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Development of the Portable Ground Motion Simulator of an Earthquake

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Abstract— **In recent decades, the devastating earthquakes, which can damage a lot of houses and buildings, have frequently happened. To slow down or prevent the disastrous damages of the earthquake, the various technologies have been required. Of these technologies, the ground motion simulator of the earthquake can be used to alert people to the dangers of the earthquake. This paper introduces a potable earthquake simulator, called a Jishin-The-Vuton 3D, which realizes the up-and-down motion with the holonomic omni-directional motions in order to simulate three-dimensional ground motion of the earthquake. Focusing on the design concept, structure, and feature of this new simulator, the authors discuss its implementation and verify its feasibility with preliminary experimental results.**

I. Introduction

Since there are seismically active regions of the world, technologies and activities to reduce the risk of latent earthquakes are required. As most of damages by the earthquake are due to the collapse of buildings and unban infrastructures, it is crucial to evaluate their existing seismic capacities and then to retrofit and rehabilitate accordingly [1]. In order to be applied to the earthquake-proof evaluations for the constructive structures, or to the observation of destructive mechanisms, shaking tables have been developed [2], [9], [10], [11], [12]. This table simulates high level ground motions; it is called a ground motion simulator of the earthquake (or an earthquake simulator). Since the first operational earthquake simulators in the world were introduced in the 1970s, generally the earthquake simulators have been electro-hydraulic servo systems. These simulators are large, can generate artificial motions with reliability, and usually display enough degrees of freedom to qualify as true earthquake motions. By using these simulators, engineers observe visually and record the dynamic response of structural subassemblies and systems under controlled circumstances. By the way, existing earthquake simulators have been designed for estimating the effects of the ground motion of the earthquake on large-scale structures such as tall buildings, large bridges, power facilities, railway vehicles, etc. [8]; the size of most simulators is above 3m x 3m. Because of their great sizes, they were built and fixed in facilities of companies or research centers or universities. For this reason, many people rarely know about the simulators except for researchers (or engineers) who need to understand the seismic response of structures. However, these simulators are not helpful for only researches. From a different point of view, the simulators can be also used for people's earthquake experience. In the world, at least hundreds millions of people are exposed to a substantial seismic risk of catastrophic damage. However, many people are not conscious of its serious effect on their lives. on their lives. People think that they have already known the danger of the ground shaking motion by the earthquake and can cope with this terrible situation. However, the real experience of the earthquake can throw people into a state of panic. Thus, it is necessary to educate peoples on how to feel and behave when an earthquake happens, and to provide good plans to emergency professionals on how to cooperate with each other in a big disaster [13], [14]. From this point of view, the earthquake simulator can be utilized to alert and educate people to the dangers of the earthquake from the simulation of its disaster. In this paper the authors propose a portable earthquake simulator, called a Jishin-The-Vuton 3D. I-n comparison with existing simulators, the proposed one is small and thus portable. Therefore, many people can easily experience destructive ground motions of the earthquake. The proposed simulator realizes up-and-down motions as well as horizontal holonomic omni-directional motions in order to simulate the 3-D ground motion of the earthquake. In Section II the design concept, structure, and feature of Jishin-The-Vuton 3D are presented. Section III discusses the implementation of the proposed simulator and then provides its validation through demonstration. In Section IV, conclusions are followed.

II. Proposition of Design Concept

A. Design concept

As shown in Fig. 1, there are complicated spatial distributions of the seismic waves when an earthquake happens. The ground motion of the earthquake has various patterns; the nature of ground motion can be investigated quantitatively by the numerical calculation of seismic waves propagating in the seismic center. Therefore, an earthquake simulator should realize various ground motions first.

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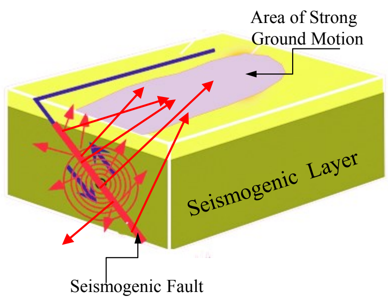


Fig. 1. Propagation of seismic waves on the ground.

