Rocking Shallow Foundations as Seismic Energy Dissipaters: Theoretical Analyses of Experimental Findings

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ABSTRACT: This paper presents the analyses and interpretation of centrifuge and shaking table experimental results on rocking shallow foundations available in the literature. Two key parameters that primarily control the cyclic load-displacement, moment-rotation, and energy dissipation characteristics of rocking shallow foundations are critical contact area ratio (A/A_c) of the foundation and the aspect ratio of the structure (H/B). Combining these two parameters, a dimensionless parameter called rocking coefficient (C_r) of the structure-foundation system can be obtained. Experimental results for energy dissipation in foundation soil and rocking induced maximum rotation and total settlement of the foundation are correlated to C_r, A/A_c, H/B and the intensity of the earthquake. Useful correlations have been obtained among these parameters that can be used to optimally design shallow foundations with controlled rocking that take advantages of the beneficial effects of foundation rocking while minimizing the adverse effects

1 INTRODUCTION

1.1 *The concept of rocking shallow foundations*

It has been shown that foundation rocking and soil yielding can be used for seismic protection of structures (Gajan and Kutter 2008, Anastasopoulos et al., 2010, and Deng et al., 2012). However the conventional seismic design of shallow foundations forces plastic hinge (column yielding) to occur at the base of the column. This is typically done by making sure that the moment capacity of the column be smaller than that of the soil-foundation system. Deng et al. (2012) showed that plastic hinging can be forced to occur at foundation soil during rocking by making sure that the rocking coefficient (C_r) is smaller than the base shear coefficient (C_y) of the column; where C_r and C_y are non-dimensional moment capacities of soil-foundation system and column respectively. Fig. 1 shows both concepts schematically: conventional design with plastic hinging at the base of the column and rocking foundations with plastic hinging in soil, which avoids structural failure (slightly modified after Anastasopoulos et al., 2010).

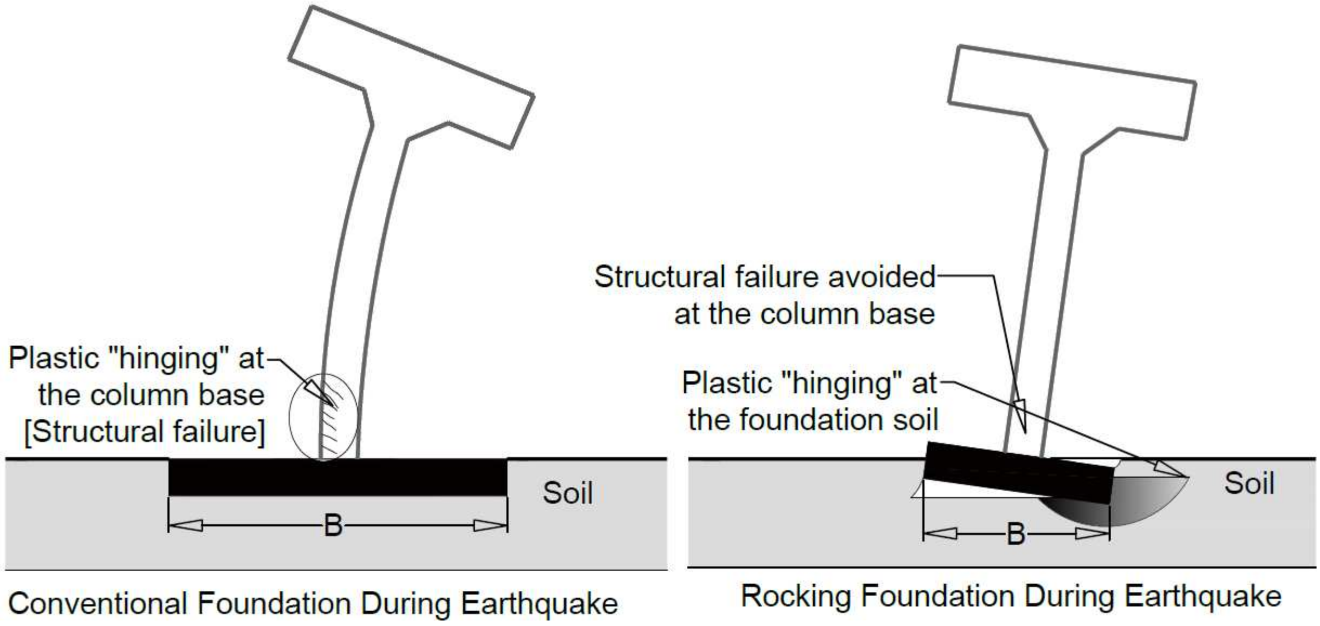

Fig.1 Comparison of conventional shallow foundation with rocking shallow foundation

