VISION AND CURRENT STATUS IN DEVELOPMENT OF THREE-DIMENSIONAL SEISMIC ISOLATION SYSTEM BY FLUID LEVITATION

K. Kajiawra (1), M. Yamada (2), E. Sato (3), T. Horiuchi (4), H. Kase (5),
M. Hayatsu (6), T. Tomizawa (7), M. Yasuda (8)

(1) *Director, E-Defense, National Research Institute for Earth Science and Disaster Resilience, kaji@bosai.go.jp*
(2) *Research Fellow, E-Defense, National Research Institute for Earth Science and Disaster Resilience, m-yamada@bosai.go.jp*
(3) *Chief Researcher, E-Defense, National Research Institute for Earth Science and Disaster Resilience, eiji@bosai.go.jp*
(4) *Research Fellow, E-Defense, National Research Institute for Earth Science and Disaster Resilience, thori@bosai.go.jp*
(5) *Mechanical Designer, Engineering Department, Nemoto Project Industry Co., Ltd. h-kase@nemoto-kikaku.com*
(6) *Senior Chief Engineer, Development Center, Hitachi Plant Mechanics Co., Ltd. masaki.hayatsu.wz@hitachi.com*
(7) *Senior Assistant Professor, Department of Architecture, School of Science and Technology, Meiji University, tomizawa@meiji.ac.jp*
(8) *Professor, Department of Mechanical Engineering, Setsunan University, ma-yasud@mec.setsunan.ac.jp*

Abstract

It is becoming necessary to upgrade earthquake countermeasure technologies for further mitigation of infrastructure damages. For this purpose, we are making efforts to realize a “Zero Earthquake Damage Area” that is an effective way for protecting safety and security of people. Here, “Zero Earthquake Damage Area” means a city block with area of some tens of thousands square meters under seismic isolation. This area could not only provide safety and security from large earthquakes within the area but also play an important role in rescue and recovery from damages of community functions in surrounding areas because the economic and community activities in the area do not terminate even after large earthquakes by virtue of the seismic isolation. For this sake, we are developing a type of three-dimensional seismic isolation system by fluid levitation. This paper describes the vision, current status, lessons learned and the future plans of this development.

Keywords: Earthquake; Three dimensional seismic isolation; Air levitation; Negative stiffness; Block isolation;

1. Introduction

Reflecting recent large earthquakes such as the Great East Japan Earthquake of 2011 and the Kumamoto Great Earthquake of 2016, it is said that Japan has been in an earthquake active period and also Tonankai Trough earthquake in the near future should be prepared. To prepare this situation, we are making efforts to realize a “Zero Earthquake Damage Area” that is an effective way for protecting safety and security of people. We are considering two approaches to achieve this. One is to establish an analysis platform to clarify the cost-effectiveness of technology application. We call this, “the Urban Cyber Physical System (CPS)”. Another is to propose and realize an excellent seismic isolation system. An image of the development system is shown in Fig.1.

