FUTURE PERSPECTIVE OF CONTRIBUTION TO RESEARCH ON EARTHQUAKE-DISASTER RISK REDUCTION WITH E-DEFENSE

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Abstract: E-Defense, the NIED's communal-use testing facility with a 300 square meter (20m x 15m) 6-DOF shake table, has completed 125 experiments mainly on full-scale structures, since its operation started in 2005. These experiments were conducted to observe the failure process of structures to clarify collapse mechanisms, evaluate current or new technologies, and assess damage to the functionality of structures. As many of their datasets are accessible to those involved in disaster risk reduction, it is expected that they will be used as evidence-based results not only in the research projects of the experiments but also in other studies. While these datasets are currently provided as is via a website, their wider use not limited to earthquake hazards, such as the development of numerical simulation techniques and the consideration of various hazard issues, requires additional fundamental materials to develop a common understanding of the experiment, such as a data paper describing the experiment. In addition, to continue to obtain valuable data from future E-Defense experiments, it could be effective to find global ideas through discussions among various researchers and engineers, establish research infrastructure networks including E-Defense to promote collaborative research and development, and co-create the evidence-based knowledge on disaster risk reduction are very valuable.

1 NIED's research infrastructures

The National Research Institute for Earth Science and Disaster Resilience, NIED, is a national research and development agency under the Ministry of Education, Culture, Sports, Science and Technology of Japan. NIED promotes research and development of science and technology for disaster risk reduction to transform society to develop sustainability or "resilience" prepared for all types and scales of future natural disasters. Through research and development for the establishment of a resilient society, NIED contributes to the safety of people's lives, properties, activities, and businesses.

NIED also operates the unique infrastructure facilities that support research and development, including observation networks and experimental facilities developed by the Japanese government. For example, the Monitoring of Waves on Land and Seafloor, MOWLAS, which consists of about 2,100 observation stations from seven observation networks, monitors earthquakes, tsunamis and volcanoes covering all land and sea areas in Japan. In terms of experimental facilities, the Large-Scale Rainfall Simulator has the world's largest rainfall area and sprinkling performance for research related to landslides, debris flows, soil erosion, urban flooding, etc., and the Cryospheric Environment Simulator has outstanding performance in reproducing crystalline snow to clarify snow and ice phenomena and verify the effectiveness of countermeasures against snow disasters. In addition, as an infrastructure platform for relevant organizations responding to disasters, NIED operates SIP4D, the Shared Information Platform for Disaster Management, which is a system that aggregates the information needed for disaster response activities from various information sources and provides it in an easy-to-use form, so that it can be shared among organizations.

2 E-Defense: a large-scale shake table testing facility

The Three-Dimensional Full-Scale Earthquake Testing Facility, E-Defense, is one of the experimental facilities operated by NIED, which has one of the world's largest shake tables, as shown in Figure 1.

Figure 1. E-Defense: Panoramic view of the facility and shake table.

E-Defense was developed in the aftermath of the 1995 Great Hanshin-Awaji Earthquake Disaster, which caused devastating loss of life and property due to collapsed structures and fires (Otani et al., 1998). In May 1995, the Committee on the Promotion of Science and Technology for Earthquake Disaster Prevention, organized by the Research and Development Bureau of the Science and Technology Agency, identified research topics for early application and reported that it was necessary to develop and improve large-scale earthquake testing facilities and nationwide observation networks, which are essential for research and development. A report issued in May 1996 by the Committee on Research Infrastructure for Earthquake Disaster Prevention established by the Science and Technology Agency pointed out the need to promote comprehensive research on earthquake disaster mitigation, especially in urban areas, at a new research center. The report also identified a large-scale three-dimensional earthquake testing facility as a specific facility that should be established as a new research center, as it is necessary to develop a large-scale communal-use facility that has been difficult for institutions to establish and operate. In addition, the Director-General of the Science and Technology Agency submitted a consultation to the Council for Aviation and Electronics Technology on how to effectively develop the infrastructure for earthquake disaster prevention research, and the Council submitted its report in September 1997. The report identified a large-scale three-dimensional testing facility as the core center of the research infrastructure for earthquake disaster prevention, and mentioned the results of a detailed examination, the required fundamental performance, and the specifications of the facility. To implement the reports of the Council, committees, and others, it was decided in 1998 to begin construction of a three-dimensional full-scale earthquake testing facility. NIED began construction of the facility in Miki, northwest of Kobe, Hyogo, and began operation of E-Defense upon its completion in 2005.

