Large-scale Experiment using E-Defense on Dynamic Behaviors of Underground Structures during Strong Ground Motions in Urban Areas

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LISBOA 2012

SUMMARY:
A series of E-Defense shake table tests with a large-scale soil-underground structure specimen was conducted at the end of February, 2012 in order to investigate on interaction between soil and underground structures. In the specimen, totally 5 fully-instrumented underground structure models were complicatedly distributed to represent underground space in urban areas. As a result of the shake table experiments, a large number of valuable sensor records and movies became available, especially on localized behaviors around structural joints and border of different soil strata. For total assessment of phenomenon, comparison of the sensor records and the movies needs to be performed, and more detailed information will be available soon.

Keywords: Soil-Structure Interaction, Underground Structures, Large-scale Shake Table Test

1. INTRODUCTION

In mega-cities, for instance, Tokyo, New York, London and Paris, there are many difficulties concerning on lack of land available above the ground surface, and therefore, underground space has needed to be effectively used. Due to this fact, many underground structures have been complicatedly distributed beneath the mega-cities, and probably more in future. For convenient usage of the underground structures, they are usually connected to their adjacent structures “under” the ground.

However, each underground structure is often owned by different organizations, designed with each code, and/or built in different period. Because of this situation, it is sometimes quite difficult to design joints of the underground structures with careful consideration on interaction between the structures connected each other. In addition, different dynamic properties of the structures may induce significant localized deformation and force around the joints. As a result, inappropriately-designed joints are probably failed during great earthquake events, and underground water and soil around the joints may flow into the underground structures. It may induce fatal damage of underground structure networks and economic loss due to disconnection at the joints and closure around the joints.

In light of this, using a large-scale test specimen composing of soil strata and structure models, a series of E-Defense shake table experiments was performed at the end of February, 2012 at Hyogo Earthquake Engineering Research Center (E-Defense), National Research Institute for Earth Science and Disaster Prevention (NIED), Japan in order to achieve the following objectives; 1) obtain better understanding on the interaction between underground structures and surrounding soil, 2) clarify complicated dynamic behaviors around the joints, and 3) investigate localized behaviors of underground structures crossing a border between different soil strata with large impedance ratio as an additional objective. After completion of the shake table tests, the specimen was dismantled, and damage condition of the structure models were inspected during removing the soil from the container.

In this paper, descriptions of the E-Defense facilities, the test specimen including the test setup and construction procedure, and input motions applied are presented. In addition, some examples of prompt test results including damage inspection of the structure models and sensor records are provided.

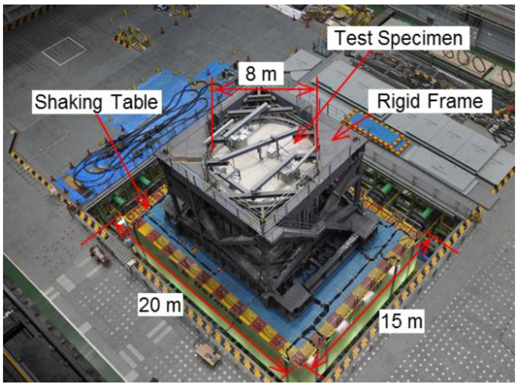
2. SPECIFICATIONS OF E-DEFENSE SHAKE TABLE TEST

In this chapter, specifications and characteristics of E-Defense test facilities (i.e. the shake table and soil containers) are introduced. Also, detailed information of the test setup, instrumentation, and input motion are provided.

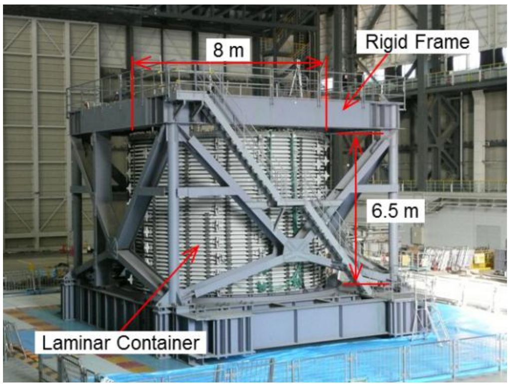
2.1. E-Defense Shake Table and Soil Container

The key element of E-Defense is a 20 m by 15 m shake table controlled by hydraulic system (Figure 1(a)). As of April 30, 2012, the specifications of the table shows capability of reproducing the seismic motions recorded in the 1995 Kobe earthquake for a 12-MN model structure. Since 2011 Tohoku Earthquake, long duration earthquakes have been focus of engineering interest, and then, E-Defense shake table will be made more powerful soon to enable inputting long motions. Details of the current specification are available elsewhere (Ohtani et al. 2003), and the new specification will be published in close future.

