Experimental Investigation of The Rocking Response of SDOF Systems on Sand

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ABSTRACT: Highly inelastic foundation response is inevitable in a strong earthquake event. Shallow foundations supporting bridge piers or building columns and frame walls may experience sliding and/or uplifting from the supporting soil or bearing capacity failure. However, such non-linear foundation response may be beneficial for the overall system performance since high energy dissipation occurs at the foundation level, thus limiting the ductility demands exerted on the structural components. This paper presents an experimental investigation of the rocking response of surface foundations on dry sand. A comparison between centrifuge tests and equivalent reduced scale 1g slow cyclic tests is presented in order to explore the effects associated with the low confining stresses prevailing at 1g test conditions.

1 INTRODUCTION

Highly inelastic foundation response is inevitable in a strong earthquake event. Shallow foundations supporting bridge piers or building columns and frame walls may experience sliding and/or uplifting from the supporting soil or bearing capacity failure. However, this non-linear foundation response may be beneficial for the overall system performance as indicated by several researchers (Paolucci 1997, Pecker 1998, Gazetas et al. 2003, Gajan et al. 2005, Harden & Hutchinson 2006, Gajan & Kutter 2008). Potentially followed by large permanent soil deformation, the above mechanisms may result in high energy dissipation, thus in limiting the ductility demands exerted on the structural components (Martin & Lam 2000, Pecker & Pender 2000). In the framework of performance based design, the soil-shallow foundation non-linear interaction has been investigated analytically (Nova & Montrasio 1991, Butterfield & Gottardi 1994, Paolucci 1997, Bransby & Randolph 1998, Gazetas & Apostolou 2004, Allotey & El Naggar 2003, 2007, Gourvenec 2007) and experimentally (Maugeri et al 2000, Faccioli et al. 2001, Gajan et al. 2005, Gajan & Kutter 2008, Paolucci et al. 2008, Anastasopoulos et al. 2012, Deng et al. 2012, Drosos et al. 2012) for several systems under static, cyclic or seismic loading conditions.

Experimental studies have significantly contributed to the understanding of the rocking response of shallow foundations. Nevertheless, many of them have been conducted at a low confining stress environment (reduced scale 1g tests). Even though reduced scale 1g testing is easy and economical to perform, it is also followed by uncertainties associated with the inability to reproduce the actual stress field. The low confining stresses prevailing at 1g test conditions lead to overestimation of the angle of shearing resistance, therefore 1g test results should be carefully interpreted. In an attempt to clarify these uncertainties, commonly referred to as 'scale effects', this paper presents a qualitative and quantitative comparison of the rocking response of shallow foundations between centrifuge and reduced scale 1g experiments. The rocking response of a single degree of freedom (SDOF) system on a square foundation is evaluated. A series of slow cyclic tests were conducted in the 3m radius, 150g-ton capacity centrifuge at the Center for Earthquake Engineering Simulation (CEES) at Rensselaer Polytechnic Institute. The corresponding reduced scale 1g tests were performed at the Laboratory of Soil Mechanics at the National Technical University of Athens.

2 EXPERIMENTAL METHODOLOGY AND CONFIGURATIONS

2.1 *Design considerations*

The prototype system under investigation is shown in Figure 1. A rigid and elastic single degree of freedom oscillator was subjected to slow cyclic lateral loading. The oscillator was founded on a square foundation (B=3m) and the center of mass was located at h=6.9m above the foundation level, result-

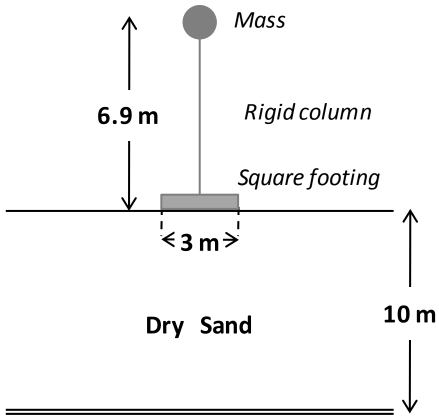

Figure 1. Schematic illustration of the prototype system under investigation.

ing in a slenderness ratio h/B=2.3. Two homogeneous soil profiles of depth D=10m were considered: a loose sand of D_r=45% and a dense sand of D_r=90%. The prototype system was scaled down according to the appropriate centrifuge and 1g scaling laws. A scale of 1:50 was selected for the centrifuge tests and a scale of 1:20 was selected for the 1g tests. The resulting geometries are summarized in Table 1.

