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Rocking shallow foundation in cohesive soil subjected to oblique cyclic loading in the field

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ABSTRACT

This paper presents a field study of obliquely-loaded rocking shallow foundations resting on cohesive soil. Lateral cyclic loading tests at an oblique angle of 45° with respect to the footing axes were carried. The cyclic loading consists of five packets of which each contain 3-4 cycles of similar displacement amplitude to a drift ratio up to 7%. The rocking foundation system consisted of a 1.5 m by 1.0 m concrete footing, column and deck to simulate a prototype bridge system. A geotechnical investigation was carried out to determine the soil conditions before and after the experiments and soil response during the rocking. The estimated initial factor of safety against bearing capacity ranges from 4 to 20. Nonlinear behavior of the foundations and underlying soil was evident and typical performance graphs, such as moment vs. rotation and settlement vs. rotation, were analyzed. Energy dissipation, equivalent damping, residual rotation, settlement, re-centering ratio and stiffness degradation observed in the tests were discussed and compared with the results from previous studies with orthogonal loading. A method of estimating the rocking moment capacity of footing subjected to oblique loading was developed and validated by the present tests.

Keywords: Rocking foundation, Field test, Cohesive soils, Oblique cyclic loading, Non-linear behaviour.

INTRODUCTION

The benefits of rocking shallow foundations have been studied experimentally using centrifuge [1-3], shake table test [4-5], and reduced scale laboratory test [6-7]. These studies found that rocking foundation significantly reduces the peak deck drift due to flexure, peak acceleration on the deck and the column base shear and moment when compared to fixed-base design. Past earthquakes have also demonstrated that shallow foundation may have avoided severe damage on structure by rocking about its footing [8]. Previous research predominantly focused on the performance of model foundations in sandy soils under the orthogonal loading condition (i.e. aligned footing). The moment capacity equation for a footing under orthogonal loading is well developed and verified by experimentally and numerically as well. However, there is no prediction method for determining the moment footing capacity of an obliquely loaded rocking shallow foundation. Rocking shallow foundations subjected to oblique loads are more complex than their pure axial and lateral loaded counterparts. Limited studies on foundations embedded in cohesive soils have been conducted so far, such as centrifuge model tests [9-10] and field tests [11-12]. In these field tests, however, the footing rotation was notably small (<0.8%) and rocking system performance such as the periods, re-centering ratio, residual settlement of the footing, and change in soil properties was not characterized. Thus, a field test study of rocking shallow foundation in cohesive soil subjected to oblique loading is needed. As it is difficult to conduct field scale dynamic loading test, slow cyclic loading can be an alternative for simulating the moment-rotation behavior of a shallow foundation during a dynamic event [1]. Slow cyclic loadings for the performance assessment of structures are also recommended by FEMA-461 [13].

This paper characterizes the rocking isolation of shallow footing under oblique loading founded on a cohesive soil. A series of field tests of rocking shallow foundation subjected to oblique cyclic loading was carried. The rocking foundation system consisted of a 1.5 m by 1.0 m concrete footing, steel column and concrete deck to simulate a prototype single-degree-of-freedom (SDOF) system. The system is considered a full-scale implementation of the rocking foundation concept. Field tests were conducted for foundations with varying initial factors of safety against the bearing failure (*FSv*), rotation amplitudes and embedment. In-situ investigation and laboratory tests were performed to characterize the soil before and after the test. The initial *FSv* ranged from 3 to 20. This paper presents system performance indicators, such as moment capacity, damping, stiffness, settlement and re-centering capability of rocking shallow foundation under oblique loading and compares to the performance of footings subjected to orthogonal loading.

EXPERIMENTAL PROGRAM

Site Investigation

Field tests were carried out in a cohesive soil site, located on the university farm in Edmonton, Alberta. A geotechnical investigation was undertaken prior to the tests to characterize the properties of the soil. Site investigation consisted of pre-test CPT, Shelby tube sampling before and after field tests, and laboratory testing of undisturbed soil samples. Laboratory test program consisted of the unconfined compressive strength (UCS), undrained shear strength (s_u) using direct shear under various normal stresses, Atterberg limits, and physical properties. The critical soil properties are followed: shear strength, s_u = 65–75 kPa, USCS classification MH, water content = 28 – 32%, plastic limit = 35.6, liquid limit = 89.0. Detailed characterization and results of subsurface soil are presented in Sharma and Deng [14].

