Prediction of seismic induced forces in an upliftable structure

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Abstract

A large number of studies has been done to identify the uplift behaviour of structures. Research has shown that structural uplift can reduce the force activated in a structure, thus improve its seismic performance. However, uplift behaviour is not being widely applied to current seismic design practice, because it is still not well understood. In this study, a numerical approach is developed for estimating the response of an upliftable structure in earthquakes. Using an empirical formula based on equation of motion for rocking structures the influence parameters have been proposed by other researches, however, without any validation. In this study the natural period of an equivalent single degree-of-freedom (SDOF) structure with uplift was determined using free rocking tests. This experimental result is used to adjust the formula for developing the numerical approach. Shake table test was conducted on the structure to evaluate the performance of the numerical approach. The experimental results confirm that the modified approach is capable of predicting the forces activated in an upliftable structure.

Keywords: upliftable structure, seismic design, numerical approach, shake table test

1. INTRODUCTION

After the Valdivia earthquake in Chile in May 1960, a good seismic performance of several water towers had been reported by Housner (1963). Structural uplift has been suggested as a possible earthquake resistance solution for structures. Compared to the conventional approach, the stepping action of structural footing on the supporting ground due to uplift can consumed part of the earthquake energy. To understand the uplift behaviour, Psycharis and Jennings (1983) used Winkler and 'two-spring' foundations to simulate the uplift of a rigid structure. Result suggested that the rocking frequency of a rigid structure is influenced by the amount of the uplift. Wang and Gould (1993) had extended the analytical study of structural uplift by including sliding behaviour. Kodama and Chouw (2002) investigated the effect of soil-foundation-structure interaction on upliftable structures. Hung et al. (2008) performed a number of quasi-dynamic tests on concrete bridges with allowable uplift. This investigation concluded that allowing structures to uplift could lead to a reduction of the maximum deformation and forces activated in the structure. Consequently, the design strength and ductility demand of a structure could be reduced. On the other hand, Qin and Chouw (2010) have concluded that the displacement of structure with allowable uplift can be increased and hence pounding potential between adjacent structures. Kafle et al. (2011) extended the study using a series of shake table test to identify the peak displacement demand of a rigid structure with various geometrical characteristics. Qin et al. (2013) investigated the uplift behaviour of structure with soil nonlinearity and structural plastic hinge. The beneficial effect of this nonlinear structure-foundation-soil interaction (SFSI) on the response of structure and secondary structure was considered.

Uplift behaviour has been considered in a number of design guidelines to control seismic response of structure. FEMA 356 (2000) had proposed a guideline for rocking rigid structure with allowable uplift based on a shake table test result (Priestley et al. (1978)). One of the remarkable structures designed with rocking mechanism is the Rangitikei Railway Bridge built in New Zealand (Beck and Skinner, 1974). In the retrofit programme of the Lions Gate Bridge in Vancouver (Crippen, 2002), structural uplift was implemented to improve the seismic resistance of the bridge. Although the beneficial effect of structural uplift has been recognized and a design framework is available, structures with capability to uplift are still very limited. Also, these works were conducted based on the assumption that the structure is rigid. Only a very few work has provided an analytical frame work in calculating the deformation in a flexible structure with allowable uplift e.g. Psycharis (1981 and 1991) and Acikgoz and DeJong (2012). Experimental data has not been used to confirm the accuracy of the existing analytical model.

In this study, shake tablet test was conducted to validate an empirical formula for estimating the deformation of an upliftable structure. The formula was originally developed by Psycharis (1981, 1991). For the test, a SDOF model was considered. Bending moment at the column was measured. It was found that the original formula will underestimate the bending moment in the structure during an earthquake. To improve the formula, free rocking test on the model was performed. Result suggested that the behaviour of structure during uplift was dependent on the amplitude of footing vertical displacement. The natural period of an equivalent SDOF model with uplift was determined. By incorporating the natural period of upliftable model, the empirical formula can predict the bending moment in the model.

2. SHAKE TABLE EXPERIMENT

2.1 Experimental setup

Shake table test using simulated excitations based on Japanese Design Spectra (2000) was conducted (Chouw and Hao, 2005). Three different ground excitations were considered in this study. Figure 1(a) shows the acceleration (*a*) time history of the applied excitation. The simulation of the excitation was based on stochastically approach and is demonstrated. Figure 1(b) shows the spectrum acceleration (*Spa*) of the excitation with a damping ratio of 5%.

