CENTRIFUGE MODELING OF INNOVATIVE FOUNDATION SYSTEMS TO OPTIMIZE SEISMIC BEHAVIOR OF BRIDGE STRUCTURES

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ABSTRACT:

The effects of rocking bridge foundations were investigated by two series of highly instrumented centrifuge tests. Slow cyclic tests on shallow foundations supporting rigid elastic columns were performed to capture the nonlinear moment-rotation behavior of foundations. Dynamic shaking tests were performed on lollipop bridge structures with variable footing dimensions supporting yielding columns. Results show that the test columns produced a well-defined moment capacity. Plastic rotation demand on the column decreases consistently with a decrease in the foundation moment capacity and a rocking footing can reduce ductility demand and permanent drift, improving bridge system behavior. Numerical analyses were implemented in OpenSees, an open source finite element platform, to validate the experimental results by using nonlinear Winkler springs simulating footing behavior. Numerical analysis is shown to be able to capture the experimental results satisfactorily. If settlement associated with rocking may be significant, experiments show that the settlement may be reduced by strategically locating relatively small zones of improved soil.

KEYWORDS: Shallow foundations, rocking, bridge, centrifuge, seismic performance, numerical analysis

1. INTRODUCTION

Current seismic design guidelines for the California Department of Transportation (Caltrans) discourages rocking of shallow foundations for bridges (Caltrans 2006). Very large shallow foundations or pile foundations are often specified to preclude rocking. Previous earthquakes, experiments and numerical analyses have consistently shown that a rocking foundation has predictable moment capacity and good energy dissipation characteristics (Taylor et al. 1981, Gajan et al. 2005, Mergos and Kawashima 2005, Ugalde et al. 2007, Deng et al. 2008). Taylor et al. (1981) suggested that spread footings may be intentionally designed to yield during high-intensity earthquakes and that this may be preferable to yielding of columns. Gajan et al. (2005) presented data of non-linear load displacements of shallow foundations resting on moderately dense sand. Ugalde et al. (2007) conducted centrifuge experiments on single degree of freedom elastic bridge columns with square footings. Mergos and Kawashima (2005) developed a numerical model using Winkler foundation springs and established that inelastic rocking has a significant isolation effect and that this isolation effect increases as the size of the foundation decreases.

An ongoing research project at the University of California, Davis aims to explore possible innovative foundation systems that will optimize the seismic performance of bridge systems. Plastic rotation demand in columns, energy dissipation capacity of the system and displacement demand of the superstructure are assumed to be the main parameters that quantify the seismic performance of bridges. In the conventional design practice, the superstructure and foundation components are designed to behave elastically. Columns are designed to be ductile and allowed to go into the inelastic range during seismic shaking. As a direct consequence of the design philosophy, bridge columns have often been observed to suffer significant damage during strong shaking.

Centrifuge model tests and numerical analyses were performed to investigate the consequences of allowing rocking of bridge systems. It is hypothesized that ductility demands on the columns may be reduced by allowing some rocking of the footing. Several slow cyclic tests were performed on footings of different sizes to quantify the moment-rotation-settlement behavior of the footings. Then, models of 'lollipop' type structures supported on flexible columns and a plastic hinge were subjected to a suite of earthquake motions obtained by scaling earthquake records from the 1999 Chi-Chi earthquake, the 1971 San Fernando and the 1984 Morgan hills earthquakes.

A numerical model was also developed using the finite element platform OpenSees to study the effects of foundation flexibility. The modeling of soil-foundation interaction used a system of nonlinear subgrade reaction springs which were based on design guidelines for spring stiffness taken from FEMA-356 (FEMA 2000). Model development was an evolving process; selected comparisons between experiment and simulation are presented in this paper.

