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 investigated extensively and has 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. A series of preliminary shaking table tests of a simple inverted pendulum reinforced concrete bridge column was conducted for horizontal and vertical components of excitation. The underlying soil is modeled in these tests with a simple neoprene material on which the pier is allowed to rock. Results presented illustrate the effects of multi-directional earthquake excitation on the elastic response of bridge columns. Comparisons of analytic simulations of the elastic rocking response and fixed base response illustrate the benefits of foundation uplift.

Introduction

Bridge structures residing on competent soil are typically designed with rectangular spread footings, 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 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 columns subjected to unidirectional excitation, and related analytical studies, have similarly demonstrated the feasibility of the rocking mechanism to resist seismic effects.

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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 analyses and earthquake shaking table tests of moderate-scale models of bridge columns under multidirectional earthquake excitations. Efforts underway at UC Davis focus on analytical studies accounting for the nonlinear behavior of the supporting soils, and carrying out geotechnical centrifuge tests to validate models for soil-foundation interaction, including uplift. This paper highlights some of the preliminary work underway at UC Berkeley.

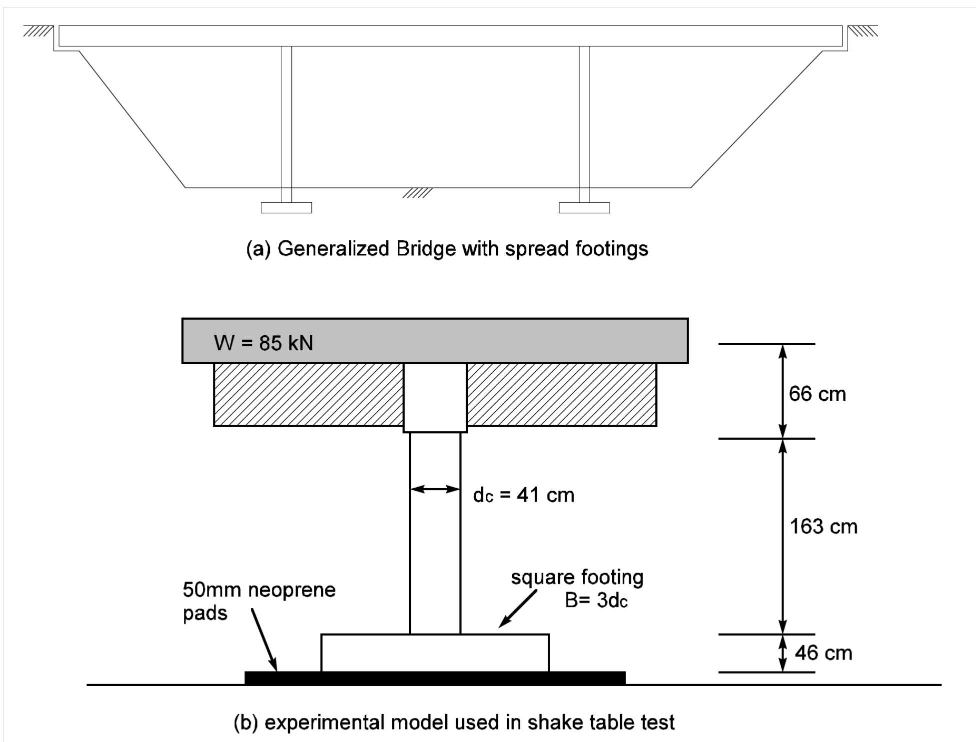


FIGURE 1: (a) GENERAL BRIDGE PIER (b) EXPERIMENTAL TEST SETUP

Experimental Program

The 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 (to idealize 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. 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 employed value of 10%; however, the mass was adequate to excite rocking response for various ground motions. A second phase of testing, 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. 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, evaluate the test setup and assess 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 present 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 to examine the behavior of rocking for square footings. 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 amplitude of each individual component 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 often resulting in larger responses. Even though this level of excitation would have damaged a fixed base column, the test column had no damage and re-centered following the shaking.

