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BRIDGE-ABUTMENT-BACKFILL DYNAMIC INTERACTION MODELING BASED ON FULL SCALE TESTS

P. Wilson[1] and A. Elgamal[2]

ABSTRACT

At high levels of seismic excitation, the bridge-abutment-backfill interaction can substantially affect the overall longitudinal dynamic response. In this regard, full scale tests were performed in order to investigate the resistance provided by 1.7 m of dense sand backfill, which extended behind an abutment wall to a distance of 5.6 m in a large soil container. The static passive earth pressure force-displacement relationship was recorded first. Next the model abutment and backfill were subjected to shake table excitations with passive pressure mobilized behind the wall. Results from the conducted tests illustrate how the instantaneous passive resistance depends on the backfill inertia, in addition to the wall displacement. Based on the test results, simplified abutment models are presented, which include the observed backfill inertial effects along with the passive force-displacement resistance. Finite element bridge simulations demonstrate the implementation and the effects of including the calibrated abutment models.

Introduction

In seismic design (Caltrans 2004, AASHTO 2007, Shamsabadi et al. 2007), an abutment system relies on the soil backfill to provide resistance to longitudinal bridge deck displacement. During strong shaking, if the deck impacts the abutment, a sacrificial portion (the backwall) can break off into the backfill. Resistance to further displacement of the deck and backwall is then provided by passive earth pressure within the densely compacted soil (Shamsabadi et al. 2007).

This abutment resistance can decrease the demand placed on other seismic components such as the bridge columns and foundation (AASHTO 2007). Current available models include bilinear representations of very limited data from tests performed using static backfills (Caltrans 2004, AASHTO 2007). As a result, more accurate representation of the abutment backfill resistance may lead to a safer or more economic seismic bridge design.

To aid in this regard, experiments performed on an abutment backwall, full scale in

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[1] Graduate Student Researcher, Dept. of Structural Engineering, University of California, San Diego, La Jolla, CA 92093-0085
[2] Professor, Dept. of Structural Engineering, University of California, San Diego, La Jolla, CA 92093-0085

height, are described. Static passive earth pressure force-displacement tests are performed first. Next, the soil container-backwall-backfill system is subjected to shake table excitation in order to record the effect of shaking on the mobilized passive resistance. Based on data and observations from the conducted experiments, simplified bridge finite element (FE) models are then described and demonstrated, which can include both the static backfill passive force-displacement resistance and the inertial effects observed from the dynamic tests.

Large Scale Tests

Test Configuration

Primary components of the experimental configuration (Wilson 2009) included a large laminar soil container restrained from translation by two stiff towers (Figure 1), a model of a plane strain section along the width of an abutment backwall (Figure 2b), a loading mechanism (Figure 2a) and a compacted sand backfill (Figure 2c). The model abutment consisted of a separate seat box resting beneath a suspended sacrificial backwall (Figure 2b), which supported 1.7 meters of backfill (typical abutment backwall height).

Hydraulic jacks reacted through load cells onto concrete-filled steel posts (Figure 2a) to push the wall into the backfill. During the static backfill passive force-displacement tests, the load cells measured the total lateral resistance from the soil. In shake table tests, the load cells measured the lateral earth thrust plus the test wall inertia. As such, the load cells measured the force that the bridge deck would experience during impacts once the backwall is sheared from its stem.

Well-graded sand with about 7 percent fines (cohesion of about 14 kN/m^2 was observed in direct shear and triaxial tests, Wilson 2009) was compacted (Figure 2c) for each test in compliance with Caltrans (2004) standard specifications for structural backfill. The unit weight of the dense sand backfill was approximately 20.6 kN/m^3. Dimensions of the backfill were about 2.9, 5.6 and 2.15 m in width, length and height, respectively.

Figure 1. Soil container and restraining towers on shake table during backfilling.

a) Loading mechanism

b) Backwall suspended above seat box

c) Compacting the backfill inside the soil container

Figure 2. Test configuration photographs.

