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EARTHQUAKE RESPONSE OF TWO–LEVEL VIADUCT BRIDGES

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ABSTRACT

The nonlinear effects in the earthquake response of two–level viaduct type bridges are investigated. The nonlinear response is due to the hinge opening and pounding between adjacent frames, tension only cable restrainers, compression only abutments, and plastic hinge formation in the columns. The linear and nonlinear dynamic analyses of typical multiple–frame viaducts are performed using "stick" models for a range of parameters for a typical viaduct. The study shows that it may be necessary to perform nonlinear analysis to determine the effects of hinge opening and closing on the ductility demands. Large hinge openings increase the displacement of interior frames of the viaduct with abutments compared with the case of closed hinges. Considering variable site response effects along a bridge, there can be significant amplification of the frame on stiff soil because of the pounding from an adjacent frame on soft soil. The non–uniform ground motion generally increases the out–of–phase response between the adjacent frames. A large number of restrainers is needed to limit the hinge opening between frames to the yield displacement of the restrainers.

KEYWORDS

Viaduct; bridge; restrainers; hinge opening; nonlinear response.

INTRODUCTION

The damage and collapse of two–level viaducts in the 1989 Loma Prieta earthquake have prompted intensive examination of the seismic response and performance of these important components of the transportation system. These type of long structures are particularly vulnerable to ground motion in the longitudinal direction because of the problematic longitudinal framing system, although the response due to transverse motion is also important. The opening and closing of hinges during an earthquake produces discontinuities which change the load paths in the structure, and hence change the system response. Cable restrainers are provided to restore some continuity between adjacent frames, but they exhibit nonlinear behavior because they can only resist tension and may yield. The abutments are only effective in resisting compression. The yielding of structural members in a viaduct changes the kinematics and internal force distribution, assuming non–ductile failure modes such as shear and joint failure are prevented by proper design. This study examines all these effects to provide the insight for performing earthquake evaluation of two–level viaducts. The study also presents the earthquake response due to the effects of varying site ground motions for a long viaduct.

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Three–dimensional elastic and two–dimensional inelastic models are used to understand the system response due to the ground motion in the longitudinal direction. One of the goals of the study is to compare the nonlinear response of the viaducts with the approximate elastic response.

MODELS OF VIADUCT AND ANALYSIS METHODS

The structure selected for this study is representative of a typical pre–1970 construction for a two–level reinforced concrete viaduct with two–column bents. The viaduct has four 270 ft long frames of three bents each. These frames are separated by hinges at the upper and the lower levels. More recent viaducts have hinges further apart. The hinges in this viaduct are connected by cable restrainers 3/4 in. diameter, 20 ft long. The viaduct with abutments used in this study has stiff abutments at the lower level and soft abutments at the upper level. The stiff abutment is representative of the typical construction and soil conditions and the soft abutment is representative of the stiffness of a single–level frame of three spans.

The models used in the study have beam elements for bent caps and box girders and beam–column elements for the columns. The shear capacity of the column is assumed to be greater than the shear demands for the purpose of investigating flexural ductility demands. The models do not account for the failure mode due to large torques in the short outriggers and the strength degradation due to cyclic loading.

The SADSAP computer program (Wilson, 1991) is used in this study for the earthquake analyses of elastic models of the viaduct. A three–dimensional stick model with linear frame elements, shown in Fig. 1, includes local nonlinearities due to the opening and closing of hinges and seats at the abutments. The gross moments of inertia and torsional moment of inertia are multiplied by a factor of 0.60 to approximate the cracked section properties. Corresponding to the gravity axial load of 1,350 kips per column, the moment capacity of the column is 13,300 kip–ft. Based on this flexural strength, the columns at the lower–level yield when the shear force is 700 kips. Each hinge in the box–girder is modeled by two gap elements. The abutments and restrainers are modeled as compression–only and tension–only elements, respectively but these elements remain elastic. The slack in the restrainers is accounted for in the model. The total longitudinal stiffness of the stiff abutment, obtained using the method described in Chapter 14 of *Bridge Design Aids* (Caltrans, 1990), is 62,400 k/ft. Based on the stiffness of a single–level frame of three spans, the soft abutment has the longitudinal stiffness of 20,000 k/ft.

