Centrifuge Tests of Rocking Shallow Bridge Foundations

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ABSTRACT: The effects of rocking bridge foundations were investigated by a series of highly instrumented centrifuge tests at the University of California, Davis. Slow cyclic tests on shallow foundations supporting rigid elastic columns were performed to capture the nonlinear moment-rotation behaviour of foundations. Relatively small zones of improved soil were strategically located in some slow cyclic tests to study ways in which to reduce settlement associated with rocking foundations. Dynamic shaking tests were performed on lollipop type bridge structures with variable footing dimensions supporting yielding columns. Results show that 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 behaviour. Numerical analyses were implemented in OpenSees, an open source finite element platform, to validate the experimental results by using a nonlinear spring bed model. Numerical analysis is shown to be able to capture the experimental results satisfactory.

1 INTRODUCTION

Current seismic design guidelines in New Zealand and in the USA discourage rocking of shallow bridge foundations. Very large shallow foundations or pile foundations are often specified to preclude rocking. Previous earthquakes, experiments and numerical analysis have consistently shown that a rocking foundation had a 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 bed of spring's type numerical model and established that inelastic rocking has a significant isolation effect and that this isolation effect increases as the size of the foundation decreases.

The aim of the project was to explore possible innovative foundation systems that will optimise the seismic performance of bridge systems. Plastic rotation demand of columns, energy dissipation capacity of the system and displacement demand of the superstructure are assumed to be the main properties that quantify the seismic performance of bridges. In the conventional design practice, the superstructure and foundation components are designed to behave elastically and columns are designed to yield into the inelastic range during strong seismic shaking. Thus the columns absorb all or most of the earthquake energy and as a direct consequence bridge columns have often been observed to suffer significant damage during strong shaking. Figure 1 shows a damaged bridge column after the Kobe earthquake in 1995.

Figure 1: A damaged column after the 1995 Kobe earthquake. (Courtesy of UC Davis archives.)

The University of California, Davis is equipped with a 9m radius arm centrifuge used for geotechnical earthquake modelling. Centrifuge tests and numerical analyses were performed to investigate the consequences of allowing rocking of bridge foundations. It is hypothesized that ductility demands on columns may be reduced by allowing some rocking of the foundation. Several slow cyclic tests were performed on foundations of different sizes to quantify the moment-rotation-settlement behaviour. Subsequently, single degree of freedom 'lollipop' type structures supported on flexible columns 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. The idea behind flexible columns is, theoretically, column yielding and foundation rocking can occur at the same time.

Two numerical models were developed using the finite element platform OpenSees to study the effects of foundation flexibility. Both modelled the soil-foundation interaction using a system of nonlinear subgrade reaction springs. The model that was developed at UC Davis was based upon design guidelines for spring stiffness taken from FEMA-356 (FEMA 2000). The model developed at the University of Auckland was based on a previous model developed by Wotherspoon (2008). Model development is still an ongoing evolving process. Selected comparisons between experiment and simulation are presented in this paper.

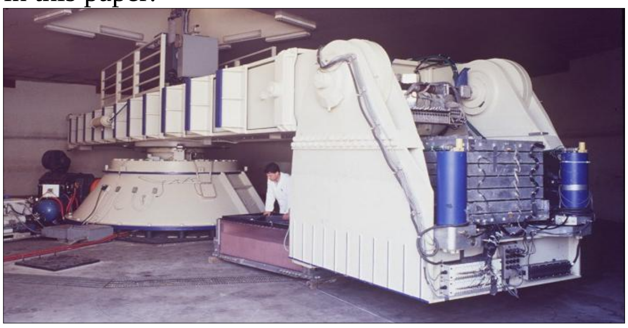


Figure 2: Centrifuge facilities of the University of California, Davis.

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 2. 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 modelling laws. All dimensions are based upon a real prototype bridge, the Sanguinetti Rd On/Off-Ramp (Caltrans bridge No. 32-00625), highway overpass 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. Pluviation of the sand was necessary to achieve required relative densities. The initial relative density, D_r was 73% and it was estimated that the friction angle associated with this density was 38°. During the slow cyclic tests, the sand density was altered to achieve more settlement of the model structure. The altered relative density was 45%. 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 was discovered to provide a small amount of apparent cohesion to the fine sand. The small cohesion minimised 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 aluminium, was designed to be rigid during slow cyclic tests. Rectangular footings were fixed at the base of the wall. The foundations were made of aluminium plates and were consistent with the footing dimensions which were to be tested in later dynamic shaking tests. Steel blocks were bolted to the aluminium wall to increase the weight of the structure so that the mass would match the prototype bridge mass. Figure 3a 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 (string pots) were used to measure settlement and rotation, again this can be seen in Figure 3a.