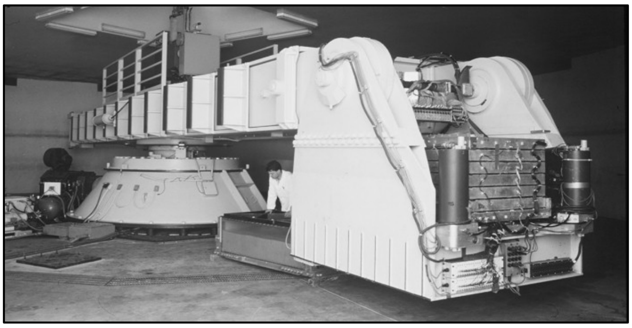

Figure 1. Centrifuge facilities of University of California, Davis

2. EXPERIMENTAL SETUP

The principles of centrifuge testing and scale factors have been well developed (e.g., Kutter 1995). The centrifuge facilities of UC Davis are shown in Figure 1. In this project, 49 g centrifugal acceleration was adopted, and length dimensions were scaled by a factor of 1/49. The mass, stiffness, natural frequency, and column moment capacity (among other parameters) were scaled according to standard centrifuge modeling laws, and based upon a real prototype bridge located in Sonora, California. Small, medium, and large footings with L/D = 2.7, 4 and 5 were used in the experiments. L represents the footing length and D the prototype column diameter.

2.1. Soil Properties

The model structures were built upon dry Nevada sand in a 1.8 m long by 0.9 m wide rigid container. Some properties of the Nevada sand are given in Table 1.

Table 1. Properties of Nevada sand

Soil	Nevada Sand
Classification	Uniform, fine sand; SP
Specific gravity	2.67
Mean grain size, D_{50}	0.17mm
Coefficient of uniformity, C_u	2.0
Maximum void ratio[1], e_{max}	0.887
Minimum void ratio[1], e_{min}	0.511
Dry unit weights in experiments, γ_d (kN/m^3)	γ_d =15.2, γ_d =16.3
Relative density, D_r	D_r =44%±5%, D_r =73%

[1] Gajan (2006)

WD40® was sprayed around the perimeter of the footings and the surface of the sand for all spins. It is a widely-used penetrating oil spray solution which did not evaporate too quickly and was discovered to provide a desired small amount of apparent cohesion to the fine sand. The small cohesion minimized the raveling of sand into the gap that opened beneath the footings as they rocked. Without this cohesion, footings with a high factor of safety against bearing failure in slow cyclic tests were observed to rise up a little with every cycle of rocking, and this did not seem realistic.

2.2. Model Properties

2.2.1 Slow Cyclic Test Model Properties

The structure, fabricated with aluminum, was designed to be rigid during slow cyclic tests. Rectangular footings were fixed at the base of the wall. The foundations were made of aluminum plates and were consistent with the footing dimensions which were to be tested in later dynamic shaking tests. Steel blocks were bolted to the aluminum wall to increase the weight of the structure so that the mass could match the prototype bridge mass. Figure 2 shows a slow cyclic structure in its setup position. The lateral loading was applied approximately 280 mm above the footing base using a servo-hydraulic actuator connected to the structure with a linear bearing to prevent loading transverse to the actuator piston. A load cell measured the actuator loads. Two linear variable differential transformers (LVDT's) were mounted to measure lateral displacement and rotation of the structure, and two string potentiometers were used to measure settlement and rotation, as shown in Figure 2.

2.2.2 Dynamic Test Model Properties

The structures consisted of an aluminum rectangular footing, a column made from 38 mm x 19 mm rectangular aluminum tube, and three plates to provide the appropriate deck mass, which is shown in Figure 3. The bending stiffness of the prototype column was accurately modeled by the selected tube. In order to capture the yield moment, the column was notched near the base of the column where a plastic hinge is typically located. The dynamic structure was highly instrumented so that accelerations and displacements of the deck and footing could be measured directly. LVDT's were used for measuring relative displacement between the deck and the footing, and are visible in Figure 3. During each dynamic test, two structures with different footing dimensions were placed in parallel and shaken simultaneously so the effect of footing dimension could be determined in side-by-side comparisons.