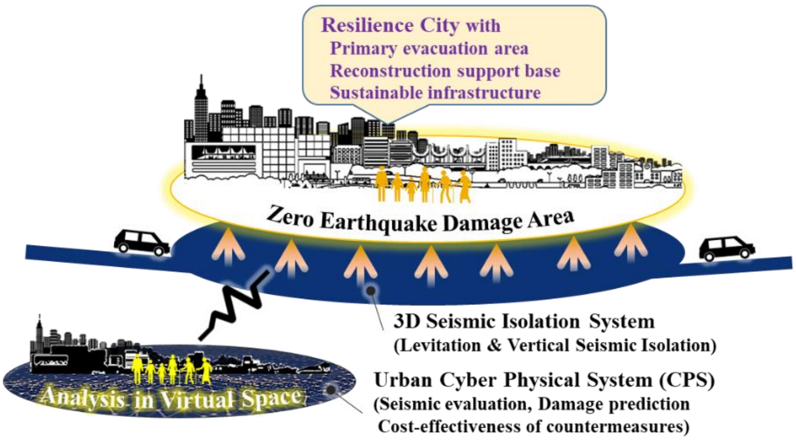


Fig.1 – Image of the development system

2. The Urban Cyber Physical System (CPS)

2.1 Basic concept

In the 2018 White Paper on Disaster Management [1], "Investment for disaster risk reduction" was mentioned as the most necessary future disaster countermeasures. It is said that "The major players engaging in preparation measures, namely, local governments, private companies and residents, must recognize "how much damage" will be inflicted at "what frequency of occurrence" to promote investment in disaster risk reduction." Many seismologists have studied the prediction of the frequency of earthquakes and have improved their accuracy. For example, the National Research Institute for Earth Science and Disaster Resilience (NIED) to which we belong, opens the Japan Seismic Hazard Information Station (J-SIS) to the public [2]. On the other hand, "how much damage" is difficult to predict on a case-by-case basis. Therefore, we will consider the effective use of NIED's data from experimental facilities, seismograph networks, existing technologies and other researches.

In order to integrate this information, we plan to build the CPS as a platform. An image of this concept is shown in Fig. 2.

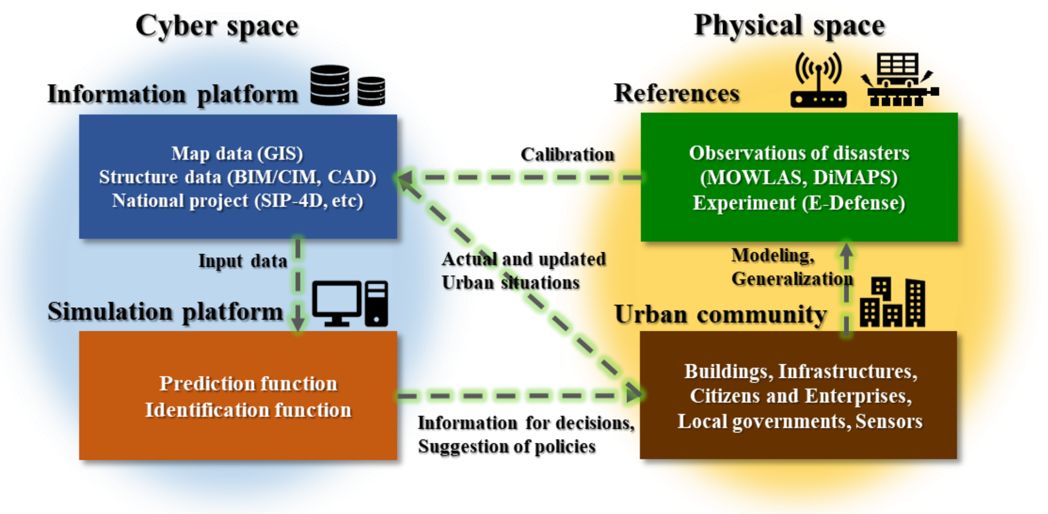


Fig. 2 – Concept of the urban cyber-physical system

In the cyber space, prediction calculations based on physical simulations and evaluation calculations based on statistical models, machine learning, system identification, etc. are performed using the data of city models. The city models are constructed by integrating detailed data, observation data, statistical information, etc. of BIM / CIM structures in addition to the data of various elements that make up the city, such as terrain and GIS of structures. In the physical space, we deal with urban space containing various information such as buildings and social infrastructure structures, citizens who use them, and data on experiments that reproduce actual phenomena related to earthquakes (e.g. E-Defense experiments).

The plan is to integrate these systems into a single simulator to provide information on seismic performance evaluation, damage prediction, cost-effectiveness of countermeasures, and damage assessment that contributes to improve earthquake response capability. The cost-effectiveness of disaster countermeasures would become possible to be quantitatively calculated by the CPS. This is expected to provide an incentive to introduce measures to strengthen earthquake response capabilities, and to enable social implementation of newly developed strengthening technologies.