The most unique feature of E-Defense is the performance of the shake table to collapse a structure with a maximum weight of 1,200 tons under three-dimensional motion, and E-Defense can conduct experiments to observe the collapse behavior of a structure in detail through more than 900 channels of sensors and cameras. E-Defense also has sufficient performance to simulate the ground motion recorded in events such as the 1995 Southern Hyogo Prefecture Earthquake and the 2011 off the Pacific coast of Tohoku Earthquake. These features make it possible to demonstrate the seismic performance and effectiveness of countermeasure technologies through experiments on specimens of full-scale structures that can be considered the same or similar to the actual structure; the results of research and development with the E-Defense test results can be said to be evidence-based and gain an advantage in terms of reliability.

As shown in Figure 2, the shake table is a steel box-type structure that is 20m long, 15m wide, 5.5m high, and weighs 775 tons. To simulate 3-D shaking based on an actual earthquake ground motion, the table is driven by 24 high-pressure fluid actuation units consisting of actuators and 3-D joints controlled by 44 electrohydraulic servo valves. Three and one servo valves are equipped with horizontal and vertical actuators, respectively, to control the high-pressure oil. The thrust force of each actuator is 4.4 MN, and these actuators can withstand the rotational moment induced by a specimen and shake table. This shake table mechanism allows shaking of a 1,200-ton specimen at the maximum acceleration, velocity, and displacement shown in Table 1. Rotational motion of up to ±2.5 degrees can also be applied in each of the horizontal and vertical axes.

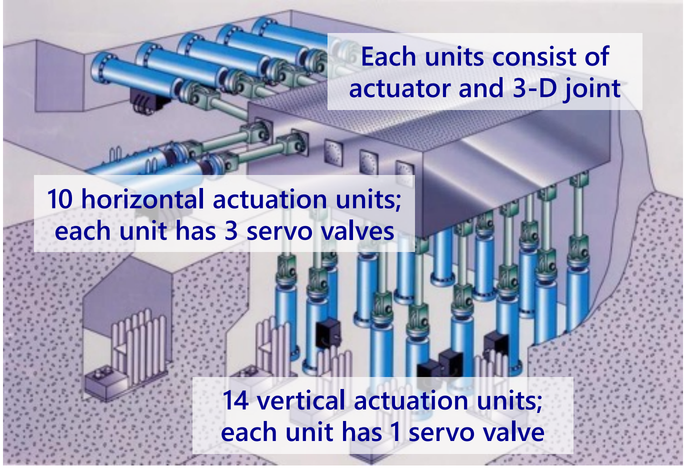

Figure 2. Arrangement of shake table and actuating units.

Table 1. Specifications of shaking performance.

Maximum load	1,200 ton	
Area	300m^2 (20m x 15m)	
Shaking direction	horizontal	vertical
Max acceleration	900cm/s^2	1,500cm/s^2
Max velocity	200cm/s	70cm/s
Max displacement	±100cm	±50cm