A cylindrical laminar container used for the shake table tests has 8 m in diameter and 6.5 m in height. The container is composed of 40 laminar rings connected with 2-dimensional linear bearings (Figure 1(b)). Therefore, each ring moves in horizontal directions, but no vertical movement is allowed.



(a) 20 m x 15 m Shake Table



(b) ϕ 8 m x 6.5 m Laminar Container

Figure 1. Shake Table and Soil Container

2.2. Test Specimen

2.2.1. Setup

The setup of the test specimen and 3-dimensional rendering image are shown in Figure 2. The specimen was composed of inclined bedrock (cement-mixed sand), dry sand (not fully dry; average water content was approximately 5 %), and fully instrumented large-scale structure models including 2 vertical shafts interconnected with a cut-and-cover tunnel and 2 shield tunnels crossing inclined bedrock. All the models and the soils were placed in the laminar container.

Along one of the shield tunnels, a flexible portion simulated with laminated rubber was installed right above the surface of the bedrock (Figure 2, C-C section), and no flexible portion was along the other tunnel (B-B section). In addition, the tunnels had elbows at both ends, and their inside radius of curvature was 1 D (D: diameter of the tunnels).

The cut-and-cover tunnel and the vertical shafts were connected as “fixed joint” with stainless bolts at one end, and as “flexible joint” installing flexible portion between at the other end (Figure 2). After completion of the 2nd day shakings (refer Table 3 below), some stainless bolts at the “fixed joint” were replaced to resin ones in order to represent inappropriate joint. At the same time, the “flexible joint” was made inactivated to develop concentrated damage at the inferior “fixed joint”.

2.2.2. Soil Materials

Approximately 1000-ton of #48 Albany silica sand is stored in stock yard at E-Defense. The properties of the sand are presented in Table 1. Because the Albany sand was used for the previous series of experiments performed in 2006 and fine content was probably washed away then, its characteristics are changed. Also, details of its deformation characteristics were investigated performing cyclic torsional shear tests of hollow cylinder specimen with various relative densities. They may be also slightly changed from the original before any shake table test due to the outflow of fine content.

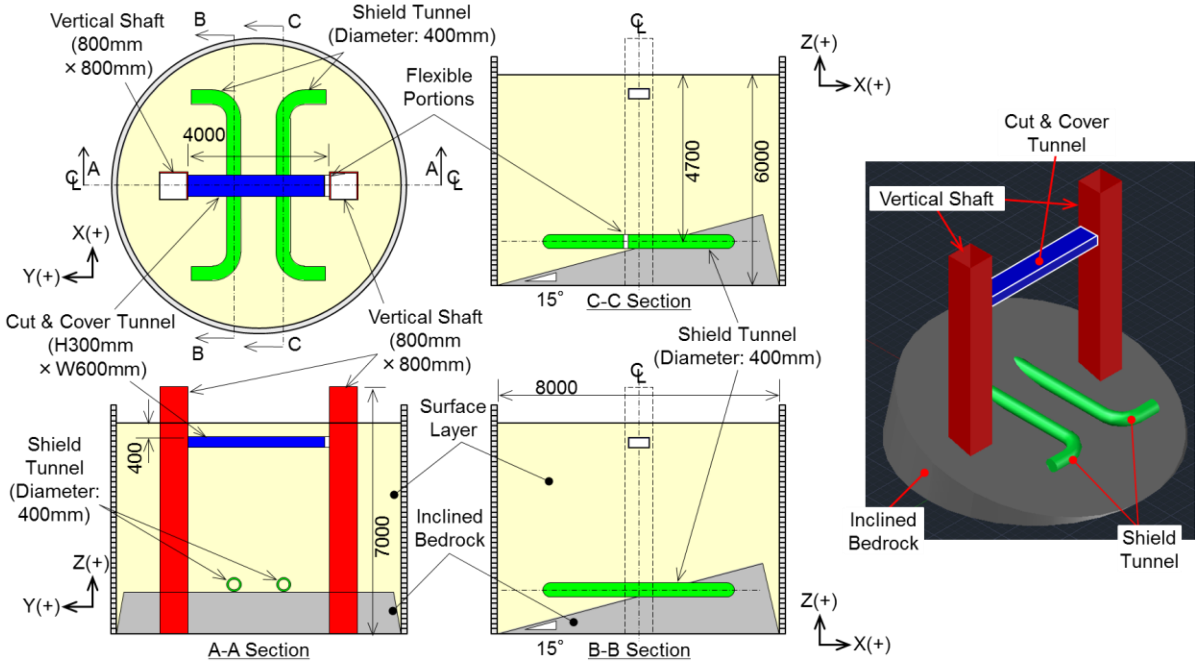


Figure 2. Setup of Test Specimen and 3-dimensional Image w/o the Container and Surface Layer

