Closure to "Fault Rupture Propagation through Sand: Finite-Element Analysis and Validation through Centrifuge Experiments" by I. Anastasopoulos, G. Gazetas, M. F. Bransby, M. C. R. Davies, and A. El Nahas

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On behalf of the authors, the writer thanks the discusser for his interest in the paper, for presenting results from his own research, and for opening up the discussion on the importance of proper soil modeling in finite-element (FE) simulation of fault rupture propagation through soil.

The main goal of our research (presented in the discussed paper) was to develop a *validated* analysis methodology to study the phenomenon of fault rupture propagation from the base rock to the ground surface and its effect on structures. The developed methodology (Anastasopoulos et al. 2007) was validated through successful Class A predictions of centrifuge model tests that had been conducted in the University of Dundee. (The prediction had been posted in the appropriate University of Dundee site and the tests followed.) Then, the methodology was used to conduct a parametric analysis of the effects of dip-slip faulting. Emphasis was given on response parameters of engineering significance, such as: (1) the required bedrock displacement (dislocation) for the fault to outcrop; (2) the location where outcropping will occur; (3) the height of the fault scarp once the fault outcrops; and (4) the vertical displacement profile along the ground surface. The methodology developed in the discussed paper was later employed to analyze the response to dip-slip faulting of strip foundations and foundation–structure systems (Anastasopoulos et al. 2009), which was the ultimate goal of our research. Analytical Class A predictions were again compared to centrifuge model tests, revealing an also quite good accord.

The discusser, who has conducted similar research on the subject (Athanasopoulos and Leonidou 1996, 2003; Athanasopoulos et al. 2007), compared his results with the analytical and experimental results by the authors. Basing apparently his judgment on the similarity between all analyses and experiment in terms of the *total ground offset*, the discusser claimed that he could also achieve an excellent agreement with the experiments even if his modeling did not incorporate the strain softening of the soil. Thus, the discusser questioned the necessity of a refined FE model with strain softening capability for the soil.

Yet, a closer look in the deformation of the ground surface reveals a logical flaw in these claims: the total ground offset is *an imposed boundary condition*, not a response variable! It is not computed but externally imposed. Even an extremely crude FE discretization (e.g., with 10 m × 10 m elements) would have produced the correct free-field downward displacement of the hanging wall ($\Delta_y = h$). What is needed is to predict the (detailed) *shape* of the ground surface deformation, as well as the conditions under which the fault will outcrop. It will be shown below that a simplified Mohr-Coulomb model, such as the one used by the discusser, is not at all capable of adequately (let alone realistically) predicting the shape of surface deformation. And what is even more significant for an engineer, it cannot predict the effect of the fault rupture on structure–foundation systems founded along the path of the fault rupture. The focus will be on showing that strain softening is indeed crucial for a realistic simulation of fault rupture propagation through soil and its interaction with overlying structures. It is hoped that the following presentation will shed some light on crucial computational aspects of the problem, which in the paper were only briefly outlined.

