Numerical Study of Rocking Pier in Mitigating Bridge Responses to Earthquake Ground Motions

Hong Hao[1] and Max Daube[2]

1. Corresponding Author. Winthrop Professor, School of Civil and Resource Engineering, The University of Western Australia, WA6009
Email: hong.hao@uwa.edu.au

2. Final Year Student, School of Civil and Resource Engineering, The University of Western Australia, WA6009

Abstract

Foundation uplifting or rocking has been explored as an isolation technique by many researchers. It introduces alternate modes of nonlinearity and energy dissipation as compared to plastic hinge rotations in fixed base structures. Allowing foundation to uplift, the moment capacity of the bridge pier is limited to that required to cause uplift, and as such reduces ductility and strength demands on the bridge piers. A number of researches, mainly experimental based, have been reported on the performance of columns and bridge piers to resist earthquake ground motions. Rocking foundations have also been used in some of the bridge constructions around the world, such as the South Rangitikei Bridge in New Zealand and Golden Gate Bridge in USA. However, allowing foundations of bridge piers to uplift increases the displacement response of bridge girders, which may increase the relative displacement between bridge structures resulting in pounding and unseating damage of bridge decks. Pounding between bridge girders usually causes damages to the bridge girder around the pounding area, and in extreme cases results in unseating of bridge decks. No publication can be found in the literature that studies possible pounding between bridge decks with uplifting foundations. This paper presents numerical results of dynamic responses of a bridge structure with rocking pier to spatially varying earthquake ground motions. Spatially varying ground motions compatible to design response spectrum in Australian Earthquake Loading Code are simulated as inputs in the analysis to calculate the nonlinear inelastic responses of bridge structures. It is found that allowing foundation to uplift effectively reduces the shear force and bending moment in bridge pier, but increases the pounding damage between bridge decks and between deck and abutments.

Keywords: bridge structure, foundation uplift, ground motion spatial variation, nonlinear response, pounding

INTRODUCTION

Many bridges are used as lifelines. The consequence of damage to bridges could be catastrophic. Immediately after an earthquake, bridge damage prevents emergency personnel and material from timely access to the damaged sites, possibly causing further loss of life and preventing control of further damage. Repair and replacement of the damaged bridges could take several years, resulting in a significant increase in commuting time and cost during the period the bridges are out of service.

In the conventional seismic resistant design of bridges, the superstructure and foundations are designed to respond elastically to earthquake loading, whilst the bridge piers are designed to be ductile and deform inelastically to dissipate energy. As a result of this design approach, bridge piers typically incur significant amounts of damage during seismic events, and may require substantial repair or replacement. In view of the significant consequences that may be induced by bridge damage, recent research has been towards damage avoidance design besides the conventional design against collapse and loss of life. One way to do this is by increasing the strength and stiffness of the designed structure to limit the inelastic response and reduce displacements of the structure. This would inevitably increase the construction costs, as well as the seismic-induced accelerations in the structure which could potentially cause damage to other structural elements. Another approach is to isolate structure and/or provide energy dissipation damping devices or let selected structural members yield to absorb energy. The use of isolation, damping or energy dissipation devices is particularly attractive in bridges, as they are easy to incorporate into the design, damage potential can be concentrated in a few elements which may be easily checked and replaced, and the response of the bridge can be controlled in a predictable way (Priestley et al. 1996). Allowing foundation uplifting or rocking, which arguably comprises elements of both seismic isolation and passive energy dissipation, has attracted more and more attentions in research and design. Structures allowed to rock on their base introduce alternate modes of nonlinearity and energy dissipation (Mahin 2008). By utilising uplift in the system, the moment capacity of bridge pier is limited to that required to cause uplift, and as such reduces ductility and strength demands on the bridge pier. This limits the damage to the pier, and reduces residual displacements of the bridge.

