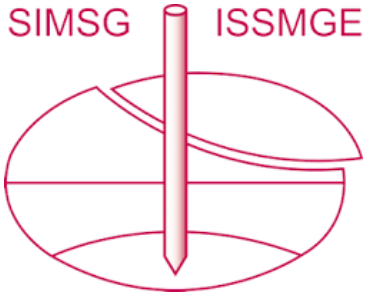
INTERNATIONAL SOCIETY FOR
SOIL MECHANICS AND
GEOTECHNICAL ENGINEERING



This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:

https://www.issmge.org/publications/online-library

This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE and maintained by the Innovation and Development Committee of ISSMGE.

The paper was published in the proceedings of the 7th International Conference on Earthquake Geotechnical Engineering and was edited by Francesco Silvestri, Nicola Moraci and Susanna Antonielli. The conference was held in Rome, Italy, 17 – 20 June 2019.

Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions – Silvestri & Moraci (Eds)
© 2019 Associazione Geotecnica Italiana, Rome, Italy, ISBN 978-0-367-14328-2

Seismic effectiveness of different restraining systems for skewed bridge decks supported on elastomeric bearings

M. Hassoun & B. Fatahi
University of Technology Sydney, Sydney, Australia

S. Mirlatifi
John Holland, Sydney, NSW, Australia

ABSTRACT: Past earthquakes have shown that isolated bridges are susceptible to excessive movements at the expansion joints. Reconnaissance reports have exposed various isolated bridges that have collapsed due to this excessive movement in a phenomenon known as unseating. This problem is particularly evident in skewed bridges as the bridge experience coupled lateral and rotational movements. The study seeks to understand the effectiveness of various restrainers, namely cable restrainers and viscous dampers in limiting both lateral and rotational movements of the bridge deck. In order to approximate the complex behavior of isolated restrained bridges, the models used in this study include the effect of soil-structure interaction behind the abutment backwall and the pile foundations. Moreover, the inelastic behavior of highly damaged bridge elements such as abutment backwall, pier and shear-keys are studied, and results are presented.

1 INTRODUCTION

The highly urbanised nature of the today's society leads to increases in the construction of non-orthogonal crossings over waterways and roads. Bridges with abutment aligned non-orthogonally to the deck are referred to as "skewed bridges". Previous earthquakes such as Maule, Loma Prieta and Northridge have shown that the seismic response of skewed bridges is significantly different to straight bridges (Kawashima et al., 2011, Jennings, 1971). Skewed bridges tend to rotate about the vertical axes under seismic loading which could lead to shear key damage, deck unseating and total collapse of the bridge. The main cause of deck rotation is the eccentric passive response of the soil backfill behind the abutment's backwall. It has been observed from previous reconnaissance reports that the main mode of failure for skewed bridges is unseating due to the excessive rotation of the deck about the bridge centre of rigidity (Kawashima et al., 2011, Jennings, 1971). Structural pounding due to seismic excitation does not only effect bridges but neighbouring buildings as well (Fatahi et al., 2018). Nguyen et al. (2016) studied the effect of foundation size on building response as an effective way to reduce cost and enhance seismic performance. Moreover, engineers have been looking for ways to control the seismic drift in structures utilising novel techniques such as redesigning the abutment end-wall (Mitoulis et al., 2014) and inserting a layer of geogrid between building's mat foundation and piles (Xu and Fatahi, 2019).

