Performance evaluation of Equivalent Shear Beam (ESB) model container for dynamic geotechnical centrifuge tests

Dong-Soo Kim, Sei-Hyun Lee & Jeong-Gon Ha
Department of Civil and Environmental Engineering, KAIST, Daejeon, Korea
Joo-Hyun Seong & Soo-Hyung Jung
Korea Infrastructure Safety & Technology Corp, Seoul, Republic of Korea

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ABSTRACT
An ESB (equivalent shear beam) model container was built with a stack of light-weighted aluminum frames separated by rubber to have the similar dynamic stiffness and natural frequency with the inside soil model. In this paper, a significant number of dynamic centrifuge tests and the corresponding seismic response analyses were performed to evaluate the dynamic performance of the ESB model container. From the results, it appears that the end walls of ESB model container behave in accordance with the behaviors of the soil deposit although there is a difference of natural period depending on the relative density of the sand deposit. This is attributed to the heavier mass and the corresponding higher inertia of the inside soil model relative to the end walls. However, for incompletely filled soil model in the model container, significantly different seismic responses are observed in the end walls and the soil deposit due to seismic interaction caused by upper unfilled frames of the container. These findings suggest that dynamic model tests using the ESB model container should be conducted with the completely filled soil models in the container.

RÉSUMÉ
Un conteneur ESB modèle (cisaillement équivalent) a été construit avec une pile de cadres en aluminium très léger séparés par de caoutchouc pour avoir la rigidité similaire dynamique et la fréquence naturelle avec le modèle de sol à l'intérieur. Dans ce papier, un nombre important de tester des centrifugeuses dynamique et les analyses correspondantes réponse sismique ont été réalisées pour évaluer les performances dynamiques du conteneur de modèle ESB. A partir des résultats, il semble que les murs d'extrémité de l'ESB modèle de conteneur se comportent en conformité avec les comportements du dépôt de sol bien qu'il y ait une différence de période naturelle en fonction de la densité relative du dépôt de sable. Ceci est attribué à la plus lourde masse et l'inertie correspondante supérieur du modèle sol à l'intérieur par rapport aux parois fin. Toutefois, pour le modèle du sol incomplètement remplie dans le conteneur de modèle, sensiblement différentes réponses sismiques sont observées dans les parois d'extrémité et le dépôt de sol due à l'interaction sismiques provoquées par les cadres supérieurs vacants sur le conteneur. Ces résultats suggèrent que les tests de modèle dynamique à l'aide du conteneur de modèle ESB doit être menée avec les modèles de sol complètement rempli dans le récipient.

1 INTRODUCTION

In reduced-scale physical modeling using dynamic geotechnical centrifuge tests, accurate boundary conditions are required in order to create the same seismic behaviors with prototype semi-infinite soil layers in finite model containers.

Various types of model containers have been used for dynamic geotechnical centrifuge tests over the past three decades. In the early period of, rigid-walled model containers were used to construct soil models. However, in a model with rigid end walls, strain dissimilarity is caused between the model and the corresponding prototype, because the soil near the end wall is restricted from deformation. In addition, the interaction between the soil and end walls causes lateral compression and generates undesirable P-waves. The rigid end walls also reflect earthquake waves, and thus the combined vibrations of P- and S-waves are propagated vertically through the soil models (Zeng and Schofield 1996, Teymur and Madabhushi 2003).

Schofield and Zeng (1992) at University of Cambridge first designed an ESB (equivalent shear beam) model container, which was built with a stack of light-weighted aluminum frames separated by rubber to have the same deflection and natural frequency as the soil model. The ESB model container has flexible frictional end walls that have dynamic stiffness corresponding to that the inside soil model and hence they move together. However, according to the basic concepts of the ESB model container, various ESB model containers with different dynamic stiffness or various combinations of aluminum and rubber are required for modeling various types of soil conditions ideally. The dynamic stiffness of the soils is significantly affected by the initial void ratio and the effective stress depending on the g-levels and strain levels during base shaking. This is the reason why the usage of the model container is restricted to specific conditions where the soil stiffness is within a certain limited range. In addition, the ESB model container cannot satisfy the requirements when a gross decrease in soil stiffness occurs due to liquefaction. As explained above, the ESB model container has some limitations, but is broadly used for studying the seismic behaviors of geotechnical structures and soil-structure interaction problems. Therefore, the boundary effects of the ESB model container should be explicitly assessed to accurately model prototype structures and to quantify the seismic performance of the soil models with a variety of experimental situations.