The DRAIN–2DX computer program (Prakash, Powell, and Filippou, 1992) is used to perform the inelastic analyses. The two–dimensional model takes advantage of the symmetry of the viaduct along the longitudinal axis and uses one–half the section properties. The columns are modeled as inelastic elements with concentrated plastic hinges at the ends. The second order P–Δ effects are included in the analyses. The ductility ratios are defined for displacement and section curvature. The ductility ratio for each quantity is defined as the ratio of its maximum value normalized by the yield value. A static pushover analysis gives yield displacement of 2.2 in. for a single frame of the viaduct. The moment–curvature relationship for the columns for static axial load gives the yield curvature of the column as 0.000072 rad/in. The maximum curvature is determined by dividing the maximum plastic rotation at the top of the lower–level column by the plastic hinge length, which is assumed to be one–half the column depth (36 in.). The secant stiffness of moment–curvature curve gives an estimated cracked section modulus approximately 60 percent of the gross section modulus. The nonlinear model accounts for the capacities of the abutments and restrainer yielding.

EARTHQUAKE GROUND MOTION

A ground motion record derived for the location at pier E3 of the San Francisco–Oakland Bay bridge due to a San Andreas fault event (Bolt, 1992) is used as the stiff soil site motion. This record has peak ground acceleration of 0.48g. The base motion derived for rock soil site record is filtered through the SHAKE program to give the ground acceleration for a typical San Francisco soft soil site. This ground motion has a peak acceleration of 0.54g. The spectra for both the soil site ground motions, shown in Fig. 2, have spectral accelerations of the order of 2g for a broad range of periods. The vertical component of the ground motion is not considered as it is expected to have small effect on the response of the viaducts with short outriggers.

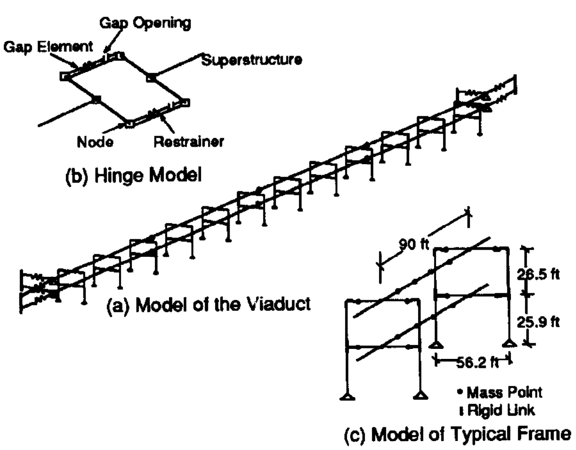

Fig. 1 Three–dimensional model of two–level viaduct.

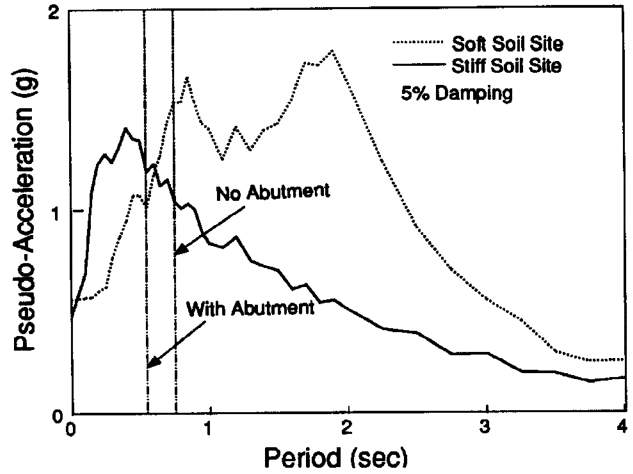

Fig. 2 Response spectra for the ground motion at stiff and soft soil sites.

