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3-D Full-Scale Earthquake Testing Facility (E-Defense)

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1 Introduction

In the Kobe Earthquake, which occurred in January 1995, a great number of structures were destroyed including reinforced concrete buildings and expressway bridges that had been thought immune from destruction in an earthquake thus far imagined.

In November 1995, the then Science and Technology Agency established the Round-table Conference for the Study of Bases of Research into Earthquake Disaster Prevention. The conference recommended, in May 1996, that a new research base be created to carry out "comprehensive research aiming at the reduction of earthquake-caused disasters mainly in urban areas" and that a large-scale three-dimensional earthquake testing facility be installed at the new research base.

This article outlines the world's largest 3-D Full-Scale Earthquake Testing Facility (E-Defense), which the National Research Institute for Earth Science and Disaster Prevention, an independent administrative institution, started building in the Miki Earthquake Memorial Park (name provisionally given to the park) in Miki City, Hyogo Prefecture in March 2000 and is to be completed in 2005, 10 years after the occurrence of the Kobe Earthquake. The article outlines also the planned experiments as well as the future prospect of the facility.

The nickname of the facility, E-Defense, which has the letter 'E' to represent the word 'Earth', is a selection from the nicknames collected through a public contest to suggest the best nickname.

2 Kobe Earthquake

The Kobe Earthquake caused more than 6,400 deaths and an economic loss amounting to 12 trillion yen.

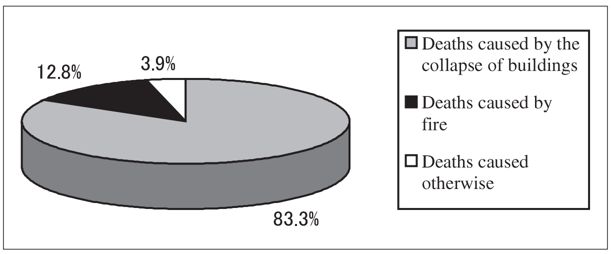
Should the predicted Tokai earthquake occur, damage of 37 trillion yen is estimated.

Most of the deaths in earthquakes since the Great Earthquake of 1923 were considered due to earthquake-related fires. However, more than 80% of the deaths in the Kobe Earthquake were suffocation and crushing due to the collapse of buildings.

This has made it necessary to clarify the process of collapse of buildings (why, how, and to what extent buildings collapse) and to develop and verify new technologies, such as reinforcement methods to prevent buildings from collapse and disintegration, to provide public safety and a sense of security.

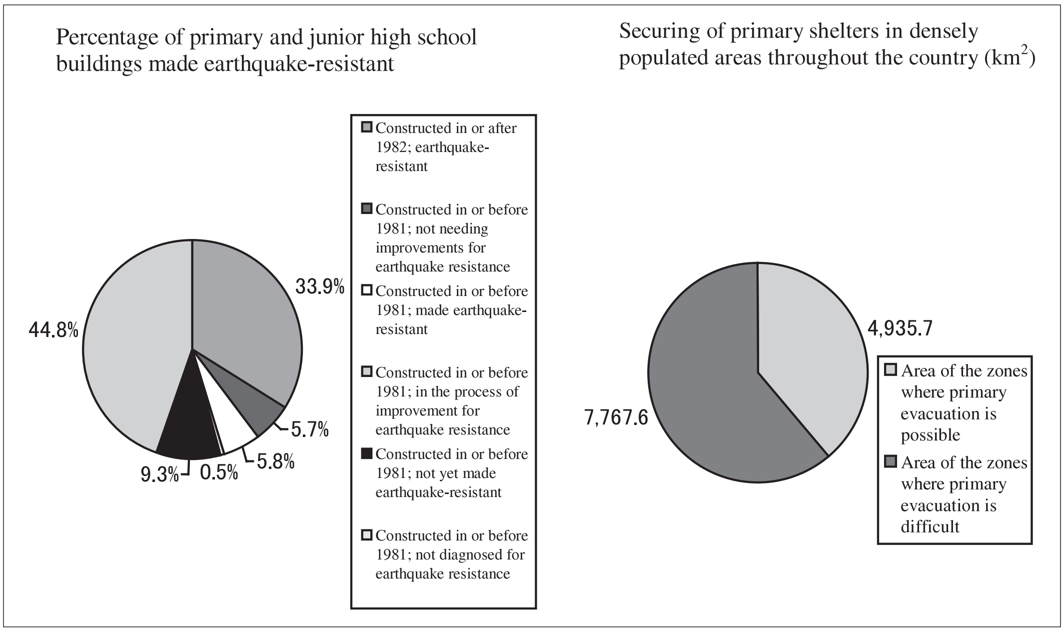
The current Enforcement Ordinance of the Building Standards Act is based on the revision to introduce a new earthquake-resistant design, which was made in 1981 in the wake of the Miyagi-Oki

