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FAULT-RUPTURE RELATED HAZARD TO ENGINEERED STRUCTURES -PARAMETRIC NUMERICAL ANALYSES

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ABSTRACT

The propagation of a bedrock dip-slip fault-rupture through an overlying soil formation to the ground surface is studied numerically for both cohesionless and cohesive soil types. Parametric finite element analyses were conducted to establish the effects of fault characteristics, i.e. type (normal vs. reverse), slip magnitude and dip-angle, on the free-field angular distortion, β, and horizontal strain, ε_h, at the ground surface. The results are combined to produce graphs for predicting the propagation path of soil rupture, the maximum values of free-field surface distortion parameters as well as the width of surface zones within which the deformations exceed a set of appropriately selected critical (or allowable) values. A limited number of analyses have also provided results on the effect of fault-structure interaction, indicating that the distortions transmitted to the foundations of common reinforced concrete structures may be reduced by more than 50%, compared to the free-field values. For a bedrock fault of known characteristics, the graphs proposed in the paper can be used 1) for estimating the expected fault-rupture induced damages to existing structures and 2) for designing countermeasures in the case of new structures. The findings of this study can also form the basis for introducing rational seismic code provisions for the design of structures in the vicinity of earthquake faults.

INTRODUCTION

It is known that in several recent strong earthquakes a significant portion of the damage to buildings, facilities and other engineered structures was caused by the ground deformations occurring in the vicinity of ruptured faults (Vallejo and Shettima, 1991, Liang 1995, Wang and Wang, 1995, Desmond et al. 1995, Lazarte and Bray, 1995, Olden, 1996, Gheng and Nuguid, 1996, Lau et al. 1996, Bray 2001, 2005). Thus, it has become evident that when performing earthquake risk analyses, both hazards (i.e. the one from strong motion and the one from fault-rupture) have to be taken into account (Petersen et al. 2004, Kimball and Rizzo, 2006). As shown in Fig. 1 the fault-rupture hazard may be either of type-A (in which the rupture reaches the ground surface and produces a step like free-field displacement field) or of type-B (in which the rupture propagation does not reach the ground surface and generates a field of distributed deformation) (Bray 2001, 2005).

Careful observation of the behavior of engineering structures founded on or in the immediate vicinity of both, dip-slip and strike-slip fault ruptures, has shown that it is possible to device countermeasures against the fault-rupture hazard (Bray 2001, 2005). These countermeasures may be of two types: a) modification of the properties of the soil layer overlying the ruptured bedrock, e.g. by using the reinforced soil technology (Bray et al., 1993) or EPS geofoam inclusions (Tani, 2004) and b) appropriate design of the foundation and/or superstructure elements to make them capable to withstand the distress imposed by ground deformations. In either of the above two types of counter-

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Figure 1. Propagation mechanism of bedrock rupture in overlying soil formation (a) full propagation, (b) partial propagation (adapted from Bray, 2001)

measures the availability of information on the type, peak values and distribution of free-field ground deformations produced by the bedrock rupture propagation, as well as on the fault-structure interaction mechanism, is a prerequisite. Based on the above considerations the importance of studying the propagation of bedrock fault-rupture in overlying soil formations becomes obvious.

The quasi-static ground deformations associated with fault-rupture have been the subject of many studies, following two main directions: 1) assuming elastic half space behavior and trying to predict the fault characteristics from a known stress or deformation field (and vice versa) (Sanford, 1959, Okada, 1985, Feigl and Dupré, 1999, Wang et al. 2003), and 2) assuming a non-linear behavior for the soil formations overlying bedrock and trying to predict the fault propagation characteristics, the ground deformations and their interaction with engineered structures in the vicinity of the fault (Duncan and Lefebvre, 1973, Bray 1990, Bray et al. 1994a, 1994b, Ghaly 1996, Tani 1996, Athanasopoulos and Leonidou, 1996). The latter direction of study has attracted the interest of many researchers, during the last three decades, who are using field observations, physical model testing and computational approaches. The results of field studies and observations have helped to clarify several of the characteristics of normal, reverse and strike slip fault-rupture propagation (Bonilla 1970, Lazarte and Bray, 1995). Many useful insights into the mechanism of fault-rupture propagation have been also obtained through testing of small scale physical models under normal gravity conditions or in the centrifuge (Emmons 1969, Cole and Lade, 1984, Johansson 2004, Roth et al., 1981, CORNELL Project, 2006, QUAKER Project, 2006). Finally, a number of computational studies (using analytical solutions and numerical analyses e.g. Scott and Schoustra, 1974, Roth et al., 1982, Lade et al., 1984, Bray et al., 1994) have shown that a) the most critical soil parameter affecting the rupture propagation is the soil failure strain, ε_f, (obtained from triaxial testing) and b) the propagation height, h_f, of the rupture increases exponentially with decreasing values of ε_f. By utilizing the results of computational studies Bray et al. (1993) have used the values of the angular distortion of ground for the quantitative assessment of the damage potential of affected structures, whereas Athanasopoulos and Leonidou (1996), Leonidou (2000, 2003) and Leonidou and Athanasopoulos (2000), have proposed the utilization of distribution of β values at ground surface as a means for establishing the width B_{cr} of critical zones at ground surface.

