ROCKING OF BRIDGE PIERS SUBJECTED TO MULTI-DIRECTIONAL EARTHQUAKE LOADING

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ABSTRACT

Rocking as an acceptable mode of seismic response has been extensively studied and has been shown to potentially limit local displacement demands. Rocking can act as a form of isolation, reducing displacement and force demands on a bridge, thereby allowing for design of smaller footings and members. As part of a larger, Caltrans-funded investigation to develop guidelines for the design of bridges supported on piers that rock on their foundations, a series of preliminary shaking table tests of a simple inverted pendulum reinforced concrete bridge column was conducted. These tests are among the first to consider the effects of three components of excitation. For the shaking table tests, the underlying soil is modeled by a neoprene pad, upon which the pier is allowed to rock. Preliminary results from these tests comprise the focal point of this paper. To supplement the idealized conditions employed in these tests, bidirectional tests on smaller-scale models are being conducted on a geotechnical centrifuge at UC Davis. These shaking table and centrifuge experiments provide data to validate analytical models that are in turn used to assess and improved design guidelines related to rocking foundations.

INTRODUCTION

Bridge structures residing on competent soil are typically designed with rectangular spread footings (Fig. 1(a)), which are sufficiently proportioned to allow for a fixed base response. This generally leads to inelastic behavior at or near the column to footing interface during moderate to large earthquakes. This mode of behavior dissipates input energy, but results in damage to the column. Consideration of rocking or uplift of the bridge pier foundation on the supporting soil introduces other modes of nonlinearity (rocking) and energy dissipation (soil inelasticity). Limited soil nonlinearity combined with uplift can reduce demands on the bridge structure, effectively acting as an isolation mechanism. The consideration of rocking as an acceptable mode of response can impact design costs by reducing the required footing size. In addition, the simultaneous rocking of a properly designed foundation and flexural deformation of the supported column is expected to eliminate, or substantially reduce, damage in the column and residual displacements in the bridge following a major earthquake.

Many previous studies have investigated the benefits of allowing a column and footing system to uplift (e.g., Chopra 1985). Analytic studies of bridge column response to one horizontal earthquake component have illustrated the combined effects of rocking and column flexural displacements (Alameddine and Imbsen 2000; Kawashima and Hosoiri 2003). Recent

earthquake simulator tests (Sakellaraki *et al* 2005) on small-scale steel columns subjected to unidirectional excitation, and related analytical studies, have similarly demonstrated the feasibility and benefit of the rocking mechanism in resisting seismic effects.

Because of the potential economic and performance benefits of using rocking in new construction, and the desirability of developing reliable analysis procedures for evaluating existing bridge structures, a series of experimental and analytical investigations has been begun in a joint effort at UC Berkeley and UC Davis. These studies will develop guidelines for the design of bridge pier foundations allowed to uplift during severe earthquakes. The work at UC Berkeley focuses on development of design procedures, and validating these via more refined structural analyses and earthquake shaking table tests of moderate-scale models of reinforced concrete bridge columns under multidirectional earthquake excitations. Efforts underway at UC Davis focus on analytical studies accounting for the nonlinear behavior of the supporting soils, soil-foundation interaction effects, and carrying out geotechnical centrifuge tests to validate models for soil-foundation interaction, including uplift. This paper highlights some of the preliminary work underway within this project. Emphasis is placed on the recent results from the first phase of shaking table tests at UC Berkeley.