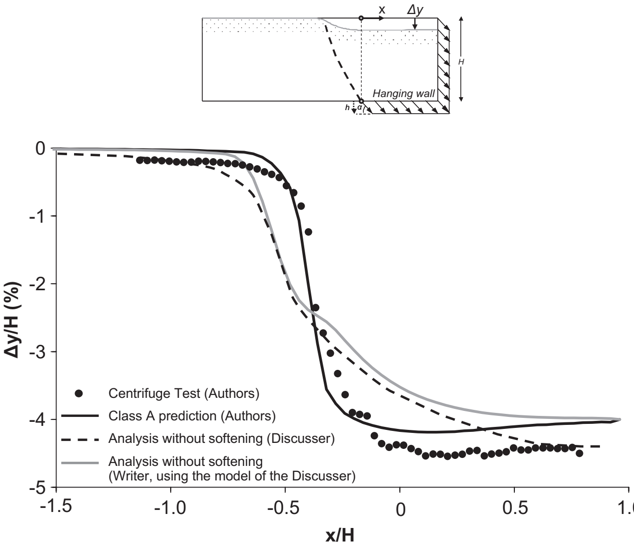


Fig. 1. Test 12: normal faulting at 60°, soil with $Dr = 60\%$

Free-Field Fault Rupture Propagation

To illustrate the main differences between the two modeling methodologies, we focus on the comparison provided by the discusser. It refers to normal faulting, emerging on the basement rock at $\alpha = 60°$, and propagating through a stratum of medium-loose ($D_r = 60\%$) Fontainebleau sand (Test 12 in the discussed paper). The thickness of the stratum, H, is 25 m. As discussed in our paper, soil parameters ($\varphi_p = 34°$, $\varphi_{res} = 30°$, $\psi_p = 6°$, $\gamma_y = 0.03$, $\gamma_p^P = 0.06$, and $\gamma_f^P = 0.244$) were obtained on the basis of direct–shear test data on Fontainebleau sand with $D_r = 60\%$ [El Nahas et al., 2006]. It should be stressed, that for $D_r = 60\%$ the Fontainebleau sand exhibits softening behavior, especially at the small stress levels of main interest (near the ground surface).

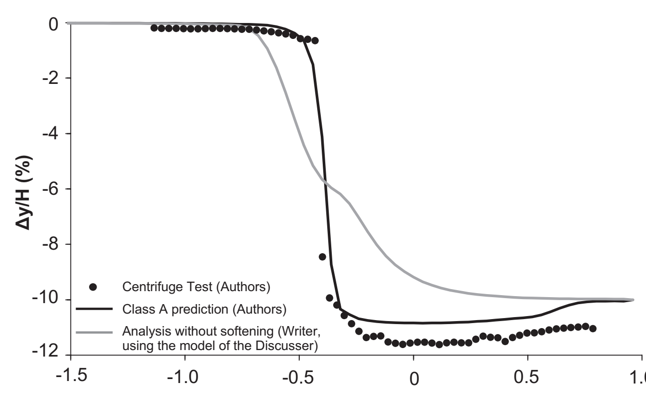


Fig. 2. Test 12: normal faulting at 60°, soil with $Dr = 60\%$

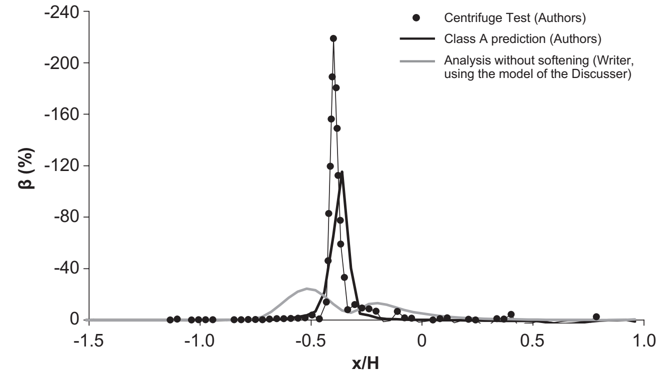


Fig. 3. Test 12: normal faulting at 60°, soil with $Dr=60\%$

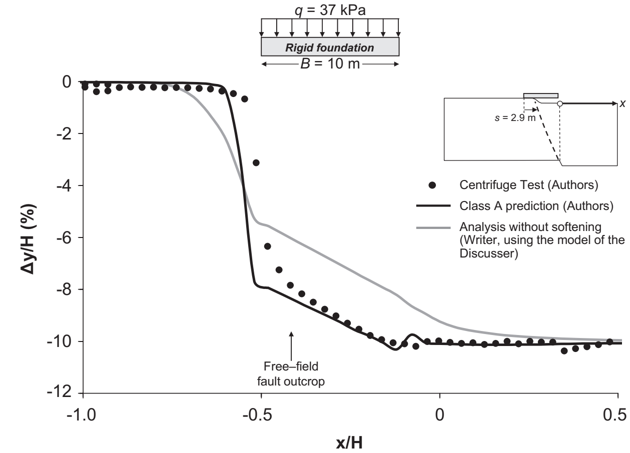


Fig. 4. Test 15: rigid $B=10$ m foundation with superstructure load q =37kPa, at $s=2.9$ m

