# Effect of Rocking Foundations on Seismic Behavior of Horizontally Curved Bridges with Different Degrees of Curvature

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**SUMMARY:**
It is important to design bridges that can have no damage after small and medium earthquakes and limited damage after significant earthquakes. One method for achieving this objective is to allow the foundations of the bridge piers to rock. In this study, bridges with different curvatures were analyzed with different footing sizes under seismic loads, using time history analyses. Distribution of the demands on different bridge components were compared to systems without rocking. Initial findings indicate that rocking reduces the damage in the substructures, but increases the superstructure and the abutments demands. The degree of horizontal curvature is also a factor that contributes to the distribution of the seismic load demands. As part of the project, a two-fifth scale of one of the analyzed curved bridges was tested using shake tables. The experimental setup is also explained in this paper.

*Keywords: Curved Bridges, Large Scale, Experimental Testing*

## 1. INTRODUCTION

Despite the fact that early research studies, as those of Housner (1963) and Priestly et al. (1978), documented the ability of tall slender structures with rocking behavior under seismic loads to survive large earthquake rather than overturn, the common practice in bridge design for bridges built on relatively competent soils, with spread footings, is to proportion the footing to allow for a response of a fixed base column. This practice leads to a behavior that is governed by plastic hinging (damage) in the columns that may result in replacing the whole pier in the post earthquake response. Analytical and experimental studies on piers with relatively small footings, that incorporate uplift, proved that it can provide viable means of resisting earthquake effects and reduce the damage in the columns (e.g. Espinoza and Mahin (2006) and Kawashima and Nagai (2006)). Other analytical and experimental studies focused on the behavior of soil under the rocking footings, and its ability to dissipate energy through soil yielding (e.g. Harden and Hutchinson (2009) and Negro et al. (1998)). The effect of rocking footings on bridge systems has not been investigated. This paper describes the initial procedures of the ongoing analytical and the experimental work at the University of Nevada, Reno on the rocking behavior of bridges under seismic loads that included a three-span curved bridge experiment that is supported on two single column piers with their footings allowed to rock and two end abutments.

## 2. ANALYTICAL PARAMETRIC STUDY

In the project, part of the analytical study included a parametric study to investigate the effect of rocking foundations on curved bridges. In this parametric study, five bridges, with different horizontal configurations were investigated. Bridge-1 was a straight bridge, and all other bridges were horizontally curved with different curvature radii. Table 1 illustrates the curvatures of the five bridges used in the study. The cross section of the superstructure and the substructure of the five bridges were the same. The superstructure cross section was a steel plate girder cross section with three girders spaced at 135 in (3.43 m), topped with a 30 ft (9.15m) wide concrete slab of thickness equals to 8.125 in (206.4 mm). The substructure was a single column pier with a hammer head cap beam, with a column diameter of 40 in (1.02 m). The total length of all the bridges was 362 ft (110.4 m) measured along the centreline of the middle girder, divided into two end spans of length equals to 105 ft (32.0 m) and a middle span of length equals to 152 ft (46.3 m). The total weight and mass of all the bridges was the same.

To include the effect of footing sizes on the behavior of rocking in the study, different footing sizes were used for each bridge. Square footing lengths equal to 120 in (3.05 m), 140 in (3.55 m), 160 in (4.06 m), and 180 in (4.5 m) were modelled. These sizes corresponded to 3, 3.5, 4, and 4.5 times the diameter of the column used in the pier, respectively. A fixed base column pier was also used in the study to relate the rocking effects to the fixed base model. The soil stiffness that was used in the study was equal to 180 psi/in (48.86 kPa/mm), which is a common modulus of subgrade reaction for flexible soils.