The idea of introducing a rocking mechanism in structures can be dated back to the work of Housner (1963), who observed the survival of elevated water tanks during the Chilean earthquakes in 1960, as well as similar incidents of seemingly unstable structures performing well under earthquake due to the development of a “rocking” mechanism. Since then many researchers have investigated the possibility of using rocking mechanism to protect structures. Mander and Cheng (1997) developed a concept termed Damage Avoidance Design (DAD) in which bridge piers were allowed to rock. Unbonded tendons were utilised for stability and ductility purposes, and steel plates were used at the rocking interface to prevent damage during movement. Testing on a full-size bridge pier showed good agreement with predicted theoretical results, and no damage was noted. Cheng (2007) tested precast columns anchored by unbonded steel bars running through the centre to investigate the performance of columns anchored with different diameter bars, in order to ascertain the optimum detailing of the steel anchorage, such that the column deforming elastically without inciting rocking behaviour under small to medium ground excitations, but rocking when subjected to large earthquakes. Cheng (2008) also investigated the damping of the rocking bridge piers and the effect of sliding during the rocking motion on energy dissipation of the system. Palermo et al. (2005 and 2007) followed on from the work of Mander and Cheng (1997) and Billington and Yoon (2004) also investigated the potential of the “hybrid” system for bridge structures, and compared the results to the traditional monolithic bridge pier design.

A limited number of bridge structures in existence have utilised the concept of rocking in an attempt to improve seismic performance. These include the Lion’s Gate Bridge in Vancouver, Canada (Dowdell and Hamersley 2000), the Golden Gate Bridge in San Francisco, California (Ingham et al. 1996) and the South Rangitikei Bridge in New Zealand (Cormack 1988). Analyses demonstrated that using rocking foundation led to smaller and reparable damage during strong earthquakes. The rocking of the bridge piers was considered a viable technique to reduce stresses in the bridges, and a readily achievable solution to mitigate seismic forces.

Most of the previous studies have been conducted on a single bridge pier. A few studies that included a bridge model in the analysis did not consider seismic ground motion spatial variations. Seismic ground motion spatial variations may increase the relative displacement response between bridge structures, allowing foundation uplifting or pier rocking may further enhance these relative responses. Large relative displacement responses may result in pounding between adjacent bridge structures. Pounding induces large impact forces that always cause localized damage to bridge deck near the impacting area. In extreme cases, pounding may push the adjacent deck off the bridge pier and result in unseating damage. No study in the literature has investigated the responses of bridge structures with rocking piers subjected to spatially varying ground motions.

In this study, a two-span, simply-supported reinforced concrete box-girder bridge typical of highway overpass bridges found in the Perth Metropolitan Area with rocking pier subjected to spatially varying ground motions is analysed. Spatially varying ground motions are simulated to be compatible with the design spectrum in Australian Earthquake Loading Code (2007) individually and an empirical coherency loss function (Hao et al. 1989) between each other. Nonlinear inelastic response analyses are carried out. Parametric calculations with varying ground motion spatial variations and pier rotational spring stiffness varying from 0 representing no rotational restraint to infinity representing monolithic bridge pier are carried out. Influences of pier rocking on shear force, bending moment in bridge pier, displacement and pounding responses of bridge decks are investigated. Numerical results are presented in this paper. The advantages and disadvantages of using rocking piers in seismic resistance bridge design are discussed.

BRIDGE MODEL

The bridge model investigated is a two-span, simply-supported reinforced concrete box-girder bridge. A schematic view of the model is shown in Figure 1. The structural elements modelled in this study include the bridge pier, deck segments, isolation bearings at top of pier and abutments, abutments and expansion joints. The foundation is modelled with equivalent springs and dampers to approximately simulate soil-structure interaction. Lumped nodal masses are calculated by assigning the mass of half the corresponding structural elements. The nodal masses for the bridge pier and deck are 69 tonnes and 500 tonnes, respectively. Computer program DRAIN2D-X (Prakash et al. 1993) is used in this study to calculate bridge responses.