The comparison is conducted for a vertical component of bedrock downward displacement $h=0.04H$, (i.e., in normalized form $h/H=4\%$ [Discusser: 4.4%]). Fig. 1 depicts the comparison in terms of the nondimensional vertical displacement $\Delta y/H$ of the ground surface. Centrifuge test results and the analytical Class A predictions of the paper are compared with (1) the results obtained by the discusser; and (2) new results obtained with a simplified Mohr-Coulomb model *without post-peak strain softening* (i.e., using a soil model similar, if not identical, to that of the discusser).

A first obvious conclusion is that the results of the writer using the simplified model (without softening) are in very good agreement with the results of the discusser. Some minor discrepancies are attributable to the difference in the numerical FE code: PLAXIS with triangular elements (discusser) versus ABAQUS with quadrilateral elements (writer). A second conclusion is that the simplified models predict reasonably well the location of fault outcropping (although as it will be shown later, some discrepancies *do* exist). In stark contrast, however, the vertical surface displacement profiles of the simplified models appear dramatically different from the centrifuge test results and the Class A prediction given in the discussed paper. While the analysis with post-peak strain softening captures correctly the localization of the deformation within a narrow zone, this is far from being achieved with the simplified models (without strain softening).

To further elucidate the discrepancies, we present the results for a larger bedrock offset $h/H=10\%$ (Fig. 2). Centrifuge experimental results and theoretical Class A predictions, already presented in the discussed paper, are compared with results obtained by the writer, employing a simplified model without softening (similar to the model of the discusser). Evidently, the discrepancies are now even more pronounced. As also revealed by the angular distortion β along the surface (Fig. 3), the centrifuge results exhibit a localized deformation zone of width $0.13H$ (i.e., 3.25 m), approximately. The numerical Class A prediction yields a somewhat wider zone, of width $0.18H$ (i.e., 4.5 m), but still the localization is evident. By contrast, the analysis with the simplified model (without softening) yields an unrealistically wide deformation zone of width $0.96H$ (24 m). In addition, the location of fault outcropping (defined as the point of maximum ground slope, β) is also different: while the centrifuge test indicates fault outcropping at $x/\mathrm{H}=-0.4$ and the Class A prediction (with strain softening) at $x/\mathrm{H}=-0.37$, the analysis by the writer using the simplified model (without strain softening) yields $x/\mathrm{H}=-0.52$. (But this is perhaps a smaller error than the error in ground slope.)

Soil–Structure Interaction

As previously discussed, the ultimate goal of our research has been to analyze the interaction between a rupturing fault and various overlying structure–foundation systems (Anastasopoulos and Gazetas 2007; Anastasopoulos et al. 2009). To further illustrate the importance of post-peak strain softening, we present the comparison in terms of $\Delta y/H$ for the case of a rigid $B=10$ m foundation with a uniformly distributed superstructure load q =37 kPa, subjected to normal faulting that would have emerged at a distance $s=2.9$ m from the corner of the foundation, if the latter had no effect on the rupture (Test 15 of the paper).

In Fig. 4, the centrifuge test results and the Class A prediction of the paper (Anastasopoulos et al. 2009) are compared to analysis by the writer, employing a simplified Mohr–Coulomb model without softening (similar to the model of the Discusser). The comparison is shown for bedrock offset $h/H=10\%$. Evidently, while the "rigorous" model that takes account of strain softening (Class A prediction) captures correctly the response of the foundation, the simplified model does not. Fig. 5 illustrates the comparison in terms of a centrifuge model test image [Fig. 5(a)] compared to FE deformed mesh with superimposed plastic shear strain contours [Figs. 5(b and c)]. While the Class A prediction of the paper [Fig. 5(b)] is in very good agreement with the experiment, the predicted deformation using the simplified model without softening [Fig. 5(c)] is substantially different: the shear zone is very diffused, not localized as in the centrifuge experiment.