This study investigates two common types of earthquake resisting system namely cable restrainers and fluid viscous dampers. Both viscous damper system and cable restrainers are referred to as seismic resisting links in this study. Both systems are connected to the deck and abutment in a similar way as shown in Figure 1. On each abutment there are four seismic resisting links, oriented as illustrated Figure 1. The seismic links are oriented at 20 degrees to the abutment (i.e. direction of deck rotation) in this study to minimise

transverse and rotational response of the deck. The links on abutment 1 are oriented in the opposing direction to other links on abutment 2 to enable the system to create a large resisting couple moment in both clockwise and anti-clockwise rotational directions. Both seismic resisting systems work by transferring inertial forces from the deck into the abutments and further into the piles, dissipating the impact force into the soil. However, since the fluid viscous dampers resistance is velocity dependant, it will produce reaction in the abutment that is out of phase to the bridge movement. This feature in the viscous dampers will result in reduced structural actions in the abutment piles compared to the reactions in the cable restrainers system as discussed in this paper. On the other hand, the same velocity dependability of the viscous dampers limits their ability to actively reduce the displacement of the bridge compared to the cable restrainers which have a more direct mechanism linked to the deck relative displacement. However, a key disadvantage of the cable restrainers is they must function purely in elastic manner, resulting in great forces transferred through them, imposing high stresses on elements such as deck bottom flange or end-diaphragms.

2 BRIDGE DESCRIPTION

The bridge presented in this study represents a typical highway overcrossing designed in a seismic region such as California or New Zealand. The bridge has two equal spans each being 30 m supported by one circular pier bent. The bridge deck is skewed in a 45 degree angle from the abutment. The deck is a cellular prestressed box girder type bridge that is 13.0 m wide and 1.70 m deep. The top and bottom flanges of the girder are 200 mm thick while all four webs are 160 mm thick. The bridge bent is formed from a single 1.5 m diameter pier constructed from reinforced concrete, reinforced with 38 bars that are 28 mm in diameter and 16 mm diameter spiral hoop at 150 mm spacing. The pier is 10 m high founded on a 1.5 m thick reinforced concrete pile cap. According to Nguyen et al. (2017) the type and size of the pile foundation has significant effects on the dynamic properties of the structure. The pile cap is to connect four evenly spaced piles. The pile foundations are 12 m long and 0.9 m in diameter embedded into Class D soil with undrained shear strength S_u of 200 kPa in accordance with Caltrans (2010) while their base is socketed rock classified as type B. The deck is supported on both end on seat type abutments with backwall to deck gap of 40 mm. The abutment is supported on four piles founded on the same strata as the bent foundation piles. The deck is supported by the abutment through four circular elastomeric bearings on each side. The bearings are 450 mm in diameter and 100 mm in height. The deck is restricted from transverse movement by the shear keys formed by the U-shaped abutment lock as shown in Figure 1. Furthermore, this type of bridge construction has no inherent restraint between the deck and the abutment in the longitudinal direction.

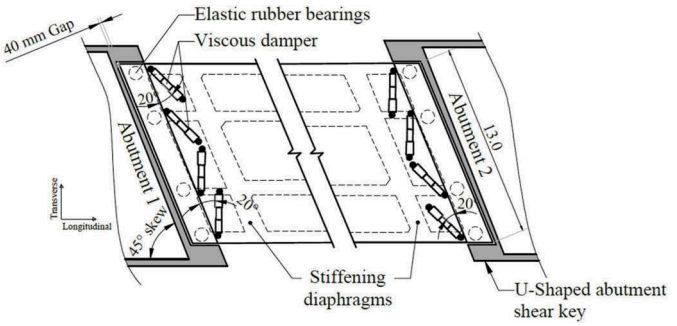


Figure 1. Plan of the bridge deck with viscous dampers to abutments connection.

