Shake table simulation of dynamic forces of a structure

X. Qin, H. Xu, N. Chouw, T. Larkin & H.M. Osinga

The University of Auckland, New Zealand.

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ABSTRACT:

When the structural response to a ground motion is calculated, the equation of motion that is applied describes the relationship between the structural response and the load. The load is usually defined as the product of the mass of the structure and the sum of the ground acceleration and the acceleration that results from deformation of the structure. This study experimentally addresses a more rigorous approach for evaluating the structural loading. Shake table tests on a model structure using a range of dynamic excitations were conducted. Four load cells were placed at the interface between the shake table and the base of the structure. The acceleration at the base of the model structure was recorded using accelerometers. From these measurements a closer approximation to the actual load was determined. The results show the degree of approximation commonly used in the evaluation of the structural response.

1 INTRODUCTION

Major earthquakes, e.g. the 1995 Kobe Earthquake in Japan (Chouw, 1996), the 2010 Maule Earthquake in Chile (Kawashima et al., 2011), the 2011 Canterbury Earthquake in New Zealand (Chouw and Hao, 2012), or the 2011 Tohoku Earthquake in Japan (Orense et al., 2014), remind us of possible consequences of strong earthquakes for structures. Despite efforts and advancements made in the past decades and implementations of the latest knowledge in the design specifications, damage to structures still took place. The most recent M7.8 Kaikoura Earthquake on November 14, 2016, showed that some commercial buildings throughout the nearby Wellington area suffered damage, even though they were built according to the latest design specifications. In many buildings, damage to exterior cladding was also observed that posed a potential threat to people in the walkways below.

Multiple causes of structural damage have been identified. One possible cause, i.e. the uncertainty resulting from the influence of the supporting ground, has been discussed in the recent international workshop on seismic performance of soil-foundation-structure (SFS) systems at the University of Auckland (Chouw et al., 2017). During an earthquake, the movement of soil causes movement of structures and this structural response, in turn, influences the movement of soil. This structure-footing-soil interaction (SFSI) can cause the response of a structure to be different from that of an identical structure with an assumption of an idealized fixed base. This process will likely cause the response of the soil to be different from what would be measured under a free-field condition, i.e. with the structure absent (Qin and Chouw, 2017). In reality, not only the existing structure has an influence on the development of the ground movements, but also the adjacent structures can have a significant effect. The results of the shake table investigations using a large laminar box showed that, depending on the frequency content of the incoming seismic waves and the location of the structure, the effect of clustered structures can be beneficial or detrimental [Needs a reference!]. Observations from major earthquakes, including those from the 2010-2011 Canterbury earthquakes, have identified the significant influence that the behaviour of a foundation soil can have on the overall seismic performance of SFS systems. The behaviour of SFS systems becomes even more complex if the supporting ground liquefies.

The other uncertainty is the loading itself. In the conventional seismic design, the earthquake load is assumed to be given. The ground movement used is either the movement recorded on a ground surface during an earthquake or the movement simulated based on a particular design spectrum. In the analysis of the structural response to the earthquake, the structure is often assumed to be fixed to a rigid support and the load is defined as the sum of the ground acceleration (a_t) plus the acceleration resulting from structural deformation (a) times the mass of the structure, $m(a+a_t)$ in Equation (1) below. The influence of the flexible soil support and the structural response on the actual ground movement and the effect of soil on the structure as well as the effect of the structural properties on the development of the actual load of the structure are ignored. For simplicity in current design the seismic load is assumed to be independent of the interaction between the structure and the soil.

In the simplest case of a single degree-of-freedom (SDOF) system the forces acting on the system are given in Equation (1). These forces represent the restoring forces due to stiffness, energy loss represented by an assumed viscous damper, and the inertia force due to the absolute acceleration of the assumed lumped mass of the structure.

$$k u + c v + m(a + a_t) = 0 \qquad (1)$$

where k, c and m are the stiffness, the coefficient of a viscous damper and the mass of the structure, respectively. u, v and a are the horizontal displacement, velocity and acceleration, respectively, resulting from the structural deformation of the column, and a_t is the acceleration of the ground movement. The load is then defined as the product of the mass m and the absolute acceleration acting on the mass while the SDOF system is assumed to be fixed at the support.

