successfully provided the soil’s nonlinear stress-strain behaviour is adequately modeled\(^3\). In Fig. 4, are summarized the results of FE analyses of dip-slip fault movements, for normal and reverse faults\(^3\). These FE studies have demonstrated the importance of soil’s failure strain which actually determines how far the shear rupture zone propagates in the overlying soil for a specified bedrock fault displacement. It is thus concluded that the FEM can provide a viable basis for evaluating the effect of a bedrock fault displacement on overlying soil deposits.

3 The Agia Triada Fault

During 1989 the city of Patras was shaken by a series of earthquakes with magnitudes \(M_s \approx 5\), focal depths of about 1 km and epicentral distances ranging from 5 km to 10 km. These earthquakes caused damage to buildings along a narrow elongated zone in an area of the city called Agia Triada\(^5\). Subsequent reconnaissances revealed the existence of a surface rupture, approximately 1500 m long, having a mean strike N70\(^\circ\)E and lying along the zone of observed earthquake damages, Fig. 5. A subsequent study of a series of recent and old stereopairs of airphotos (1945-1988) revealed the existence of a normal fault with a prevailing scarp coinciding in general with the present
Figure 4: Results of FE analyses of dip-slip fault movements. (a) Deformed mesh for 60° normal fault propagating through a 24 m deep soil deposit; (b) Stress level contours for 0.6 m displacement of a 60° normal fault; (c) Stress level contours for 0.6 m displacement of a 90° reverse fault.

Figure 5: Area of the city of Patras affected by the 1989 earthquakes.
surface rupture. This old fault was apparently activated by the seismic activity in the area and resulted in the observed surface rupture. The strike of this fault (which was visible only in the older airphotos) was parallel to one of the two groups of normal faults (NE-SW, NW-SE) which cross the greater area and have affected the plio-pleistocene deposits since the period of upper Neogene.

The aperture of the main rupture and its vertical displacement progressively increased since the date of main earthquake (August 1989). Few days after the event the aperture was 1 cm wide and the vertical displacement (downthrow of the south side) less than 5 mm. Few months later, these were increased to 3 cm and 2 cm respectively. Monitoring of vertical and horizontal displacements of the area was continued until June 1993 by establishing a vertical and horizontal geodetic network. In 1993 the maximum vertical displacement of the hanging wall of the fault was 15 cm whereas its horizontal displacements had a S-SE direction and a magnitude equal to 8 cm.

4 Geotechnical Data

Following the Patras earthquakes of 1989 and the accompanying development of surface rupture a detailed geotechnical investigation programme was carried out including the execution of borings, cone penetration tests (CPT), crosshole tests, standard penetration tests (SPT) and laboratory testing, Fig. 5. Based on the results of this programme, the geotechnical cross section of the area in the N-S direction was established as shown in Fig. 6. The geotechnical units shown in this section are described in the following. The unit 1 consists of clays, which are either of medium strength (1a) or stiff overconsolidated (1b). These are classified as ML or ML-CL. The units 2a, 2b, 2c consist of mixtures of clay, silt, sand and gravel in varying proportions, with the unit 2a been classified as sandy clay with gravels (CL or ML), the unit 2b as clayey sand and gravels and unit 2c as clay with intercalations of sands and silts (CL or CL-ML). The unit 3 is classified as clayey sand and gravel and conglomerate (medium to well cemented). Finally, unit 4 consists of marls which constitute the geological bedrock in the area up to the maximum investigated depth of 330 m. The basement rocks of the area consist of flysch formations.

Figure 6: Geological/geotechnical cross section through the boreholes D6, D1, D2, D3 and D5
and of thin-bedded limestones and radiolarites, which outcrop in the mountainous area eastward to south-eastward of Patras.

5 Finite Element Analyses of the Fault Rupture Propagation

It was mentioned previously that the movement of the Agia Triada fault was most probably triggered by the earthquakes that shook the city of Patras in 1989. Since this fault crosses a populated area, its movement caused serious structural damage to buildings and other facilities. It would be very interesting, then, to investigate the consequences of this fault being activated and becoming the causitive fault of a future earthquake. An estimate of these consequences could be based on a FE analysis similar to the ones mentioned in section 2 of this paper. Before proceeding to this analysis, however, it is necessary to obtain an estimate of the maximum expected bedrock slip for the particular fault.

It is known that the fault slip is related to the magnitude of the earthquake generated by the fault, and to the pertinent magnitude of the seismic moment. For central Greece the following Eq. 1 has been proposed:

$$\log M_o = 10.7157 + 0.7902 M_L$$

where:  
- $M_o$: seismic moment, Nm  
- $M_L$: earthquake magnitude (local)

whereas for the Patras area Eq. 2 has also been found to apply:

$$\log M_o = 11.9281 + 0.9257 (\log S)$$

where:  
- $M_o$: seismic moment, Nm  
- $S$: fault slip, mm

Based on the size of the Agia Triada fault, it is estimated that it can generate an earthquake having a magnitude $M_L = 4.7$ at maximum. It follows, then, from Eq. 1 and Eq. 2 that the maximum expected fault slip is $S_{\text{max}} = 0.5$ m. Based on the results of related investigations, the dip angle of the fault will be taken equal to 75°.

