1-g Experimental Investigation of the Metaplastic Rocking Response of 1-dof Oscillators on Shallow Footings

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ABSTRACT: This paper experimentally investigates the effect of shallow soil improvement layer on the rocking response of 1-dof systems. A series of 1-g horizontal monotonic and slow cyclic pushover tests were conducted in the laboratory of soil mechanics of the National Technical University of Athens (NTUA) with the depth of the soil improvement layer being varied parametrically. It is shown that due to the very nature of foundation rocking which mobilizes only a shallow stress bulb within the soil underneath the foundation, the presence of a shallow zone of mitigation acts very effectively towards limiting the shaking–induced settlement of the foundations.

1. INTRODUCTION

Contemporary earthquake engineering norms (e.g. EC8, FEMA 356 guidelines) while allowing ductility-controlled inelastic behavior of the superstructure -during low probability earthquake events- they dictate elastic foundation response ignoring the additional ductility that may be oferred by the soil-foundation system. Only recently, and perhaps contrary to common expectations, new studies (Paolucci 1997; Pecker, 1998, 2003; FEMA 356; Gazetas et al, 2004; Anastasopoulos et al , 2010; Gelagoti et. al., 2011) have shown that permitting non-linear soil-foundation response may overall enhance the seismic performance of the structure; nonlinearity of the soil-foundation system can act as a fuse mechanism, dissipating earthquake energy and potentially reducing demands exerted on the structural components of the building.These findings have been further verified by numerous experimental centrifuge, large scale and 1-g reduced scale tests— (Faccioli et al., 2001; Kutter et al., 2003; Gajan et al, 2005; Kawashima et al., 2007)

This paper experimentally investigates the effectiveness of non-linear foundation response in the form of rocking, for the case of 1-dof systems. It is noted that foundation rocking although desirable incorporates the peril of introducing permanent deformations (settlements and rotations) in case of low FS_v values which may possibly be unacceptable for the design. Thus, for foundation rocking to materialize through uplifting rather than settlement, the designer must ensure an adequately high safety factor against vertical loads. However, uncertainties in the exact estimation of in-situ soil properties would also hinder the exact assessment of FSv, and subsequently would practically limit the applicability of rocking-isolation in earthquake design.

In an effort to overcome this obstacle, this paper investigates the potential of *shallow* soil improvement, a concept commonly applicable in geotechnical engineering as a means to increase soil strength and reduce settlements. The competence of shallow mitigation stems from the very nature of foundation rocking which indeed mobilizes only a shallow stress bulb within the soil

(Anastasopoulos et. al., 2011b). Motivated by this behavior, a series of 1-g horizontal monotonic and slow cyclic pushover tests were conducted in the laboratory of soil mechanics of the National Technical University of Athens (NTUA) with the depth of soil improvement being varied parametrically.

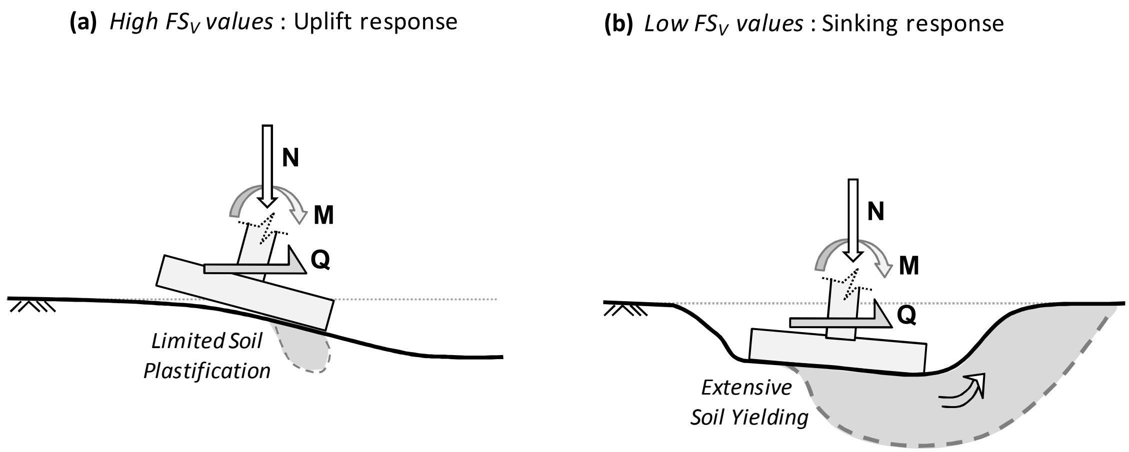


Figure 1: Rocking response of the soil–foundation systems under combined (M, Q, N) loading: (a) uplifting dominated response (high FS_v values); (b) bearing capacity failure mechanism prevails (low FS_v values).