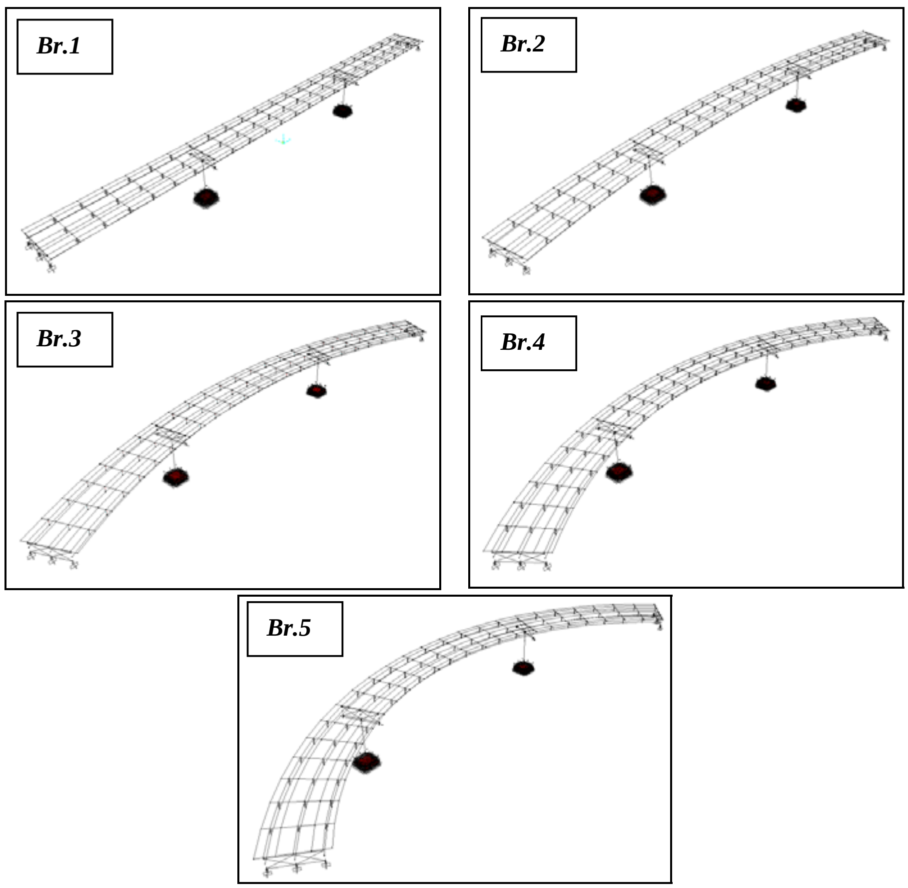


**Figure 1.** 3D view of the analytical models for the five bridges used in the study

**Table 1.** Bridges description

| Bridges | Radius of Curvature |
|---|---|
| Bridge-1 (Br.1) | Straight bridge |
| Bridge-2 (Br.2) | 800 ft (143.8 m) |
| Bridge-3 (Br.3) | 400 ft (121.9 m) |
| Bridge-4 (Br.4) | 265 ft (80.7 m) |
| Bridge-5 (Br.5) | 200 ft (61.0 m) |

The five bridges were modelled in SAP2000 using grillage models as shown in Fig. 1. The models only contained frame elements representing the superstructure in locations as shown in Fig. 2, and frame elements that represented the substructure as shown in Fig. 3. Inelastic fiber hinges were defined at the upper and the lower plastic hinge locations of the columns to account for nonlinear behavior.

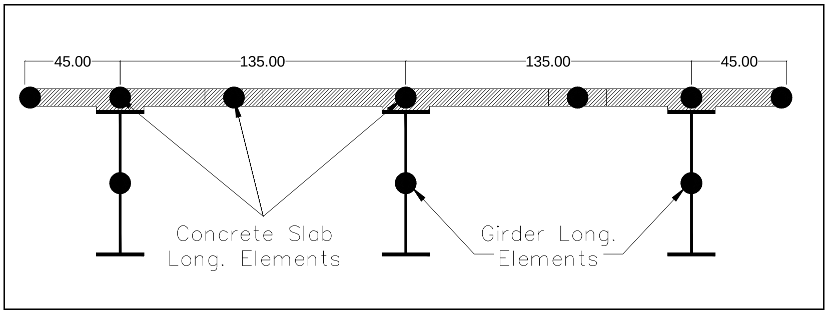


**Figure 2.** Bridge cross section with the locations of the longitudinal elements used in the analytical models

Soil springs were defined underneath the footings with zero tension capacity and the stiffness of the soil lumped at nodes in compression. At this point of the study, nonlinearity was only considered at the column plastic hinging not in the soil behavior. Fig. 4 shows the force-displacement curve for the gap elements used in the model.