Table 1. Summary of centrifuge and 1g model properties.

Properties	Centrifuge Model	1g Model
Scale	1:50	1:20
Footing width B	6 cm	15 cm
Location of the Center of mass	13.8 cm	34.5 cm
Slenderness ratio h/B	2.3	2.3
Column	Rigid	Rigid
Soil stratum	Sand	Sand
Soil depth D	20 cm	50 cm

The vertical factor of safety (FS_V) and the slenderness ratio (h/B) are key parameters to the rocking response of systems on shallow foundations governing the moment capacity, the overturning potential and the accumulation of settlement during cyclic loading. Aiming to alleviate the effect of the low confining stresses prevailing in 1g testing an alternative design methodology was followed: Instead of preserving the mass analogy between the prototype system and the centrifuge and 1g models, the SDOF systems were designed in order to preserve an analogy between the factor of safety and the slenderness ratio. To this end, bearing capacity tests were performed prior to the design of the SDOF systems. The surface foundations lying on either the loose sand (D_r=45%) or the dense sand (D_r=90%) were subjected to displacement controlled vertical push tests. The ultimate vertical loads of the soil-foundation systems were determined and the appropriate superstructure mass was defined for the centrifuge and the 1g model in order to achieve the desired FS_V values. The systems on loose sand were considered as the reference cases and the superstructures mass was adjusted so that a relatively low vertical factor of safety (FS_V=5) was achieved for both models. The same models lying on the dense sand profile yielded FS_V=11 (centrifuge soil-foundation system) and FS_V=14 (1g soil-foundation system).

2.2 *Centrifuge test description*

The experimental configuration for the centrifuge slow cyclic tests is depicted in Figure 2. A steel structure was placed in a rigid container and adequate distance from the box lateral boundaries (4B) was assured in order to minimize boundary effects. A 4-degree of freedom in-flight robot, capable of performing multiple tasks while the centrifuge is spinning, was used in this experimental series. A custom tool for the robot-end effector was fabricated in order to apply the cyclic load path at the top of the structure without imposing any lateral or vertical restrictions to it.

A biaxial load cell was connected to the robot tool and measured the lateral force in the loading and the transverse direction. The horizontal and vertical displacements and rotation of the structure was captured by a system of on-board cameras and specialized tracking software was used to analyze the recorded videos and extract the displacement time histories. Prior to cyclic loading, the robot was used to level the soil surface without disturbing the soil density. The structure was then precisely aligned to the loading axis and placed by the robot at the specified test location.

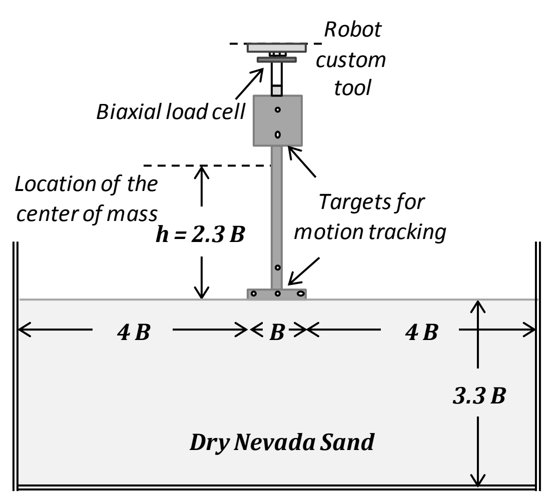

Figure 2. Experimental configuration for the centrifuge tests.

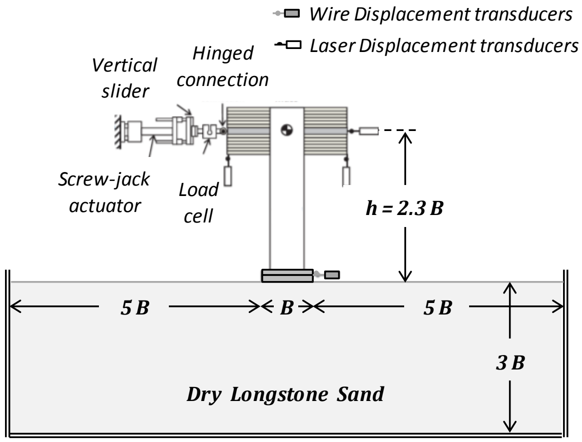

Figure 3. Experimental configuration for the 1g tests.