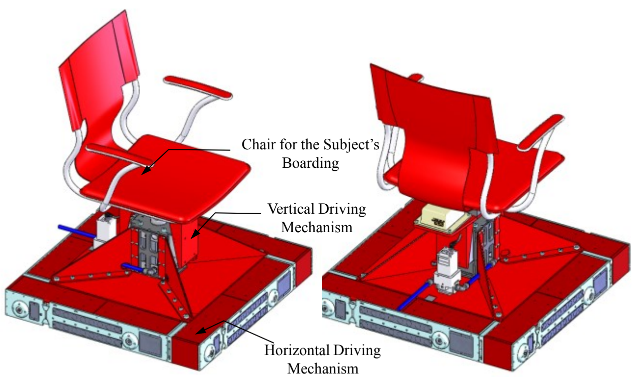


Fig. 2. Structure of Jishin-The-Vuton 3D.

The damage by the earthquake to infrastructures over a wide region is directly caused by seismic acceleration and speed at the base of the structure from seismic strong ground motion. Even if the destruction of buildings in an urban setting is also associated with the dynamic and kinetic characteristics of the medium, information on reliable ground motion related to the acceleration and speed is critical for analyzing the damage mechanisms and destructive processes. Similarly, human beings feel earthquake ground motions due to seismic acceleration and speed. Thus, in order to develop a simulator for experience of the ground motion, it is needed to design an earthquake focal mechanism which can produce the seismic acceleration and speed as well as various motions. Based in this idea, the authors designed Jishin-The-Vuton 3D, which largely consists of a horizontal driving mechanism, a vertical driving mechanism, and a chair on which subject seats, as shown in Fig. 2.

B. *Horizontal driving mechanism*

Since objects placed on the ground are affected by an earthquake, various ground motions mean the movements on the horizontal plane. Thus, for implementing the various motions, the simulator should have the omni-directional driving mechanism for horizontal movement as shown in Fig. 3(a). The horizontal driving mechanism of the Jishin-The-Vuton 3D is based on the omni-directional mobile vehicle which was developed in 1993 [3]. Since both of them are all about the same in basic structure, in this sub-section it is briefly overviewed; for more details such as internal components of the mechanism and its control strategy, you can refer to [2], [3].

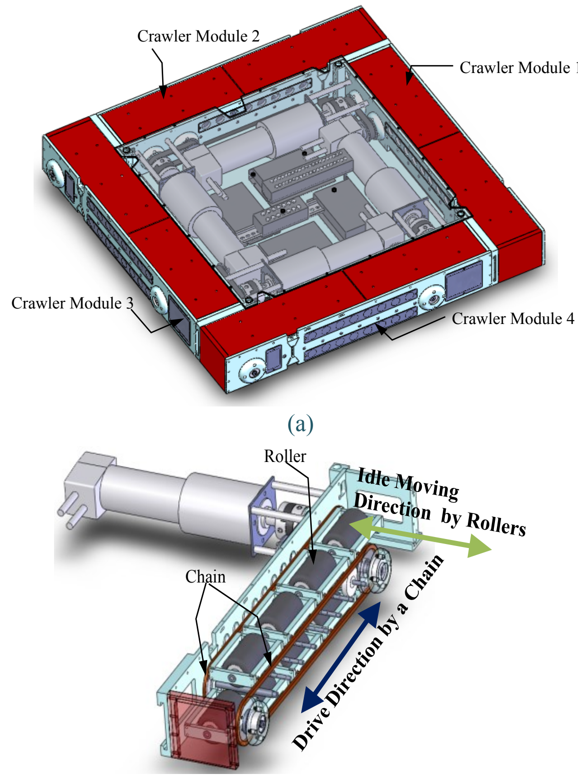


Fig. 3. Structure of the horizontal driving mechanism. (a) Overview. (b) Crawlier module of the horizontal driving mechanism.

This horizontal movement driven by powerful DC motors provides holonomic omni-directional motions to reproduce the acceleration and speed on a plane caused by the ground motion. It is characterized by the large load capacity because the big load is driven by four crawler modules individually as depicted in Fig. 3. In addition, since instant acceleration/deceleration is possible by using combination of the modules, it can be an actuating mechanism suitable for an earthquake simulator reproducing the high acceleration. The crawler module is a mechanism where two rows of chains are driven synchronously by a geared motor and belt. Between the two chains, a number of frames with rubber wheels (roller) are connected. When the chains move, the rubber wheels in contact with the floor generate an actuating force between the floor and the mechanism in the direction of chain movement by gripping the floor. In the direction perpendicular to the movement of the chains, each rubber wheel can rotate freely and carries the load only from above. The crawler module works as an actuating mechanism in a direction parallel to the axis of the roller and as the supporting mechanism following in a direction perpendicular to the axis of the roller.