As mentioned previously, the testing program consisted of both static passive force-displacement and dynamic excitation tests. First, the hydraulic jacks (Figure 2a) were used to push the backwall into the backfill in the two tests. The force-displacement relationship was recorded up to and beyond the peak measured resistance. In additional experiments, dynamic excitations were imparted on the system by the shaking table while the hydraulic jacks (Figure 2a) were locked in a fixed position. Changes in measured force (and pressure) were recorded throughout the shake-table excitations.

Passive Force-Displacement Tests

As the test wall was displaced laterally into the static backfill, the passive resistance increased until a peak was reached, before decreasing to a residual level (Wilson 2009). The peak resistance was close to the Log Spiral theory predictions, and occurred as the wall displacement reached about 3% of the supported backfill height. Hyperbolic models (e.g., Duncan and Mokwa 2001, Shamsabadi et al. 2007) were able to provide a good match with the recorded passive force-displacement relationship up to the peak. Using the test data, calibrated FE models were also employed to produce passive force-displacement curves for a wider range of backfill soils and depths (Wilson 2009).

Dynamic Excitation Tests

As mentioned above, the abutment wall and supported backfill were also subjected to shake table excitations in 3 different test series (Wilson 2009): i) with the wall and backfill in a near at-rest condition (near zero lateral wall displacement relative to the backfill), ii) with a portion of the peak passive resistance mobilized behind the wall (with the wall displaced into the backfill, but not beyond the peak resistance), and iii) with a passive failure wedge mobilized in the backfill (with the wall displaced into the backfill beyond the peak resistance range). A harmonic input motion and a modified 1994 Northridge earthquake record were scaled to produce different peak accelerations on the shake table in 26 different tests (Wilson 2009).

In the passive (ii) and passive failure (iii) condition tests, instantaneous changes in the mobilized passive force were recorded by the load cells during the shake table excitations (e.g., Figures 3 and 4). The load cell force *F* (normalized per meter of wall width) includes the earth thrust and the test wall inertia during shaking. Before and after the shaking, *F* represents the static passive earth pressure resultant force (initially, about 240 kN/m in Figure 3 and 140 kN/m in Figure 4).

Figures 3 and 4 illustrate how the passive thrust is influenced by the ground motion during shaking. At instants when the backfill inertia is directed away from the abutment wall, the passive resisting force is lower than the static level (e.g., at about 14.5 seconds in Figures 3 and 4). In contrast, at instants when the backfill inertia is directed towards the abutment wall, the passive resisting force is higher than the static level (e.g., at just after 15 seconds in Figures 3 and 4). As a potential consequence, the instantaneous passive resistance to bridge deck impacts at the abutments could depend on these backfill inertial effects.

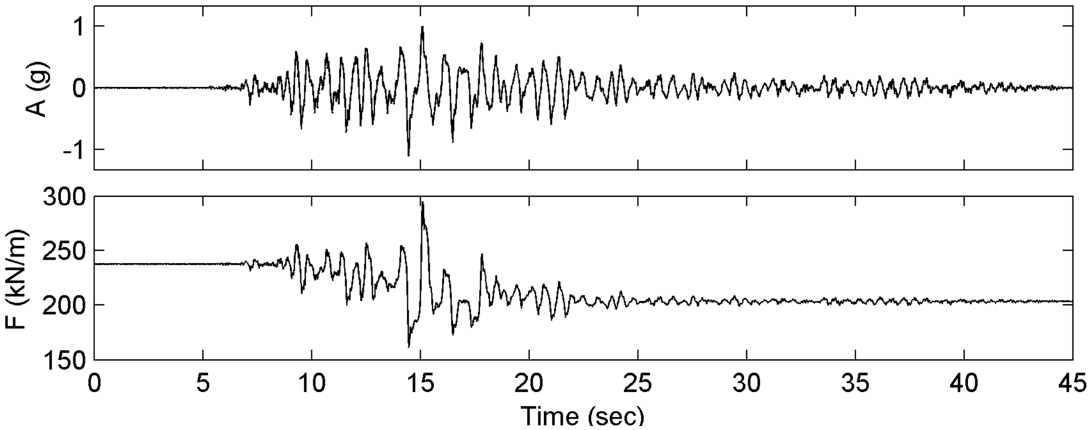

Figure 3. Recorded base acceleration (A) and load cell force (F) from a passive condition test.