2.3 *Reduced scale 1g test description*

The experimental configuration used in the 1g test series is illustrated in Figure 3. A pushover apparatus, fixed to a reaction wall and consisting of a servomotor attached to a screw-jack actuator, was used to apply the cyclic load path. The free end of the actuator was connected to the structure model using a vertical slider and a hinged connection in series in order for the system to freely settle, slide or rotate as horizontal displacement was applied. The horizontal load was measured by a load cell inserted between the vertical slider and the hinged connection. Horizontal and vertical displacements were recorded through a system of wire and laser displacement transducers as shown in Figure 3. Four mechanical jacks were used to accurately position the structure without disturbing the soil surface.

2.4 *Cyclic load path*

The SDOF systems were subjected to slow cyclic loading of increasing lateral displacement in order to evaluate their performance when loaded into their elastic as well as their metaplastic regime. The normalized displacement (to the toppling displacement of the equivalent rigid block on rigid base δ_R=B/2) that corresponds to the center of mass of both systems is depicted in Figure 4.

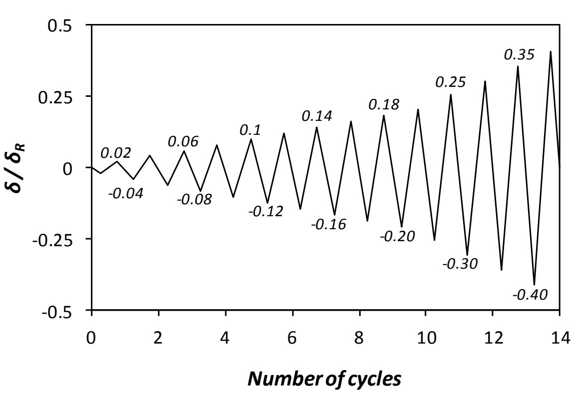

Figure 4. Lateral displacement load path applied at the center of mass of the SDOF systems.

2.5 *Soil properties*

Nevada sand was dry pluviated in the centrifuge test container to the desired relative density. Dry Longstone sand of the same relative density was layered in the 1g test container by an electronically-controlled system that has been calibrated to produce a specific range of relative densities (Anastasopoulos et al. 2010b). The properties of both sand specimens are summarized in Table 2.

Since the stress level prevailing in the 1g tests is low, the shear resistance of Longstone sand needs to be evaluated at a wide range of stresses. Figure 5 provides a diagram with the dependence of the angle of shearing resistance on the stress level for Longstone sand of two relative densities. The friction angle of Nevada sand for three relative densities at a reference mean effective stress of 100 kPa is also shown. The two sand specimens have similar friction angle at similar relative densities at large stress level. As expected the friction angle of Longstone sand is overestimated at low confining stress. This phenomenon is expected to affect the rocking response of the 1g system and the comparison to the centrifuge tests..

Table 2. Summary of soil properties.

Soil Properties	Nevada Sand	Longstone Sand
e_{max}	0.887	0.995
e_{min}	0.511	0.614
D_{50}	0.15 mm	0.15 mm
C_u	2.35	1.42
G_s	2.67	2.64

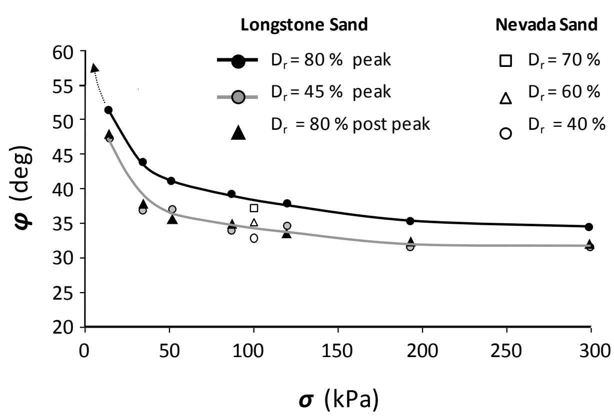

Figure 5. Direct shear test results for Longstone sand: dependence of the angle of shearing resistance on stress level (Anastasoloulos et al. 2010b). Friction angle for Nevada Sand: evaluation from isotropically consolidated undrained compression tests at reference mean effective normal stress 100 kPa (Arulmoli et al. 1992).

