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Numerical investigation of stone columns as a method for improving the performance of rocking foundation systems

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ABSTRACT

Allowing a shallow foundation to rock during an earthquake offers many benefits and importantly has demonstrated potential for improving a system's overall performance and increased likelihood of rapid post-event recovery. However, when the soil is soft, excessive foundation rotations could induce significant residual or differential settlement, both of which could have a negative impact on the post-event functionality of the structure. This paper aims to study the rocking response of a shallow foundation that is founded in a soft clayey environment and reinforced by stone columns via numerical simulations. The implementation of stone columns is intended to reduce the likelihood of post-earthquake residual deformations. The investigation includes a sensitivity study considering the impact of various stone column material properties and design variables on the performance. Numerical analyses results show that inclusion of stone columns increases the moment capacity, improves the re-centering capability, and reduces residual settlement for a rocking foundation particularly when footings supporting large axial loads are of concern. Parametric study results indicate that the shear modulus and friction angle of the stone column material have a slight influence on the footing's moment capacity; however, they could substantially affect the residual settlement. Key stone column design parameters, namely; length (both edge columns and central columns) and area replacement ratio, also have a pronounced impact for the seismic response of the reinforced foundation. These results also suggest that shortening the installation length and/or placing a reduced length stone column in the footing central region can optimize the footings performance.

1. Background and scope

Extensive recent experimental and numerical investigations have been conducted to understand the seismic response of rocking shallow footings. These efforts repeatedly illustrate that under competent soil conditions, foundation rocking can provide beneficial characteristics to a system's response, improving its overall seismic performance. Most importantly, it includes the potential for seismic isolation, energy dissipation, and re-centering [e.g. 1–4]. These merits combined are capable of enhancing the seismic performance of building-foundation systems [e.g. 5–7] and bridge-foundation systems [e.g. 8, 9]. However, when the surrounding soil is weak, excessive rocking (e.g., footing rotation is greater than 0.05 rad) can lead to significant residual or differential settlement or tilting, which in turn could affect the functionality and/or occupancy of the structural system or even cause system-level failure. In such situations, it is highly desirable to improve the surrounding soft soil prior to foundation construction. To preserve the beneficial seismic response features, namely re-centering and energy dissipation, of the rocking foundation, such improvements should focus primarily on increasing soil stiffness and thus the strength of the overall foundation-soil system.

Installing stone columns into soft soils, particularly clays, provides a viable and economic solution for stiffening and reinforcing the ground. Stone columns, sometimes referred to as granular columns, gravel drains, or aggregate piers, are usually constructed by compacting crushed stones, granular soils, or recycled concrete in vertical predrilled boreholes via a vibrator. The stone column materials are usually stiffer and stronger than the surrounding native soil therefore they improve the bearing capacity and importantly reduce settlement. Installation of stone columns has been recognized as an effective ground improvement strategy for many years [28]. With advancements in machinery, their utility has become more pervasive in practice. Importantly, research has been conducted to study the load-settlement behavior of single stone columns [e.g., 10–13], the behavior of a group of stone columns

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or stone column-supported foundations [e.g., 14–17]. In parallel, numerous numerical simulations have been carried out to investigate the effect of stone column design variables, such as the area replacement ratio, stone column length, and spacing, installation method, and material properties on the behavior of the reinforced foundation-soil system [e.g., 16, 18, and 19]. It is generally concluded that, for soft soils, stone column-reinforced foundations or embankments have an improved stiffness and strength and thereby an improved stability and increased bearing capacity compared to the unreinforced native soil condition. Therefore, the settlement under vertical load will be significantly reduced compared with that of the unreinforced cases. For cohesionless soils, installation of stone columns has also shown its effectiveness in mitigating liquefaction hazards to structures founded on liquefiable ground, such as seismically induced lateral spreading of the ground and residual settlement of foundations as the stone column inclusion has a high permeability [e.g., 20–22].

For soft cohesive soils, prior work on stone columns mostly focused on evaluating the vertical response of stone columns or stone column-reinforced foundations under static loads. Limited research has been conducted to assess the seismic performance of the stone column-reinforced foundation-soil systems, particularly, when the foundation is expected to rock during earthquake loading. The research in the present paper is seeking to understand the benefits of introducing stone columns into rocking foundation-soil systems. Initially, a 2-D plane-strain numerical model of a baseline rocking foundation-soil system is constructed, and the model is then validated against experimental data. Subsequently, the response of rocking foundations considering improved and unimproved soil conditions are compared, and a parametric study is conducted to understand the sensitivity of the design variables of the stone column and its associated material properties on the performance of the reinforced rocking foundation-soil system.

