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Important Roles of Large-scale Shaking Table Testing in Geotechnics

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ABSTRACT: The E-Defense facility, one of the world's largest shaking testing facilities, has been in operation for over 20 years since its operation began in 2005. As of September 2025, it has conducted 14 series of E-Defense large-scale geotechnical shaking table tests. The objectives of these experiments range widely, from academic research focused on clarifying phenomena to governmental and industrial research focused on verifying the seismic performance of soil structures and foundation damage monitoring technology. Through these achievements, large-scale shaking table experiments have proven to be a powerful approach, with the advantage of minimizing scaling effects and enabling capture of detailed behaviors. However, conducting large-scale experiments requires significant costs, making it difficult to repeat, and thus they are not suitable for accumulating data, the importance of which has been rapidly recognized in recent years. Therefore, it is essential to explore methods that mutually complement research results based on large-scale shake table tests with other experimental and numerical research. This will require clearly defining the roles that only large-scale experiments can accomplish. This paper summarizes how E-Defense experiments have contributed to both academia and industry. Based on the summary, it reexamines the unique advantages of large-scale experiments and discusses their potential. Also, the issues involved in applying the results of these experiments to capturing actual ground response will be discussed. Finally, as an example of a new challenge, it addresses ground damage during multiple seismic motions and discusses methods for 1-g large-scale shake table experiments to efficiently contribute to solving this problem.

1 INTRODUCTION

The 3-D Full-Scale Earthquake Testing Facility (hereinafter referred to as E-Defense), managed by the National Research Institute for Earth Science and Disaster Resilience (NIED), Japan, is one of the world's largest 3-dimensional and 6 degree-of-freedom shaking tables. E-Defense, which was designed, developed and constructed after the 1995 Hyogo-ken Nanbu Earthquake and started its operation 10 years after, had been celebrated its 20th year of operation in 2025.

During this period, E-Defense large-scale shaking table tests have made significant contributions to the academic and industrial communities by clarifying disaster phenomena and developing and verifying seismic retrofitting and building health monitoring technologies, by taking its unique advantage. Meanwhile, the maintenance costs for such large-scale testing facilities are extremely high due to their scale. To keep obtaining budget for maintenance, it is always necessary to keep proving that the facilities are still valuable by validating their importance from various perspectives. Therefore, in accordance with changing needs in earthquake disaster mitigation research, the primary objectives of the E-Defense experiments have also changed. Recently, with the popularity of AI-driven research, research utilizing large-scale experimental facilities are also being required to advance to the next stage.

Considering the above, important roles that E-Defense large-scale physical experiments should play now and in the future are discussed in this paper, focusing on geotechnical engineering research. First, the contributions of large-scale physical experiments using E-Defense to academia and industry are summarized with case examples. Following this, the unique features of large-scale physical experiments are reviewed to examine their possible essential roles. Finally, initiatives fulfilling the role of large-scale physical experiments, as presented in this paper, within the ongoing E-Defense geotechnical research project are described.

2 PAST E-DEFENSE CONTRIBUTIONS TO ACADEMIA AND INDUSTRY

To clarify the role large-scale shaking table experiments utilizing E-Defense should play now and soon, it is necessary to review its histories have been conducted in the past. First, since conducting large-scale shaking table experiments costs significant time and money, the experiments must focus on issues achievable only through such large-scale testing. Therefore, it is necessary to maximize the advantages of large-scale physical experiments.

The purposes of conducting large-scale physical experiments using E-Defense are quite various. In the early days of E-Defense operation, experiments primarily focused on "reproducing damage conditions and clarifying phenomena" and "verifying the performance of high seismic resistance technologies." With the subsequent revisions to seismic design standards and improvements of building seismic performance, the main objectives of the experiments have been changed to "verification of structural health monitoring technology" and "enhancement of structural functionality and business continuity." Even at present, experiments aimed at clarifying phenomena or verifying the effectiveness of high-performance seismic technologies have never disappeared. But it is obvious that the primary research objectives have transitioned in accordance with the needs of earthquake disaster mitigation research at each stage.