To further elucidate the quantitative and even qualitative differences that stem from the two models, we analyze the same B =10 m rigid foundation with a uniformly applied pressure q =20 kPa (lighter superstructure), subjected to a base dislocation of vertical component $h=2.0$ m, from a normal fault rupture propagating through idealized dense sand, and emerging at distance $s=1$ m. Fig. 6 illustrates the comparison in terms of deformed mesh with superimposed plastic strain contours. In the complete analysis, which properly simulates strain softening [Fig. 6(a)], the rupture is diverted and outcrops on the left edge of the foundation. It is localized within a narrow band. As a result, the foundation experiences loss of support near its middle. In contrast, our analysis with the simplified model (without strain softening) predicts a very diffuse and unrealistically wide deformation zone, which does not lead to any loss of support.

In Fig. 7 we extend this comparison in terms of the normalized

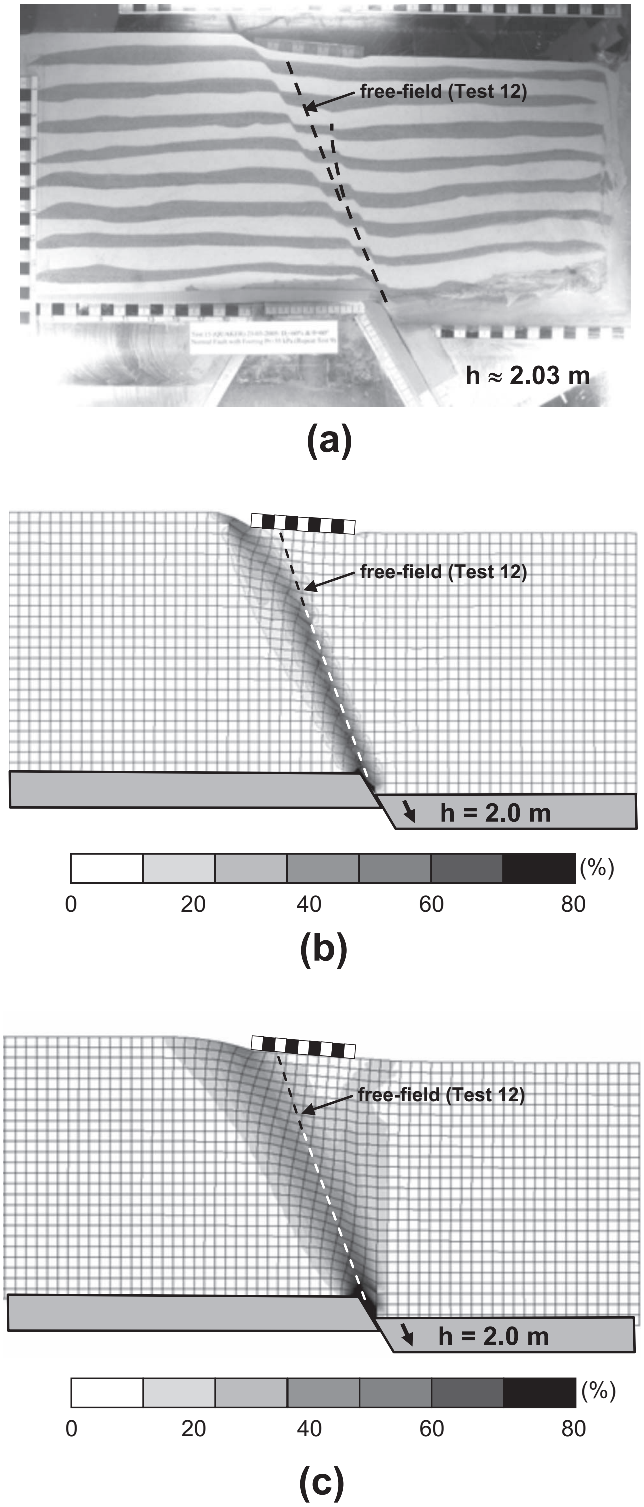


Fig. 5. Test 15: Rigid $B=10$ m foundation with superstructure load $q=37$ kPa, at $s=2.9$ m: (a) centrifuge model test images reported by the authors compared to (b) Class A prediction (FE deformed mesh with shear strain contours) by the authors (model with strain softening); and (c) new analysis results (FE deformed mesh with shear strain contours) by the writer

