Effects of underground structures on amplification of seismic motion for sand with varying density

Osama Abuhajar, Hesham El Naggar & Tim Newson Geotechnical Research Center, University of Western Ontario, London, Ontario, Canada



ABSTRACT

Kinematic interaction of underground structures can alter the ground input motion parameters. In this paper, the effect of box culverts on ground input motion is investigated with scaled physical modelling in a centrifuge. The centrifuge experimental program was executed to evaluate the ground input motion with different surface cases in dry Nevada Sand at different relative densities at 60g. Three earthquakes with different amplitudes and frequencies were applied. The results show that the presence of structures can cause up to 50% reduction in the free field Peak Ground Acceleration when compared to the structure field. This observation can be helpful when assessing the seismic hazard or evaluating the input ground motion for buildings overlying significant underground structures (e.g. culverts or tunnels).

RÉSUMÉ

L'interaction de cinématique de structures souterraines peut changer les données de sol font signe des paramètres. Dans ce papier, l'effet de buses de boîte sur le sol mouvement d'entrée est examiné avec le modelage physique gradué dans un centrifugeur. Le centrifugeur programme expérimental a été exécuté pour évaluer le sol le mouvement d'entrée avec les cas de surface différents dans le Sable de Nevada sec aux densités relatives différentes à 60g. Trois tremblements de terre avec les amplitudes et les fréquences différentes ont été appliqués. Les résultats montrent que la présence de structures peut causer jusqu'à 50% réduction dans l'Accélération de Sol de Sommet de champ libre quand en comparaison du champ de structure.

1 INTRODUCTION

Kinematic interaction results from the inability of the structural system to conform to the deformations of the free field motion. In free field, the ground motion is not influenced by the presence of a structure. The kinematic interaction causes the motion of the base of the structure to deviate from the free field motion. This concept generally applies when comparing the free field input motion with the motion underneath the base of an embedded foundation or a structural system. Kinematic interaction of underground structures can alter the ground input motion parameters and may introduce additional vibration modes to structures (Kramer, 1996). Evaluating these effects can be helpful when assessing the seismic hazard for existing buildings or the input motion parameters for performance-based design.

In this paper, the kinematic effect of underground square box culverts on the ground input motion parameters was investigated in an experimental study using centrifuge modeling. The experimental program was conducted at the Rensselaer Polytechnic Institute (RPI) centrifuge facility in Troy, NY, USA. The tests involved evaluating the ground input motion in the free field as well as the structure field. Dry Nevada sand was used in these tests for a range of relative densities. Three different earthquake time histories were used to examine the effect of amplitudes and frequencies. For the purpose of comparison, three ground surface load cases were adopted. The first case was purely self weight loading from the overlaying sand. The second case was a strip foundation directly above the culvert position. The third case was a rectangular foundation overlying the square

culverts. All of the simulated shakings were executed at a 'g' level of 60g.

2 EXPERIMENTAL METHOD

2.1 Box Culvert Model

Buried culverts and conduits are commonly used in transportation infrastructure, e.g. to span highways. These are also used to control water flow, storm runoff, divert municipal services, allow vehicular access and for other related activities. The geometry of these structures is usually circular or rectangular in cross-section and can have single or multi celled openings. In this research, a reinforced concrete square box culvert was selected for centrifuge testing. In general, box culverts are constructed from short sections of reinforced concrete, which are joined together to form the final desired cross-section. After investigating the dimensions of box culverts used in practice, a square aluminum tube with a 76 mm side length was chosen to represent a 4.5 m culvert at 60g in the centrifuge tests.

The centrifuge model material can be different from that of the prototype provided the correct scaling law is used to ensure proper modeling of structural deflection. Past researchers have used different materials to model the behaviour of reinforced concrete box culverts, such as mild steel (Stone et al., 1991) and aluminum (Stone and Newson, 2002). This is due to the difficulties involved in constructing model culverts from a micro-concrete aggregate with appropriate reinforcement. The scaling law for stiffness is given by Eq. 1:

$$E_m I_m = \frac{E_p I_p}{n^4}$$
[1]

where, E = Young's modulus of the material, I = second moment of area per unit length of the material and n = scaling factor. The subscripts 'm' and 'p' refer to model and prototype, respectively. The relationship between the model and prototype wall thickness can therefore be evaluated using Eq. 2:

$$t_p = n t_m a^{1/3}$$
 [2]

where t = wall thickness, and $a = E_m/E_p$.