As of mid-November 2025, the 135 series of E-Defense large-scale shaking table experiments, including 14 series of geotechnical engineering tests, have been conducted. This chapter describes the specification of E-Defense first, and then, how past E-Defense geotechnical engineering large-scale tests have contributed to academic and industrial communities by classifying examples of geotechnical engineering experiments according to their respective objectives. Past E-Defense experiments, including those involving experiments in geotechnical engineering as represented herein, are introduced in elsewhere (Nishi et al., 2023).

2.1 E-Defense Testing Facility

E-Defense is a common-use experimental facility with established track records of conducting collaborative research with overseas research institutions. It is one of the world largest shaking tables with dimensions of 20 m×15 m in the plan (Figure 1), and enables to obtain reference data with minimized scale effects of the specimen. Using 10 horizontal actuators (5 in each direction) and 14 vertical actuators, E-Defense can generate three-dimensional and three-rotational motions. Specification of E-Defense is summarized in Table 1. Because the original E-Defense was designed to reproduce seismic motions recorded in the 1995 Southern Hyogo Prefecture Earthquake, long duration motions due to subduction zone earthquakes could not be generated. Through upgrade of the device in the fiscal year 2013, E-Defense now can apply most of seismic motions observed in the world including long-duration motions recorded in the 2011 off the Pacific coast of Tohoku Earthquake.

2.2 Reproducing damage conditions and clarifying phenomena

In 2006, two series of pile foundation experiments utilizing E-Defense were conducted. These experiments aimed to understand the detailed behaviors of pile foundations during earthquakes. The first series focused on pile foundations in dry sand, while the second series targeted pile foundations in loose saturated sand (e.g., Tokimatsu et al., 2007). The results of these experiments clarified the interaction between the soil, pile foundation, and superstructure, as well as the damage process of pile foundations.

In 2012, a series of E-Defense shake table experiment was conducted on underground structures arranged in a complicated configuration beneath mega cities. This experiment focused on the localized response around the in-ground joints of buildings, which are one of the most critical portions of underground structures. The results of shaking tests indicated that insufficient strength of the underground joints could lead to significant bumps and soil inflow at the joints (Kawamata et al., 2016).

Such large-scale experiments primarily focusing on reproducing disaster damage conditions and clarifying phenomena are research-oriented rather than practical applications. Thus, these experiments have mainly contributed to the academic community by publishing findings.

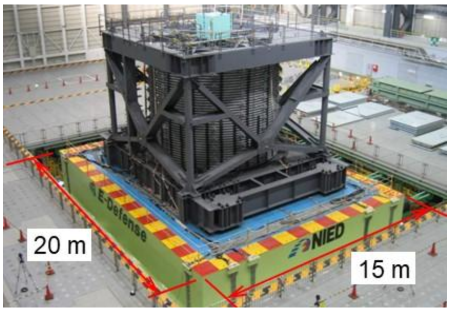

Figure 1. E-Defense Shaking Table

Table 1. Specifications of E-Defense at maximum payload

Max. Payload	12 MN	
Directions	Horizontal	Vertical
Max. Acceleration	9.0 m/s^2	15.0 m/s^2
Max. Velocity	2.0 m/s	0.7 m/s
Max. Displacement	±1.0 m	±0.5 m

2.3 Verifying the performance of high seismic resistance technologies

A series of E-Defense experiments of an existing industrial complex facility on a waterfront landfill site was conducted in collaboration with the National Institute of Maritime, Port and Aviation Technology in 2017. Two 1/8-scale test specimens of the target industrial complex consisting of ground, a pier-type mooring, an access bridge, sheet pile seawall, oil embankment, and an oil storage tank were constructed with and without liquefaction countermeasure. Through the shaking table experiments, the effectiveness of the countermeasures could be verified (Ito et al., 2018).

In 2021, a collaborative shaking table experiment with water pipeline manufacturer Taisei Kiko Co., Ltd. was conducted to verify seismic reinforcement methods for water pipeline joints. The subjects of this experiment included a seismic reinforcement which is expected to be widely utilized in the future, characterized by eliminating the need for water supply interruptions in surrounding areas during reinforcement work. Through this verification experiment, its high seismic performance was confirmed. (Kawamata et al., 2023).