foundation bending moment M/M_o, where M_o is the maximum static bending moment for $h=0$ (i.e., before imposing the fault dislocation). The value $M_o=0.015qB^2$ is also given in the figure. The normalization with M_o is a direct way to illuminate the difference between the tectonically induced distress of the foundation, and its static stressing due to the surcharge load q. We observe that while the rigorous analysis (with strain softening) predicts *sagging* deformation, with $M/M_o \approx 6$, the simplified model (without softening) predicts *hogging* deformation, with $M/M_o \approx -2.5$. In other words, not only does the simplified soil model underestimate the foundation structural stressing, but it also produces bending in the opposite direction!

Finally, Fig. 8 provides a sketch illustrating the qualitative difference between the two models. With the model that takes

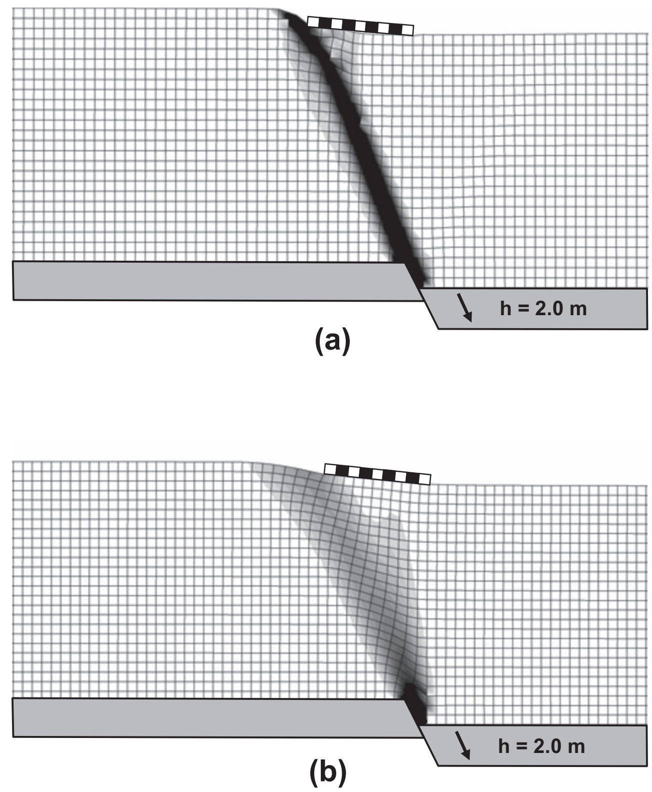
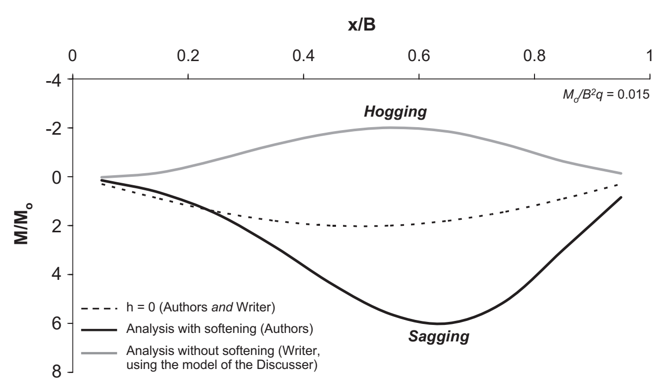


Fig. 6. Analysis of rigid $B=10$ m foundation with superstructure load $q=20$ kPa, subjected to $h=2$ m normal faulting ($\alpha=60°$) through idealized dense sand, at $s=1$ m. Deformed mesh with superimposed plastic strain contours for: (a) analysis with strain softening by the authors, compared to (b) analysis by the writer, employing a simplified model without softening.



