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NUMERICAL AND PHYSICAL MODELING OF REVERSE FAULT PROPAGATION

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Abstract. Regions subjected to greater geological activity can induce faults, through sedimentary deposits, to the surface of the seabed, affecting structures sensitive to loss of support, especially direct foundations, piles and pipelines. In the case of a pipeline design crossing an area with geological and geotechnical threats, there are two options: (1) change the route, which can represent a significant increase in costs; or (2) allowing the pipeline to cross through the fault with proper design and understanding of the expected fault movement. Surface fault rupture case histories provide valuable insights regarding the response of soils to underlying bedrock fault movements. The current studies for understanding the phenomena of faults propagation are mostly concentrated in dry non-cohesive granular soils. Therefore, the present work aims to investigate the mechanisms of reverse fault propagation in loose sand through numerical analyses using the finite element method (FEM). The elastoplastic Mohr-Coulomb constitutive model has been adopted. The numerical results obtained from *ABAQUS* and *Plaxis 2D* were qualitative compared with those from the literature. This work is part of a research project to carry out centrifuge and numerical modeling of fault propagation in offshore seabed. The results obtained through ABAQUS were quite helpful in the design and planning of the centrifuge tests. The analyses undertaken varied the vertical bedrock displacement (U) at the base up to 20% of the soil layer thickness in order to understand their effect on the fault propagation and ground deformation using the geotechnical drum centrifuge at COPPE-UFRJ. Results were compared and conclusions were drawn on the most suitable software to be used for the present studies.

Keywords: Reverse Fault Propagation, Finite element method, Sand.

1 Introduction

The behavior of alluvial deposits subjected to rock base fault displacement is one of the main problems for structures designed in the fault region (Takemura et al. [27]). Understanding the propagation of faults in sedimentary soils is very important to assist in the decision-making process of structural engineering projects such as buried pipes, bridges, tunnels and buildings, which might be situated in an active or potentially active fault zone.

Displacements and disturbances caused by propagation of normal and reverse faults have already caused numerous losses of life and damage to structures. Many studies have been conducted to understand this phenomenon.

The research of the fault propagation phenomenon in soil deposits begins with the field studies of Slemmons [25] and Oakeshott [18]. They investigated the effects of the normal fault on the 1954 Dixie Valley-Fairview Peak earthquake in Nevada. They concluded that normal fault tends to become more vertical and diffuse as it approaches the surface, and that soft and deformable soils can absorb relative fault-induced displacement, converting it to distributed differential settlement of the soil surface.

The objective of this work is to investigate the mechanisms of fault propagation induced by geological movements through reverse fault displacements in loose sandy soils. Thus, numerical modeling was performed using the finite element method in ABAQUS and Plaxis 2D. These results gave important information to the conception and design of the centrifuge modeling set-up to be performed in the COPPE mini drum centrifuge.

2 State-of-the-art

Lately, seismic engineering studies have focused on analyzing the dynamic response of soils and the effects of soil-structure interaction in the occurrence of strong seismic events. This is because seismic waves reach long distances affecting large areas, while fault movement is important only when the fault propagation reaches the ground surface.

Published works are divided into numerical modeling and physical modeling. Within the experimental studies there are those that use 1g scaled models and tests on geotechnical centrifuges. Kelson et al. [13], Dong et al. [9], Cole Jr and Lade [8], Bray et al. [4], Lin et al. [15], Ahmadi et al. [1] performed 1g experimental models to evaluate the development of fault movement in the overlying soils. Roth et al. [22], Ng et al. [17], Cai and Ng [6] developed centrifuge models to analyze the propagation of faults in alluvial soils, as well as the zone of influence and deformation on the soil surface.

2.1 Numerical Modeling

The study of soil fault propagation through numerical modeling began with Bray et al. [5]. The authors analyzed the failure behavior in normally consolidated clays through a finite element analysis using Duncan's nonlinear hyperbolic constitutive model. They recommend the adoption of a refined mesh in the failure region and the use of a nonlinear constitutive model for FEM analysis.