Including the shake table and the pressurized fluid circulation lines, the E-Defense facility area is mainly divided into three functions as shown in Figure 3: experiment and preparation, control and data acquisition, and hydraulic supply. The experiment and preparation area includes the Experiment Building with the shake table and its actuation system, the reaction floor, and two 400-ton overhead cranes for placing a specimen on the table, as well as yards and the preparation building for constructing a specimen. There are also large soil containers for liquefiable ground, a sand desiccation pit, and vehicles such as a 900-ton carrier for transporting specimens to and from the table. For control and data acquisition, the Operation Building, adjacent to the Experiment Building, houses the shake table control, data acquisition, and video recording systems, as well as laboratories, meeting rooms, and offices. The hydraulic supply area includes the Hydraulic Fluid Supply Building with four pump units supplying 20.4MPa high hydraulic pressure to the actuators and accumulator units storing 24 kiloliters of high hydraulic pressure, as well as outdoor equipment such as tanks and cooling systems.

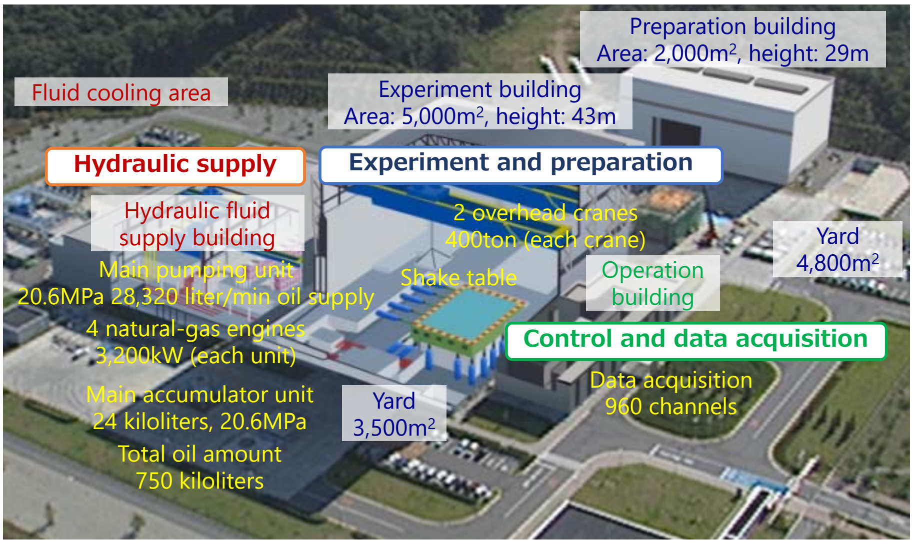

Figure 3. Facility layout.

As of the end of September 2023, 125 experiments have been completed since the start of operations in 2005. NIED has promoted the use of its experimental facilities through facility rental and collaborative research with research institutes and/or companies: 33 experiments were conducted through collaborative research, and 51 experiments were conducted through facility rental. For the 80 of these experiments, datasets, footage, and related materials are provided through the "Archives of Shaking-table Experimentation dataBase and Information (ASEBI)" website shown in Figure 4.

Figure 4. Archives of Shaking-table Experimentation dataBase and Information (ASEBI) (https://doi.org/10.17598/nied.0020).

Due to the large scale and complexity of the facility, equipment and specimens in E-Defense, the use and maintenance of the facility and equipment, as well as the preparation of the specimens, their set on the shake table, shaking, reset from the table and disassembly, are all carried out under strict safety control, and the record of no accidents exceeds a total of 2.56 million hours as of the end of September 2023. It can be said that such a safety record is also a remarkable and important know-how that should be accumulated in the operation of large facilities.

3 Experimental research to evaluate the seismic performance of structures

Through the E-Defense experiments, NIED has been promoting research and development to improve the seismic performance of structures such as buildings and infrastructure to contribute to improving the resilience of society, especially society's ability to resist and absorb natural hazards and recover from disasters.

As shown in Figure 5, from the beginning of E-Defense operation until recent years, experiments were mainly conducted to clarify the collapse mechanisms of buildings, infrastructure, and ground, to evaluate current or new technologies, and to assess the damage to the functionality of a structure, assuming the event when a large-scale earthquake occurs. Then, based on the results of such experiment, research and development to improve the seismic performance and the ability of sustainable functionality have been implemented. This paper here presents some examples of experimental research with E-Defense as summarized by Nishi et al (2023).

