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E-DEFENSE IMPROVED PERFORMANCE AND POSSIBLE GEOTECHNICAL MODEL TESTS ON LIQUEFACTION BEHAVIORS FOR SATURATION EVALUATION

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Abstract

E-Defense is the earthquake testing facility with the largest three-dimensional shake table and successfully completed 80 shaking tests so far, including three tests on liquefaction problems. When E-Defense completed 40 shake-table tests, the 2011 off the Pacific coast of Tohoku earthquake hit a wide area in the eastern Japan and its ground motion with long duration led to extensive damage induced by liquefaction. After this earthquake, because researches on behavior under strong, long-duration, long-period ground motion was emphasized to prepare a future megathrust earthquake probably hitting Japan, E-Defense expanded its shaking performance to simulate long-duration, long-period input motion to a large-scale model specimen. This expanded performance is enabled by the improvement work for pressurized hydraulic fluid supply to the table actuating system. Employing this improved performance, the authors plan a shaking test on liquefaction behavior specially focusing on various saturation conditions so as to clarify the mechanism and develop saturation-evaluation procedure for countermeasures against liquefaction. Prior to the planned E-Defense test, authors and colleagues conducts a shaking test of model grounds with different saturation conditions at the Large-scale Earthquake Simulator for investigation of the feasibility of the test. In this paper, the E-Defense improved performance and some shaking tests are introduced. The paper also provides the idea of a possible E-Defense shaking test on liquefaction phenomena and the outline of the preliminary shaking test to examine its feasibility.

Keywords: shake table test, liquefaction, long-duration ground motion, long-period ground motion

1. Introduction

E-Defense is the earthquake testing facility with the largest three-dimensional shake table shown in Fig.1, operated by National Research Institute for Earth Science and Disaster Resilience (NIED) in Japan. Since its operation start, 80 shaking tests have been completed with no trouble. As presented in Table 1, one of the unique features of the E-Defense shake table is its 300m^2 area and 1,200-ton maximum payload. In addition, the table can apply accurate three-dimensional motion with large acceleration, velocity and displacement to the model placed on it so as to simulate behavior to be observed when a large earthquake occurs. Shaking motion of the table is applied by 10-horizontal and 14-vertical actuators shown in Fig.2. The actuators give table motion by pressurized hydraulic fluid supplied from accumulators.

Fig.1 - E-Defense shake table.

Table 1 - E-Defense shaking performance.

Table size		20m x 15m = 300m^2	
Maximum payload (loading capacity)		1200ton (12MN)	
Maximum performance	Direction	Horizontal (x, y)	Vertical (z)
	Acceleration	9m/s^2	15m/s^2
	Velocity	2m/s	0.7m/s
	Displacement	±1m	±0.5m

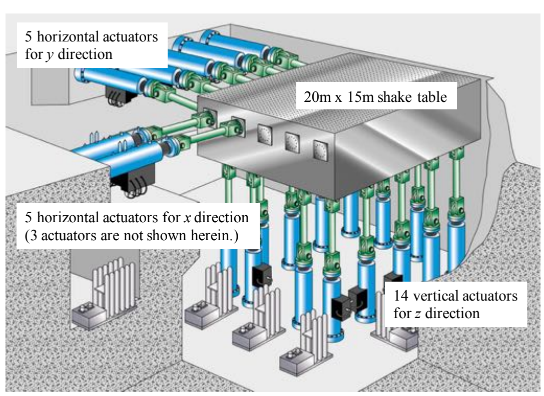

Fig.2 - Arrangement of the horizontal and vertical actuators for the shake table.

The original concept of the E-Defense shaking performance was designed after the 1995 southern Hyogo prefecture (Hyogoken-nambu) earthquake, and NIED started its operation in 2005. The performance was sufficient to observe any situation anticipated by most researchers and engineers because the table was able to reproduce any ground motion recorded in the Hyogoken-nambu earthquake that was the most noticeable earthquake at that time. Of course, the Hyogoken-nambu earthquake has been still one of the severest earthquakes causing catastrophic disaster in our history.