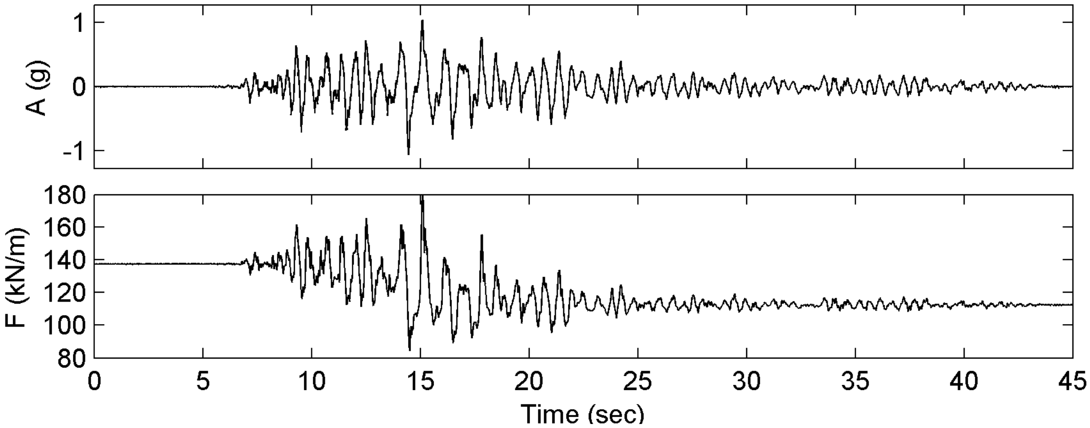

Figure 4. Recorded base acceleration (A) and load cell force (F) from a passive failure condition test.

Abutment-Bridge Interaction Modeling

In this section, a 2D bridge model is developed using the Pacific Earthquake Engineering Research Center (PEER) FE analysis code, Open System for Earthquake Engineering Simulations, or OpenSees (Mazzoni et al. 2006). A spring material which can be used to represent the static backfill passive force-displacement resistance is presented first. Next, a lumped mass is added to the bridge model to account for the effect of the backfill inertia. Finally, sample results are presented from two earthquake record simulations.

Static Passive Force-Displacement Resistance

Within the overall collaborative framework of an investigation into highway bridge seismic performance (Saiidi 2004), a new spring material has recently been implemented and is available for use in the OpenSees. For that purpose, a "HyperbolicGapMaterial" (Figure 5) was developed with the help of Matthew Dryden of the University of California at Berkeley, as a part of his PhD study under the supervision of Professor Gregory Fenves (Dryden 2009, Wilson 2009).