The combined movement of these modules in the oblique direction can also be generated. With four modules' control, an actuating force can be generated in any directions in Jishin-The-Vuton 3D as depicted in Fig. 4.

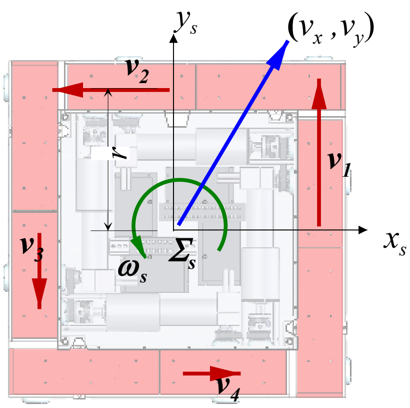


Fig. 4. Schematic diagram of the horizontal driving mechanism.

The velocity command values v_i (i=1~4) to the four crawler modules can be calculated from the velocity command values (v_x, v_y) and the rotational angular velocity $\boldsymbol{\omega_s}$ around the coordinate frame Σ_s at the center of the body :

$$\begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \end{bmatrix} = \begin{bmatrix} 0 & 1 & r \\ -1 & 0 & r \\ 0 & -1 & r \\ 1 & 0 & r \end{bmatrix} \cdot \begin{bmatrix} v_x \\ v_y \\ \omega_s \end{bmatrix}. \tag{1}$$

Here, r is the distance from the horizontal mechanism's center point to each crawler module, and the counter-clockwise rotation is assumed positive. The 4 × 3 matrix is the Jacobian matrix of the control of the omni-directional vehicle.

C. Vertical driving mechanism

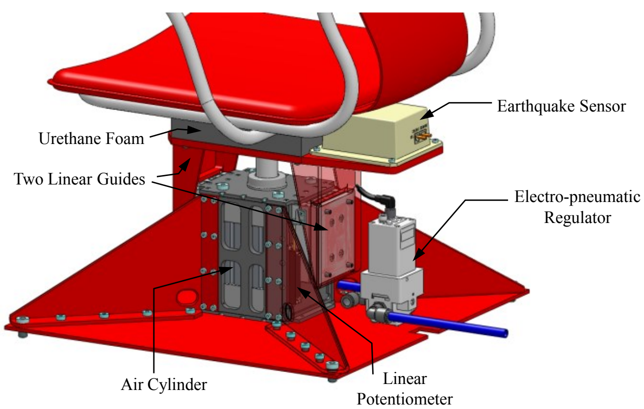


Fig. 5. Components of the vertical driving mechanism.

Since the acceleration change of the vertical ground motion of an earthquake is very fast, the vertical driving mechanism should instantly lift the subject at high acceleration. Thus, an actuator to produce powerful force at a time is required. An air cylinder using the compressed air is suited for this case. Figure 5 shows the vertical driving mechanism equipped with cylinder as its driving actuator.

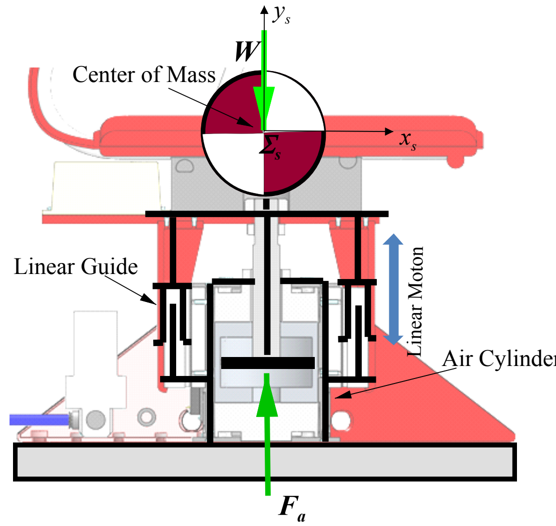


Fig. 6. Schematic diagram of the vertical driving mechanism.