There are two key aspects to the assumptions made in the usual design process:

1) In reality, no structure has a fixed-base condition. The flexibility of the soil means that the structural loading depends on the foundation soil, since the ground acceleration will be altered by this flexibility.
2) The structural response will also affect the ground acceleration since this response will affect the foundation soil and hence the acceleration applied at the base.

The response of a structure can only be accurately determined if the loading is precisely known. Thus, no matter how accurate the structure is modelled the usefulness of the analysis also depends on evaluating the real loading. Ignoring the factors described above, although attractive from the point of view of expediency, can have severe consequences for the estimated structural response.

Investigations have been performed by a limited number of researchers. Todorovska and Lee (1989) formulated a finite-difference approach based on the wave equation to determine the dynamic response of structures. Kohler et al., (2007) used this formulation to obtain the dynamic response of a steel moment resistant frame structure. In 2011, Zhang et al., also applied this approach to solve the seismic response of high rise building. Osinga (2017) developed a computational approach that calculates the dynamic response of a structure, while taking into account nonlinear behaviour. However, despite these studies a reasonable determination of the seismic load is still not available.

In current practice, Equation (1) can be rearranged to the following form:

$$k u + c v + m a = P(t) \qquad (2)$$

where P can be obtained using mass times the ground acceleration (a_t).

In this study shake table experiments have been performed to determine the horizontal force (P) transmitted from the base to the top of the structure. A comparison will be made between the force measured in the experiments and that calculated from the measured horizontal acceleration and the mass of the structure, as noted above.

2 SHAKE TABLE EXPERIMENT

The base of the SDOF model is 1.0 m x 0.7 m, the model has a total height of 1.2 m and is constructed from steel sections. The base can be assumed rigid. The total mass m of the SDOF model, i.e.

including the base and the upright steel column was 36 kg.

Shake table experiments were performed to investigate the influence of the activated inertial force from an additional mass of 169 kg that was attached to the base or to the top of the model, respectively. The total mass of the model is thus 169 + 36 kg. When the mass was attached to the base, the mass at the top of the model may be considered as half the mass of the upright, which is considered negligible in the analyses that follow. The model can be considered rigid, i.e. the deformation of the upright is ignored. When the mass was attached to the top of the model, the model can be considered as a SDOF system. The fundamental frequency of the SDOF model was determined experimentally as 2 Hz.

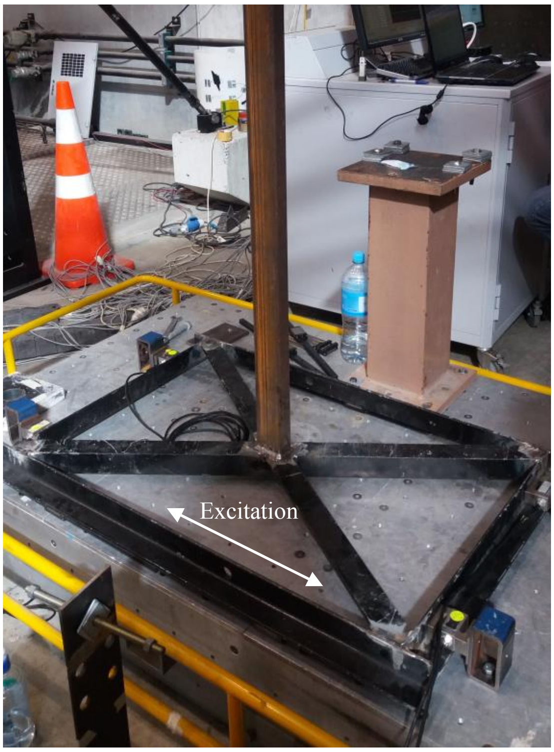

Figure 1. Configuration of the model on the shake table.

To enable an understanding of the manner in which the system responded to base shaking, a single frequency, 0.5 Hz, harmonic load was applied. This is not what occurs under earthquake loading, where there is a range of frequencies, each with a different amplitude.