The FEM formulation of the problem was based on a simplified subsurface cross-section in a direction normal to the trace of surface rupture, as shown in Fig. 7. The values of deformation and strength parameters of the materials shown in Fig. 7 were derived, based on the results of laboratory tests and on empirical correlations and are summarized in Table 1.

The analysis was performed with the finite element program ZSOIL V2.1 which allows non-linear modelling of the behaviour of soil materials in association with a Drucker-Prager failure criterion. The finite element mesh has length equal to 1200 m, a depth equal to 375 m and consists of approximately 1000 elements. The fault slip was simulated by imposing a forced displacement to the left-hand half of the base of the mesh equal to 0.5 m, making an angle of 75° with the horizontal, Fig. 8. The forced displacement
was imposed in 16 equal steps. This number of steps, although lower than the ones used by other investigators, was found, by parametric analyses, to give satisfactory accuracy of results.

6 Results and Discussion

The results of the stability analysis of the fault rupture area are shown in Fig. 9. In this figure the deformed shape of mesh is first shown indicating the intense soil deformation of soil in the footwall of fault. The graph of node displacement vectors clearly indicates the direction of propagation of soil displacement from the rigid base to the ground surface. The values of the vertical and horizontal displacements of ground surface is given in Table 2. According to this table the vertical displacement of the surface points in the vicinity of the observed surface rupture is approximately equal to 0.34 m. Of particular interest is the distribution of differential ground settlements and angular distortion along a length equal to 500 m as shown in Fig. 10. According to this plot the distortion of ground surface is much greater at the surface of the footwall of the fault when compared to its hanging wall. The maximum value of angular distortion appears at a distance of approximately 300 m from the observed surface rupture on the footwall of the fault. The plot of Fig. 10 also indicates that some values of angular distortion exceeded the most often used safety limit of $2 \times 10^{-3}$ (1/500) against cracking of infill walls of buildings. If this limit value is assumed to hold in the case of the buildings.

Table 1: Material parameters used in the analyses

<table>
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<tr>
<th>Parameter</th>
<th>Material 1</th>
<th>Material 2</th>
<th>Material 3</th>
<th>Material 4</th>
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surrounding the Agia Triada fault then the width of a critical zone, with $\beta > 2 \times 10^3$, can be established as shown in the plot of Fig. 10. The width of this zone is approximately equal to 150 m and its centerline lies approximately 250 m away from the observed surface rupture on the footwall of the fault (north side of fault).

**Figure 8: Finite element mesh used in the analyses**

**Figure 9: Results of the stability analyses of fault area**
Table 2: Vertical and horizontal displacements of ground surface

<table>
<thead>
<tr>
<th>Point</th>
<th>$\Delta X$ (cm)</th>
<th>$\Delta Y$ (cm)</th>
<th>Point</th>
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<th>$\Delta Y$ (cm)</th>
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It is worth noting that although the maximum differential settlements and angular distortions develop at the surface of the footwall of the fault, the maximum total settlements appear at the surface of the hanging wall of the fault (south side of fault). Their value is approximately equal to 0.33 m, thus indicating that the soils overlying the bedrock caused the dissipation of an amount of deformation equal to the 34% of the bedrock slip.

Finally, it should be noted that the results of the analysis presented above, were obtained for a fault slip equal to 0.50 m and would be different if this value were changed. Nevertheless, the method of approach used herein may be utilized for obtaining data and information to help the engineer when siting and designing structures and other facilities in the vicinity of active normal (or reverse) faults.

### 7 Conclusions

The FEM was used to analyze the stability of soil formations overlying the Agia Triada normal fault in the event this fault is activated and undergoes a slip equal to 0.50 m (compatible with the maximum earthquake expected from this fault). It was found that the maximum differential settlements were developed at the surface of the footwall of the fault whereas the maximum total...
settlements appeared at the hanging wall. By assuming a safe limit value of $2 \times 10^{-3}$ (1/500) for the angular distortions of buildings, a critical zone was defined at the surface of the footwall of the fault, having a width equal to 150 m. It is expected that buildings lying within this critical zone, may undergo angular distortions $> 1/500$ and run the risk of undergoing various degrees of damages, in case the fault is activated. The method of approach used in this work could become a useful tool when delineating critical zones (with respect to expected damages in buildings and other facilities) in populated areas crossed by normal (or reverse) faults.

References


100 Earthquake Resistant Engineering Structures

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