RESPONSE OF VIADUCT SUBJECTED TO UNIFORM GROUND MOTION

The viaduct models analyzed for uniform ground motion are shown in Table 1. As shown in Table 2, the common assumption of equal elastic and inelastic displacements is true for the viaducts without abutments. It must be recognized, however, that the displacement histories are substantially different. The inelastic displacements are greater than the elastic displacements for Cases 2A and 2B of the viaduct with abutments because the abutments yield, reducing the restraint of the end frames assumed in the elastic model. The large compression displacements in the abutments and the force demand–to–capacity ratios of up to 5 observed for Case 2B indicate that the abutments would experience substantial damage and that the elastic abutment model overestimates the restraint of the abutments. It should be noted, however, that if an iterative procedure for the linearized abutment stiffness is used for the elastic analysis, the inelastic to elastic displacement ratios would not be as large.

Table 1. Viaduct models for uniform ground motion.

Case	1A	1B	2A	2B	3A	3B
Abutment	No	No	Yes	Yes	Yes	Yes
Hinge Opening (in.)	0.75	0.75	0	0	1.5	1.5
Seat Opening (in.)	—	—	0	0	1.4	1.4
Ground Motion for Soil Site	Stiff	Soft	Stiff	Soft	Stiff	Soft

The initial hinge opening does not affect the response of the viaducts without abutments subjected to uniform ground motion as all the frames move in phase. However, the response of a viaduct with abutments is sensitive to the initial hinge opening because it affects the amount of restraint that develops between the adjacent frames. The restrainers have little effect on the response of the viaducts with frames of similar stiffness and subjected to uniform ground motion because the out–of–phase displacement between the adjacent frames is small even without restrainers.

The ductility demands from the inelastic analyses and the moment overstrength ratios from the elastic analyses are listed in Table 2. Although the displacement ductilities are moderate, the curvature ductilities for the plastic hinging at the top of the lower–level columns are large. This is a characteristic of the inelastic response of the two–level viaducts because the plastic hinges form in the lower–level columns. Comparing the displacement ductility demands with the elastic overstrength ratios, it is clear that the displacement ductility demands of 2.3 to 4.5 for the viaducts without abutments exceed the moment overstrength ratios of 1.3 to 3.4. The plastic hinges formed at the top of the lower–level columns produce a soft story mechanism in the lower–

level. Therefore, substantially larger ductility capacities must be provided in the columns than indicated by the moment overstrength ratios. The comparison of Cases 2B and 3B indicates that initial hinge opening can substantially increase the moment overstrength ratios and the ductility demands in the viaduct with abutments.

Table 2. Elastic and inelastic response of viaducts subjected to uniform ground motion.

Case	1A	1B	2A	2B	3A	3B
Ratio of Max. Inelastic to Elastic Displacement	1.06	1.06	1.19	1.76	0.82	1.23
Moment Overstrength Ratio in Lower–Level Column	2.43	3.43	1.46	1.25	2.25	2.49
Displacement Ductility	3.27	4.54	2.30	2.90	2.29	3.82
Curvature Ductility	12.8	17.7	7.1	12.5	7.5	17.9

The earthquake response of a long viaduct with frames of approximately similar stiffness can be bounded by two simple models, so that a nonlinear analysis is not necessary to obtain an approximate response of the viaduct subjected to uniform ground motion. A model of a typical single frame in the viaduct gives a reasonable upper bound of the displacement response, as shown in Fig. 3(a). The lower bound of the displacement response can be obtained by analyzing a complete viaduct in which the hinges are represented by rotational releases to allow the rotation about the vertical and the transverse axis of the viaduct. In this model, the abutments are modeled as linear springs with one half the stiffness of the compression only abutment. Figure 3(b) shows the comparison of elastic displacement for Case 2B with the lower bound model.

RESPONSE OF VIADUCT SUBJECTED TO NON–UNIFORM GROUND MOTION

The large number of bents in a long viaduct provide multiple points of input for the earthquake ground motion. The cases presented in this paper examine the effects of non–uniform ground motion from non–uniform soil sites. The effects of a non–uniform soil site are incorporated in the model by applying two different longitudinal ground motions for the four–frame viaduct model. The first two frames are subjected to the soft soil ground motion and the remaining two frames are subjected to the stiff soil ground motion. The non–uniform ground motions used in the study may be considered limiting cases for the type of motions experienced at an actual site.