Figure 5. Outline of the experimental research with E-Defense from its operation start to recent years.

For research on the clarification of collapse mechanisms, experimental studies were conducted on wood-frame houses, reinforced concrete and steel-frame buildings constructed according to the design codes before 1981, which were damaged and collapsed in many cases during the Great Hanshin-Awaji Earthquake. The E-Defense experiments in these studies provide detailed time-history data on the response of the specimen structures during the process of their damage and collapse due to motion recorded in the 1995 Southern Hyogo Prefecture Earthquake, as well as footage of the collapse process. Some studies demonstrated the effectiveness of reinforcement countermeasures. An example of the studies is shown in Figure 6, which is the experiment on two wood-frame houses that followed by the design codes before 1981. These two houses were originally built in 1964 in Akashi, Hyogo. These were transported and placed on the shake table, and one was reinforced and the other was as is, that is, not reinforced. In the experiment on these houses, while the non-reinforced house collapsed due to the strong motion recorded in the 1995 Southern Hyogo Prefecture Earthquake, the reinforced house survived. The experiment also evaluated the validity of the diagnosis of the seismic performance of a wood-frame house and the effectiveness of reinforcement countermeasures. In addition to the experiments on houses and buildings described above, experiments were also conducted on damage to pile foundations and their surroundings due to deformation and/or liquefaction of ground, and on road bridge piers designed in the 1970s.

Figure 6. Experiment on wood-frame houses: Comparison of damage between unreinforced (left) and reinforced houses.

As an example of the evaluation of current or new technologies, the experiment of the 10-story reinforced concrete building followed by the current design code, as shown in Figure 7, is presented. The experiment demonstrated that the building did not collapse even when applied by motion recorded in the 1995 Southern Hyogo Prefecture Earthquake, which was equivalent to a seismic intensity of 6 upper on the Japanese scale. On the other hand, with regard to its continuous use after the earthquake, damage to the column and beam connections was observed that required consideration for repair or reconstruction. Then, the research team proposed a new design method that absorbs forces at the beam ends to prevent damage to the columns, and validated its effectiveness by observing that no damage occurred even after being subjected to the same applied motion three times (Architectural Institute of Japan, 2021). Other experiments related to technology evaluation include experiments on steel-frame buildings, wooden houses, and buildings with base isolation.

Figure 7. Experiment on the 10-story reinforced concrete building: Overview of the specimen building and detailed view of the damage to the column and beam connection.

In order to assess the damage to the functionality of a structure, taking advantage of E-Defense's unique feature that the specimen can be the same size as an actual building, experiments were conducted to evaluate the influences of earthquakes on the functions of buildings such as hospitals, schools, offices, and residences by setting up an interior space with actual products of non-structural members, such as ceilings and partition walls, facilities, equipment, furniture, fixtures, etc., inside a specimen building.

In the experiment assuming a hospital building, when subjected to the shaking caused by the 1995 Southern Hyogo Prefecture Earthquake as a near-field earthquake, the effect of the seismic isolation installed to the four-story reinforced concrete building in mitigating damage to interior furnishings and equipment was demonstrated, indicating that the influence on the continuation of hospital functions after the earthquake could be limited. However, it should be noted, that inadequate or improper securing of equipment was found to cause damage due to its shifting or overturning as shown in Figure 8, which could fail the medical functions that the building must perform as a hospital after a disaster occurs. On the other hand, when shaking motion with long-periodic components assuming an ocean trench-type earthquake was applied to the specimen building similar to that described above, even in a building with base isolation, equipment on unlocked casters moved significantly and repeatedly hit the walls, causing scattered conditions in the room, and the lid of the water tank on the roof was damaged, causing water to spill. Various observed damages, including these, suggest the possibility of difficulties with the continuity of medical functions in the building. Based on these findings, NIED summarizes these findings in a handbook for earthquake disaster preparedness and distributes it to medical professionals and others (NIED, 2012).