The objective of the present study was the use of the finite element method for conducting systematic parametric analyses on the subject of dip-slip fault-rupture propagation in soil formations. The analyses aimed at producing results in a format facilitating the assessment of damage potential to existing structures, the design of countermeasures for new structures and the incorporation of provisions into seismic codes for designing against the fault-rupture hazard. Details on the study are given by Leonidou (2003) and Athanasopoulos and Leonidou (2003).

METHOD OF ANALYSIS

In the present study the propagation of a dip-slip bedrock fault-rupture in an overlying soil formation is analyzed by using the simplified model shown in Fig. 2. In this model a soil layer of constant thickness, H, overlies a horizontal bedrock interface, the left half of which undergoes a forced displacement at an angle α with the horizontal (dip-angle of the bedrock fault). A downward displace-

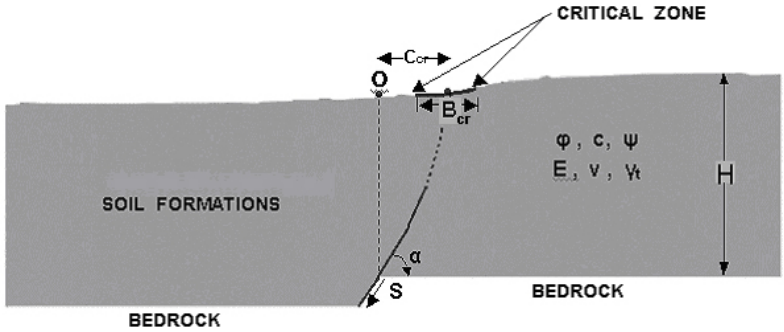

Figure 2. Simplified model for studying the propagation of a fault rupture in soil formations

ment, (or slip), S, simulates the case of a normal fault whereas the case of a reverse fault corresponds to an upward direction of displacement. It is known that the value of slip, S, has been correlated to the magnitude of the design earthquake as well as to the causitive fault dimensions (Walsh and Watterson, 1988, Wells and Coppersmith, 1994). The values of dip-angle, α, used in the analyses, ranged from 45^o to 80^o and from 20^o to 50^o, for the cases of normal and reverse faults, respectively, whereas the magnitude of fault slip, S, was varied from 0.2% to 5% of the thickness, H, of soil formations. The lateral boundaries of the model are assumed to be far enough from the fractured zone in order to avoid the interaction with the propagation of the rupture into the soil material.

The behavior of soil material is assumed to be elasto-plastic (Fig. 3a) following the Mohr-Coulomb failure criterion and described by the friction angle, φ, cohesion c, dilatancy angle, ψ, modulus of elasticity, E, failure strain, ε_f, Poisson's ratio, ν, and unit weight, γ_t. Separate analyses were conducted for purely cohesive and purely cohesionless materials (Fig. 3b), for both normal and reverse faults. In all analyses the strength as well as the stiffness of the soil formations were assumed to increase linearly with depth, with the bottom value being always two times the top value. It may be shown that under the assumptions described above the behavior of soil (either purely cohesive or purely cohesionless) can be adequately described by a single parameter: the normal strain at failure, ε_f. The values of ε_f used in the analyses ranged from 0.5% to 15% and from 0.5% to 5%, for cohesive and cohesionless soils, respectively. Most of the analyses were conducted for "free-field" conditions, i.e. without the existence of any structure in the vicinity of the fault-rupture propagation. A limited number of analyses were also conducted for the case of a surface foundation of finite rigidity with varying values of contact pressure. The results of these analyses were used for comparing the free-field distortions to the distortions transmitted to the foundation, in order to draw conclusions regarding the interaction between the fault-rupture and foundation behavior.