1.2 *Objectives of the paper*

The objective of this paper is to present the results, analyses, and interpretation of thirty-two centrifuge and shaking table experimental results for rocking induced settlement of the foundation and maximum rotation of the structure and seismic energy dissipation in foundation soil during rocking as functions of rocking coefficient (C_r), critical contact area ratio (A/A_c), aspect area ratio of the structure (H/B), and the intensity of the earthquake (Arias intensity and maximum shaking acceleration). Note that the sliding displacement of the foundation is not considered in this study because it has been shown that as long as $H/B > 1.0$, the rocking motion dominates and sliding displacements are negligible (Gajan and Kutter, 2009).Note that all the parameters used in the analyses are defined in next section.

2 THEORITICAL ANALYSIS

Fig. 2 shows the configuration of forces and displacements of a rocking system that are discussed in this section.

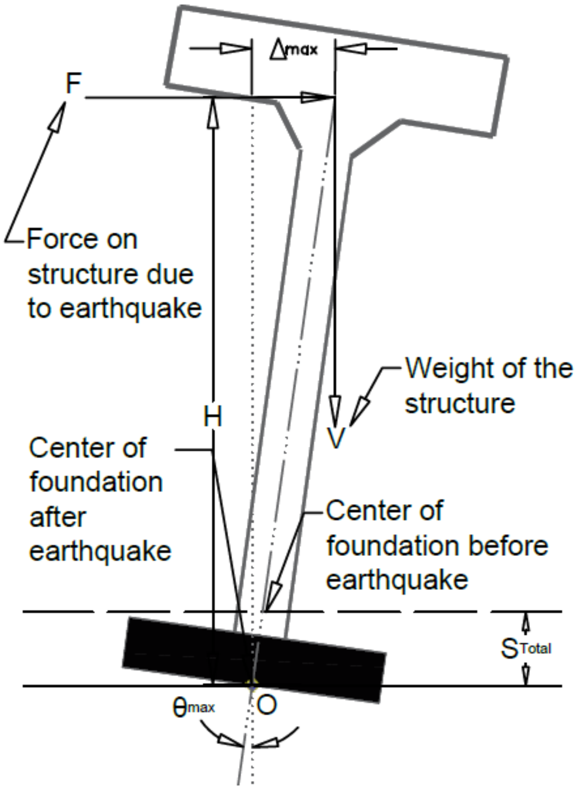

Fig. 2 Configuration of forces and displacement of rocking system

The rocking coefficient depends on two parameters: critical contact area ratio of the soil-foundation system (A/A_c) and the aspect ratio of the structure (H/B); where A is the total base area of the footing, A_c is the minimum footing contact area required to support the applied vertical loads (un-factored) on the foundation (which can be calculated from conventional bearing capacity equation (static) and the associated shape and depth factors), H is the effective height of the structure (Fig. 2) and B is the dimension of the footing in the direction of shaking (Fig. 1). By considering equilibrium equations and the moment capacity of soil-foundation system, the following equation can be derived for C_r:

$$C_r = \frac{B}{2 \times H}\left(1 - \frac{A_c}{A}\right) \tag{1}$$

One way of quantifying the intensity of the earthquake is Arias intensity. Arias intensity (I_a) combines the magnitude, frequency content, and duration of the earthquake and is defined as,

$$I_a = \frac{\pi}{2g}\int_0^{\infty} [a(t)]^2 \, dt \tag{2}$$

where g is the gravitational acceleration and a(t) is the acceleration time history.