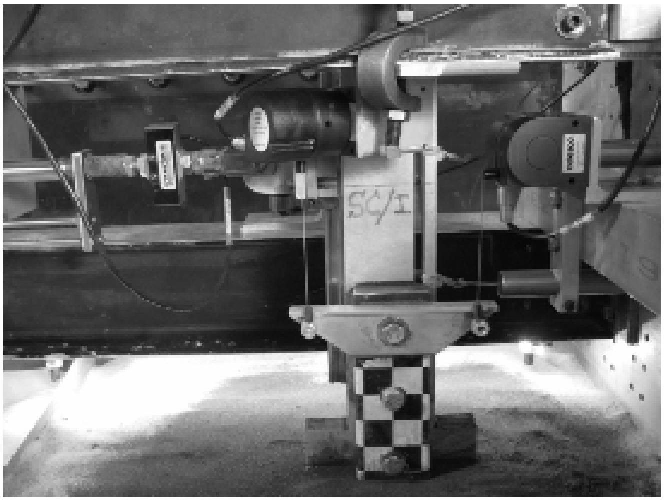

Figure 2 A typical structure setup during a slow cyclic test

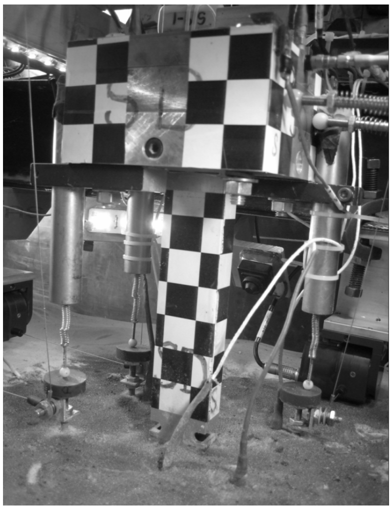

Figure 3 Setup of the model during a dynamic test in the centrifuge arm

3. EXPERIMENTAL RESULTS

3.1. Slow Cyclic Test Results

Several packets of three uniform displacement-controlled cycles producing total drift ratios ranging between 0.15% and 5% were applied to the structure. One of the goals of the project was to engineer innovative foundation design that could be economically reproduced on prototype scale. Previous test series on rocking shallow foundations observed modest settlements, (e.g., Ugalde 2007) so in an attempt to reduce this disadvantage of rocking, four cement pads were embedded under the footing in one of the slow cyclic tests. The addition of the pads was to simulate the possibility of ground improvement by, for example, jet grouting along the edges of the footing.

The results from the non-improved and improved foundations during two slow cyclic tests are presented for comparison. For these two particular tests the density of the sand was 44%. Figure 4 shows the foundation pads, the image on the left shows an excavated foundation post testing and the image on the right shows the configuration of the pads with a foundation outlined as the dashed rectangle.

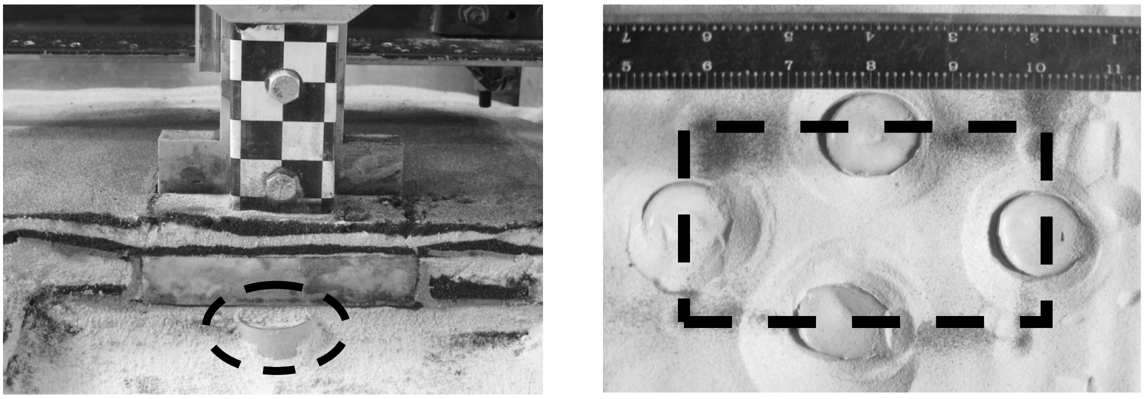

Figure 4 Excavated views of the foundation pads used in the slow cyclic tests (circled with dotted line)