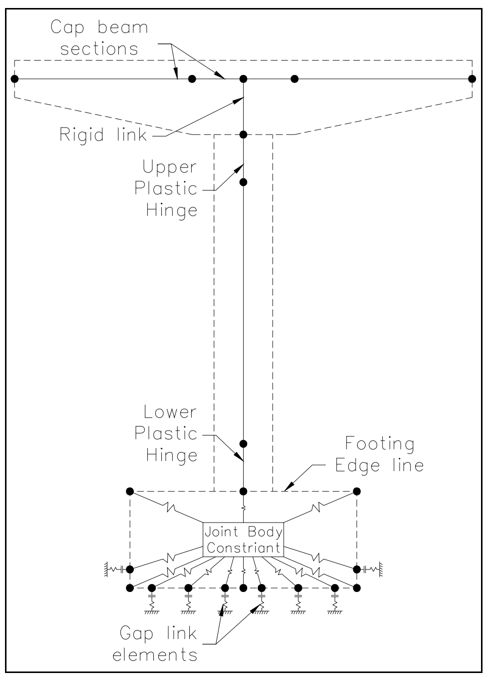


**Figure 3.** Modeling of the pier elements in SAP2000

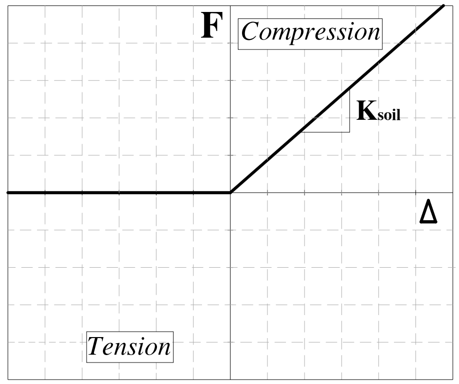


**Figure 4.** Force-displacement relationship for the gap elements used in defining the soil springs

The time histories that were used in the analyses were based on the Northridge earthquake recorded at Sylmar station. The record was scaled to match the response spectrum curve for a bridge designed in Seismic Zone 3 with a 1,000 year spectral acceleration at 1.0 sec equals to 0.4 g. The used scale factor was 0.475. Three levels of the earthquake were used, the mentioned scaled record was called the Design Earthquake (DE) or 100%DE, and then the amplitude was scaled to 200%DE and 300% DE. These records had Peak Ground Accelerations (PGA's) of 0.4g in the X-direction and 0.287g in the Y-direction for the 100%DE level, and PGA's of 0.801g in the X-direction and 0.574g in the Y-direction for the 200%DE level, and PGA's of 1.201g in the X-direction and 0.861g in the Y-direction for the 300%DE level. Where the X-direction (Syl-360 degrees) was taken as the longitudinal direction of the bridges, and the Y-direction (Syl-90 degrees) was taken as the transverse direction of the bridges. The records are shown in Fig. 5.