In this paper, a significant number of tests have been performed to evaluate the dynamic performance of an ESB model container and to quantify the range of testable soil conditions. The tests were involved with an empty ESB model container for identifying its own seismic characteristics and with dry sand models constructed with different initial relative densities and soil deposit heights. Acceleration time histories at various depths and at locations of different distances away from the end walls were measured to assess and quantify the boundary effects of the model containers on seismic soil behaviors. All dynamic centrifuge test results were compared through one-dimensional site response analyses to ensure the reliability of the test results.

2 TESTING EQUIPMENTS

The dynamic geotechnical centrifuge facility at KAIST was used to perform the experimental studies. An electro-hydraulic earthquake simulator is mounted on the centrifuge, which has an effective radius of 5 m and a maximum capacity of 240 g-tons and used to simulate a one-dimensional prescribed base input earthquake motion. The base shaking acceleration can be exerted to a maximum value of 20gh with a maximum payload of 700 kg, which corresponds to 0.5gh in prototype scale at 40gc centrifugal acceleration. The dimensions of the payload platform are 670 mm × 670 mm × 650 mm in length, width, and height, respectively.

The ESB model container at KAIST was formed by stacking 10 light-weight aluminum alloy rectangular frames on a base plate to create internal dimensions of 490 mm × 490 mm × 630 mm and external dimensions of 650 mm × 650 mm × 650 mm in length, width, and height, respectively. Each aluminum frame is 60 mm in height and is separated by inside ball bearings and rubber spacing layers. The ball bearing system permits single-axis movement parallel to the longitudinal axis of the container during base shaking and makes the dynamic stiffness of the rubber layers constant independent of the levels of centrifugal acceleration. A total of 9 rubber layers having roughly about 3 mm thickness each lead to discrete step-like deflection of the end walls. The rubber layers ensure sealing of the model container and shearing behaviors of the frames and inside soil models. The design concept is that the deflection of each frame matches that of the soil column at the middle of the frame. The increase in discrete deflection would cause discontinuity in the shear strain of soil near the end walls, but shear sheets attached on the end walls reduce this effect (Zeng and Schofield 1996). At KAIST, sand paper is attached on the end wall to provide approximately the same friction as the adjacent soil. The designation of sand paper used in this study is CC-80cw. The average grit diameter of the sand paper is 0.19 mm, which is similar to the median particle size (D_{50}) of the test material in this study.

3 EXPERIMENTAL CONFIGURATION

Table 1 gives a summary of the performed model tests and the soil conditions. The seismic characteristics of the empty ESB model container were evaluated for various input shaking acceleration levels, ranging from below 0.1gh to above 0.2gh at centrifugal accelerations of both 20gc and 40gc; this is designated as test E00-00. The natural periods of the container were deduced from spectral analyses of the responses of accelerometers attached on the end wall of each aluminum frame. The effects of the initial relative density and the height of sand deposit on seismic responses were studied by comparing the test results of E60-81 to those of E60-44 and E43-70, respectively. 1-D site response analyses were subsequently carried out for all test cases in order to verify the reliability of the test results.

Figure 1 shows a cross-section and a plane view of the ESB model container, the soil model, and instrumentation layout for models E60-81 and E60-44. Before model preparation, a pair of bender element arrays was placed on the base of the model container. Dry silica sand was poured into the ESB model container from a sand raining system at a constant falling height of 80 cm over the surface of the sand deposit to provide a fairly uniform specimen with the desired Dr. Different Dr values were achieved by varying the opening size and the traveling rate of the sand raining system. Accelerometers were embedded into the soil at pre-determined locations during model preparation. Five accelerometers, namely, from A1 to A5, were placed in three arrays, one on the inside of the end wall of the container (ESB), another at the middle of the soil deposit (Center), and the other 12 cm away from the end wall (Side). One accelerometer (A0) was attached on the outside surface of the bottom frame to measure the input base motion. Figure 2 shows a cross-section for model E43-70. Four accelerometers (A1 to A4) were placed in three arrays having the same locations as in E60-81.

Table 1. Summary of soil model and performed test conditions for each test case.