Table 1. Properties of #48 Albany Silica Sand

	Before the previous shake table test, 2005	After the previous shake table test, 2009	After the previous shake table test, 2010
Soil particle density	2.630 g/cm^3	2.643 g/cm^3	2.656 g/cm^3
Maximum void ratio	0.738	0.796	0.790
Minimum void ratio	0.513	0.500	0.512
Mean grain size	0.20 mm	0.28 mm	---
Uniformity coefficient	1.64	2.08	---
Coefficient of curvature	1.13	1.07	---

2.2.3. Structure Models

Specifications of the structure models are summarized in Table 2. Scales and section shapes of all the models were approximately 1/20 and typical ones of their prototype structures, respectively. Materials used for the models and their wall thicknesses were carefully selected with considerations on equivalent stiffness of their prototype structures and workability of the model production.

Table 2. Specifications of Structure Models

Structure Model	Material	Section Shape	Outside Dimensions	Wall Thickness	Qty.
Vertical Shafts	Aluminium	Square	800 mm × 800 mm	12 mm	2
Cut-and-Cover Tunnel	Aluminium	Rectangle	H300 mm × W600 mm	8 mm	1
Shield Tunnels	Acryl Plastic	Circle	ϕ400	8 mm	2

2.3. Sensors and Data Acquisition System

At E-Defense, approximately 50 full- or large-scale tests have been performed with various types of test specimens including soil-pile-superstructure models (for example, Tabata et al. 2007, and Tokimatsu et al. 2007). Therefore, many kinds of instruments are now available for geotechnical engineering testing. To achieve the research goals, many kinds of sensors were installed in/on the soil, along/in/on the structure models, on the container and the shake table as follows; 1) Soil: inclinometers, accelerometers, velocity and displacement transducers, 2) Structure models: accelerometers, strain gauges, displacement, earth pressure transducers, and a tactile sensor sheet measuring distribution of pressure on the sheet, 3) Container and Shake Table: accelerometers and displacement transducers. The number of the sensor in total was more than 900. The data will be available for anyone in two years.

Video cameras were also placed above the ground surface to see behaviors of the ground surface, especially around the vertical shafts. In addition, 3 tiny high-speed cameras were installed at the joints between the shafts and the cut-and-cover tunnel and the flexible portion in the shield tunnel using inside space of the models (refer Figure 4(f)).

2.4. Input Motions

There were 2 types of input motions applied to the specimen for this series of the shake table tests as summarized in Table 3. Step Sine motion is shown in Figure 3, and JR Takatori motion is plotted later in this paper.

Table 3. Summary of Input Motions

	Motion	Acc. Level[1)]	Direction[2)]
1st Day	Step Sine 1 – 20 Hz	0.1 m/s^2	0 Deg.
		0.1 m/s^2	90 Deg.
		0.3 m/s^2	0 Deg.
		0.3 m/s^2	90 Deg.
		0.3 m/s^2	30 Deg.
		0.3 m/s^2	45 Deg.
		0.3 m/s^2	135 Deg.

	Motion	Acc. Level[1)]	Direction[2)]
2nd Day	Step Sine 1 - 20 Hz	0.3 m/s^2	90 Deg.
		0.5 m/s^2	0 Deg.
		0.5 m/s^2	90 Deg.
	JR Takatori	50 %	See Note[3)]
3rd Day	Step Sine 1 - 20 Hz	0.3 m/s^2	90 Deg.
		0.3 m/s^2	0 Deg.
	JR Takatori	80 %	See Note[3)]

1) “Acc. level” shows the maximum acceleration for Step Sine motion, and amplification from the actual records for JR Takatori motion.
2) “Direction” means angle from x-axis; i.e. 0 degree is x-axis and 90 degree is y-axis.
3) EW and NS components of JR Takatori were input in x- and y-axes, respectively.

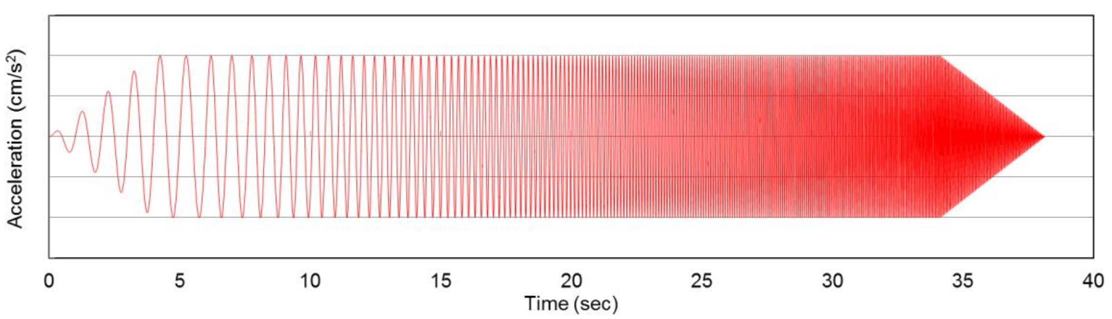


Figure 3. Step Sine Motion (1 - 20 Hz)