Experimental Model

A SDOF system was designed for the study. The system consisted of a rectangular reinforced-concrete (RC) spread footing, a steel tubular column and RC slabs used as the superstructure weight (Figures 1 and 2). The height of the steel tubular column is 2.0 m, and the column has an outer dimension of 0.2 m by 0.2 m and a thickness of 12.7 mm. The column rigidity (*EI*) is 6.444 MN-m^2. The first yield moment (M_{c_col}, 113 kN-m) of the column is designed to be stronger than the rocking moment capacity (M_{c_foot}) of the footing and thus the rocking response would be enabled. Figure 1c defines the Cartesian coordinate system. The *x* and *y* axes are along the axis of the footing respectively, and the *x*' axis is along the loading direction. The directions of a moment (*M*) and footing rotation (θ) are labelled as a double arrow.

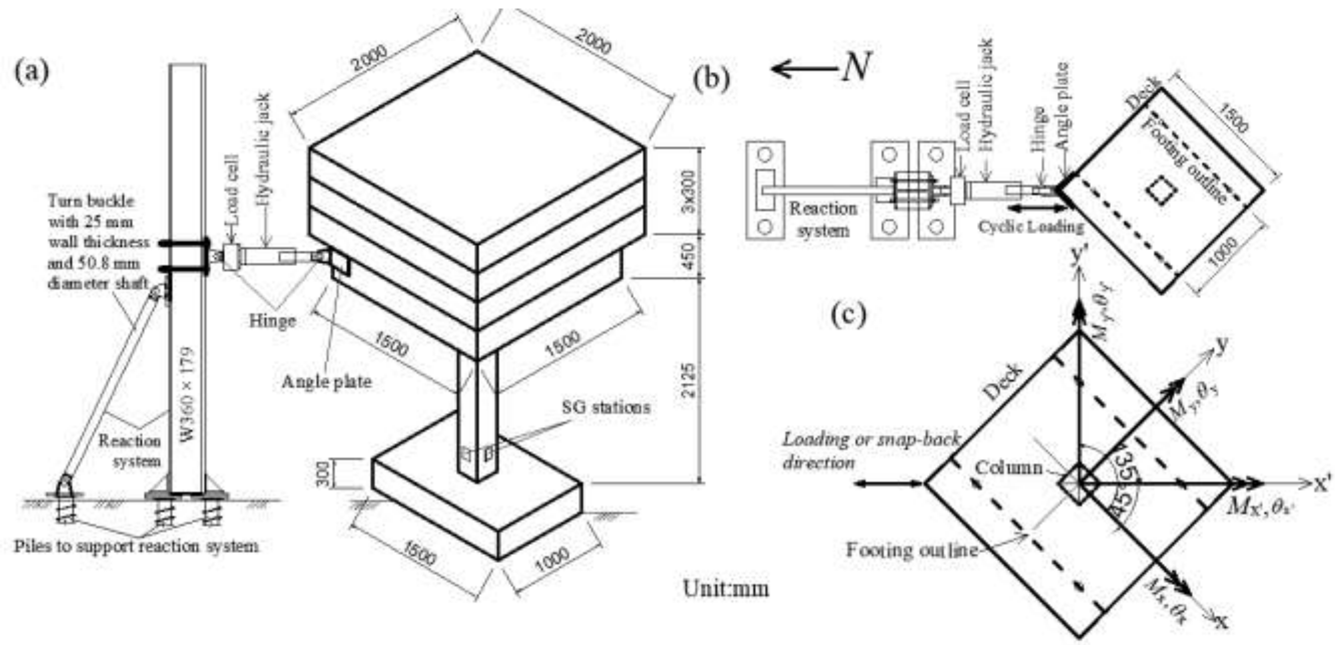

Figure .1 Schematic of the experimental model: (a) a semi-3D view, (b) top view, and (c) Definition of Cartesian coordinate system.