Test Cases	Model Height (mm)	D_r (%)	Prototype Soil Properties (20gc/40gc)		Input Shaking Acceleration (gh)	
			H (m)	T_G (m/s)	20gc	40gc
E00-00	-	-	-	-	0.117-0.293	0.089-0.210
E60-81	600	81	12/24	0.26/0.41	0.092-0.375	0.089-0.203
E60-44	600	44	12/24	0.31/0.46	0.106-0.311	0.054-0.245
E43-70	430	70	8.6/17.2	0.21/0.35	0.082-0.280	0.072-0.292

The site period (T_G) for each test case were estimated from the thickness of the soil layer and the shear wave velocity profile (V_S-profile) obtained from bender element tests before shaking at the testing centrifugal accelerations or from RC (resonant column) tests using soil samples remolded in laboratory.

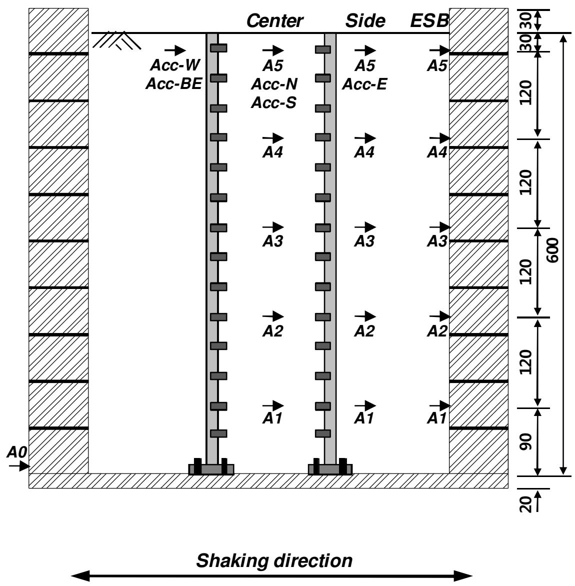


Figure 1. Soil models and instrumentation layouts for test cases of E60-81 and E60-44

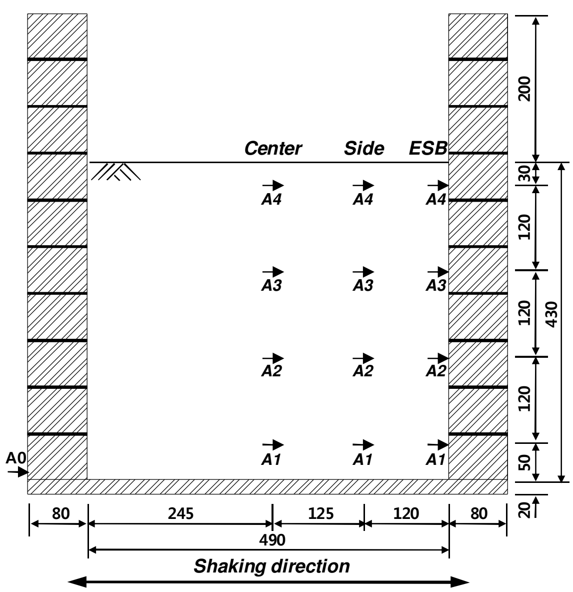


Figure 2. Soil models and instrumentation layouts for test case of E43-70

In this study, all models were successively tested at centrifugal accelerations of 20gc and 40gc. The Northridge earthquake, which occurred on January 17, 1994 in California, was used for the input base motion. In advance, the earthquake data was calibrated according to scaling rules (Taylor 1995). The calibrated input base motion was gradually loaded from small to large amplitude based on the ranges of shaking acceleration given in Table 1.

4 TEST RESULTS AND DISCUSSIONS

4.1 Test Case E00-00: Empty ESB Model Container

Test case E00-00 was performed to evaluate the natural period (or frequency) of the ESB model container itself at testing centrifugal accelerations of 20gc and 40gc. The response spectra on the end walls of the top and bottom frames were calculated from the acceleration time histories for some shaking events. Figure 3 shows the RRS (ratio of response spectra) or the transfer function at both 20gc and 40gc, obtained by normalizing the response spectra on the top frame by those on the bottom frame. It is noted from the figure that the maximum RRS values occurred at a period of 0.2 s and 0.4 s regardless of the shaking acceleration for 20gc and 40gc, respectively. This indicates that the KAIST ESB model container has a natural period of 0.01 s (or natural frequency of 100 Hz) according to the scaling rule. The value is similar to that of the ESB model container at University of Cambridge (i.e. 98 Hz, calculated by Butler (1999), and 105.3 Hz, measured by Madabhushi (1994)).

