Displacement Based Design of Bridge Abutments

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Abstract

The present study deals with the drift and displacement capacities of reinforced concrete (RC) bridge abutments subjected to seismic excitations. Two dimensional (2-D) finite element (FE) analyses have been conducted to investigate the behavior of the bridge abutment taking into account dynamic actions of the backfill in seismic conditions. The capability of scaled down bridge abutment models is also investigated in order to replicate the dynamic behavior of prototype bridge abutments. The analyses have taken into account interactions between the abutment and the backfill, which can significantly affect the seismically induced displacement behavior of the bridge abutments. It was observed that scaled down bridge abutment models could effectively replicate the seismic behavior of prototype bridge abutments. The stiffness of the bridge abutment degrades significantly with increasing intensity of ground motion. The location of the point of rotation of the bridge abutment is almost constant irrespective of the height of the stem wall. Drift and displacement behavior of the bridge abutment is highly controlled by the thickness of the stem wall.

Keywords: Bridge, abutment, design, seismic, performance, similitude.

1. Introduction

The behavior of bridges under seismic excitations is an important concern for structural engineers. Earthquake response of bridge is mainly influenced by the response of the piers, the foundation system and the abutment behavior. To ensure satisfactory performance of the bridge in an earthquake, it is essential to evaluate the capacity of the bridge abutment and its foundation. It is relatively easy to assess the earthquake induced deformation and damage to the bridge piers. However, combined behavior of the abutment and backfill is highly uncertain due to the effect of soil structure interaction. It can be difficult to assess the accurate behavior of the bridge abutment given that the behavior of the backfill may also influence abutment behavior. The present study deals with the drift and rotation capacity of the bridge abutment. The capability of scaled down abutment models is also studied in order to replicate the response behavior of full scale (prototype) bridge abutments. The present study is part of an ongoing doctoral research program carried out at the Department of Infrastructure Engineering, the University of Melbourne.

2. Seismic Behavior of Bridge Abutments

Earthquake induced excitations may generate forces and deformation in the longitudinal, transverse and vertical directions. The direction of the seismic actions depends on the direction of the ground motion (Whitman and Liao 1985). Earthquake loading generates inertial forces on the bridge abutment and the backfill. These inertial forces results in additional thrust acting on the abutment stem wall (Seed and Whitman 1970; Siddharthan et al. 1994). Elgamal and Wilson (2012) investigated the effects of inertial forces developed by the backfill material for different backfill types and abutment stem wall height conditions based on laboratory experiments. Backfill materials have been found to have a high influence on the seismic response behavior of abutment.

The displacement assessment of bridge abutment is an important functionality aspect for any bridge. A small amount of abutment displacement is required to mobilize the active earth pressure in the backfill leading to backfill failure, which compromises the functionality of the bridge (Gamal 1996; Choudhury and Chatterjee 2006). The amount of abutment displacement and rotation is highly influenced by the distribution of dynamic earth pressure behind the abutment (Huang et al. 2009). It was observed that the passive resistance of the backfill decreases significantly when subjected to earthquake excitations. However, investigations show that the properties of the backfill may not influence the complete abutment behavior since the failure surface can be generated anywhere in the backfill (Wilson and Elgamal 2009; Khaleghi 2013). The stiffness of the bridge abutment plays an important role on its seismic response behavior. In the initial phase of the ground shaking, the abutment behaves in a stiff manner. However, the abutment stiffness can decrease significantly with increment in the intensity of the ground motion (Maroney et al. 1994).

Wilson and Elgamal (2015) studied the seismic behavior of rigid retaining walls. Shaking table results of the full scale walls were compared with analytical solutions. It was observed that the dynamic pressure behind the abutment wall acts in a parabolic manner, and the amplitude and direction of the earth pressure changes with increment in the ground acceleration. The Mononobe-Okabe (MO) method proposed by Mononobe and Matsuo (1929) can be used to estimate the dynamic active and passive pressure on the abutment backfill interaction. However, many researchers are doubtful of the validity of the MO method for predicting the dynamic earth pressure behind the bridge abutment wall (Sherif and Fang 1984; Psarropoulos et al. 2005; Yazdani et al. 2013).