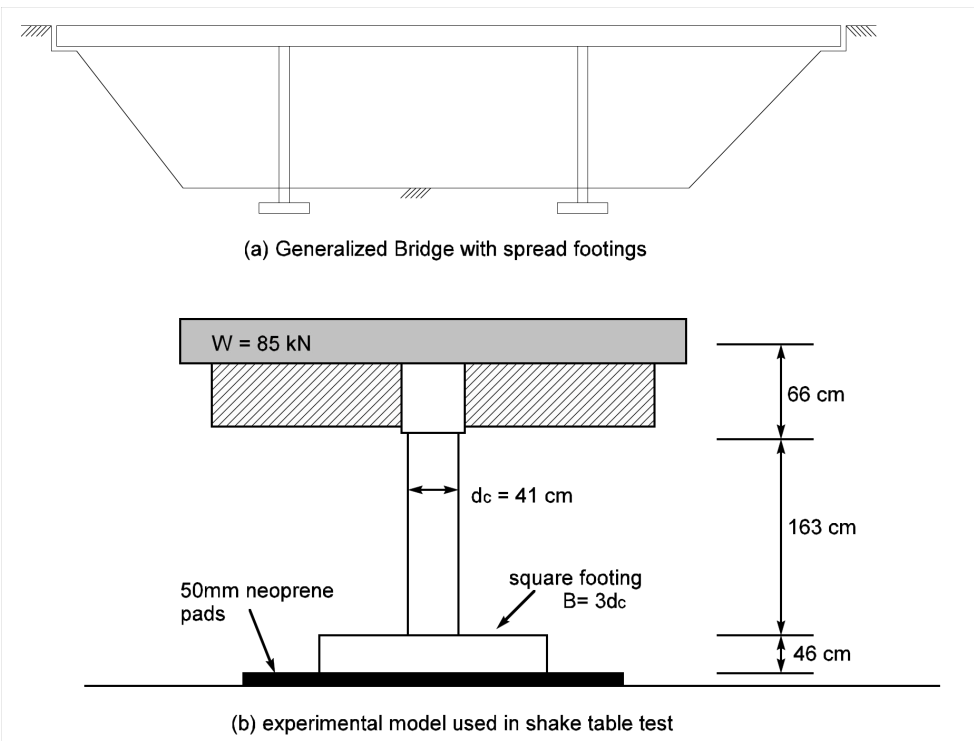


Fig 1: (a) General Bridge Pier Configuration (b) Simplified Experimental Setup

SHAKING TABLE EXPERIMENTAL PROGRAM

The idealized model of a bridge pier allowed to uplift was accomplished using a simple reinforced concrete column and footing that rests on a 50 mm thick neoprene (Duro-60) pad. This pad highly idealizes the soil beneath the footing. The 1/4.5-scale circular column has a diameter of 410 mm, a longitudinal reinforcement ratio of 1.2%, and spiral reinforcement. For the series of tests presented herein, the column is expected to remain elastic. To achieve a

rocking mode, the width of the square footing is selected as 3 times the diameter of the column (a common value for spread footings in California bridges). Figure 1(b) illustrates the test setup. The column is designed based on the Seismic Design Criteria (Caltrans 1999). Dead load on the column is 3% of A_g*f'_c which is below the commonly value of 10%; however, the mass was adequate to excite rocking response for various ground motions. A second phase of testing, to be conducted later in 2005, will explore a fuller range of loading conditions and configurations.

Since several one-dimensional studies have been conducted previously, it was decided to look at this condition in addition to cases with two and three-dimensional excitations. The effect on response of possible interaction along both horizontal principal axes due to uplift of a rectangular footing may result in conditions not treated in earlier investigations. When a footing lifts about a corner under two horizontal components of motion, it may tend to (1) 'roll' towards one edge or the other, resulting in erratic response, or (2) pivot about a vertical axis due to the eccentricity of the reaction point and the center of mass. In addition, the presence of inertial forces due to vertical excitations, especially those associated with near-fault excitations, might have a large influence on rocking response. Thus, in these preliminary tests emphasis was placed on acquiring data on basic response modes, evaluating the ability of the neoprene pad to mimic soil behavior, evaluating the test setup, and assessing the ability of analytical methods to predict rocking response. As a consequence, the amplitude of motions was kept below levels that would yield the column, and no restraint of rotation about a vertical or horizontal axis was provided to the foundation (even though these might be partially restrained in an actual bridge). Moreover, no restraint of sliding response was provided. Two recorded earthquake excitations were considered at different amplitude levels or frequency scales. For each record, various combinations of 1, 2 or 3 components of excitation were imposed (see Table 1).