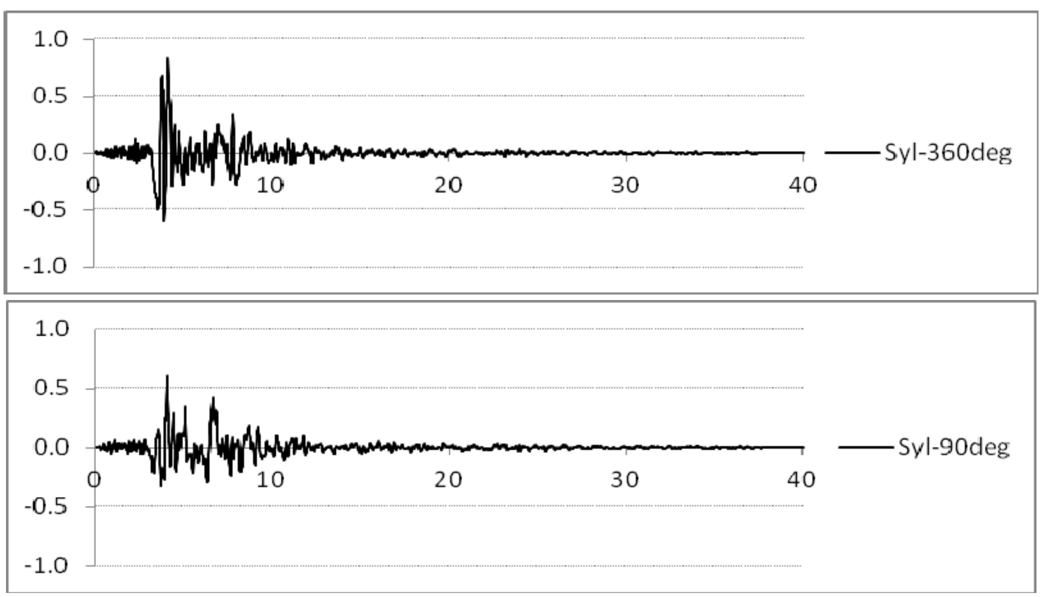


**Figure 5.** Acceleration time histories of Northridge earthquake recorded at Sylmar station in both directions

## 3. RESULTS

The recorded footing uplift from the time histories indicated that smaller footing sizes had increased uplift than larger footing sizes and accordingly higher rotations of the footing was achieved. This footing rotation resulted in less plastic hinge rotations in the lower plastic hinges of the columns, which means less damage in the lower part of the columns. Fig. 6 shows the relation between the maximum plastic hinge rotation in one of the columns and the footing sizes for different bridges used in the study. The overall rotation of the column base for the two piers was higher with smaller footings than the larger footings, which increased the rotation in the upper plastic hinge of the columns in the double curvature direction. But the overall amount of damage in the footings with higher uplift is less that those with less uplift.

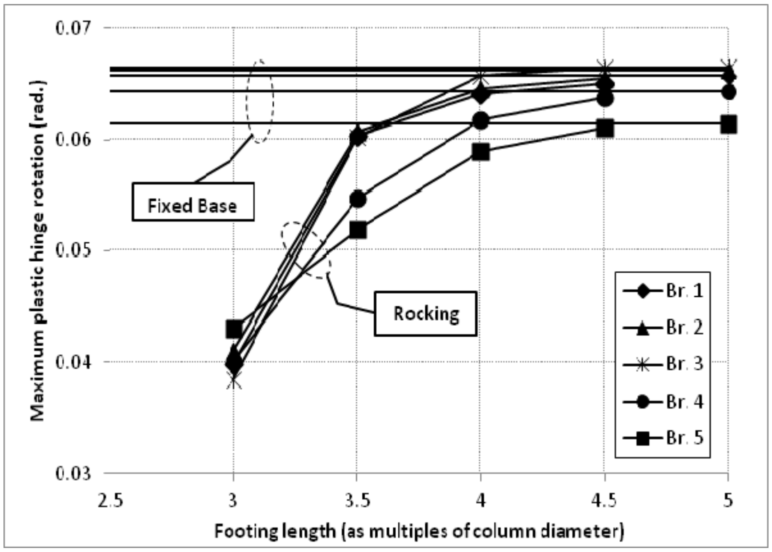


**Figure 6.** Maximum plastic hinge rotation in the lower hinge of the first pier column vs. footing size for the 300% DE level

In addition to having a less damage in the column's lower plastic hinges, smaller footings resulted in an increase in the overall displacements of the bridge, which is similar to the behavior of an isolated bridge. Fig. 7 shows the relation between the maximum displacements of one of the abutments versus the footing sizes for different bridges used in the study.

