Physical Modelling in Geotechnics

Centrifuge study on the response of surface foundations subjected to strike-slip faulting on dense sand

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ABSTRACT: The present paper presents the key outcomes of a centrifuge study on the response of surface foundations resting on dense sand and subjected to a propagating strike-slip fault rupture. With the aid of a specially designed three-section split-box container, a series of centrifuge model tests were performed to identify the key mechanisms that govern fault rupture-soil-foundation-structure interaction. Firstly, a free-field (without foundation) fault rupture propagation test was conducted and used as reference for the following four fault rupture-foundation interaction tests. In the latter, the location, surcharge load, aspect ratio and rigidity of a surface foundation positioned at the ground surface were varied. The centrifuge tests revealed the complex three-dimensional (3D) fault rupture pattern developing in dense sand when sheared and its surficial manifestation termed Riedel (R) shears. A surface foundation when intersected by an R shear exhibits primarily fault-parallel horizontal displacement and rotation with respect to the vertical axis, with the other 3D response components being less pronounced. The foundation kinematic constraint is shown to control the response, by altering the shear stresses at the soil-foundation interface and the soil underneath.

Keywords: centrifuge, surface foundations, strike-slip faulting, Riedel shears, soil-structure interaction

1 INTRODUCTION

When an active tectonic fault slips, the adjacent structures may be subjected (in addition to seismic shaking) to permanent ground deformation. In the case of moderate to strong seismic events, the fault offset at the bedrock level might reach the ground surface, propagating through the overlaying soil layers. The latter poses a potential threat only for the structures in the immediate vicinity of the active fault and therefore the specific problem has received relatively limited attention by earthquake engineers. Nevertheless, various strong seismic events have showcased the vulnerability of existing infrastructure (such as buildings, bridges, dams, tunnels and pipelines) to permanent ground deformation (e.g., Yang and Mavroeidis, 2018). Interestingly, very strong and stiff structures were able to divert the propagating fault rupture and experienced relatively small damage with rigid body displacement/rotation (e.g., Faccioli et al., 2008). The term Fault Rupture-Soil-Foundation Interaction (FR-SFI) is typically employed to describe this interesting interplay between the outcropping fault-rupture, the soil and the foundation of the structure.

The last twenty years or so and especially after the 1999 major earthquakes of Chi-Chi and Kocaeli, which resulted in a plethora of case histories involving FR-SFI, a significant amount of both experimental (e.g., Bransby et al., 2008) and numerical (e.g., Anastasopoulos et al., 2007) work has been devoted to the seismic faulting problem. Its key goal was to understand the mechanics of fault rupture propagation through soil and its interaction with foundations and structures. The majority of these studies have examined the less computationally demanding plane-strain problem of dip-slip faulting (i.e., slippage takes place along the dip of the fault). With respect to the purely three-dimensional (3D) strike-slip faulting problem (strike-parallel slippage), mostly geologists have performed various experimental studies, employing small-scale 1g physical models (“analogue”) to identify deformation patterns of upper crustal rock (e.g., Riedel, 1929; Tchalenko, 1970). With respect to FR-SFI, the research focus has been primarily to the interaction of strike-slip faults with buried pipelines, employing experimental (e.g., Ha et al., 2008; Argyrou et al., 2019) and numerical (e.g., Vazouras et al., 2015; Dey et al., 2020) tools. On the contrary, the interaction of foundations of buildings and bridges with strike-slip faults has received limited attention (Agalianos et al., 2020a; 2020b; Rasouli and Fatahi, 2021).

Aiming to bridge the apparent literature gap, this paper employs physical modelling in a geotechnical centrifuge to reveal the mechanics related to the propagation of a strike-slip fault rupture through dense sand and its interaction with a surface foundation. Firstly, a free-field (without foundation) fault rupture propagation test is conducted and used as reference for the following four FR-SFI tests. In the latter, the location, surcharge load, aspect ratio and rigidity of a surface foundation positioned at the ground surface are varied to identify the controlling response mechanisms.