Based on the results of the analyses the following quantities were determined: rupture propagation path, distribution of free-field angular distortions β and horizontal tensile strains ε_{xx} along the ground surface, maximum values of surface distortions, β_{max}, and ε_{xxmax}, and width, B_{cr} (as well as position) of

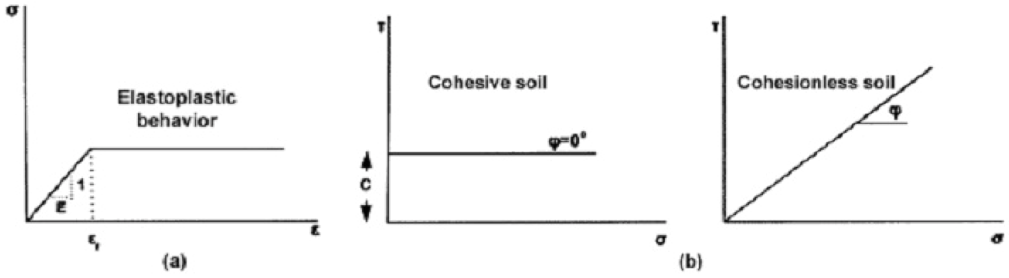

Figure 3. Stress-strain relation and failure envelopes used to describe the behavior of soil materials

critical surface zones, characterized by β and ε_{xx} values exceeding some prescribed allowable level. Several studies during the last fifteen years have shown that the potential of soil deformations to damage shallow foundations can be conveniently described by different combinations of angular distortion and normal tensile strain (Skempton and MacDonald, 1956, Boscardin and Cording, 1979, Wahls, 1981, Burland, 1985, Clough and O' Rourke, 1990, Wahls 1994, Boone, 1996, Potts and Addenbrooke, 1997, Finno et al., 2005, Son and Cording, 2005). Furthermore, it has also been shown that the distortions transmitted to usual shallow foundations by the underlying ground deformations is reduced by more than 50%, compared with the free-field values (Boscardin and Cording, 1979).

The idealized model of fault-rupture propagation depicted in Fig. 2 was numerically modeled by using the finite element code PLAXIS v.7. The meshes used in the analyses were composed of 15-node triangular elements and had a length equal to ten times their height whereas the forced displacement was applied to the left half of the base in 100 steps. Parametric analyses showed that the thickness of the soil layer does not affect the rupture propagation mechanism as long as normalized (with respect to the thickness) values of length dimensions are used. Examples of initial and deformed meshes, used for modeling the propagation of a normal and a reverse fault are shown in Fig. 4.

For each analysis the output files of PLAXIS was post-processed by a specially written Visual Basic Program (FAULT) which was able to produce the following graphical displays:

- Deformed shape of soil layer
- Location of soil yield (and tension) points
- Distribution of angular distortion β and horizontal tensile strain ε_{xx} values along the ground surface as well as location of their maximum values
- Width and position of a critical surface zone in which the values of β and ε_{xx} exceed selected prescribed values, and
- Location of points with maximum values of angular distortion, β_{max}, shear strain, γ_{xymax}, horizontal strain, ε_{xxmax} and vertical strain ε_{yymax}, on a vertical plane.

RESULTS OF ANALYSES

1. Cohesive Soil Formations

The results of an analysis for the case of a normal fault with a dip angle $\alpha=45^o$, soil failure strain $\varepsilon_f=0.5\%$ and a relative slip magnitude S/H=1% are shown in Fig. 5. The distribution of angular