Figure 5 shows the moment rotation and settlement rotation plots for the non-improved and improved foundations respectively. The settlements on each system show the benefits of the foundation pads used, reducing the prototype settlement from 0.045 m (0.115-0.070 m) to 0.022 m (0.098-0.076 m) – a reduction of over half, while the energy dissipation characteristics (the area of the moment rotation loops) were not affected significantly. The slight 'S' shaped curve of the moment rotation graph on the right arises from non-uniform resistance offered by the foundation pads during the rocking cycle.

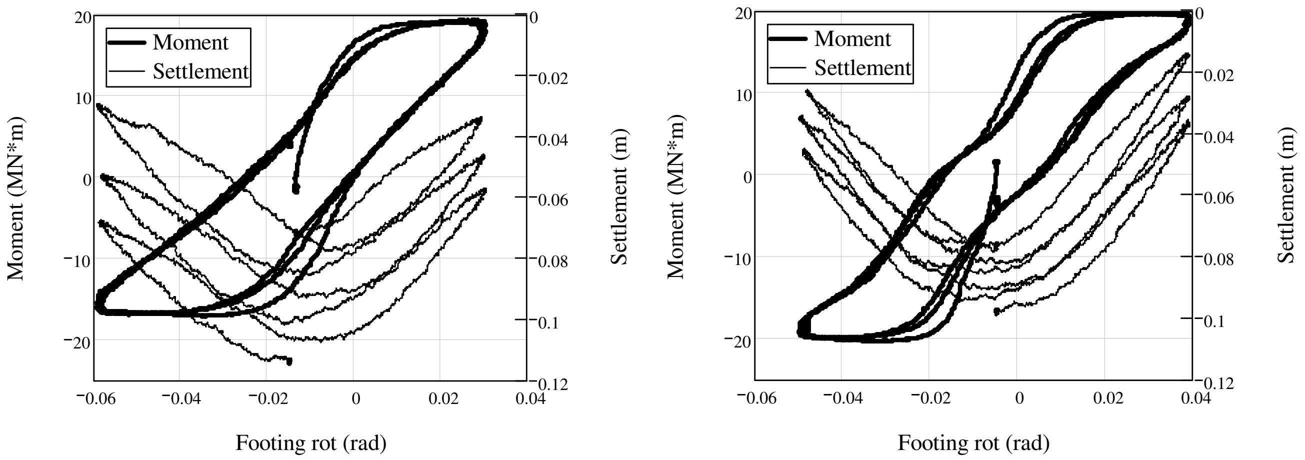

Figure 5 Moment rotation and settlement rotation for non-improved (left) and improved (right) small footings

3.2. Dynamic Results

The structures were subjected to several different earthquake intensities, beginning at 20% amplitude ratio for each record and increasing to 100% amplitude. Three different ground motions were used with the most severe motion being from the San Fernando earthquake from 1971. Figure 6 shows a base motion of the centrifuge box for this record, having a peak ground acceleration of 0.75g.