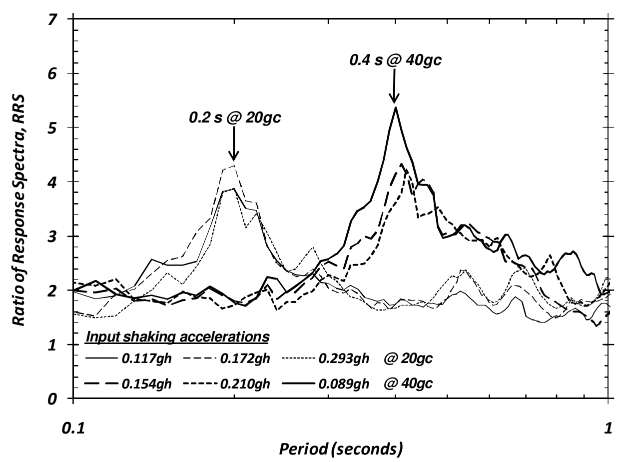


Figure 3. Ratio of response spectra (RRS) for some shaking events at test case of E00-00

4.2 Test Case E60-81: H=60cm, D_r=81%

Figure 4 compares typical PGA (peak ground acceleration) measured at the three accelerometer arrays for an event subjected to maximum shaking acceleration of 0.235gh at 20gc to those predicted using site response analyses. Site response analyses were performed for all shaking events using the 1-D equivalent linear procedure implemented in the computer program EERA (Bardet et al. 2000). The V_S-profiles and nonlinear dynamic soil properties (G/G_{max}-logγ and D-logγ) were used as input soil parameters for these analyses. The acceleration time traces recorded at the base of the model container (A0) were used as the input base shaking motions of the soil profile.

It can be seen from Figure 4 that there is good agreement among the experimental responses at all depths regardless of the array locations, and the numerical responses also show good agreement with the experimental responses. Thus the test results are considered to be reasonable and the ESB model container functions appropriately; that is, the end walls of the model container act as a shear beam having equivalent stiffness to the adjacent soil layers.

The PGA values measured at A5 (near surface) for the ESB and Side arrays and predicted by EERA are plotted with those measured at the same elevation for the Center array in Figure 5. The ranges of the corresponding maximum input base acceleration are also noted. In addition, the lines of 0, ±10, ±20, and ±30% variations relative to the PGA of the Center array are also plotted to quantify the boundary effects of the container. The line of 0% variations is the equality line. It is observed that the points for the ESB and Side arrays at both centrifugal accelerations exist mostly within -10% and 10% variations regardless of the location. Although one point in EERA shows roughly a 15% change at low acceleration range, the difference of absolute values of acceleration is insignificant.

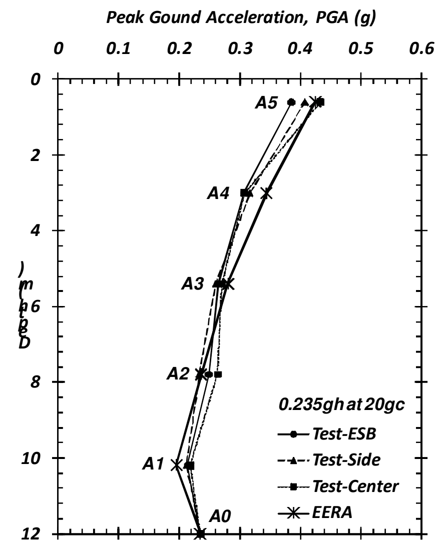


Figure 4. PGA with depth for input shaking acceleration of 0.235gh at 20gc in test case E60-81