Figure 1 : A breakdown of the deaths caused by the Kobe Earthquake



Source: A document prepared by the Cabinet Office on the basis of the Statistics of the Results of Autopsies in Kobe City (by the coroners of Hyogo Prefecture - 1995)

Figure 2 : Nationwide investigation of the status of earthquake disaster prevention facilities



Earthquake, which occurred in 1978. The Enforcement Ordinance has undergone revisions concerning the design seismic coefficient, the earthquake-proof criteria and other items repeatedly after large-scale earthquakes.

More than 3,800 school buildings were damaged in the Kobe Earthquake, with those school buildings constructed before the introduction of the new earthquake-resistant design (1981) being most severely damaged. This indicated the necessity of pressing ahead with a plan to make school buildings constructed before the introduction of the new design method earthquake-resistant.

To grasp and analyze the actual situation of the country's measures taken against earthquakes, the Cabinet Office made the first general investigation of the status, as of the end of Fiscal 2001, of earthquake disaster prevention facilities throughout the country, with the final report of the investigation summarized in January 2003.

It turned out that only 46 percent of 151,624 primary and junior high school buildings had been made earthquake-resistant. This points out the urgency of measures such as the making of human-life-related buildings earthquake-resistant and the securing and provision of shelters and evacuation routes.

3 Special project for earthquake disaster mitigation in urban areas

In Fiscal 2002, the Ministry of Education, Culture, Sports, Science and Technology started a program in which subjects of research and development are preliminarily selected in five fields consisting of the four strategic fields of "Life Sciences," "Information and Communication Technologies," "Environmental Sciences," and "Nanotechnology and Materials" plus "disaster prevention" to be consigned as projects to selected execution organizations. These consigned projects are handled under the collective designation of "Research Revolution 2002 (RR2002)."

Among them, the RR2002 consigned project in the "disaster prevention" field is a Special Project for Earthquake Disaster Mitigation in Urban Areas (to be executed 2002 through 2007 with a total budget of 15 billion yen).

The Special Project for Earthquake Disaster Mitigation in Urban Areas consists of the four programs that follow:

(i) Prediction of earthquake motion (strong motion): Regional Characterization of the Crust in Metropolitan Areas for Prediction of Strong Ground Motion;

(ii) Dramatic improvement of earthquake resistance: Research Aimed at the Improvement of Earthquake Resistance Using a Shaking Table;
(iii) Optimization of disaster-handling strategies such as rescue of disaster victims: Research into Disaster-addressing Strategies; and
(iv) Incorporation into earthquake disaster prevention measures.

Program (ii) will be carried out by using the 3-D Full-Scale Earthquake Testing Facility with the aim of contributing to the improvement of earthquake resistance and to the verification of simulation technology.

4 3-D Full-Scale Earthquake Testing Facility (E-Defense)

4-1 Purpose

The Kobe Earthquake of 1995 made us realize the impossibility of designing structures immune from damage. To avoid catastrophic damage caused by an earthquake and protect human lives even if a certain degree of damage is unavoidable, it is necessary to clarify the process of collapse of buildings (why, how, and to what extent buildings collapse).