Bearing capacity of soil was calculated using the equation developed by Meyerhof [15] to determine how large the foundations needed to be. Oblique lateral loading causes biaxial moments (M_x and M_y) and eccentricity in both directions. Meyerhof (1953) conducted laboratory tests of model footings on clay and sand under two-way eccentricity and concluded that the contact area was no more rectangular. Highter and Anders (1985) developed an analytical method to estimate the shape and size of the soil-footing contact area under two-way eccentricity. Triangular shape of the critical contact area and its rectangular idealization for bearing capacity estimation were based on Highter and Anders's [16] equations for two-way eccentricity. Critical contact area of the footing was calculated by iterative process as explained in Sharma and Deng [17]. In order to achieve various *FSv* against the bearing failure, additional vertical loads from concrete slabs were added to the superstructure. Consequently, the footing was 1.5 m long, 1.0 m wide and 0.3 m thick. The shallow foundations had an initial *FSv* ranging from 4 to 20.

Instrumentation

Linear potentiometers (LP) of 200 mm stroke were used to measure the vertical and horizontal movement of the footing and deck. These LPs were attached to a steel frame anchored to the ground at each end. A load cell was used to measure the force applied at the connection of the hydraulic jack and concrete deck (Figure 1); additionally, two full-bridge strain gauges were attached at the base of column to measure the bending moment.

Cyclic loading

A series of cyclic loading tests were conducted. Figure 2 shows the test system setup with the reaction system and hydraulic jack. The oblique load was to be applied at an angle of 45° (i.e., *x*' axis in Figure 1c) with respect to the footing axis. The experimental setup was designed so that the load can be applied at the corner of the concrete deck using a double-hinged hydraulic jack mounted to the reaction frame (Figure 1 and 2). The two hinges were used to avoid any unwanted moment or vertical force component. The reaction system was supported by groups of screw piles and an inclined strut (Figure 1). It was assumed that the primary movement of the deck was in the direction of the load, i.e. along *x*' axis. However, some movement may be out of plane along *y*' axis. The out-of-plane movement was also measured. There were two reasons for considering an oblique angle of 45°. First, the system loaded at this angle serves as a case study; and secondly, the angle plate (Figure 1) was fabricated to enable the loading at 45° only.

Figure 2. Field set up for the test SS14.

Cyclic loadings were carried out following the displacement-controlled method. The loading system was designed to produce rotational displacements to induce footing uplift on both sides as the load was reversed. The point of lateral load is 2.525 m above from the footing base. The cyclic loading consists of 5 packets, each of which contains 3 to 4 cycles of the same displacement amplitude, up to the maximum drift ratio of about 6%. The drift time histories are shown as the sinusoidal cycles (Figure 3). The average period of the cyclic loading was about 140 sec that is sufficiently long enough to avoid the generation of an inertia force. The embedded depth of footing (*D*) and *FSv* were systematically varied during the field tests for cyclic loading test. Table 1 outlines the key parameters of the field tests including the *FSv*, *D* and estimated moment capacity of footing subjected to orthogonal loading about *y* and *x* axes i.e. M_{c_footy} and M_{c_footx}. The moment capacity (M_{c_foot}) of a footing subjected to orthogonal loading is estimated using the equation derived by Gajan et al. [18]. Each test is given a test ID as follows: the first character "O" stands for the oblique loading, the second for the footing embedment where "S" for surface footing and "E" for embedded footing, the first and second numbers for the station number and test sequence respectively.