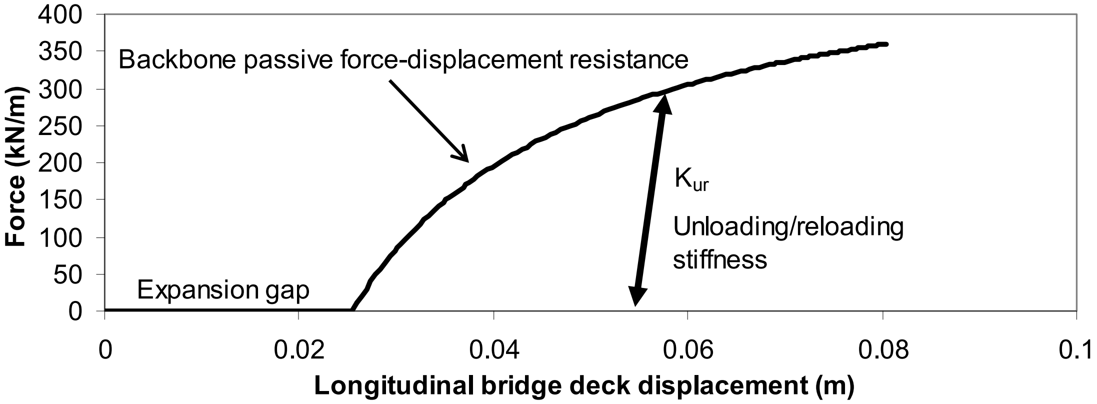

Figure 5. Hyperbolic Gap Material force-displacement behavior.

The model follows a hyperbolic backbone curve (Duncan and Mokwa 2001) for virgin loading, based on the passive pressure force-displacement relationship. For use in the model, hyperbolic curves considering several different soil types and wall heights were developed for based on experimental and numerical data (Wilson 2009).

In addition, the Hyperbolic Gap Material (Figure 5) includes an adjustable expansion gap (between the end of the bridge deck and the abutment wall). An unloading and reloading stiffness K_{ur} is also included for subsequent response cycles (Figure 5). The model assumes that if the bridge deck pushes the abutment backwall into the backfill and then retreats, the wall essentially remains at its furthest penetration (the small soil cohesion helps the deformed backfill to retain its shape). On subsequent loading cycles, it is assumed that the abutment loses its resisting capacity up to the point of prior unloading. For the implemented model, a high K_{ur} value, such as the initial stiffness of the employed hyperbolic model curve, may be adopted. It is also noted that moderate changes in K_{ur} were not found to produce noticeable changes in the overall bridge model response (Wilson 2009).

Figure 6 demonstrates the implementation of the Hyperbolic Gap Material as a spring at the abutments in a simple 2D (longitudinal direction) 2 span elastic bridge OpenSees model. Bridge dimensions and associated model parameters were set to approximately match the "Route 14 bridge (R14)" highway overpass in California, as reported by Aviram et al. (2008). The bridge deck ends are supported on rollers allowing free lateral movement until the expansion gap is closed (Figure 6). The bridge columns were modeled as fixed at the base and at the connection to the bridge deck (deforming in double-curvature). With that configuration, the first mode in the longitudinal direction had a first natural period of about 0.7 seconds.

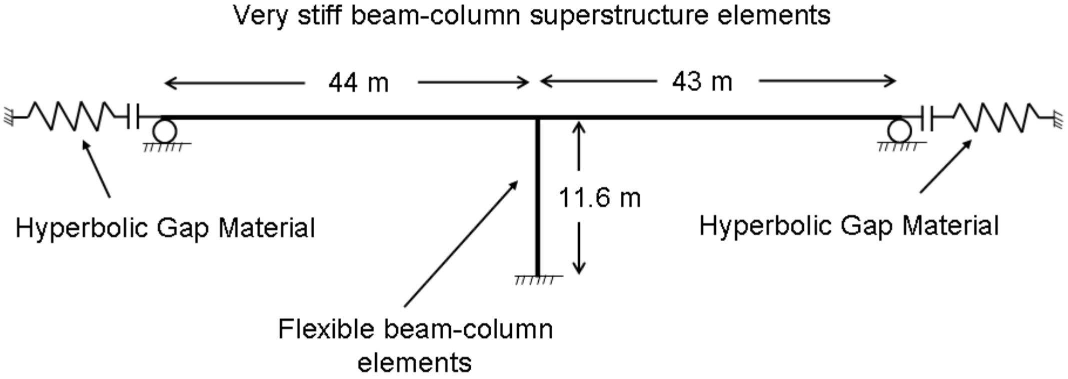

Figure 6. 2D bridge model implementation of the Hyperbolic Gap Material to simulate the abutment passive force-displacement resistance.

