Low damage seismic design of structure using footing uplift

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ABSTRACT: In conventional seismic design of structures, plastic hinge development was permitted. In recent earthquake events, it became clear that the damage to structures due to plastic hinge development can be too costly. Thus 'damage avoidance' seismic design of structures has been proposed as one of the major design approaches for future buildings. Allowing a structure to uplift is one of the practices to significantly reduce or even eliminate the development of plastic hinges in the structure. However, the challenge of this practice is to accurately calculate the response of structure with uplift. Previous studies have developed numerical formulas for this propose. This paper presents an experimental validation of these numerical formulas. Shake table test was conducted on a model. The response of structure obtained in the experiment was compared against that obtained using existing numerical formula. An approach to calculate the response of structure with uplift was developed.

1 INTRODUCTION

1.1 Structure with uplift

The system considered is shown in Figure 1, it is a SDOF model with a base width 2*b*, a height *h* and the dynamic properties (mass *m*, lateral stiffness *k* and damping *c*). It is assumed that the supporting ground is rigid, i.e. only the positive vertical displacement at the footing can develop (Figure 1(b)). During the base excitation, if uplift is not permitted or initiated (Figure 1(a)), a fixed base condition can be assumed. The horizontal displacement at the top of structure relative to the column footing (*u*) due to base excitation can be calculated by using an equation of motion. On the other hand, when the inertia force in the structure produces a moment at *o* or *o*' (Figure 1(b)) greater than that due to gravity, rotation about *o* or *o*' can occur, respectively. Footing vertical displacement *v* in Figure 1(b) other than the rotation pivot will develop. The total horizontal relative displacement in the structure is the combined movement due to the rocking motion (*x*) and structural deflection (*u*). Because the structural deflection (*u*) determines the seismic performance of the upliftable structure, it is necessary to be quantified for design.

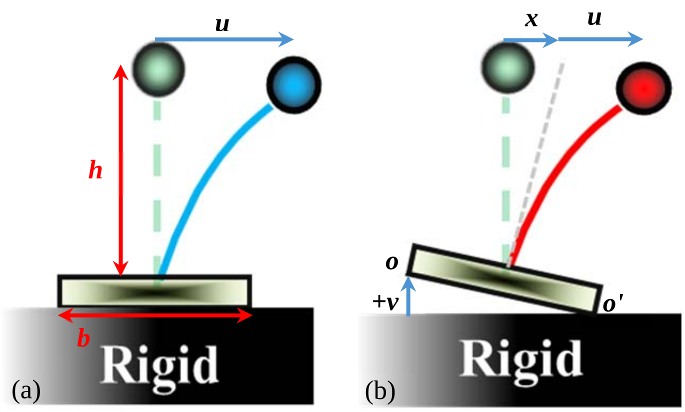

Figure 1: Effect of uplift on the bending moment

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

1.2 Previous studies

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. Kafle et al. (2011) had conducted a series of shake table test to identify the peak displacement demand of a rigid structure with various geometrical characteristics. Loo et al. (in print, 2012) and Ormeno et al. (in print) considered upliftable structures with slip-friction connectors and fluid-structure interaction, respectively. Ali et al. (2013) investigated the effect of uplift throughout the structure on the seismic performance of low-damage earthquake-resistant structures. 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 guideline 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). Experimental data has not been used to confirm the accuracy of the existing analytical model.

2 SHAKE TABLE EXPERIMENT

2.1 Experimental setup

Figure 2(a) shows the setup of the shake table experiment. A SDOF frame structure was considered with a height and a width of 0.83 m and 0.40 m, respectively. 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 an assumed fixed base was 0.34 s. The property of the SDOF model was obtained and scaled from a six storey prototype structure described in the study by Qin and Chouw (2012).

Shake table test using stochastically simulated excitations based on Japanese Design Spectra (2000) was conducted (Chouw and Hao, 2005). Three different ground excitations were considered in this study. Figure 2(b) shows the acceleration (a_g) time history of the applied excitation. Figure 2(c) shows the spectrum acceleration (*Spa*) of the excitation with a damping ratio of 5%.