Table 1. Cyclic loading field test matrix

Station	Test ID	Initial *FSv*	D (m)	M_{c_footy} (kN-m)	M_{c_footx} (kN-m)
0	OS01	15.7	0	24.5	15.5
	OS02	8.1	0	41.8	27.8
	OS03	5.1	0	56.6	37.5
	OS04	3.6	0	69.39	45.8
1	OE11	18.3	0.5	28.5	16.9
	OE12	9.3	0.5	43.8	29.3
	OE13	6.0	0.5	64.3	40.5
	OE14	4.2	0.5	74.8	48.5

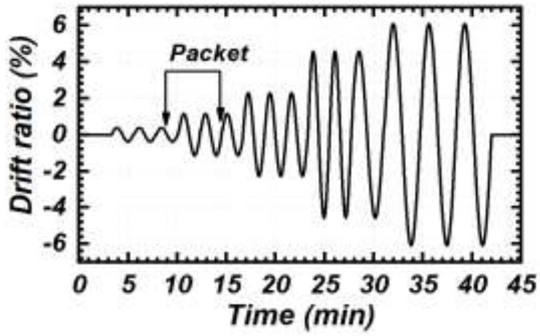

Figure 3. Typical time history of the drift under cyclic load.

RESULTS AND DISCUSSION

Moment-Rotation and Settlement-Rotation correlations

Figure 4 shows the curves of rocking moment vs. footing rotation and settlement (w) vs. footing rotation, using the test OE53 as an example. When the cyclic loading is applied to the rocking foundation system, irrespectively of the loading direction, the system performs similarly in terms of overturning moment-rotation. For comparison, the dash lines in Figures 4a and 4b represent M_{c_footx} and M_{c_footy}. It is shown that M_x exceeded M_{c_footx} whereas M_y was yet to reach M_{c_footy} although the footing rotations were very large. It is likely that the moment capacities during oblique tests are coupled; if the capacity about one axis is decreased from the orthogonal capacity then the capacity about another axis will be increased from the orthogonal counterpart. Figures 4d and 4e show the settlement vs. rotation curves about x and y axes respectively, which illustrate the re-entering behaviour for rocking foundations and also the considerable residual settlement (w_r).