The air pressure of the air cylinder is steplessly controlled in proportion to an electric signal by the electro-pneumatic regulator, which is connected to an air compressor. The end of the rod of the cylinder is attached to the chair. Two linear guides, which are mounted to the bottom of the chair and to the two sides of the housing of the cylinder, support the linear vertical motions of the simulator, as shown in Fig. 6. The up-and-down motions can be realized due to the relation between the given force W in the $-y_s$ direction by the subject's weight including the chair's weight and the controlled force F_a in the $+y_s$ direction by the operating pressure of the air cylinder (where y_s is y-axis of the coordinate frame Σ_s on the subject's center of mass). In other words, the subject who is constant in weight is moved up and down by the control of the air pressure of the electro-pneumatic regulator. The relation between this pressure P_a and the acceleration of the vertical movement a_v is simply driven by

$$\begin{aligned} (m_s+m_c)a_v &= F_a - W = P_a A_a - (m_s+m_c)g, \\ a_v &= \frac{P_a A_a}{(m_s+m_c)} - g, \end{aligned} \tag{2}$$

where m_s and m_c denote are the subject' mass and the chair's mass, respectively. A_a represents the cross sectional area of the air cylinder and g is the acceleration of gravity. Since a linear potentiometer measures the displacement of this motion, the feedback control of the motion can be executed. An earthquake sensor (seismometer) attached to the chair detects the three-dimensional earthquake ground motions, which are produced by Jishin-The-Vuton 3D.

III. Implementation

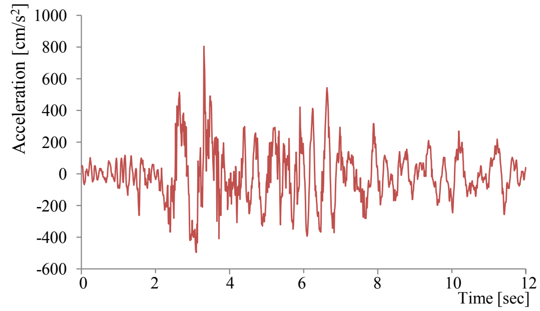
A. System setup and preliminary experiments

Characteristics of the ground motion and the associated damage have been examined [6]. In these studies, a destructive damage zone is defined where maximum acceleration of ground motion is equal to or greater than 800 cm/s^2 and the maximum velocity of the motion is equal to or greater than 100 cm/s. In the gigantic ocean trench earthquake predicted for the near future, long-period ground motion with a structural response of 100cm/s or more is expected to predominate in the sedimentary plains. Accordingly, a prototype of the ground motion simulator was constructed to reproduce maximum destructive ground motion corresponding to seismic intensity scale 7 with around 1 Hz, and to reproduce a motion of more than 100 cm/s in long-period range as a target. Based on these requirements, Jishin-The-Vuton was developed (see Fig. 7).

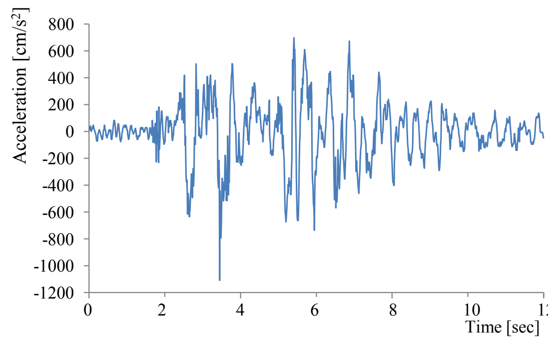
Fig. 7. Prototype of Jishin-The-Vuton 3D. Air cylinder (model: MB1 series, bore size: 100mm, maximum operating pressure: 1.0MPa, stroke: 50mm, manufacturer: SMC). Electro-pneumatic regulator (model: ITV3000series, regulating pressure range: 0.005 to 0.9MPa, manufacturer: SMC). (+25mm).

It weighs about 85kg and measures 744mm × 744mm × 905mm. An external DC power source is used to actuate the simulator. A capacitor circuit for recovery and storage of regenerative power from the motor can be connected externally because reproduction of the ground motion requires actuation of frequent acceleration and damping (deceleration). This enables actuation of high acceleration and velocity of the horizontal moving mechanism. A Windows PC is used to control the simulator. For control of the motors, velocity command data are transmitted in real time via serial communication using CAN bus with a general purpose servo-amplifier. The velocity command data are recorded in CSV text file format in 0.01-second time steps.