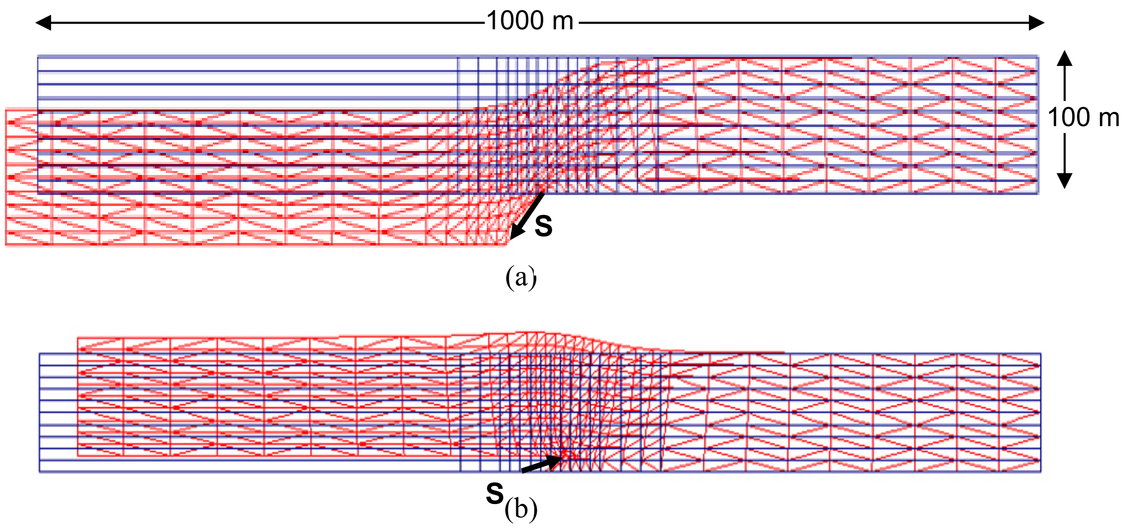

Figure 4. Examples of deformed finite element mesh under the action of forced base displacements (a) normal fault, (b) reverse fault

distortion and horizontal tensile strain values greater than 2‰ with distance are shown in Fig. 5 in grey and red color, respectively. It may be observed that the locations of maximum values of β and ε_{xx} almost coincide horizontally whereas the critical zone of tensile strains falls approximately within the limits of the angular distortion zone. Furthermore, in the graph of Fig. 5 the soil plastic points and the tension points are shown in blue and green color, respectively, providing a rough picture of the rupture propagation path, which in this case reaches the ground surface. However, a more clear picture of the propagation path may be obtained from the diagram of Fig. 6 depicting the location of β_{max}, γ_{xymax}, ε_{xxmax} and ε_{yymax} points on a vertical plane. This diagram indicates that the path of $\beta_{max}/\gamma_{xymax}$ curves coincides with that of their $\varepsilon_{xxmax}/\varepsilon_{yymax}$ counterparts along the entire height of soil layer; in this case the $\beta_{max}/\gamma_{xymax}$ curves are taken to represent the trace of rupture propagation from the bottom to the top of the soil layer. When the pair of $\beta_{max}/\gamma_{xymax}$ curves follows closely the path of the $\varepsilon_{xxmax}/\varepsilon_{yymax}$ pair of curves up to a limited height in the soil layer (and then deviates following a nearly vertical direction) this height is taken to represent the rupture propagation height, h_f. Also, by establishing a best fit straight line to the propagation curves, the mean value of propagation angle, φ_δ, can be determined.

The results of all analyses of the present study for normal faults can be summarized as follows: 1) the relative propagation height h_f/H is a function of relative slip S/H and soil failure strain, ε_f, whereas the rupture reaches the surface only when $\varepsilon_f \leq 3\%$, 2) the average propagation angle of rupture increases linearly with the bedrock dip angle, 3) the maximum value of surface angular distortion increases linearly with S/H, being higher for small values of failure strain, 4) the relation $B_{cr2‰}$ - (S/H) is linear and independent of failure strain, ε_f, up to S/H=1%, and 5) the relative distance C_{cr}/H depends primarily on the dip angle, α.

The results of all parametric analyses for reverse faults showed similar trends as those for the normal faults and may be summarized as follows: i) for increased values of relative vertical slip (S_v/H an additional secondary rupture propagates in a direction opposite to that of the main rupture, generating surface distortion to the left of point O, ii) the propagation height of rupture depends mainly on fault slip magnitude and soil failure strain and it is more difficult in this case for the rupture to reach the ground surface (compared to the normal faults), iii) the mean propagation angle depends mainly on dip angle and increases linearly with the α values, iv) the maximum angular distortion increases linearly with the fault slip magnitude depending also on the soil failure strain values, v) the width of surface critical zone increases linearly with the fault slip magnitude (up to a value of S_v/H=0.5%), and vi) the distance C_{cr} depends on both the fault slip value and its dip angle.