When its operation started, most ground motions of shaking tests ranged between the periods of around 0.2 and 2.0 seconds and lasted for less than one minute because many studies mainly concentrated on strength and collapse process of a structure. Indeed, such input motion is adequate for investigation on collapse behavior of a structure induced by an inland or near-field earthquake like the Hyogoken-nambu earthquake. In contrast, at that time, E-Defense had difficulty in reproducing input motion lasting for long shaking time with long period domains. The reason of this difficulty was due to shortage of pressurized hydraulic fluid supplied from the accumulators to the actuators. Therefore, E-Defense was not so suitable for producing long-duration, long-period input motion so as to assume scenario of a large plate-boundary or interplate earthquake such as the 2011 off the Pacific coast of Tohoku earthquake.

Even before the year 2011, NIED focused on the behavior under long-duration, long-period ground motion assuming large plate-boundary or interplate earthquakes such as future Tokai, Tonankai, Nankai earthquakes, and carried out some shaking tests with various manners to simulate long-duration, long-period motion. In one research project, in order to observe situations in the upper-floor rooms of a high-rise building under one scenario motion induced by a future Nankai earthquake, horizontal motion was amplified by isolating rubbers installed between a model structure and the shake table as shown in Fig.3, and the table was horizontally shaken by adequate motion obtained by prior calculation [1]. This manner is effective to evaluate the behavior inside the rooms on an upper floor of a high-rise building under earthquake ground motion with long duration and long period.

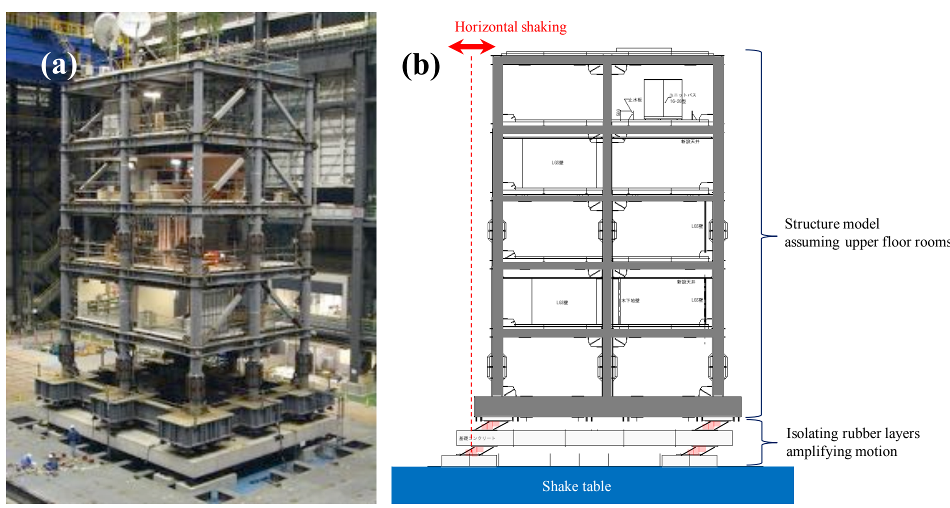

Fig.3 - Shaking test on the upper-floor rooms of a high-rise building: (a) Model specimen and (b) illustration of the amplification system between the model and table (after Nagae, 2009).

When E-Defense completed 40 shake-table tests, the 2011 off the Pacific coast of Tohoku earthquake hit a wide area in the eastern Japan and caused extensive damage even in the Kanto region far from the epicenter. In this magnitude-9.0 earthquake, seismic ground motion was propagated even to the Kanto region including the metropolitan areas. In some areas, recordings lasted for more than 10 minutes. Such earthquake ground motion with long duration led to liquefaction phenomena.

After this earthquake, many researchers and engineers recognize that the study on behavior under stronger, longer-duration, longer-period ground motion than those expected before is essential to prepare future megathrust earthquakes probably hitting Japan. However, E-Defense did not have performance to produce such recordings and no testing facility could do so. Therefore, NIED improved the shaking performance of E-Defense in order to apply longer-period and longer-duration input motion to a large-scale model for investigation of structure's behavior under ground motion induced by a large plate-boundary or interplate earthquake like a possible Nankai-trough megathrust earthquake, for instance.

2. Improved performance of E-Defense

As described above, the limitation of long-duration, long-period motion application depends on insufficiency of pressurized hydraulic fluid supply. In order to overcome the limitation, NIED improved the E-Defense performance in two ways as illustrated in Fig.4 [2].