2.2.2 *Dynamic Test Model Properties*

The structures consisted of an aluminium rectangular footing, a column made from 38 mm x 19 mm rectangular aluminium tube, and three plates to provide the appropriate deck mass, the structure is shown in Figure 3b. The bending stiffness of the prototype column was accurately modelled by the selected tube. In order to capture the yield moment, the column was notched near the base, 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 3b. During each dynamic test, two structures with different footing dimensions were placed parallel to each other and shaken simultaneously so the effect of footing dimension could be determined in side-by-side comparisons.

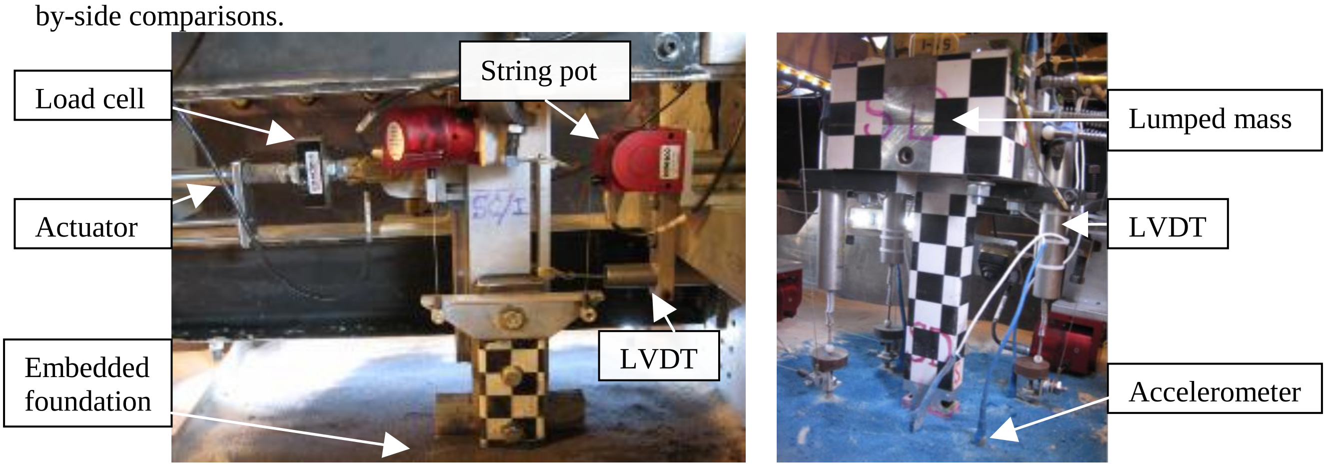


Figure 3: a) A typical structure-foundation setup for a slow cyclic test. b) A typical structure-foundation setup for a dynamic test.

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 tests 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 foundation.

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, reducing 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 significantly affected. 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.

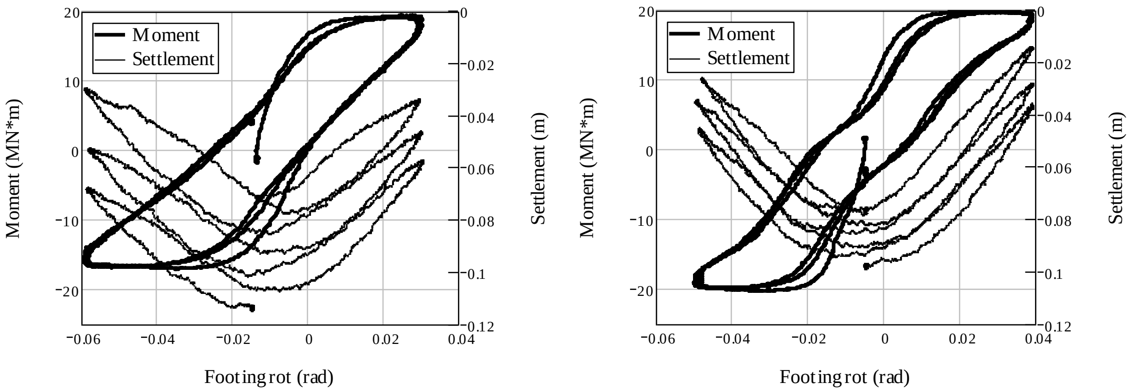


Figure 5: Moment rotation and settlement rotation for non-improved (left) and improved (right) small footings.

3.2 Dynamic Results

The structures were subjected to several different earthquake intensities, beginning at 20% amplitude for each record and increasing to 100% amplitude. Three different ground motions were used with the most severe motion being 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.