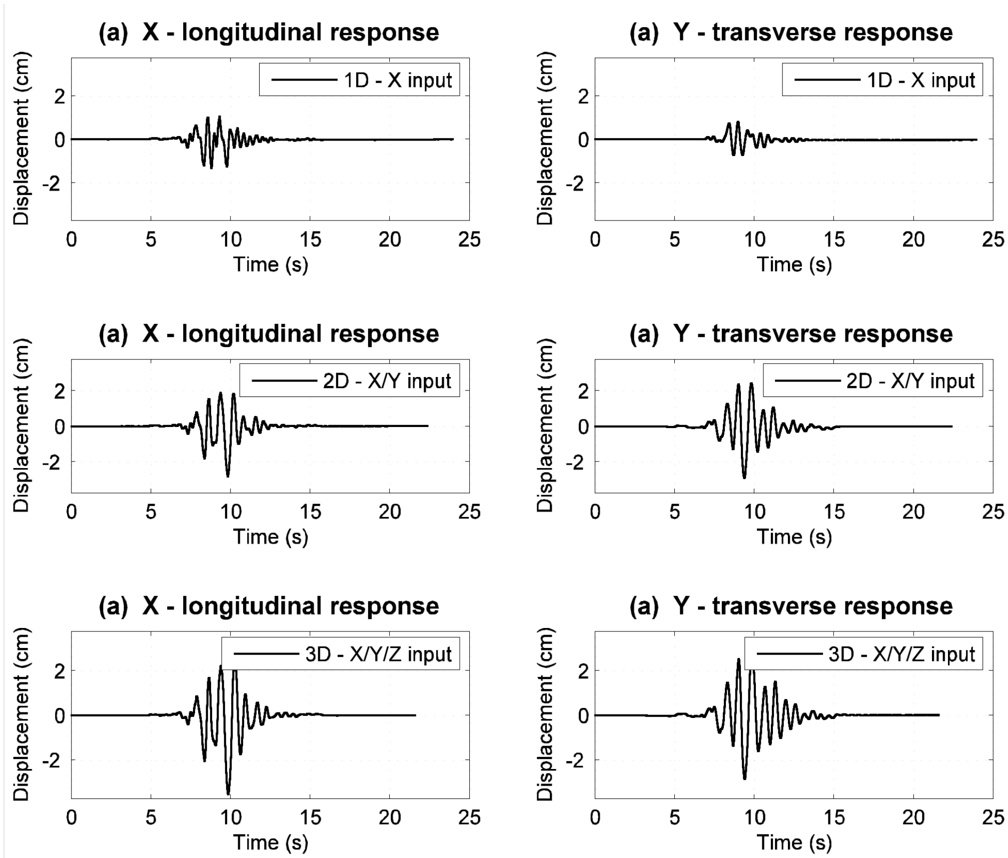


FIGURE 2: EXPERIMENTAL RESULTS ILLUSTRATING DISPLACEMENT INTERACTION FOR SEVERAL INPUT EXCITATIONS (LOS GATOS RECORD)

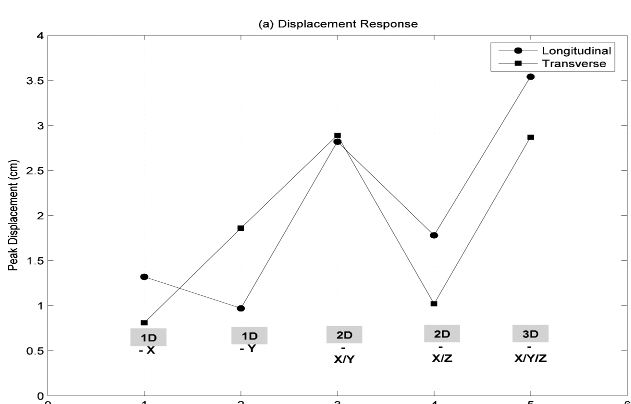


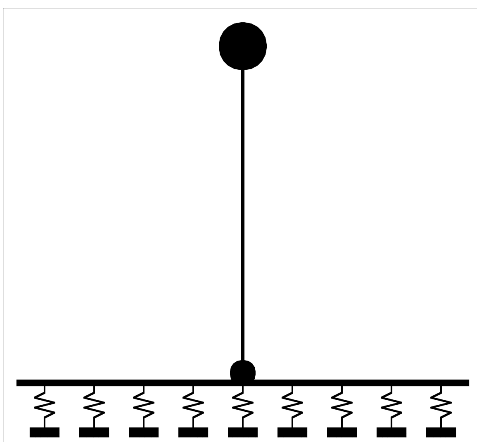
FIGURE 3: PEAK DISPLACEMENTS FOR 5 INPUT EXCITATIONS FROM LOS GATOS RECORD

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.

Analytic Comparison

The experimental setup modeled using OpenSees (OpenSees 1998). The model was based on a lumped mass idealization resting on elastic beams and nonlinear vertical springs. This is 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 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. A better characterization of the neoprene pads is warranted here.