Experiments for the purpose of verifying the performance of seismic reinforcement often make considerable contribution directly to industrial communities. In the former experiment, the operating company of the tested industrial complex implemented earthquake countermeasures based on the experimental results. The latter experiment has contributed to the widespread adoption of a leading seismic reinforcement method, and its application is enhancing the overall resilience of the region.

2.4 Verification of structural health monitoring technology

In 2015 and 2017, two series of experiments on detecting system of damages along piles (Shibata et al., 2021, Yamazoe et al., 2018). In these tests, various kind of sensors were installed along the reinforced and prestressed concrete piles. The results indicate that the degree of pile damage could be evaluated by the records of optical fiber sensors directly installed along the piles, but not from the other sensors.

Pile damage detection system is necessary for determining whether structures can continue to be used and if repairs are required. If developed and validated, it will make significant contributions not only to academia but also to industry. However, the studies above have not yet progressed beyond the research and development stage and have not reached the implementation phase. Therefore, further discussion within the academic community is necessary.

2.5 Enhancement of structural functionality and business continuity

In 2016 and 2018, large-scale shaking table tests on agricultural reservoir levees were conducted in collaboration with a local government. As test specimens, levees were constructed using actual construction procedures, incorporating impermeable artificial bentonite sheets within the levees. These experiments focus not on whether the structure of the levee itself would be damaged by major earthquakes, but rather on whether the water storage capacity of the levee would be compromised. This series of shaking tests indicated that while significant cracking occurred at the top of the levee due to the installation of bentonite sheets, no water leakage was observed downstream, confirming that the water storage capacity was maintained (e.g., Sawada et al. 2018).

In 2019, shaking table tests were conducted on a test specimen consisting of a three-story wooden house with high seismic performance built on the sandy soil, and various utility pipelines. As the result of the experiment, the wooden house slipped on the ground, causing critical damage to the sewage pipeline and resulting in the complete loss of sewage functions. This is probably due to houses with higher seismic performance becoming less prone to deformation, which in turn makes them more likely to slide and suggests that to maintain building functions, it is necessary to consider the possible side effects of enhancing the seismic performance of the structure itself. (Kawamata et al. 2020).

The results of the former experiments are being utilized in government agricultural administration decision-making, indirectly making a significant contribution to industry. Regarding the latter experiment, the loss of sewage functions is expected to significantly impact business continuity following major earthquakes. It serves the academic and industrial communities by suggesting challenges to be solved as soon as possible.

2.6 Summary of E-Defense Contributions

In this chapter, past E-Defense geotechnical experiments are categorized by their objectives and summarized in terms of their contributions to academia and industry. Reviewing the above E-Defense experiments indicates that research outcomes have been achieved by leveraging the following advantages of large-scale physical experiments.

- Minimize the influence of scale effects
- Prepare test specimens using the same or similar construction methods as the actual structure
- Capture localized behaviors in detail
- Assess soil characteristics using ground investigation methods employed at actual construction sites
- Attract social attention

With the above advantages, large-scale shaking table experiments have enhanced their uniqueness to advance the clarification of phenomena, the development and verification of technologies, and the improvement of resilience. This has contributed to activating academic discussions and developing and spreading outstanding technologies in industry. However, considering the costs and time invested in conducting large-scale physical experiments, it is hard to conclude that their potential is being effectively utilized. Merely publishing academic papers or research reports using experimental results and releasing difficult-to-use data give insufficient contribution to communities related to earthquake disaster mitigation. Considering these issues, the roles that E-Defense experiments should play to maximize contributions to academia and industry are discussed in the next chapter.

3 EXPECTED ROLES OF E-DEFENSE EXPERIMENTS

In recent years, the increasing severity of natural disasters due to global climate change has led to a worldwide dispersion of disaster mitigation research resources. However, even under such circumstances, the possibility of a major earthquake occurring always exists, and the importance of developing and verifying efficient earthquake risk reduction measures remains. Therefore, it is anticipated that the mutual outsourcing of research resources is going to become increasingly important in the near future.