2.2 Information platform

It is important to utilize existing open data sources as the elements for making up the information data of the CPS. For example, the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) provides Integrated Disaster Information Mapping System (DiMAPS), which is a fusion of Geographic Information System (GIS) and disaster information. The system for collecting and sharing information during the initial response to disasters has been strengthened [4]. And the "BIM / CIM" technology [4] led by MILT are rapidly becoming widely used. Enterprises are also moving to 3D product information in units of equipment, devices, and facilities. Furthermore, the Shared Information Platform for Disaster Management (SIP-4D) [5] developed by the Cabinet Office has begun to function as a basic network system for mutual exchange of disaster resilience information. We would utilize this system to update the information platform of the CPS in the future.

2.3 NIED's facilities and seismograph networks

We plan to apply some of NIED's functions as components of the CPS reference. NIED have constructed and been operating the 3-D Full-Scale Earthquake Testing Facility (E-Defense) since 2005. A schematic view of the E-Defense and examples of various experiments are shown in Fig.3. E-Defense is the world's largest shaking table, which can simulate high level ground motions. By using E-defense, we can obtain the actual earthquake response data of houses, buildings, bridges, ground, tanks, etc. that are directly linked to damage prediction.

(a) Schematic view of the E-Defense

(b) Six-story reinforced concrete building excitation test

(c) Conventional wooden houses excitation test

(d) Reinforced concrete bridge pier excitation test

Fig. 3 – The 3-D Full-Scale Earthquake Testing Facility (E-defense)

Also, NIED has established four nationwide land observation networks (Hi-net, K-NET, KiK-net, F-net) to improve understanding and assessments of earthquakes and their impacts. NIED also has established 16 volcanoes to monitor their activities (V-net) and a seafloor observation network(S-net). In April 2016, NIED took over the operation of another seafloor network (DONET) from Japan Agency for Marine-Earth Science and Technology (JAMSTEC). Integrated operations of these networks have started in November 2017, and the networks were collectively named MOWLAS (Monitoring of Waves on Land and Seafloor) [3]. The MOWLAS observation network is shown in Fig.4.