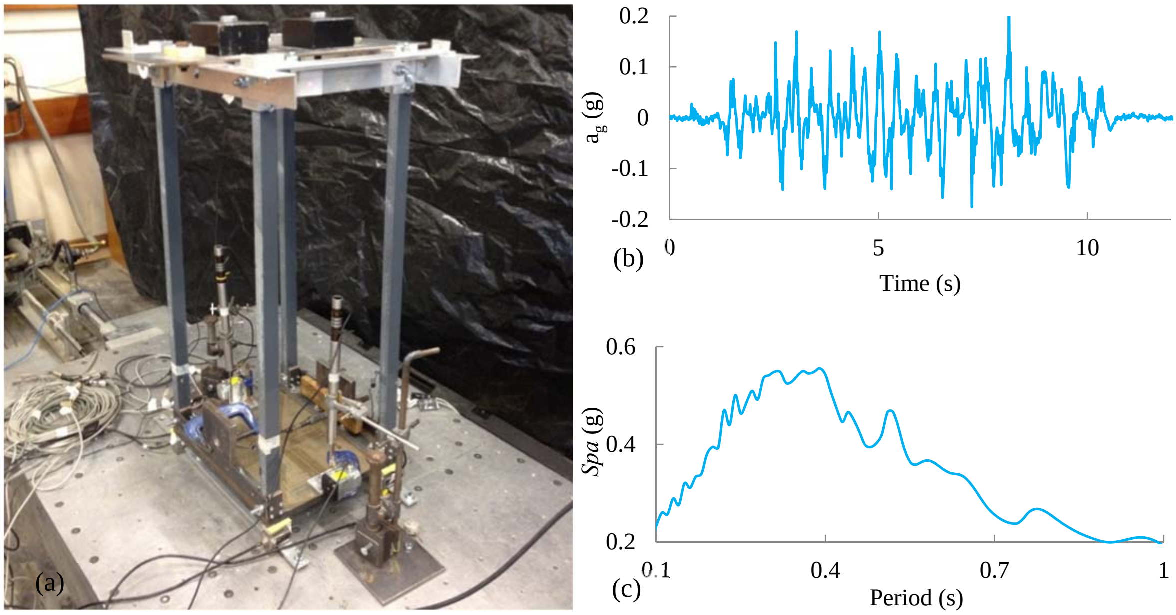

Figure 2: Shake table test. (a) Setup, (b) Excitation and (c) response spectrum

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, 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 2(a)). Sand paper was attached at the interface between the footing and the support to minimize sliding when uplift occurs.

2.2 **Experimental results**

Figure 3 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. The period of the structural response increases with the time, if uplift was permitted. Figure 4 shows the time history of footing rotation. It is found that the change of the period of the structural response occurred when uplift was initiated.

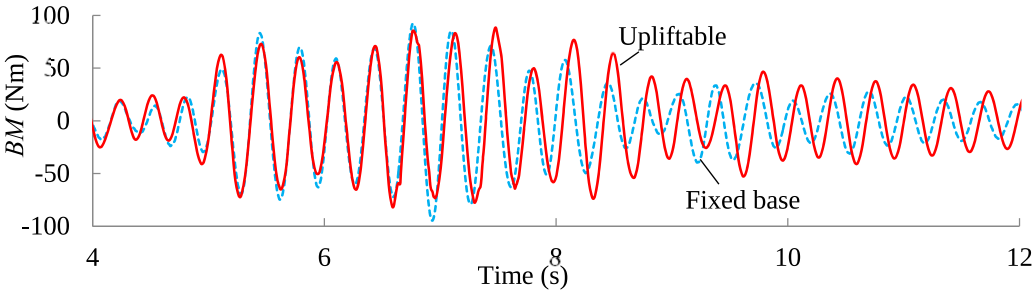

Figure 3: Effect of uplift on the bending moment

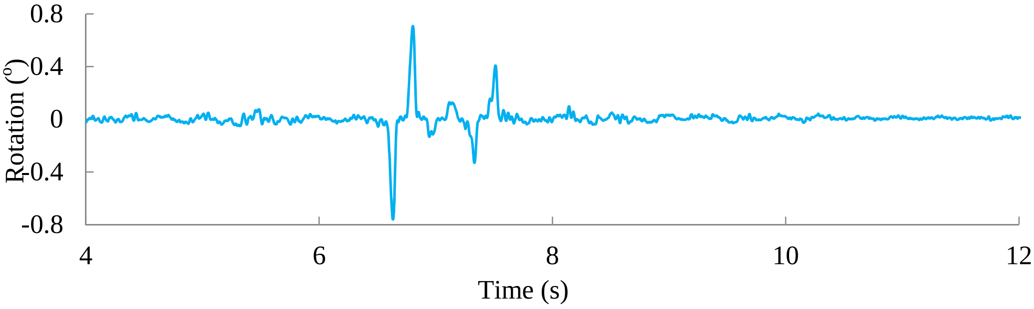

Figure 4: Time history of footing rotation during excitation

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 (Equation (1)).