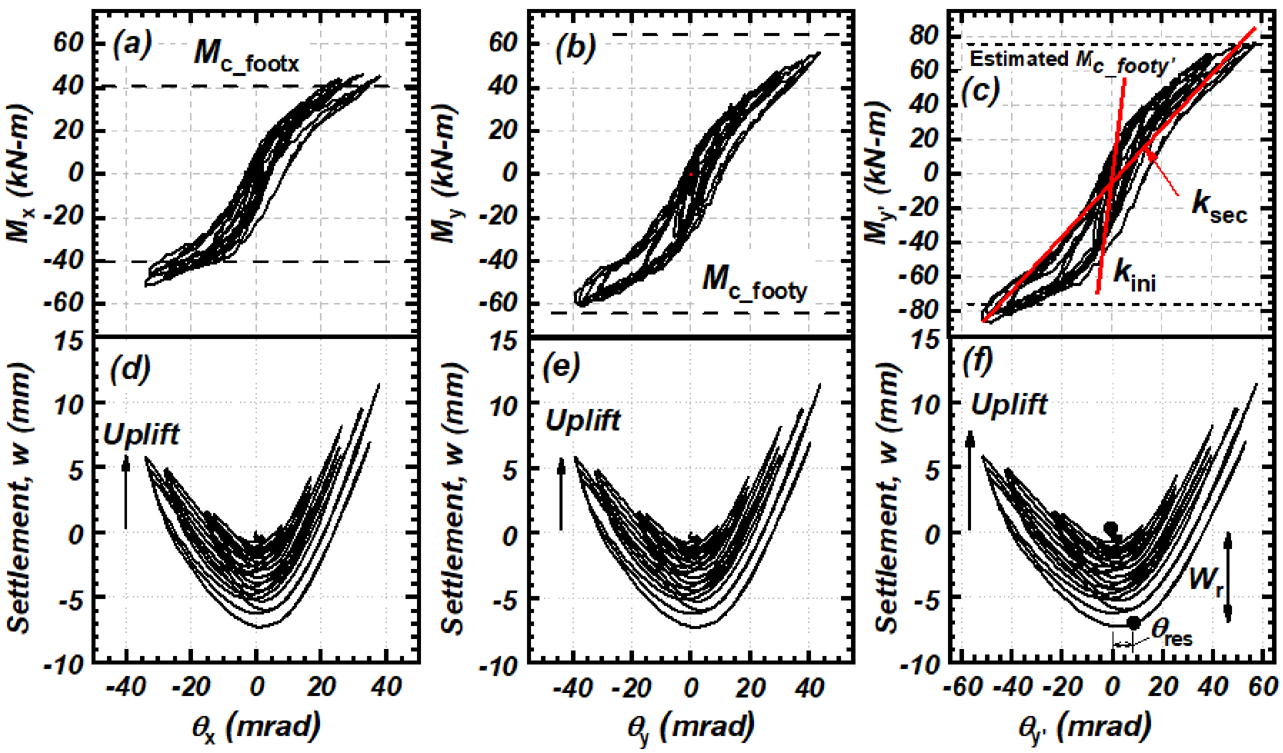

Figure 4. Results of test SE03 (a) M_x vs. θ_y and w vs. θ_y and (b) My vs. θ_x and w vs. $\theta_{x,}$ and (c) resultant moment (M_R) vs. rotation (θ_R) and settlement (w) vs. rotation (θ_R) for test OE03.

Figure 4c shows the typical rocking moment ($M_{y'}$) vs. footing rotation ($\theta_{y'}$) and settlement (w) vs. footing rotation ($\theta_{y'}$) relationships at the base center of the footing, using the test OE03 as an example. The rocking moment and footing rotation measured about x' and y' axes were calculated as follows:

$$M_{y'} = M_y \cos\ (45°) + M_x \sin\ (45°), \text{ in-plane moment} \qquad [1a]$$

$$M_{x\prime} = M_y \sin\ (45°) - M_x \cos\ (45°), \text{ out-of-plane moment} \quad [1b]$$

$$\theta_{y\prime} = \theta_y \cos\ (45°) + \theta_x \sin\ (45°), \text{ in-plane rotation} \quad [2a]$$

$$\theta_{x\prime} = \theta_y \sin\ (45°) - \theta_x \cos\ (45°), \text{ out-of-plane rotation} \quad [2b]$$

where M_x, M_y, θ_x, and θ_y are the measured rocking moment and footing rotation about its respective axis. Equation 2 is based on the principle of vector analysis of rigid body rotations; it is noted that Equation 2 is valid only at a small rotation [19].

The $M_{y'}$ vs. $\theta_{y'}$ curve shows that a rocking foundation on cohesive soils has non-degrading moment capacity irrespective of the loading direction, which was also observed for orthogonal loading of foundations in both cohesive soil and sands [14, 20]; in fact, $M_{y'}$ slightly increased with the number of cycles, possibly due to the strengthening of soils. The settlement (w) vs. footing rotation ($\theta y'$) curve shown in Figures 4f illustrates the re-entering behaviour of rocking foundations in this clay. The troughs of the curves show the amount of permanent vertical deformation accumulated with cycles. The residual settlement (w_r) was observed to increase with the increasing amplitude and number of cycles, which is similar to the observation of previous studies on orthogonal loading in both cohesive soil and sand [9, 14]. The dash lines in Figure 4c show the estimated moment capacity of footing about y' axis, $M_{c\_footy'}$ (= M_{c_footy} cos45° + M_{c_footx} sin45°, which essentially follows Equation 1). The estimated $M_{c\_footy'}$ agrees very well with the maximum $M_{y'}$ in this test. Similar results were obtained for all tests listed in Table 1. This may suggest a new valid method of estimating the capacity of rocking foundations subjected to oblique loading, although the obliquity has altered the orthogonal capacities. As the method for estimating $M_{c\_footy'}$ is valid for the present tests at an oblique angle of 45°, a general equation may be recommended to estimate the capacity of the footing at any oblique angle as Equation 6:

$$M_{c\_foot\alpha} = M_{c\_footy} \cos\ (\alpha) + M_{c\_footx} \sin\ (\alpha), \quad \text{for } 0 \leq \alpha \leq 90° \quad [3]$$

where α is the oblique angle with respect to the x axis of footing.