Data obtained from a single large-scale physical experiment reflects only the conditions tested, and it may not be the same under different conditions. It is important to evaluate the impact of each condition by conducting a series of physical experiments by changing the conditions one by one. Particularly in the field of geotechnical engineering, since each site possesses unique conditions, it is critically important to clearly identify the impact each condition has on the degree of earthquake damage. Considering the cost of large-scale experiments, conducting numerous large-scale physical experiments under various conditions is not reasonable. Maximizing results through complementary approaches involving small-to-medium-scale physical experiments and numerical analysis is necessary. However, with the recent shortage of research resources, it is practically impossible for a single research facility to conduct comprehensive research covering them all.

Based on the above, the most important role of large-scale geotechnical physical experiments is to provide reference-quality data to the international research community. This enables the data obtained to be utilized to the fullest extent by many researchers in the world, stimulates discussion within the academic and industrial community, and promotes the sharing of research data among researchers, thereby maximizing the achievements of the community. In this chapter, construction of international research networks is proposed, including the data sharing and effective utilization of large-scale experimental facilities such as E-Defense. In addition, as an example of such initiatives, the efforts currently being conducted in the ongoing E-Defense geotechnical experiments are introduced.

3.1 Construction of international research network

If individual researchers keep working independently toward catastrophic disasters that may occur at any time in the near future, it would take too long to achieve sufficient outcomes. Therefore, it is important to establish “big themes” that lead to common goals and create frameworks where many researchers work together toward solving those themes. To achieve this, it is necessary to establish international projects and build research networks that enable all participating researchers to efficiently carry out the research activities required to achieve common project goals. Figure 2 shows an example of the research network. Within this network, large-scale physical experiments, including the E-Defense experiment, provide reference experimental data. These data are available to researchers worldwide and serve as a hub connecting numerous studies. Research utilizing these data, as well as data from related studies, are similarly uploaded to open databases.

The effectiveness of such international initiatives has been verified through the Liquefaction Experiments and Analysis Projects (e.g. Manzari et al.,2018). By incorporating large-scale physical experiments, including E-Defense, into such international initiatives, it is expected that overall research potential would be enhanced.

3.1.1 Sharing of E-Defense test data

Sharing research data is the cornerstone of international collaboration efforts, and its importance