2. PROBLEM DEFINITION AND METHODOLOGY

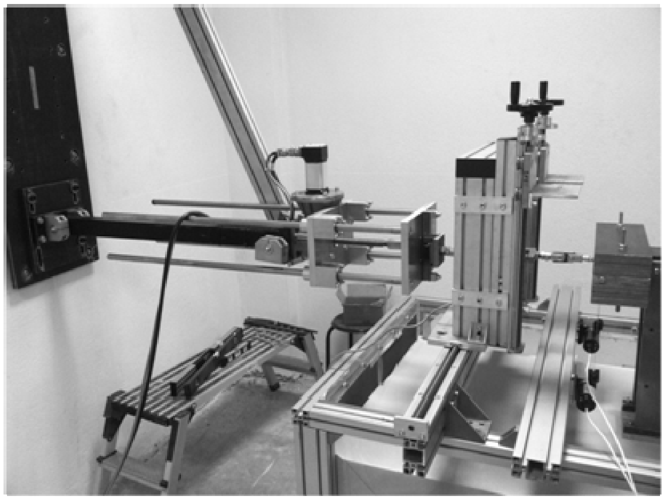
A single degree of freedom system has been investigated which may be considered as representative of a relatively slender bridge pier, supported on surface square foundation. Unless otherwise stated, all dimensions mentioned hereafter refer to model scale. The experimental set-up is outlined in Figure 2.

Soil Modeling

The soil used in the experiments was dry Longstone sand, an industrially produced and uniform quartz sand material. The parameters of this sand are D_{50} = 0.15mm and C_u = 1.42. The void ratios were measured to be e_{max} = 0.995 and e_{min} =0.614 and the specific solids weight G_s = 2.64. The sand was layered using dry pluviation on a rigid container with dimensions of 160 x 90 x 75 cm. Sand layering is accomplished by means of a sand raining system calibrated so as to achieve the desired soil density (Anastasopoulos et al. 2010). The height of the soil deposit ranges from 50 to 55 cm.

Superstructure Model

The foundation–superstructure model consists of a square foundation of dimensions 15 cm x 15 cm x 2 cm, two rigid columns of height 45 cm and a slab located 45 cm above the foundation level. The aspect ratio of the system yields h/B = 3. Sandpaper was placed under the foundation in order to achieve the desired friction coefficient. The 1-dof model is then placed on its position atop the soil surface by means of four jacks enabling its accurate positioning without disturbing the soil surface. Electronic spirit levels placed on the superstructure certify that the foundation is placed parallel to the soil surface, with no inclination.



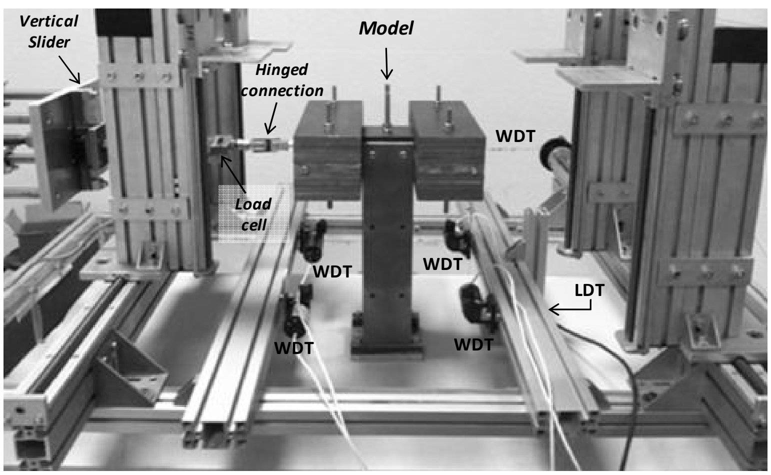


Figure 2: (a) Push over Apparatus, and (b) model instrumentation

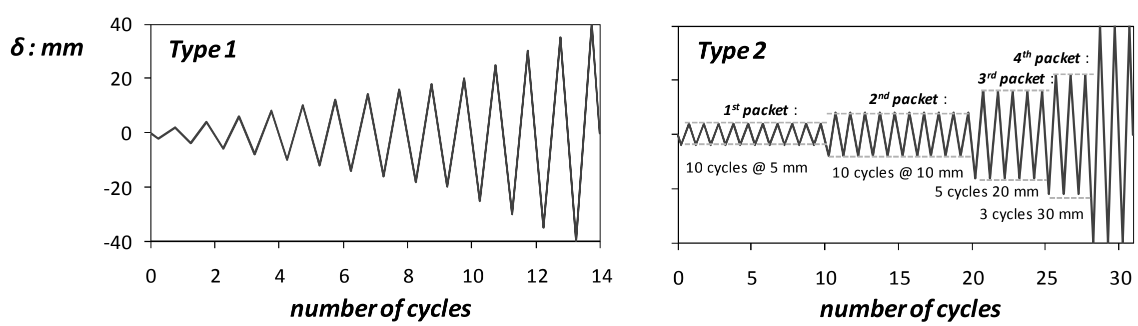


Figure 3. Two displacement protocols have been used for cyclic loading tests.

Load Application

The desired horizontal displacement is applied directly on the center of mass through a pushover apparatus consisting of a servomotor attached to a screw-jack actuator (Fig. 2a). The pushover apparatus is rigidly attached to the reaction wall while its end is connected to the foundation-superstructure model using a pin and clevis attachment (hinged connection) enabling the system to freely settle, slide and rotate as horizontal displacement is applied. The intervention of a linear guideway between the actuator and the servomotor allows the model to be subjected to exclusively horizontal loading at the mass level. Foundation and superstructure displacements were recorded through a combined system of wire and laser transducers (Fig. 2b).