Figure 1(c) shows the setup of the shake table experiment. A SDOF frame structure with height and width of 0.83 m and 0.40 m, respectively was considered. The beams of the model were assumed to be rigid and constructed using aluminium section. The columns of the model were constructed using PVC and assumed massless. The mass at the top of the model were 29.7 kg. The fundamental period of the model with fixed base was 0.34 s. The property of the SDOF model was obtained and scaled from a six story prototype structure described in the study of Qin and Chouw (2012).

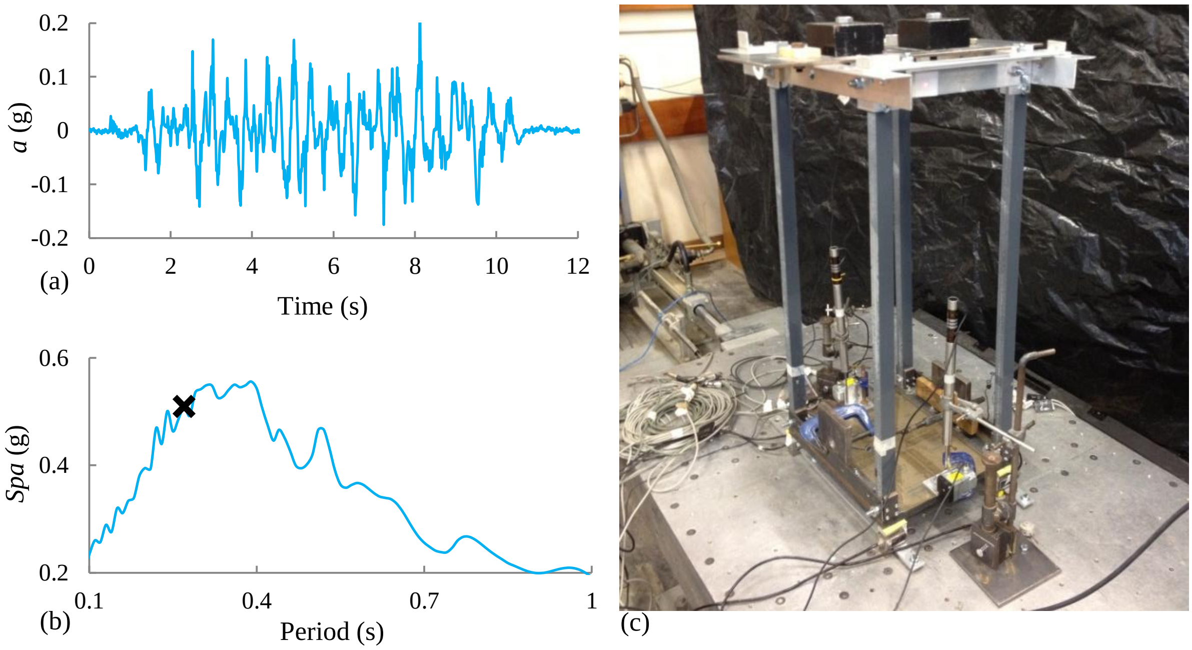

Figure 1: Shake table test. (a) Excitation, (b) response spectrum and (c) setup

Two sets of shake table experiment were conducted to reveal the effect of structural uplift on the seismic force development in the structure. To obtain the seismic force in the model, strain gauge was attached at the base of columns. Two Linear Voltage Differential Transformers (LVDTs) were placed at the edges of the footing to measure the vertical displacement of footing when uplift was permitted (Figure 1(c)). Sand paper was attached at the interface between the footing and the support to minimize sliding when uplift occurs.

2.2 Experimental result

Figure 2 shows the time history of bending moment with and without uplift ability. With uplift the bending moment is smaller. While the maximum bending moment in the upliftable model was 87.4 Nm, the maximum bending moment in the fixed base model was 94.6 Nm. Figure 2 also shows that the period of the structural response was increasing with the time if uplift was permitted. Figure 3 shows the time history of footing rotation. It is found that the change of period of structural response occurred when uplift was initiated.