The non–uniform ground motion is applied to the two–dimensional model of the viaduct as specified ground displacement histories at the supports. The abutments are assumed to be monolithic. The abutment is modeled for the elastic analysis by a spring with one–half the compression stiffness. The abutment is modeled similarly for the inelastic model but it is allowed to yield at its estimated compressive strength.

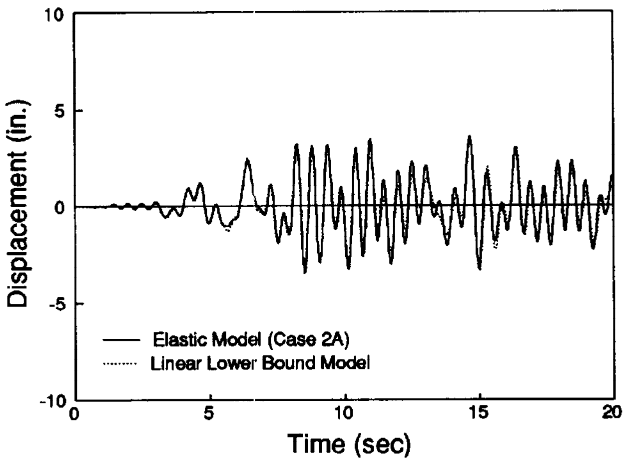

Fig. 3(a) Longitudinal displacements of viaduct with abutments and lower bound model.

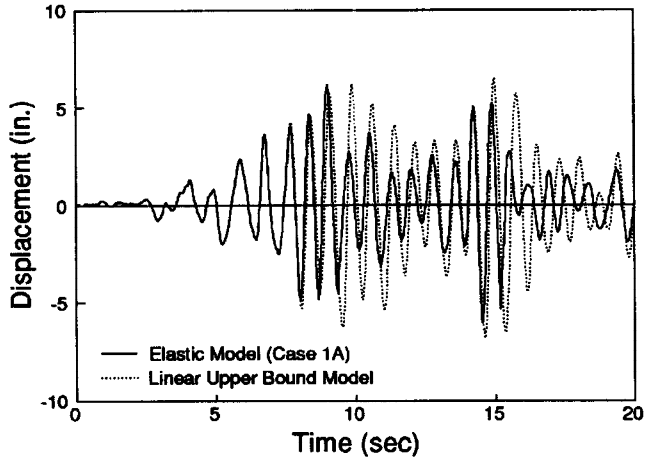

Fig. 3(b) Longitudinal displacements of viaduct without abutments and upper bound model.

The cases analyzed for viaducts on non–uniform soil site are shown in Table 3. The non–uniform ground motion causes pounding between adjacent frames due to the out–of–phase response between these frames. Figure 4 illustrates the relative displacements of the interior frames on the soft and stiff soils according to the elastic and inelastic models for Case 4B. The displacement of the stiff soil frame relative to ground is greater than the soft soil frame because the latter pushes (through pounding at the hinge) on the former. The pounding results in a significant yielding, with residual displacement, of the stiff soil frame. Clearly, the restraint of the soft soil frame and the effect of pounding on the stiff soil frame are more significant for the inelastic model than for the elastic model. The pull from adjacent frames through restrainers may increase the displacement of the frames after the columns yield and, therefore, further increases the offsets in displacement of the yielded columns in a typical frame. The residual displacements due to plastic hinging are also exacerbated by the P–Δ effects. The effects of non–uniform ground motion on the response of viaduct with abutments are similar to that for the viaduct without abutments.

As shown in Table 4, the displacement ductility demand for a viaduct subjected to non–uniform ground motion is as much as 6.1 for the stiff soil frames (Case 4A) compared with the ductility demand of only 3.3 for a viaduct subjected to the uniform stiff soil site ground motion (Case 1A). The displacement ductility reduces as the number of restrainers increases. A comparison of Cases 4A and 4D indicates that the initially open hinges reduce the pounding between the interior frame and the end frame, thereby reducing the ductility demand on the stiff soil frame and increasing the ductility demand on soft soil frame. In the limit with large hinge opening, the response of a frame is approximately equal to its independent response

Table 3. Viaduct models for non–uniform soil site ground motion.