Load protocol

The systems were subjected to monotonic and slow cyclic horizontal loading. Type I, the primary cyclic load protocol, consists of 14 cycles of increasing displacement, ranging from 2mm to 40mm, while Type II consists of 31 cycles, divided into 10 cycles of 4mm, 10 cycles of 8mm, 5 cycles of 16mm, 3 cycles of 24mm and 3 cycles of 40mm, in increasing order. The maximum displacement amplitude imposed is the same for both loading types (Fig. 3).

4. EFFECTIVENESS OF SHALLOW SOIL IMPROVEMENT FOR A LIGHTWEIGHT STRUCTURE

The following sections investigating the effectiveness of “shallow soil improvement” (i.e. the replacement of a shallow soil layer with soil of known properties) on the rocking response of 1-dof systems. Two different superstructure systems have been tested supported on foundation of the same width: System A refers to a lightweight (high FS_v) structure while system B represents a heavily loaded system (Figure 4). The model properties were selected so that the two systems demonstrate distinctly different behaviors, from uplift-dominated response to strictly sinking response. (Soil improvement is obviously applied on the corresponding to each system low density profiles (D_r = 45% for the lightweight system and Dr = 65% for the heavyweight one) by replacing the top sand layer with high density sand (Dr=93%), as depicted in Figure 4c. The depth (z) of soil improvement is expressed as a fraction of the foundation width (B) and has been varied parametrically in order to assess the optimum. Results are presented for the cases of z/B = 0.25, z/B = 0.25, and z/B = 1. The response of the foundation under high FS_V conditions (i.e. Dr = 93% yielding $FS_v = 5$ for the heavy structure and $FS_v = 14$ for the lightweight one) is considered to be the upper bound which should ideally be approached by the foundations on improved soil. It is noted that the FS_v values have been derived experimentally by means of vertical Push-down tests.

Monotonic Loading

Test results are displayed in Figure 5. In terms of Moment–rotation curves (Fig. 5a), it is obvious that the maximum moment rises with the increase in the depth of the soil improvement, as a result of the progressively enhanced soil strength. A similar trend may be observed for the overturning angle; the larger the depth of soil improvement, the greater its rotational capacity. [Even though experimental data have not been recorded until complete toppling of the models, the gradual increase of overturning angle θ may be derived from the slope of the descending branch of M-θ]. As expected, the increase in soil improvement depth reduces the extent of soil deformation and plastifications which are always limited only within the high density layer. Hence, the behavior of the models on the layered soil profile at large rotation angles closely resembles the response of the upper bound system (model on the homogeneous dense sand). Note that for the lightly loaded superstructure, the upper bound case (homogenous dense profile) yields a $FS_V = 14$, which implies almost no compliance, and thus for this limit case the rocking response almost approaches the response of a rigid block rocking on rigid base .