3 NUMERICAL MODEL

The bridge models are constructed and analyzed using the commercial software SAP2000 v20.1 (Computers and Structures, 2017). The bridge models are analyzed using nonlinear time history analysis by Hilber-Hughes-Taylor step by step integration technique. To capture the complex nonlinear behavior of the skewed bridge, the numerical models include plastic hinges, pile soil-structure interaction, plastic hinge deformation in piers and backfill nonlinear springs. The bridge deck is modelled as a spine using elastic frame elements and lumped mass in accordance with Kappos et al. (2012) and Isakovic (2012). The pier and piles were modelled using elastic frame elements, where frame elements in SAP2000 are distinct from beam element behavior by the inclusion of biaxial loading adopting beam-column formulation (Mang, 1977). The pier frame elements were assigned with plastic hinges at the top and bottom of the pier, while the piles were assigned plastic hinges only at the top both in accordance with the ASCE 41-13 model (ASCE, 2013). The plastic hinge assignment allows the monitoring of the element damage state during the earthquake excitation. Moreover, the pier and piles stiffnesses were reduced by 35% to comply with ACI 318-2014 concrete design code to account for the flexural cracks due to high bending induced stresses (ACI Committee 318, 2014). The numerical model of the bridge superstructure and substructure is illustrated in Figure 2. The numerical models of the bridge consider 45 degree skew angle between the deck and the abutment.

Nonlinear p-y springs were assigned to the pile frame elements with 1 m interval in both longitudinal and transverse directions of the bridge as shown in Figure 2 (detail A) to simulate pile soil-structure interaction. In addition, the pile elements were modelled with fixed base as the bridge piles are socketed into class B rock. Welch and Reese (1972) p-y model for dry stiff clay was adopted for the p-y springs backbone model. Equation (1) describes the p-y constitutive model used where p_u is the ultimate clay lateral capacity and y_{50} is the pile deformation corresponding to half the principle stress difference taken ε_{50} as 0.005 (Welch and Reese, 1972).

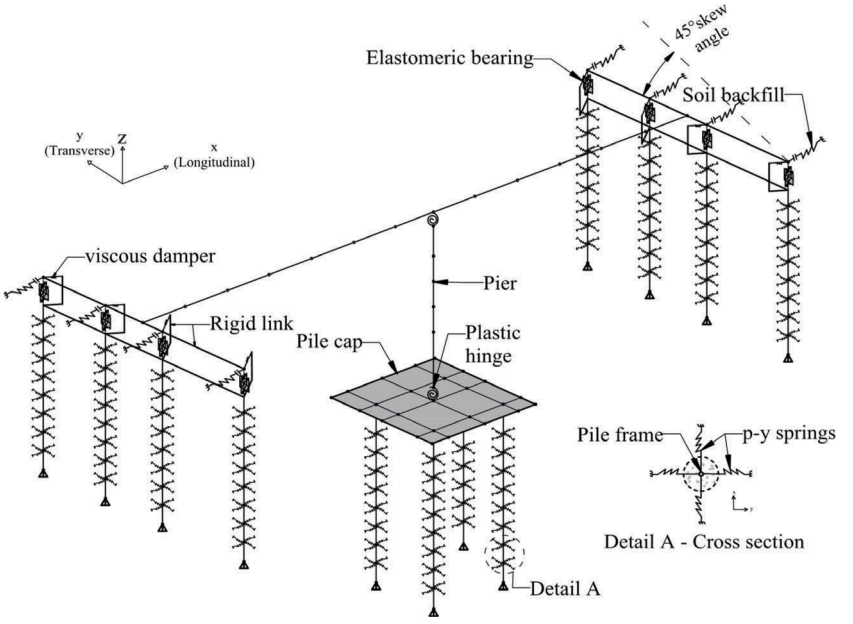


Figure 2. Bridge numerical model.

$$P = 0.5p_u\left(\frac{y}{y_{50}}\right)^{1/4} \quad (1)$$

The backfill passive resistance is included in the model in the form of springs modelled perpendicular to the abutment in accordance with Caltrans design criteria v1.6 (Caltrans, 2010), which allows the use of hyperbolic soil model proposed by Shamsabadi et al. (2007). For cohesive backfill, the hyperbolic model is a function of the backwall displacement and height (Shamsabadi et al., 2007) with the later taken as 1.5 m. The shear key that provides transverse displacement resistance to the deck is modelled using Silva et al. (2009) model which is based on strut and tie analogy. The shear key model takes into consideration both the contribution of the reinforcement and concrete in the overall shear capacity in accordance with Han et al. (2016).