Loukidis et al. [16] and Ng et al. [17] used the finite difference method (FDM) with an elastoplastic constitutive model based on Mohr-Coulomb rupture criterion with the insertion of post-peak softening. Similar constitutive models have been successfully employed to model embankment and slope failure in hard clays. Potts et al. [19], Potts et al [20], Scott and Schoustra [24] used the finite element method and an elastic perfectly plastic model with Mohr-Coulomb rupture criterion and compared the experimental results with real cases.

However, when dealing with stiffer or denser soils, softening needs to be implemented to properly reproduce the fault propagation mechanism as stated by Roth et al. [23], Potts et al. [19], Anastasopoulos et al.[2], Loukidis et al. [16].

2.2 Centrifuge Modeling

Interest in the study of faults through physical modeling began in the 1980s, mainly related to the identification of the shape, zone and location of fault propagation in overconsolidated soils caused by normal and reverse failure Takemura et al. [27]. Roth et al. [22] undertake the first centrifuge model tests of this problem in alluvial soils using a fault simulation actuator in a small Caltech centrifuge. The results showed that the fault displacement rate can affect the surface failure shape and location.

Stone and Brown [26], White et al. [29] analyzed the influence of particle size on centrifuge tests using a trapdoor system. Another aspect studied was the post-peak behavior of the soil, since it proved to be a decisive factor in the propagation of soil failure (Cole Jr and Lade [8], Lade et al. [14]).

In 1999 several earthquakes occurred in Taiwan and Turkey. Anastasopoulos and Gazetas [2], Lin et al. [15] describe the behavior of the faults that reached the surface and highlighted the structures that were affected. El Nahas et al. [10] developed a centrifuge model capable of reproducing normal and reverse fault using a triangular shaped block as a base, supported by two hydraulic cylinders. Such apparatus was used for the studies by Anastasopoulos et al. [3], which compared the results of numerical modeling with centrifuge modeling.

Takemura et al. [27] developed a model to study the influence of buried pipe failures. Ng et al. [17] and Cai and Ng [6] developed a normal centrifuge fault simulator to assess the effect of pre-existing faults on the propagation and deformation mechanism of cemented and non-cemented clays.

3 Development of the fault simulator in the drum centrifuge

The COPPE geotechnical centrifuge (Gurung et al. [12]) is a 1.0 m diameter mini-drum manufactured by APV Baker, UK, under the direction of G-Max, Scotland in 1995 (Figure 1). The whole machine is about 1.7 m in length, width and height, weighing 4.1 ton. The face plate where the instrumentation is housed is 0.7 m in diameter. The channel is capable of rotating at 900 rpm (450 g) carrying a 200 kg payload, which means a full load capacity of 90 g-ton. The centrifuge is provided with a tilt mechanism, activated by means of an electrical motor, to facilitate model preparation, allowing rotation to start with the axis located either in a horizontal or vertical inclination. It also comprises 20 slip rings, with half of them used for power connections and the other half for signal connections, 16 data acquisition channels, a linear actuator and a turntable upon which the linear actuator is mounted.

A new actuator system was designed for the fault simulation proposed in this work. In order to avoid handling a large amount of soil, it was decided not to use the whole centrifuge channel. A 230 mm wide and 180 mm high strongbox was adopted instead (Figure 2). According to Roth et al. [22] the model width should be at least equal the soil depth to reduce boundary effects. The length of the model was maximized to 300 mm. A numerical modeling was developed to verify boundary effects of the box dimensions and validate the centrifuge modeling. The box was divided in two parts by an acrylic wall which allows the visualization of the soil mass movements and the application of a particle image velocimetry analysis. Three GoPro cameras were placed in one side of the box for image acquisition of the whole test.

A servo-hydraulic actuation system was adopted to generate the fault, raising (reverse fault) or lowering (normal fault) half of the soil contained in the box, while the other half remains stead. The soil is drive by means of a moving platform which is placed above the hydraulic actuator. The hydraulic system was chosen since this kind of mechanism is capable of dealing with a larger amount of load when compared to pneumatic or mechanical systems. Two vertical track rail linear guides were placed on the box side wall to stabilize the moving platform displacement and make it as smooth as possible.