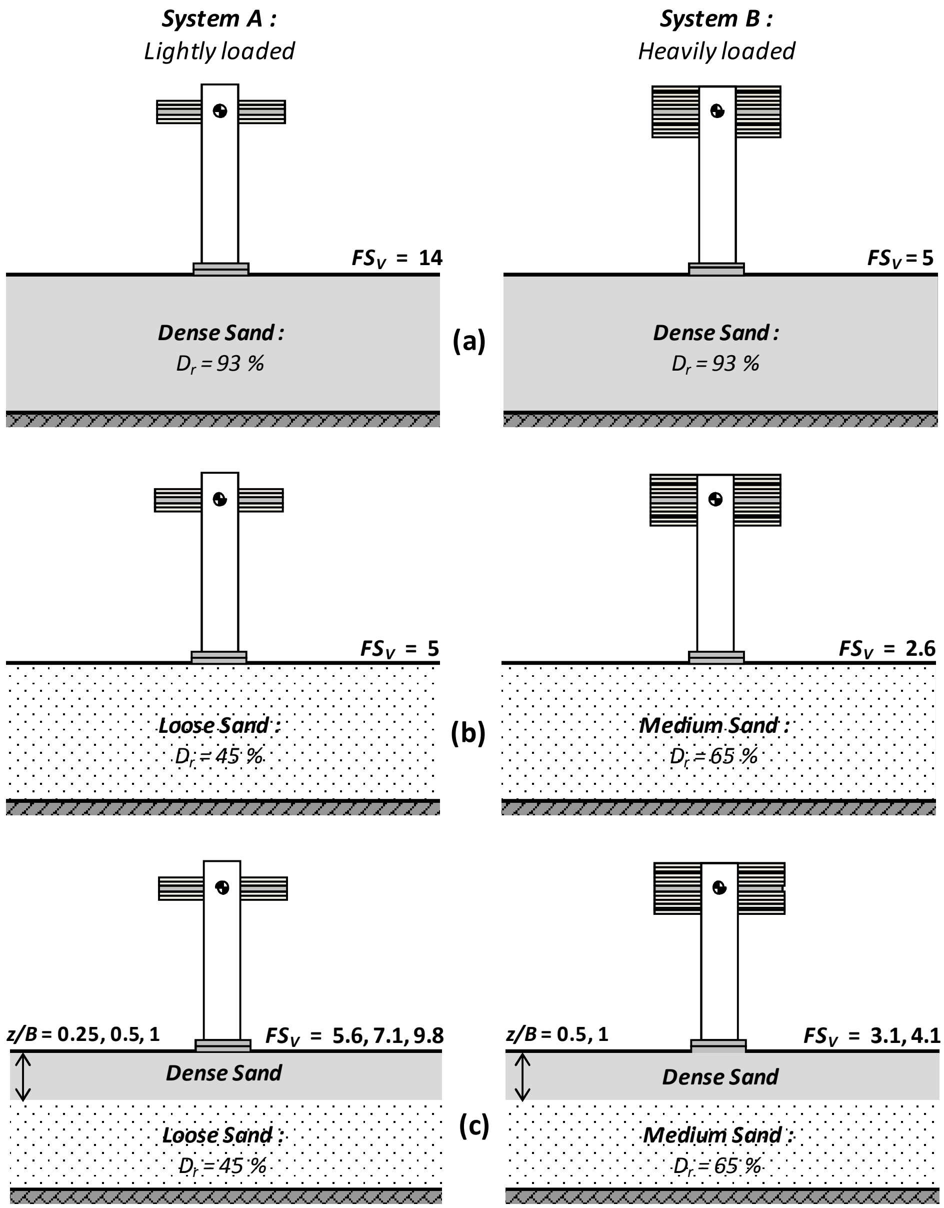


Figure 4**.** Schematic illustration of the studied soil-structure systems. a lightly loaded system (left), and a heavily loaded (right) founded on : (a) dense sand,; (b) medium and loose sand,; and (c) soil improvement with a shallow soil crust of dense sand, of varying depth (*z/B* = 0.25 to 1).

The differences between the 4 systems are more conspicuous in terms of settlement-rotation (Fig 5b). It is evident that with increasing the depth of soil improvement, foundation uplifting is promoted for a wider range of rotations. Indeed, in the unimproved soil, footing rotation would be accompanied by settlement up to an amplitude of $\theta > 0.08$; yet this value drops considerably to $\theta \approx 0.045$ when improving soil above depth z/B = 0.5 and to a mere $\theta \approx$ 0.015for z/B = 1. Moving to higher θ values (where foundation uplift dominates) the response of the models on both layered profiles almost matches the response of the upper-bound system (the three curves evolve in parallel). In fact, foundation uplift results in decrease of the effective foundation breadth in contact with the soil, which in turn reduces the size of the generated stress bulb (which is a direct function of the effective width). In effect, the rocking-induced stresses are transmitted to a smaller depth, which enhances the effectiveness of the improved soil's stiffness. In other words, for $\theta > 0.045$ the foundation on the mitigated soil profiles responds as if founded on a stiffer soil. Notice that although the z/b=1 curve practically coincides with the dense sand line it abruptly tends to override it for greater rotation values. Apparently, this behavior is attributable to some kind of flaw in the dense sand experiment and should be ignored.

The last chart (Fig. 5c) compares the experimentally derived rotational stiffness with respect to the amplitude of rotation. As calculated, K_R refers to a specific oscillator with h/B = 3 and incorporates the coupled rotational stiffness produced under simultaneous moment and shear force action on the foundation. Experimental complexities prevent the exact measurement of the initial rotational stiffness (i.e. the elastic response). At low rotation amplitude, for a given confinement stress (i.e. structural mass), the rotational stiffness K_R should be relative to the Shear Modulus G, which is affected by sand density. Thus, greater depths of soil improvement result in larger rotational stiffness. As the imposed rotation θ amplifies, foundation uplifts, K_R drastically decreases, and all profiles tend to behave identically.

Cyclic Loading

Moving from monotonic to slow cyclic loading, the results in terms of moment-rotation are displayed in Figure 6, along with the monotonic backbone curves. It is obvious that as the depth of soil improvement increases, the loops tend to transform from oval-shaped, resembling the loose sand model, to S-shaped, similar to those produced in the dense sand model. Interestingly, contrary to monotonic loading, in cyclic loading all systems seem to display the same moment capacity. While in case of the dense sand, the monotonic moment-rotation curve clearly "envelopes" the loops of the slow-cyclic tests, the latter tend to overly exceed as FS_v is reduced. This phenomenon is probably attributable to sand densification underneath the foundation due to multiple loading cycles (especially for the case of loose sand)

The foundation response in terms of settlement-rotation is portrayed in Figure 7. Even for a relatively shallow improvement depth of z/B=0.5, the foundation manifest a palpably superior behavior compared to the lower bound case of the loose soil profile, although the settlement accumulated during each cycle of loading is not as little as in the dense sand case. When the improved zone deepens to z/B = 1, the behavior quite replicates that of the model lying on dense homogenous sand, both in terms of residual displacement and tendency to uplift. These results are in full accord with the monotonic curves.