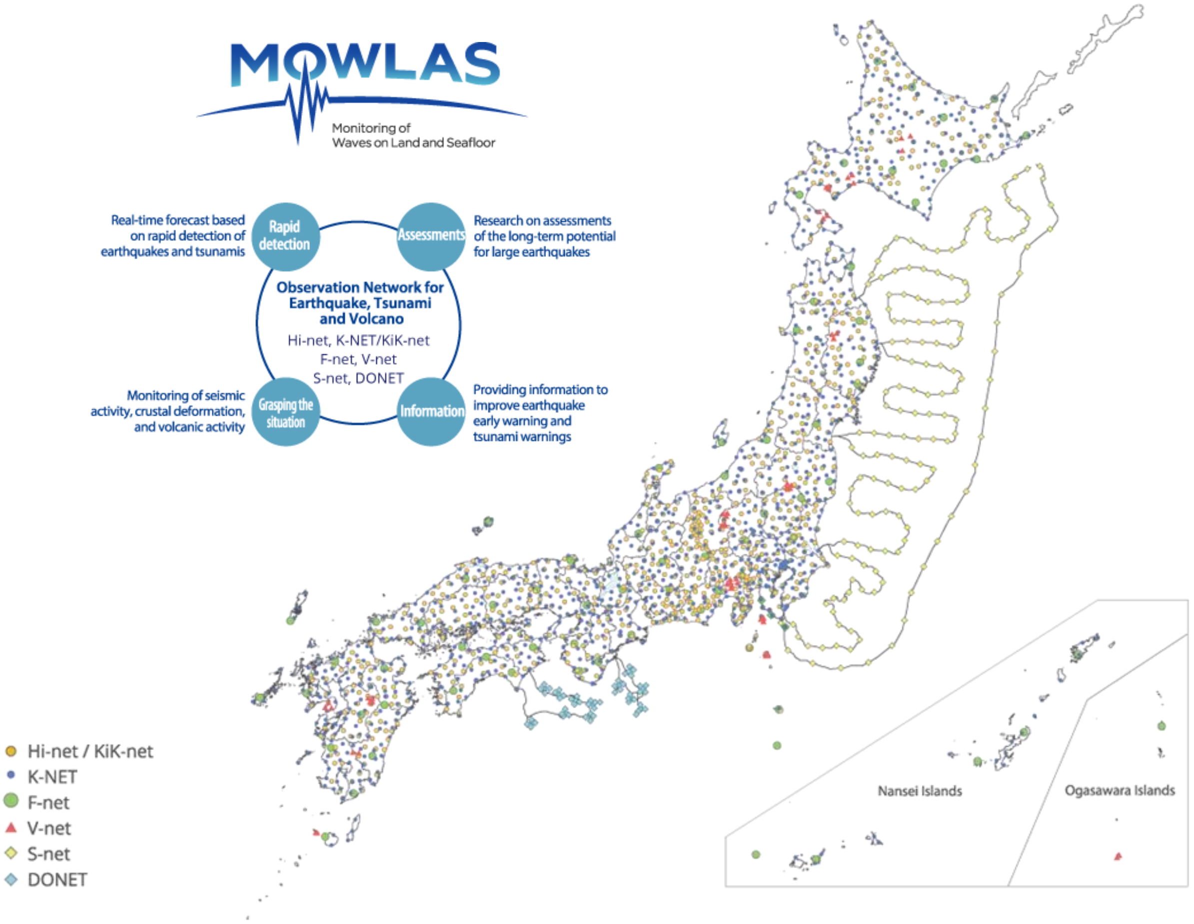


Fig.4 – The MOWLAS observation network [3]

3. Development of 3D Seismic Isolation System

3.1 Target Performance of 3D seismic isolator

At the start of the development, we defined the target performance. As described above, the purpose of this development is to realize the area that continues economic activities even after large earthquakes. In most of infrastructures (gas supplies, elevators, etc.), operation suspensions and / or inspections are required after earthquakes with JMA seismic intensity of Lower 5 or larger. Therefore, the seismic intensity 4 or less on the seismic isolation device was set as the current target value. It is noted that the Japan Meteorological Agency (JMA) seismic intensity class is an index unique to Japan that expresses the magnitude of earthquake. This index has 10 levels measured by 3D acceleration time history data where the detection value of the accelerometer is adjusted to the human sense by emphasizing the periodic component that has a large effect on buildings and humans. The relationship between the period and acceleration of the earthquake and the seismic intensity is shown in Fig.5.

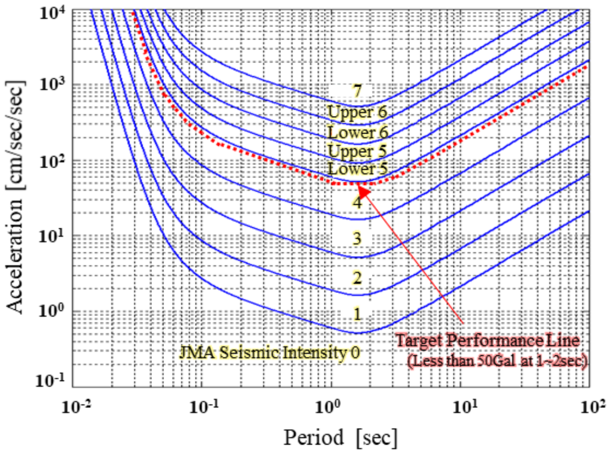


Fig.5 – Relationship between earthquake period, acceleration, the JMA seismic intensity (theoretical value, When the vibration of a uniform cycle continues for several second) and target performance line of 3D seismic isolation device

Created with reference to the JMA website
https://www.data.jma.go.jp/svd/eqev/data/kyoshin/kaisetsu/comp.htm

3.2 The first prototype and excitation experiments

NIED started to develop levitating three-dimensional seismic isolation devices in 2016, taking advantage of its strength in possessing E-Defense. To date, four prototypes have been manufactured and evaluated by excitation experiments. Initially, it started with the concept that if a city or building was levitated like a hovercraft, it would be cut off from the ground and become softer vertically. However, a huge air flow would be required to levitate heavy objects. Therefore, we changed to a system that levitates very low on a flat floor to reduce air flow. It is because height does not matter if it levitates for seismic isolation. The first prototype (No.1) is shown in Fig.6. The horizontal seismic isolation system was a system that levitated by blowing compressed air from air pads and slid on a tempered glass plate with extremely low friction. The levitation height was set to be less than 100μm to reduce the flow rate. On the other hand, vertical seismic isolation used a negative stiffness link mechanism to reduce stiffness while to support large loads. The schematic view of the negative stiffness link mechanism viewed from the side is shown in Fig.7. In the support mechanism, the support force decreases when compressed downward. It can be adjusted stepwise from positive stiffness to negative stiffness depending on the mounting position of the spring. This system has successfully achieved the natural period of