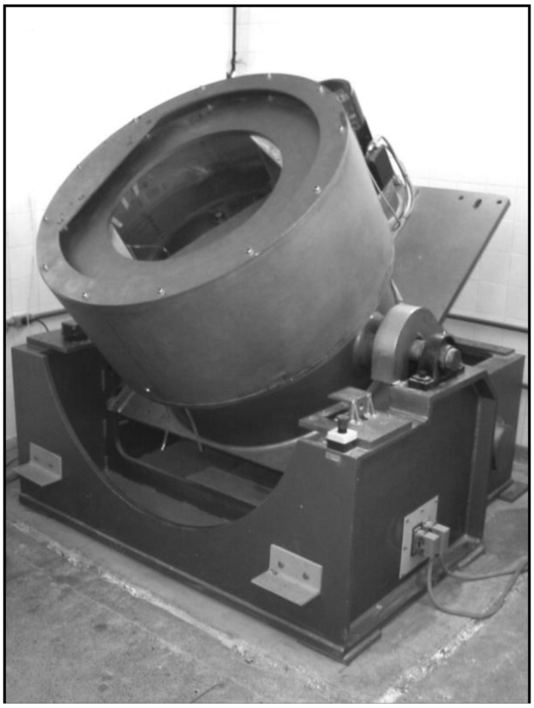


Figure 1. COPPE geotechnical mini-drum centrifuge.

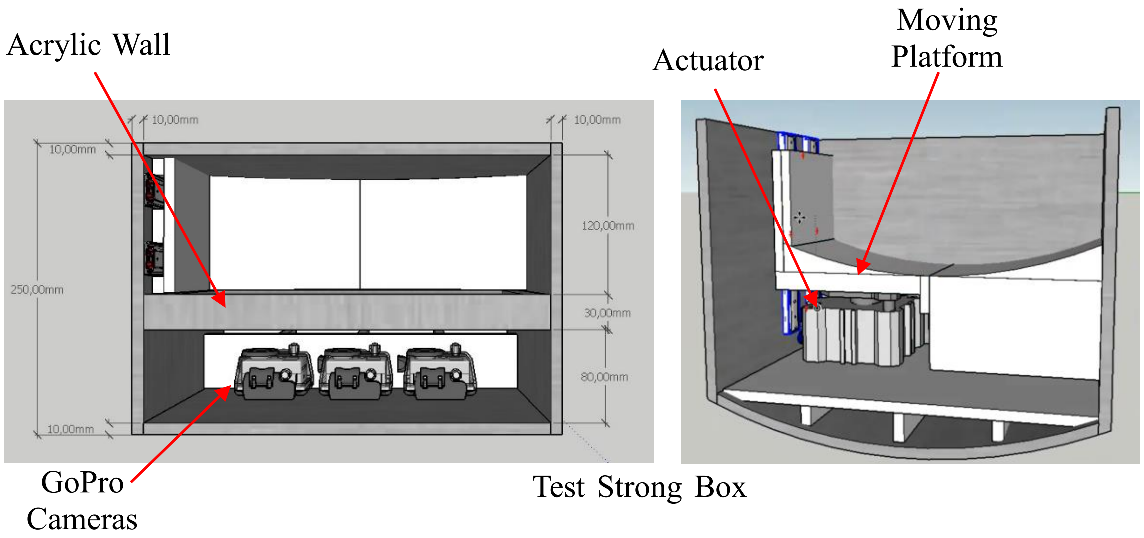


Figure 2. Fault Actuator System.

4 Finite Element Model

Dry sand response on reverse faults was numerically explored using the finite element method through *ABAQUS v. 6.13-4* and *Plaxis 2D v. 2015*. The fault propagation mechanism involves high relative displacements, so it is important to have an adequately refined mesh in the neighborhood of the potential rupture zone.

