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SHALLOW FOUNDATIONS OVER RUPTURING NORMAL FAULTS : ANALYSIS AND EXPERIMENTS

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ABSTRACT

Observations in past earthquakes where surface fault ruptures crossed civil engineering facilities have revealed that while many structures collapsed or were severely damaged, some survived the rupture almost unscathed. In a few cases the rupture path appeared to have diverted from its initial position as if to "avoid" the structure. Such observations indicate the existence of an interplay between the outcropping fault rupture, the deforming soil, and the structure. This paper presents a combined analytical and experimental study of this interaction, focusing on shallow foundations over a normal fault rupture. The paper : (i) develops a two-step non-linear finite element methodology to study the propagation of a fault rupture through soil and its interaction with strip foundations, (ii) applies the developed methodology to conduct Class "A" predictions of centrifuge model tests, and (iii) compares numerical predictions with experimental results. Thus, it derives validated insights on the mechanics of the problem. It is shown that a heavily loaded rigid foundation can indeed divert the rupture path substantially, which may avoid outcropping underneath the structure. The latter undergoes rigid body rotation, sometimes loosing contact with the soil. It is concluded that structures in the vicinity of active faults could be designed to survive faulting dislocations of substantial magnitude.

Keywords: Fault rupture, soil-structure interaction, finite element, centrifuge model tests, prediction

INTRODUCTION

The threat of a major seismic fault rupturing underneath a structure is an important part of the earthquake hazard. Lack of understanding of the mechanics of the rupturing process and the limited experience on how structures behave on top of a fault had led to an absolute prohibition of building "in the vicinity" of a fault in all seismic codes [e.g., EC8, 1994]. The term "vicinity" was interpreted differently in various codes, ranging from a few hundred meters to a few kilometers.

However, such a strict prohibition is difficult (and sometimes meaningless) to obey for a number of reasons : (a) It is difficult to reliably determine which of the numerous geologic faults encountered in engineering practice is potentially active in the earthquake sense ; (b) The prediction of the exact location of a fault break-out on the surface is not that straight forward, even when the fault is well-known and mapped ; (c) the location and magnitude of the fault outcrop depends not only on the type and magnitude of the fault rupture, but also on the geometry and material characteristics of the overlying soils ; and (d) the presence of a structure on top of the soil deposit may further modify the rupture path. Depending on the rigidity of the foundation and the surcharge load, even complete

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diversion of the rupture away from the structure may take place. An interplay develops between the fault rupture, the soil, and the foundation. This interplay is crucial for the performance of a structure.

Recent earthquakes have shown that a more optimistic attitude is justified. In the Kocaeli 1999 earthquake, for instance, several simple structures survived with minimal damage a fault dislocation of more than 2 meters (Figure 1). Clearly, the type of foundation and the nature of the supporting soils played a decisive role [Anastasopoulos & Gazetas, 2007 ; 2007b]. Indeed, recent analytical studies [Anastasopoulos, 2005] have shown that a structure on top of the ground interacts with the deforming soil and the outcropping fault rupture. The presence of a structure may lead to a diversion of the rupture path, as the latter propagates to the ground surface, as well as to modification of the surface displacement profile caused by the emerging fault rupture.

The prime objective of the research presented herein is to explore the role of this interaction, both numerically and experimentally. More specifically, this paper : (i) Develops a two-step nonlinear finite element methodology to study fault rupture propagation through soil and its interaction with strip foundations ; (ii) Applies the developed methodology to conduct Class "A" predictions [Lambe, 1973] of centrifuge model tests ; and (iii) Compares analytical with experimental results to derive validated insights on the deeper mechanisms of the problem.

Figure 1. Two story building in Denizevler, east of Gölcük, having survived a tectonic dislocation of almost 2 meters. Observe the diversion of the fault scarp next to the building.

METHODOLOGY

As depicted in Figure 2, we consider a uniform soil deposit of depth H at the base of which a normal fault, dipping at angle α produces downward displacement of vertical amplitude h. Analysis and centrifuge experiments are conducted in two steps. First, fault rupture propagation through soil is analysed in the free-field, ignoring the presence of the structure. Then, knowing the location of fault rupture emergence in the free-field (i.e. ignoring the presence of the structure), a strip foundation of width B subjected to uniform distributed load q is placed at pre-specified distance s relative to the fault outcrop, and the soil-structure system is subjected to tectonic deformation. Centrifuge model tests and numerical analyses are conducted assuming plane-strain conditions. The "offset" is applied to the right part of the model quasi-statically in small consecutive steps.