5. EFFECTIVENESS OF SHALLOW SOIL IMPROVEMENT FOR A HEAVYWEIGHT STRUCTURE

Monotonic Loading

Figure 8a shows a comparison in terms of moment-rotation. As far as ultimate moment is concerned, it is again obvious that the improvement in soil quality increases the foundation capacity, although the difference is not as large as for the lightweight model. Similarly, deepening of the mitigated zone produces larger overturning angles, although the increase does not follow that of the FS_v. This might be attributed to the fact that for such relatively low FS_v values, the overturning angle is mainly governed by soil failure rather than being a geometrical consequence.

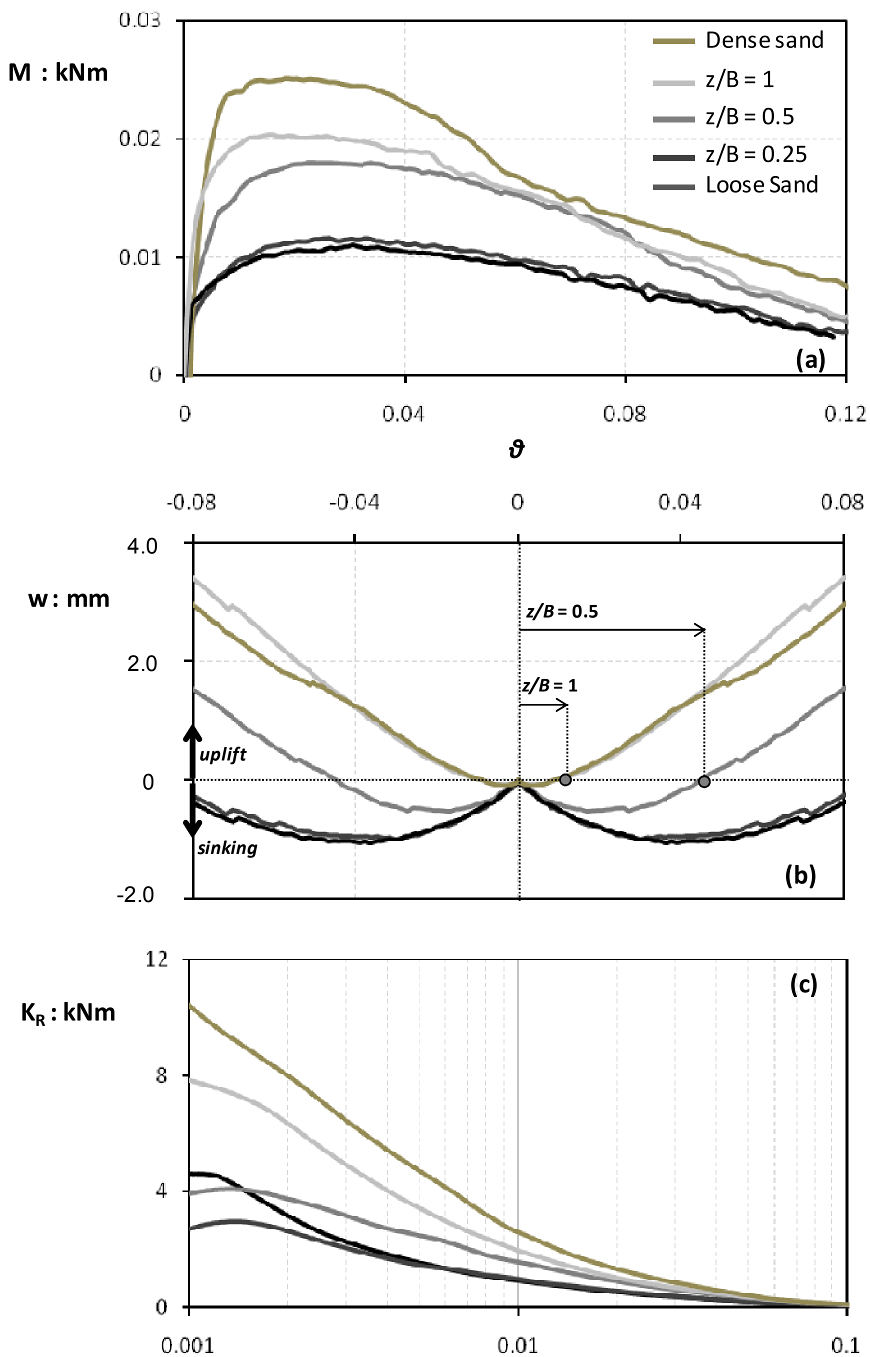


Figure 5. Effectiveness of soil improvement when the **lightly loaded system A** is subjected to monotonic loading. Comparative assessment in terms of : (a) moment–rotation, (b) settlement–rotation response ; and (c) rocking stiffness K_R