The abutment force-displacement response from a bridge simulation using a modified Century City Station record from the 1994 Northridge earthquake (Saiidi 2004) is shown in Figure 7. The model successfully captures the effects of the expansion gap and the nonlinear passive force-displacement resistance, with a simplified linear unloading and reloading stiffness to allow for simulation of cyclic loading.

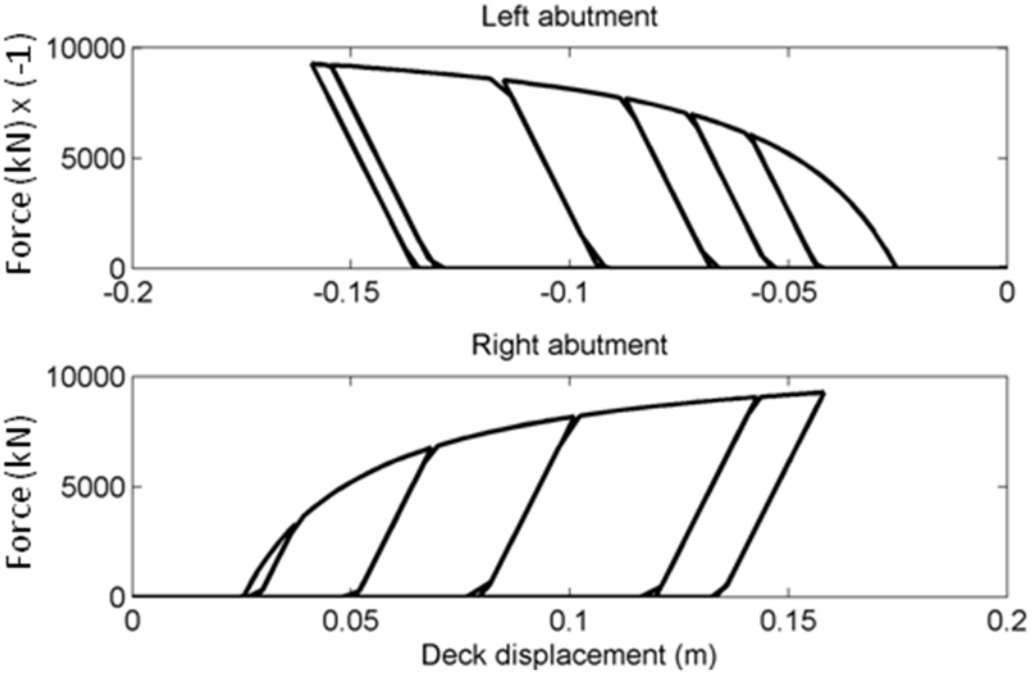

Figure 7. Hyperbolic Gap Material response during simulation of the Century City Station (Northridge 1994) earthquake record.

Including the Backfill and Backwall Inertia

In order to include an approximation of the observed backfill inertial effects from the dynamic tests, a lumped mass is added to the bridge model (Figure 8). The participating lumped backfill mass (Figure 8) is determined based on the size of the passive failure wedge (Wilson 2009) and the backwall mass. The required additional spring stiffness (Figure 8) is estimated based on the shear stiffness of the backfill. The force exerted by the mass on the bridge deck was also validated against the recorded changes in passive thrust from the dynamic tests (e.g., Figures 3 and 4).

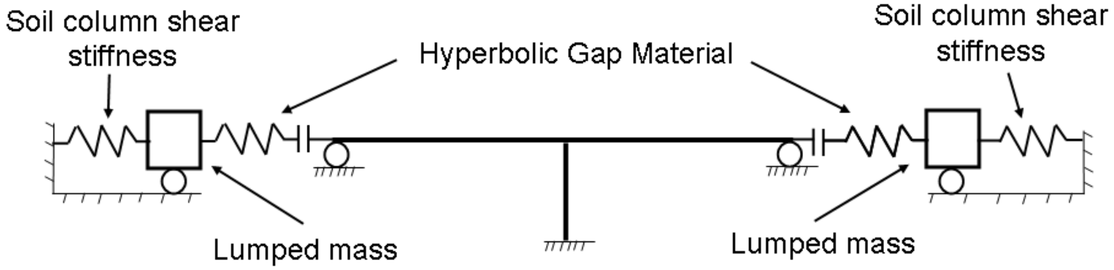

Figure 8. 2D bridge model implementation of the backfill inertia effect using a lumped mass.