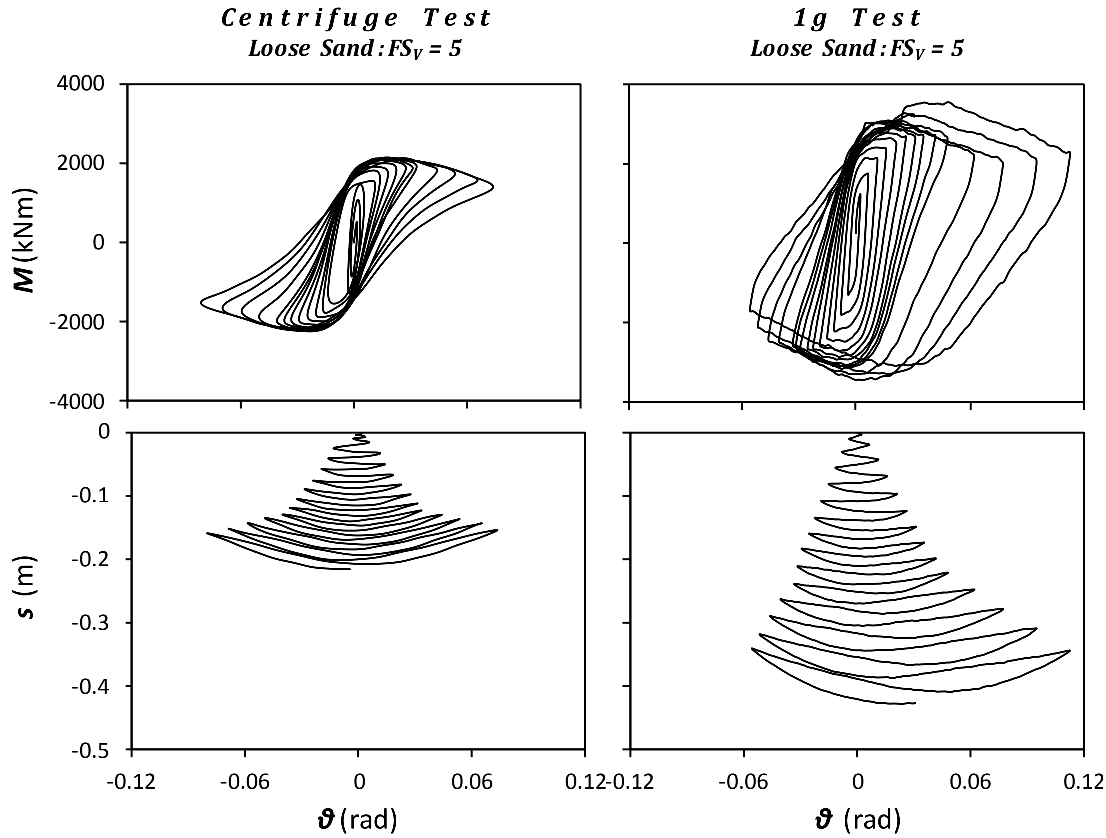

Figure 6. Foundation response under slow cyclic loading in terms of moment-rotation and settlement-rotation for the systems lying on the loose sand profile (D_r=45% and FS_V=5).