2 PROBLEM DEFINITION AND METHODOLOGY

The problem of a surface foundation resting on dense sand and subjected to a strike-slip fault offset was examined, employing physical modelling in a geotechnical centrifuge. The experimental campaign was conducted at the Center for Earthquake Engineering Simulation (CEES) of the Rensselaer Polytechnic Institute (RPI), utilizing the CEES geotechnical beam centrifuge. A specially designed three-section split-box model container of inner dimensions 1.14 m × 0.76 m × 0.2 m (Fig. 1a) was placed on the swinging basket of the centrifuge (Fig. 1b) and spinned-up to the targeted 75g centrifugal acceleration, where all tests were performed. Only the central section of the model container was moved horizontally (relative to the other two sections) at each test, simulating thus two strike-slip fault offsets at the base (representing the bedrock) simultaneously. The container offset was applied in a controlled slow quasi-static manner with the aid of hydraulic actuators.

The key attributes and dimensions of the prototype problem are illustrated in Fig. 2, which plots a plan view snapshot of the centrifuge model (before testing) with instrumentation. A free-field test (i.e., without foundations) was initially performed as reference for the following FR-SFI tests. Nevada 120 sand (mean grain size d_{50} = 0.15 mm) was dry-pluviated controlling the drop height, velocity and flow rate to create a uniform layer of H = 7.5 m depth and relative density $D_r \approx$ 85%. In the case of the FR-SFI tests, after pluviation two surface foundations (a lightly and a more heavily loaded) of plan-view dimensions $b \times l$ (fault-normal × fault-parallel) and thickness t were positioned at the ground surface at fault-normal distance s from the base fault trace (measured from the foundation side on the stationary block). Each foundation was then subjected to a strike-slip fault rupture of base offset $h \leq 1.5$ m. Table 1 summarizes the key foundation parameters that were varied in the FR-SFI tests: (a) its location with respect to the base fault trace s/b; (b) its surcharge load q_{ps}; (c) its aspect ratio b/l; and (d) its rigidity.

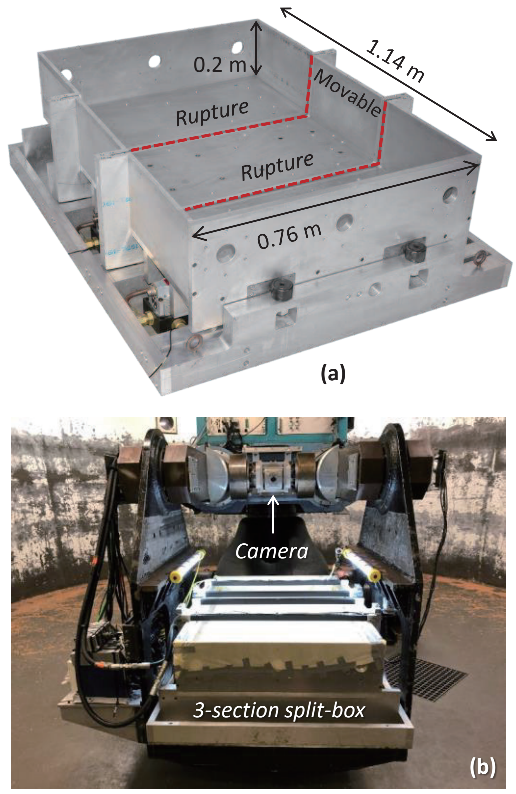

Fig. 1. Centrifuge testing at RPI CEES: (a) three-section split-box container; and (b) side view of the experimental setup.