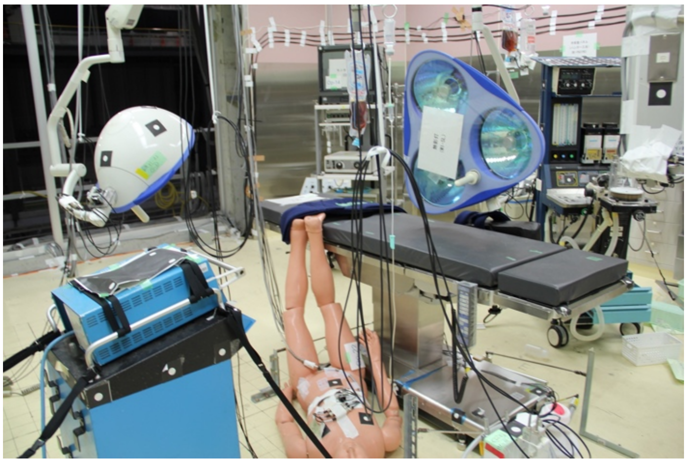

Figure 8. Experiment on the four-story building assuming a hospital: Damage in the operating room.

In addition, to prevent the propagation of earthquake-induced ground motions into buildings, experiments have been conducted to develop floating isolation systems, an example of which is shown in Figure 9, which allow the building and its foundation to be lifted slightly off the ground surface by air or water pressure to significantly reduce horizontal shaking.

Figure 9. Experiment on the floating isolation systems: Overview of the performance demonstration of a specimen and close view of the isolation device.

Based on the data obtained from these experiments, a numerical simulation technology "E-Simulator" has also been developed (see Figure 10). E-Simulator can simulate the behavior of structures observed in the E-Defense experiments with high accuracy.

Figure 10. Website of the E-Simulator Research and Development Project (https://e-simulator.bosai.go.jp/)

4 New research topics on resilience enhancement in regional areas

As a research and development project with E-Defense in NIED's 7-year action plan for the 5th period starting in April 2023, NIED is promoting the project entitled Research and Development for Resilience Enhancement in Region Areas with E-Defense and Research Infrastructure. The outline of the project is shown in Figure 10, which consists of four subprojects as of September 2023. As the next step in the research and development with E-Defense, this project expands the scope of consideration to a group of structures "multiple structures" in a regional area that is a place of social and economic activities, by developing the achievements related to single structures and their functions, which have been the main target of the series of E-Defense research and development projects so far. In addition, this project will contribute to the development of technologies for "preparedness to proactive and future risks" to enhance the resilience of regional areas by improving the performance of social and economic sustainability against a large earthquake and its subsequent series of earthquakes "multiple event" in preparation for future earthquakes such as the Nankai Trough Earthquake.

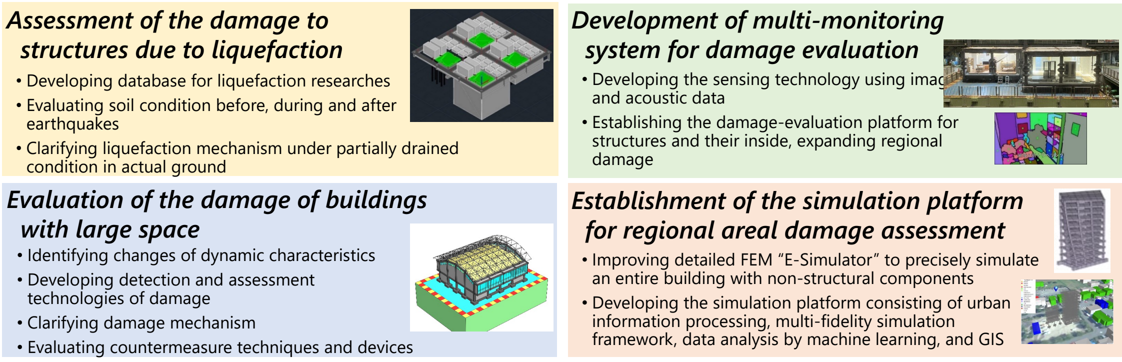

Figure 10. Outline of the "Research and Development for Resilience Enhancement in Region Areas with E-Defense and Research Infrastructure" project, consisting of four subprojects.