TABLE 1: EXPERIMENTAL TEST SCHEDULE

Excitation Input	A) Los Gatos	B) Los Gatos	C) Tabas	D) Tabas	E) Los Gatos	F) Tabas
1) 1D – longit. 2) 1D - transv 3) 2D – long/transv 4) 2D – long/vert 5) 3D	10 % original record	35% original record	11% original record	40% original record	35% original record *Period shift*	50% original record *Period shift*

EXPERIMENTAL RESULTS

The fundamental period of the test specimen resting on the neoprene pads was measured by low-level snap-back tests to be 0.52 secs. When the column was on a fixed base, the period was 0.28 secs. During testing, the peak amplitude of each individual component of excitation was held constant so that the effect on response of having multiple components of excitation could be easily detected. Representative results from the Group B (Los Gatos records, at 35% scaling) tests are shown in Figure 2. Figure 3 illustrates that even when there was only one component of motion there was significant response in the perpendicular direction (due to difficulty of aligning specimen and minor motion of table in this direction). Moreover, Figure 3 also shows that the peak responses due to each component are not simply additive, but interact resulting in larger responses. Even though this level of excitation would have damaged a column on a fixed base (a displacement ductility of 3), the test column had no damage and re-centered following each test.

Because the rotation of the footing was unrestrained, after about 30 runs there was a permanent rotation about the vertical axis of approximately 2%. The bridge deck and soil surround the footing would tend to restrain this rotation.

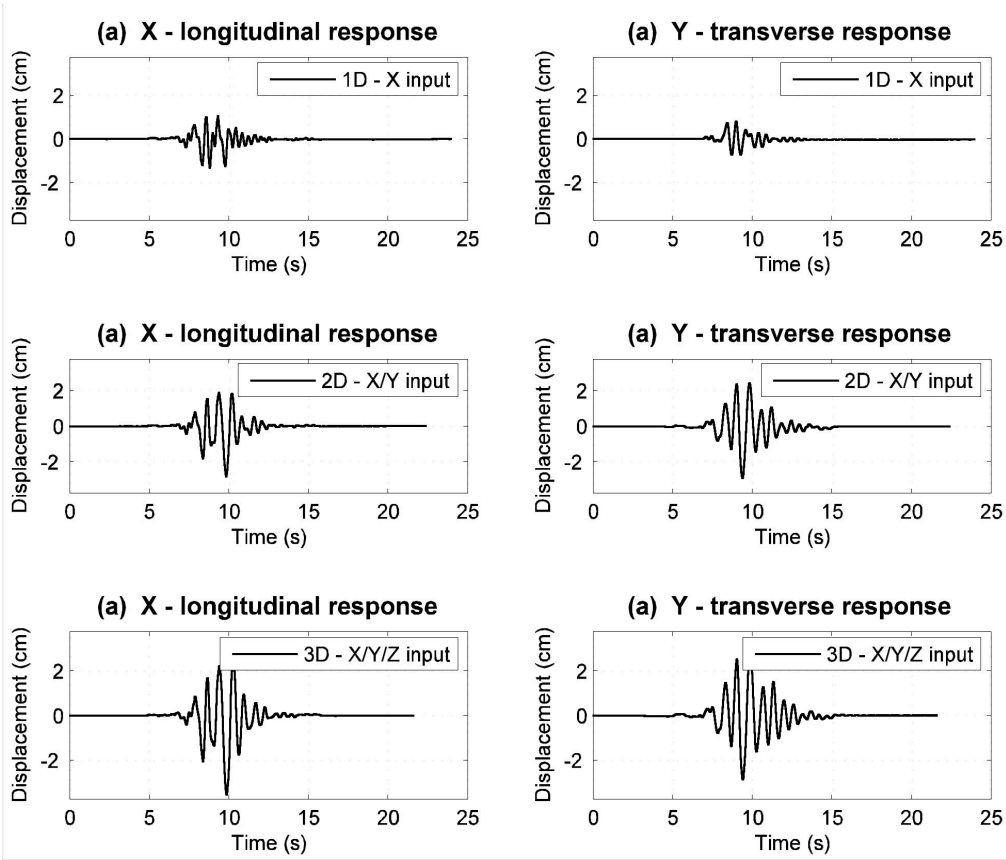


Fig. 2: Experimental Results Illustrating Displacement Interaction for Several Input Excitations (Los Gatos Record-35%)