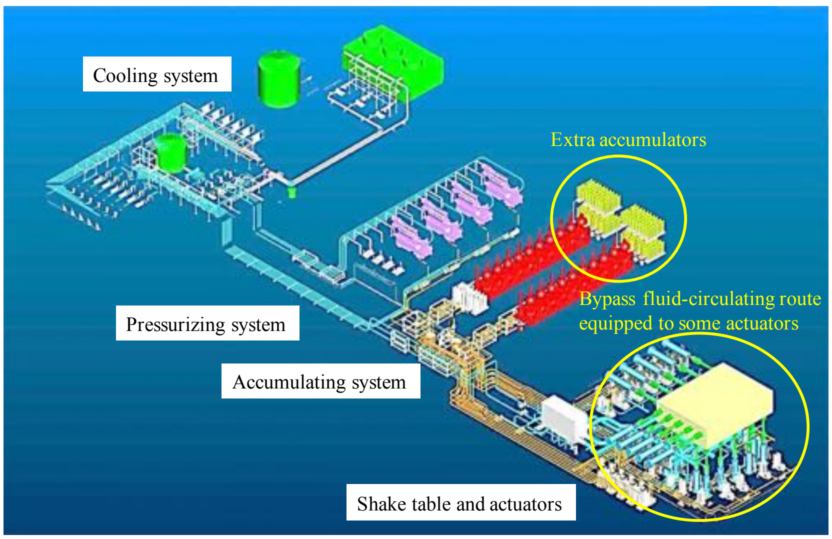

Fig.4 - Improvement work for pressurized hydraulic fluid supply.

One was installing extra accumulators to increase the total volume of pressurized fluid supplying to the actuators. 360 units of 11-liter bladder-type accumulator were added to the original accumulating system, and the total volume of pressurized hydraulic fluid became 24 kiloliters. This installation means 20-percent increase of the volume of pressurized hydraulic fluid.

The other was equipping a bypass fluid-circulating route to an existing actuator to save unnecessary fluid consumption. A bypass fluid-circulating route was added to some existing actuators. The bypass function is activated for the actuator that is not needed to apply load to the table; the saved pressurized fluid by this bypass activation is used to other loading actuators. The maximum 6 vertical and 6 horizontal actuators out of 24 actuators can be activated, which sets 37 bypassed fluid-circulating patterns by formation of loading and unloading actuators.

Table 2 shows the volumes of pressurized hydraulic fluid consumed for shaking with respect to three ground motions recorded at Takatori Station in the Hyogoken-nambu earthquake, K-NET Sendai and Furukawa observation stations in the Tohoku earthquake, and Sannomaru scenario motion of the possible Nankai earthquake. Before the improvement work, because the Sendai, Furukawa and Sannomaru motions consumed pressurized hydraulic fluid exceeding 20 kiloliters that was the total volume of the previous accumulating system, E-Defense was not able to reproduce these motions as input to the table adequately. After the improvement, the Sendai motion is executable with no bypass activation, while the Furukawa and Sannomaru are applicable for shaking with bypass activation reducing fluid consumption.

Table 2 - Pressurized hydraulic fluid consumption of four different input ground motions (after Abe and Kajiwara, 2013).

Ground motion	Consuming fluid volume (kiloliter)	Shaking applicability before improvement (max. 20 kiloliters)	Shaking applicability after improvement (max. 24 kiloliters)
Takatori Station	14.5	✓ Executable	✓ Executable
K-net Sendai	23.2	N/A (Exceeding 20 kiloliters)	✓ Executable
K-net Furukawa	49.1	N/A (Exceeding 20 kiloliters)	✓ Executable with bypass circulation (21.7 kiloliters)
Sannomaru scenario	42.5	N/A (Exceeding 20 kiloliters)	✓ Executable with bypass circulation (23.6 kiloliters)

After improvement of the performance, with respect to shaking application of long-duration, long-period input motion, NIED conducted some E-Defense shaking tests on reinforced concrete building with base isolation, large-space structure and so on. For example, in the test on a base-isolated building shown in Fig.5(a), long-duration, long-period shaking excited the motion of the structure, resulting in exceeding the clearance between the foundation and surrounding retaining walls and crashing the walls by the structure's impact [3]. In the test on a large-space structure shown in Fig.5(b), a scenario of multiple large aftershocks was simulated, and gradual spread of hanging ceiling damage was observed [4].