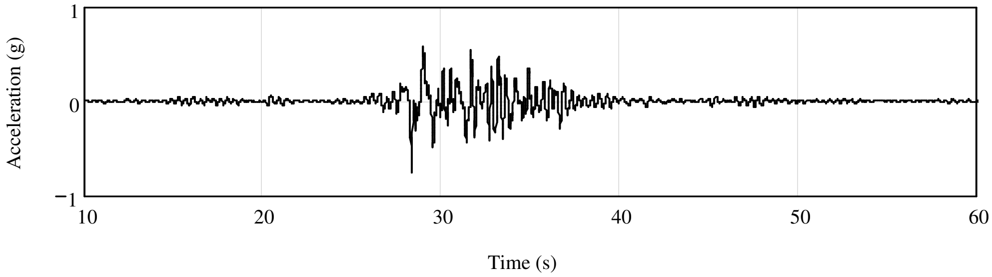

Figure 6 The time history of the San Fernando earthquake as recorded on the centrifuge box

One major measurement of interest was the drift demand of the system which is critical to the serviceability of bridges. Figure 7 shows the total drift, column rotation and footing rotation for the medium and small footing respectively. The medium footing displays a total drift of 7.2% while the small footing displays only 2.6%.

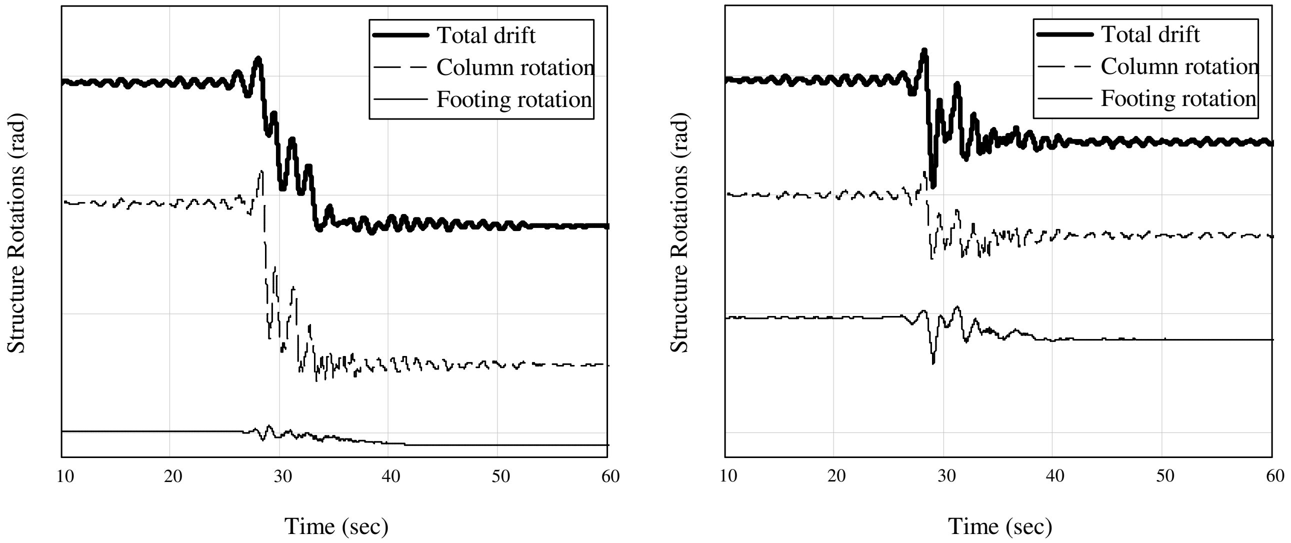

Figure 7 Total drift, column rotation and footing rotation plots for the medium (left) and small footing (right)
Note: each y-axis grid line represents 5% rotation

As the graph on the left shows, most of the drift in the medium footing occurs in column rotation and footing rotation can almost be assumed negligible. Subsequently the small footing shows some of the drift occurs in column rotation and some in footing rotation. The reduction in column rotation is very beneficial because it will result in less column damage. A rocking structure would tend to re-center to its original position because of the gap formed between footing and soil. Therefore permanent total drift on the system was reduced greatly by allowing foundation rocking. The superstructure is may be less likely to sustain damage and the chance of catastrophic failure is potentially reduced.

Notches were drilled out of the columns to create a local ‘weak’ point where column yielding would occur. These were located at half the column diameter up from the top of the footing – the standard assumed position for the center of the plastic hinge region in a reinforced concrete column. The size and shape of the notches were found by extensive column loading tests prior to the centrifuge tests. The moment capacity of the model column matched the moment capacity of the prototype bridge with the inclusion of the notches.