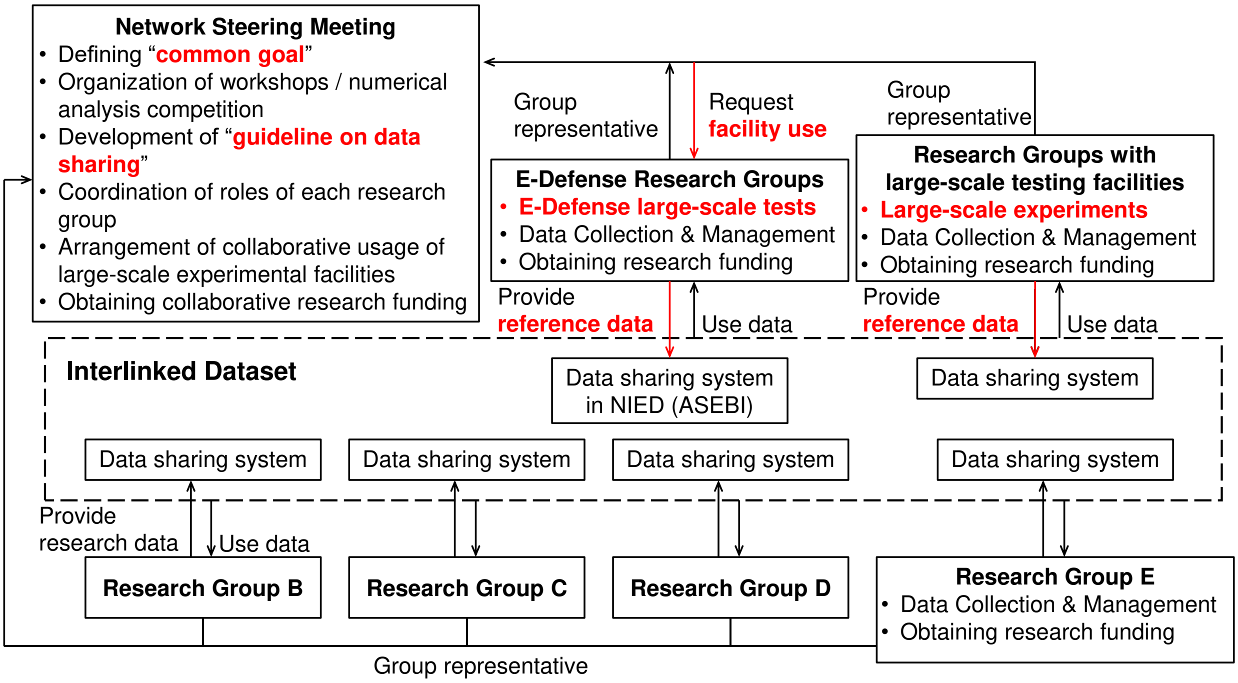

Figure 2. Configuration diagram of possible research network

has grown significantly in recent years. For example, DesignSafe-CI in the United States conducts highly systematic data release. E-Defense experimental data is also available to researchers and practitioners through the Archives of Shakingtable Experimentation dataBase and Information (ASEBI).

As of mid-November 2025, 101 series of experimental data are released, excluding highly confidential experiments conducted by private companies. ASEBI is a user-registration-based system. Since its launch, it had restricted data users to researchers residing in Japan or foreign researchers with counterparts residing in Japan. In 2025, the main portions of ASEBI website have been upgraded to display both Japanese and English language. Most datasets, such as drawings and measurement data, are currently available only in Japanese and translations into English will be considered upon request. Additionally, the DOI identifiers previously assigned to the ASEBI site itself have been assigned individually to each experimental dataset to improve data accessibility. However, the current number of active accounts is approximately 400, and the recognition of ASEBI both within Japan and internationally has not been particularly high.

Furthermore, data release in ASEBI to date has been from the perspective of data providers, and if evaluated critically, the release of data itself had become the goal. Data users who did not participate in the experiment lack the opportunity to confirm the actual test specimens and have to assume many details based solely on released information. Such circumstances may be a psychological barrier to utilizing data provided by third parties. Therefore, discussions from the perspective of data users as well as the providers are also necessary to promote more efficient data sharing. For example, actively providing information about the experiment before it is conducted may be effective in enhancing the data users understanding of the experiment. Furthermore, when data is released, it is necessary to make some efforts to provide the information requested by data users in a way that minimizes omissions, such as by holding hybrid workshops related to the experiments.

3.1.2 Effective use of E-Defense test facility

The effective utilization of large-scale experimental facilities is also one of the key components for constructing international research networks. The E-Defense facility is an international shared experimental facility, and in fact, it has conducted several collaborative experiments with NHERI in the United States. Since the facility opened, the shaking table had been in constant use and had been always occupied, and the occupancy rate of the facility slowly decreased as user demand stabilized. Since then, with the impact of COVID-19 and other factors, occupancy rates have dropped significantly, reaching an extremely low rate in 2023 when the COVID-19 state of emergency ended. Except in 2023, the occupancy rate of the E-Defense experimental facility has hovered approximately 50% for these years. There is an urgent need to improve this rate, by promoting not only domestic but also international facility usage, thereby contributing more significantly to the community.

The primary obstacle to facility utilization is the substantial cost including all expenses, such as specimen construction and demolition fees, sensor management fees, and utility costs for operating test equipment, when conducting large-scale experiments. More reasonable options are being considered for facility users to improve operational efficiency, such as gathering multiple experimental groups and sharing the space on the shaking table with plane dimensions of 15 m by 20 m.

3.2 Ongoing challenges of E-Defense geotechnical testing

In the seven-year medium-to-long-term plan for fiscal years 2023 to 2029 of the National Research Institute for Earth Science and Disaster Resilience (NIED), geotechnical experiments using E-Defense are planned for fiscal years 2026 and 2029. In careful consideration of the features and important role of the large-scale physical experiments mentioned above, this series of large-scale E-Defense shaking table experiments can be being considered as a trial initiative, serving as an example of international research collaboration. Details are described below.