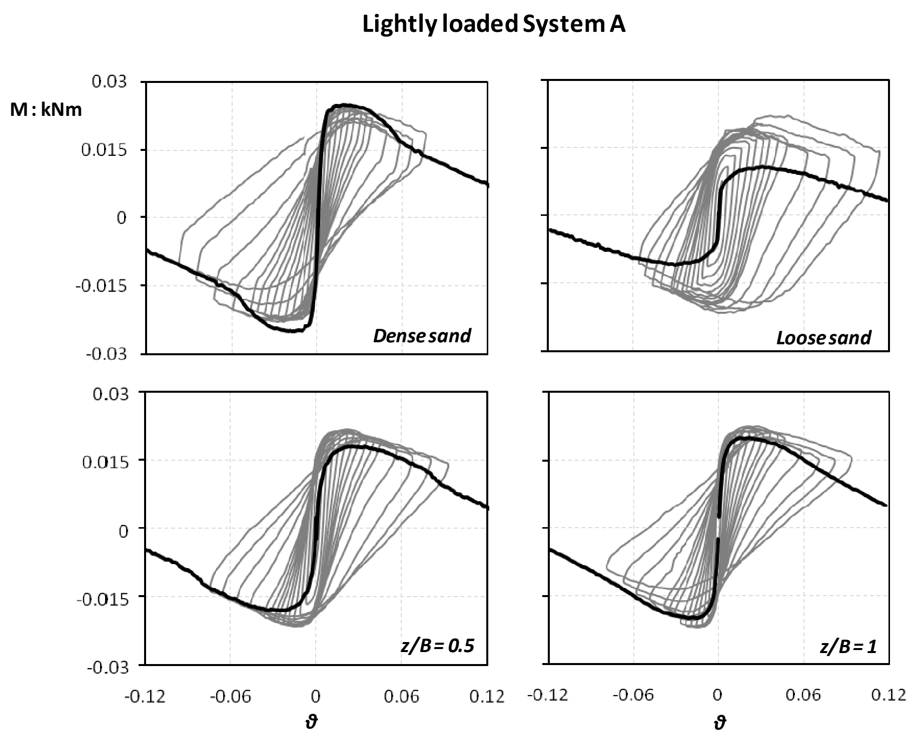


Figure 6. Effectiveness of soil improvement for the lightly loaded system A subjected to cyclic loading (Type 1 protocol). Comparative assessment in terms of moment–rotation response.

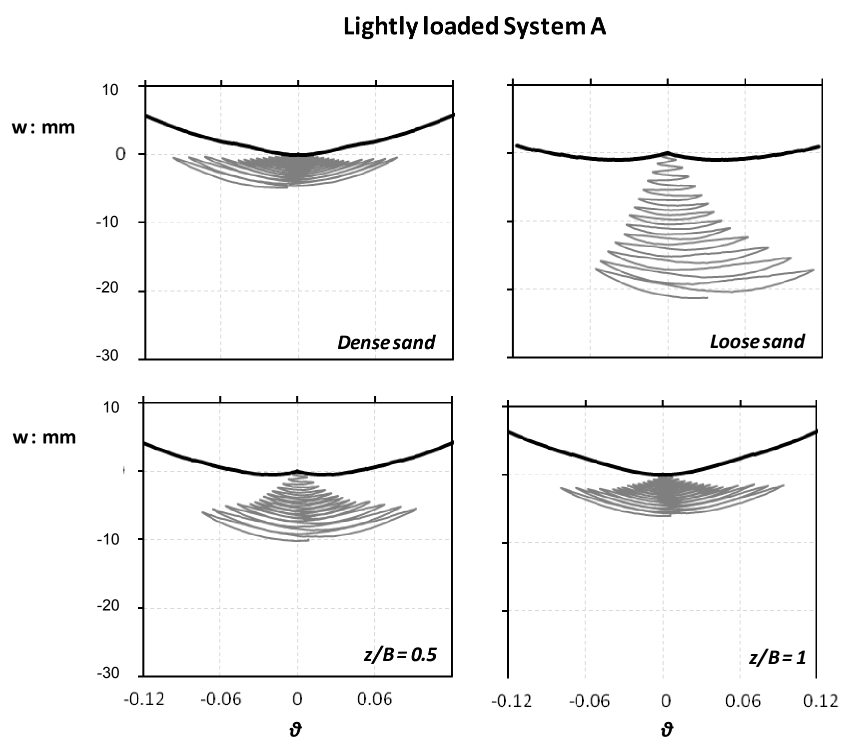


Figure 7. Effectiveness of soil improvement for the **lightly loaded system A** subjected to cyclic loading (Type 1 protocol). Comparative assessment in terms of settlement–rotation response.

In terms of settlement-rotation (Fig 8b) the main conclusions drawn in case of the lightweight system still hold true, with the main difference being the critical improvement depth (i.e. the zone thickness necessary to promote uplifting). The behavior of the models on improved sand seems to be almost identical with that on loose sand when the imposed displacement amplitude is relatively small, which reveals a negligible effect of soil improvement. Indeed, during the initial stages of loading the entire width of the footing maintains contact with the ground thus transmitting the stresses (due to the heavy superstructure) to a large depth exceeding the shallow improved zone; however as the effective contact area reduces due to foundation uplifting during subsequent stages of loading, the role of soil improvement becomes significant and disparities among the four curves are more prominent. In fact, the z/B = 1 curve demonstrates a similar pattern as the dense sand one, with the evolution of the former being parallel to that of the latter due to the (irrecoverable) settlement acquired at the initial loading stages (i.e. before uplifting). When the improvement depth is z/B = 0.5, the response of the footing remains sinking dominated for imposed rotation of up to $\theta = 0.12$; this value reduces to 0.05 when z/B increases to 1 but it never actually reaches the dense sand uplifting threshold of $\theta = 0.03$. Even this value however is by far higher than the corresponding threshold of the lightweight structure described earlier which is less than 0.01.