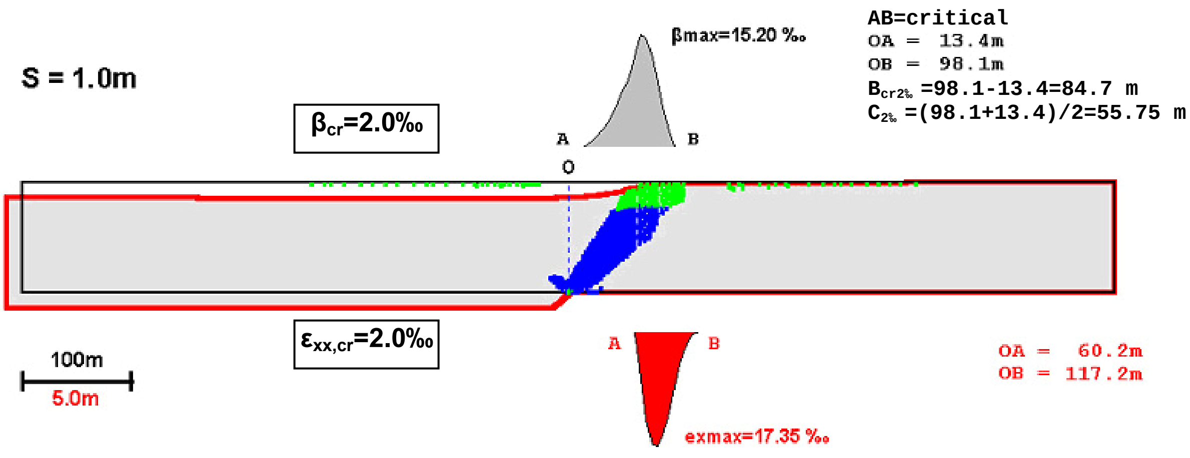

Figure 5. Distribution of angular distortion and horizontal tensile strain values (greater than β_{cr}=2.0‰) along the ground surface: case of normal fault with α=45°, S/H=1% and cohesive soil with ε_f=0.5%

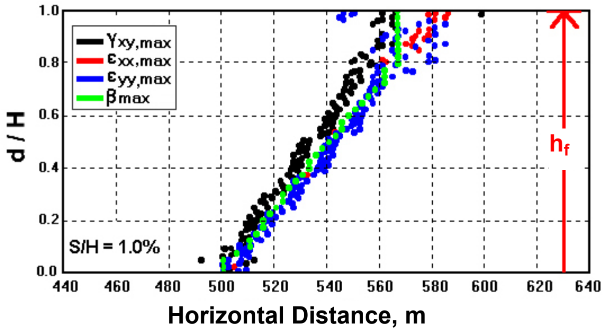

Figure 6. Horizontal and vertical coordinates of maximum values of β, γ_{xy}, ε_{xx} and ε_{yy}

2. Cohesionless Soil Formations

The results of analyses for the case of normal faults indicate that the mechanism of normal fault rupture propagation in cohesionless soils follows the trends found for the case of cohesive soils. In this case a secondary fault rupture (as the one mentioned above) may be propagated and thus makes it necessary to enlarge the overall width of the critical surface zone in order to include both the main and secondary distortion zones. Interestingly, the development of secondary rupture propagation in inhibited by larger dip-angles and increasing soil dilatancy angles.

For the case of reverse faults the analyses indicate that a secondary surface distortion zone–in addition to the main zone which contains the maximum values of distortion–is beening developed for large values of slip magnitude. Additional analyses have also shown that the value of soil dilatancy angle, ψ, has a minor effect on the rupture propagation mechanism.

PREPARATION OF GRAPHS

The results of all analyses conducted in the present study were combined to produce graphs providing information on the mechanism of fault-rupture propagation (for free-field condition) for the cases of normal and reverse faults in both cohesive and cohesionless soils. The information obtained from the graphs includes the mean propagation angle φ_δ, the rupture propagation height, h_f, the maximum angular distortion, β_{max}, and the relative width and location of critical surface zones, B_{cr}/H, C_{cr}/H. The above information can be used in fault-rupture hazard analyses aiming at designing countermeasures or assessing the vulnerability of existing structures in the vicinity of earthquake faults. Examples of the type of graphs are shown in Fig. 7, Fig. 8 and Fig. 9.

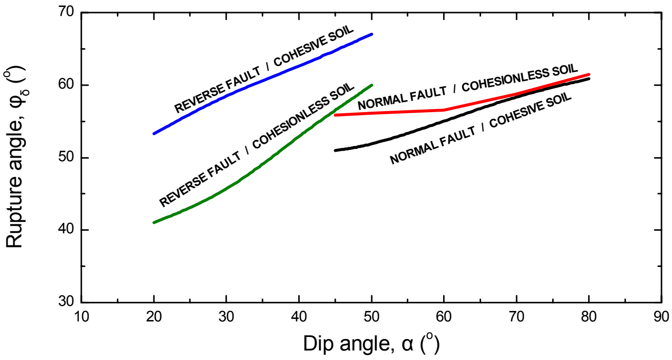

Figure 7. Rupture propagation angle φ_δ for normal and reverse fault rupture in cohesive and cohesionless soils