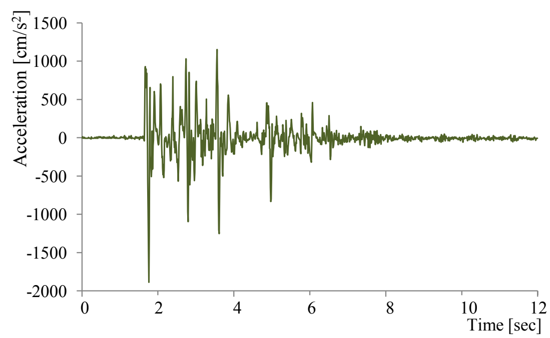
The vertical moving mechanism with the air cylinder to realize the up-and-down motion drive and the electro-pneumatic regulator to control air pressure is combined with four triangle-shaped frames and fixed on the horizontal moving mechanism.



(a)



(b)



(c)

Fig. 8. Acceleration waveform simulated by Jishin-The-Vuton 3D. (a) Horizontal motion (x-axis direction). (b) Horizontal motion (y-axis direction). (c) Vertical motion (z-axis direction).

To evaluate the proposed mechanism, one experiment after another was performed by using the real earthquake ground motion data such as the acceleration waveform recorded at JMA Kobe in Southern-Hyogo Prefecture Earthquake, 1995. After the subject boards Jishin-The-Vuton 3D, the air pressure of the air cylinder is increased by the regulator until the subject begins moving upwards, in order to find the subject's weight (when W is equal to F_a in Fig. 6, the subject's weight can be measured considering the relation of the two forces). Then, the supplied air pressure to realize the up-and-down motion is set up to offset the subject's weight and the subject starts to experience the earthquake ground motion of the vertical stroke 50mm.

Fig. 8 shows the acceleration waveforms, which are sensed by the embedded earthquake sensor, are produced by

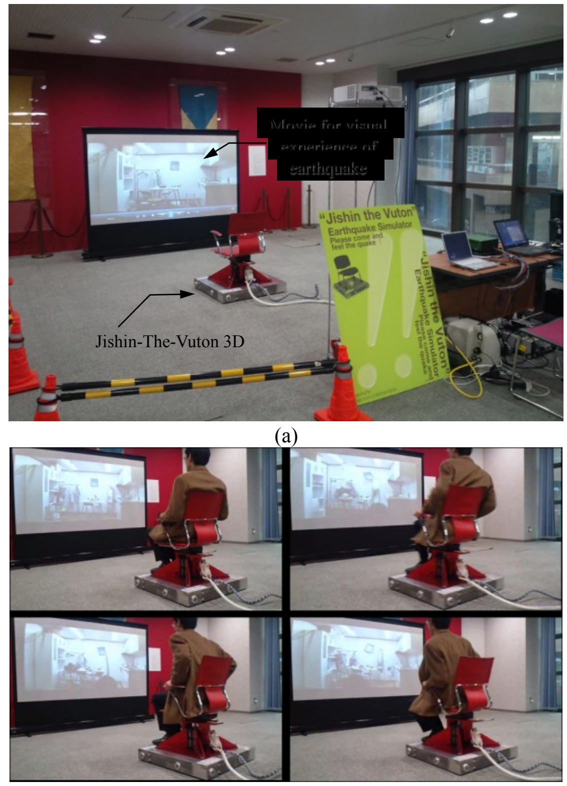
Jishin-The-Vuton 3D. In these experiments, horizontal and vertical accelerations produced by Jishin-The-Vuton are above 700 gal (cm/s^2). These showed successful results of the development of the earthquake simulator because the acceleration of the ground motion of the earthquake is known as about 400 gal, when seismic intensity is 7 (JMA scale: 0~7).

B. Demonstration

According to a recent questionnaire survey about earthquake damage, about 40 percent of injuries are caused by falling furniture. And about 30 percent of the causes of personal injury are due to ground motion. Accordingly, the authors set up the program to experience earthquake ground motion watching the movie which shows how furniture will respond to an earthquake. The movie that shows the simulated room shaken and vibrated by an earthquake plays in the front of the subjects to add realism to them as shown in Fig. 9.

Fig. 9. Vibration platform with furniture and articles arranged in the simulated room.