Case	4A	4B	4C	4D	5A	5C
Abutments	No	No	No	No	Yes	Yes
Hinge Opening (in.)	0	0	0	1.5	0	0
Restrainers at Upper Level	0	60	120	60	0	120
Restrainers at Lower Level	0	50	100	0	0	100

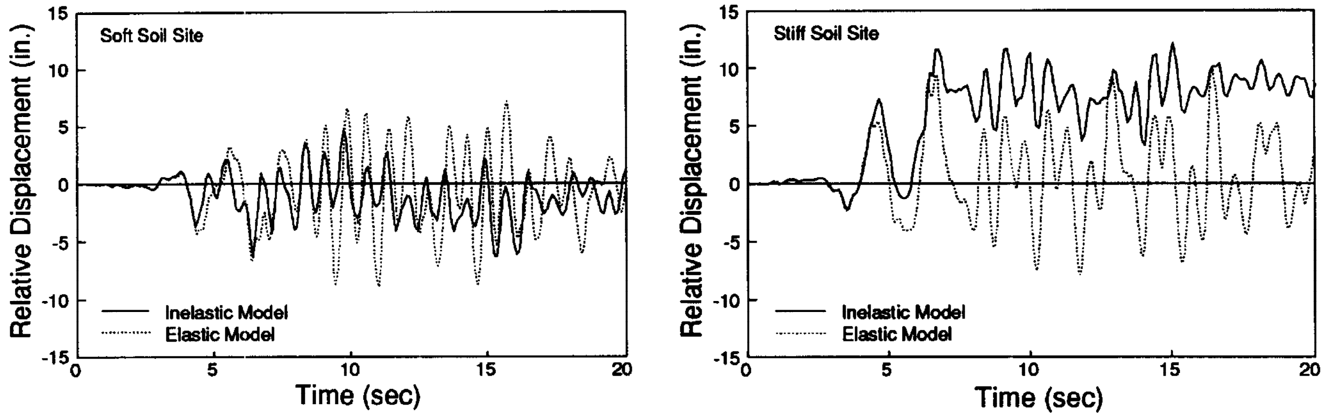

Fig. 4 Longitudinal displacement relative to ground for interior frames on soft and stiff soil sites (Case 4B).

When the number of restrainers is increased from zero (Case 4A) to twice the nominal number (Case 4C), the moment overstrength ratio decreases by less than 5 percent in an interior frame on soft soil site. In contrast, the inelastic response indicates that the ductility demand decreases by about 50 percent for this frame in Case 4C compared with Case 4A. The inelastic response generally shows larger displacement ductility demands for frames on stiff soil site compared with frames on soft soil site for all the cases studied. However, the moment overstrength ratios are not significantly different for frames on stiff or soft soil site in the elastic model. In summary, the elastic model does not accurately predict the inelastic response of the viaduct.

Table 4. Elastic and inelastic response of viaduct subject to non–uniform site ground motion

Case	4A	4B	4C	4D	5A	5C
Max. Inel. Displ. to Elastic Displ.						
Interior Frame on Soft Soil	1.04	0.55	0.53	0.58	0.86	0.71
Interior Frame on Stiff Soil	1.18	1.06	0.99	0.79	1.39	1.11
Moment Overstrength Ratio						
Interior Frame on Soft Soil	4.17	3.96	4.03	3.61	3.11	3.08
Interior Frame on Stiff Soil	4.16	4.11	4.28	3.84	3.56	3.63
Displacement ductility						
Interior frame on Soft Soil	5.4	2.8	2.6	3.3	3.5	3.0
Interior frame on Stiff Soil	6.1	5.5	4.9	4.4	6.2	5.2

Table 5 shows the maximum hinge opening between the two interior frames on different soils from the inelastic and elastic models. The inelastic model gives substantially larger hinge openings compared with the elastic model. Since the inelastic model gives more out–of–phase motion between adjacent frames compared with the elastic model, the restrainers appear to be more useful. As the restrainers yield, however, they become less effective in limiting the out–of–phase response compared with the elastic model. Figure 5 shows that a large number of restrainers is required to limit the maximum hinge opening to less than the yield displacement of the restrainers.

