SHAKE TABLE TEST OF EARTHQUAKE LOADING OF STRUCTURES

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ABSTRACT

In the calculation of structural responses to an earthquake loading, the equation of motion is commonly applied. An equivalent load is used. This load is assumed to be the product of the ground acceleration and the mass of the structure, while the structure is assumed to be fixed to a rigid support. However, this assumption is only valid if the structure is rigid. Depending on the bending stiffness and geometry of the structure as well as the frequency content of the excitation, the load can be different from the equivalent load. This work experimentally investigated the development of the actual load in a structure during earthquakes. Shake table experiments were performed on a structure model using simulated ground excitations. A total of three models were considered. The acceleration at the footing of the structure was recorded using accelerometer. The force transmitted from the shake table to the structural footing was measured by the load cells or calculated using the acceleration recorded. The results show that the force measured using the load cells can be different from that calculated using the measured acceleration.

Keywords: Computation of structural response; Shake table experiment; Transmission of seismic force; Earthquake load

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 newest 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 newest design specifications. In multiple buildings, damage to exterior cladding were also observed that posed a potential threat to people in the walkways.

Multiple causes of structural damage have been identified. One possible cause, i.e. the uncertainty resulting from the influence of the supporting ground have 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 seismic 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

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an absence of the structure (Qin and Chouw, 2017, Qin et al., 2018). In reality, not only the existing structure has an influence on the development of the ground movements, but also the adjacent structures. 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 considered the effect of clustered structures can be beneficial or detrimental. Observations from major earthquakes, including those from the 2010-2011 Canterbury earthquakes, have identified significant influences that the behaviour of soil can have, on the overall seismic performance of SFS systems. This SFS systems become even more complicated, 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 the 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 ground acceleration times the mass of the structure. The influence of the soil support on the actual ground movement and on the structure as well as the effect of the structural properties on the development of the load are ignored. In this current conventional approach the seismic load is assumed to be independent of the structure considered.

In the simplest case of single degree-of-freedom (SDOF) system the forces acting on the system is given in Equation (1) (Clough and Penzien, 1993). These forces represent the restoring forces due to stiffness, energy loss represented by a viscous damper and the inertia force due to the absolute acceleration of the assumed lumped mass.

\[ ku + cv + m(a + a_I) = 0 \]  

where \( k \), \( c \) and \( m \) is the stiffness, the coefficient of viscous damper and the mass of the structure, respectively. \( u \), \( v \) and \( a \) is the horizontal displacement, velocity and acceleration, respectively, and \( a_I \) is the acceleration of the ground movement. The load is then defined as the product of the mass \( m \) and the acceleration \( a_I \) acting on the mass while the SDOF system is assumed to be fixed at the support.

This common approach clearly oversimplifies the actual loading, because no matter how flexible the structure is, the load is defined as the structure is rigid, i.e. the whole structure will always moves like the ground. Consequently, the whole structure will experience the same acceleration, i.e. the ground acceleration. The structural response has no influence on the load. This means the load will remain the same as long as the structures considered have the same mass \( m \).

Since the response of a structure can only be as accurate as the assumption of the load, no matter how accurate the structure is modelled, this oversimplification of the load can have a severe consequence for the estimated structural response. Investigations have been performed by a few of researchers. Todorovska and Lee (1989) and Zhang et al., (2011) formulated e.g. a finite difference approach based on wave equation to determine the dynamic response of structures. Osinga (2016) developed a formulation to calculate the dynamic response of structure with nonlinear behaviour. However, a reasonable determination of the seismic load is still not well understood.

In this study shake table experiments have been performed to determine the horizontal force transmitted from the ground movement to the structure. A preliminary result is presented. A comparison between the force measured in the experiments and that calculated from the measured horizontal acceleration and the mass of the structure will be discussed.

2. METHODOLOGY

Shake table experiments was performed. The footing of the SDOF model has a size of 1.0 m x 0.7 m and a total height of 1.2 m. The model was made of steel sections. The footing can be assumed rigid. The total mass of the SDOF model without an additional mass was 36 kg.

To investigate the influence of the activated inertia mass pieces of 30 kg each were attached to the
footing and to the top of the model. Table 1 shows the mass arrangement. In Cases 1 to 3 considered, the masses were attached at the footing of the model. Because there was not top mass, the model can be assumed rigid. In Cases 4 to 6, the masses were attached at the top of the model, simulating three different SDOF models. The preliminary results presented in this paper focus only on the forces obtained from Cases 1 to 3.