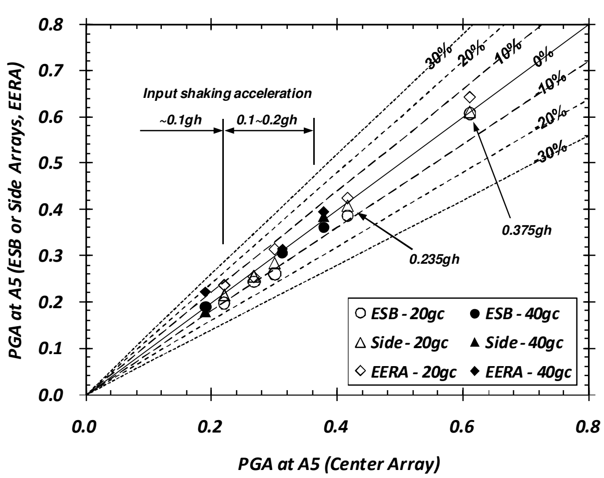


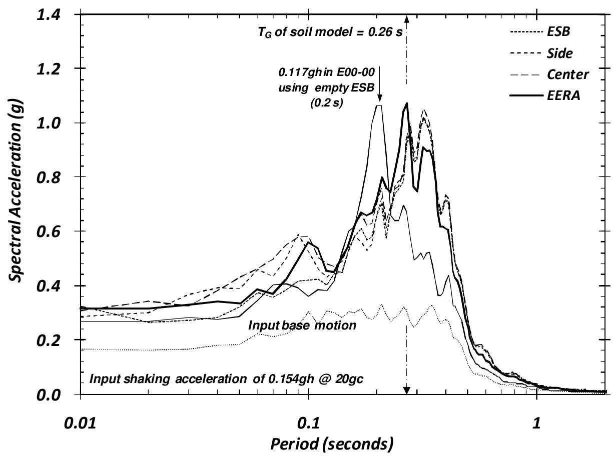
Figure 5. PGA measured at A5 of ESB and Side arrays and EERA against Center array in test case E60-81

It can be seen from Figure 4 that there is good agreement among the experimental responses at all depths regardless of the array locations, and the numerical responses also show good agreement with the experimental responses. Thus the test results are considered to be reasonable and the ESB model container functions appropriately; that is, the end walls of the model container act as a shear beam having equivalent stiffness to the adjacent soil layers.

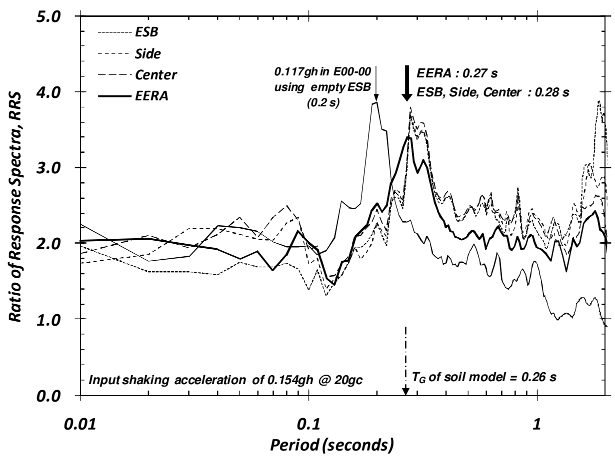
The PGA values measured at A5 (near surface) for the ESB and Side arrays and predicted by EERA are plotted with those measured at the same elevation for the Center array in Figure 5. The ranges of the corresponding maximum input base acceleration are also noted. In addition, the lines of 0, ±10, ±20, and ±30% variations relative to the PGA of the Center array are also plotted to quantify the boundary effects of the container. The line of 0% variations is the equality line. It is observed that the points for the ESB and Side arrays at both centrifugal accelerations exist mostly within -10% and 10% variations regardless of the location. Although one point in EERA shows roughly a 15% change at low acceleration range, the difference of absolute values of acceleration is insignificant.

The RS (response spectra) under a damping ratio of 5% for the input shaking acceleration of 0.154gh at 20gc and the corresponding RRS are shown in Figure 6. The RS for the acceleration measured at A5 (near surface) of the three arrays and at A0 (base of model container) were calculated and compared with the RS obtained from EERA and the RS of the empty ESB model container with 0.117gh at 20gc in test model E00-00. At 20gc, the natural period of the ESB model container was found to be 0.20 s in the previous section and the TG of the soil deposit was estimated to be 0.26 s, as listed in Table 1. The periods do not match with the difference of 0.06 s, and this difference is not accounted for by the basic concepts of the ESB model container. However, it is noted from Figure 6(a) that the spectral accelerations are equally amplified regardless of the accelerometer locations in a range of 0.25 – 0.30 s, which reflects the T_G of the soil model. This is clarified with the RRS in Figure 6(b). From this result, it appears that the soil layer and the end walls behave together during the earthquake excitation and the behavior of the soil layer leads that of the end walls. This is attributed to the heavier mass and the corresponding higher inertia of the soil deposit relative to the ESB model container. Note also that the RS obtained from EERA shows good agreement with the test results.