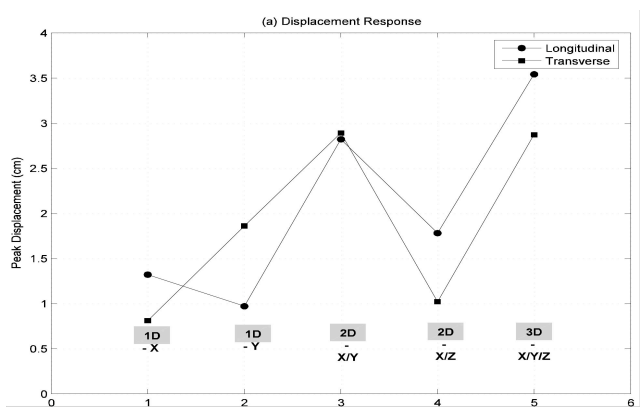


Fig. 3: Peak Displacements for Five Combinations of Input Excitations for Los Gatos Record (35%)

ANALYTIC COMPARISON

The experimental setup was modeled using OpenSees (OpenSees 1998). The model was based on a lumped mass idealization resting on elastic beams and nonlinear vertical springs. This is

called a Beam-on-Nonlinear-Winkler-Foundation model (BNWF). Figure 4(a) illustrates the model configuration and Figure 4(b) illustrates the measured constitutive relationship for the vertical response of the neoprene pads.