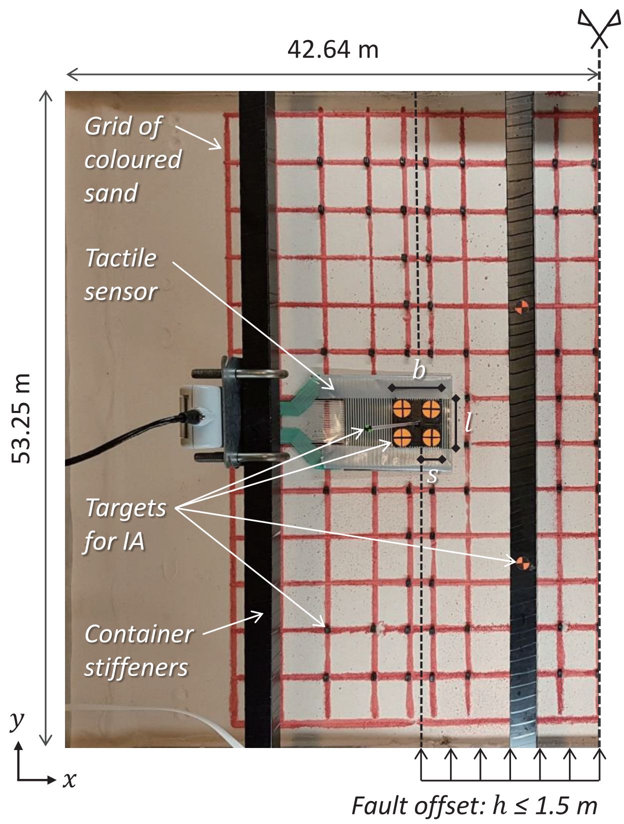

Fig. 2. Problem definition with key attributes and prototype dimensions: plan view snapshot of centrifuge model (before testing) with instrumentation.

Table 1. Key foundation parameters varied in the FR-SFI tests

Test ID	SB05-BL1-R	SB07-BL1-R	SB05-BL02-R	SB07-BL1-F
Location, s/b (-)	0.5	0.7	0.5	0.7
Surcharge load, q_{ps} (kPa)	27/105	27/105	21/98	21/94
Aspect ratio, b/l (-)	1	1	0.2	1
Rigidity (-)	Rigid	Rigid	Rigid	Flexible

Focusing on some key details of the employed model preparation technique, petroleum jelly was applied at the intersections between the three sections of the split-box, overlaid by a sandwich of plastic wrap. This technique contributed, in addition to preventing sand grains from entering the small gap between the sections, to reduction of parasitic boundary effects related to the use of a split-box. Interface sliding at the container base was prevented by firmly attaching to it a sandpaper layer. A grid of coloured sand was also formed at the ground surface (after pluviation and leveling) to enable visualization of the surficial fault pattern. Moreover, with the aid of an on-board high-resolution camera Image Analysis (IA) techniques were applied. For this reason, targets were added at the coloured grid intersections (made of cut zip-tie heads) to extract the evolution of displacements at the ground surface in function of the applied offset at the model base. Targets were also glued at the top surface of the foundations to calculate with IA their displacement and rotations. Furthermore, the foundation normal pressure distribution was monitored with tactile pressure sensors placed at the foundations' bottom surface, followed by a layer of sandpaper to prevent sliding at the soil-foundation interface.

3 KEY RESULTS

3.1 Free-field fault rupture propagation

As previously mentioned, a free-field test was initially conducted to identify the mechanics controlling strike-slip fault rupture propagation through dense sand. According to the test results, the applied offset along the single and straight base fault trace propagates through the overlaying dense sand layer and outcrops at the ground surface forming a complex surficial fault rupture pattern. This is clearly depicted in Fig. 3, which plots a plan view snapshot of the centrifuge model (after testing) corresponding to applied base fault offset h/H = 19%. Three main diagonal ruptures (per base offset) are clearly visible at the ground surface, described in literature as Riedel (R) shears (Riedel, 1929). These are the surficial manifestation of more complex 3D "flower" structures of helicoidal geometry, typically observed in dense sand. Due to dilation of dense sand, the R shears initiate from a single trace at the bedrock and then rotate in space while propagating towards the ground surface.

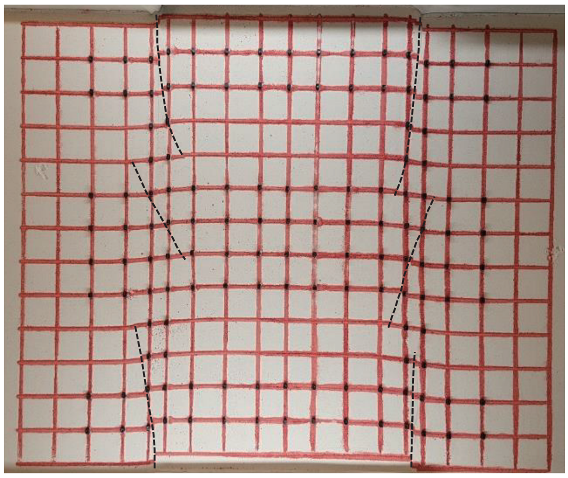

Fig. 3. Free-field strike-slip fault rupture propagation through dense sand: plan view snapshot of the centrifuge model (after testing) for applied base fault offset h/H = 19%.