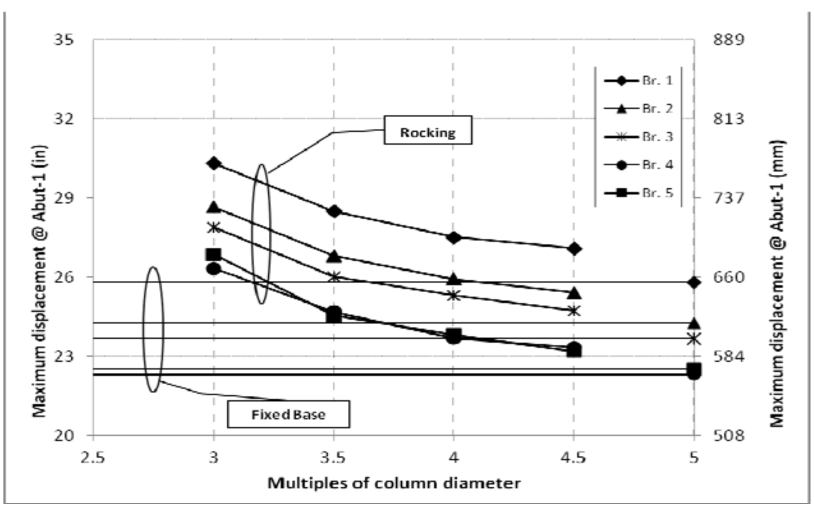


**Figure 7.** Maximum displacement in the first abutment vs. footing size for the 300% DE level

It was also observed from the results that different bridges with different curvatures had different distributions of the seismic demands on their superstructures. This can be noticed through the records of the girder uplift at the abutments during high level earthquakes, as seen in Fig. 8. Girder uplift values at abutment-1 for bridges 2 and 3, with a fixed base, were higher than the uplift values for other bridges. These uplift values increased with the rocking behavior for these bridges. For bridge 4 with the fixed base columns, the girders did not encounter any uplift, while the rocking models had uplift with different values increasing with the smaller footing sizes.

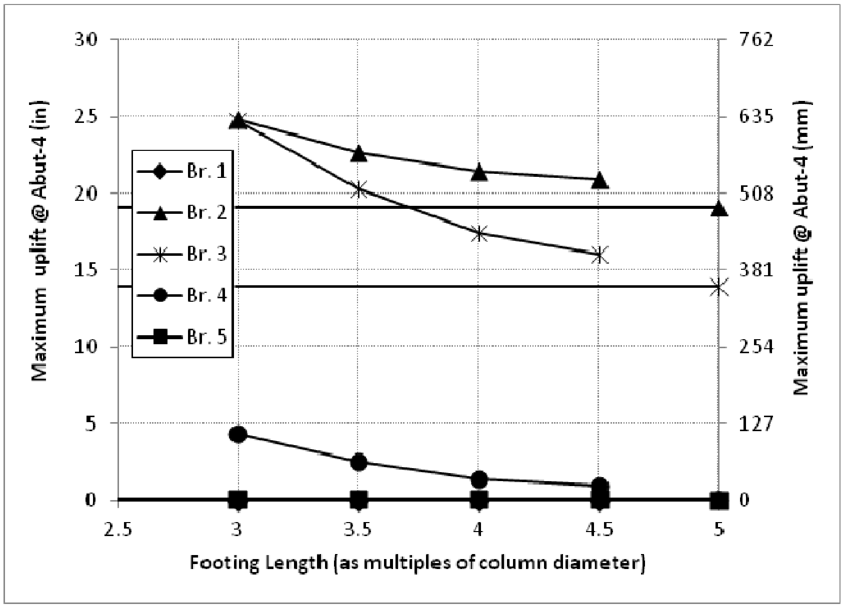


**Figure 8.** Maximum displacement in the first abutment
vs. footing size for the 300% DE level

## 4. EXPERIMENTAL VERIFICATION

In order to validate of the results in the parametric study, a two-fifth scale of bridge 5 from the parametric study was constructed and tested in the Large-Scale Structures Laboratory at the University of Nevada Reno. It was built on four shake tables as shown in Fig. 9. It had a superstructure with horizontal curvature of $104^o$ (1.814 rad), and three girder lines. The radius of the centerline of the bridge was 80 ft (24.4 m). The total length was 145 ft (44.2 m), divided into two end spans of length equal to 42 ft (12.8 m) and a middle span of length equal to 61 ft (18.6 m), measured along the centerline of the bridge. The piers were single columns with hammerhead cap beams. The footings were placed on rubber pads to simulate the soil stiffness. The dimensions of these pads were 8 in x 8 in x 2 in (203.2 mm x 203.2 mm x 50.8 mm) with a durometer of 44 which is equivalent to a modulus of elasticity of around 300 psi (2068.43 kPa). The final stiffness of each pad was 32.0 kip/in (5604.06 N/mm) which resulted in a soil stiffness of 320 psi/in (86.85 kPa/mm) for the soil underneath the footing. The pier setup is shown in Fig. 10.