The reinforced concrete bridge pier and decks are modelled with beam-column element. The concrete strength is assumed to be 40 MPa, Poisson's ratio 0.3, strain hardening ratio 0.15, and 5% Rayleigh damping corresponding to the first two modes. To simulate uplifting the bridge pier is modelled using two vertically aligned elements, spaced at a distance equal to the width of the bridge pier to represent the lateral stability. These vertical elements are horizontally linked to simulate the movement of the bridge pier as one entity.

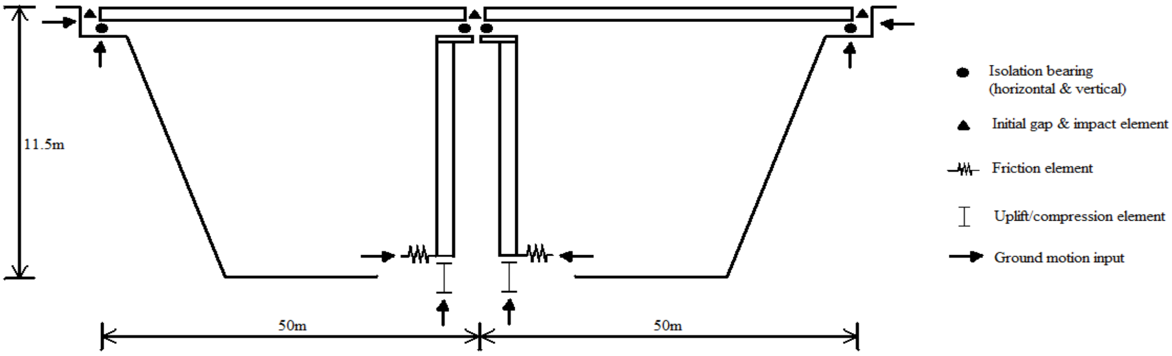


Figure 1 Schematic view of the bridge model considered in the study

Rigid elements are located at the top of each side of the bridge pier to represent the top surface of the pier; this facilitates the correct positioning of the isolation bearings and superstructure elements. It is assumed that these elements will not yield and will simply transmit forces between the superstructure and bridge pier. Table 1 lists the properties of the deck and pier. The corresponding yield surface of the deck and pier is shown in Figure 2.

Table 1 Pier and deck properties

	Pier	Superstructure
Width (m)	2.5	14
Depth (m)	4	1.2
Cross Sectional Area (m^2)	10	17
Mass of Individual Section (kg)	$276x10^3$	$1x10^6$
Material Density (kg/m^3)	2400	1176
Cross Section Moment of Inertia (m^4)	5.2	5.67
Reinforcement Ratio (%)	1.76	-
Yield moment (positive)	88 000 kNm	30 000 kNm
Yield Moment (negative)	88 000 kNm	-30 000 kNm
Tensile Yield Force	66 000 kN	-
Compressive Yield Force	-236 000 kN	-
M/M_y^+ for Point A*	0.9	-
M/M_y^- for Point B*	0.9	-
P/P_{yc} for Point A*	0.9	-
P/P_{yt} for Point B*	0.9	-

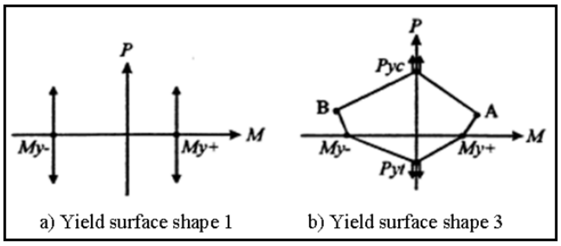


Figure 2 Yield surfaces of a) RC deck segments, and b) RC bridge pier

Each isolation bearing is modelled by a bearing element in DRAIN2D-X with the horizontal and vertical stiffness of $2.33\text{x}10^4$kN/m and $1.87\text{x}10^7$kN/m, respectively. Stiffness proportional damping of 14% is assumed for each bearing element. In order to concentrate on investigating the nonlinear inelastic response of the main bridge structure, bearing element is assumed to be linear elastic by specifying a very large yield force.