Abutment is considered as a rigid structure and its design is carried out using the forced based approach. Abutments designed with strength based approach shows maximum displacement much lower than that allowed by the design codes of practices (Siddharthan et al. 1994). However, the stiffness of abutment may degrade gradually with increasing seismic loading. Rocking behavior may lead to a higher displacement and rotation of the bridge abutment and the foundation system (Maroney et al. 1994).

To understand the seismic response behavior of the bridge abutments and abutment foundation system, a detailed experimental and analytical investigation would be required to investigate the amount of drift and displacement of the abutment, distribution of the dynamic earth pressure and behavior of the backfill.

3. Research methodology

Present study deals with the drift and rotational behavior of the bridge abutment subjected to the earthquake excitation. Finite element (FE) software Abaqus was used for analyzing different abutment models. Validity of the numerical software for replicating the shaking table experiment has also been studied. As mentioned earlier the present study is part of an ongoing experiment on scaled down abutment models at the University of Melbourne. Hence, a comparison is also presented between the seismic response behavior of the prototype and scaled down abutment models.

4. Numerical modelling of the bridge abutment structure

To understand the drift and rotational behavior of the bridge abutments under seismic loading, two set of abutment systems have been analyzed. Figure 1 shows the FE models and abutment dimensions considered in Set 1 and Set 2. Table 1 shows the details of both sets considered in the present investigation.

Table 1 Cases considered for drift and rotational behavior of abutment

Set no.	Stem height	Stem thickness	Stem height to thickness ratio
1	(i) 2.5 m (ii) 5 m (iii) 6 m	0.25 m	(i) 10 (ii) 20 (iii) 24
2	(i) 2.5 m (ii) 5 m (iii) 6 m	(i) 0.25 m (ii) 0.5 m (iii) 0.6 m	10

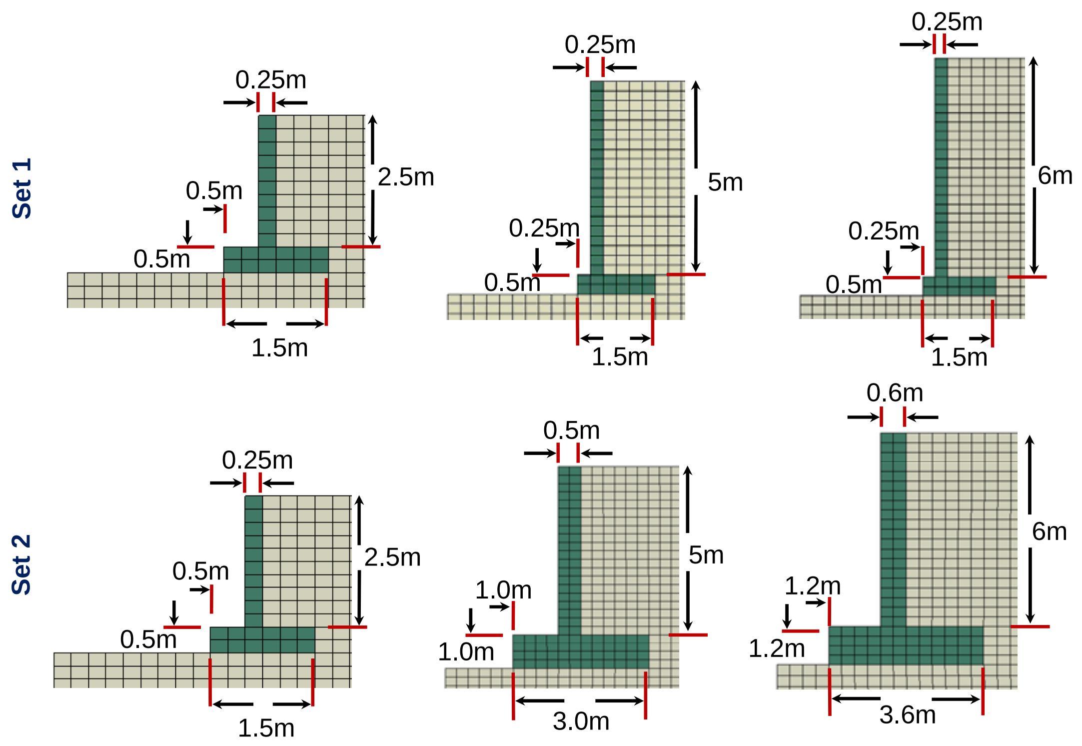
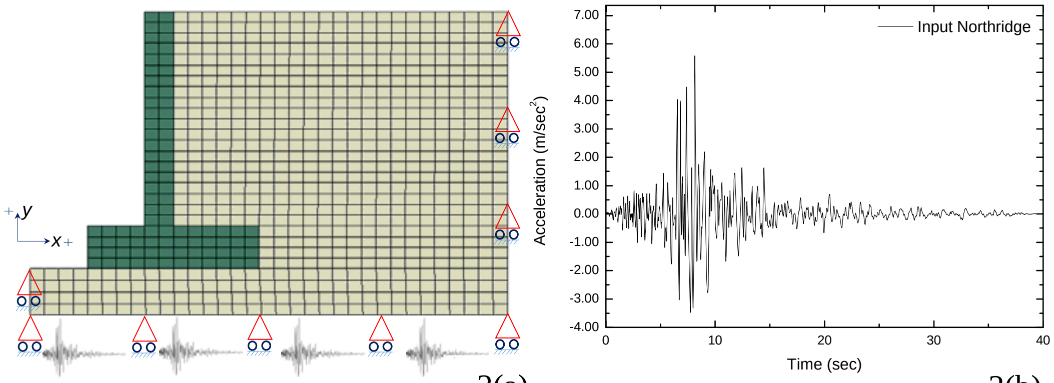