Because soil-underground structure interaction is quite complicated, the Step Sine motion, which has relatively simple characteristics, was selected in order to simplify assessment of the test results. The frequency of the Step Sine motion was gradually increased from 1 to 20 Hz, and the steps of the increase were 1/8 Hz between 9 and 17 Hz, and 1/4 Hz in the other frequency regions because the first mode natural frequency of the specimen was approximately 13 Hz in prediction analysis. 2 cycles of any frequency motion was input. In addition, 4 seconds of tapering motions were applied before and after the main Step Sine motion for better hydraulic system control.

Also, JR Takatori motion in 1995 Kobe Earthquake was used to induce large ground displacement. Because the axial direction of the cut-and-cover tunnel was expected as the most critical direction, the main component, NS component of JR Takatori motion, was input in y-axis, and EW component was in x-axis (refer Figure 2). In this test series, no vertical motion was applied.

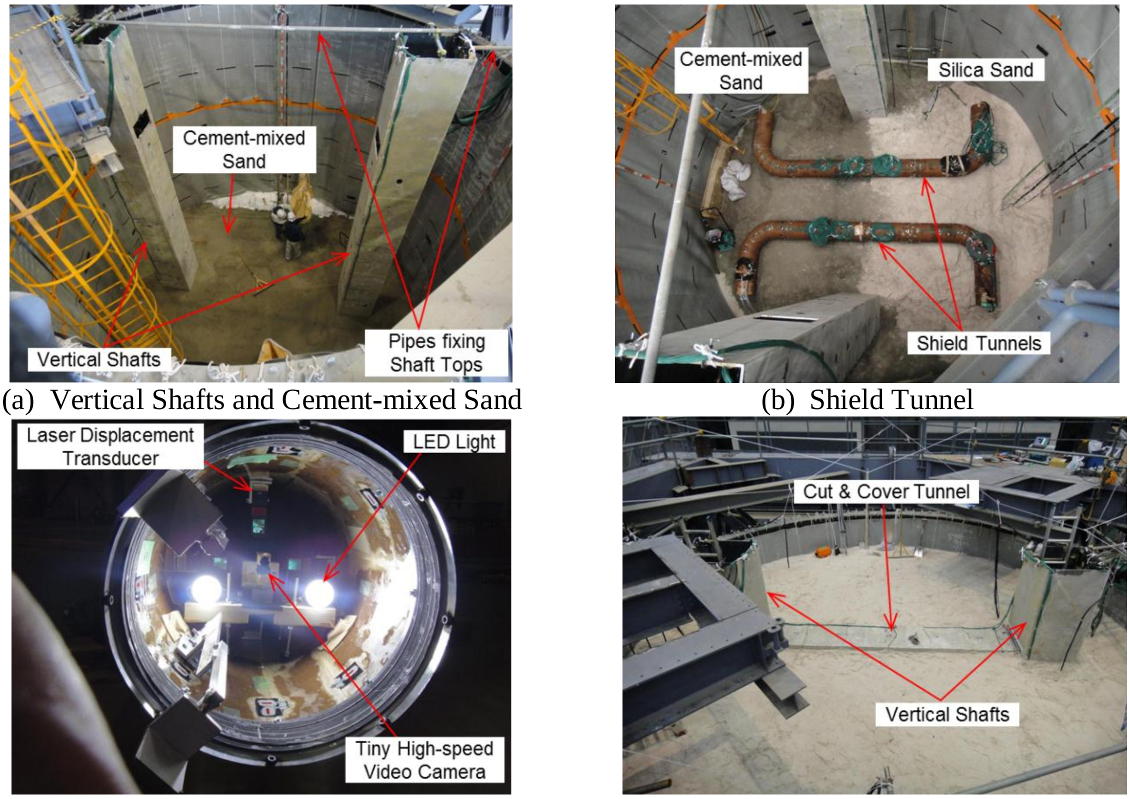
3. CONSTRUCTION OF TEST SPECIMEN

It is very important to build reasonable test specimen for great success of the experiments. In this chapter, construction procedure of the test specimen is briefly described.