The rocking induced total settlement is primarily a function of two key parameters, C_r and I_a, as they incorporate the effects of foundation geometry, aspect ratio of the structure, soil parameters, and intensity of the earthquake:

$$S_{Total} = f(C_r, I_a) \tag{3}$$

It was found that the rocking induced maximum rotation of the foundation, on the other hand, is primarily a function of aspect ratio of the structure (H/B) and maximum acceleration of the earthquake (a_{max}).

$$\theta_{max} = f\left(\frac{H}{B}, a_{max}\right) \tag{4}$$

For relatively rigid structures supported by rocking foundations, the maximum lateral displacement at the height of center of gravity of the structure (Δ_{max}) can then obtained by,

$$\Delta_{max} = \theta_{max} \times H \tag{5}$$

The amount of energy dissipation (ED) in foundation soil during rocking comes primarily from the area of the hysteresis loops in the cyclic moment-rotation (M-θ) relation of the soil-foundation system,

$$ED = \int_0^{\theta_{fin}} M \, d\theta \tag{6}$$

A non-dimensional energy dissipation (NED) was then obtained by normalizing ED by the weight of the structure (V) and the dimension of the footing in the direction of shaking (B),

$$NED = \frac{ED}{V.B} \tag{7}$$

3 EXPERIMENTAL PROGRAMS

Results of seventeen centrifuge experiments conducted at University of California, Davis (UCD) (Ugalde et al., 2007 and Gajan and Kutter, 2008) and the results of fifteen shaking table experiments conducted at the National Technical University of Athens (NTUA), Greece (Drosos et al., 2012, and Anastasopoulos et al., 2013) have been considered in this study.

3.1 *Types of soils, foundations, structures and loading*

The soil type used in UCD experiments was dry Nevada sand (Dr = 80% and $\Phi = 42^o$) while the soil type used in NTUA experiments was dry Quartz sand (Dr = 85% and $\Phi = 44^o$). The properties of both sands are similar, which makes the comparisons meaningful. Gajan and Kutter (2008) tested rigid shear wall structures supported by shallow foundations while Ugalde et al. (2007) modeled relatively flexible reinforced concrete columns connected to a deck mass supported by shallow foundations. In NTUA experiments, deck mass connected to rigid columns supported by shallow foundations were used. Note that majority of the experiments were conducted on surface footings while some experiments included a shallow embedment of the footings in soil. Both UCD and NTUA experiments included base shaking of actual earthquake recordings and artificially generated acceleration time histories as well (e.g., sine waves).

4 RESULTS AND DISCUSSION

4.1 *Total permanent settlement*

Rocking induced total permanent settlement (S_{total}) was obtained from the cyclic settlement-rotation relations presented by all the researchers. Fig. 3 presents the variation of S_{total} with C_r for different sets of Arias intensity of the earthquake (I_a). Though the data is scattered, in general, for a given I_a, as C_r increases, S_{total} decreases. This is intuitive because as C_r decreases, the vulnerability of the footing to rocking increases and hence more rocking induced settlement. As expected, for a given C_r, S_{total} increases as the intensity of the earthquake (I_a) increases. Overall, based on the thirty two experimental results, given C_r and I_a, the total settlement of a rocking system can be estimated with reasonable accuracy.

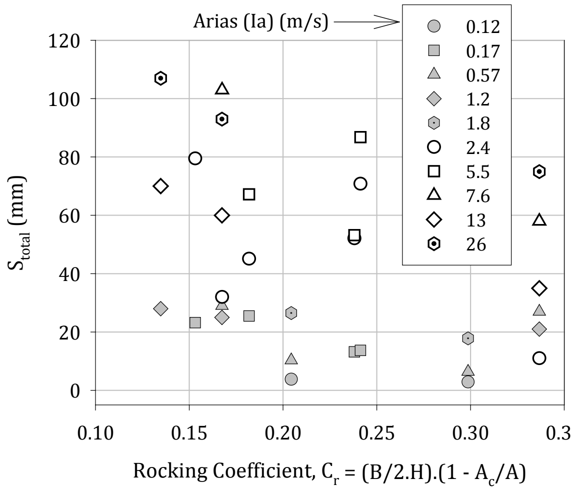

Fig. 3 Variation of the rocking induced total settlement with rocking coefficient (C_r) and arias intensity (I_a)

4.2 *Maximum rotation*

While total settlement is cumulative, the maximum rotation (θ_{max}) of a rocking system is instantaneous (due to the reversing nature of the seismic shaking and the self-centering characteristic of rocking shallow foundation). For this reason, θ_{max} is correlated to a_{max} rather than I_a. Fig. 4 presents the variation of θ_{max} with a_{max} for different sets of aspect ratio of the structure (H/B). As expected, for a given H/B, θ_{max} increases as the intensity of the earthquake (a_{max}) increases. Though there is scatter in the data, in general, for a given a_{max}, θ_{max} increases as H/B increases (as taller structures tend to rotate more than shorter structures). Based on the correlation presented in Fig. 4, the maximum lateral displacement (Δ_{max}) of the structure during earthquake can be predicted with reasonable accuracy.