3.2.1 E-Defense test plan

The devastating liquefaction damage that occurred across wide areas during the 2024 Noto Peninsula Earthquake is well-remembered. For example, in Uchinada Town, Ishikawa Prefecture, significant lateral spreading caused numerous houses to tilt (Figure 3). The earthquake recorded in Uchinada Town reached a maximum seismic intensity of 5 lower, but multiple large aftershocks occurred within short intervals, implying that lateral spreading gradually progressed due to these aftershocks. The phenomenon of large-scale aftershocks occurring frequently within short intervals has been observed worldwide, including the 2011 Tohoku Pacific Offshore Earthquake, the 2023 Turkey-Syria Earthquake, and the 2024 Hualien Earthquake. A similar phenomenon is anticipated for the Nankai Trough earthquake, predicted to occur in Japan soon. Therefore, the accumulation of damage due to soil liquefaction during multiple earthquakes can be one of the big themes worldwide.

A schematic diagram of soil liquefaction and deformation accumulation during multiple earthquakes is shown in Figure 4. To evaluate the build-up and dissipation of excess pore water pressure and the accumulated ground deformation for multiple earthquakes, it is necessary to reasonably assess the soil properties at the time of the subsequent earthquake, taking into account the influence of the prior earthquake and the time interval between the earthquakes. The shorter the interval between the prior and subsequent earthquakes, the more significant the impact of the prior earthquake is expected. For a period of two weeks to several months following the main shock, seismic activity becomes higher, requiring consideration of soil property changes over such a long-time span. However, most conventional studies have focused on ground response and settlement/displacement amounts from the time of the earthquake until the dissipation of excess pore water pressure after the earthquake. As a result, there is currently a significant lack of data necessary to evaluate the effects of multiple earthquakes.

Figure 3. Damaged houses due to liquefaction-induced lateral spreading

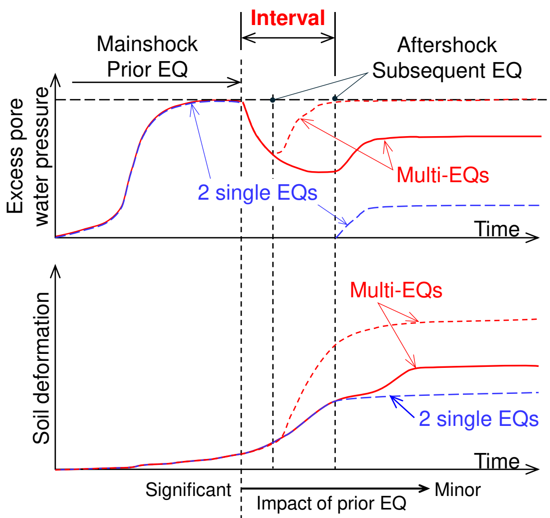

Figure 4. Schematic diagram of soil liquefaction and deformation accumulation during multi-earthquakes

Nakazawa et al. (2020) conducted soil investigations over several years following past earthquakes in liquefied ground. As results, it was confirmed that the penetration resistance in the deeper layers of the liquefied soil increased compared to before liquefaction, while the resistance in the shallower layers decreased. Furthermore, it was clarified that it took 3 months to 1 year for the penetration resistance of the ground to stabilize to a certain extent, and that strength does not recover promptly in accordance with the dissipation of excess pore water pressure. These phenomena are thought to be influenced by rearrangement of soil particles and redistribution of interparticle contact forces, suggesting that soil parameters may undergo significant changes before and after liquefaction. Furthermore, because element tests such as cyclic triaxial tests have limitations in reproducing soil particle sedimentation processes, it implies limitations in setting soil parameters for multiple seismic motions based on the element tests.

Based on the above background, at present, a research project is underway with the primary objective of establishing a method for estimating changes in soil properties after liquefaction, including two series of E-Defense experiments. Figure 5 illustrates the overview drawing of the test specimens in the current plan. Four test specimens will be prepared by installing partition walls within a rigid rectangular soil container with plane dimensions of 4 m × 16 m and a height of 4.5 m, varying combinations of two conditions: "permeability of the ground surface" and "uniformity of the ground".