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

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 the maximum horizontal displacement of the fixed base SDOF structure and u_{cr}, and

$$\tau = \frac{T_n}{T_o} \text{ for } \frac{T_n}{T_o} < 1 \text{ and} \tag{2a}$$

$$\tau = 1 \text{ for } \frac{T_n}{T_o} > 1 \tag{2b}$$

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

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 a harmonic excitation is constant. On the other hand, when an 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. In general, Fourier spectrum can be used to find the T_{min}. However, a response spectrum is more common because it is generally available in most of seismic design documents and thus considered herein.

Equation (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 Equation (4).

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

Equations (1)-(4) 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 Equations (1)-(4) 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 shows that by calculating the response of upliftable structure using the fundamental frequency of the structure with an assumed fixed base is inappropriate. It is suggested that when applying Equations (1)-(4), the fundamental period of equivalent model with uplift should be considered.

4 DETERMINATION OF THE SEISMIC FORCE IN 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 suddenly 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 5(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.

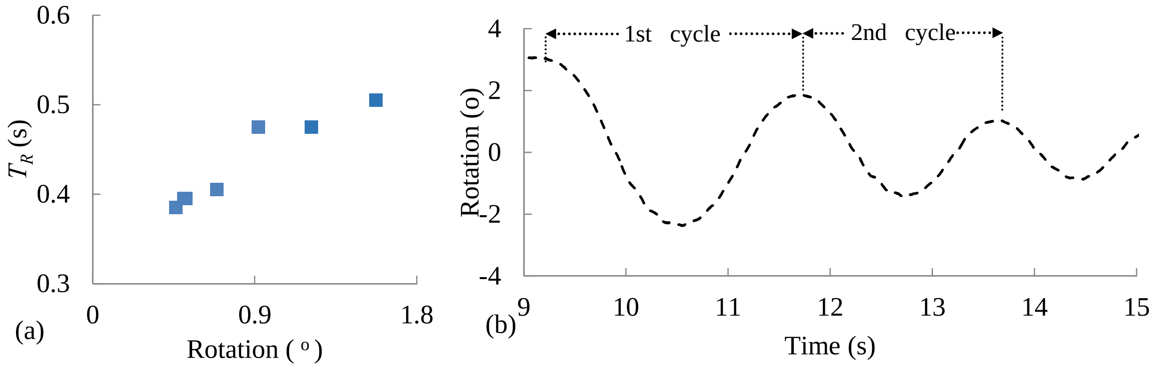

Figure 5: Free rocking. (a) Rotation amplitude-period relationship and (b) rotation time history

Because of the energy due to the impact between the footing and support, 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 5(a) shows the relationship between the initial footing rotation and the corresponding vibration period (T_v). As illustrated, the greater the initial footing rotation, the longer the period of structural free rocking motion. Using shake table measurement (Figure 4), the maximum rotation of the footing was 0.79^{o}. Figure 5(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 an assumed fixed base (0.34 s). The period of model with uplift should be used to replace the T in Equation (2).

5 PREDICTING THE MAXIMUM *BM* IN AN UPLIFTABLE STRUCTURE

Table 1 shows a comparison of the maximum bending moment obtained from Equations (1)-(4) and shake table test. The results obtained from three different excitations have shown that estimating the bending moment in the structure using the effective vibration period (T_v) of upliftable model is more appropriate than using the fixed base fundamental period (T). The average of maximum bending moment obtained using three different ground motion was 80.2 Nm. The perdition of average maximum bending moment obtained by Equations (1)-(4) using the fundamental period of fixed base model and equivalent upliftable model were 71.6 Nm and 80.4 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 Equations (1)-(4) using different structural period

Maximum *BM* (Nm)	Excitation 1	Excitation 2	Excitation 3	Average
Shake table result	87.4	73.7	79.6	80.2
Using T	83.5	65.6	65.9	71.6
Using T_v	79.5	77.9	83.8	80.4

6 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. 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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