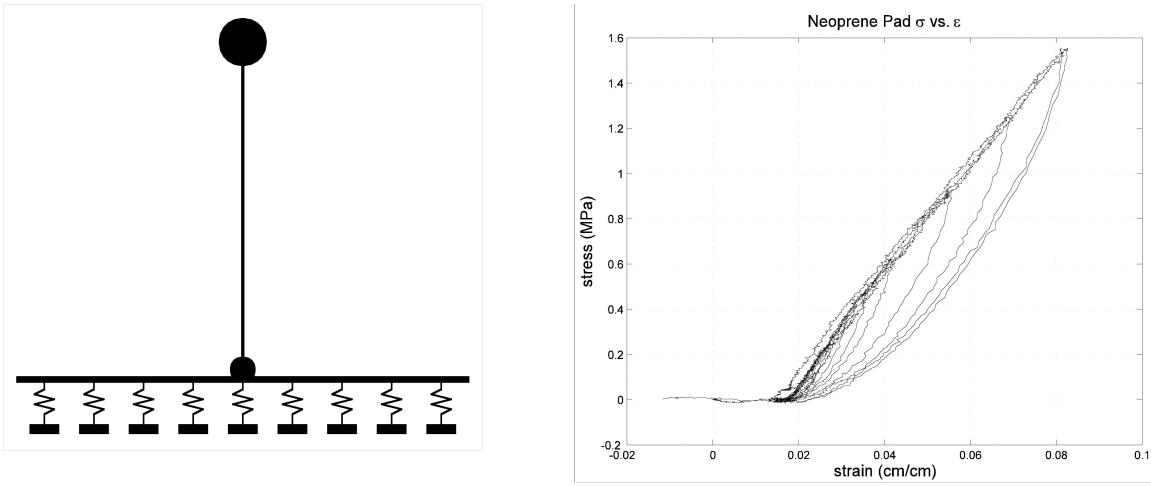


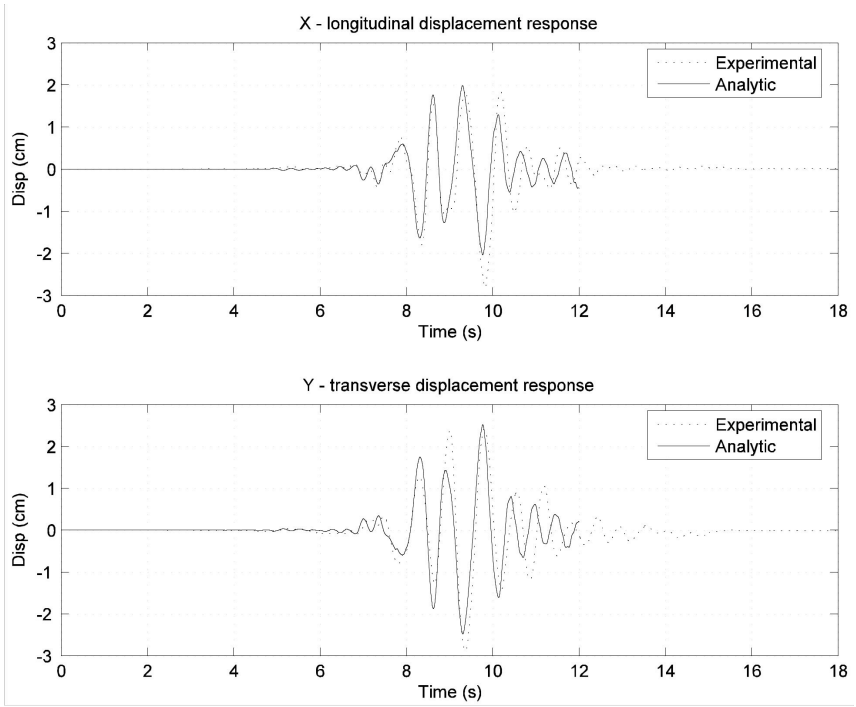
FIGURE 4: (a) Analytic Model (b) Axial Constitutive Relation for Neoprene Pad

Figure 5 (a) compares analytical and measured displacement responses for a 2D excitation with longitudinal and transverse inputs. There is a reasonable correlation between recorded and analytic model. However, there appears to be some deviation at the end of the record in terms of period and amplitudes. Figure 5 (b) shows the recorded and corresponding analytic model of uplift displacement. There is improved period matching here; however, the amplitude is rather low. Continued efforts to achieve better characterization of the neoprene pads are warranted.

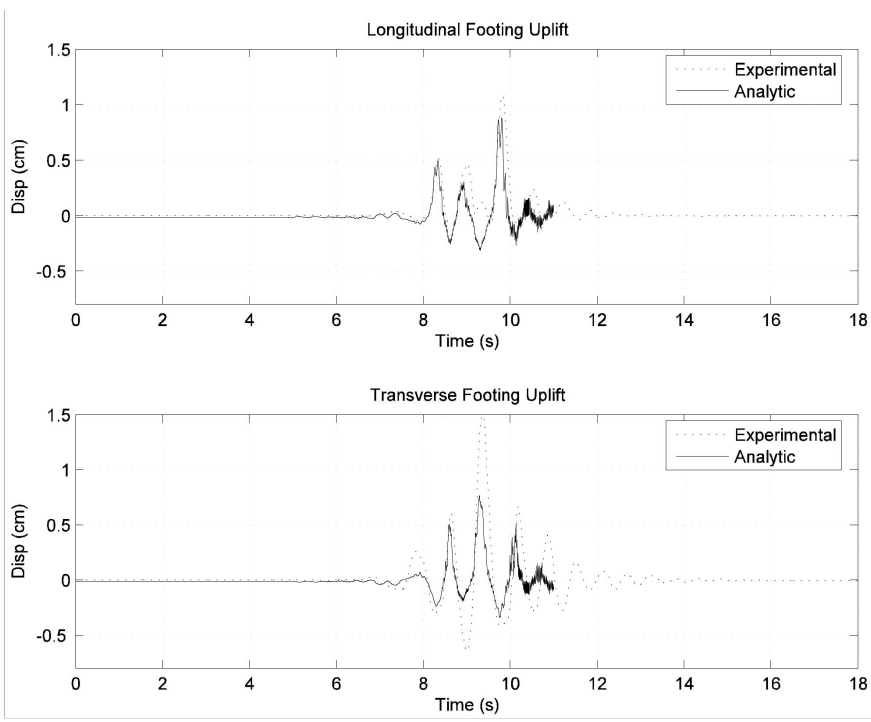
GEOTECHNICAL MODELING OF UPLIFT

The BNWF model described above has been used in a number of analytical investigations. While it conceptually mimics the behavior of a rocking foundation, and can be reasonable to use for certain types of design-oriented analysis efforts, it suffers from a number of important limitations. First, the soil springs need to be calibrated based on the particular type of soil present, and the actual 3D dynamic behavior of the soil and the soil structure interaction are far more complex. Thus, as part of this overall investigation, UC Davis investigators are comparing analytical results with data obtained from more refined three-dimensional finite element models, including foundation uplift. However, in design practice, neither the BNWF nor 3D finite element model may be practicable. As a result, work is underway to develop a generalized plastic hinge model, which internally accounts for various behavior modes (rocking, sliding, soil nonlinearity, radiation damping effects, etc.).