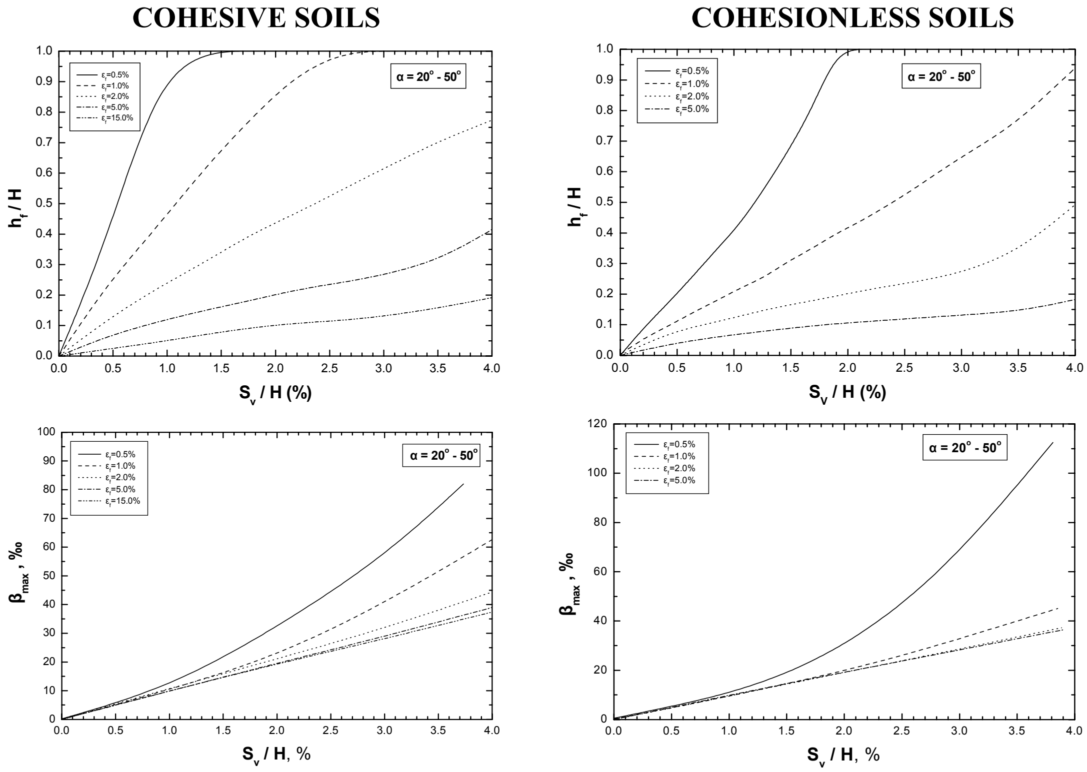

Figure 8. Example of graphs providing h_f/H and β_{max} values for the case of reverse fault propagating in cohesive and cohesionless soils

FAULT RUPTURE – FOUNDATION INTERACTION

The results presented in the previous section were obtained by analyzing the fault-rupture propagation mechanism under free-field conditions i.e. without the existence of any structure in the vicinity of the fault-rupture. However, for practical applications, involving an assessment of the fault-rupture hazard to engineered structures and facilities, it is necessary to have information on the interaction between the fault-rupture and the structure (e.g. Berrill 1983a,b). In the present study a limited number of analyses were conducted to examine the transmissibility of ground deformation – induced by the rupture propagation – to a foundation having characteristics similar to common reinforced concrete foundations. Some representative results of the analyses are shown in Fig. 10 for the case of a reinforced concrete slab having thickness equal to 1.0m and a width, b, large enough (b/H=1) to force the rupture propagation path to emerge at a point underneath the foundation. The results shown in Fig. 10 were obtained for the case of a normal fault with a dip angle $\alpha=50^o$, a relative slip magnitude S/H=3% and a cohesive soil layer with a mean value of cohesion equal to 250 kPa and failure strain $\varepsilon_f=1\%$. The contact pressure in this analysis was taken to be equal to 40kPa. By comparing the free-field case with the case involving the foundation–rupture interaction it is seen that the maximum value of angular distortion transmitted to the foundation mat is reduced by more than 50%, compared to the free-field value. This finding was also verified from the results of additional analyses with varying foundation flexibility and values of contact pressure. Results of a similar study have recently been reported by Yilmaz and Paolucci (2006) for the case of a rigid foundation with a width ratio b/H=1, resting on a cohesive soil layer having strength S_u=100kPa, $\varepsilon_f=1\%$, overlying a bedrock normal fault with a slip magnitude S/H=1.0 and a dip angle $\alpha=60^o$. The similarity of the results of the above investigation with the results of the present study is remarkable.