"Permeability of the ground surface" significantly influences the build-up and dissipation process of excess pore water pressure in the underlying ground, that is, the liquefaction behaviors of the ground during multiple earthquakes. Furthermore, the lower the excess pore water pressure dissipation rate, the slower the sedimentation rate of soil particles after liquefaction, leading to looser deposition. This is expected to significantly impact the soil properties following liquefaction. On the other hand, "non-uniformity of the ground" involves intentionally placing strata with different properties within the test ground to verify how this non-uniformity affects the liquefaction behaviors of the ground. Furthermore, as part of the ground investigation, not only detailed material tests are conducted, but conventional ground investigations such as SPT and CPT are also performed to confirm how much non-uniformity these investigations can be capture. These data are necessary for validation of test methods, such as how precisely the sedimentation velocity of soil particles needs to be

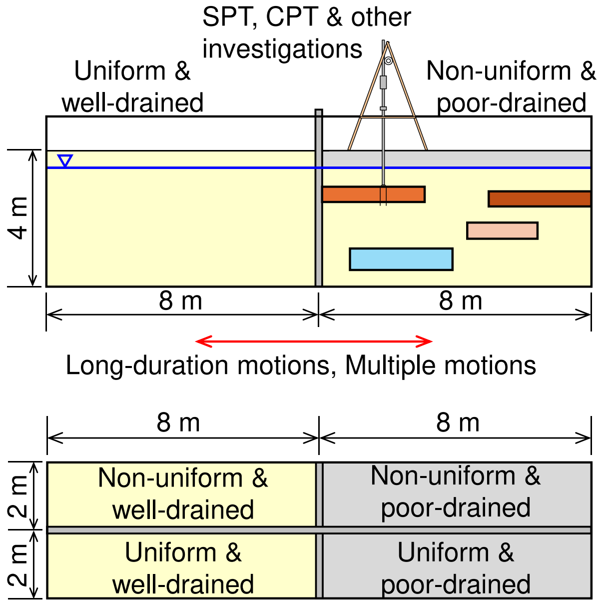

Figure 5. Overview drawaing of the test specimens in the current plan

reproduced in centrifuge model tests targeting liquefaction during multiple earthquakes, and for discussing the validity and uncertainties of design and analysis. This experiment takes unique advantage of the large-scale physical experiments: evaluating localized responses of non-uniform ground, reproducing sedimentation phenomena of soil particles with minimum scale effects, and assessing ground characteristics using actual field investigation methods. Furthermore, as a fundamental experiment using only ground material, it can provide reference data for numerous similar studies.

The shaking test will be conducted in two stages. After liquefying the test specimen in the first shaking test, the specimen will be left for a period of 1.5 to 2 months before conducting the second shaking test. During the resting period, ground surveys will be conducted regularly to evaluate the transition of ground properties over time.

3.2.2 Numerical Analysis Competition

In this experiment, a two-phase international numerical analysis competition will be conducted. In the first phase, only the results of the SCP and CPT tests conducted before the first shaking test will be provided, as well as dimensions of the soil container and input seismic motion. Participants in this competition will need to consider how to model the ground and how to evaluate the soil properties once liquefied by using only the above limited information. In the second phase, all detailed information will be provided, including detailed ground cross-sections, results from SCP and CPT tests prior to the second testing, and dynamic properties of soil materials. The participants can compare these with the results from the first phase to conduct a comprehensive validation on modeling of the soil structure and parameter setting.

By holding such numerical analysis competitions, more researchers can participate in the E-Defense experiment, promoting the widespread utilisation of the data. This takes advantage of the characteristic of large-scale physics experiments to “attract public attention”. Not only can efficiently progress in research and technological development be expected through numerous researchers discussing the same theme, but it can also provide opportunities for co-creation with researchers worldwide.

3.2.3 Data sharing

The data obtained from the E-Defense experiment will be promptly released to ASEBI once the numerical analysis competition concludes and the journal paper and data paper describing the experiment are published. At the time of data release, a hybrid workshop will be held to announce the results of the numerical analysis competition and provide detailed reports on the experiments. The results of the competition and research findings utilizing this data will be considered for publication in a special journal issue. Furthermore, like the E-Defense experiment results, the results of related experiments being conducted will also be considered for release in ASEBI.

4 SUMMARY

This paper describes the roles the E-Defense large-scale physical experiments have fulfilled to date and will fulfil in the future. The data obtained from these large-scale experiments can serve as a hub connecting numerous researchers, playing a critical role in the construction of international research networks. The ongoing E-Defense geotechnical research project will serve as one of trials for advancing various initiatives.

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