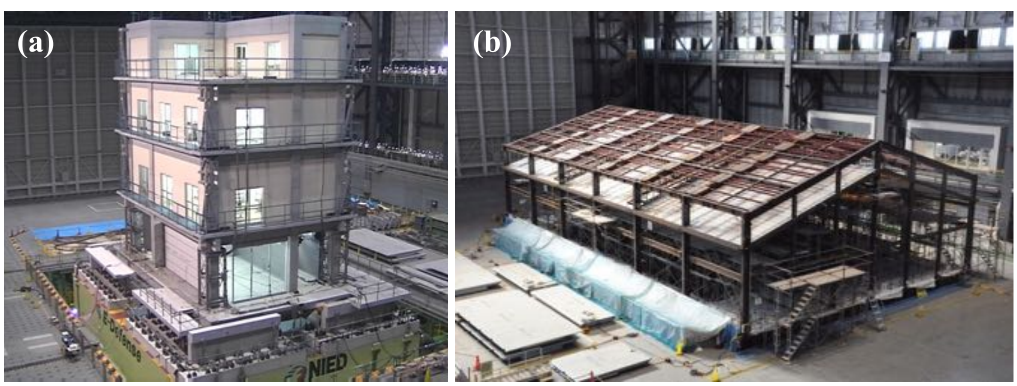

Fig.5 - Shaking tests on (a) a base-isolated building and its surrounding retaining walls (Sato et al., 2017) and (b) ceilings and non-structural components in a large-space structure (Sasaki et al., 2017).

3. Possible tests for liquefaction problems

With respect to study on liquefaction phenomena, three shaking tests at E-Defense have been performed so far [5, 6, 7]. One of the tests shown in Fig.6(a) was conducted to investigate soil-pile-structure interaction. In this test, the structure with a 3-by-3 pile group foundation installed to liquefiable sand layer prepared in a cylindrical laminar shear container. Figure 6(b) shows the liquefiable ground model with a pile-foundation structure behind quay walls in a rectangular rigid container in order to observe damage induced by lateral spreading due to liquefaction. In these tests, ground motions recorded in the Hyogoken-nambu earthquake were mainly applied to the model specimens. As shown in Fig.6(c) for example, such motion finally caused collapse of the structure in the liquefiable layer. Following these tests after the performance improvement, no E-Defense test on liquefaction problems has been carried out. At present, employing the improved performance for study on liquefaction phenomena, the authors plan a shaking test of liquefiable grounds with various saturation conditions.

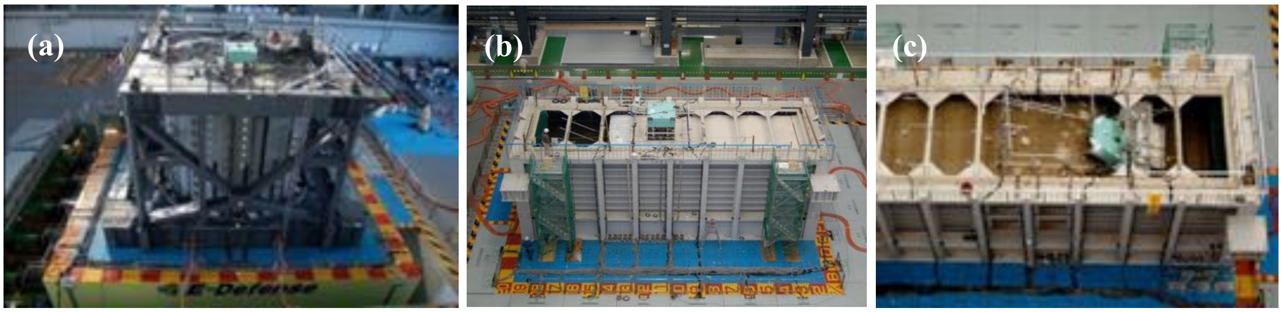

Fig.6 - Shaking tests on liquefaction phenomena: (a) Tests on soil-pile-structure interaction and (b) lateral spreading and (c) observation of liquefaction and collapse of the model after shaking.

As previously introduced, because long-duration ground motion induced by the Tohoku earthquake caused unprecedented severe damages due to liquefaction in the metropolitan areas, several countermeasures against liquefaction have been developed. Some of the authors and their colleagues concentrate on one of these countermeasures that is an air-injection method to make a liquefiable layer un-saturate [8]. The construction work of this method is injecting water with micro-air bubbles (MB water) into liquefiable layers so as to increase liquefaction resistance. For construction management of this method, evaluation procedure of unsaturation conditions of air-injected ground is needed to assess its introduction effectiveness.