A special experimental apparatus [El Nahas et al., 2006] was designed and manufactured in the University of Dundee to simulate dip slip faulting and its interaction with strip foundations. Two oil-driven hydraulic cylinders were used to push the right part of the apparatus up or down, to simulate reverse and normal faulting, respectively. A central guidance system and three aluminum wedges were installed to impose fault displacement at the desired dip angle α. Perspex windows were installed at both sides to allow observation of fault rupture propagation. Images of the deformed soil specimen were captured using a digital camera at different bedrock displacements. Vertical and horizontal displacements at different positions within the soil specimen were computed through image analysis, using the Geo-PIV program [White et al., 2003].

A set of centrifuge model tests of fault rupture propagation in the free-field was first conducted. Fontainebleau sand [Gaudin, 2002] was utilised for all the experiments. One such test (Test 12: normal faulting on medium-loose Fontainebleau sand with $D_r \approx 60\%$) was selected as the reference for fault rupture – strip foundation interaction experiments : the location of fault outcropping in the free-field is necessary to define the relative distance s (Figure 2). The specimens were prepared by raining Fontainebleau sand from a specific height with controllable mass flow rate (both affect the density of the prepared sand). Before conducting five of these experiments, Class "A" predictions were conducted. The width of the foundation B was varied from 10 m to 25 m, and the distributed load q from 37 kPa to 91 kPa to explore its effect on fault rupture diversion and modification of the displacement profile. With the exception of one test, all foundations were practically rigid.

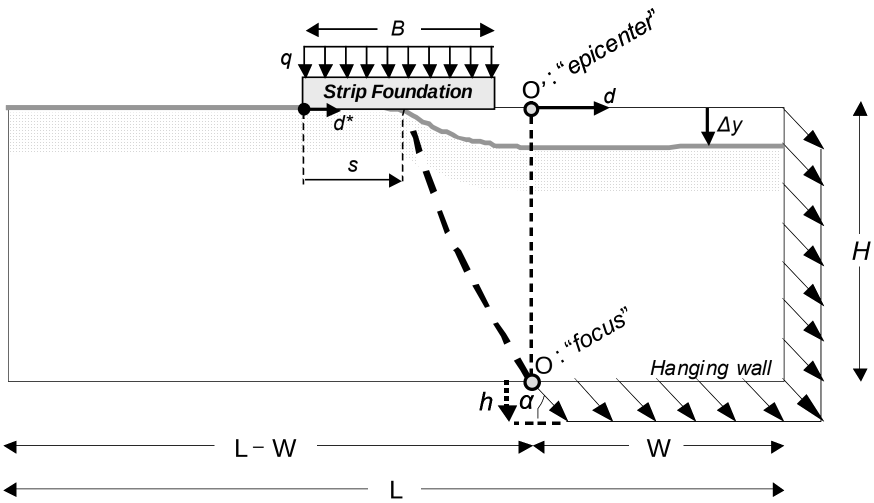

Figure 2. Problem definition and model dimensions : Interaction of normal fault rupture with strip foundation of width *B* subjected to uniform load *q*. The left edge of the foundation is at distance *s* from the point of dislocation outcropping in the free-field.

FINITE ELEMENT MODELING

Attempts to utilise the finite element (FE) method to model the propagation of a fault rupture through soil have been recently reported in the literature. Post-peak soil behavior has been shown to be a decisive factor in fault rupture propagation [e.g. Cole & Lade, 1984 ; Lade et al., 1984]. It has been shown that both the finite element (FE) method [Bray et al., 1994; 1994b] and the finite difference (FD) method [Walters & Thomas, 1982; Roth et al., 1982; White et al., 1994; Nakai et al., 1995; Loukidis, 1999; Erickson et al., 2001] can be successful in simulating fault rupture propagation through soil. A necessary prerequisite is the adoption of a refined mesh [Bray, 1990] and of an appropriate constitutive model of soil.