Expansion joint and pounding is modelled by the gap element in DRAIN-2DX. It is a compression-only element with an initial gap. When the two adjacent nodes move in with a relative displacement equal to or larger than the initial gap, impacting occurs. There is no resistance when they move away. Figure 3 shows the force-displacement relation of the gap element. The properties of the gap element are given in Table 2, in which the initial impact stiffness k1 is estimated by the axial stiffness of the bridge deck, with a 30% and 1% strain hardening ratio for k2 and k3. The viscous damping ratio is assumed to be 5%.

Table 2 Gap element properties

Initial Gap (m)	0.05
Displacement Limit 1 (m)	0.15
Displacement Limit 2 (m)	0.2
Stiffness k1 (kN/m)	$9.18\text{x}10^6$
Stiffness k2 (kN/m)	$2.75\text{x}10^6$
Stiffness k3 (kN/m)	$9.18\text{x}10^4$
Unloading Stiffness k4 (kN/m)	$9.18\text{x}10^6$

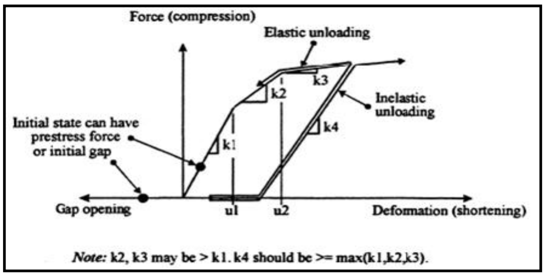


Figure 3 Force-displacement relation of the gap element

The foundations at the pier and abutments are modelled using horizontal, vertical and rotational springs and dashpots as shown in Figure 4. The foundations are assumed to rest on a homogeneous half-space and the spring stiffness and damping coefficient are estimated according to (Mylonakis et al, 2006). Soil is assumed as linear elastic. The foundation properties are listed in Table 3.

Table 3 Foundation stiffness and damping

Element Orientation	Isolation Bearing		Foundation	
	Stiffness (kN/m)	Damping (t/s)	Stiffness (kN/m)	Damping (t/s)
Horizontal	2.330E+04	9.557E+02	5.617E+06	2.520E+05
Vertical	1.867E+07	2.705E+04	7.128E+06	2.520E+05
Rotational	N/A (Fixed)	N/A (Fixed)	2.604E+08	7.693E+06