At 40gc, the natural period of the container and the T_G are almost identical at around 0.40 s. This is the ideal testing condition with the KAIST ESB model container. The amplifications of both the RS and the RRS for all recorded responses equally occur in the vicinity of T_G of the soil deposit, as expected, and they are also consistent with the EERA results. These results demonstrate that the ESB model container behaves properly in the dense soil condition with test model E60-81.



(a) Response spectrum



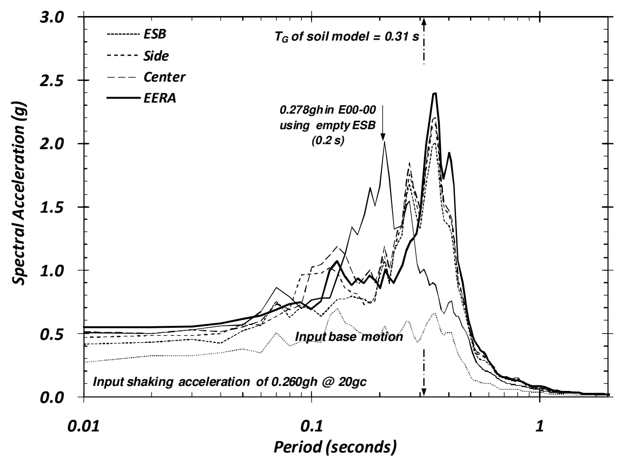
(b) Ratio of Response Spectra (RRS)

Figure 6. Spectral analysis for 0.154gh at 20gc in test case E60-81 and comparison with the test case E00-00

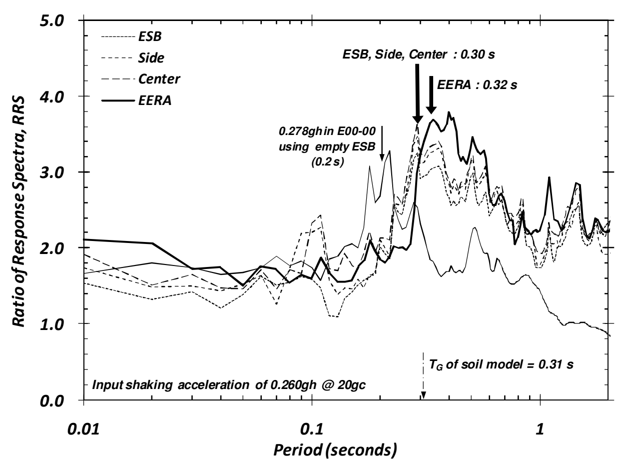
4.3 Test Case E60-44: H=60cm, D_r=44%

Test case E60-44 was performed to investigate the dynamic performance of the ESB model container for a loose sand deposit, which has considerable difference with the natural period of the container. The sand deposit prepared with D_r = 44% has a T_G of 0.31 s at 20gc and 0.46 s at 40gc in Table 1, respectively, and the corresponding differences with the natural periods of the container are found to be 0.11 s and 0.06 s. Figure 7 shows the typical RS and the RRS for shaking acceleration of 0.260gh at 20gc. The maximum spectral acceleration and RRS values at the soil as well as on the ESB end wall occurred close to the T_G of the test model in spite of the considerable period differences. This can also be attributed to the points of the heavier mass and the higher inertia force, as explained in the previous section. The mass of the ESB model container is 140 kg including the aluminum base plate of 20 mm thickness. The soil deposit inside the container is 201 kg, which is much greater than the mass of the end walls, although it corresponds to the loose soil condition. Therefore, it appears that the end walls behave in accordance with the behaviors of the soil deposit.

The PGA values measured using the accelerometers and predicted by EERA and the lines of percent variations are plotted in Figure 8. The points for the ESB, Side, and EERA are almost distributed within bounds of -15% to 15% irrespective of the input shaking acceleration. Although these values are more scattered than those of test model E60-81, the differences are not significant. From the observed results, we can infer that the ESB model container in this study functions appropriately for test model E60-44 and can be used for sand models in the whole range of relative densities as well as for compacted soil models, which are denser than sand models. However, further studies are required to investigate whether the ESB model container can be employed for tests using soft clay models.