The induced force, P, was defined as the horizontal force transmitted from the shake table to the base of the model. Two rigid uprights were fixed on the shake table perpendicular to the direction of the shaking. The uprights fixed the model base to the shake table in the direction of the excitation. Sliding of the model is prevented and the model was excited by the horizontal force generated from the rigid uprights. Four load cells were place between the rigid uprights and the base (Figure 2). The horizontal force generated from the rigid upright that excited the model is deduced from the response of the load cells. It was necessary to avoid friction forces developed at the base-shake table interface so that the model was excited solely by the force generated from the rigid uprights. To realize this condition, rollers were placed on the rails attached to the base of the model to prevent the development of friction forces.

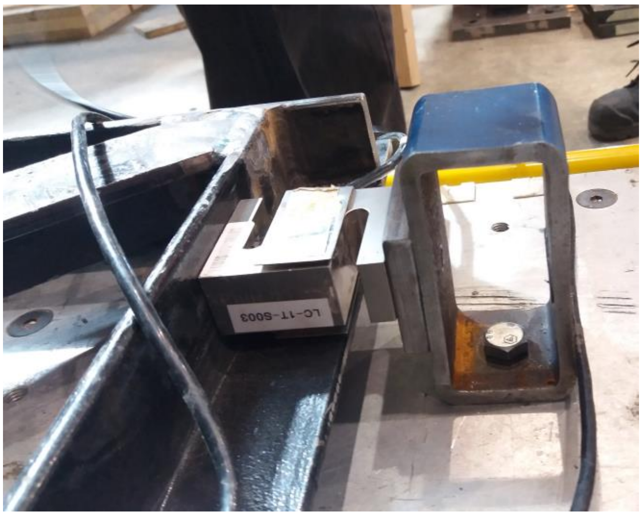

Figure 2. Set-up of the load cells.

A laser displacement transducer was used to measure any possible relative movement between the rigid upright and the base in the direction of the excitation as a result of compliance of the load cell or fixity of the hollow uprights to the table. Two accelerometers were used to measure the horizontal acceleration at the base and at the shake table during the experiment. The horizontal displacement and acceleration at the top of the model were also measured using a laser transducer and accelerometers, respectively. The excitations used were harmonic excitations with a frequency of 0.5 Hz.

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Seismic force for a rigid structure

In the calculation of structural response, the equation of motion Equation (1) is commonly applied. For this section, the model can be considered rigid because the 169 kg mass was attached at the base of the model. In this case, the applied load is commonly assumed to be the acceleration at the base of the model multiplied by the total mass of the model, as in Equation (2). In this study, the force at the base of the model due to table movements was directly measured using the load cells. Figure 3 shows a comparison between the measured force and that calculated using the measured base acceleration multiplied by the model mass. The dashed line shows the force calculated from the acceleration measured at the base of the model times the total mass of the model. The solid line shows the sum of the forces measured using the load cells. For the rigid structure, the force at the base calculated using the measured acceleration was slightly larger than that measured using the load cells. However, overall, the measurement by the load cells is very similar to that calculated using the acceleration and mass.

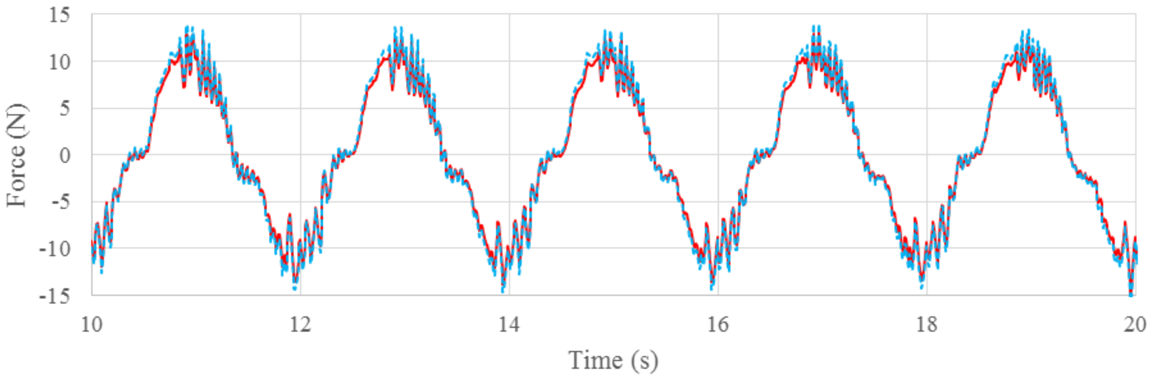

Figure 3. Horizontal force at the base of the rigid model.