Cyclic Loading

The response of the four heavily loaded systems when subjected to slow cyclic lateral loading, are illustrated in Figures 9and 10. Quite interestingly**,** during these tests all models reached higher values of moment than the corresponding monotonic case. In fact the overstrength ratio increases rapidly as the safety factor drops resulting in an almost identical cyclic moment capacity of all footings irrespectively of the depth of the mitigation.

With respect to the settlements, all systems conspicuously reflect a sinking-dominated response (Figure 10), accumulating a considerable amount of settlement during each cycle. In this case study, contrary to the lightweight model, the improvement depth of z/B = 0.5 reduces settlements by only 30%. In order to achieve a significant reduction, the use of a deeper zone of improvement of z/B = 1 proves essential.

6. CONCLUSIONS

The primary scope of this investigation was to experimentally test and evaluate the concept of shallow soil improvement. It is concluded that under monotonic loading the ultimate moment M_u increases for higher ratios of z/B. This doesn't hold true when the systems are subjected to cyclic loading. In this case, for large amplitude cycles all models (irrespectively of the depth of the mitigation) tend to reach the same ultimate moment.

Moreover, due to the very nature of foundation rocking which mobilizes only a shallow stress bulb within the soil underneath the foundation, the presence of a shallow zone of mitigation acts very effectively towards limiting the shaking–induced settlement of the foundations. Even a shallow z/B layer ensures uplift-dominated behavior at high rotational amplitudes, while at very small rotations (when the whole foundation width is in contact with the soil) all models accumulate settlement. Yet the rate of accumulation as well as the range of rotation amplitudes where sinking prevails, is controlled by the achieved FS_V. For light systems a z/B = 0.5 was found sufficient, while for heavier systems a z/B = 1 was judged necessary in order to approach the upper bound (desired) response.