Based on these requirements, the model culvert (shown in Figure 1) was made from an aluminum square section with an external dimension of 76.2 mm (3 inch) and two wall thicknesses; thick walled t = 6.35 (1/4") and thin walled t = 3.18 (1/8") mm.

2.2 Centrifuge Model Tests

The centrifuge model testing was conducted at the RPI centrifuge facility. The centrifuge test procedure started with placing the sand into a rectangular rigid box with dimensions of 863.6 mm long x 381 mm wide x 355.6 mm high. Three sides of the centrifuge box were made of waffle shaped aluminum and the fourth front side was a thick plexiglass to enable visualisation of the model as shown in Figure 2.

Dry 120-Nevada Sand was used for all tests. This is a uniform sand classified according to USCS as a poorly graded sand (SP) with a d_{10} = 80 µm and maximum and minimum densities of 1.71 and 1.51 g/cm³, respectively.

To achieve the required relative densities, Nevada Sand was placed in layers by air pluviation for 50% relative density, while for 90% relative density each sand layer was tamped after air pluviation. Figure 3 shows a schematic diagram of the centrifuge model including the box culvert with the surrounding sand layers. 127 mm sand layers were placed underneath the box culvert and 76 mm sand layers on both sides of the culvert, which had the same height as the culvert, and then further 127 mm sand layers over that. This created the total height of the model of 330 mm

The box culvert model was instrumented with various sensors to achieve the overall objectives of the study. In this paper, only the accelerometers will be discussed, which were placed inside the sand and around the culvert to measure the change in the acceleration time history during shaking as shown in Figure 3. As shown in Figure 3, the accelerometers Ac2, Ac3, Ac4, Ac5 and Ac6 were used to measure the horizontal acceleration time history inside the sand body along a vertical section away from the structure (box culvert). This was assumed to be the Free Field (FF) condition. On the other hand, the accelerometers Ac7, Ac8, Ac9, Ac12, and Ac13 were used to measure the horizontal acceleration time history along a vertical section in the area of the box culvert, and

therefore, were defined as the Structure Field (SF) condition.



Figure 1. Box culvert models.



Figure 2. Photo of completed model.

In each of the tests performed, a set of accelerometers were placed outside the centrifuge box and on the shaker as shown in Figure 3, to ensure that the demand and the actual accelerations at the base of the centrifuge box model were the same. After finishing the process of building the model, a one-dimensional shaker was placed on the centrifuge platform and then the centrifuge model box was placed over it. All sensors used in the model, including the accelerometers, were checked and connected to the data acquisition system.

The centrifuge was then accelerated incrementally and held at the following acceleration levels, 10g, 20g, 30g, 40g, 50g and 60g to check stability of the sensor readings. At 60g, all of the earthquake signals were sent to the shaker. Data from the accelerometers were recorded continuously during the test.



Figure 3. Schematic diagram for centrifuge tests. (a) No foundation, (b) With foundation. (All units are in mm)



Figure 4. One Dimensional Box Shaker.

Each test included three cases. Case 1: with sand only, Case 2: with a surface strip foundation positioned right over the box culvert location, and Case 3: with surface rectangular foundation centrally positioned right over the box culvert location.

2.3 Earthquake Records

Figure 4 shows the one-dimensional shaker that was used to apply the earthquake records to the centrifuge box model. The shaker is a mechanical system with a displacement- controlled actuator, and does not directly accept acceleration time histories of earthquake records as input. Therefore, all earthquake records were scaled to voltage, and sent to the shaker as an electric signal. The response of the shaker to this signal will be in the form of displacement that can be measured using an LVDT (Linear Variable Differential Transducer). To make sure that the voltage signal sent to the shaker gave the best match to the earthquake record, an accelerometer was connected to the shaker to monitor and record the acceleration time history and then compare it to the original earthquake record. Additionally, the displacement recorded by the LVDTs were compared to the displacement time history calculated by double integrating the acceleration time history recorded from the shaker. It is also important to compare the acceleration time history recorded from the shaker and that of the base of the centrifuge box, which will be considered as the earthquake record applied to the tested model.

To ensure that all the earthquake records used in these tests have the best match in terms of the amplitude and frequency, a dummy test was conducted before starting the actual tests. In the dummy test, an equivalent model was built and subjected to all earthquake records with different amplitudes. The results of the dummy test were used to establish a relationship between the voltage values and the amplitudes recorded to establish the values of voltage that give the required level of shakings.