Stiffness Degradation

Figure 5a shows the progress of secant stiffness (k_{sec} = $M_{y'max}/\theta_{y'max}$) vs. the maximum footing rotation ($\theta_{y'max}$). The secant stiffness is normalized by initial stiffness (k_{ini}) which is the slope of the linear portion of the moment vs. rotation curve, and $\theta_{y'max}$ is the maximum footing rotation at each drift packet applied to the deck. In this figure, a mean stiffness reduction trend was computed for each level of rotation for all tests. It is seen that the rotational stiffness degrades as footing rotation increases. The mean stiffness reduction trend is important when (while) developing the design principle of rocking foundation, because the secant stiffness is a critical index in the displacement-based design for a rocking foundation. The best estimate of stiffness degradation vs. $\theta_{y'\_max}$ correlation of the present study is obtained as follows:

$$\frac{k_{sec}}{k_{ini}} = a\theta_{y\prime max}{}^{b} = 0.013\theta_{y\prime max}{}^{-0.681} \quad [4]$$

The stiffness reduction trend of the obliquely loaded foundation is similar to the trend of foundation under orthogonal loading [21], where the fitting parameters are: a = 0.0157 and b = -0.503.

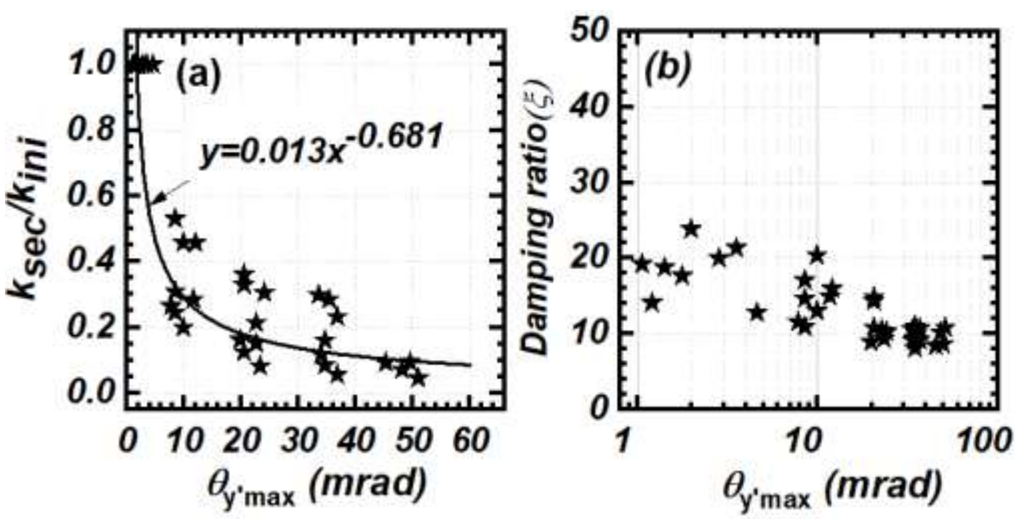

Figure 5. (a) Rotational stiffness degradation versus maximum footing rotation (b) damping ratio vs. footing rotation.

Damping Ratio and Energy Dissipation

Figure 5b shows the equivalent damping ratio (ξ) with respect to maximum footing rotation ($\theta_{y'max}$). The equivalent damping ratio (ξ) during the cyclic loading was calculated using the area bounded by the $M_{y'}$ vs. $\theta_{y'}$ hysteresis [13]. A significant scatter is shown for ξ in oblique loading tests. The value of ξ is about 8 to 30% for all cyclic tests as shown in Figures 5b. This is promising in applications as the observed ξ is greater than ξ considered in many design guidelines [22]. In contrary to previous studies on sand [1, 5, 7], ξ decreases as footing rotation increases. This might be attributed to the skinny moment-rotation hysteretic loops at the higher amplitude of rotation as shown in Figure 4 [14]. The pattern and ranges of ξ under oblique loading are fairly similar to the equivalent ξ of footing under orthogonal loading [14].