3.2 Seismic force for a SDOF structure

In contrast, when the SDOF model, i.e. with the 169 kg mass attached at the top of the model, was considered, the dynamic response of the model affected the force developed at the model base. The force measured using the load cell and that calculated using the base acceleration multiplied by the model mass is different. Figure 4 shows that the force (from the action of the total mass of the model) at the base obtained from the load cell (solid line) and that calculated using the base acceleration times the total mass of the SDOF model (dashed line). Figure 5 shows a comparison of the force at the base in the frequency domain. As can be seen, the force at the base calculated using the base acceleration has only one peak. This peak can be observed at 0.5 Hz, which was the frequency of the cyclic excitation. On the other hand, the force measured using the load cell has two peaks in the frequency domain. The first peak occurs at 0.5 Hz and the second peak at about 2.0 Hz. As shown, the first peak took place at the same frequency as the frequency of the base acceleration. The second peak can be found at the fundamental frequency of the SDOF model.

It has been shown that the dynamic force developed at the base of the structure is a result of the ground motion and the structural response. The conventional equation of motion, which calculates the response of a structure using the base acceleration excitation to obtain the applied dynamic load acting on a structure, cannot accurately calculate the response of structure.

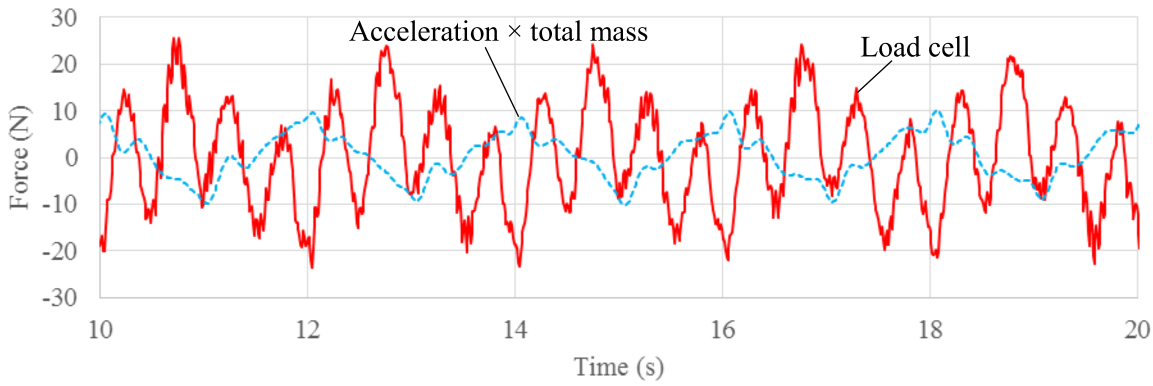

Figure 4. Horizontal force at the base of the SDOF model.