Three different earthquakes with different amplitudes and frequencies were adopted for use in these series of tests. The three earthquakes were: the Kobe earthquake (North-East component of the Port Island down hole array -79 m record), Western Canada, and Vancouver Cascadia Subduction (Artificial records corresponding to 2% probability of occurrence in 50 years). The predominant frequencies of these earthquakes are 1.453, 0.647, and 0.464 Hz, respectively. It was challenging for the shaker to provide an exact match for the original shapes of these earthquakes and therefore a process of filtering and trial and error was applied on the dummy model until a good match was found between the filtered records and the response at the base of the centrifuge box model. The final shapes of the filtered earthquakes that were used in all of the tests are shown in Figure 5. In Figure 5, all records were scaled to 0.1g. However, the records were scaled up to 0.2g and 0.3g for different tests.

Another important aspect that might affect the results obtained from the accelerometers used in the centrifuge tests was the effect of centrifuge box boundaries. Since the box used in the tests was rigid, the effect of boundary was investigated during the dummy test. Several accelerometers were distributed inside the sand at the same elevation and different distances from the boundary, and also on the centrifuge box to examine the boundary effect. The recorded acceleration time histories from all accelerometers within the soil bed were checked and compared. The results showed that there was no effect for the boundary on the results. The acceleration time history recorded from the accelerometers that were positioned at the same elevation and at different distances from the box side gave almost the same results. It should be noted that the closest accelerometer to the box side was placed at 3mm from the sides of the centrifuge box. It should also be noted that the box walls were not very thick (7 mm model scale or 420 mm at 60g).

3 TEST RESULTS

Large amounts of data were generated in each centrifuge run. Consequently, for the purposes of this paper, the results from one earthquake will be reported in detail showing the effect of change in soil density on the results for all of the test cases. The results for the Kobe earthquake (KEQ) will be presented here showing the effect of the presence of box culvert structure inside the sand body on the values of Peak Ground Acceleration (PGA) with depth. Four test groups were performed as part of this study as demonstrated in Table 1. Three different test cases were considered within each test group as shown in Table 2. The three cases are: Case A represents the effect of the self weight of the overlaying sand only, Case C is same as Case A but with adding a strip foundation on the surface directly above the culvert, and Case D is same as Case C but replacing the strip foundation with a rectangular one at the middle of the model surface. It should be noted that Case B involved static loading and is not discussed here. Each of the test cases shown in Table 2 was subjected to three earthquake records at different amplitudes.

The results from all test cases were repeatable and a typical result for the change in PGA with the depth of soil profile is shown in Figure 6. Figure 6 shows the results from Test 2 (Case C) at 0.2g base acceleration. It is clearly noted from Figure 6 that the PGA values of the SF, where the box culvert was buried in the middle, decreased in comparison with the sand model representing the FF condition, where there is no structure buried inside the sand. The results obtained demonstrate that the reduction in the amplification of the PGA values due to the presence of structure is a function of the earthquake amplitude at the base of the model. As the PGA of the earthquake at the base of the model increased, the reduction in PGA increased (i.e. the effect of structure is more pronounced). These repeatable results show clearly the kinematic effect due to the presence of the rigid culvert structure inside the sand body. For the FF condition, the sand response is consistent with the well established behaviour of soil profiles demonstrating an amplification of response (i.e. higher PGA values) as the seismic waves propagate towards the surface. Meanwhile, the SF response is affected by the presence of the relatively rigid structure. As the propagating seismic waves hit the relatively rigid structure of the culvert box, which can not conform to the



Figure 5. Earthquake time histories.

Table 1: Centrifuge Tests:

Test No.	Culvert	Relative Density (%)
Test 1 (T1)	Thick	90
Test 2 (T2)	Thick	50
Test 3 (T3)	Thin	50
Test 4 (T4)	Thin	90

Table 2: Centrifuge Test Cases:

Test No.	Test Case
T1A, T2A, T3A, T4A	Sand surface alone
T1C, T2C, T3C, T4C	Strip foundation on surface
T3D, T4D	Rectangular foundation on surface

movement of the deformable body of sand, the amplitude of the seismic wave is decreased. Hence, the amplitude of the seismic wave in the SF will be reduced relative to that of the FF, leading to the observed reduction in the PGA values.

For the purpose of comparing the PGA values at the base with that at the surface, the results of Tests 1 and 2 are compared as well as the results of Tests 3 and 4, since each group has the same culvert thickness. The PGA values in the FF condition and that at the SF condition for Tests 1 and 2 are compared in Figure 7, while the results for Tests 3 and 4 are presented in Figure 8. Generally, it is clear from the results shown in Figures 7 and 8 that there is a reduction in the peak ground acceleration at the SF condition compared to the PGA at the FF condition. The percentage decrease in peak ground acceleration of the SF condition was larger as the PGA of the acceleration time history at the centrifuge box base is increased.