Figure 1 Set-up of rigid beam and footing of a SDOF structure on the shake table
The seismic force was defined as the horizontal force transmitted from the shake table to the footing of the model while responding to the shaking. Two rigid beams were fixed on the shake table perpendicular to the direction of the shaking. The beams claimed the model footing in the direction of the excitation. Therefore, sliding of the model can be avoided and the model was excited by the horizontal force generated from the rigid beam. Four load cells were place between the rigid beams and the footing (Figure 1(a)). The horizontal force generated from the rigid beam that excited the model can be measured by the load cell. It was necessary to avoid friction forces developed at the footing-shake table interface so that the model was excited with the force generated from the rigid beam only. To realize this condition rollers were placed on the rails under the model footing so that the friction force developed at the footing-shake table interface can be avoided (Figure 1(b)).

A laser displacement transducer was used to measure any possible relative movement between the rigid beam and the footing in the direction of the excitation. Two accelerometers were used to measure the horizontal acceleration at the footing and at the shake table during the experiment. The horizontal displacement and acceleration at the top of the model were also measured using laser transducer and accelerometers, respectively (Figure 2). The excitations used were harmonic excitations and artificial excitation simulated based on Japanese design spectrum for a hard soil condition (Chouw and Hao, 2005).

Figure 2. Instrumentation at the top of the model

3. RESULTS AND DISCUSSION

For rigid models (e.g. Case 1 and Case 2), the horizontal force that excited the model can be calculated

<table>
<thead>
<tr>
<th>Case</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of masses on the footing</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of masses at the top</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
using the mass at the footing and the acceleration of the table (a) measured by an accelerometer. Figure 3 compares the horizontal force measured by the load cells and that calculated force using mass and the table acceleration. The dotted line represents the result from the calculated force and the solid line shows the measurement of the load cells. The results show that at the beginning of the excitation (up to 2 s in Figure 3), the calculated result and the measurement matched well. However, as the excitation increased (beyond 2 s), the measured force was slightly larger than the calculated force.

Figure 4 shows the comparison between the measurement and the calculated result of Case 2 (i.e. 2 masses were added). Because additional masses were attached, the horizontal force between the footing and the rigid base increases. With additional masses, the calculation still matches the measurement well at the beginning of the excitation (i.e. before 2 s). When the amplitude of the excitation increased (beyond 2 s), the measured force was greater than the calculated force. Similar observation can be made when Case 3 was considered (Figure 5).

It is shown that when the excitation is relatively small, the horizontal force developed at the footing can be obtained using the mass of the footing and the horizontal ground acceleration. However, when the excitation increased, this calculation underestimate the horizontal force. The results show that the structural response during an earthquake cannot be calculated accurately using the ground acceleration and the structural mass.

![Figure 3. Comparison of calculated and measured horizontal force for no additional mass](image)

![Figure 4. Comparison of calculated and measured horizontal force for two additional masses](image)
The difference between the measured and the calculated force can be obtained using Equation (2).

\[ \Delta(t) = \text{Abs}(F(t) - m \times a_t(t)) \]  

(2)

Figure 6 shows \( \Delta(t) \) when different structural masses are considered. Over the excitation, the larger the structural mass, the greater the difference between the experimental measured force and the calculated force. The results show that the difference does not depend on the amplitude of the structural response. As can be seen from Figures 3 to 5, the maximum force measured took place at the 4.5 s of the excitation. The maximum \( \Delta \) in Cases 1 and 2 took place at around the 8th s and the 9th s, respectively.

Figure 6. Absolute difference between the calculated and measured forces
4. CONCLUSIONS

This paper presents the preliminary results of an investigation using shake table experiments to reveal the actual loading of a SDOF structure by comparing the forces measured and the force obtained from conventional approach, i.e. mass times the ground acceleration. The rigid models considered had different masses. Load cells were used to measure the force generated from the shake table to the models during excitation. The excitation used were simulated excitation based on Japanese design spectrum for a hard soil condition. In all cases considered, the results show that when the horizontal ground acceleration was small the calculated force developed at the model footing using the table acceleration match with the force measured by the load cells. However, when the amplitude of the ground acceleration increased, the calculation underestimate the force generated from the ground.

5. ACKNOWLEDGMENTS

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