(a) Response spectrum



(b) Ratio of Response Spectra (RRS)

Figure 7. Spectral analysis for 0.260gh at 20gc in test case E60-44 and comparison with the test case E00-00

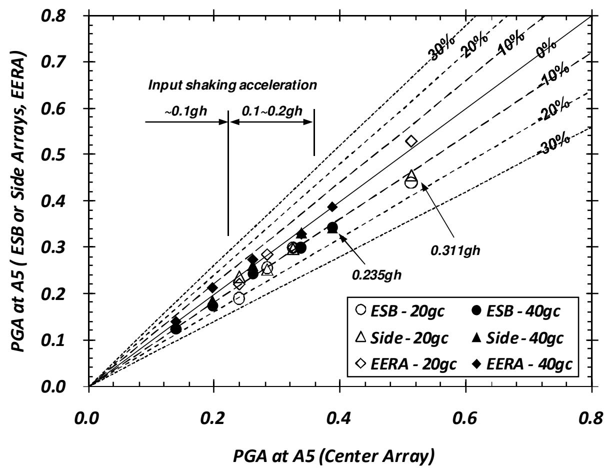


Figure 8. PGA measured at A5 of ESB and Side arrays and EERA against Center array in test case E60-44

4.4 Test Case E43-70: H=43cm, D_r=70%

In some cases we used soil models that incompletely filled the model container in order to simulate various kinds of prototype geotechnical structures and geological conditions. Test case E43-70 was performed to investigate the dynamic performance of the ESB model container filled about two-thirds full with sand and the effects of the upper unfilled frames on the seismic responses. Figure 9 shows the PGA values measured at the three accelerometer arrays and predicted using EERA for an event subjected to shaking of 0.169gh at 40gc. Unlike the previous results obtained for E60-81 and E60-44, there was considerable difference among the experimental responses measured at ESB, Side, and Center arrays and they are not consistent with the numerical responses given by EERA. Overall, the PGA values at the Center array are the largest, and those attached on the ESB end wall are the smallest. The difference increases as the depth for measurement is close to the surface. This trend is fairly consistent irrespective of the input shaking acceleration and testing centrifugal acceleration throughout the test case. It can be noted from Figure 10 that the PGA values measured at A4 for the ESB and Side arrays in Figure 2 are distributed below the line of 0% variation, which is an equality line, and the PGAs for the Side array are larger than those for the ESB array. This is more obvious in the results at 40gc. The PGA values predicted from EERA are mostly larger than those measured during shaking. The measurement data points are distributed throughout a range of 0% to -30% beyond and the EERA data points are distributed throughout a range of -10% to 30% beyond compared to the Center array. The data are greatly scattered compared with the previous test cases shown in Figures 5 and 8.

The sand deposit of test model E43-70 has a T_G of 0.21 s at 20gc and 0.35 s at 40gc, respectively. Although the model container was incompletely filled, the T_G values are close to the natural periods of the container, showing a difference of only 0.01 s at 20gc. The RS values were calculated using the acceleration time histories at A4 for the input shaking acceleration of 0.169gh at 40gc and shown in Figure 11. The periods at which amplifications at the measurement data occurred, differ significantly from the T_G of the test model, even considering degradation of the shear modulus of the soil during earthquake excitation.

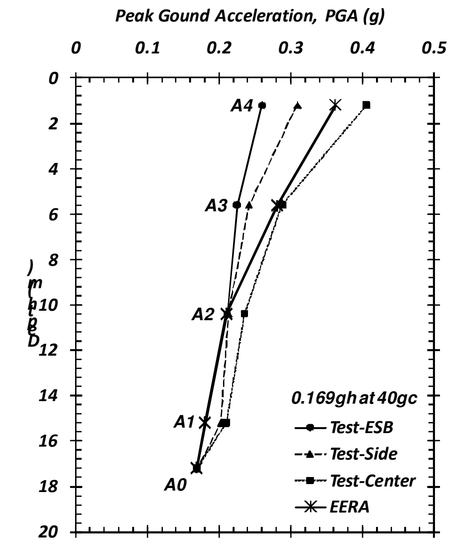


Figure 9. PGA with depth for input shaking acceleration of 0.169gh at 40gc in test case E43-70