4.3 *Energy dissipation*

Normalized seismic energy dissipation (NED) in foundation soil during rocking was also found to correlate well with a_{max} and C_r rather than I_a. Fig. 5 presents the variation of NED with a_{max} for two sets of C_r values. For a given range of C_r, NED increases as the intensity of the earthquake (a_{max}) increases. For a given a_{max}, NED increases as C_r decreases. This is also intuitive as systems with small C_r values have more tendency to rock and hence more energy dissipation. Also note that this increased energy dissipation comes at the expense of slightly increased settlement for rocking systems with smaller C_r values (Fig. 3). Finding an optimum C_r value for a given type of soil-structure system, where NED can be maximized while not exceeding the allowable settlement and rotation limits of the structure, is essential.

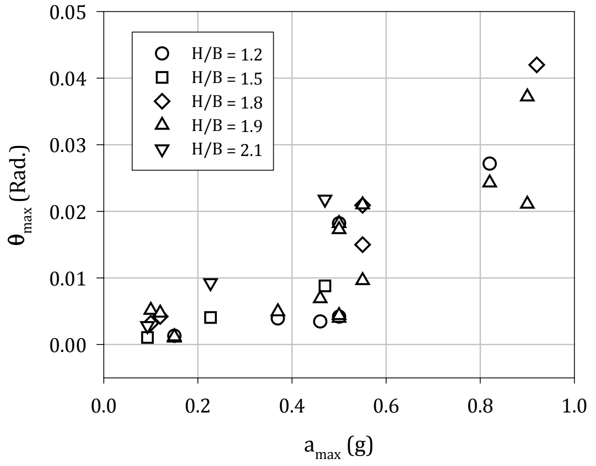

Fig. 4 Variation of maximum rotation (θ_{max}) with a_{max} and H/B

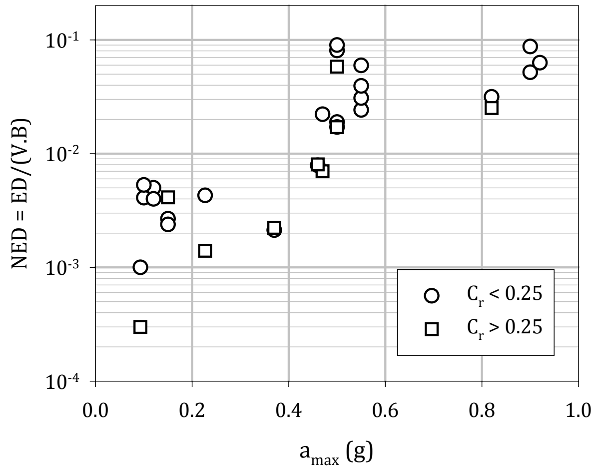

Fig. 5 Variation of normalized energy dissipation (NED) in foundation soil with a_{max} and C_r

5 CONCLUSIONS

This paper summarized and analyzed thirty two centrifuge and shaking table experimental results of rocking shallow foundations. The results for rocking induced total settlements and maximum rotation of rocking systems and the seismic energy dissipation in foundation soil are correlated to rocking coefficient, aspect ratio of the structure, Arias intensity and maximum acceleration of the earthquake. The results presented in this paper confirmed the hypothesis that rocking systems with small C_r values (compared to C_y values) have a higher tendency to rock and hence would result in higher settlement and rotation and higher energy dissipation. The presented correlations can also be useful in estimating the deformations and energy dissipation of a rocking system given the structural and soil properties and the intensity of the earthquake. Future research will focus on finding an optimum C_r value for a given soil-foundation-structure system where the beneficial effects of foundation rocking can be maximized while minimizing the adverse effects.

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