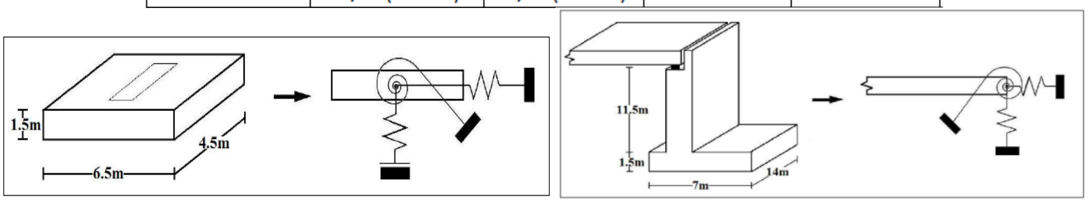


Figure 4 Pier foundation and abutment

The rocking pier is assumed resting on its foundation with a horizontal restraint at the base modelled by the bearing element in DRAIN2D-X. The element is assigned with a large stiffness and a yield force derived from the frictional restraining force due to the concrete pier resting atop concrete foundation. The value for the coefficient of friction between two concrete surfaces is assumed to be 0.5 (BS 1997). If the yield force of the friction element is exceeded, the frictional stiffness is reduced to almost zero to model the possible sliding. To facilitate the representation of any permanent displacements due to sliding, the friction elements are assumed to unload inelastically following the initial stiffness. To model vertical uplifting of the pier, a compression-only element is used to link the pier element and the foundation. The element has no tensile resistance and is assigned a compressive stiffness according to the properties of the underlying foundation and soil. A rotational spring with varying stiffness is also used to connect the pier and foundation. Zero stiffness represents no restraint and the pier is free to rock, and very large stiffness represents monolithic connections between pier and foundation. When modelling fixed pier to the foundation, the horizontal friction element is assigned a very large stiffness and an additional vertical restraint is added along the compression-only element.

SPATIALLY VARYING GROUND MOTIONS

Spatially varying earthquake ground motions at the three bridge supports are stochastically simulated. The simulated ground motion time histories are individually compatible to design response spectrum given in the Australian Earthquake Loading Code (Australian Standard AS1170.4, 2007) normalized to 0.162g for 2500 year return period design earthquake for Perth, and to an empirical coherency loss function (Hao et al. 1989) between each other. For parametric study, without losing generality, 6 ground motion cases with assumed site conditions and ground motion spatial variation characteristics as listed in Table 4 are considered, representing uniform input, spatially varying ground motions with different apparent velocities and coherency losses. For each case, three sets of spatial ground motions are independently simulated. Three independent analyses are carried out and the average results are presented. Owing to page limit, ground motion spatial variation model and simulation technique are not included here. Detailed information can be found in (Bi and Hao 2011). Figure 5 shows the typical simulated horizontal ground motion acceleration and displacement time histories. Both horizontal and vertical ground motions are simulated and used as input in the analysis.

Table 4 Considered ground motion cases

	Ground Type*	Apparent Wave velocity (m/s)	Wave Coherency
Uniform	$D_eD_eD_e$	∞	Perfect
Case 1	$D_eB_eD_e$	500	Intermediate
Case 2	$D_eB_eD_e$	1000	Intermediate
Case 3	$D_eB_eD_e$	2000	Intermediate
Case 4	$D_eB_eD_e$	1000	High
Case 5	$D_eB_eD_e$	1000	Weak

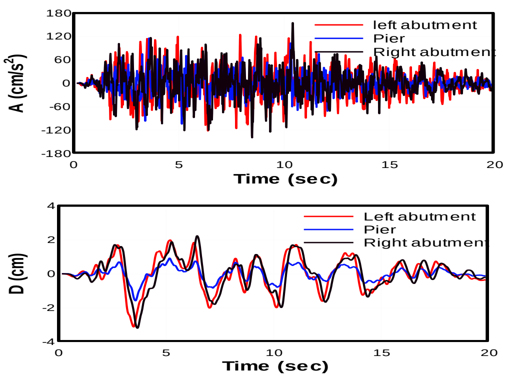


Figure 5 Typical simulated ground motions

NUMERICAL RESULTS AND DISCUSSIONS

Numerical results of the bending moment and shear force of bridge piers, as well as the pounding forces between bridge decks and deck and abutments are presented in this section. Figure 6 shows the pier bending moment and shear force obtained from different ground motion cases corresponding to the varying rotational spring stiffness connecting the foundation and the pier. A shown, when the rotational stiffness is very small, the bending moment at the base of the pier is almost zero because rocking pier does not provide any rotational constraint. Increasing the rotational spring stiffness increases the bending moment at the pier base. Similar trend is also observed for the shear force in the pier. However, the shear force is not zero even the rotational spring stiffness is zero because of the frictional resistance at the interface. Ground motion spatial variation significantly influences the bridge structure responses. It generally reduces the pier bending moment and shear forces owing to the out-of-phase movement of the decks induced by spatially varying ground motions. These observations demonstrate the effectiveness of using rocking piers in mitigating seismic effects on bridge piers and the importance of considering the ground motion spatial variations in bridge structural response analysis.