As Figure 8 shows, the column rotation of the medium footing is significantly larger than the small footing. The additional moment capacity of the medium foundation, because of its increased size, means more ductility demand is placed on the column. Figure 8 shows a photo of the two notched regions after the testing for the medium and small foundation respectively. The figure on the left, the medium foundation size, can be observed to have greater plastic yielding than the column on the right. Thus for the entire series of ground motions, the column supported by small foundation performed better than the column supported on the medium footing. Other experiments (not presented) indicate that the performance of the medium and large footings was nearly identical – both were significantly stronger than the column.

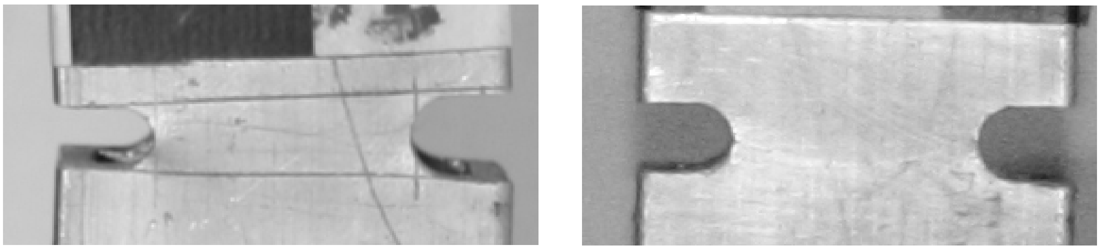

Figure 8 The notched area of the medium (left) and small (right) post-testing

4. NUMERICAL MODEL

4.1. Initial Model Development

An initial mathematical model was developed so preliminary numerical analysis could be carried out on the system. The model was developed using past centrifuge tests from Ugalde (2007) and Gajan (2006). It utilizes a Winkler spring based system and was based on FEMA 356 guidelines for shallow foundation modeling. The foundation has two different zones of springs; one inner zone and two outer zones as suggested by FEMA 356. As opposed to the FEMA guidelines which use elastic springs, inelastic springs were used to fully capture the inelastic behavior of the soil-footing system. The nonlinear springs were modeled using the q-z material along with the zero length elements in the OpenSees analysis platform. The capacity and spacing of each spring was computed using the bearing capacity theory.

A sensitivity study using different combinations and numbers of springs to model the soil footing system was carried out and the results obtained from each numerical model were compared with the experimental results. The detail of this modeling work is out of the scope of this paper and will be summarized in detail in future publications. The configuration found to give best estimates of the experimental results in terms of initial stiffness, moment capacity, maximum rotation and maximum settlement demands were used in the future analysis.

4.2. *Post Experiment Comparison*

Following the testing, experimental results were compared to results from the numerical model in OpenSees. Drift ratio, acceleration time history, settlement, and moment rotation results obtained from numerical and experimental studies were compared. Figure 9 shows a comparison of the drift ratios for the medium and small footing respectively. Initially the foundation parameters were calibrated based on slow cyclic test data. It was found that the foundation capacity was too large and negligible foundation yielding was predicted in dynamic tests. The moment capacity of both footings was reduced by about 20% to account for the reduction in bearing capacity associated with shear stresses caused by shaking of the soil mass. This effect has also been described by Gajan and Kutter.

(2008) and Kumar and Rao (2002). In addition, the moment capacity of the column on the medium footing was reduced by 2% because the size of the notch was slightly larger than the small foundation notch, thus making it a weaker column. The plots show that the model captures the natural frequency of the structure and the two plots on each graph are in phase with each other. The small foundation shows an excellent prediction of the total drift on the structure. The medium footing shows a prediction of total drift less than experimental results, but the trends are considered to be promising. This numerical model is part of the ongoing work at UC Davis and still requires further validation and development against experimental data.