Figure 1 Finite element (FE) models and abutment dimensions in Set 1 and Set 2.

Figure 2(a) shows the FE model of typical abutment and backfill. The implicit solution scheme of the FE software Abaqus was used in the numerical analysis. The equilibrium of geostatic stress was also considered by introducing the gravity step in the analysis. During the gravity step analysis the abutment was restrained from lateral movement. However, it was free to displace, or rotate, on the ground. The interaction between the abutment surface and soil was modelled as a surface to surface interaction. It was assumed that during the separation of the abutment surface from the backfill, the angle of internal friction (ϕ) of the backfill was completely mobilized. Northridge accelerogram with a maximum ground acceleration of 0.57g was used in the present investigation. Figure 2(b) shows the acceleration time history of Northridge accelerogram. Time step for dynamic analysis was kept of 0.01 sec in order to capture every peak of the accelerogram. The bottom of the soil domain was restrained in the vertical direction (*y* direction) and was free to move laterally (*x* direction). The vertical boundaries of the soil domain were also restrained in the vertical direction (*y* direction) and were free to move laterally (*x* direction). Acceleration was applied at the base line of the soil domain. Two dimensional plain strain elements were used to mesh the FE model.



2(a) 2(b)

Figure 2 FE model and boundary conditions (during dynamic step), time history of Northridge accelerogram.

5. Constitutive modelling of concrete and backfill

Concrete damaged plasticity (CDP) model was used for modeling the behavior of the concrete. CDP model is extensively used to model the concrete as it can simulate the behavior of concrete under compression and tension. Drucker prager plasticity model, which is extensively used to model the granular materials, was used to model the backfill (Abaqus user manual 2013). Table 2 shows the properties of the concrete and the backfill considered in the present investigation. Constitutive relationship for concrete (characteristic compressive strength of 30 MPa) was obtained using equations proposed by Carreira and Chu (1985). Backfill was modelled in accordance with tri-axial compression test results on gravels reported by Anhdan and Koseki (2005).

Table 2 Material properties for FE modelling.

Description	Concrete (Carreira and Chu 1985)	Gravel (Anhdan and Koseki 2005)
Constitutive model	Concrete damaged plasticity	Drucker prager plasticity
Density (Kg/m^3)	2356	2010
Modulus (GPa)	27.4	0.6
Poison's ratio	0.3	0.4
Friction angle	-	40°

6. Validation of FE software for replication of shaking table experiment

In order to validate the capability of the FE software for ensuring the replication of results of the shaking table experiments, experiments performed by Watanabe et al. 2003 were simulated using FE software Abaqus. Upadhyay et al. 2011 also modelled the same experiment numerically. Watanabe et al. 2003 and Upadhyay et al. 2011 modified the ground motion as per the frequency requirements. However, modification to the ground motion had not been presented in any of the above mentioned articles. In the present study similitude law was used to scale the time dimension by a factor of 3.16 (given that the abutment wall investigated by Watanabe et al. 2003 represents a prototype abutment of 5m in height, meaning a 10 scaled down model). Table 3 shows the material properties considered for the numerical modelling by Upadhyay et al. 2011.