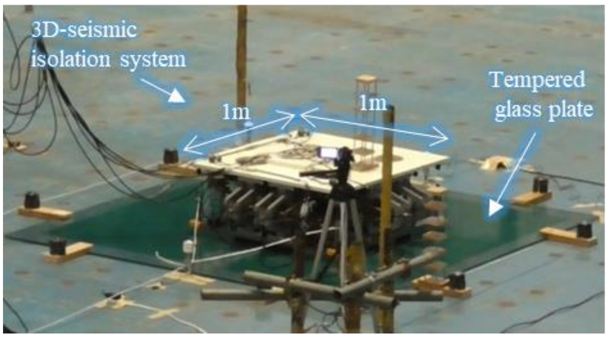


Fig. 6 – The first prototype No.1 (2016).

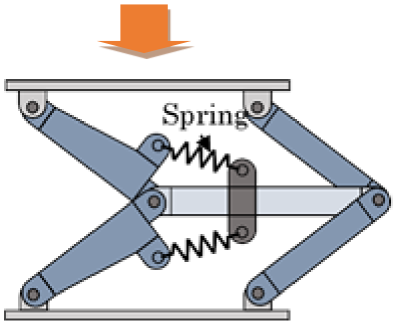


Fig. 7 – The negative stiffness link

vertical seismic isolation as long as 4 seconds. The supporting load was 250kg and the size was 1-m square. Restoration of the position could be possible with a method of pulling with a rope from outside the shaking table, and was primitive but aperiodic. The excitation experiment was conducted with E-defense. We inputted JR Takatori [6] waves of the Hyogoken Nanbu Earthquake and good results were obtained. The acceleration responses of the isolated structure were successfully reduced to 1/10 in the horizontal direction and 1/3 in the vertical [7][8].

3.3 The second prototype and excitation experiments

The second prototype (No.2) is shown in Fig.8. The supporting load of No.2 was 1 ton, four times larger than that of No.1. The horizontal seismic isolation system was the air levitation, which was the same as No.1, and the vertical seismic isolation system consisted of the negative stiffness link mechanisms and air springs. The air spring used was a cylinder type called Air damper. A schematic view of the Air damper in comparison with an air cylinder is shown in Fig.9. The air damper had a seal-less structure to reduce frictional resistance. The gap between the piston and the cylinder was about 70 μm. They are supported by linear guides so as to prevent contact between the piston and the cylinder. In the excitation experiments, No.2 also obtained good results with the maximum horizontal acceleration reduced to 1/10 or less and the maximum vertical acceleration to 1/3 or less. However, there were issues in adjusting the verticality of the air damper and the huge amount of air leakage [9].

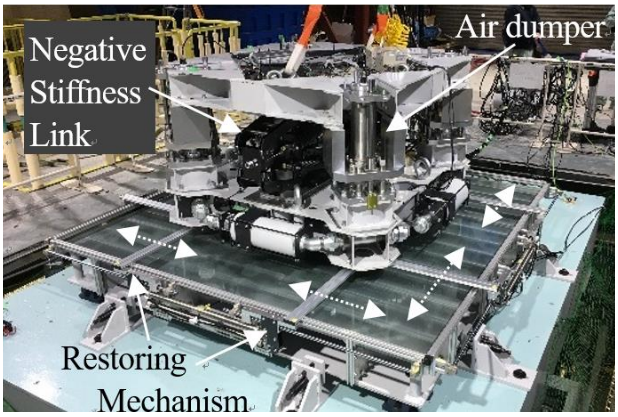
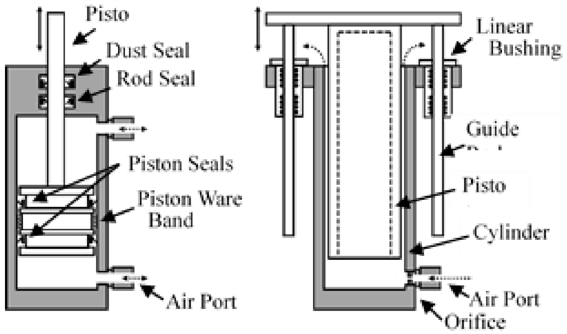


Fig. 8 ─ The second prototype No.2 (2017).