To extend the scope to multiple structures, in addition to evaluating the seismic performance of the structure itself, it is also important to understand the effects of the interaction through the ground on the structures, such as damage to the underground structure, connecting infrastructure, and the influence of adjacent buildings, caused by series of earthquakes. Focusing on the ground, which is the foundation of buildings and supports infrastructure, the subproject, which is mainly concerned with geotechnical engineering, investigates the influence of the change in ground conditions caused by sequential earthquakes as multiple events on the structure. Through the investigation, the subproject is planning an E-Defense experiment on liquefiable ground to clarify the liquefaction mechanism under partially drained conditions assuming the actual ground situation, contributing to the development of technologies for assessing the damage to the structure.

To seamlessly assess damage and risk in a large area spanning rooms and the city block, it is considered effective to employ more efficient and rapid monitoring technology in addition to their assessment based on observations from sensors directly equipped to structures. In order to efficiently and speedily detect the spatial change in space in the building or area in the region caused by an earthquake, the subproject for multi-monitoring system development promotes the development of sensing technology to detect and recognize the conditions through spatial data such as footage and acoustics, which will be established based on the results of the E-Defense experiments as well as existing data. The knowledge gained from the subproject will be applied to damage and risk assessment technologies based on spatial data and resulting information, from the rooms of buildings to their surroundings and even to the area in the region.

Large-space buildings such as gymnasiums, which are expected to be used as shelters and logistics centers in emergency response to disasters, are among the buildings in the regional area whose safety and functionality must be maintained. The subproject for building damage evaluation is working to develop technologies to ensure the safety and functionality of a large space building, such as damage evaluation after an earthquake and technology to attenuate the response that causes damage.

In addition, in order to provide reasonable information for regional damage and risk assessment, the project will develop the "regional level" numerical simulation platform, including the E-Simulator, which is based on the knowledge gained from the E-Defense experiments as the core technology, and the cyberspace models based on various buildings and soil conditions.

It is expected that the combination of knowledge gained from this project, including data and results from experiments and numerical simulations, as well as various information and technologies, will lead to improved preparedness for future earthquake disasters.

5 Expected contribution of E-Defense to research on disaster risk reduction

Ensuring the continuity of social and economic activities, that is, establishing reliable resilience against earthquake disasters, is a common goal in countries where earthquakes occur frequently. In order to contribute to the achievement of these common goals, it is necessary to share the datasets, and their resulting findings and knowledge gained from E-Defense experiments globally.

With respect to the E-Defense datasets, since many of them are accessible online, it is expected that they will be used not only in the original research projects of the experiments, but also in other studies. For example, if researchers can properly understand the data, they will gain knowledge similar to that of the researchers who participated in the experiments, and will facilitate comparison and verification with the results of experiments and numerical simulations in their research. While these datasets are currently provided as is, additional materials essential for developing a common understanding of the experiment, such as a data repository and a data paper describing the fundamental interpretation of an experiment, need to be provided globally for their wider use.

In order to continue to obtain valuable data from future E-Defense experiments and to contribute to resilience enhancement for social and economic activities, which must not be limited to earthquake engineering issues, it is convinced that finding "global ideas" through discussions among various researchers and engineers, establishing research infrastructure networks including E-Defense to promote collaborative research and development, and co-creating "evidence-based knowledge" on disaster risk reduction are very valuable.

6 References

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