Recentering ratio

In order to quantify the re-centering ability of a rocking system, the displacement re-centering ratio (R_d) is introduced as follows:

$$R_d = 1 - \frac{\theta_{y'res}}{\theta_{y'max}} \quad [5]$$

where $\theta_{y'res}$ is the residual foot rotation about y' axis at zero moment. The re-centering characteristic of a rocking foundation is a result of the closure of the gap that forms between soil and footing. As the size of the gap is related to A/A_c, R_d was observed to correlate with the A/A_c ratio [23]. Figure 6 shows the R_d with respect to A/A_c. In cyclic loading tests, R_d was obtained at zero moment condition after each packet (i.e. three full cycles at a given drift ratio). From Figure6, it is seen that R_d is relatively high, ranges from 0.7 to 1.0, for all the tests regardless the A/A_c, and embedded depth. The results indicate a good potential for the rocking structure to maintain its initial position given a reasonably high A/A_c (~*FSv*) in cohesive soils. Furthermore, despite the large θ_{max} (up to 7%) during the tests, θ_{res} may still be acceptable, due to the re-centering characteristic of the rocking foundations. The empirical equation of R_d vs. A/A_c curve obtained from the rocking shallow foundation subjected to oblique loading is regressed as follows:

$$R_d = \frac{1}{1.9\frac{A_c}{A} + 0.97} \quad [6]$$

Figure 6 compares the R_d vs. A/A_c curve for footings subjected to oblique loading to the curve for footings aligned with cyclic loading [14]. It is shown that when the cyclic loading is applied to the rocking foundation system, irrespectively (irrespective) of the loading direction, the system performs similarly in terms of re-centering ability. However, R_d for oblique loading is slightly greater than aligned loading, indicating an even better re-centering ability for foundations subjected to oblique loading.

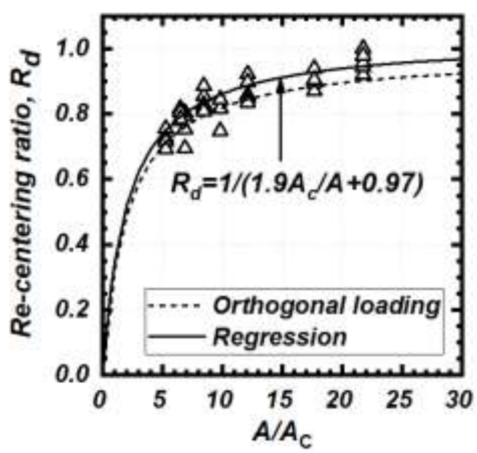

Figure 6. Effect of A/Ac on re-centering ratio.

Residual Settlement

Figure 7 shows the results of residual settlement (w_r) vs. cumulative footing rotation ($\theta_{y'c}$), where the residual settlement (w_r) was obtained after 5 packets of 3 to 4 cycles of similar drift amplitude to a maximum drift ratio of 7%. The residual settlement was calculated for all *FSv* at each station. The concept of cumulative footing rotation is explained in Deng et al. [2] and Hakhamaneshi [9]. In general, it is shown that the w_r vs. $\theta_{y'c}$ results are approximately linear. The results show that residual settlements can be significant if A/A_c is small. If A/A_c is large (e.g., > 10), w_r appeared to be very small even at $\theta_{y'c}$ of

200 mrad, which is seldom reached during a strong motion. Even for very large rotations (250 mrad), the cumulative residual settlement of the footing was about 17 mm which corresponds to only 1.7% of the narrow width of foundation. The settlement response is sinking dominated for the surface footing while it is uplift dominated for the embedded footing. The value of w_r of the embedded footing is minimal even under the lowest A/A_c and at $\theta_{y'c}$ of 350 mrad (Figure 7b). This might be attributed to the soil flow into the gap from the backfill; the filled soil was observed after removing the footing. This is promising for rocking foundations on cohesive soils subjected to oblique loading, since it indicates that the residual settlement may not be a major concern during a real earthquake.