First of all, the vertical shafts were placed in the container. At that time, the locations of the shafts were carefully monitored using survey device. Since their setting locations were determined, their tops and bottoms were fixed to the top and the bottom of the container in order to avoid any movement of the shafts during placement of the soil (Figure 4(a)). Next, the container was filled with the cement-mixed sand and the dry sand until height of the soil strata reached at the ground level of the bottom of the shield tunnels (Figure 4(a)). The soil was compacted to the target density using vibration plates. And then, the shield tunnels were installed on the ground (Figure 4(b)). At the placement of the shield tunnels, tiny high-speed cameras and laser displacement transducers were set inside of the tunnel (Figure 4(c)). After that, the soil was placed into the container and compacted with careful works to prevent any damage of the sensors, the cables, and the structure models. When the height of the soil strata became at the level of the cut-and-cover tunnel, the tunnel was fixed to the shafts with and without the flexible portion (Figure 4(d)). Other high-speed cameras were installed at the joints. And finally, the rest of the soil strata were built.

4. SHAKE TABLE TEST RESULTS

Because this test series was completed at the end of March, 2012 including dismantling the specimen, more time is needed to conclude the test results. In this chapter, some test results observed during and after 80 % JR Takatori motion are presented as examples. More analyses of the test results have been now performed, and will be published in close future. It is noticeable that the “flexible joint” was fixed before 80 % of JR Takatori motion.



(a) Vertical Shafts and Cement-mixed Sand (b) Shield Tunnel

(c) Inside of Shield Tunnel (d) Cut-and-Cover Tunnel

Figure 4. Construction of Test Specimen

4.1. Table Motions

Comparison of target and observed table motions are shown in Figures 5 and 6. In the time histories, the target and the observed table motions show reasonable agreement in both of x and y directions (refer Figure 2 on the directions). However, as shown in Figure 6, large differences between the target and the observed motions appear in short period region comparing acceleration response spectrum with damping ratio of 5%. It is due to noise in hydraulic system, interaction between the table and the specimen and nonlinear behavior of the test specimens. In fact, the trend that the target and the observed motions did not match in the short period components was also given at input of the step sine motions.

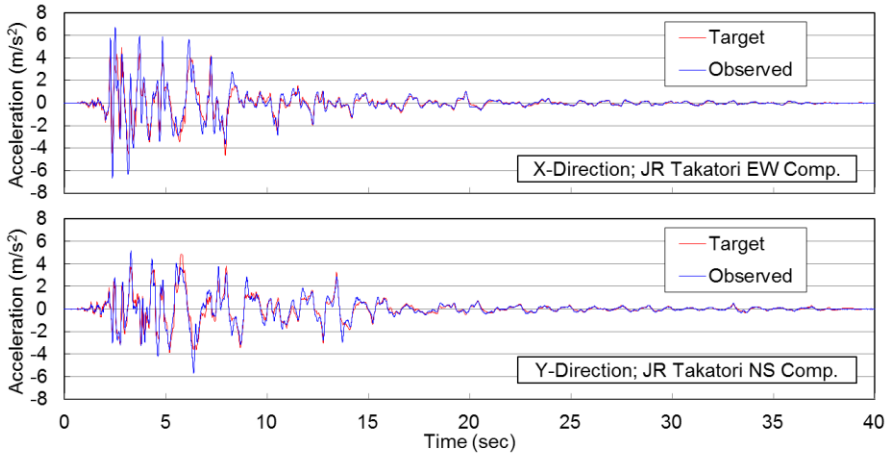


Figure 5. Comparison of Target and Observed Motions, Acc. Time Histories, JR Takatori 80%

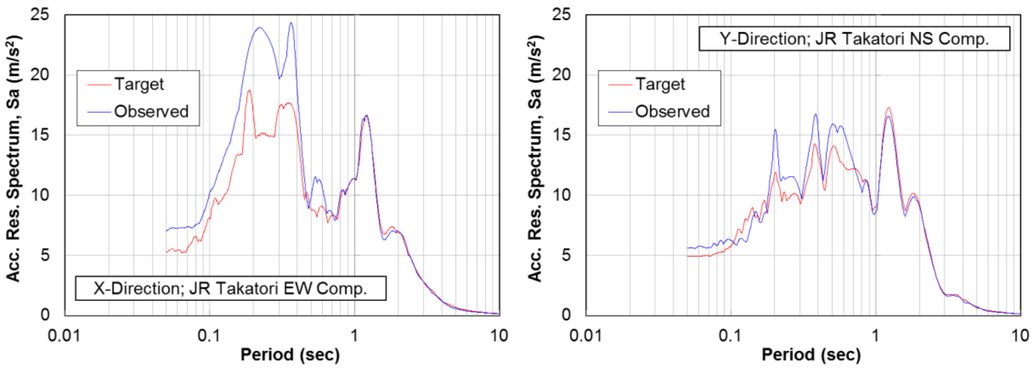
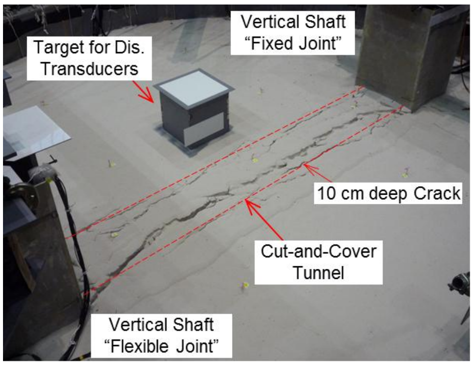