In order to develop the evaluation procedure, the authors intend to perform shaking tests to investigate liquefaction behavior of ground model with various saturation conditions including air-injected conditions. The improved performance and features of E-Defense are very advantageous for this experimental study: To observe behavior in detail, a large-scale liquefiable-ground model to be prepared for E-Defense tests is suitable to install many sensors including accelerometers, displacement and pore water pressure transducers. Indeed, one of the serviceable soil containers for E-Defense is 16m long, 4m wide and 4.5m high, as shown in Fig.6(b), enabling installation of hundreds of sensors. In such large-scale model ground for E-Defense, behaviors, such as deformation and pore water pressure change, induced by shaking can be obtained more distinctly than those observed from other shaking test facilities. Additionally, capability of long-duration shaking application is good to observe the processes of buildup and dissipation of pore water pressure that are assumed as a large plate-boundary or interplate earthquake. Furthermore, E-Defense can apply multi-directional motion to a model, producing valuable results for estimating realistic in-situ situations.

To prepare this E-Defense test, authors and colleagues conducts a preliminary shaking test of ground model with different saturation conditions at the Large-scale Earthquake Simulator operated by NIED at Tsukuba. The Large-scale Earthquake Simulator is also an earthquake testing facility with horizontally one-dimensional shake table, as shown in Fig.7, and its specifications presented in Table 3. While its loading capacity is smaller than that of E-Defense, the table is adequate to examine the feasibility of the planned E-Defense test.

Fig.7 - Shake table of the Large-scale Earthquake Simulator.

Table 1 - Shaking performance of the Large-scale Earthquake Simulator.

Table size		15m x 14.5m = 217.5m^2
Maximum payload (loading capacity)		500ton (5MN)
Maximum performance	Direction	Horizontal
	Acceleration	9.4m/s^2 for 200ton load 5m/s^2 for 500ton load
	Velocity	1m/s
	Displacement	±0.22m

In this test, as presented in Fig.8, a small soil container is used and shaken by sinusoidal motion in the longitudinal direction. The container is divided into two sections; one section is for fully saturated ground, while the other is for air-injected ground with MB water. To these grounds, some investigations are performed before and after the shaking to evaluate change of saturation conditions for comparison between fully saturated and air-injected grounds. The results of the test conducted at the Large-scale Simulator is presented in detail in the other paper [9].

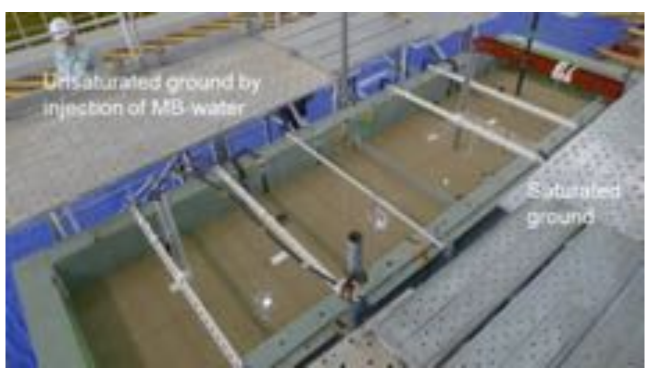

Fig.8 - Model for the preliminary shaking test on liquefaction behavior at the Large-scale Earthquake Simulator (Nakazawa et al., 2017).

4. Summary

E-Defense is the unique testing facility with the largest three-dimensional shake table and has conducted shaking tests of various types of large-scale model including liquefiable ground. After the 2011 off the Pacific coast of Tohoku earthquake, its shaking performance expanded into the application of long-duration, long-period input motion to a model specimen. This expanded performance is suitable for simulating situations induced by ground motion in a large plate-boundary or interplate earthquake, such as observation in the metropolitan areas in the Tohoku earthquake. Employing the expanded performance, the authors plan a shaking test on liquefaction behavior specially focusing on evaluating various saturation conditions. To assess the feasibility of the E-Defense shaking test, authors and colleagues conducts a preliminary shaking test of model grounds with different saturation conditions at the Large-scale Earthquake Simulator. This paper explains the E-Defense improved performance and introduces some shaking tests. The paper also describes the idea of a possible E-Defense shaking test on liquefaction phenomena and the outline of its feasibility shaking test, while the other paper presents the results from the test in detail.

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