Preliminary observations of the experiment indicated that rocking took place and the footing corners uplifted by about 2 in (50.8 mm) in some cases. This resulted in a behavior similar to that of an isolated bridge. There was some damage to the columns, which provided energy dissipation. Moreover, spalling of the concrete cover in the top plastic hinges was also observed, which was expected as the rotation of the bridge pier due to rocking increased the rotation in the top plastic hinges. Data processing is still in progress along with the calibration of the analytical models.

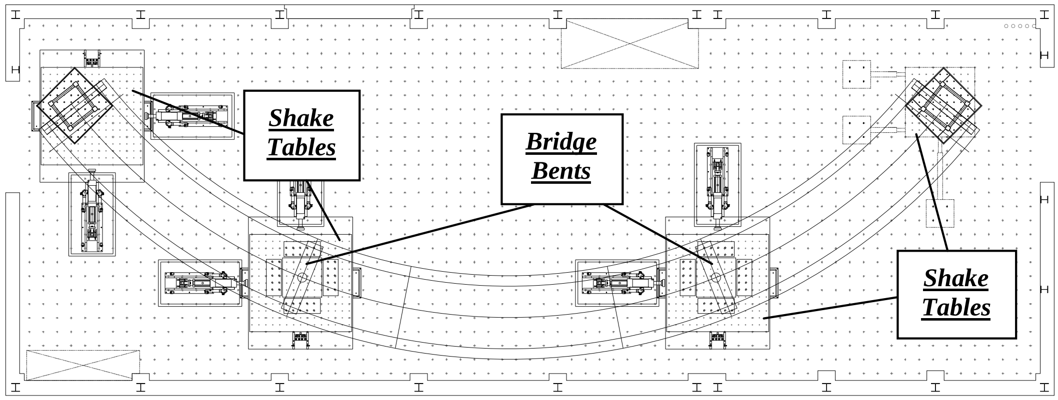


**Figure 9.** Plan view of the laboratory including the bridge

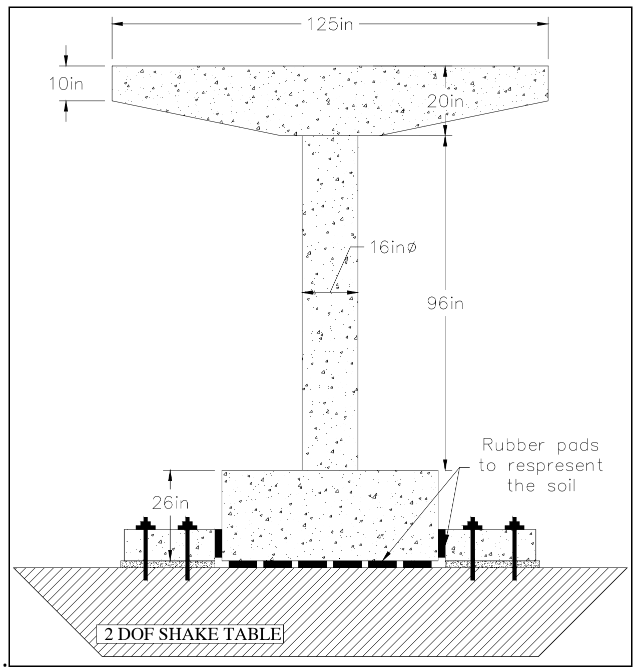


**Figure 10.** Experimental setup for the bridge pier

## 5. CONCLUSIONS

In this ongoing study, the rocking behavior of bridge footings under seismic load is under investigation analytically and experimentally. This study aims to determine the degree to which rocking reduces the effect of earthquakes on bridges as systems. Preliminary theoretical work indicates that horizontal curvature in a bridge can affect the distribution of forces in the system when rocking occurs. The experimental work on a 3-span highly curved bridge showed that rocking does indeed have a similar effect on bridge response as found with seismic isolation.

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