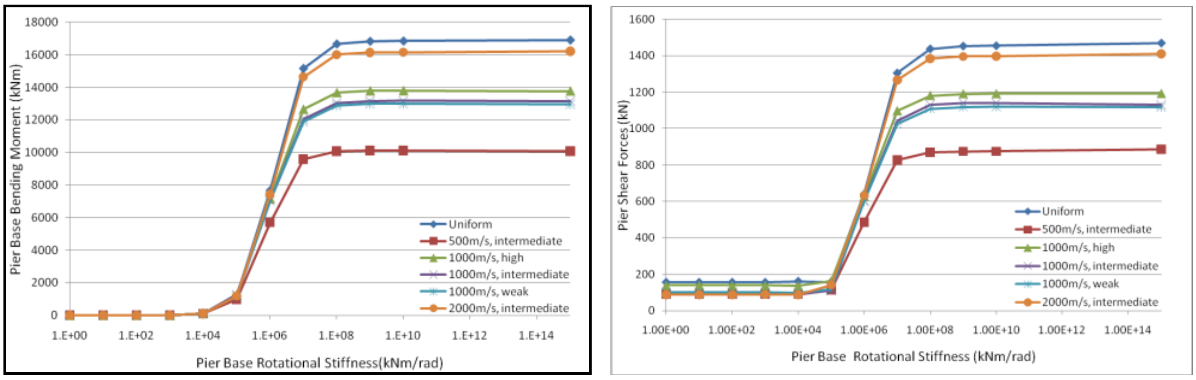
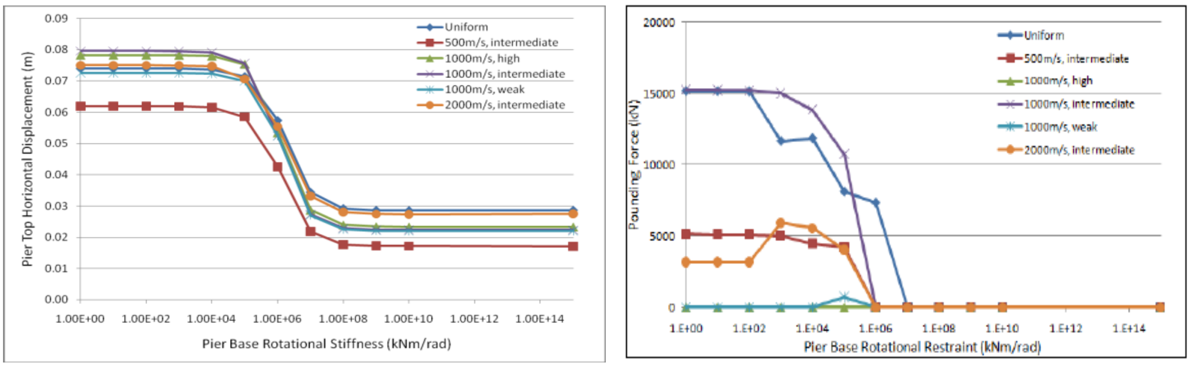