Closely examining the free-field test results, it can be observed that the three R shears initiating from the left-side base offset differ from each other and from the ones of the right-side base offset in both length and exact location. These discrepancies are attributed to the small but always present spatial variation of soil properties in the centrifuge model. Moreover, the two edge R shears close to the fault-normal model boundaries outcrop first (i.e., for small base offset), followed by the in-between one for larger base offset. The earlier development of the two edge R shears can be explained by the fault-normal boundaries of the split-box container, where the offset is applied to both the base and sidewalls. Overall, the free-field test results confirm the high complexity and sensitivity-to-details of the examined 3D problem.

3.2 Fault Rupture-Soil-Foundation Interaction

In the case of the FR-SFI tests, surface foundations of different configurations (Table 1) were positioned at the ground surface and were then subjected to the previously described complex surficial fault rupture pattern of dense sand. The latter results in a purely 3D response of the surface foundation, with the fault-parallel component of displacement Δ_y and the rotation with respect to the vertical z axis θ_z prevailing. As also shown in Agalianos et al. (2020a) by means of Finite Element modelling, two distinct FR-SFI mechanisms govern the foundation response: (i) a rotational, where the rotation θ_z is pronounced; and (ii) a translational, where θ_z is suppressed and Δ_y prevails instead. More importantly, each mechanism leads to different foundation distress: the rotational mechanism results in significant positive bending moments, whereas the translational to pronounced negative bending moments.

Figure 4 presents indicative centrifuge test results for the case of a relatively heavily loaded (q_{ps} = 105 kPa) square (b/l = 1) rigid foundation, positioned at two locations s/b ≈ 0.5 and 0.7 (relative to the base offset trace). The two aforementioned distinct response mechanisms are clearly depicted in Fig. 4a: (i) for s/b ≈ 0.5, the middle R shear intersects the foundation close to its centerline, resulting in the development of a rotational mechanism; (ii) for s/b ≈ 0.7, the middle R shear barely intersects the foundation, leading thus to a translational mechanism. Overall, the centrifuge test results (not all shown here) reveal that the foundation kinematic constraint controls FR-SFI and foundation distress, since it alters the shear stresses developing at the soil-foundation interface and the soil underneath.