The abutment force-displacement response from a bridge simulation using the Century City Station record is shown in Figure 9. This model adds the effect of the backfill inertia which causes the passive force-displacement relationship to diverge (Figure 9) from the static resistance behavior shown in Figure 7.

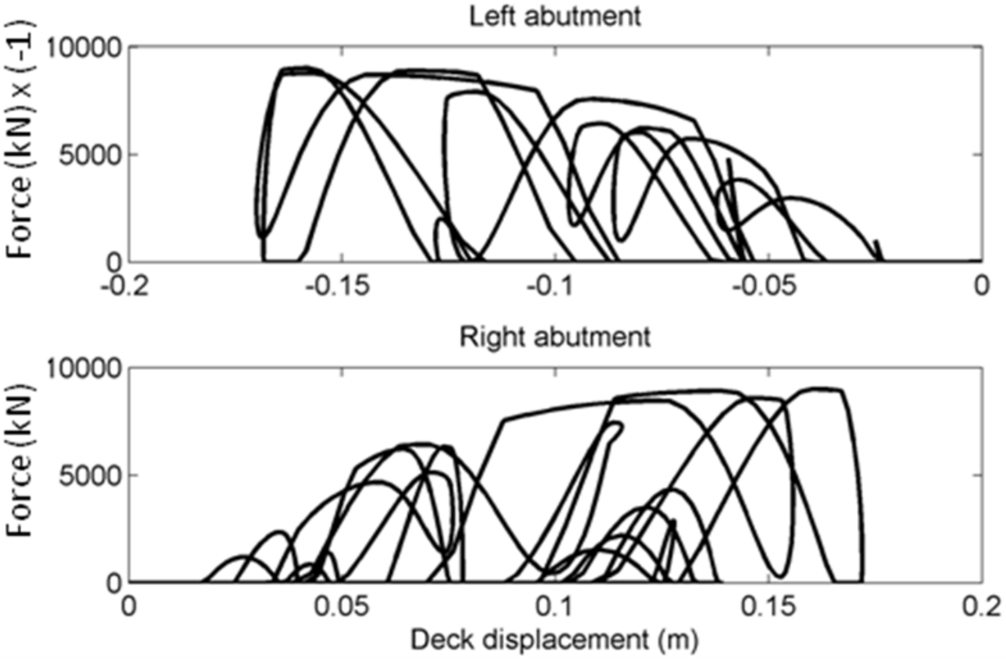

Figure 9. Force-displacement response at the bridge deck-abutment interface including the backfill inertial effect during simulation of the Century City Station earthquake record.

Simulation Results

The bridge model response is compared in terms of the column deformation for two earthquakes in Figures 10 and 11 using three different abutment models: i) no resistance provided by the abutments (using roller supports without any springs), ii) considering only the static backfill passive force-displacement (spring), and iii) including both the static force-displacement resistance and the backfill inertia effects (spring-mass).