2. Plane-strain numerical model

2.1. Numerical model overview

When modeling the soil-footing interface, there are several strategies to capture the interaction between the soil and the foundation. One common method is to more completely model the soil medium directly using finite elements. The main advantage of this selection lies at its capability for simulating complex or heterogeneous soil conditions, such as cases where the underlying ground is composed of layered soils with different mechanical or fluid properties, or reinforced by ground improvement strategies. However, this strategy typically requires tremendous computational effort and time, particularly in the 3-dimensional domain. To reduce the computational effort and degrees of freedom, Tan et al. [23] proposed to convert large-scale 3-D problems into equivalent 2-D plane-strain models, particularly for the case of stone column-reinforced ground. In this method, the stone column in-plane width is reduced accordingly to maintain the stone column area replacement ratio. A numerical study of a stone column-reinforced embankment by Tan et al. demonstrated that this conversion method is able to reasonably estimate the nonlinear inelastic response of the system in the 2D domain. Thus, in present study, the equivalent plain-strain 2-D domain using the conversion method by Tan et al. [23] is utilized.

In the present study, the first step is to establish a plane-strain element based model of a rocking foundation and stone column-reinforced foundation-soil system and validate its robustness by comparing with a pair of foundation experiments. The numerical model of the rocking foundation-soil system is constructed using the OpenSees platform [24]. Fig. 1a schematically shows a mesh of the numerical model for a typical rocking foundation-soil system, and part (b) depicts the modeling strategy for the soil-footing interface that allows separation between the footing and the soil during cyclic load. The soil domain is discretized using a number of 2D Nine_Four_Node_QuadUP elements in OpenSees. This element is a 9-node quadrilateral plane-strain element that includes four additional degrees of freedom to capture fluid pressure at edge nodes, which is capable of simulating the dissipation and redistribution of pore water pressure [25]. From the OpenSees material library, the nonlinear material property of the cohesive soils is simulated using the *PressureIndependMultiYield* constitutive model, whereas the *PressureDependMultiYield* constitutive model is used to model the behavior of the cohesionless soils and stone columns [21]. The soil constitutive model simulates a linear-elastic volumetric response and non-linear elastic perfectly-plastic deviatoric stresses in response to shear strains, and is appropriate for rapid, undrained loading. The structural components include the footing and the shear wall and are modeled using elastic beam-column elements with significantly large flexural and axial stiffnesses. In addition, as shown in part (b), a series of linear-elastic zero-length uniaxial vertical spring elements are employed to connect the soil and footing nodes at the soil-footing interface. The materials of these elements are modeled using the Elastic-No Tension (ENT) uniaxial material with a significantly large stiffness in compression (10 times axial stiffness of each discrete elastic footing element shown in Fig. 1b) and zero stiffness in tension, which allows separation when tension is expected. To optimize computational effort, the soil domain mesh is arranged such that it is relatively fine near the footing location and gradually becomes coarse towards the boundary of the domain. Regarding the boundary conditions, the vertical and horizontal movement are fully fixed at the bottom layer of soil nodes, and the horizontal movement is fixed for the nodes along the two sides of the domain. Note that soil domain dimensions are provided separately for different cases in subsequent sections.

2.2. Validation of the model with physical experiments

Fig. 2 shows schematics of the two foundation experiments considered and compares the test response results to that predicted using the plane-strain numerical model. Part (a) provides a schematic of a centrifuge experiment that was conducted to investigate the rocking response of shallow footings founded in clayey soil [4]. The structure-foundation model specimen was constructed using a rigid shear wall attached to a rectangular shallow spread footing supported on overconsolidated clay, which had an undrained shear strength of 59 kPa. The resultant factor of safety of this foundation against bearing failure corresponds to 4.1 [4]. The shear wall-footing model was subjected to a series of displacement-controlled loading with increased footing rotation amplitudes. Modeling of the rocking foundation behavior follows the abovementioned modeling strategy in Section 2.1 (see also [26]). The right plot compares the observed hysteretic response of the rocking footing to that obtained in the numerical analysis in term of the moment-rotation relationship at the footing-soil interface. In general, the 2-D plane-strain numerical model is able to reasonably predict the measured footing rocking response including the moment capacity and the salient characteristics of the hysteresis including loading and unloading stiffness.

The second test of interest was carried out to investigate the effect of design and construction variables of stone columns on the load-settlement behavior of reinforced footing-soil system [17]. Fig. 2b shows a schematic of the test setup used for testing an isolated single stone column. The stone column was constructed with a diameter of 0.74 m and a length of 3.05 m by vibrocompacting uniformly graded crushed gravel into a predrilled hole. The native soils at the test site largely consisted of overconsolidated clays (for more information see [27]). In like fashion, the numerical model of the stone column reinforced footing-soil system is constructed in OpenSees following the abovementioned strategy. Note that the stone column was simulated using the plane-strain elements with a *PressureDependMultiYield* constitutive soil material model [26]. The load-displacement response of the stone column-reinforced footing-soil system is compared in part (b). In general, the load-settlement curve obtained from the numerical analysis