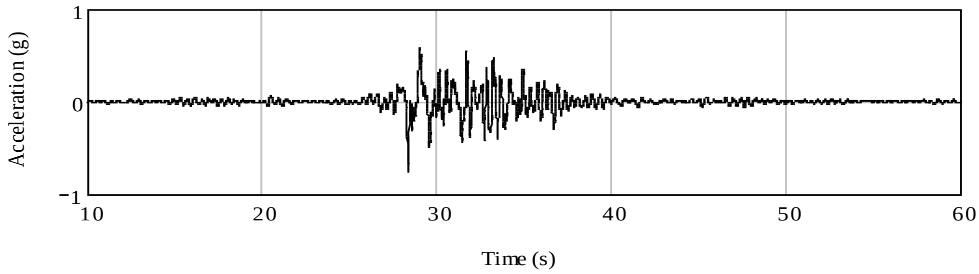


Figure 6: The time history of the San Fernando earthquake as recorded on the centrifuge box.

Drift demand is of particular interest in dynamic tests because it 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. Total drift of the models were calculated by the summation of column rotation and footing rotation. The medium footing displays a total drift of 7.2% while the small footing displays only 2.6%.

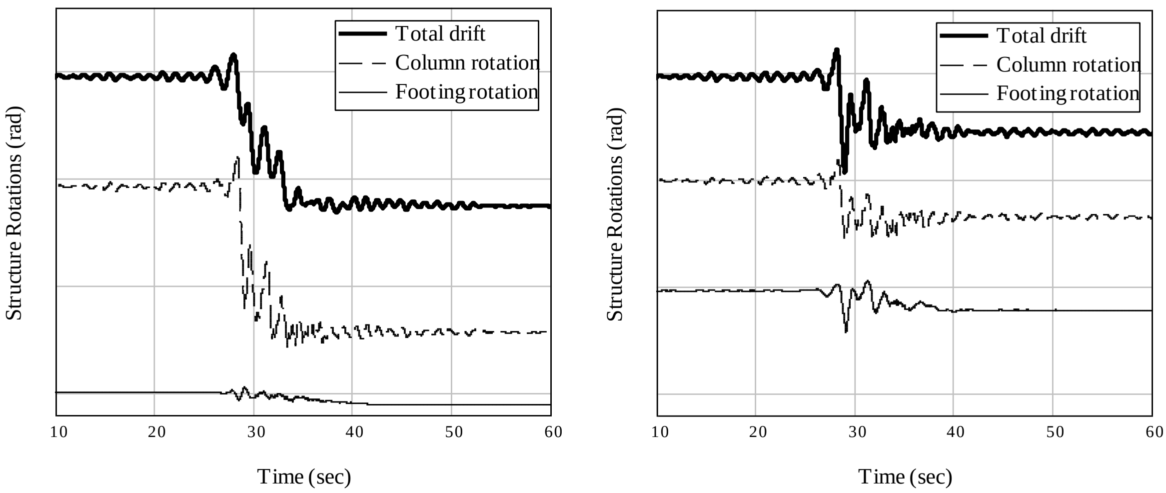


Figure 7: Total drift, column rotation and footing rotation plots for the medium (left) and small (right) footings. Note: each y-axis grid line represents 5% rotation.

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. Rocking would tend to re-centre to its original position because the gap formed between footing and soil will close under the superstructure weight. Therefore permanent drift on the system was reduced greatly by allowing foundation rocking. The superstructure is then possibly 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 centre of a 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 7 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 testing for the medium and small foundation respectively. The figure on the left, the medium foundation, 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.

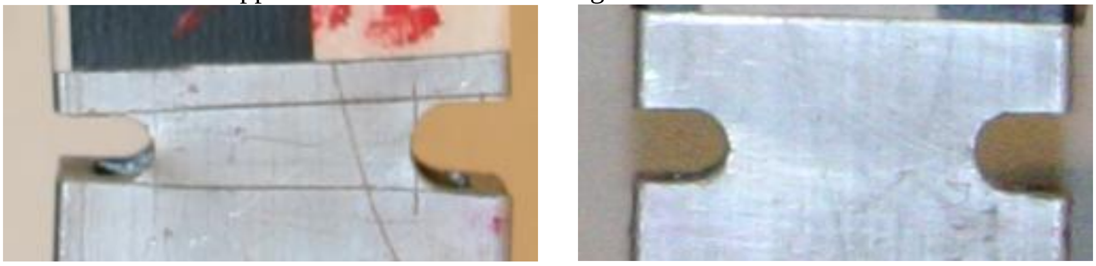


Figure 8: The notched area of the medium (left) and small (right) columns post testing.