Following a thorough review of the literature [Anastasopoulos, 2005], a similar elastoplastic Mohr-Coulomb constitutive model with isotropic strain softening was adopted. Strain softening is introduced by reducing the mobilised friction angle φ_{mob} and the mobilised dilation angle ψ_{mob} with the increase of octahedral plastic shear strain.

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

$$\psi_{mob} = \begin{cases} \psi_p \left(1 - \dfrac{\gamma_{oct}^P}{\gamma_f^P}\right) & \text{, for } 0 \le \gamma_{oct}^P < \gamma_f^P \\ 0 & \text{, for } \gamma_{oct}^P \ge \gamma_f^P \end{cases} \tag{2}$$

where : φ_p and φ_{res} the ultimate mobilised friction angle and its residual (or critical state) value, ψ_p the ultimate dilation angle, and γ_f^P the plastic octahedral shear strain at which softening has been completed.

The constitutive model is encoded in the finite element code ABAQUS [2004] through a user subroutine. Model parameters are calibrated through the direct shear test — a test closely mimicking the shearing from a fault. Despite the aforementioned unavoidable non-uniformities, the effect of progressive failure has been shown to be only slight [Potts et al., 1987], allowing the interpretation of test results as quasi-simple shear. Pre-yield behaviour is modeled as linear elastic, with a secant modulus $G_S = \tau_y / \gamma_y$, where γ_y and τ_y the “yield” shear strain and stress, respectively. More details on the calibration methodology are given in Anastasopoulos et al. [2007].

The capability of the modified Mohr-Coulomb constitutive model to reproduce soil behavior has been validated through a series of FE simulations of the direct shear test. The results of such a simulation on Fontainebleau sand have been presented and compared satisfactorily with experimental soil data [Gaudin, 2002] in Anastasopoulos et al. [2007].

FREE–FIELD FAULT RUPTURE PROPAGATION

The consistency of the developed numerical methodology was first verified [Anastasopoulos, 2005] through qualitative comparison with published case histories [Slemmons, 1957; Oakeshott, 1973; Gilbert, 1890; Brune & Allen, 1967; Witkind et al., 1962; Taylor et al., 1985; Barrientos et al., 1985; Stein & Barrientos, 1985] and experimental research [Horsfield, 1977; Cole & Lade, 1984].

The method was further validated through successful Class “A” predictions of centrifuge model tests of dip slip fault rupture propagation through sand in the free field [Anastasopoulos et al., 2007]. A series of centrifuge model tests were conducted in the University of Dundee, as part of a joint European research project (“*QUAKER*”). More details on these tests can be found in El Nahas et al. [2006]. The tests consisted of two normal and two reverse fault ruptures at α = 60^o through dry medium-loose ($D_r \approx 60\%$) and dry medium-dense ($D_r \approx 80\%$) Fontainebleau sand [Gaudin, 2002].

Calibrated through direct-shear test data on Fontainebleau sand with $D_r = 60\%$ [El Nahas et al., 2006], the following model parameters were used : φ_p = 34^o, φ_{res} = 30^o, ψ_p = 6^o, γ_y = 0.03, $\gamma_p^P = 0.06$, and $\gamma_f^P = 0.244$ .In all cases, the numerical modelling technique predicted with reasonable accuracy both the location of fault outcropping and the displacement profile of the ground surface [Anastasopoulos et al., 2007].

At a second stage, knowing the location of fault outcrop in the free-field, the foundation, modeled with linear elastic beam elements, is positioned on top of the soil model and connected to it through special contact elements. The latter are rigid in compression but tensionless, allowing detachment of the foundation from the soil. Whilst positive normal force is transmitted, the interface shear properties follow Coulomb's friction law, allowing for slippage.

Light Foundation (Test 15)

This test refers to a B = 10 m rigid foundation subjected to surcharge load q = 37 kPa, positioned at distance s = 3.0 m. Figure 3 compares the profile of vertical displacement Δy at the surface. The agreement between analysis and experiment is satisfactory for all levels of imposed deformation, from h = 0.4 m to 2.5 m. The analysis predicts correctly the diversion of the rupture to the left of the foundation. The latter experiences significant differential displacement, expressed as rigid body rotation. For h = 2.5 m (experiment: $h \approx 2.46$ m), the analysis suggests that ~0.6 m of the imposed dislocation is converted to rigid body rotation, while the rest ~1.9 m are localised to the left of the foundation. The numerical prediction is successful with respect to the rotation of the foundation.