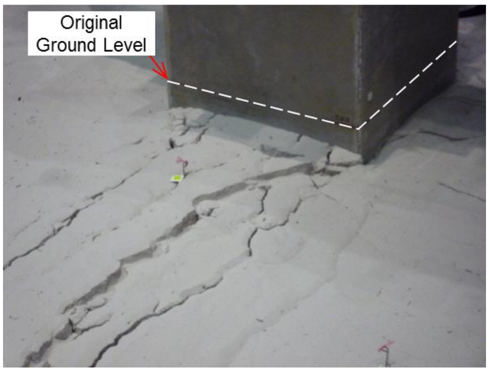
Figure 6. Comparison of Target and Observed Motions, Acc. Response Spectrum, JR Takatori 80%

4.2. Crack at Ground Surface above Cut-and-Cover Tunnel

Damage conditions of the soil around the cut-and-cover tunnel are summarized in Figure 7. Significant cracks were observed right above the cut-and-cover tunnel (Figure 7(a)). Because the tunnel supported the soil above, the less settlement above the tunnel than the other areas appeared and induced the cracks at the ground surface. Depth of these cracks reached approximately 10 cm in maximum. Some of the cracks were inclined, and it implies the soil moved laterally. Figure 7(b) shows detailed surface cracks around the vertical shaft on the "Fixed Joint". The original ground level shown in the figure is the ground level before any shaking. The ground surface slightly sank around the shaft on the "fixed joint" side, but not on the "flexible joint" side.



(a) Soil Cracks above Cut-and-Cover Tunnel



(b) Around Shaft on "Fixed Joint" side

Figure 7. Crack and Settlement of Soil around Cut-and-Cover Tunnel

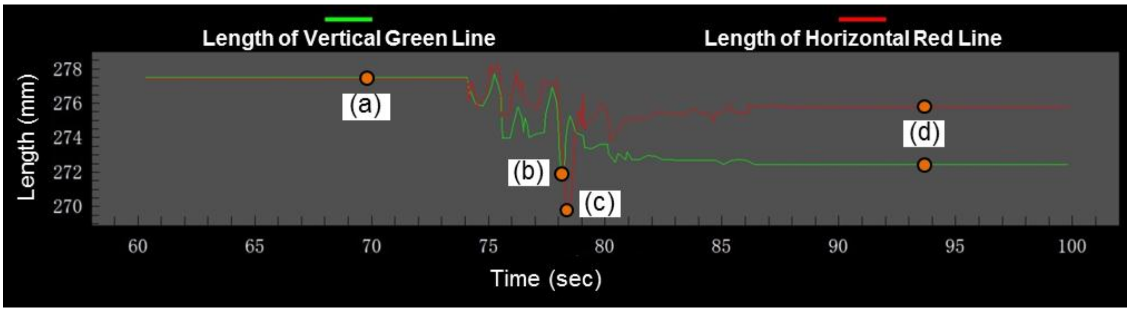
4.3. Damage Condition of the Joint

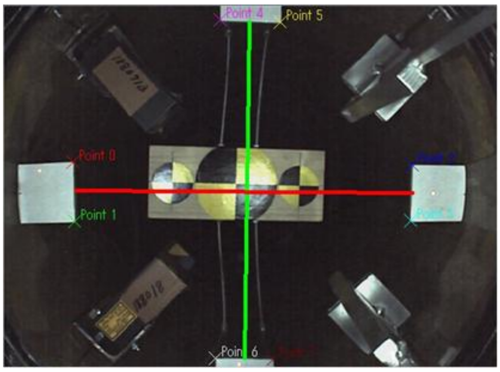
During 80% of JR Takatori shaking, the resin bolts at the "fixed joint" were broken, and then, sand around the tunnel flowed into inside of the tunnel. Figure 8 shows sand in the tunnel after the shaking test, and this sand flow induced the minor settlement around the "fixed joint" shown in Figure 7(b).