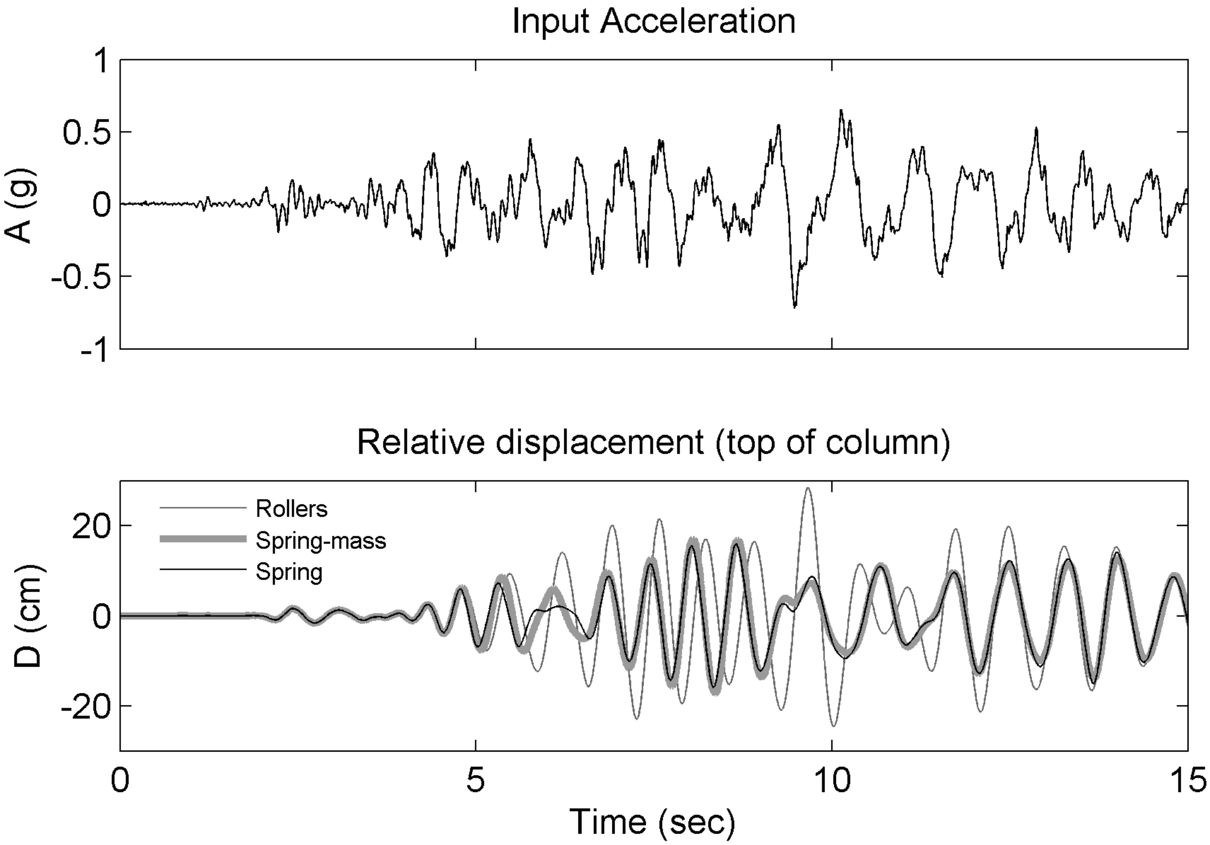

Figure 10. Bridge displacement response to Century City Station earthquake record.

From Figures 10 and 11, by including the effect of the abutment (as opposed to using only rollers), the predicted column displacement demand is reduced substantially. In Figure 10, the difference in column displacement response obtained by including (spring-mass model), and not including (spring only model) the effect of the backfill inertia is relatively small. This is partly due to the fact that the backfill inertial force is changing direction rapidly, causing both increases and decreases in the available resistance.

During the Rinaldi input record (Northridge 1994) of Figure 11, influence of the backfill inertia is more pronounced. In Figure 11, the sudden, strong acceleration jolt at about 2.5 seconds results in a larger displacement (about 20% more) when the backfill inertial effect is included. At such instances, the backfill inertial force reduces the available abutment resistance (detrimental effect). In some other cycles (e.g. around 5 seconds), the backfill inertia increases the abutment resistance, and reduces the corresponding bridge displacement (beneficial effect).