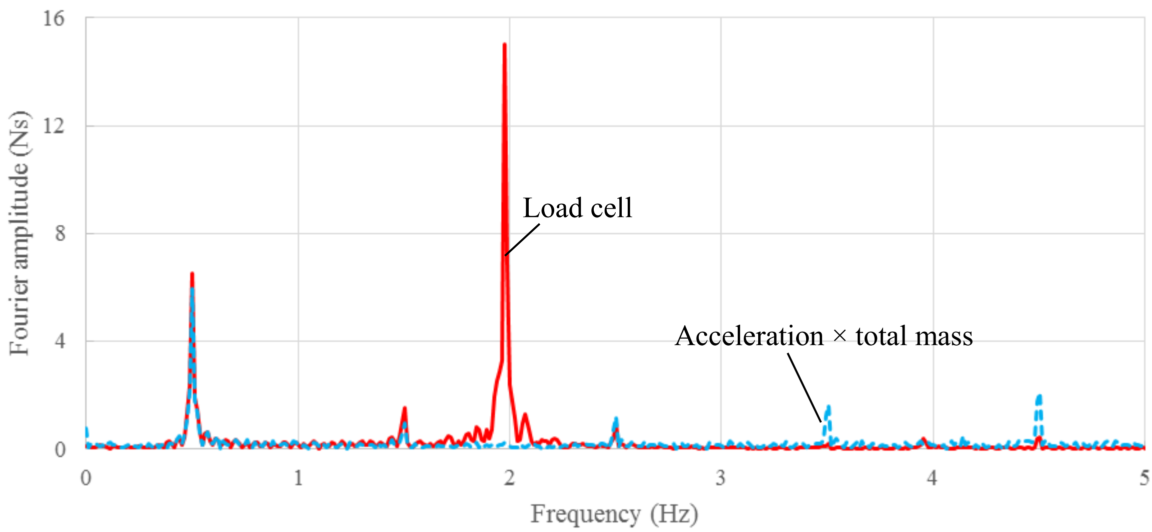

Figure 5. Fourier amplitude of the force at the base of the SDOF model.

4 COMPUTATION OF MODEL RESPONSE

In this study, the response of the model was calculated using Equation (2). The parameters of this equation were evaluated from the free vibration of the model. The equation was solved using either the force measured directly from the load cell (solid line in Figure 4) or the acceleration at the base of the model (dashed line in Figure 4). It has been shown that the frequency content of the acceleration obtained from the accelerometer and the load cells was different. These two acceleration time histories were used to calculate the dynamic response of the model. It is anticipated that the structural response calculated using these acceleration time histories will be different.

Figure 6 shows the horizontal acceleration at the top of the model calculated using the base acceleration obtained using the load cell measurement, and Figure 7 shows that calculated using the measurement of the accelerometer at the base of the model. As expected, the model responses predicted using different acceleration time histories are different. In comparison, the horizontal acceleration of the model calculated using the load cell measurement is much larger than that using the accelerometer measurement.

The results show that when predicting the response of a structure using the conventional equation of motion and the base acceleration as the excitation, the dynamic response of a structure will be underestimated.

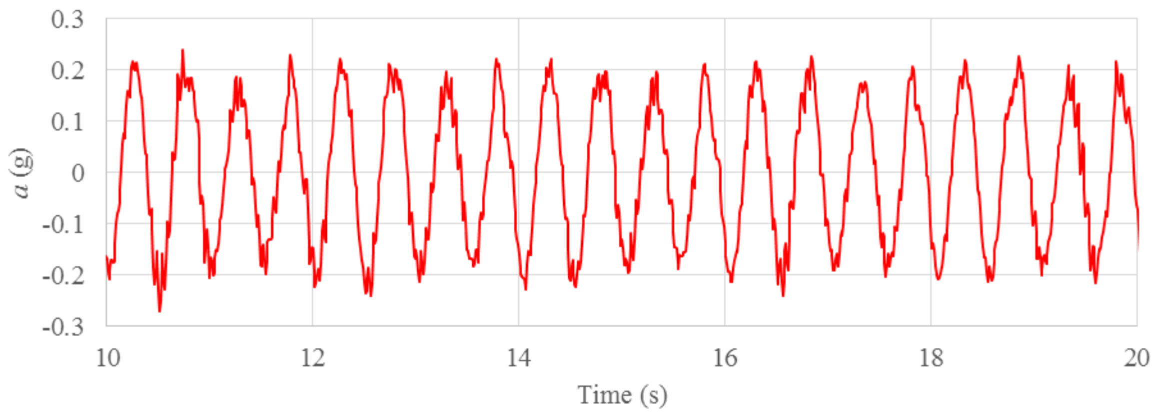

Figure 6. Model acceleration calculated using the force at the base.