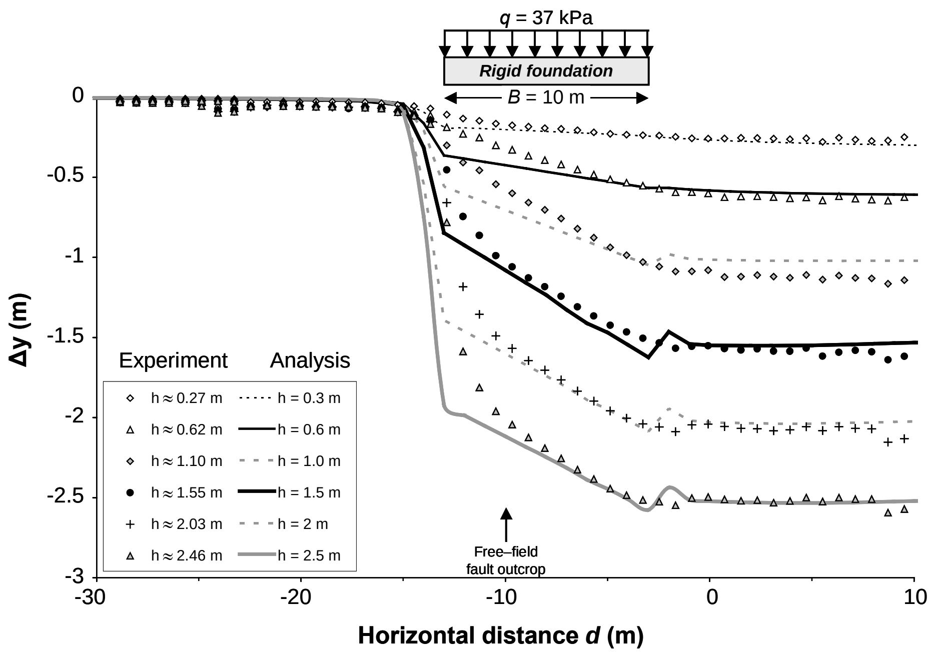

Figure 3. Test 15 – Rigid B = 10 m foundation, subjected to distributed load q = 37 kPa, at s = 3.0 m : Comparison of numerical with experimental vertical displacement at the surface.

Heavy Foundation (Test 14)

This test is practically the same, but with q = 90 kPa. Figure 4 compares experimental with numerical results in terms of vertical displacement at the surface. The agreement is quite satisfactory for all levels of imposed deformation. Flow of sand between the left edge of the foundation and the Perspex window of the experimental apparatus may be responsible for the slight inaccuracies in the centrifuge measurement, and its discrepancy from the analysis near the left edge of the foundation. The FE analysis predicts correctly the diversion of the rupture path to the left of the foundation. While in the free-field (Test 12) the rupture outcrops at d = –10 m, in the presence of the foundation it outbreaks at d = –13 m (i.e. a diversion of ~3 m towards the footwall). Despite this diversion, the foundation experiences significant differential displacement, which is expressed as rigid body rotation. For h = 2.5 m (experiment: $h \approx 2.36$ m), the analysis suggests that about 0.3 m of the imposed dislocation is converted to rigid body rotation, while the remaining 2.2 m are localized to the left of the foundation in the form of a distinct fault scarp. Evidently, the analytical prediction is successful also with respect to foundation rotation.