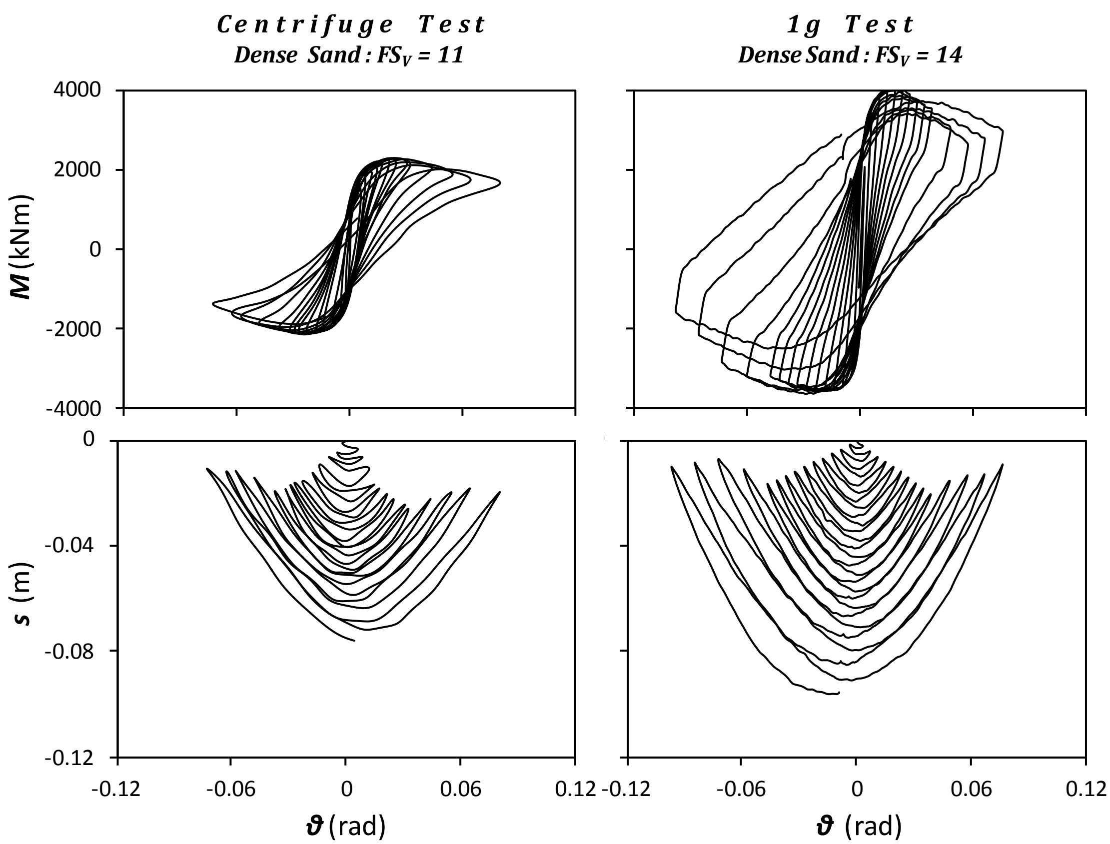

Figure 7. Foundation response under slow cyclic loading in terms of moment-rotation and settlement-rotation for the systems lying on the dense sand profile (D_r=90% and FS_V=11 for the centrifuge model and FS_V=14 for the 1g model).

3 FOUNDATION RESPONSE UNDER SLOW CYCLIC LOADING

3.1 *Loose soil profiles*

The performance of the SDOF systems on the loose sand profile (FS_V=5) is shown in Figure 6 in terms of moment-rotation and settlement-rotation. The moment is calculated at the bottom of the footing and the settlement refers to the settlement induced due to cyclic loading.

The comparison reveals interesting quantitative similarities between the rocking response of the studied systems. Focusing on the moment-rotation curves, a significant amount of energy is dissipated at the soil-foundation interface as denoted by the large area of the hysteresis loops generated at both the centrifuge and the 1g tests. The two systems exhibit ductile behavior as no significant moment capacity degradation is noticed. The rotational stiffness decreases when large displacement amplitudes are imposed and separation between the foundation and the supporting soil occurs. In terms of moment capacity, the moment measured in the 1g test is higher than in the centrifuge test. Considering that the effective friction angle can be significantly higher in the 1g test environment the moment capacity is unavoidably overestimated. Additionally, the loss of the footing contact area and the subsequent rotational stiffness degradation is represented by the characteristic S-shaped loop in the centrifuge test whereas a more oval shape is observed in the 1g test.

The most prominent difference between the centrifuge and the 1g test lies in the accumulated settlement. Both plots indicate settlement at the very first loading cycles and uplifting accompanied by settlement at larger rotational amplitudes. Even though the slope of the curves is similar, the rate of settlement accumulation is greater in the 1g test. By the end of the cyclic loading the settlement accumulated in the 1g test exceeds the settlement accumulated in the centrifuge test by almost a factor of 2 (0.43m versus 0.22m). The settlement divergence can be explained as follows: An apparent higher vertical stiffness governs the performance of the SDOF system in the centrifuge test possibly resulting in a more pronounced uplifting behavior and therefore in smaller settlement accumulation. Due to the low confining stress in the 1g test the initial vertical stiffness of the system and the potential increase of the vertical stiffness during cyclic loading is underestimated and leads to considerable settlement accumulation.