4.4. Deformation of the Shield Tunnel

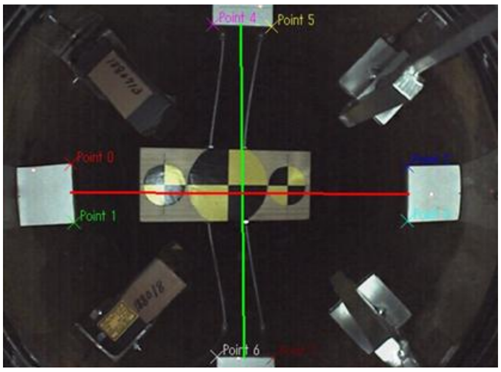
Figure 9 provides an example of image analysis on deformation of the circular-shaped shield tunnel for 80 % of JR Takatori motion. At Point (a), the section already had residual deformation due to the previous shaking tests. Lengths of the green and the red lines in the photos showed the minimum values at Points (b) and (c). Finally, at Point (d), residual deformation was accumulated approximately 5 and 2 mm more in the vertical and horizontal directions, respectively. It is one of the most remarkable observations that the lengths of both the lines indicate in-phase responses. It implies the circular-shaped tunnel deformed to elliptic-shaped during and after motion.

Figure 8. Damage Condition of Joint between Vertical Shaft and Cut-and-Cover Tunnel

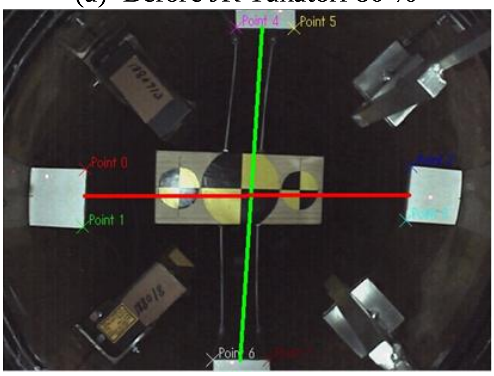




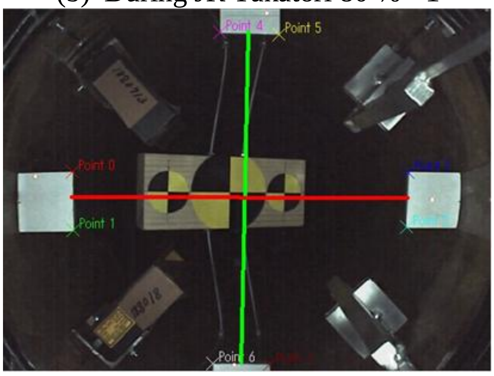
(a) Before JR Takatori 80 %



(b) During JR Takatori 80 % - 1



(c) After JR Takatori 80 % - 2



(d) After JR Takatori 80 %

Figure 9. Deformation of Shield Tunnel

4.5. In-ground Inspection

During in-ground inspection performed after all the shake table tests, approximately 7 cm of settlement was observed below the cut-and-cover tunnel as shown in Figure 10(a). This observation is consistent the surface cracks, and probably it significantly affects to the behaviors of the vertical shafts as well as the cut-and-cover tunnel because of the following possible reasons; 1) less friction was generated due to lack of the soil at the bottom of the tunnel, 2) the soil above the tunnel behaved with the tunnel and worked as an additional weight inducing greater inertial force, and 3) the sand around the tunnel became looser because the sand flowed to the gap beneath the tunnel. It may result in larger deformation of the soil. In addition, approximately 15 mm wide gap was observed at the damaged joint as shown in Figure 10(b). This inspection result indicates joints between different types of underground structures will be significantly damaged with strong earthquake motions, if the joints are poorly designed and/or constructed.

(a) Settlement beneath Cut-and-Cover Tunnel (b) Gap generated at Joint

Figure 10. Damage Condition of Joint between Vertical Shaft and Cut-and-Cover Tunnel

4.6. Deformation of the Ground Surface

Displacement time histories of the ground surface at the center of the container and the neighbour of the container wall (refer right figure) are plotted in Figure 11. From this figure, both the behaviors were obviously identical. It implies the laminar container and the underground structures did not affect to the displacement of the ground surface. The residual settlement is approximately 10 cm, and therefore, the top layer of the dry sand settled about 3 cm comparing to the 7 cm settlement below the cut-and-cover tunnel shown in Figure 10(a).