Figure 6 Peak bending moment at pier base and peak shear force in the pier



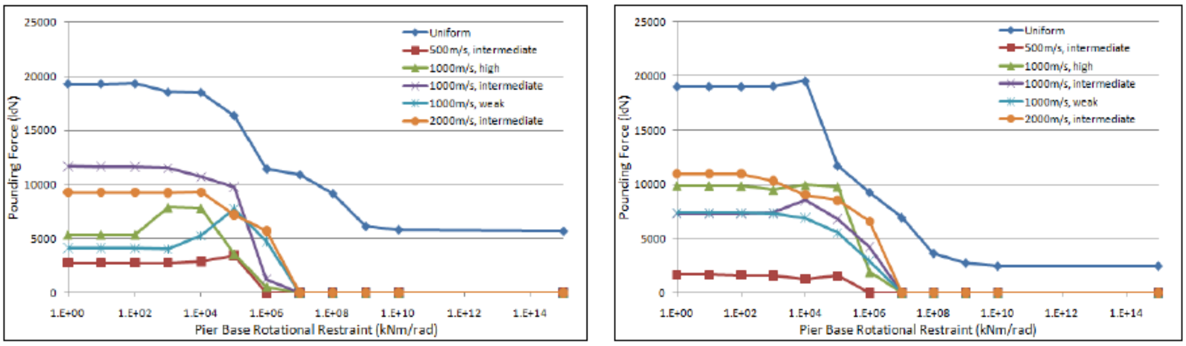


Figure 7 Pier top drift and pounding forces between decks and deck and abutments

However, as expected, releasing the restraint at the pier base increases the displacement of the pier and deck, which results in more poundings between adjacent decks and deck and abutments as shown in Figure 7. The pier top drift is about 3 times larger when the pier is allowed to rock compared to that of the fixed pier. When the pier is fixed, pounding between adjacent decks and deck and abutments may not occur. As shown, uniform input induces relatively larger impact forces. This observation is different from many previous studies that uniform input usually results in smaller responses and hence less pounding potentials. The reason is that in this study, the uniform input at the three supports used in the analysis is compatible to ground motion spectrum on soft soil site De, whereas the input at the pier corresponds to ground motion on rock site Be in the spatial ground motion input as indicated in Table 4. Ground motion on rock site has smaller displacement than that on soil site as shown in Figure 5, therefore leads to smaller pier responses. As also shown in the figure, when the pier has relatively large rotational restraint, no pounding occurs between the adjacent decks, indicating the relative displacement is less than the initial gap of 5 cm between the decks. However, uniform ground motion always induces pounding between deck and abutments. This is because abutments move with the ground displacement while the deck response is affected by the pier response. Relative displacement between deck and abutments always exist. The results also show that the impact force between decks can be as large as 15000 kN and that between deck and abutments can be 20000 kN. Although the duration of the impact force is very short as shown in Figure 8, a typical time history of impact force between deck and abutment, such a large impact force is likely to cause damage to the deck and abutment near the impacting locations.

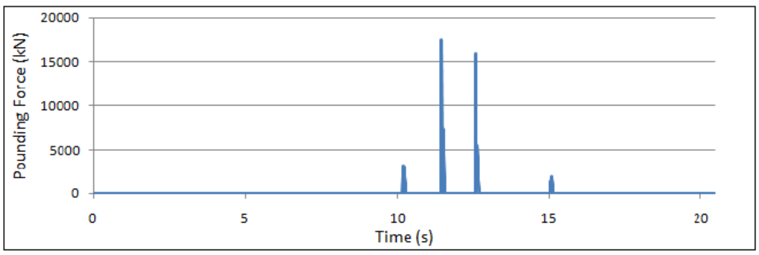


Figure 8 Time history of impact force between deck and abutment

The above observations demonstrate that rocking bridge pier is effective in mitigating seismic loading effect on pier responses, however, it results in larger displacement response of bridge super structures and hence may increase pounding potentials between adjacent decks and deck and abutments. Therefore a thorough consideration of the influence of using the concept of rocking foundations in bridge structure design is needed to avoid large impact damage and possibly unseating damage of bridge super structures while protecting the bridge piers.

CONCLUSIONS

Using rocking foundation to mitigate seismic responses of structures has been investigated by a number of researchers. Most of these studies are however, limited to a single structure column or bridge pier. None of the previous study has considered seismic responses of a complete bridge model with rocking foundations to spatially varying earthquake ground motions. This study analysed the responses of a simple two-span girder bridge with rocking pier to spatially varying earthquake ground motions. It is found that while allowing the bridge pier to rock effectively mitigate the bending moment and shear force in the pier, it increases the displacement response of the bridge deck and hence the pounding potentials between decks and deck and abutments. Ground motion spatial variations generate different structural responses from the uniform ground motion. Neglecting earthquake ground motion spatial variations may lead to inaccurate predictions of bridge responses to earthquake loadings.