Table 3 Material properties considered by Upadhyay et al. 2011 for modelling the abutment and backfill.

Description	Concrete (Upadhyay et al. 2011.)	Gravel (Upadhyay et al. 2011.)
Constitutive model	Elastic	Mohr Coulomb Plasticity
Density (Kg/m^3)	2500	1950
Modulus (GPa)	25	0.06
Poison's ratio	0.15	0.33
Friction angle	-	37°
Dilation angle	-	10°
Yield cohesion	-	1 kPa

Table 4 shows the comparison of results from the current numerical simulations with experimental results by Watanabe et al. 2003 and numerical results by Upadhyay et al. 2011. Reasonable agreement can be observed between the different experimental and numerical results. Hence, the current modelling approach can be used to simulate the proposed experimental investigations at the University of Melbourne with scaled down models.

Table 4 Comparison of the results of current simulations with the experimental investigations performed by Watanabe et al. 2003 and numerical investigations performed by Upadhyay et al. 2011.

Sr. No.	PGA (g)	Residual displacement at the wall top (mm)		
		Watanabe et al. 2003	Upadhyay et al. 2011	Present study
1	0.2	3.70	3.19	8
2	0.3	5.56	5.2	11.96
3	0.4	9.22	7.81	16.04
4	0.5	14.0	11.2	20.65
5	0.6	21.4	Not reported	25.66
6	0.7	36.5		31.39
7	0.81	63.3		39.92

7. Similitude analysis of scaled down abutment models

Seismic behavior of the bridge abutment can be investigated by shaking table experiments. However, due to limited facilities and size of the shaking table, it is not possible to perform experiments with prototype models. Many researchers used scaled down models for investigating the behavior of prototype structures. (Watanabe et al. 2003; Paolucci et al. 2008; Crosariol 2010; Li et al. 2013). In the present study, the results of prototype bridge abutment models were compared with the 10 scaled down bridge abutment models. Details of the prototype and scaled down models are presented in Table 5. Figure 3 shows the dimensions considered for the prototype and the 10 scaled down bridge abutment models. Similitude analysis has been performed for finding the dimensions of the 10 scaled down abutment model. Same material and same acceleration (1g) was assumed for similitude analysis. To represent the actual abutment behavior at 1g, additional non-structural mass of 21614.68 kg/m^3 and 18440 kg/m^3 has been assigned to the scaled down bridge abutment model and backfill respectively. The scaled down abutment model also satisfies Cauchy conditions and true model conditions as well (Harris et al. 1999). The time domain of input Northridge accelerogram has been scaled down by a factor of 3.16, which is an essential requirement for similitude analysis.

Table 5 Details of the prototype and the 10 scaled down abutment models.

Description	Prototype model	10 scaled down model
Maximum compressive strength of concrete (MPa)	30	30
Density of concrete (kg/m^3)	2356	2356
Modulus of Concrete (GPa)	27.4	27.4
Weight of abutment (kN)	648 (5m) 265 (6m)	0.648 (0.5m) 0.265 (0.6m)

It should be noted here that the 6 m height bridge abutment represents the flexible system with less thickness and base area. The 5 m height bridge abutment with a higher stem wall thickness and higher base area represents a stiff structure. These two different parameters were used to check the capability of the scaled down models to replicate the seismic response behavior of the flexible and rigid structures, and to validate the capability of scaled down models for capturing the strain levels in the prototype models. The displacement response of the scaled down model should be scaled up while comparing the displacement response of prototype and scaled down models.