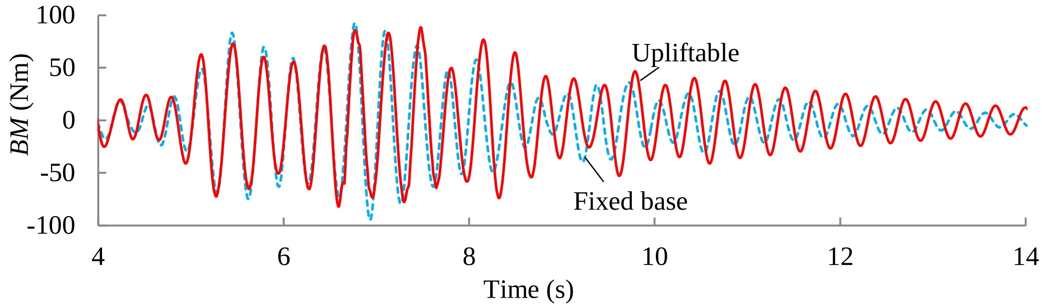

Figure 2: Effect of uplift on the bending moment

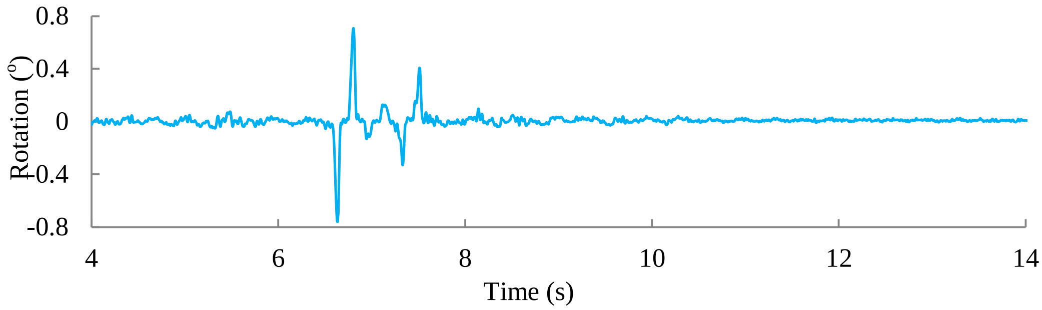

Figure 3: Time history of footing rotation during excitation

3. ESTIMATING THE SEISMIC FORCE IN STRUCTURE

When a fixed base was considered, the response of the structure can be calculated using the equation of motion. When uplift is permitted, the horizontal top displacement of the structure relative to ground is the combination of the horizontal displacement due to structural deformation (u) and footing rotation.

Psycharis (1991) proposed an empirical formula to estimate the maximum deformation in an uplifting structure. By assuming a small horizontal top displacement due to footing uplift, the response of system with uplift was then assumed to be linear. Equation of motion that governs the lateral response of upliftable structure was derived. The equation was used to conduct a parametric study to reveal the influence of the natural frequency, damping ratio and slenderness of structure on the uplift behaviour. The result obtained from numerical study was used to establish a set of empirical formula for determining the normalized maximum horizontal displacement relative to the column footing (Eq. (1)).

$$\frac{u_{max}}{u_{cr}} = 1 + 0.73\frac{\beta^{1/2}\alpha^{1/3}}{\tau}e^{-35\xi\tau^2} \tag{1}$$

where u_{cr} is the critical displacement in the structure for uplift to occur, α is the slenderness coefficient, ξ is the damping ratio of fixed base condition, β is the ratio between maximum horizontal fixed base displacement and u_{cr}, and

$$\tau = \frac{T}{T_o} \text{ for } \frac{T}{T_o} < 1 \text{ and } \tau = \frac{T_o}{T} \text{ for } \frac{T}{T_o} > 1 \tag{2}$$

$$u_{cr} = \frac{bg}{h\omega_n^2} \tag{3}$$

where T is the natural period of the fixed-base SDOF structure and T_o is the period of the harmonic excitation or T_{min} of an arbitrary earthquake; h and b are the height and half of the base width of the model, respectively; g is the gravitational acceleration.

The period of harmonic excitation is constant. On the other hand, when excitation with a range of predominant periods are considered (e.g. earthquake), research in the past (Psycharis, 1991 and Chopra and Yim, 1985) has confirmed that the minimum value (T_{min}) of the predominant period range can be used. In this work, T_{min} of different excitations are obtained by examining the response spectrum of the corresponding excitation (denoted as "x" in Figure 1(b)). In general, Fourier spectrum can be used to find the T_{min}. However, response spectrum is more common because it is generally available in most of seismic design documents and thus considered herein.