Table 5. Maximum hinge openings at upper level between adjacent interior frames on soft and stiff soil sites. Ductility demand on restrainers is shown in parentheses.

Case	4A	4B	4C	4D	5A	5C
Max. Hinge Opening (in.)						
Elastic Model	17.8	7.8	6.0	7.1	16.7	6.2
Inelastic Model	30.2 —	21.1 (5.0)	9.9 (2.3)	20.4 (4.8)	27.1 —	8.5 (2.0)

The restrainers between two frames on the same soil site tie the frames together. As the adjacent interior frames on different soil sites move out–of–phase, the restrainers between these frames have to pull more than one frame on each side. The current design criteria for calculating the number of restrainers between two adjacent frames do not account for the pull these frames may experience from other frames. Also, the current criteria do not consider the dynamic effects which can significantly increase the forces in restrainers. Whereas older viaducts with 6 in. seat widths at the hinges and no seat extenders would unseat (and collapse) for the cases presented here, new viaducts with seat widths of at least 30 in. are adequate for the cases considered.

RECOMMENDATIONS FOR DESIGN

Linear elastic models can estimate the upper and lower bounds of the earthquake response of straight viaducts subjected to uniform ground motion. The restrainers do not significantly affect the response of the straight two–level viaducts subjected to uniform ground motion. Instead, the large initial hinge openings significantly increase the response of viaducts with abutments. The viaducts with frames of different stiffness show pounding between adjacent frames due to out–of–phase response.

The design provisions should ensure that the plastic hinging would occur in the columns prior to reaching a less desirable, nonductile failure state. The displacement ductility demands, though large, may be acceptable for most viaducts subjected to uniform ground motion. However, the displacement ductility demands indicated in the present analyses for viaducts subjected to non–uniform ground motion are difficult to achieve. The inelastic analyses indicate that abutments do not provide significant restraint in long viaducts.

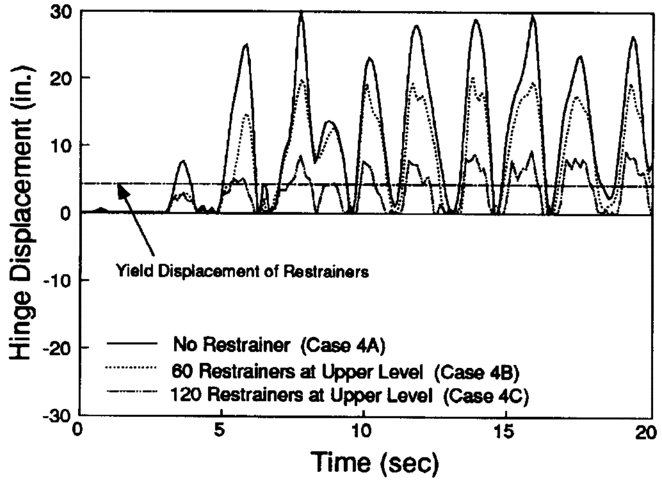

Fig. 5 Effect of restrainers on hinge displacement between adjacent frames on stiff and soft soil site in viaduct without abutments.

The response of a viaduct subjected to non–uniform site ground motion shows that the frames subjected to the amplified soft soil ground motion are restrained by the frames subjected to the stiff soil ground motion. The pounding between adjacent frames due to the out–of–phase motion can substantially increase the response of frames on stiff soils. An unrealistically large number of restrainers are needed to limit the hinge openings to less than the yield displacements of the restrainers. The large maximum hinge opening between adjacent frames of viaducts subjected to non–uniform ground motion indicates that the viaducts should be designed with seat lengths of 30 in., as is the current practice.

Nonlinear analysis should be considered for the design evaluations because of the following reasons: (i) the common practice to correlate the moment overstrength ratio from elastic analysis with the displacement ductility from inelastic analysis invariably underestimates the local demands in multi–column two–level viaducts as the inelastic action is concentrated in lower–level columns; (ii) the effects of restrainers and the abutment restraints are overestimated in the linear analysis; and (iii) the nonlinear analysis is particularly important for analyzing viaducts subjected to non–uniform ground motion to capture the effects of pounding and the interaction between adjacent frames.

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