The fluid viscous damper is modeled as a nonlinear link where the force in the damper is determined using Equation (2) (Hwang et al., 2006, Soneji and Jangid, 2007, Sullivan and Lago, 2012).

$$f_c = c.v^{\alpha} \quad (2)$$

Where c is the damping constant set to 15000 kN.s/m and value of power a is 0.35. Moreover, the cable restrainers are designed according to seismic design code of Japan Road Association (2016). where the cable force H_f was determined using Equation (3).

$$H_f = \alpha \times {}^{W}/_{m} \quad (3)$$

Where α is a safety factor of 1.5, W is the weight of structure equal to 18 MN and m is the number of cable restrainers. The cable restrainers were modelled as a multilinear plastic link with a maximum first and second yield forceds of 6.0 MN and 7.0 MN in each cable, respectively.

4 INPUT GROUND MOTIONS

Previous earthquakes have shown that skewed bridges are prone to high forward pulse seismic excitations. Therefore, the following earthquake signals were selected from the PEER data base: Imperial Valley Array #7 1979, Kobe Takatori 1995, Loma Prieta Los Gatos 1989 and Landers Lucerne 1989. The signals are applied in both longitudinal and transverse directions of the bridge with the highest velocity signal applied in the longitudinal direction. All seismic signals are scaled to match California target response spectrum with site hazard level corresponding to magnitude 8 and PGA 0.7g (Caltrans, 2004). The scaled signals and target response spectrums in both longitudinal and transverse directions are showing Figure 3a and Figure 3b respectively.

5 DISCUSSION

The deck displacement results in an increase in bending moment actions experienced by the bent pier. Therefore, it is important to review the flexural damage experienced by the pier in order to better compare both restraining systems considered. Figure 4 demonstrates the bending moment versus rotation at the base of the pier about the transverse direction for both viscous damper equipped bridge and cable restrained bridge subjected to Imperial Valley seismic excitation. It is evident that the viscous damper bridge pier experienced a large plastic damage

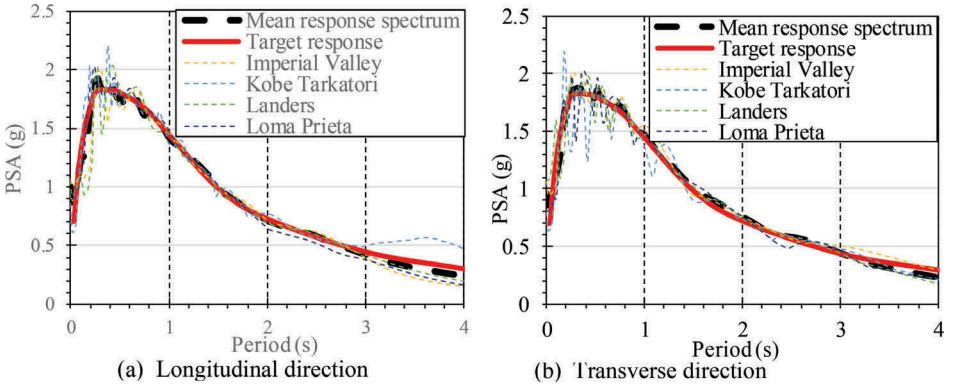


Figure 3. Target and matched signals response spectrum.