Inspecting the results for case A, where there is no foundation on the sand surface, it is noted that the reduction in PGA values is similar for all ground shakings. The same observation applies to case C where there is a strip foundation on the sand surface, but the reduction in case C is larger than that for case A. The variation of results between cases A and C clearly demonstrates the effect of kinematic interaction in the case of the strip foundation. As case D had a small rectangular foundation on the sand surface, the kinematic interaction effect was less significant as can be noted from the results in Figure 8, which shows that the reduction in PGA is between the results of case A and case C.

To explore the effect of sand density on the PGA values, Figure 7 compares the results of Tests 1 (sand relative density = 90%) and Test 2 (sand relative density = 50%). On the other hand, Figure 8 compares the results of Test 3 (sand relative density = 50%) and Test 4 (sand relative density = 90%). Tests 1 and 2 involved the thick box culvert while Tests 3 and 4 involved the thin box culvert.

For the SF condition in cases A and C, the PGA is close for the 50 and 90% sand relative densities, while the FF condition is different. The values of PGA for the 50% relative density are higher than the 90% relative density values. This is expected since the loose sand causes more amplification for the PGA than the 90% case.

Comparing the cases A and C with case D shown in Figure 8, it is noted that the SF in case D is also changing with the relative density. In case D, the 50% relative density gave a wider range than the 90% relative density PGA values when comparing the FF and SF conditions. Even though the 50% relative density FF PGA values is higher than the 90 % relative density case, the opposite is happening in the SF PGA values. This shows the kinematic interaction effect for the foundation on the surface in addition to the box culvert buried in the sand. In cases A and C, the surface of sand is either clear or has a large strip foundation over the width of the centrifuge box, while in case D, the sand surface was covering all of the area except for a small part over the middle of the sand surface.



Figure 6. Change in PGA with depth.



Figure 7. Comparison between Free Field and Structure Field from Tests 1 and 2. ($t = 6.35 \text{ mm} (1/4^{"})$)



Figure 8. Comparison between Free Field and Structure Field from Tests 3 and 4. (t = 3.18 mm (1/4"))

The results presented in Figures 7 and 8 are for the Kobe earthquake, which has a predominant frequency of 1.453 Hz. The results show that for 0.3g base acceleration, the reduction in PGA at the surface and between FF and SF is around 50%. So if the PGA at the base is increased, this percentage might increase more than 50%.

4 CONCLUSIONS

This paper describes a series of centrifuge tests conducted at the RPI centrifuge facility to examine the kinematic soil-structure interaction effects. In general, the results showed that the effect of the presence of structure buried inside the soil is to decrease the ground input motion by a considerable amount. This is due to the interference of the relatively rigid structure with the propagation of the seismic waves and its inability to conform to the soil movements. This has led to the reduction in PGA values in the SF in comparison with FF. The effect of sand density on the amplification of PGA values was clearly observed in the FF condition, while it was not as significant in the SF condition.

The amplitude of earthquake at the base of the model is an important factor in determining how much reduction happens in the PGA at the ground surface in the Structure Field compared to the Free Field. As the amplitude of an earthquake increases, the reduction in PGA increases. Also, the kinematic interaction effect is pronounced for input motions with PGA values exceeding 0.1g. This means that the presence of buried underground structures will have minimal kinematic interaction effect if the earthquake has a PGA less than 0.1g.

The observations made in this study can be helpful when assessing the seismic hazard for existing buildings overlying significant underground structures (e.g. box culverts or tunnels). It can also be helpful when evaluating the input ground motion for the purpose of performance based design of buildings overlying significant underground structures.

ACKNOWLEDGEMENTS

The authors would like to express their sincere appreciation to the support from the NEES program and the help of the staff of RPI Centrifuge centre. In particular, the help of Drs. Tarek Abdoun and Inthuorn Sasanakul is much appreciated.

REFERENCES

Kramer, S.1996. *Geotechnical Earthquake Engineering*.1st ed. Prentice-Hall, Inc. Upper saddle River, NJ, USA.

- Stone, K.J.L., Hensley, P.J. & Taylor, R.N. 1991. A centrifuge study of rectangular box culverts. *Centrifuge 91*, Balkema, Rotterdam, pp. 107-112.
- Stone, K.J.L. & Newson, T.A. 2002. Arching effects in soil-structure interaction. 4th Int. Conf. Physical Modelling in Geomechanics, St. Johns, Newfoundland, pp. 935-939.