(a) Air cylinder (b) Air dumper

Fig. 9 – Schematic veiw of the Air dumper

3.4 The third prototype and excitation experiments

The third prototype (No.3) is shown in Fig.10. The supporting load of No.3 was 2 tons. The horizontal seismic isolation system was the air levitation as same as No.1 and No.2, and the vertical seismic isolation system consisted of the negative stiffness link mechanisms and coil springs. The negative stiffness link mechanisms had two pairs of orthogonal arrangements to guide the straightness in the vertical direction. The horizontal centering mechanism of No.2 used a slide bar to push it back to the center. However, the coefficient of friction in the horizontal direction was so small, less than 1/5000, that there was a problem that the position of the main body was shifted before

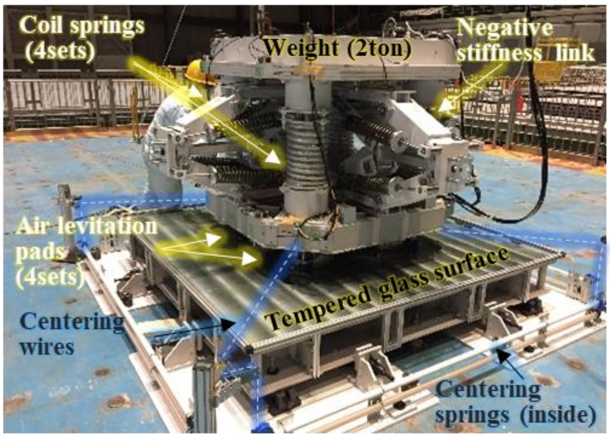


Fig. 10 ─ The third prototype No.3 (2018).

the excitation due to a slight inclination of the base surface. Therefore, the seismic isolation system and the ground were moored by a soft coil spring so that the seismic isolation system could return to the center in order to perform the excitation experiments continuously. As a result, it is not aperiodic, but the period is set to 25 seconds to prevent resonance with the main period component of the earthquake waves. In the excitation experiments, No.3 also obtained good results with the maximum horizontal acceleration reduced to 1/10 or less and the maximum vertical acceleration to 1/3 or less. The maximum response acceleration, reduction rate, JMA measured seismic intensity, and JMA seismic intensity class in each direction on the shaking table and seismic isolation system are summarized in Table 1. JR Takatori[6], K-net Sendai, and Kumamoto Apr.14(KiK-net Mashiki-machi) achieved the target seismic intensity 4 or less while Kumamoto Apr.16 (KiK-net Mashiki-machi) failed to achieve our target. It is thought that the seismic isolation device resonated due to the characteristic long period component of Kumamoto earthquake of Apr. 16[10].

Table 1 – Maximum acceleration, reduction rate, measured seismic intensity and seismic intensity class

Model	Earthquake Wave	X-dir. Acc. [cm/s^2]			Y-dir. Acc. [cm/s^2]			Z-dir. Acc. [cm/s^2]			JMA measured seismic intensity		JMA seismic intensity class	
		Shaking Table	Iso -lator	Reduction rate[%]	Shaking Table	Iso -lator	Reduction rate[%]	Shaking Table	Iso -lator	Reduction rate[%]	Shaking Table	Iso -lator	Shaking Table	Iso -lator
Prototype No.3	JR Takatori	645	67	89.7	580	48	91.8	268	59	78.1	6.4	3.6	Upper6	4
	Sendai	910	67	92.6	1494	40	97.3	307	50	83.8	6.7	3.7	7	4
	Kumamoto(Apr.14)	926	67	92.8	881	47	94.6	1,448	90	93.8	6.7	3.9	7	4
	Kumamoto(Apr.16)	1132	75	93.4	681	55	92.0	914	307	66.4	6.7	5.2	7	Upper5