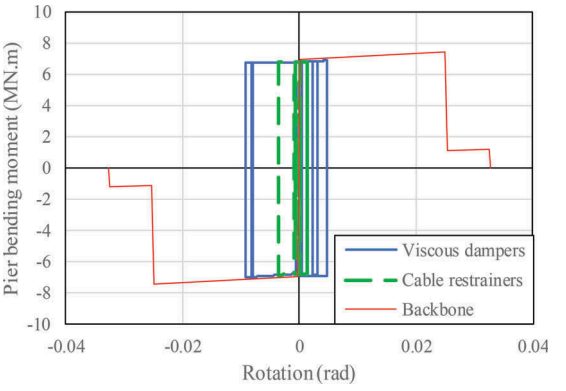


Figure 4. Pier plastic hinge hysteresis response under Imperial Valley excitation.

to its base compared to the cable restrained bridge. The rotation experienced to collapse ratio is calculated using the following equation:

$$R_r = {}^{r_p}/_{r_c} \times 100 \tag{4}$$

Where r_p is the rotation experienced by the pier in the plastic hinge and r_c is the rotation value at the collapse performance criteria in accordance with ASCE 41-13 (ASCE, 2013) which is equal to 0.0253 radians. The rotation ratio of bridge pier equipped with viscous damper is 37% while the ratio for the cable restrained bridge was less than half this value at 16%.

The displacement time histories of the bridge deck are displayed in Figure 5 for both viscous damper equipped bridge, and cable restrained bridge under all four earthquake cases. It can be observed from Figure 5a that the maximum longitudinal displacement of the bridge deck is 120 mm under Kobe Takatori in the case of the viscous damper equipped bridge compared to 62 mm of deck longitudinal displacement for the case of cable restrained bridge under the same excitation. It is noted that the cable restrained bridge experienced significantly less longitudinal displacement than the case of viscous damper bridge for all earthquakes, except Landers where both bridge systems underwent about 92 mm of displacement. Moreover, irrespective of the peak displacement response, the viscous damper bridge underwent large residual displacements, which are as large as 50 mm under Landers earthquake excitation