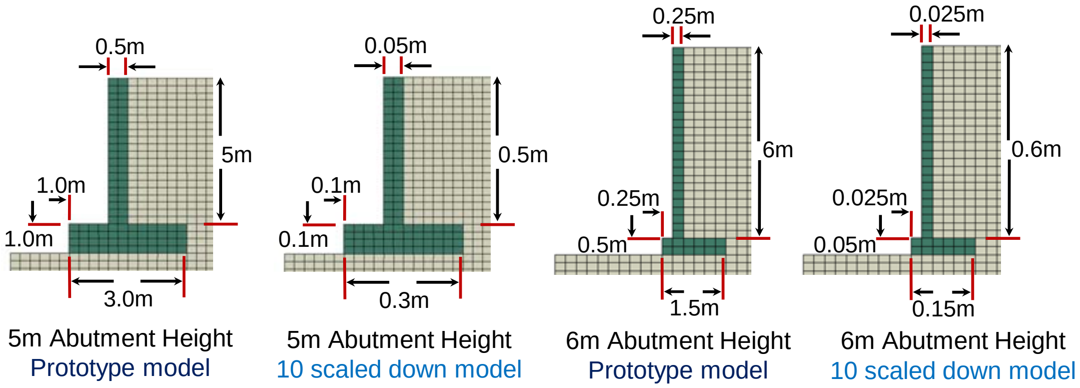


Figure 3 Dimensions considered for the prototype and the 10 scaled down abutment models.

8. Results and Discussion

8.1 Comparison of seismic response behavior of the scaled down and the prototype abutment models

Figure 4 presents the *x* directional displacement at the top of the abutment stem wall in the prototype and the 10 scaled down model. A good agreement is observed between both the 5 m height (stiffer system) and the 6 m height (flexible system) prototype and the 10 scaled down models. However, assemblage of additional mass to the scaled down models in the experimental setup is challenging. Thus, it is advisable to assign non-structural mass in such a manner that it should not affect structural behavior.

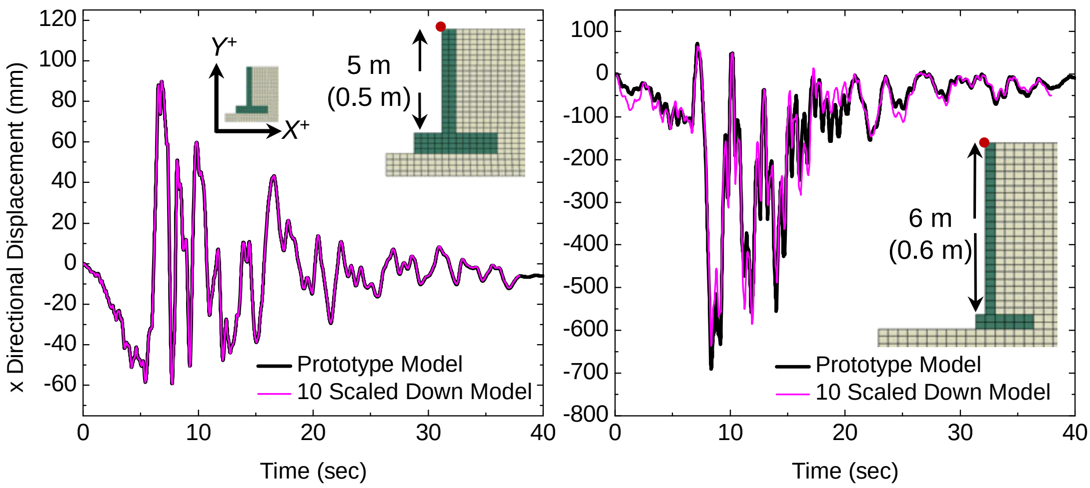


Figure 4 Comparison of *x* directional displacement of the 5 m and 6 m prototype and the scaled down abutment models.

8.2 Drift and displacement behavior of abutments

Figure 5 shows the *x* directional displacement of two different sets of abutment models. A higher amount of drift, and displacement was observed as the stem wall thickness was reduced. Rotational behavior of the abutment was also observed. The point of rotation was formed at a height of 1.35 m from the top of abutment footing for a 2.5 m high abutment. For 5 m, and 6 m high abutment, the point of rotation was observed at a height of 1.20 m from the top of abutment footing. For analysis Set 2, where the ratio of the abutment height to thickness was fixed to 10, (e.g., 2.5 m height and 0.25 m thickness) the drift, and displacement, changes from rotation to slight translation with increasing wall thickness as shown in Figure 3 (d) and 3 (e). For both the 0.5 and 0.6 m wall thickness slight displacement was observed and no rotation, this is because of the higher amount of stiffness of the abutment. However, this behavior can change with changes to the ground motion or the abutment foundation system (Maroney et al. 1994).