3.5 The fourth prototype and excitation experiments

The fourth prototype (No.4) is shown in Fig.11. No.4 had distributed legs to support the entire structure and the width and depth of the seismic isolation device were to 2: 1 rectangle considering actual applications. The supporting load increased as large as 10 tons. In this experiment, we focused on the development of horizontal seismic isolation, so we decided to use the same vertical isolation system as that of No. 3. The vertical isolation system has a footprint area as half as that of No.4, so we could experiment with changing the center of gravity depending on the mounting location of the vertical isolation setup. This is important information when applying to actual equipment. The vertical isolation system was too light, so it was mounted on to the center or end of the No. 4 frame with a weight of about 7,000 kg. The horizontal seismic isolation system was a fluid levitation type characterized by low friction in a non-periodic sliding bearing. In order to reduce the fluid flow, the levitation height was set to 100 µm. Although the fluid used in the Prototype No. 1-3 was compressed air, we found that high-pressure air a high risk of accidents and would be subject to various regulations under the High Pressure Gas Safety Act in Japan in the future development of large-scale systems. Therefore, water was selected as a new fluid that can be highly pressurized and has no risk of fire. This time, two types of levitation pads with the same diameter were prepared and their performances were compared. As described in detail elsewhere [7], these two pads achieved a low coefficient of friction of 1 / 5,000 or less.

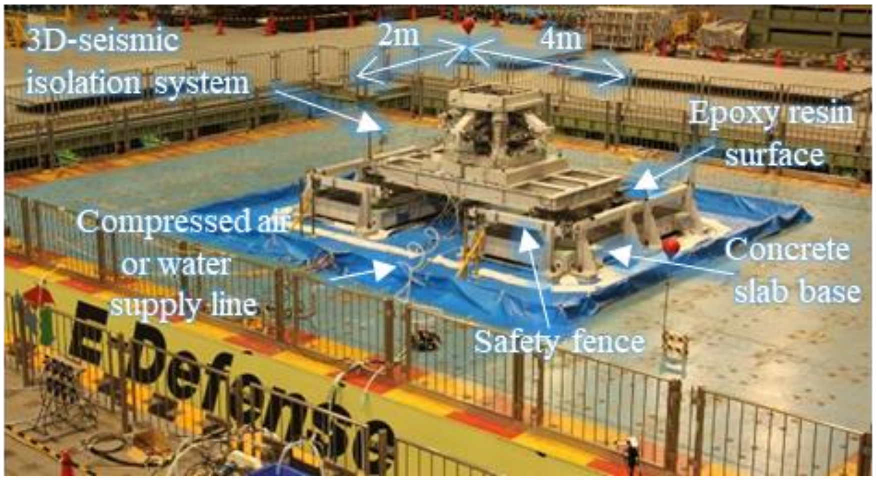


Fig. 11 – The fourth prototype No.4 (2019).

In order to confirm the performance of the seismic isolation system, excitation experiments were performed using actual seismic waves and artificial seismic waves. The actual seismic waves used were the 1995 Great Hanshin-Awaji Earthquake (JR Takatori [6]), the 2011 Tohoku-Pacific Ocean Earthquake (K-Net Sendai), and the 2016 Kumamoto Earthquake on April 16 (KiK-Net Mashiki-machi). Two types of artificial seismic waves were generated: inland earthquake type (Art. Inland) and trench earthquake type (Art. Trench). In the excitation experiments, No.4 also obtained good results with the maximum horizontal acceleration reduced to 1/10 or less and the maximum vertical acceleration to 1/3 or less. The maximum response acceleration, reduction rate, JMA measured seismic intensity, and JMA seismic intensity class in each direction on the shaking table and seismic isolation system are summarized in Table 2. The blue letters indicate the cases that achieved the target seismic intensity class of “4” or smaller, and the red letters indicate the results of “lower 5” of larger. The air levitation pad (artificial seismic waves) case was collided with the retaining wall because the period of the centering mechanism was short. When conducting experiments with water pads, the springs were replaced to avoid such problems. It should be noted that the results of the Kumamoto earthquake showed the seismic intensity of “Upper 5” in all cases. We will try to improve the system in the future. The details of this prototype No.4 is reported in another paper in 17WCEE 2020.