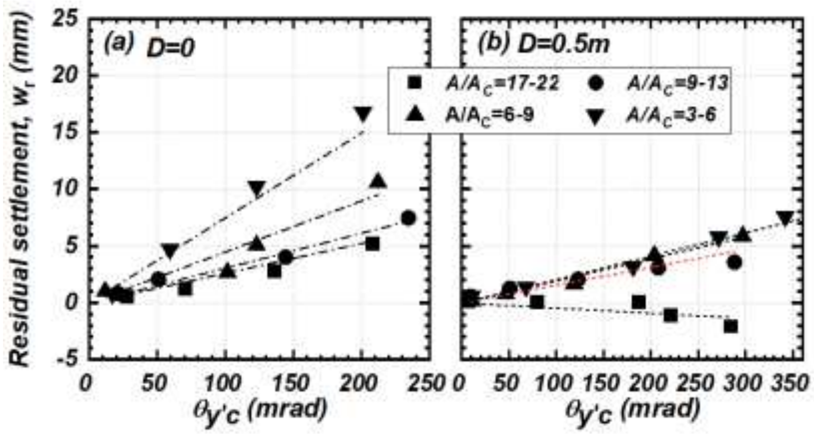

Figure 7 Normalized residual settlement vs. cumulative footing rotation of the footings grouped into different A/Ac ratios.

Settlement of footings subjected to oblique loading was less than the settlement of footing subjected to orthogonal loading. The total settlement of the obliquely loaded footing for the same A/A_c group was about 66% of the residual settlement of the footing under orthogonal [17, 24]. More rounded soil surface was observed in oblique loading cases as compared to aligned loading. Rounding of soil surface decreases the area of footing in contact with the soil. Consequently a shallower stress bulb will be developed and evidently the settlements may be restricted.

Shelby tube samples were obtained from a depth of 0 m to 1.0 m from the base of the footing, before and immediately after a test sequence. Laboratory tests consisted of UCS and direct shear were carried out. The increase in both total density (ρ_t) and s_u of soil is significant. It is seen that ρ_t of soil before tests was about 1870 kg/m^3 and increased to about 1910 kg/m^3 after all tests at Stations 0 and 1. The average s_u of soil from UCS tests before the test was about 70 kPa, which was increased to average s_u of 78 kPa at shallow depth (<0.45 m) at both Stations 0 and 1. However, we have not observed obvious changes in either ρ_t or s_u for soils deeper than approximately 0.45 m. The increased ρ_t and s_u of soil after the experiments should be attributed to the soil yielding and densification during the experiment.

CONCLUSIONS

Results from a series of oblique snap-back and cyclic loading field tests subjected to oblique loading in cohesive soils are presented. The following conclusions may be drawn:

1. When the cyclic loading is applied to the rocking foundation system, irrespective of the loading direction, the system performs similarly in terms of overturning moment-rotation. The moment-rotation relationship of the footing subjected to oblique loading is well defined and non-degrading. A method to estimate moment capacity of the footing at any oblique angle is proposed and the method is validated by tests at 45° oblique angle in the present study.
2. A rotational stiffness reduction curve was established for the rocking system subjected to oblique loading on the clay. The equivalent damping ratio based on the moment-rotation hysteresis curve ranged from 8 to 30%.
3. The rocking system exhibited a good re-centering ability. The correlation of re-centering ratio vs. A/A_c was developed. The re-centering ability of a rocking system subjected to oblique loading on clay is even better than that of an aligned footing.
4. The value of w_r was less than 1.7% of the narrow width of footing even at cumulative footing rotation of 250 mrad. As A/A_c increases, w_r reduces significantly. The settlement of footing subjected to oblique loading on clay was less than the values of footing under orthogonal loading given the similar A/A_c range.
5. Rounding of soil surface beneath the footing along the loading direction was observed, which is more significant in surface footing. An increase in the shear strength and density beneath the footing edges due to rocking cycles was observed.

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