For effective recognition of the damage caused by destructive and/or long-period ground motions inside a room, movie shows the damage caused by vibration on the large amplitude two-dimensional shaking table. The maximum displacement of the shaking table is ±100cm in the transverse direction and ±50 cm in the radial direction. Maximum acceleration of 1000 cm/s^2 and maximum velocity of 150 cm/s can be generated. Dimensions of the platform are 3.2 m × 2.5 m. A table, chairs, cupboard, and pendant light are arranged inside the room simulating a dining kitchen for the movie of the damage caused by the Kobe Wave. As for the structural response to long-period ground motion, an experiment on a high-rise building conducted by E-defense [5] indicates that a copier with a weight of more than 200 kg may move around for a long period of time because of the casters. Accordingly, for the Kobe Wave experiment where the long-period component of the motion is predominant, articles were arranged so that furniture equipped with casters could move freely while the movie was recorded.



(a)

(b)

Fig. 10. Demonstration of Jishin-The-Vuton 3D. (a) Setup. (b) The experience of the earthquake ground motion.

The demonstration setup is shown in Fig. 10(a). In this system, two operators are required. The one is for operation of the controller PC for Jishin-The-Vuton 3D and the other operates the movie projector. Based on this reliable experimental results, the authors demonstrated the earthquake ground motion simulation by using Jishin-The-Vuton 3D at Tokyo Tech, Japan for two days. In this demonstration, more than forty subjects experienced the motion, as shown in Fig. 10(b). Their main opinion after the realistic experience of the shaking motion by the simulator is that the effect by the ground motion of the real earthquake will be dangerous for people. For example, they told that when the JMA scale was more than 4, they would fall down on the simulator if they did not sit on the chair. Of course, the ground movement during an earthquake is not the direct cause of death or injury because most earthquake-related casualties result from collapsing walls, flying glass, falling objects, etc. However, the effect of the ground movement should not be overlooked because the terrible disaster derives from the movement. The subjects felt embarrassment, fear, and danger through the experience of the earthquake with the ground movement and the virtual environment in the TV. The authors expect that this demonstration is educationally helpful to the subjects.

C. Discussion

Generally, the purpose of the existing earthquake simulators is to reproduce the desired earthquake acceleration and speed to a structure on the table. The reproducibility in acceleration depends on the control performance of the hydraulic actuator. However, since the control of the electro-hydraulic servo system including a servo valve, a hydraulic actuator, a table, and sensors is not so easy, various control methods have been proposed [10], [11], [12]. On the other hand, the mechanism is the proposed simulator is the structure that can be easily controlled by using (1) and (2), and thus only PID control method is used for its control. However, in the earthquake engineering field, exact control to consider the reaction force generated by the vibration of specimen and deteriorating the table motion performance has been issued. Thus, based on further understanding of the earthquake motion, the authors will conduct more realistic simulations such as providing peak values in accordance with empirical ground motion prediction relationships and producing good waveforms with satisfactory resolution in time and frequency domain. The technology of the proposed earthquake simulator is partially commercialized by Hakusan Corporation, Japan, as shown in Fig. 11 and it mimics any type of motions in accordance with the earthquake data recorded in the past. Many people have already have experienced realistic drill of earthquake. The Jishin-The-Vuton 3D was developed for educational purpose. However, if the chair of the simulator to mimic cataclysmic events is replaced to a table, researchers can study the effects of earthquakes necessary to develop advanced technologies for protecting from earthquakes without the support of the existing huge simulators. For example, the small shaking table based on the proposed simulator mechanism can be utilized for the earthquake-resistant design and the seismic proof test of electronics and household items.

Fig. 11. The earthquake simulator VS-3201 (manufacturer: Hakusan Corporation, Japan). The horizontal motion mechanism of the Jishin-The-Vuton 3D except the vertical motion is applied to the VS-3201. The next version of it will include the vertical motion mechanism.

IV. CONCLUSION

In this paper, the authors introduced the new earthquake simulator Jishin-The-Vuton 3D that simulates three dimensional ground motion of the earthquake, and evaluated its performance by using real earthquake motion data. Effectiveness of Jishin-The-Vuton 3D as an educational tool for experience of seismic disaster was also proved. It accurately reproduces destructive and/or long period ground motions combined with the movies depicting the damaged environment inside a room.

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