Based on the above results it is suggested in practical applications to use the graphs presented in the previous sections by selecting allowable distortion values β_{cr} twice or more as large compared to the usual foundation distortion allowable values. In particular, when using the graphs presented in the

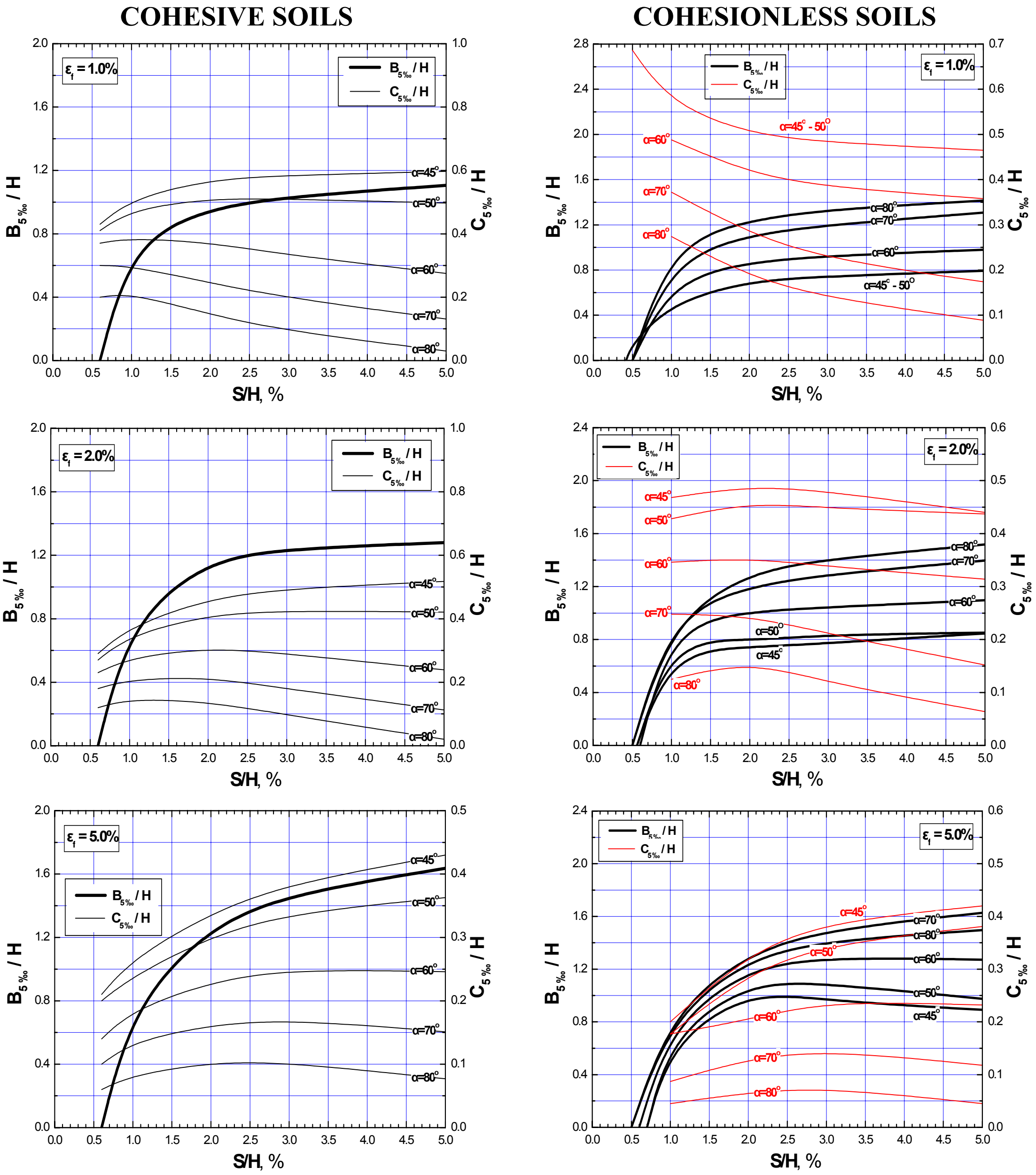

Figure 9. Example of graphs providing $B_{5‰}/H$ and $C_{5‰}/H$ values for cohesive and cohesionless soils

previous section the following critical values of angular distortion, β_{cr}, are suggested for three categories of structures:

Table 1. Suggested values of β_{cr} to be used in combination with the graphs proposed in the present study

TYPE OF STRUCTURE	β_{cr},‰
Sensitive buildings (e.g. monuments)	2
Common reinforced concrete buildings	5
Relatively rigid reinforced concrete structures	10 to 20

VALIDATION OF THE ANALYSIS METHODOLOGY

The validation of the methodology developed in the present study was based on comparisons between the behavior of dip-slip faults reported in the literature and the behavior predicted on the basis of the

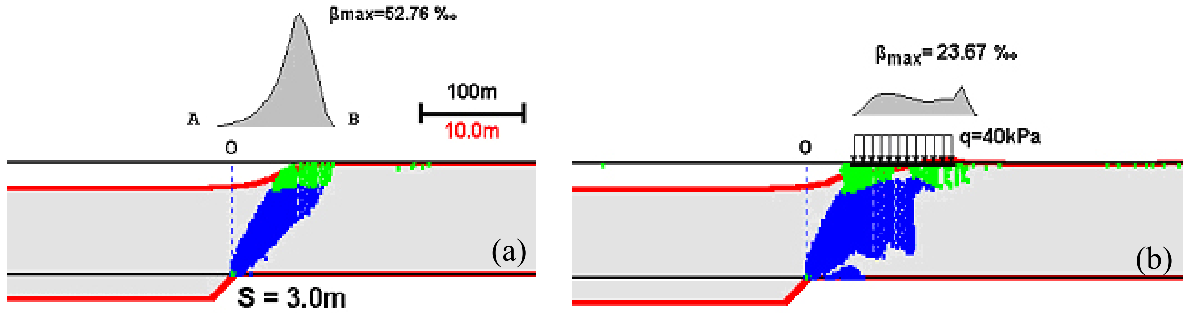

Figure 10. Distribution of surface angular distortion values for the case of a normal fault with α=50°, S/H=3% and cohesive soil (c_u=250 kPa, ε_f=1%) (α) free-field conditions, (b) with a surface foundation

graphs proposed in the paper. More specifically, the comparisons included three cases of dip-slip faults: 1) a case of observed behavior of the Agia Triada normal fault in the city of Patras, Greece (Kalteziotis et al. 1991, Telioni et al. 2006), 2) a case of small scale dip-slip physical model tests (Cole and Lade, 1984, Lade et al. 1984), and 3) a case of computational results obtained by the finite element method for dip-slip faults (Bray 2001, Bray 2005). Due to space limitations the details of the comparisons cannot be included in the present paper. It can be stated, however, that in all comparisons the agreement between the observed and the predicted behavior is considered as being more than satisfactory (Athanasopoulos and Leonidou 2003, Leonidou 2003).

CONCLUSIONS

Based on the results of the finite element analyses of the present study the following conclusions can be drawn:

1. The estimated propagation path of dip-slip faults in soil formations is in good agreement with field observations and physical modeling test results. The development of a secondary rupture propagation is associated with the cases of reverse faults in cohesive soils and both reverse and normal faults in cohesionless soils.
2. The propagation height of fault-rupture increases with the fault slip magnitude and decreases with increasing soil failure strain.
3. The maximum value of surface angular distortion increases linearly with the fault slip magnitude, taking higher values for soils with low failure strain.
4. The width and the horizontal position of a surface zone of critical deformations can be estimated from the graphs proposed in the paper. In the case of the additional propagation of a secondary fault rupture, the width of the overall critical zone should include the critical zones of both the main and the secondary rupture.
5. Soil dilatancy seems to have a minor effect on the results of the analyses of the present study (it reduces the surface distortions, increases the width of the critical zone and inhibits the propagation of a secondary fault rupture).
6. The interaction between the fault-rupture propagation and a nearby structure results in a reduction of the distortions transmitted to the foundation of the structure (compared to the free-field values) greater than 50%. This allows the use of the proposed graphs for determining the expected fault-induced structural deformations.
7. The methodology developed in the present study can form the basis for introducing seismic code provisions for designing structures against the fault-rupture hazard. The required data include the bedrock fault type, size and dip angle, and the thickness, type and failure strain of the overlying soil formations. The proposed graphs can provide an estimate of propagation height of the rupture and the deformations which should be used for the design of appropriate countermeasures or for the assessment of expected damage to existing structures.

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