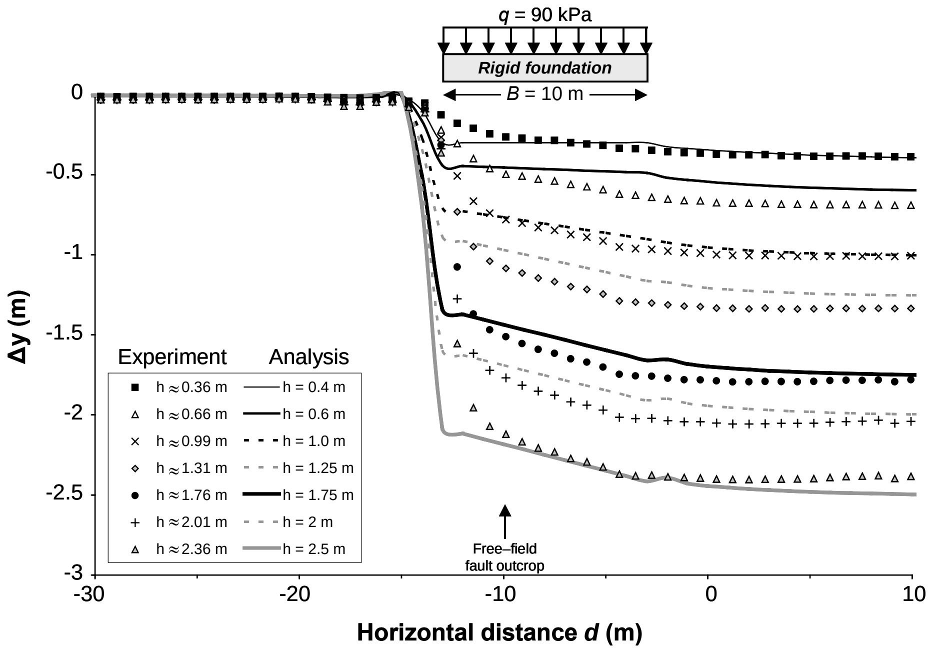

Figure 4. Test 15 – Rigid *B* = 10 m foundation, subjected to distributed load *q* = 90 kPa, at s = 2.9 m : Comparison of numerical with experimental vertical displacement at the surface.

Wide Foundation (Test 20)

This test refers to a B = 25 m rigid foundation subjected to almost the same surcharge load (q = 84 kPa), at s = 10.5 m. Model test images are compared to FE deformed mesh with shear strain contours in Figure 5. Initially, for $h \approx 1.23$ m, a steep rupture zone *S1'* propagates almost half the way to the surface. *S1'* corresponds to the free-field *S1* (Test 12), but is significantly diverted towards the hanging wall. Additionally, while *S1* did propagate up to 2/3 of H, *S1'* cannot propagate higher than 0.5H. The analysis does not predict such a steep initial rupture zone. Instead, for h = 1.25 m, a less steep rupture is about to emerge beneath the center of the foundation. At the same time, a second rupture starts forming at the left edge of the foundation, propagating from top to bottom. This second rupture starts becoming visible in the experiment image for $h \approx 1.52$ m : rupture *S2'* makes its appearance just to the left of the foundation. It can be seen to correspond to *S2* of Test 12 (free-field), but strongly diverted by ~10 m towards the footwall. The numerical prediction, for h = 1.5 m, agrees with the experiment. However, while in the centrifuge model test shear strain tends to accumulate along *S2'*, the analysis reveals stronger strain localization along *S1'*. Further increase of h to 2.0 m (experiment: $h \approx 1.99$ m), leads to deformation localization along *S2'*.

The comparison of experimental with numerical vertical displacement at the surface (Figure 6) strengthens the validity of the numerical method. The comparison between numerical analysis and centrifuge model test is satisfactory for all levels of imposed deformation. The foundation experiences significant rotation. For h = 2.0 m (experiment: $h \approx 1.99$ m), the analysis suggests that all of the imposed bedrock dislocation is converted to rigid body rotation. Evidently, the numerical prediction is successful with respect to the rotation of the foundation.