A bilinear quadrilateral 4-node mesh has been adopted in the ABAQUS model, for a plane strain analysis, reduced integration with hourglass control (CPE4R). The numerical model (Figure 3) is 10 m height and 30 m length. The mesh has been uniformly refined and composed of 0.5 x 0.5 m square elements. The size corresponds to 0.5% of the model height as recommended by Qu et al. [21] for more accurate results.

The first step of the analysis was the application of the self-weight load. The applied boundary conditions restrict vertical movements at the base and horizontal displacement at the sidewalls. In general, the bottom boundary of the numerical model represents the interface between the overlying soil layer and the fault, assuming that initially both the ground base and the ground surface are flat and horizontal.

The second step was the application of a vertical displacement to the left half base of the soil layer (Figure 3). The fault angle is 90°, i.e. half of the ground layer will be shifted vertically relative to the other half.

The same problem has also been modeled using Plaxis 2D software. The 15-node triangular plane strain element was used. The triangular element mesh has been refined where the fault rupture is expected to propagate (Figure 4). As the analysis involves large deformation, mesh update feature has been enabled based on an approach known as an updated Lagrangian formulation. The dimensions and steps are the same as those used in ABAQUS.

4.1 Soil Properties and Constitutive Model

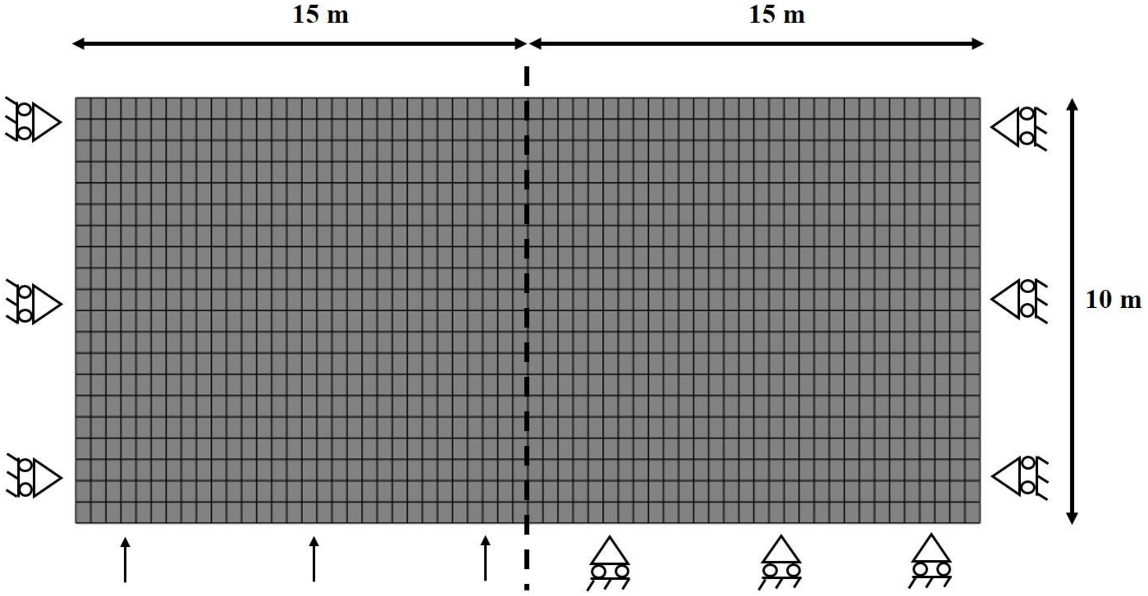


Figure 3. The 2D reverse fault propagation model in *ABAQUS*

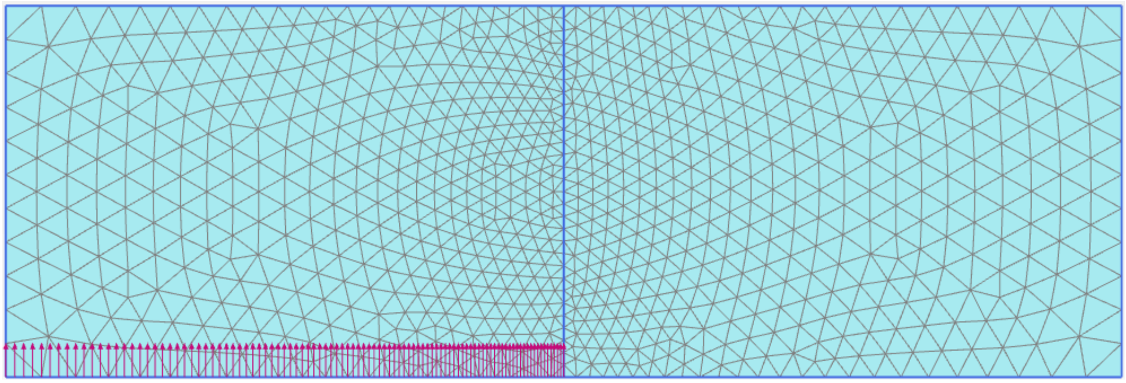


Figure 4. The 2D reverse fault propagation model in *Plaxis*

The elastoplastic Mohr Coulomb constitutive soil model has been adopted for the analyses, disregarding the softening effect after reaching peak stress. This assumption is acceptable because the parameters of the chosen soil refer to loose dry sand.

The model simulates a uniform soil layer over a rock base, represented by the boundary conditions ensuring a flat and horizontal base. Soil parameters are constants throughout the layer and given at Table

1. Cohesion and dilation have a very low value, since ABAQUS program does not allow to assign a null value to these parameters.

Table 1. Loose dry sand parameters

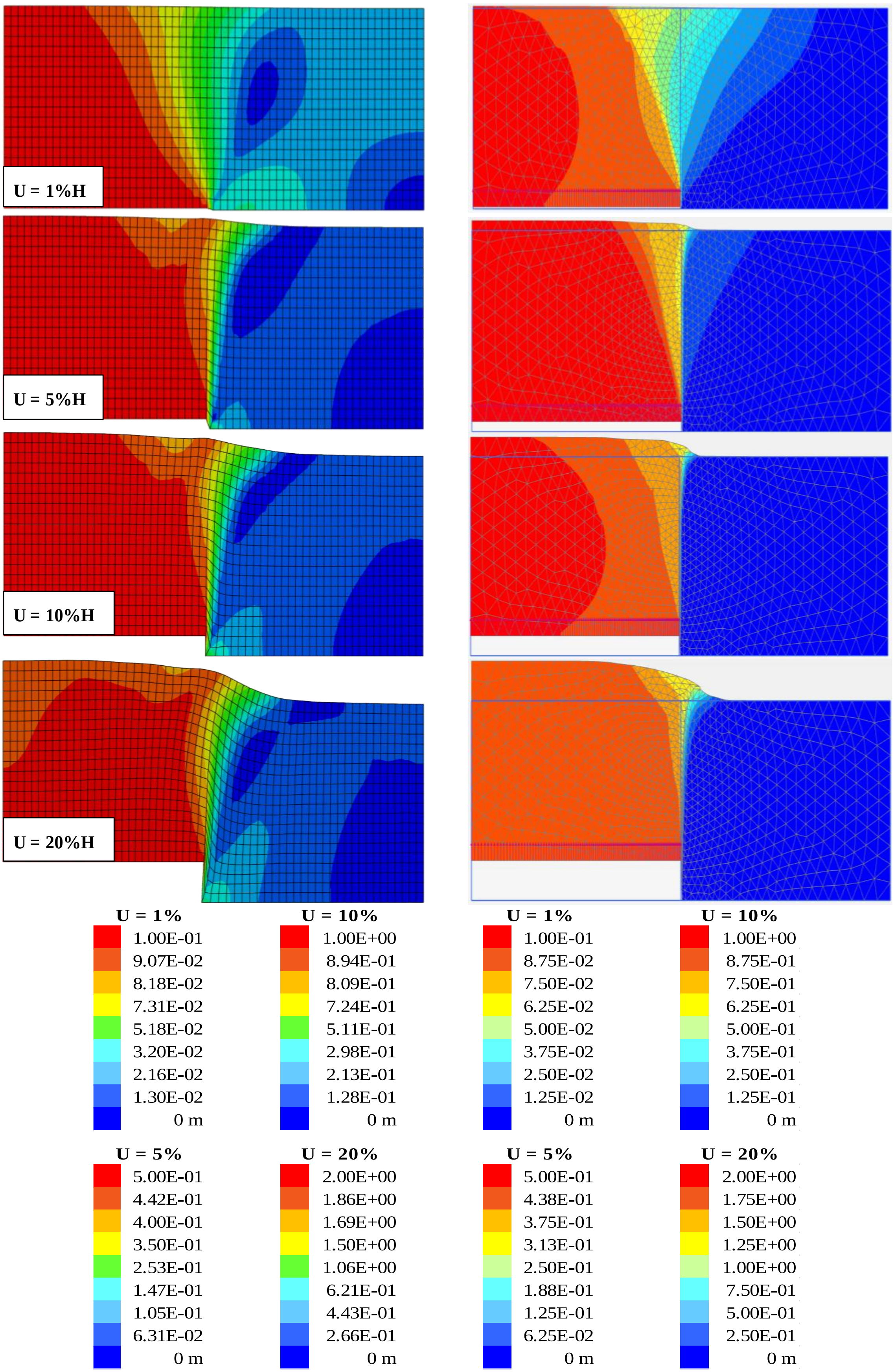
Young's modulus E (kPa)	10000
Cohesion c (kPa)	0.1
Dry Unit Weight γ (kN/m³)	18
Poisson's ratio ν	0.3
φ (°)	30
Ψ (°)	0.1