Thus far, good correlation has been obtained for competent soils between the 3D finite element models and the generalized plastic hinge model. Figure 6 shows the predicted effect of cycling on the base moment-footing rotation relation obtained using the generalized plasticity model. In addition to examining the overall effect of soil nonlinearity and rocking on global response, efforts are also focused on predicting with these different approaches localized damage to the soil and the residual displacements and rotations of the foundation.



(a) Column Displacement



(b) Footing Uplift

Fig. 5: Analytic Comparison of Column Displacement and Footing Uplift

CENTRIFUGE TESTING

It is desirable that the analytical models described above be calibrated against actual dynamic response data of columns on rocking foundations supported on competent soil. The UC Berkeley

tests do not address this problem. As such, an additional experimental setup is being readied for testing a series of smaller scale pier and foundation models on the UC Davis Geotechnical Centrifuge (Fig. 7). These will include piers subjected to monotonically increasing lateral loads, to establish static pushover curves for various bridge configurations. In addition, 2D dynamic earthquake excitations will be imposed, with different footing widths, different masses, different orientations of the footing with respect to the input motion, and with possible yielding of the column. These test results will be used to calibrate the analytical models developed for use in the parametric investigations.

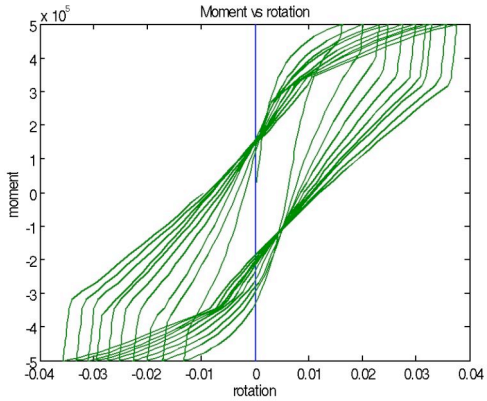


Fig. 6 Effect of Cycling on Base Moment-Footing Rotation Relation

Fig. 7 Geotechnical Centrifuge at UC Davis

CONCLUSIONS

A preliminary experimental and analytical investigation of the rocking behavior of spread footings supporting bridge piers indicates that this mechanism can provide a viable means of resisting earthquake effects. For the shaking table specimen, the measured displacements was similar to or smaller than would be expected for a comparable elastic or yielding pier with a fixed foundation. Even at these displacements, the column showed no signs of damage, and re-centered following the end of the ground shaking.

Additional analyses of the results are currently underway to improve modeling capabilities, and to plan for a second series of shaking table tests. In particular, better characterization of the neoprene pads is needed to improve the analytical modeling. The second phase of shaking table testing will examine cases with larger initial mass and dead load, additional geometric configurations, restraint of column rotation about a vertical axis, and stronger excitations, including ones leading to simultaneous foundation rocking and column yielding.

The test and analytical results will then be correlated to results obtained on small-scale models obtained on a geotechnical centrifuge, and the improved bridge, foundation and soil model will be used to develop design guidelines. To ensure that the guidelines are realistic, a series of centrifuge tests of piers supported by shallow spread footings is being undertaken. These results will be compared to analytical predictions obtained with different levels of refinement. In particular, in these initial studies emphasis is placed on competent soils conditions where a significant gravity load factor of safety (>3) is provided and where conventional design methods might be used or adapted based on the results of these studies.

ACKNOWLEDGEMENTS
Financial support for this research is provided by the California State Department of Transportation. The findings, observations and conclusions contained herein, however, are those of the authors and do not necessarily represent those of the sponsors. The thoughtful advice and encouragement provided by the Craig Whitten and Fadel Alameddine of Caltrans in planning and carrying out this work is greatly appreciated. The assistance of graduate students Hyungil Jeong, Janise Rodgers, Patxi Uriz, and the UC Berkeley and Davis laboratory staff staffs are gratefully appreciated.

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