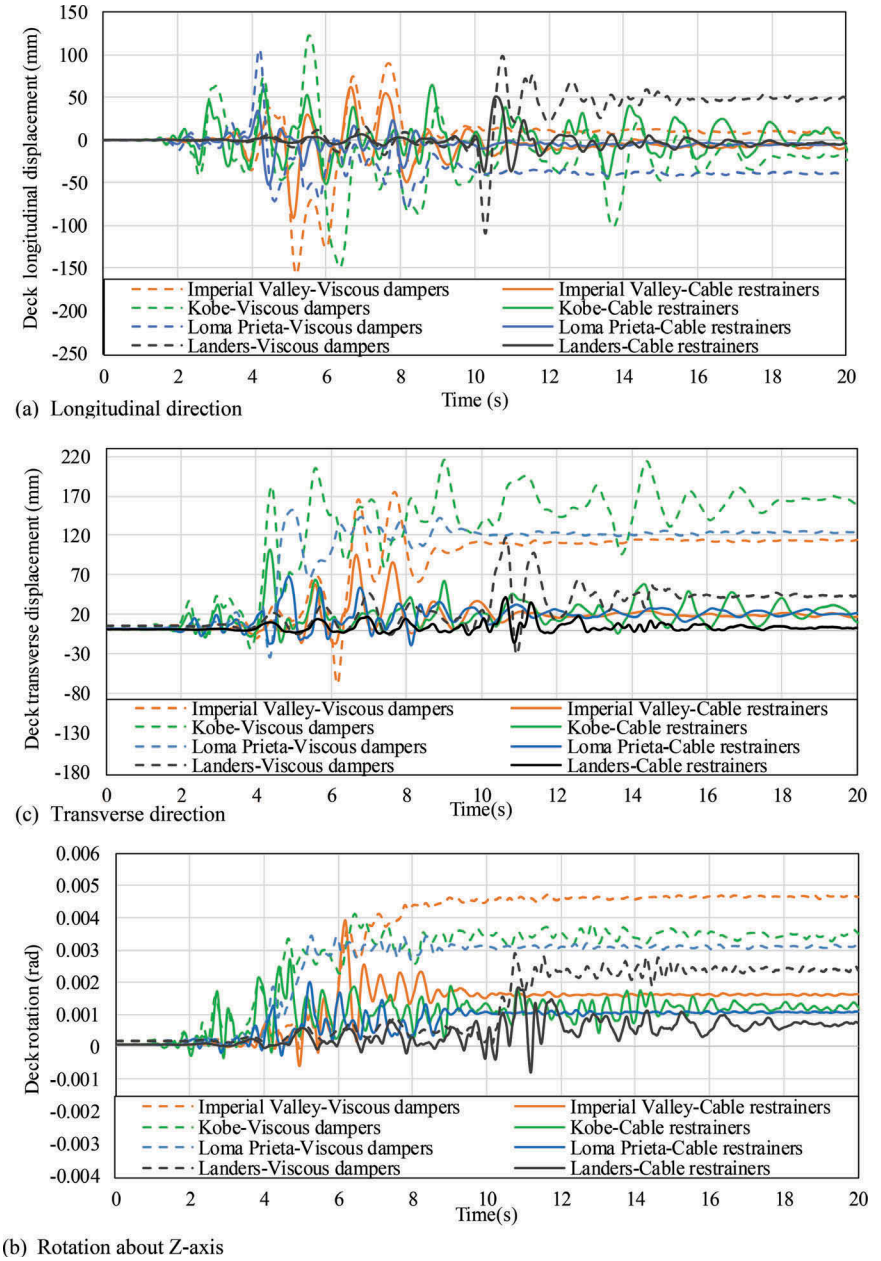


Figure 5. Time history response of the bridge deck in the following directions: a) Longitudinal, b) transverse and c) rotation about z axis.

while the cable restrained bridge undergoes nearly zero residual displacement. Similar observations can be made from Figure 5b and 5c, where the viscous damper equipped bridge experienced a maximum of 220 mm transverse displacement and a 170 mm residual displacement under Kobe excitation. On the other hand, the cable restrained bridge experienced a peak transverse displacement of 91 mm under Imperial Valley excitation with no residual displacement of the deck. It is evident from Figure 5c that the bridge equipped with viscous dampers

underwent rather large residual rotation about the z-axis, the largest being 0.0048 radians under Imperial Valley excitation. Displacement wise, the cable restrainers are far out performing the bridge equipped with viscous dampers in terms of limiting peak displacements and preventing residual displacements in longitudinal, transverse and rotational directions.

6 CONCLUSIONS

Previous earthquake events have shown that skewed bridges are especially vulnerable to high forward impulse earthquakes. Efficiency of two common earthquake restraining systems are investigated in this study namely the fluid viscous dampers and the cable restrainers for a bridge with 45 degree skew angle. The seismic restraining system is conventionally connected to the bridge deck and the abutment base, transferring the impact force to the abutment piles. The displacement response of the bridge deck was predicted in this study for longitudinal, transverse and rotational directions. It was evident from these results, that the cable restrained bridge outperformed the viscous damper bridge by limiting the peak displacement response by up to 53% in the transverse direction. Moreover, the cable restrained bridge did not experience any residual displacement in all three directions under the applied earthquake excitations compared to a 170 mm transverse residual movement of the deck in the viscous damper case. In addition, due to the great decrease in the deck displacements, the pier plastic damage was minimized in the case of cable restrainers compared to viscous dampers bridge. Overall, it can be concluded that for the bridge arrangement used in this study, cable restrainers outperformed viscous dampers considering multiple earthquake excitations, and thus cable restrainers would be the more effective earthquake resisting system; however, the designers need to properly include the effect of the force transferred from the cable restrainers to the abutment piles when designing the abutment foundations.

REFERENCES

ACI COMMITTEE 3182014. Building Code Requirements for Structural Concrete (ACI 318-14). Farmington Hills: American Concrete Institute.

ASCE2013. ASCE/SEI 41-13 : American Society of Civil Engineers : seismic evaluation and retrofit of existing buildings. Virginia: American Society of Civil Engineers.