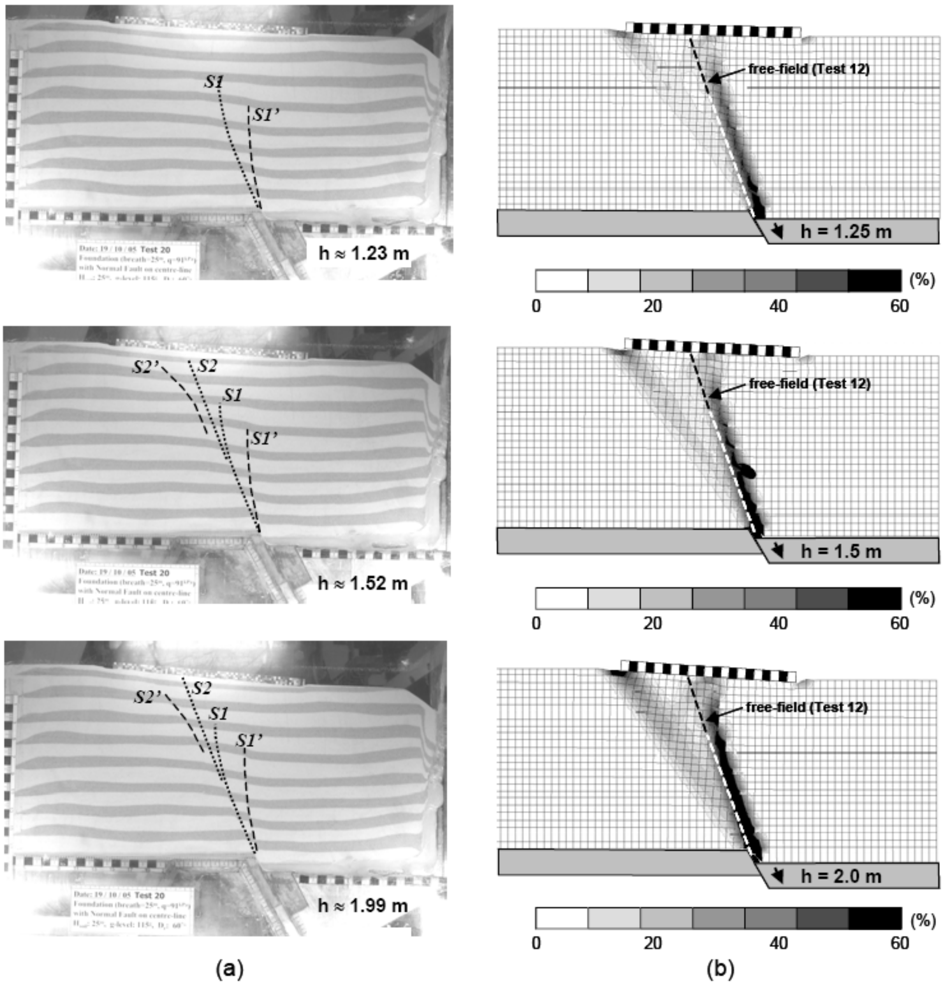

Figure 5. Test 20 – Rigid *B* = 25 m foundation, *q* = 84 kPa, at s = 10.5 m : (a) Centrifuge model test images, compared to (b) FE predicted deformed mesh with shear strain contours.

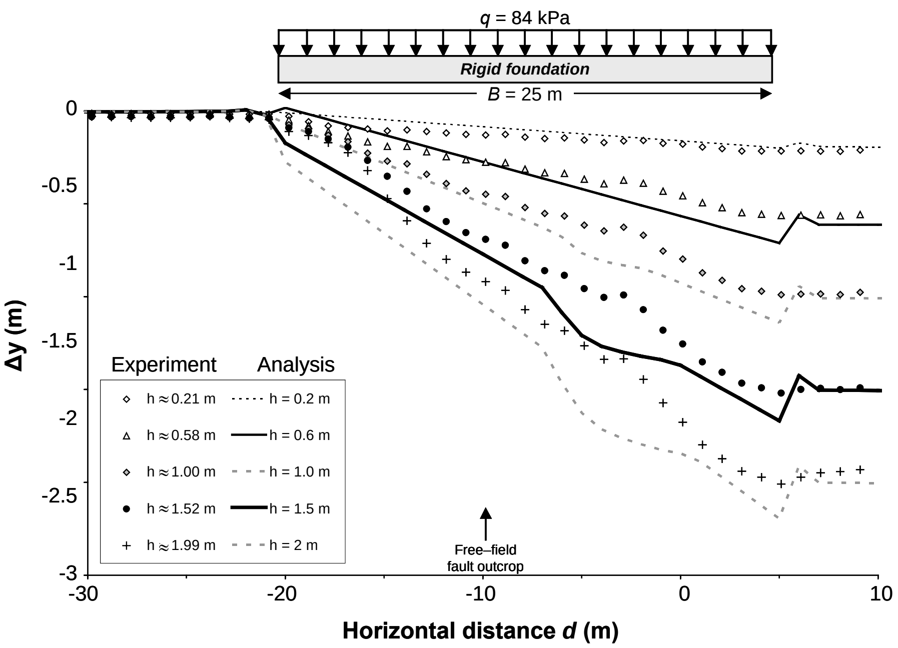

Figure 6. Test 20 – Rigid *B* = 25 m foundation, subjected to distributed load *q* = 84 kPa, at s = 10.5 m : Comparison of numerical with experimental vertical displacement at the surface.