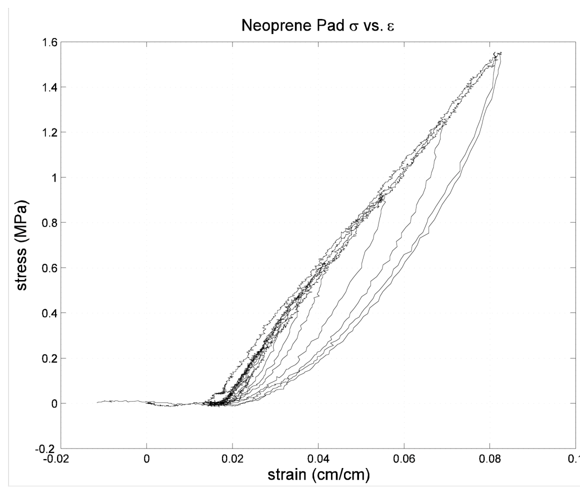
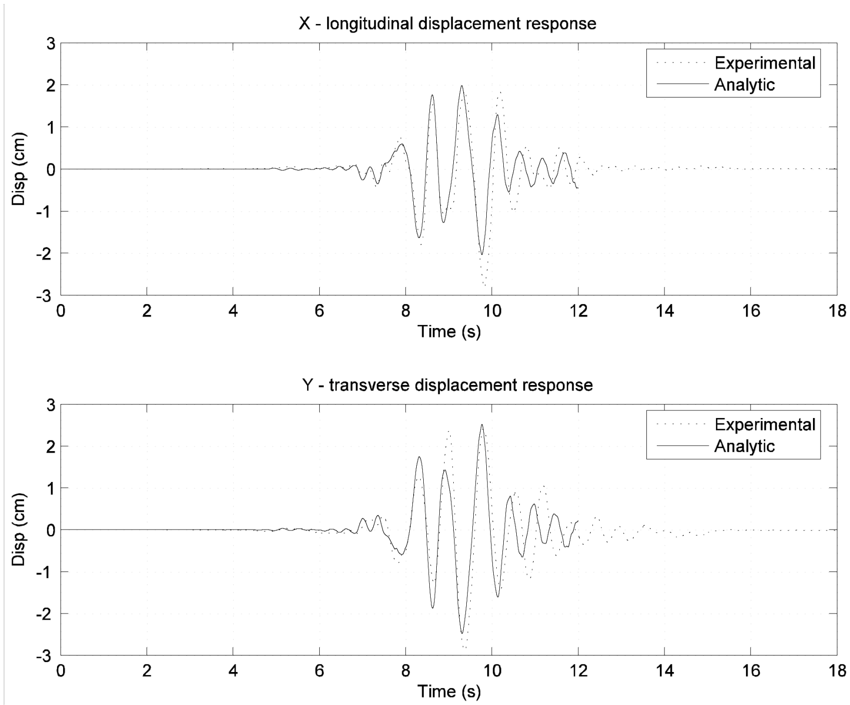


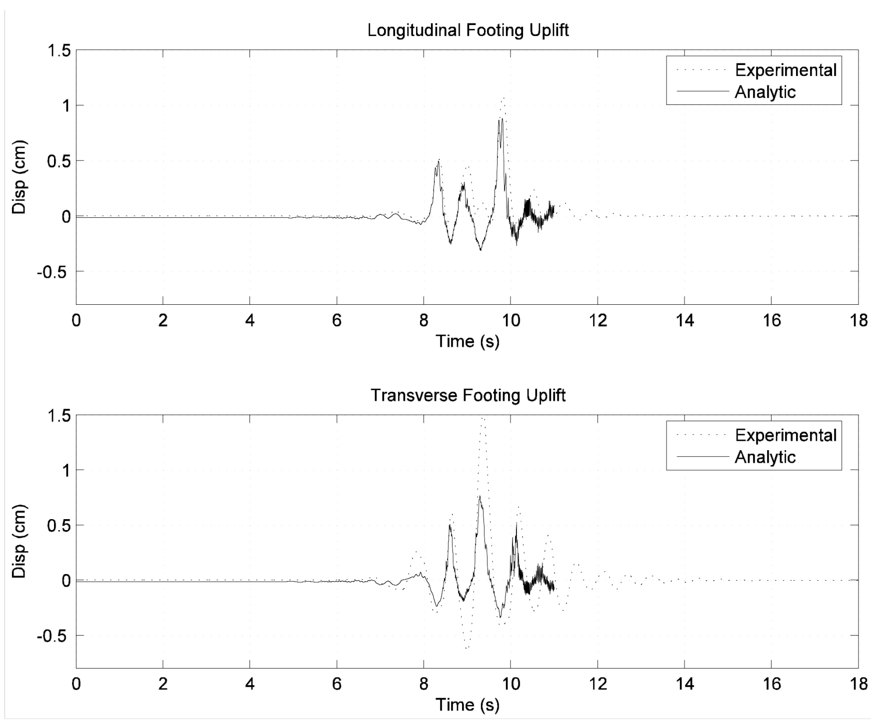
FIGURE 4: (a) Analytic Model (b) Axial Constitutive Relation for Neoprene Pad

Conclusions

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



(a) Column Displacement



(b) Footing Uplift

FIGURE 5: ANALYTIC COMPARISON OF COLUMN DISPLACEMENT AND FOOTING UPLIFT

Additional analyses of the results are currently underway to improve modeling capabilities, and to plan for a second series of tests. In particular, better characterization of the neoprene pads is needed to improve the analytical modeling. The second phase of testing will examine cases with larger initial mass and dead load, more 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.

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