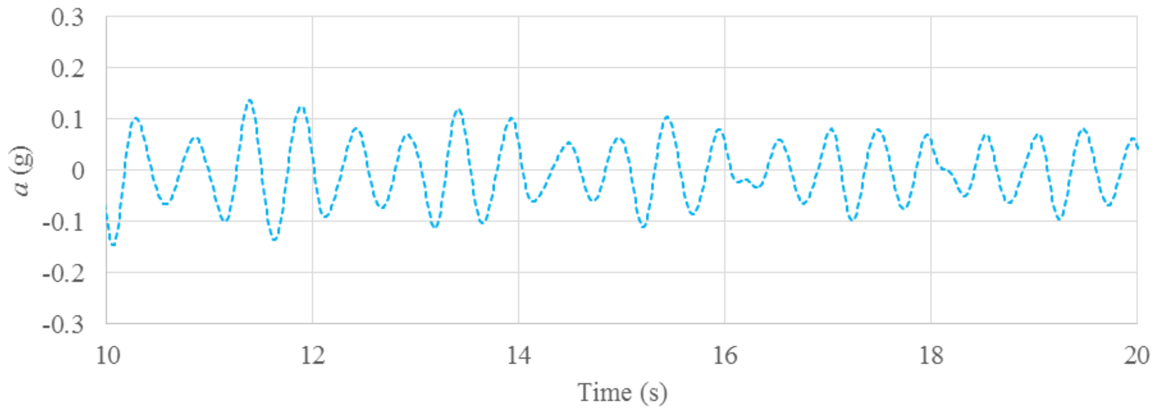

Figure 7. Model acceleration calculated using the acceleration at the base.

Figure 8 compares the experimental and the predicted horizontal acceleration at the top of the SDOF model. The dashed line shows the horizontal acceleration measured at the top of the model using the accelerometer. The solid line shows the model acceleration calculated using the acceleration at the base of the model calculated from the load cell measurement. The results show that the predicted model response using the horizontal force measured at the base of the model (see Figures 4 and 6) is closer to that predicted using the base acceleration. Compared to the horizontal acceleration at the top of the model obtained from the experiment, calculation using the measured force at the base slightly underestimated the model response.

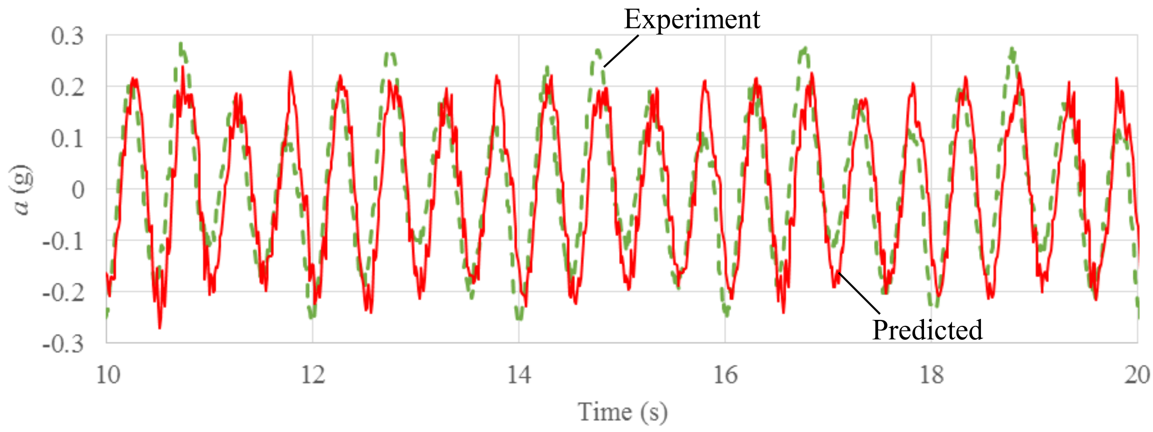

Figure 8. Comparison between experiment measurement and result predicted using Equation (2) with the ground acceleration obtained from the load cells.

5 CONCLUSIONS

This study used a shake table experiment to obtain the force developed at the base of the model so that the dynamic response of the model can be predicted using the conventional equation of motion. A model with mass attached either at the base or at the top was used in the experiment. The model can thus be considered as a rigid model or an SDOF model with a natural frequency of 2 Hz. The models were excited by a shake table using harmonic excitation of 0.5 Hz. Load cells were used to measure the dynamic force developed at the interface between the model base and the shake table. The force induced in the model from a base excitation can be determined. The dynamic response of the model during excitation was also measured.

The results show that:

- In the case of a rigid structure, the force applied to a structure due to ground motion can be calculated using the acceleration at the base of the structure.
- For an SDOF structure, the force at the base of the structure will be influenced by the structural response. The base acceleration is not influenced by the structural response and thus cannot represent the dynamic load developed in the structure.
- Numerical results show that the equation of motion using the base acceleration to obtain the applied force cannot predict the response of a structure.
- In the case when the force at the base of the structure was used, the equation of motion can give a much better prediction of the dynamic response of structures.

6 ACKNOWLEDGEMENTS

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