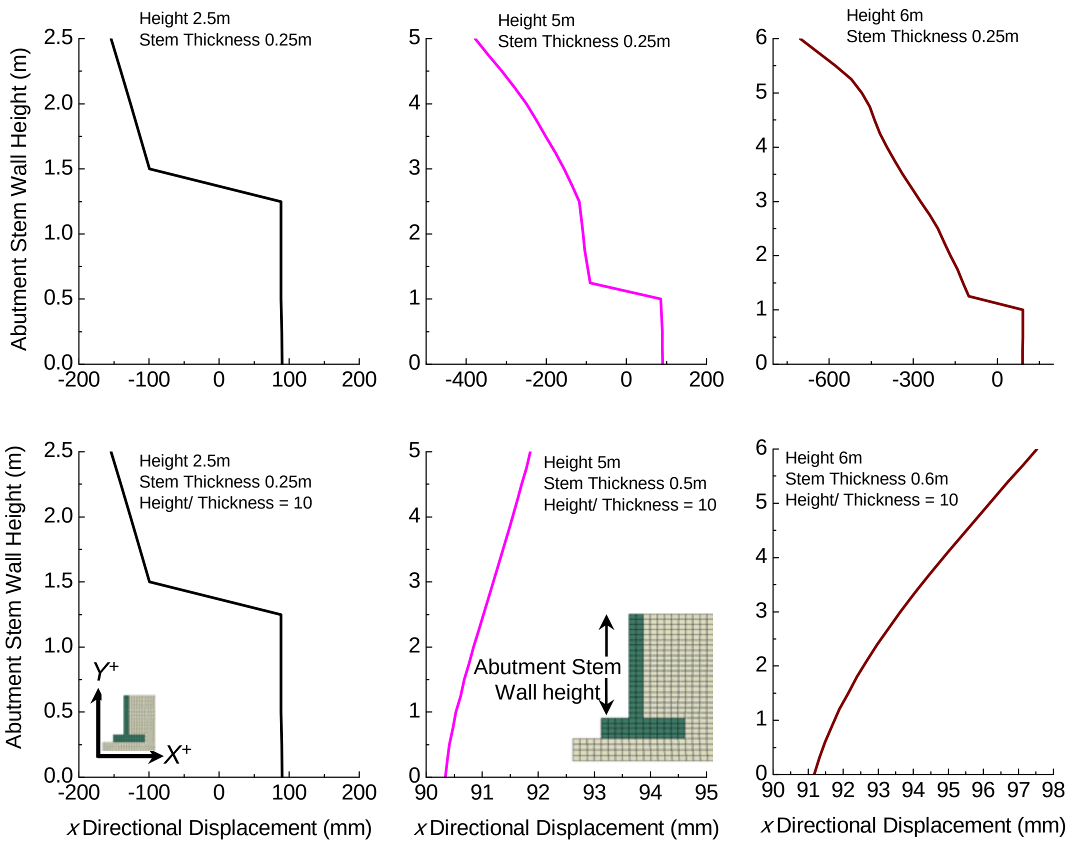


Figure 5 *x* directional displacement for different abutment models.

9. Conclusions

The present study provides a detailed review of the seismic behavior of the bridge abutment and the different aspects of the literature. The validity of the scaled down models for the shaking table experiments has also been investigated. The drift and rotational behavior of the abutment was studied. A higher amount of rotation and translation was observed for the abutment with reduced wall thickness. With increasing wall thickness the rotational behavior of the abutment decreased with increasing stiffness. However, further experimental investigations are required to understand the seismic behavior of the abutment and the role of the abutment stiffness, dynamic earth pressure and the abutment foundation system on its response behavior in an earthquake.

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References

Abaqus/Explicit User's Manual, version 6.13 (2013) Dassault Systèmes Simulia Corporation, Providence, Rhode Island, USA.

Anhdan, L. and Koseki, J. (2005) Small strain behavior of dense granular soils by true triaxial tests, Soils and Foundations, Vol 45, No 3, pp 21-38.

Carreira, D. J. and Chu, K. (1985) Stress strain relationship for plain concrete in compression, ACI Journal, Vol 82, No 6, pp 797-804.