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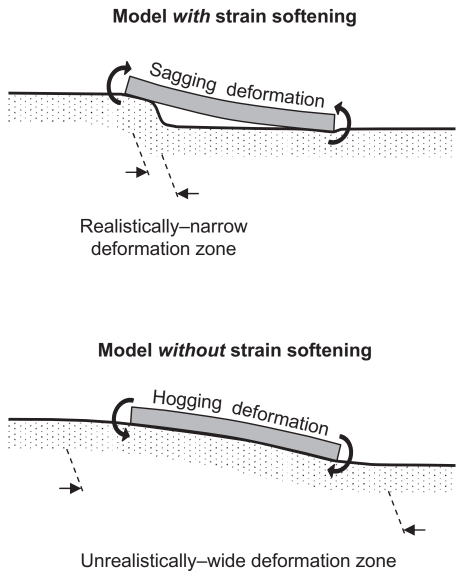

Fig. 8. Sketch illustrating the qualitative difference between the two models

account of strain softening, the predicted deformation zone is *realistically narrow*, leading to loss of support under the middle of the foundation, and producing *sagging* deformation. In stark contrast, with the simplified model (without strain softening) the deformation zone becomes *unrealistically wide*: no loss of support takes place, and the foundation is subjected to *hogging* deformation.

Scale Effects and Grain Crushing

As discussed in the paper, scale effects are incorporated in the developed FE model only in an approximate manner. With reference to the issues addressed by the discusser, we would like to point out the following:

1. In centrifuge model tests, the geostatic stress field is realistic, and therefore the friction and dilatancy angles are not overestimated. This could be the case in small-scale (1 g) tests in which the friction and dilatancy angles may be substantially larger due to particle interlocking, etc.
2. For *grain crushing* phenomena to take place, large stresses combined with large shearing speeds are required (Sassa 1994; Gerolymos and Gazetas 2007). In fact, Sassa (1994) developed a high-speed ring-shear apparatus to test soil specimens under such conditions (shearing speeds in the order of 0.3 m/s). Referring to the centrifuge tests used in our research, although such phenomena cannot be completely excluded, they constitute a rather remote possibility and—in any case—are very unlikely to be of measurable significance (due to the quasistatic nature of offset application, i.e., very small shearing speeds).

Conclusion

In conclusion, although a simplified model without strain softening may in some favorable cases capture some aspects of the problem (such as the location of fault outcropping), *it cannot achieve the observed localization of deformation within a realistically narrow zone*. Note that the comparisons presented herein refer to medium loose sand, in which the softening behavior is not highly pronounced. In dense sand, where the softening behavior is prevailing (see Fig. 5 in the original paper), the discrepancies can become even more dramatic. Note that this inadequacy had been demonstrated since 1974 by Scott and Schoustra (1974): using the FE method and an elastic-perfectly plastic constitutive soil model with Mohr-Coulomb failure criterion, they produced results contradicting reality and experiments. Most importantly, such simplified models cannot even qualitatively capture the stressing of a foundation mat due to faulting, not only leading to *gross underestimation of bending moments*, but also often failing to predict the mode of deformation: *hogging* versus *sagging* (see Fig. 8). As it has also been demonstrated by several other researchers (Bray 1990; Bray et al. 1994a,b; Roth et al. 1982; Loukidis 1999; Erickson et al. 2001; Papadimitriou et al. 2007), for a realistic simulation of fault rupture propagation through soil, *strain softening is absolutely mandatory*.

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