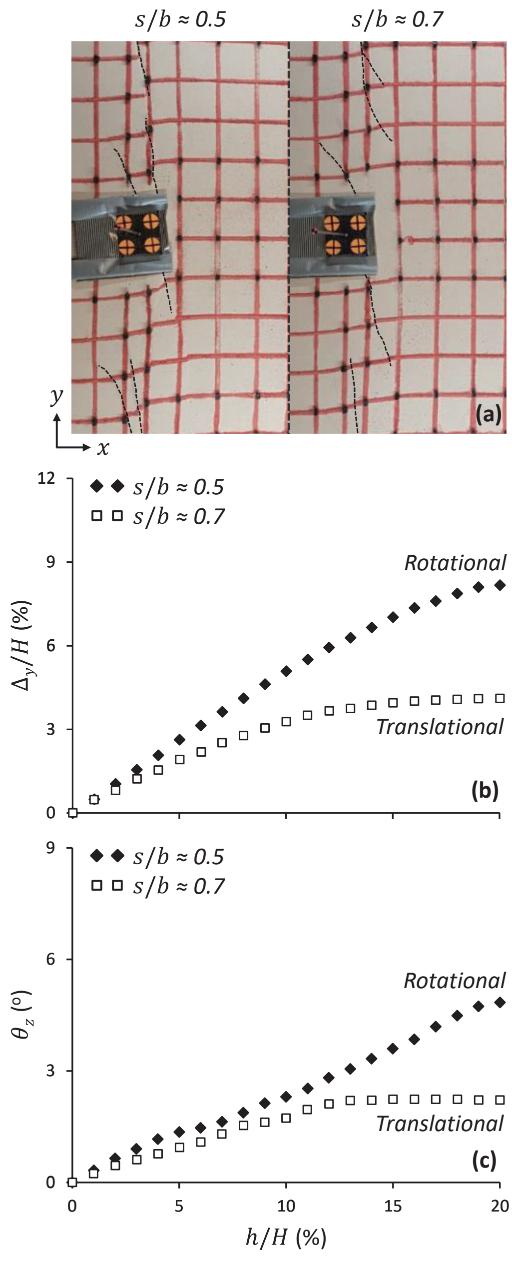

Fig. 4. Indicative FR-SFI centrifuge test results for a b/l = 1 foundation with q_{ps} = 105 kPa at s/b ≈ 0.5 and ≈ 0.7: (a) plan view snapshot (after testing) for h/H ≈ 20%; and evolution with h/H of (b) foundation displacement Δ_y/H and (c) rotation θ_z.

4 CONCLUSIONS

This paper briefly outlines a centrifuge study on strike-slip fault rupture propagation through dense sand and its interaction with surface foundations. The free-field test results predict the development of diagonal ruptures at the ground surface (R shears), attributed to dilation of dense sand when sheared. These are the surficial manifestation of complex 3D structures of helicoidal geometry. A surface foundation, subjected to this surficial fault rupture pattern, exhibits a purely 3D response, with the fault-parallel displacement Δ_y and rotation relative to z axis θ_z prevailing. The evolution of Δ_y and θ_z with applied fault offset and foundation distress depend on the prevailing FR-SFI mechanism (rotational or translational). The foundation kinematic constraint alters the shear stresses at the soil-foundation interface and therefore controls the overall 3D response.

REFERENCES

Agalianos A., de Coquereaumont O., Anastasopoulos I. 2020a. Rigid slab foundation subjected to strike–slip faulting: mechanisms and insights. Géotechnique 70 (4), 354-373.
Agalianos A., Sieber M., Anastasopoulos I. 2020b. Cost-effective analysis technique for the design of bridges against strike-slip faulting. Earth. Eng. Str. Dyn. 49 (11), 1137-1157.
Anastasopoulos I., Gazetas G., Bransby M.F., Davies M.C.R., El Nahas A. 2007. Fault rupture propagation through sand: Finite element analysis and validation through centrifuge experiments. J. Geotech. Geoenv. Engng 133 (8), 943-958.
Argyrou C., O'Rourke T.D., Stewart H.E., Wham B.P. 2019. Large-Scale Fault Rupture Tests on Pipelines Reinforced with Cured-in-Place Linings, J. Geotech. Geoenv. Engng 145 (3), 04019004.
Bransby M.F., Davies M.C.R., El Nahas A. 2008. Centrifuge modelling of normal fault–foundation interaction. Bull. Earth. Engng 6 (4), 585-605.
Dey S., Chakraborty S., Tesfamariam S. 2020. Structural performance of buried pipeline undergoing strike-slip fault rupture in 3D using a non-linear sand model. Soil Dyn. Earth. Engng 135, 106180.
Faccioli E., Anastasopoulos I., Gazetas G., Callerio A., Paolucci R. 2008. Fault rupture–foundation interaction: selected case histories. Bull. Earth. Engng 6, 557-583.
Ha D., Abdoun T.H., O'Rourke M.J., Symans M.D., O'Rourke T.D., Palmer M.C., Stewart H.E. 2008. Buried high-density polyethylene pipelines subjected to normal and strike-slip faulting – a centrifuge investigation. Can. Geotech. J. 45 (12), 1733-1742.
Rasouli H., Fatahi B. 2021. Geosynthetics reinforced interposed layer to protect structures on deep foundations against strike-slip fault rupture. Geotext. Geom. 49 (3), 722-736.
Riedel W. 1929. Zur Mechanik geologischer Brucherscheinungen. Centralblatt für Mineralogie, Abteilung B, 354-368.
Tchalenko J.S. 1970. Similarities between shear zones of different magnitudes. Geolog. Soc. of Am. Bull. 81 (6), 1625-1640.
Vazouras P., Dakoulas P., Karamanos S.A. 2015. Pipe–soil interaction and pipeline performance under strike–slip fault movements. Soil Dyn. Earth. Engng 72, 48-65.
Yang S., Mavroeidis G.P. 2018. Bridges crossing fault rupture zones: a review. Soil Dyn. Earth. Engng 113, 545–571.