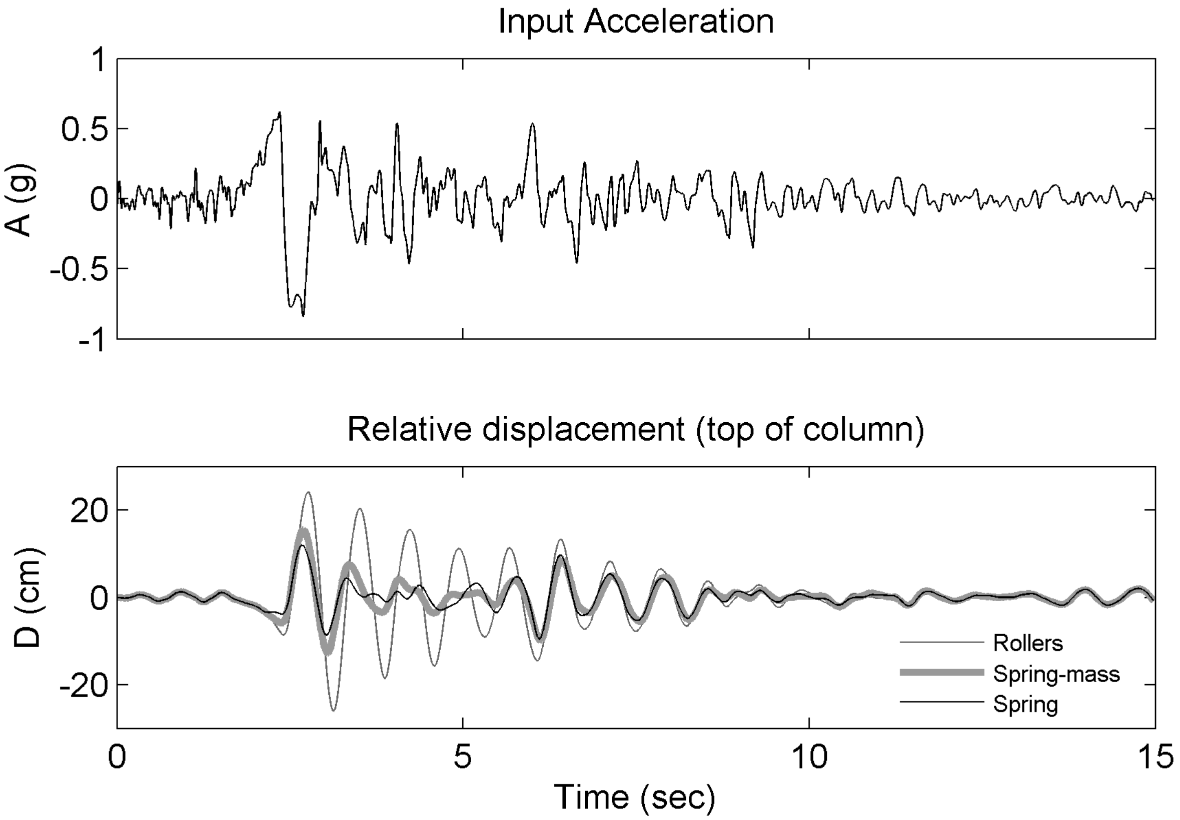

Figure 11. Bridge displacement response to Rinaldi earthquake record.

Conclusions

Full scale tests were performed in order to investigate the available abutment backfill resistance to earthquake induced bridge deck displacement. Using results from these tests, models were described which can represent the passive force-displacement resistance, and the effects of inertial forces within the backfill. The impact of these models was illustrated using a simple representative finite element bridge model.

Results from the bridge model simulations show that including a contribution which represents the abutment resistance, can substantially reduce the predicted column displacement demand. An added lumped mass to simulate the effects of inertial forces in the backfill, caused instants of both increased and decreased abutment resistance during shaking. Depending on the bridge and input ground motion configurations, the overall influence of backfill inertia may be small. In such cases, simply including the static backfill passive force-displacement resistance would be sufficient. However, additional research to further investigate the effects of backfill shaking on the abutment passive force-displacement is needed, possibly within a performance-based earthquake engineering framework.

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