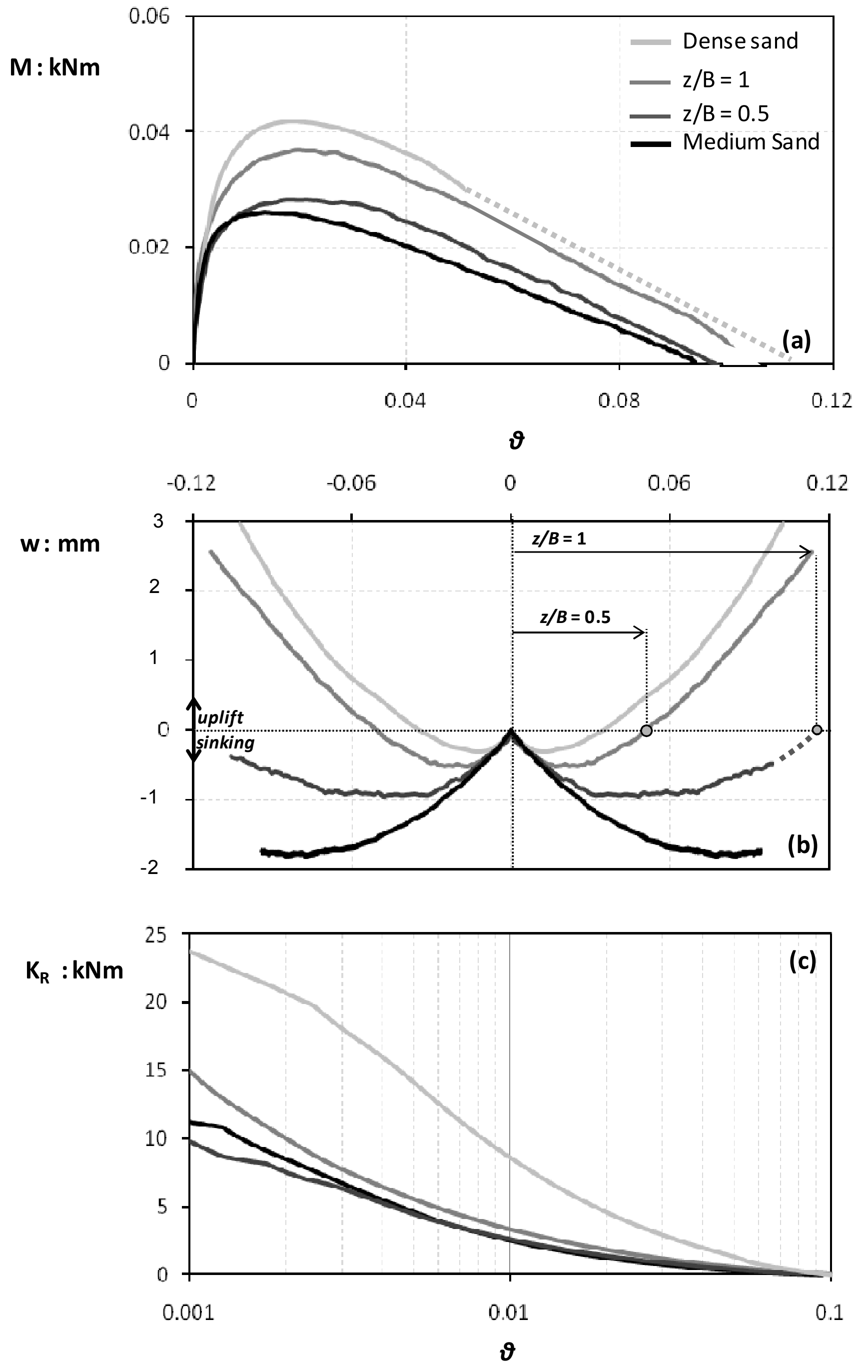


Figure 8. Effectiveness of soil improvement for the **heavily loaded system B** subjected to monotonic loading. Comparative assessment in terms of : (a) moment–rotation, (b) settlement–rotation response), and (c) rocking stiffness K_R

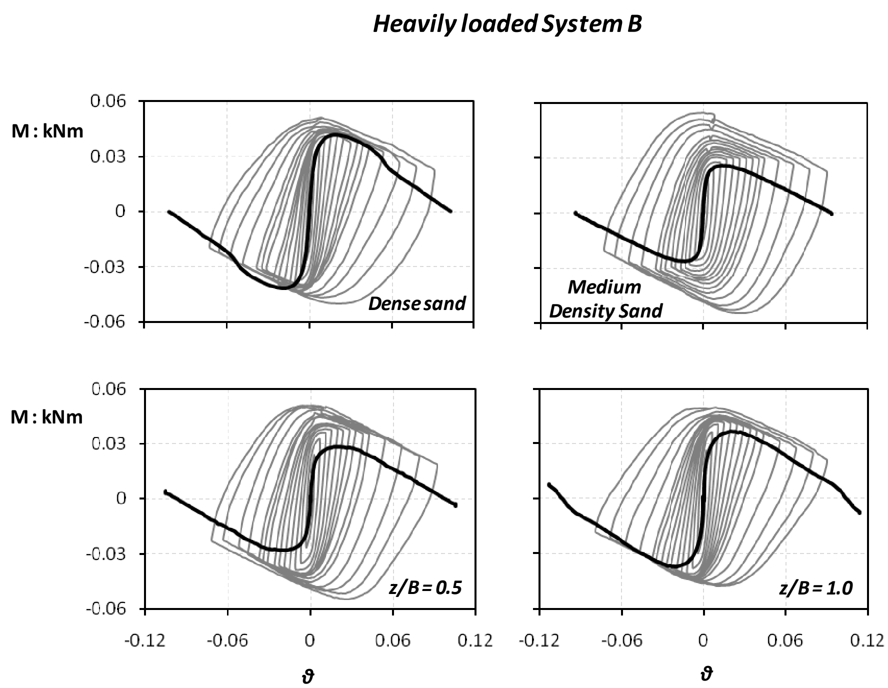


Figure 9. Effectiveness of soil improvement for the heavily loaded system B subjected to cyclic loading (Type 1 protocol). Comparative assessment in terms of moment–rotation response.

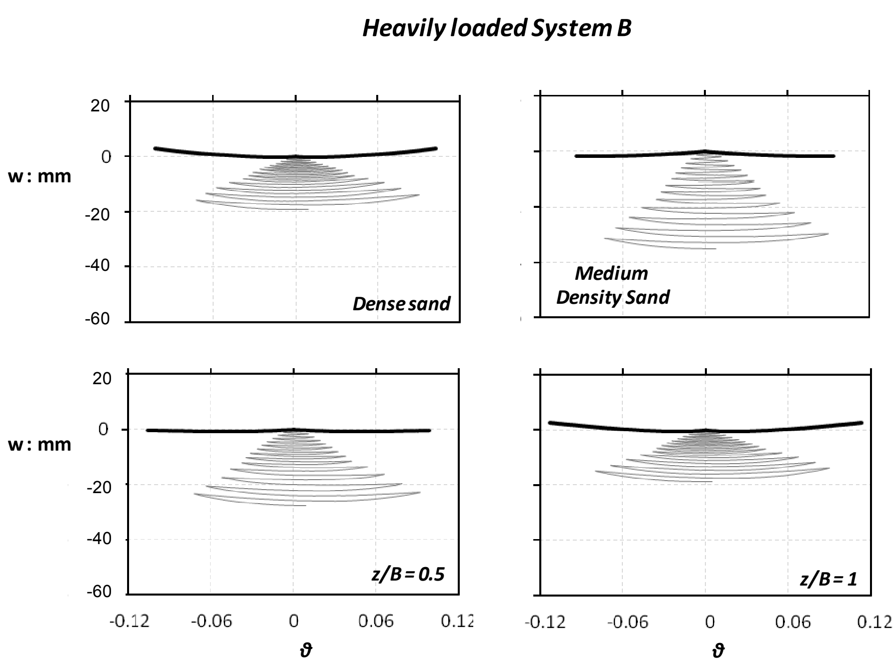


Figure 10. Effectiveness of soil improvement for the heavily loaded system B subjected to cyclic loading (Type 1 protocol). Comparative assessment in terms of settlement–rotation response.

7. ACKNOWLEDGEMENT

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