CONCLUSIONS

The main conclusions of the study presented herein are as follows :

1. A "heavily" loaded strip foundation can divert the fault rupture substantially. The increase of the distributed load *q* leads to a more intense diversion of the outcropping fault rupture. The dislocation may be diverted either towards the hanging wall or towards the footwall, depending on the relative location the free-field fault outcrop.
2. Despite the diversion, the foundation experiences significant differential displacement, expressed as rigid body rotation. As summarised in Figure 7, the rotation of the foundation is a function of the distributed load *q*, its width *B*, and the distance *s* to the free-field fault outcrop.
3. The numerical methodology presented herein was validated through comparison of Class "A" predictions with results of five centrifuge model tests. The developed modelling technique predicted with reasonable accuracy: (i) the diversion and/or bifurcation of the outcropping dislocation, (ii) the displacement profile at the ground surface, and (iii) foundation rotation. The agreement between numerical predictions and experimental results strengthens the validity of the derived conclusions.
4. Structures in the vicinity of active faults can be designed to withstand tectonic dislocations. This paper provides combined numerical and experimental evidence indicating that fault rupture diversion is possible, provided that *q* is large enough. However, it must be stressed that the stressing of the foundation is sensitive to the distance *s* to the free-field fault outcrop. Thus, when designing a foundation against fault-induced deformation, *s* must be varied parametrically.

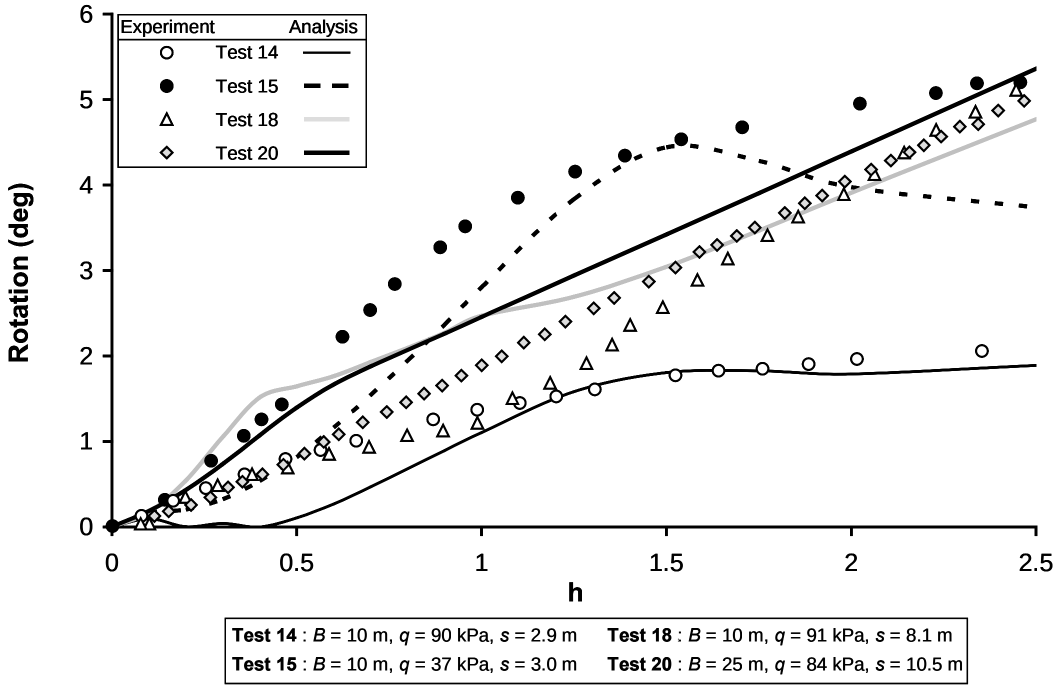

Figure 7. Summary of results : comparison of FE predicted and experimentally measured foundation rotation.

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