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REFERENCES

Australian Standard, (2007), ‘Australian Standard AS1170.4-2007: Structural Design Actions, Part 4: Earthquake actions in Australia’, Standards Australia, Sydney.

Bi, K and Hao, H. (2001), ‘Modelling and simulation of spatially varying earthquake ground motions at a canyon site with multiple soil layers’, International Journal of Probabilistic Engineering Mechanics, Accepted, 17 August 2011.

Billington, S. L. and Yoon, J. K., (2004), ‘Cyclic response of unbonded posttensioned precast columns with ductile fiber-reinforced concrete’. J. of Bridge Eng., Vol. 9 No.4, pp. 353.

British Standards Institution (1997), ‘Structural Use of Concrete, Code of practice for design and construction, BS8110-1:1997’, British Standards Institution, London.

Cheng, C. (2007), ‘Energy dissipation in rocking bridge piers under free vibration tests’, Earthquake Engineering and Structural Dynamics, vol. 36, no. 4, pp. 503-518.

Cheng, C. (2008), ‘Shaking table tests of a self-centering designed bridge substructure’, Engineering Structures, vol. 30, no. 12, pp. 3426-3433.

Cormack, L Gavin, (1988), ‘The design and construction of the major bridges on the Mangaweka rail deviation’. Transactions, Vol. 15 No. 1/CE.

Dowdell, D.J. and Hamersley, B.A., (2000), ‘Lions Gate Bridge north approach – seismic retrofit’, in Behaviour of Steel Structures in Seismic Areas: STESSA 2000, Balkema, Netherlands, pp. 319-326.

Hao, H., Oliveira, C.S. and Penzien, J. (1989), ‘Multiple station ground motion processing and simulation based on SMART-1 data,’ J. of Nuclear Eng. and design, Vol. 111, No.3, pp293-310.

Housner, G.W., (1963), ‘The behaviour of inverted pendulum structures during earthquakes’. Bulletin of the Seismological Society of America, Vol. 35 No. 2 pp. 403-417.

Ingham, T.J., Rodriguez, S., Nader, M. and Taucer, F., (1996), 'Seismic retrofit of the Golden Gate Bridge'. Proc. of the 11WCEE, 23-28 June, Acapulco, Mexico.

Mahin, S., (2008), 'Sustainable design considerations in earthquake engineering'. Proc. of the 14WCEE, October 12-17, Beijing, China.

Mylonakis, G., Nikolaou, S. and Gazetas, G. (2006), 'Footings under seismic loading: Analysis and design issues with emphasis on bridge foundations', Soil Dynamics and Earthquake Engineering, Vol. 26, no. 9, pp. 824-853.

Mander, J. B. and Cheng C.-T., (1997), 'Seismic resistance of bridge piers based on damage avoidance design'. Technical Report NCEER-97-0014, Buffalo, NY.

Palermo, A., Pampanin, S. and Marriott, D., (2007), 'Design, modelling, and experimental response of seismic resistant bridge piers with posttensioned dissipating connections'. Journal of Structural Engineering Vol. 133 No. 11 pp. 1648.

Palermo, A., Pampanin, S. and Carr, A., (2005), 'Efficiency of simplified alternative modelling approaches to predict the seismic response of precast hybrid systems'. Proceedings of the fib symposium "Keep Concrete Attractive", Budapest, 1083-1088.

Prakash, V., Powell, G. & Campbell, S. (1993), 'DRAIN-2DX Base program description and user guide: Version 1.10', Dept of Civil Engineering, University of California, Berkeley.

Priestley, M. J. N., Seible, F. and Calvi, G. M., (1996), 'Seismic design and retrofit of bridges'. John Wiley and Sons Inc., 605 Third Avenue, New York, NY 10158-0012.