Eq. (1) suggests that the maximum normalized horizontal relative displacement in the model due to the applied excitation was 1.21. Using the maximum normalized horizontal displacement, the maximum bending moment can be calculated using Eq. (4).

$$BM_{max} = u_{max} \times k \times h \tag{4}$$

where k and h are the lateral stiffness and height of the structure, respectively.

Eq. (1) suggests that the maximum bending moment in the model with uplift is 79.5 Nm. Compare to the result obtained using shake table test (87.4 Nm), it is found that Eq. (1) has underestimated the maximum bending moment. As found in the time history of bending moment obtained from the shake table test (Figure 2), the period of the structural response increased when uplift was permitted. This observation shown that calculating the response of upliftable structure using the fundamental frequency of the structure with fixed base is inappropriate. It is suggested that when applying Eq. (1), the fundamental period of equivalent model with uplift should be considered.

4. DETERMINING THE PERIOD OF UPLIFTABLE STRUCTURE

To determine the fundament period of an equivalent structure with uplift, free rocking test was conducted. The experimental procedure involved in giving an initial vertical displacement at one side of the footing by inserting a rigid block between the footing and the support. The size of the block was known and the model was tilted with an initial rotation. The block was removed instantly to create a free rocking motion of structure. Three different block sizes were utilized in this study (10.3 mm, 12.9 mm and 15 mm.) Figure 4(a) shows the time history of footing rotation during free rocking test when 10.3 mm block was used. Three significant cycles of footing rotation can be found. The response period of structure with uplift was obtained by finding the time between the peaks of footing rotation displacement.

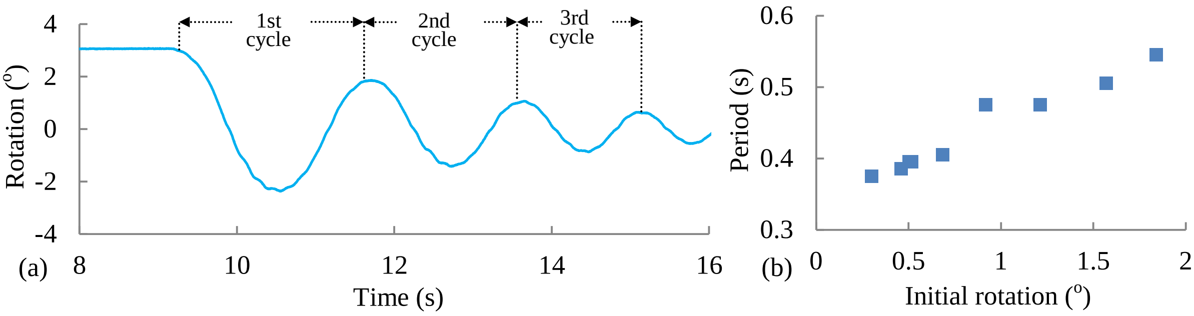

Figure 4: Free rocking. (a) history and (b) rotation amplitude-period relationship

Because of the energy loss in the structure with each uplift, the peak footing rotation at the beginning is larger than that at the end. The peak footing rotation at the beginning of each cycle is called initial footing rotation, herein. Figure 4(b) shows the relationship between the initial footing rotation and the corresponding rocking period. As illustrated, the greater the initial footing rotation, the longer the period of structural free rocking motion. Using shake table measurement (Figure 3), the maximum rotation of the footing was 0.79^{o}. Figure 4(b) suggests that the fundamental period of the equivalent model with uplift due to the excitation was 0.43 s. This period of the structural response with uplift was longer than the fundamental period of structure with fixed base (0.34 s). The period of model with uplift should be used to replace the T in Eq. (2).

5. PREDICTING THE MAXIMUM *BM* IN AN UPLIFTABLE STRUCTURE

Table 1 shows the comparison of the maximum bending moment obtained from Eqs. (1) and (4) using the period of upliftable structure and from shake table test. The results obtained from three different excitations have shown that estimating the bending moment in the structure using fundamental period of equivalent upliftable model is more appropriate than using the fixed base natural period. The average of maximum bending moment obtained using three different ground motion was 89.6 Nm. The perdition of average maximum bending moment obtained by Eq. (1) using the fundamental period of fixed base model and equivalent upliftable model were 81.6 Nm and 89.8 Nm, respectively. The results show that using the fixed base fundamental period to predict the response of structure with uplift will underestimate the maximum bending moment. The prediction of maximum bending moment using the new approach is very similar to the shake table result.