5 Results

In the present study, a parametric analysis was performed with vertical bedrock displacement (U) varying up to 20% of the soil layer thickness. Following the literature, the rates were 1%, 5%, 10% and 20%. Depending on the magnitude of the ground displacement, the shear zone may propagate to the surface resulting in a potential hazard to affected structures Chang et al, 2015 [7]. All results show the formation of only one shear contour in the soil layer.

The most disturbed soil zone follows the fault surface alignment (Figure 5). ABAQUS results (Figure 5a) show a wide propagation zone, also reaching the right side of the soil that had no displacement. On the other hand, Plaxis (Figure 5b) presented a narrower deformed region for larger displacements, almost undisturbed on the right side. Hence, the chosen centrifugal model is not affected by the boundary effects. According to the literature, in soft soils the deformed zone is wider compared to denser soils. Thebian et al. [28], Finch et al. [11], Qu et al. [21] stated that looser soil layers have a ductile macroscopic behavior, resulting in wider deformation zones, unlike denser soil layers that have narrower deformation zones, with faster and more evident fault propagation surfaces. An examination of the cover deformation shows that ABAQUS results are more consistent with those in the literature.

Additionally, the results of both numerical analyses are very similar regarding the deformation of the soil surface in the left part of the soil layer. The difference is more evident on the right side of the model, since the soil surface in Plaxis has a sharper step, while in ABAQUS is smoother.



a) ABAQUS **b) Plaxis 2D**

Figure 5. Deformation of the soil model with various vertical bedrock displacements (U).
a) ABAQUS; b) Plaxis 2D

6 Conclusions

The finite element method through ABAQUS and Plaxis was used to simulate the fault propagation mechanism in soft dry sand. Soil surface displacement and soil deformation characteristics following the failure were analyzed.

The results show that ABAQUS reproduces with greater reliability the propagation of faults in soft sandy soils. On the other hand, Plaxis 2D may faces mesh difficulties with the large offsets imposed by the analysis, even with the update mesh feature on.

The direction of the sheared zone is directly related to the fault angle. The width and deformation on the surface are related with the density of the soil, where softer soils present wider deformed areas on the surface and consequently the affected soil surface is considerably more extensive.

The test results indicate that vertical fault displacement is a significant factor in forming the failure pattern (Qu et al [21], Thebian et al. [28]). The numerical results show no evidences of boundary effects in the centrifuge model.

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