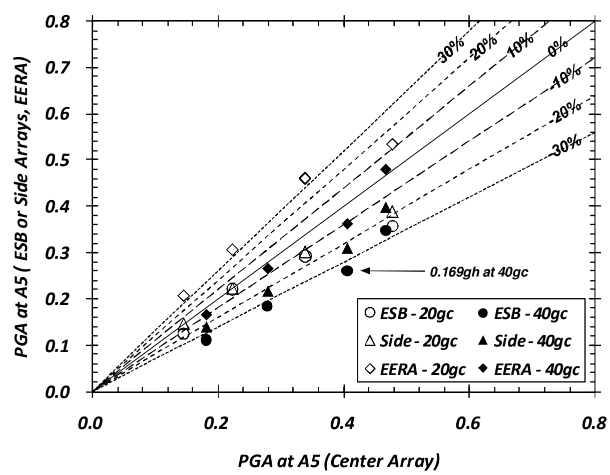


Figure 10. PGA measured at A5 of ESB and Side arrays and EERA against Center array in test case E43-70

In addition, there are significant differences in the values of spectral acceleration between the measurements and EERA. The values from EERA are greater than those from the measurements around the T_G of the soil model. An interesting observation is that undesirable low period (or high frequency) amplifications distinctly appeared in the Center and Side arrays around 0.17 s, which corresponds neither with the natural period of the ESB model container nor the T_G of the soil model. These are estimated by the seismic interaction caused by behaviors of the upper unfilled frames of the container during shaking. From the results, a prudent analysis is required when tests are unavoidably performed with incompletely filled soil models in the ESB model container. In addition, the results suggest that dynamic model tests using the ESB model container should be conducted with completely filled soil models in the container where possible, and in some cases even the level of centrifugal acceleration for simulating prototypes should be adjusted.

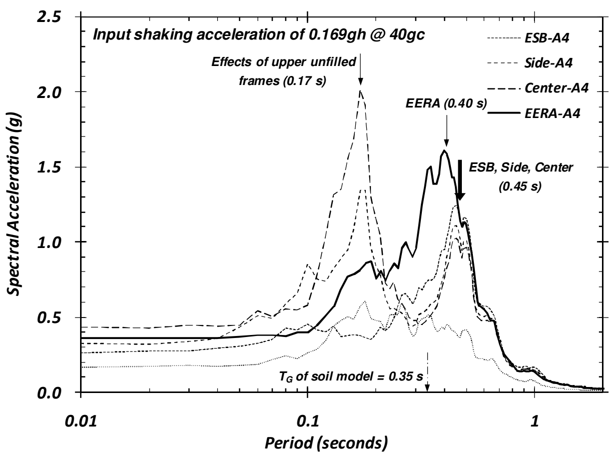


Figure 11. Response spectra for 0.169gh at 40gc in test case E43-70 and comparison with the EERA results

5 SUMMARY AND CONCLUSIONS

Empty ESB model container was excited to evaluate its natural period and it was estimated to 0.2 s and 0.4 s regardless of shaking acceleration for 20gc and 40gc, respectively, which means that the KAIST ESB model container has a period of 0.01 s (or natural period of 100 Hz).

In test case E60-81 (H=60cm, D_r=81%), the site period (T_G) of the soil deposit is consistent with the natural period of the ESB model container without significant discrepancy. As expected, the acceleration time histories and the corresponding response spectra at ESB wall, Side, and Center arrays have a good agreement at all depths and match well with the EERA results. Besides, the percent variations in PGA exist mostly within -10% and 10% variations regardless of the measurement locations. In test case E60-44 (ESB, H=60cm, D_r=44%), the loose sand deposit has the difference of maximum 0.11 s between the T_G and the natural period of the container. In spite of the considerable difference, the percent variations in PGA are mostly distributed within a range of -15% and 15%, and the maximum spectral accelerations in response spectra appear close to the T_G of the test soil deposit. These test results indicate that the ESB model container in this study functions properly for the sand models in the whole range of relative densities, that is, the end walls of the model container act as shear beam which has equivalent seismic responses to the adjacent soil layers.

However, in test case E43-70 (H=43cm, D_r=70%) involving incompletely filled soil model in the model container, there are considerable differences among the acceleration time histories measured at ESB, Side, and Center arrays, and the PGA values are greatly scattered over 30% variations. Besides, in the response spectra, the periods at which maximum amplifications occur, differ significantly from the T_G of the test model, and undesirable amplifications additionally appear in low period ranges neither the natural period of ESB model container nor the T_G of the soil model. It is estimated by the seismic interaction caused by behaviors of the upper unfilled frames of the container during shaking. The results suggest that dynamic model tests using the ESB model container should be conducted with completely filled soil models in the container.

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