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Numerical investigation of the kinematic interaction in a rigid inclusion-reinforced soft ground: site amplification response

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ABSTRACT: The presence of rigid inclusions (RI) in a soft clay ground modifies the free-field response due to kinematic interaction (KI) stemming from the stiffness incompatibility between the soft soil and the RIs. Numerical simulations of an RI-reinforced multi-layered soft soil model were performed using ABAQUS, and a full 3D nonlinear finite element model (FEM) was built based on dynamic centrifuge tests performed at Gustave Eiffel University. The soil consisted of three layers: a stiff sand layer at the base in which the RIs were anchored (end-bearing condition), a soft clay layer in which the RIs were embedded, and a sand load transfer platform (LTP). The response of the RIs was modelled as linear elastic, while the three soil layers were modelled as nonlinear using advanced hypoplastic models for sand and clay. The numerical model was validated against a dynamic centrifuge test. A parametric numerical study shows that the presence of the RI with an end-bearing condition causes a significant surface acceleration amplification.

1 INTRODUCTION

Rigid Inclusion (RI) reinforcement systems are increasingly implemented as an alternative foundation solution in soft ground, particularly in seismic regions. In this system, slender rigid columns are inserted into the soft soil to increase bearing capacity and reduce settlements, while the heads of the inclusions are disconnected from the superstructure by an intermediate granular layer referred to as the Load Transfer Platform (LTP) (see Figure 1). Compared to piled raft foundations, RI systems can reduce bending moments at the inclusion head level and allow the LTP to act as a "fuse" layer, reducing the intensity of incoming seismic waves through hysteresis damping (Pecker, 2023). A well-known full-scale application demonstrating the seismic efficiency of RI systems is the Rion-Antirrion Bridge.

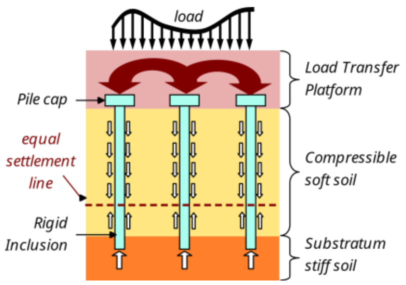

Figure 1. Concept of soil arching in a rigid inclusions reinforcement system (after Briançon et al., 2004).

This study presents a numerical investigation of kinematic soil–inclusion interaction in RI-reinforced soft ground using advanced hypoplastic constitutive models for clay and sand. The focus is placed on the modification of surface seismic response due to the presence of the RIs.

2 NUMERICAL MODEL

A three-dimensional nonlinear finite element model was developed using ABAQUS, see Figure 2. The numerical model was built based on a series of dynamic centrifuge tests performed at Université Gustave Eiffel and was calibrated and validated against experimental measurements.

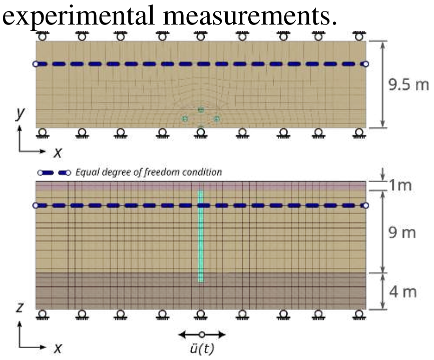

Figure 2. FEM model of the RI reinforced soft ground.

Advanced hypoplastic constitutive models (Gudehus *et al.*, 2008) were employed to simulate the nonlinear behaviour of clay and sand, with model parameters calibrated against shear modulus degradation and damping ratio curves obtained from laboratory and centrifuge tests. Rigid inclusions were modelled as linear elastic elements and assumed to be installed under a wished-in-place condition. Seismic loading was applied at the base of the model using both sinusoidal motions and recorded earthquake motions with different frequency contents and amplitudes. In this work, only the results under a single earthquake (Northridge) is presented.

3 RESULTS AND DISCUSSION

Numerical results indicate that end-bearing rigid inclusions significantly amplify ground motion within the reinforced zone compared to free-field conditions. High-frequency components of motion are amplified, with amplification ratios (kinematic interaction factor I_{EPA} , defined as the ratio of the effective peak acceleration (EPA, Kramer (2008) at the RIs head by that at the free-field) increasing with seismic amplitude. The influence zone at the ground surface extends beyond the reinforced area and becomes wider as the amplitude of the input motion increases, see Figure 3.

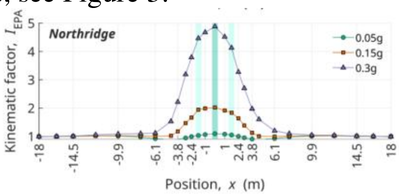

Figure 3. Kinematic interaction factor I_{EPA} at different locations at the ground surface level

Figure 4 shows the effect of RI stiffness on the maaximum kinematic interaction factor, I_{EPA} at $x = 0$. Increasing the stiffness of end-bearing inclusions further amplifies surface response and bending moments, although the amplification tends to saturate beyond a certain stiffness level.

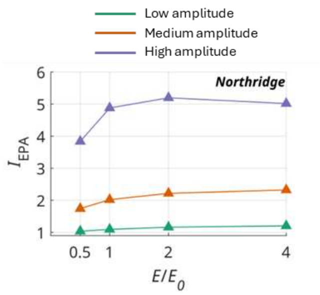

Figure 4. Effect of the RI stiffness on the kinematic interaction factor ($E_0 = 38\ MPa$).

4 CONCLUSIONS

A numerical study on the kinematic interaction of RI with soil was carried out. A 3D finite element model was built in ABAQUS (Dassault Systèmes, 2019) to investigate the influence of several parameters on kinematic interaction in Rigid Inclusion (RI) reinforced ground, such as the influence of the load-carrying condition and the stiffness of the inclusions. The behaviour of the soil was modelled using the nonlinear hypoplastic model for sands and clays. The parameters of both models were calibrated to their corresponding shear modulus degradation curves, and validated to centrifuge tests. The main conclusions and remarks could be drawn as follows. The reinforcement with RI increases the surface response compared with the surface response of the free-field. This amplification is affected by the amplitude of the input motion. A greater amplitude induces a higher amplification ratio and a wider zone of influence (area of amplified responses at the surface). In addition, a larger amplification ratio was observed during the earthquake with a frequency content further away from the response frequency of the system (such as Northridge). These observations are specific to the configuration studied and should be validated through additional configurations in future work.

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