4 NUMERICAL MODEL

4.1 Initial Model Development

Two spring bed models were developed in OpenSees. (OpenSees 2008) The experiment has been compared to both models, one developed at UC Davis and one at the University of Auckland. Both models have q-z element springs in the vertical direction. In addition the UC Davis model also has a few elastic perfectly plastic springs in the vertical direction. The UC Davis model has an elastic spring in the horizontal direction. The University of Auckland model has a non-linear t-z element spring in the horizontal direction. Both models also have simple elastic springs in the vertical direction to model sidewall effects. The q-z and t-z elements in OpenSees follow a hyperbolic force displacement curve and therefore are adequate when wanting to capture stiffness degradation of soil. (Gajan 2005)

One common problem when modelling soil-foundation-structure interaction using a bed of springs is rotational stiffness is underestimated. (Pender 2006) Chapter four of the American Seismic Rehabilitation Prestandard, FEMA 356, states that if using a bed of springs to model soil-foundation-structure interaction a foundation must be split into a mid zone and two end zones and the vertical stiffness be proportioned in each zone so that accurate rotational stiffness is obtained. The stiffness per unit length of each of the end zones and the mid zone are displayed in equations 1 and 2 respectively. (FEMA 356)

$$k_{end} = \frac{6.83 \cdot G}{1-\nu} \tag{1}$$

$$k_{mid} = \frac{0.73 \cdot G}{1-\nu} \tag{2}$$

where G = shear modulus; and ν = Poisson’s ratio.

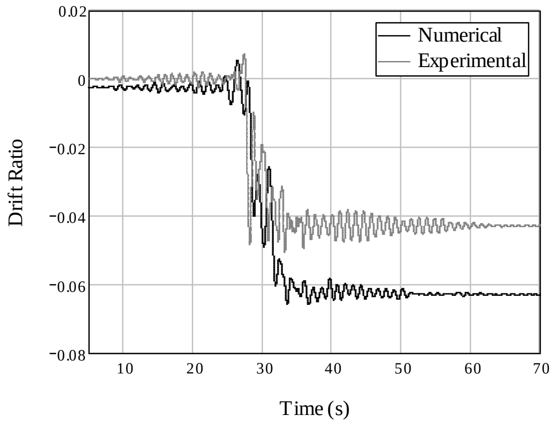
The UC Davis model utilises the formula above to model the rotational stiffness accurately. Thus that model can be said to adhere to FEMA 356 guidelines. The University of Auckland model used the same vertical spring stiffness throughout the foundation. The addition rotational stiffness came in the form of a rotational damper placed at the centre of the foundation.

4.2 Post Experiment Comparison

Following the testing, experimental results were compared to results from the numerical model. 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 between the experiment and the University of Auckland model for the medium and small footing respectively. The UC Davis model was not shown on this graph because it was almost identical to the results that the

University of Auckland model achieved. One reason could be because most of the total rotation came in the form of column rotation, not in foundation rotation. And in column behaviour, the models are identical.

Initially the foundation parameters were calibrated based on slow cyclic test data. It was found however 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 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 3% 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 well and the two plots on each graph are in phase with each other. The small foundation shows an excellent prediction of the residual drift on the structure. The medium footing shows the prediction of total drift less than experimental results, but the trends are considered to be promising. Both numerical models are part of ongoing works being carried out at UC Davis and the University of Auckland respectively. Both still require further validation and development against experimental data.



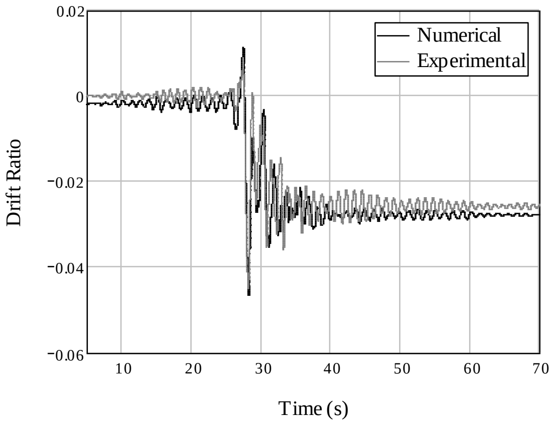


Figure 9: The comparison between the numerical and experimental results for total drift ratio for the medium (left) and small (right) footings.

5 CONCLUSIONS

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

For the smallest foundations tested, 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 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 centring effect of rocking foundations. 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 effects of foundation rocking are taken into consideration.

Additional to experimental testing, two numerical models were developed. Predictions of the system behaviour was carried out and compared with the experimental results. A good correlation between the numerical and experimental results was observed.

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