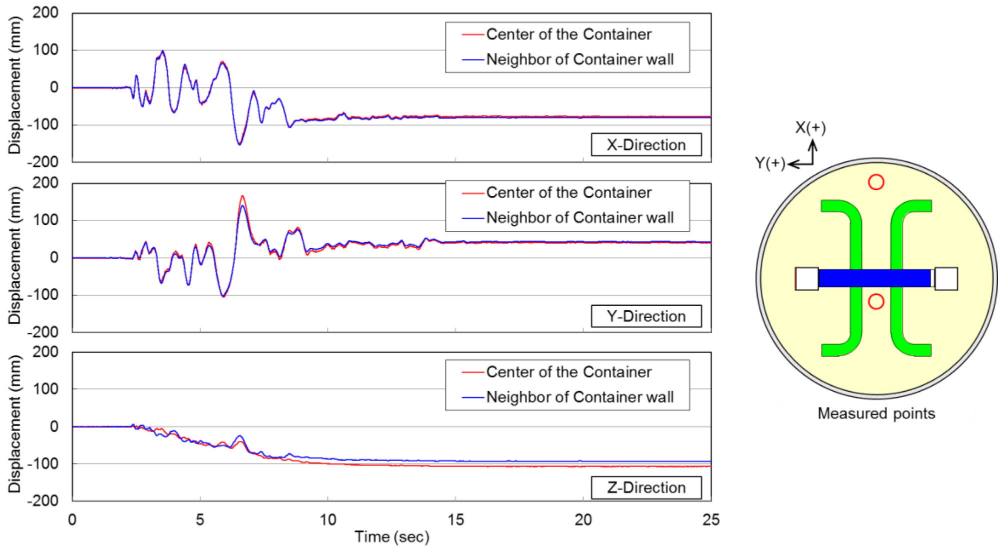


Figure 11. Displacement Time Histories of Ground Surface

4.7. Acceleration Response at the Top of the Shaft

Figure 12 shows acceleration time histories at the tops of the vertical shafts in x- and y-axes. Generally, only minor difference appeared between the responses of both the shafts in x-direction. On the other hand, the acceleration at the shaft on the “fixed joint” side had significant spikes in y-axis motion. It is probably because the joint was failed and the gap shown in Figure 10(b) was generated at the beginning of the shaking, and large impact occurred between the shaft and the tunnel due to their collision.

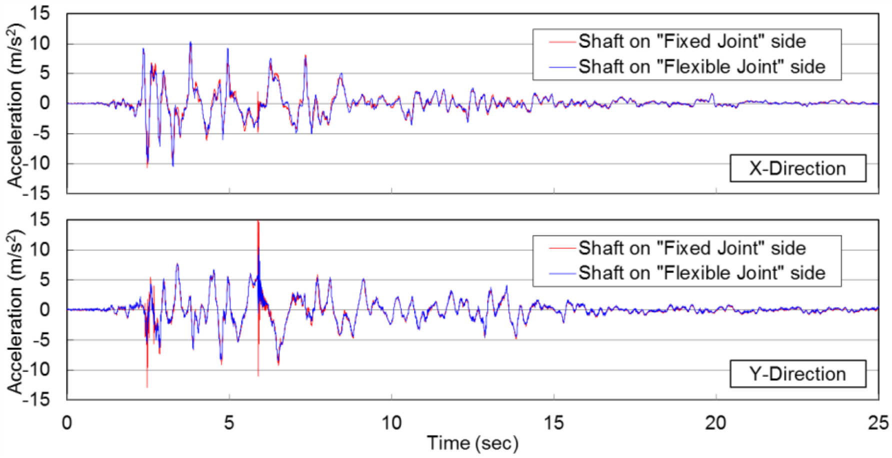


Figure 12. Acceleration Time Histories at Tops of Shafts

5. SUMMARY

Using E-Defense, one of the largest shake tables in the world, the series of shake table tests with the large-scale soil-underground structure specimen was conducted in order to obtain better understanding about interactions between underground structures and surrounding soil, and localized behaviors around structural joint and border of different soil strata. From the test series, a large number of valuable results including the examples shown in this paper could be obtained, such as movies/photos showing dynamic behaviors of the underground structures and sensor records providing quantitative responses of the structures and the soil. Analyses of the entire test data have been now in progress, and more detailed information will be published in future.

AKCNOWLEDGEMENT

To successfully promote this experimental project, many advice and comments have been given by Professor Maekawa at the University of Tokyo, Dr. Hosoi (TUGs corporation) and other persons concerned. Also, NAC image technology INC. has provided cooperation for image analysis. All their supports are greatly acknowledged.

REFERENCES

Ohtani, K., Ogawa, N., Katayama, T. and Shibata, H., (2003). Construction of E-Defense (3-D full-scale earthquake testing facility), *2nd International Symposium on New Technologies for Urban Safety of Mega Cities in Asia*, 69-76.

Tabata, K., Sato, M., Tokimatsu, K., Suzuki, H., and Tokuyama, H. (2007). E-Defense shaking table test of model ground with quay wall on liquefaction-induced lateral spreading, *4th Conference Urban Earthquake Engineering*, 825-832.

Tokimatsu, K., Suzuki, H., Tabata, K., and Sato, M. (2007). Three-dimensional shaking table tests on soil-pile-structure models using E-Defense facility, *4th International Conference on Earthquake Geotechnical Engineering*, pp. 11.