Choudhury, D. and Chatterjee, S. (2006) Displacement-based seismic active earth pressure on rigid retaining walls, Electronic Journal of Geotechnical Engineering, USA, Vol 11, Bundle c, paper No 0660.

Crosariol, V. A. (2010) Scale model shake table testing of underground structures in soft clay, Master of Science thesis, California Polytechnic State University, USA.

Elgamal, A. and Wilson, P. (2012) Full scale testing and simulation of seismic bridge abutment-backfill interaction, Special topics in earthquake geotechnical engineering, Vol 16, pp 109-127, Springer.

El-Gamal, M. E. (1996) Seismic design issues relating to bridge abutments, Ph. D. Thesis, University of Nevada, Reno, USA.

Harris, H. G. and Sabnis, G. M. (1999) Structural modeling and experimental techniques, CRC Press LLC, USA.

Huang, C. C., Wu, S. H. and Wu, H. J. (2009) Seismic Displacement Criterion for Soil Retaining Walls Based on Soil Strength Mobilization, Journal of Geotechnical and Geoenvironmental Engineering (ASCE), Vol 135, No 1, pp 74-83.

Khaleghi, B. (2013) Abutment participation as part of earthquake resisting system, Design Memorandum, Washington state department of transportation (Bridges and structures office).

Li, B., Bi, K., Chouw, N., Butterworth, J. W. and Hao, H. (2013) Effect of abutment excitation on bridge pounding, Engineering Structures, Vol 54, pp 57-68.

Maroney, B., Kutter, B., Romstad, K., Chai, Y. H. and Vanderbilt, E. (1994) Interpretation of large-scale bridge abutment test results, 3rd Annual Seismic Research Workshop, California Department of Transportation, Sacramento, California, USA.

Mononobe, N. and Matsuo, H. (1929) On the determination of earth pressures during earthquakes, Proceedings, World Engineering Conference, Vol 9, paper No. 388.

Paolucci, R., Shirato, M. and Yilmaz, M. T. (2008) Seismic behavior of shallow foundations: Shaking table experiments vs numerical modelling, Earthquake Engineering and Structural Dynamics, Vol 37, pp 577-595.

Psarropoulos, P. N., Klonaris, G. and Gazetas, G. (2005) Seismic earth pressures on rigid and flexible retaining walls, Soil Dynamics and Earthquake Engineering, Vol 25, pp 795-809.

Seed, H. B. and Whitman, R. V. (1970) Design of earth retaining structures for dynamic loads, Proceedings, ASCE Specialty Conference on Lateral Stresses in the Ground and Design of Earth Retaining Structures, pp 103-147.

Sherif, M. A. and Fang, YS. (1984) Dynamic earth pressures on walls rotating about the top, Soils and Foundations, Vol 24, No 4, pp 109-117.

Siddharthan, R., El-Gamal, M. and Maragakis, E. A. (1994) Investigation of performance of bridge abutments in seismic regions, Journal of Structural Engineering, ASCE, Vol 120, No 4, pp 1327-1346.

Upadhyay, A., Krishna, A. M. and Singh, K. D. (2011) Behavior of cantilever retaining walls under seismic conditions, Proceedings, 5th International Conference on Earthquake Geotechnical Engineering, Santiago, Chile.

Watanabe, K., Munaf, Y., Koseki, J., Tateyama, M. and Kojima, K. (2003) Behaviors of several types of model retaining walls subjected to irregular excitation, Soils and Foundations, Vol 43, No 5, pp 13-27.

Whitman, R. V. and Liao, S. (1985) Seismic design of gravity retaining walls, US Army Corps of Engineers, Washington, USA.

Wilson, P. and Elgamal, A. (2009) Full-scale shake table investigation of bridge abutment lateral earth pressure, Bulletin of the New Zealand Society for Earthquake Engineering, Vol 42, No 1, pp 39-46.

Wilson, P. and Elgamal, A. (2015) Shake table lateral earth pressure testing with dense $c-\phi$ backfill, Soil Dynamics and Earthquake Engineering, Vol 71, pp 13-26.

Yazdani, M., Azad, A., Farshi, A. H. and Talatahari, S. (2013) Extended Mononobe-Okabe method for seismic design of retaining walls, Hindwi Publishing Corporation, Journal of Applied Mechanics, Vol 2013, Article ID 136132, pp 1-10.