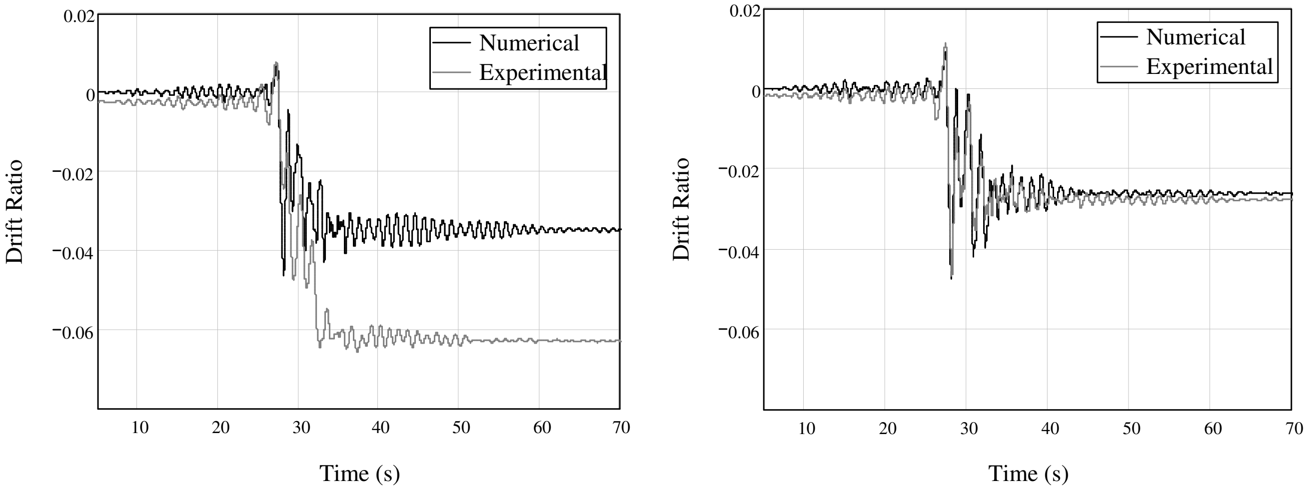

Figure 9 The comparison between the numerical and experimental results for drift ratio for the medium (left) and small (right) footings

5. CONCLUSIONS

This paper presents the results of a series of centrifuge tests performed to investigate effects of footing size on the performance of a single degree of freedom deck mass, column, footing system. It appears that performance may be better for small footings than for large footings. Hence there is potential for saving construction cost associated with large footings, and by reducing ductility demands on the column. The rocking foundations display a well-defined moment capacity and good energy dissipation characteristics. A well-defined moment capacity for both the foundation and the column will give a designer the option of column yielding, foundation yielding or a combination of both depending on physical, geological or other constraints.

For large bridge foundations on well drained sandy soil, settlements due to rocking appear to be small if the soil is denser than about 50 or 60% relative density. Rudimentary ground improvements at strategic locations along the foundation perimeter were shown to significantly reduce the settlements associated with rocking for a looser foundation soil with relative density of 44%. Circular cemented soil pads inserted under the four edges of a foundation reduced the settlement from 0.045 m to 0.022 m (prototype scale). These results show that an increase in settlement, if it becomes an issue for smaller footings on loose soils, could be counteracted with these foundation pads.

Dynamically, the structure was shaken with several different events, the San Fernando earthquake of 1971 being the most intense motion. When comparing results from the different foundation sizes, the small footing displayed less total drift demand than the medium footing due to a reduction in the column yielding and the self centering effect associated with foundation rocking, as shown in Figures 7 and 8. The reduction in column rotation was due to the reduced moment capacity of the small footing which acted like a mechanical fuse, limiting demands on the column. Therefore, having a larger foundation is not necessarily beneficial to a bridge system, especially if potentially beneficial effects of foundation rocking are taken into consideration.

The experimental results were compared to the mathematical model developed to predict the behavior of shallow foundations in OpenSees. The model was based on guidelines from FEMA 356. A good correlation between the numerical and experimental results was observed.

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