Table 1: Accuracy of Eq. (1) using different structural period

Maximum *BM* (Nm)	Excitation 1	Excitation 2	Excitation 3
Shake table result	87.4	91.1	90.2
Fixed base frequency	83.5	94.7	91.1
Proposed frequency	79.5	79.6	85.7

4. CONCLUSIONS

Experimental work was performed to validate an empirical formula for estimating the bending moment developed in an upliftable structure. The accuracy of the formula improved when the fundamental period of an equivalent SDOF model with uplift is applied. This fundamental period was determined using free rocking tests.

This study has revealed that:

1. It is found that the greater the footing rotation due to uplift, the larger the footing rocking period.
2. When uplift took place during an earthquake, the period of structural response with uplift becomes longer, and thus the bending moment in the structure cannot be estimated using the fundamental period of structure with an assumed fixed base.

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REFERENCES

Acikgoz, S. and DeJong, M.J. (2012), The interaction of elasticity and rocking in flexible structure allowed to uplift, *Earthquake Engineering and Structural Dynamics* 41(15), 2177-2194

Beck, J.L., and Skinner, R.I. (1974). Seismic response of a reinforced concrete bridge pier designed to step. *Earthquake Engineering and Structural Dynamics*, 2:4, 343-358.

Chopra, A.K. and Yim, S. C-S. (1985). Simplified earthquake analysis of structure with foundation uplift, *Journal of structural engineering*. ASCE, 111(4), 906-930.

Chouw, N. and Hao, H. (2005). Study of SSI and non-uniform ground motion effect on pounding between bridge girders, *Soil Dynamics and Earthquake Engineering*, 25, 717-728.

Crippen. K., (2002). “North viaduct to Lions Gate Bridge.” *Canadian Consulting Engineer*, 43(7), 34-35.

Federal Emergency Management Agency 2000. FEMA 356: Prestandard and Commentary for the Seismic Rehabilitation of Buildings. Washington, D.C.

Housner, G.W. (1963), The behavior of inverted pendulum structures during earthquakes, *Bulletin of the Seismological Society of America*; 53(2): 403-417.

Hung, H.H., Chang, K.C. Liu, K.Y. and Ho, T.H. (2008). An experimental study on rocking response of bridge spread foundations. *Proceedings of the 14th World Conference on Earthquake Engineering*, Beijing China. 12-17 Oct.

Japan Society of Civil Engineering (JSCE), (2000). *Earthquake resistant design code in Japan*, Maruzen, Tokyo.

Kafle, B., Lam, T.K.N., Gad, E.F., and Wilson, J. (2011), Seismic displacement controlled rocking behaviour of rigid objects, *Earthquake Engineering and Structural Dynamics,* DOI:10.1002/eqe/1107. Wiley

Kodama, T., Chouw, N. (2002). Soil-structure interaction with uplift due to near-source earthquakes. *Proc. of European Conf. on Structural Dynamics*, T. U. München, Germany, 1375-1380.

Priestley, M. J. N., Evison, R. J. and Carr, A. J. (1978), Seismic response of structures free to rock on their foundations, Bulletin of the New Zealand National Society for Earthquake Engineering, 11(3), 141-150.

Psycharis, I.N (1981), Dynamic behaviour of rocking structure allowed to uplift, *PhD thesis of California Institute of Technology*. Pasadena, California.

Psycharis, I.N. and Jennings, P.C. (1983), Rocking of slender rigid bodies allowed to uplift, *Earthquake Engineering and Structural Dynamics*, 11, 57-76.

Psycharis, I.N (1991), Effect of base uplift on dynamic response of SDOF structure, *Journal of Structural Engineering*, ASCE, 117(3), 733-754.

Qin, X., & Chouw, N. (2010). Experimental investigation of uplift effect on structures in earthquakes. In *Proceedings, New Zealand society for earthquake engineering conference, Paper* (Vol. 14).

Qin, X. and Chouw, N (2012). Shake table test on uplift behaviour of a shear frame in earthquakes, *2012 World Congress on Advances in Civil, Environmental and Materials Research,* 26-29 August 2012, Seoul, Korea

Qin, X., Chen, Y and Chouw, N (2013), Effect of uplift and soil nonlinearity on plastic hinge development and induced vibrations in structures, *Advances in Structural Engineering,* 16(1):135-147.

Wang, X.F. and Gould, P.L. (1993), Dynamics of structures with uplift and sliding, *Earthquake Engineering and Structural Dynamics*, 22, 1085-1095.