Table 2 – Maximum acceleration, reduction rate, measured seismic intensity and seismic intensity class

Model	Earthquake Wave	X-dir. Acc. [cm/s^2]			Y-dir. Acc. [cm/s^2]			Z-dir. Acc. [cm/s^2]			JMA measured seismic intensity		JMA seismic intensity class	
		Shaking Table	Iso -lator	Reduction rate[%]	Shaking Table	Iso -lator	Reduction rate[%]	Shaking Table	Iso -lator	Reduction rate[%]	Shaking Table	Iso -lator	Shaking Table	Iso -lator
Air pad, Center load	JR Takatori	723	19	97.4	708	22	96.9	255	59	77.1	6.4	3.8	Upper6	4
	Sendai 50%	436	11	97.5	797	14	98.2	165	36	78.4	5.7	3.4	Lower6	3
	Kumamoto(Apr.16)	1,569	142	91.0	1,055	85	91.9	1,519	543	64.2	6.5	5.2	7	Upper5
	Art. Inland 50%	259	121	53.2	213	323	-51.8	202	318	-57.5	5.0	5.6	Upper5	Lower6
	Art. Trench 50%	156	202	-29.7	194	239	-23.1	123	321	-161.1	4.9	5.3	Lower5	Upper5
Water pad, Center load	JR Takatori	717	34	95.3	723	66	90.9	257	79	69.5	6.4	4.3	Upper6	4
	Sendai	914	10	98.9	1,740	6	99.6	375	47	87.3	6.3	3.7	Upper6	4
	Kumamoto(Apr.16)	1,654	159	90.4	1,007	115	88.5	1,479	386	73.9	6.5	5.1	7	Upper5
	Art. Inland	541	29	94.6	439	9	98.0	443	85	80.9	5.6	3.8	Lower6	4
	Art. Trench	318	7	97.8	381	9	97.6	310	63	79.5	5.5	3.9	Lower6	4
Water pad, Edge load	JR Takatori	712	33	95.3	716	38	94.7	252	61	75.9	6.4	3.9	Upper6	4
	Sendai	911	8	99.1	1,741	41	97.6	376	53	85.8	6.3	3.6	Upper6	4
	Kumamoto(Apr.16)	1,584	79	95.0	1,082	84	92.3	1,518	363	76.1	6.6	5.0	7	Upper5
	Art. Inland 60%	315	11	96.4	254	21	91.9	232	45	80.4	5.5	3.4	Upper5	3
	Art. Trench 60%	189	12	93.4	229	24	89.5	159	31	80.5	5.0	3.5	Upper5	4

4. Conclusions

We are studying two approaches to realize “Zero Earthquake Damage Area”. One is to establish “the Urban Cyber Physical System (CPS)”. The CPS is a simulation platform that reflects and integrates existing disaster systems (MOWLAS, DiMAPS, SIP-4D), information infrastructure (GIS, BIM/CIM, 3D-CAD), and actual experimental results (E-Defense). The cost-effectiveness of disaster countermeasures would be quantitatively calculated by the CPS. This is expected to provide an incentive to introduce measures to strengthen earthquake response capabilities, and to enable social implementation of newly developed strengthening technologies.

Another is to propose and realize an excellent seismic isolation system. We are developing a sliding device with fluid levitation in the horizontal direction to avoid resonance that might happen under long-period earthquakes. For three-dimensional isolation, we combined vertical isolation systems that support structural weight with small stiffness using link-type coil spring or air spring. The first prototype (Prototype No. 1) was developed and experimented in 2016. Even though it was a small model with a support weight of 250 kg, it showed a good seismic isolation performance in which acceleration response was reduced to 1/10 under large level earthquake excitations such as Kumamoto 2016. Since then, we continue to develop larger prototypes and the latest Prototype No.4 can show almost the same isolation performance with a support weight as much as 10 tons. In the future, we plan to increase the capacity for actual applications.

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