3.2 *Dense soil profiles*

The comparison for the systems on the dense sand profiles (D_r=90%) is provided in Figure 7. In order to avoid misinterpretations of the results it should be reminded that the vertical factors of safety are slightly different in this case (FS_V=11 for the centrifuge model and 14 for the 1g model). Therefore, some dissimilarities in the moment capacity and the accumulated settlement are expected and may be attributed to the difference in the FS_V value.

The observations derived from the tests on loose sand are generally valid for this case as well. The energy dissipation, the rotational stiffness degradation as well as the highly ductile response of the systems are captured in both the centrifuge and the 1g test. Both loops have distinct S-shape and the 1g system exhibits significantly higher moment capacity, probably affected by the higher vertical factor of safety as mentioned before. With respect to the settlement-rotation plot, a distinct uplifting response is captured in both tests due to the large FS_V values. The rocking induced settlement is again larger in the 1g test. Nevertheless, the difference is not as remarkable as for the systems on the loose soil profiles. Again, this can be explained if the difference in the factor of safety is considered.

4 SUMMARY AND CONCLUSIONS

An experimental study on dry sand was performed in order to compare the rocking response of SDOF systems obtained from centrifuge and reduced scale 1g tests. Equivalent SDOF systems were subjected to cyclic lateral loading. An alternative design methodology was followed and the equivalent systems were designed so that an analogy between the vertical factor of safety and the slenderness ratio was preserved.

The reduced scale 1g tests successfully captured the qualitative rocking response of two systems: one with sinking-dominated response (relatively low FS_V) and one with distinct uplifting-dominated response (high FS_V). The energy dissipation, ductile behavior, rotational stiffness degradation observed in the centrifuge tests was also captured in the 1g tests. Figure 8 summarizes the evolution of settlement for the four studied systems in terms of normalized settlement with respect to normalized rotation per loading cycle. The settlement is normalized to the foundation width B and the rotation is normalized to the overturning angle of the equivalent rigid block (θ_R = B/2h). For both sets of systems the settlement per cycle induced in the 1g tests is larger at any rotational amplitude indicating the underestimation of the vertical stiffness at the low confining stress level.

This satisfactory qualitative comparison indicates that reduced scale 1g tests can provide valuable insight to the rocking response of SDOF systems. If the above design considerations are taken into account and the results are carefully interpreted the overall rocking response can be captured in great detail.

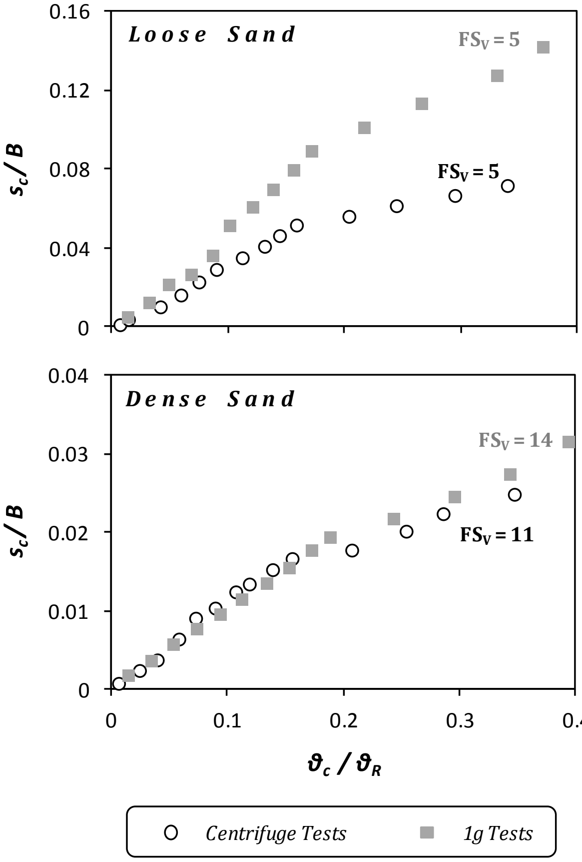

Figure 8. Evolution of settlement during cyclic loading: normalized settlement versus normalized cycle rotation.

5 ACKNOWLEDGEMENT

The financial support for this article has been provided under the research project "DARE," which is funded through the European Research Council's (ERC) "IDEAS" Programme, in Support of Frontier Research–Advanced Grant, under contract/number ERC–2–9–AdG228254–DARE to Prof. G. Gazetas.

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