CALTRANS2004. Seismic Design Criteria Version 1.3. Sacramento, California: California Department of Transportation.

CALTRANS2010. Seismic Design Criteria Version 1.6. Sacramento, California: California Department of Transportation.

COMPUTERS AND STRUCTURES, I. 2017. Pile lateral support based on P-y curves [Online]. Available: https://wiki.csiamerica.com/display/kb/Pile+lateral+support+based+on+P-y+curves [Accessed 20 Dec 2017].

Fatahi, B., Nguyen, Q. V., Xu, R. & Sun, W.-J.2018. Three-Dimensional Response of Neighboring Buildings Sitting on Pile Foundations to Seismic Pounding. International Journal of Geomechanics, 18.

Han, Q., Zhou, Y.-L., Zhong, Z.-L. & Du, X.-L.2016. Seismic capacity evaluation of exterior shear keys of highway bridges. Journal of Bridge Engineering, 22.

Hwang, J.-S., Tsai, C.-H., Wang, S.-J. & Huang, Y.-N.2006. Experimental study of RC building structures with supplemental viscous dampers and lightly reinforced walls. Engineering Structures, 28, 1816–1824.

Isakovic, A. J. K. L. M. S. S. M. N. A. L. T.2012. Seismic Design and Assessment of Bridges, Springer, Dordrecht.

JAPAN ROAD ASSOCIATION2016. Specifications for highway bridges part V Seismic design. Tokyo.

Jennings, P. C.1971. Engineering features of the San Fernando earthquake of February 9, 1971.

Kappos, A. J., Saiidi, M. S., Aydınoğlu, M. N. & Isaković, T.2012. Seismic design and assessment of bridges: inelastic methods of analysis and case studies, Springer Science & Business Media.

Kawashima, K., Unjoh, S., Hoshikuma, J.-I. & Kosa, K.2011. Damage of bridges due to the 2010 Maule, Chile, earthquake. Journal of Earthquake Engineering, 15, 1036–1068.

Mang, H. A.1977. Numerical methods in finite element analysis. International Journal for Numerical Methods in Engineering, 11, 1485–1485.
Mitoulis, S., Titirla, M. & Tegos, I.2014. Design of bridges utilizing a novel earthquake resistant abutment with high capacity wing walls. Engineering Structures, 66, 35–44.
Nguyen, Q. V., Fatahi, B. & Hokmabadi, A. S.2017. Influence of Size and Load-Bearing Mechanism of Piles on Seismic Performance of Buildings Considering Soil-Pile-Structure Interaction. International Journal of Geomechanics, 17.
Nguyen, V., Fatahi, B. & S.Hokmabadi, A. 2016. The effects of foundation size on the seismic performance of buildings considering the soil-foundation-structure interaction.
Shamsabadi, A., Rollins, K. M. & Kapuskar, M.2007. Nonlinear soil–abutment–bridge structure interaction for seismic performance-based design. Journal of Geotechnical and Geoenvironmental Engineering, 133, 707–720.
Silva, P. F., Megally, S. & Seible, F.2009. Seismic performance of sacrificial exterior shear keys in bridge abutments. Earthquake Spectra, 25, 643–664.
Soneji, B. B. & Jangid, R. S.2007. Passive hybrid systems for earthquake protection of cable-stayed bridge. Engineering Structures, 29, 57–70.
Sullivan, T. J. & Lago, A.2012. Towards a simplified Direct DBD procedure for the seismic design of moment resisting frames with viscous dampers. Engineering Structures, 35, 140–148.
Welch, R. C. & Reese, L. C.1972. Lateral load behavior of drilled shafts. University of Texas at Austin.
Xu, R. & Fatahi, B.2019. Novel application of geosynthetics to reduce residual drifts of mid-rise buildings after earthquakes. Soil Dynamics and Earthquake Engineering, 116, 331–344.