This is the very purpose of the E-Defense: to shake a full-scale structure on a shaking table three-dimensionally as in an actual earthquake and to record and analyze the process of collapse of the structure with the aim of improving the earthquake resistance of structures.

4-2 Outline of the facility

E-Defense is the world's largest shaking table facility, built on a six-hectare site at the total construction cost of about 45 billion yen. It is configured as shown below.

4-3 Features of the facility

E-Defense, the world's largest shaking table facility, has the following features:

(i) The size of the shaking table is 20 meters by 15 meters, allowing a structure weighing up to 1200 tons to be tested.

Most of the existing three-dimensional shaking test units, which are said to total nearly 30 in the world, are small-to-medium ones allowing a test structure weighing not more than 50 tons to be tested.

The shaking table of the E-Defense facility is capable of being loaded with a four-storied reinforced-concrete condominium building or an expressway bridge pier, allowing a structure to be put to a breaking experiment or an earthquake-resistant reinforcement technique to be put to experimental verification.

(ii) Capability of reproducing three-dimensional motion identical to actual earthquake motion

The X- and the Y-axis on the horizontal are each equipped with five actuators, with the Z-axis on the vertical equipped with 14 actuators, and flexible three-dimensional joints are provided to avoid interference between the axes. These arrangements have lead to the realization of the world's largest full-scale three-dimensional failure-of-earthquake-ground-motion experiment facility with the world's highest performance.

(iii) Capability of performing experiments on the basis of the records of nearly all earthquakes observed the world over

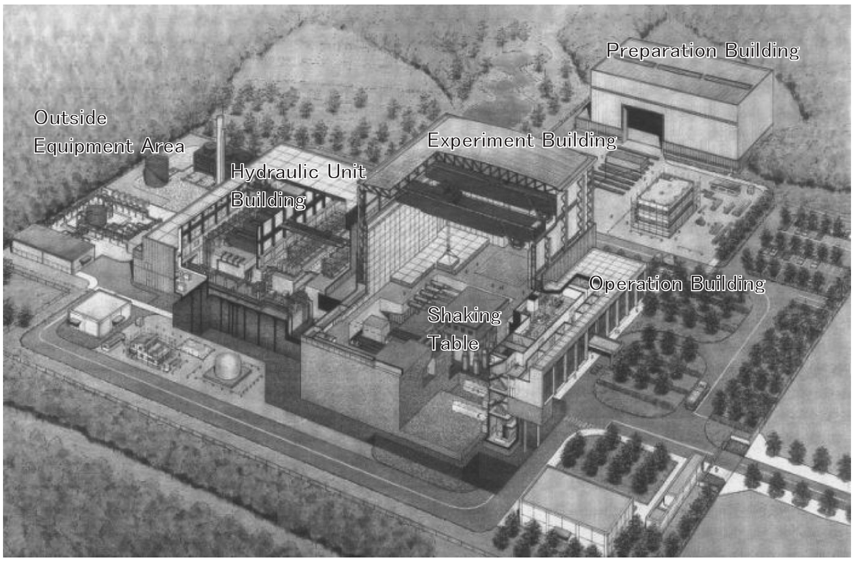
The facility is capable of reproducing the earthquake motion that occurred in the Kobe Earthquake, or in the Northridge Earthquake that occurred near Los Angeles immediately before, allowing the process of collapse accompanied with these earthquakes to be tracked down.

The Kobe Earthquake of 1995 recorded a maximum speed of 138 cm/sec and a maximum displacement of 42 cm, both on the horizontal.

The occurrence of damage to and destruction of a structure is greatly affected by the maximum acceleration; however, the maximum speed and the maximum displacement play important roles in the progress of damage toward the final collapse.

To clarify these effects, four gas-engine-driven oil hydraulic pumps and 20 accumulators (pressure accumulating devices) are installed in the hydraulic power source building, which have been used in the research and development

Figure 3 : Facility layout of the E-Defense



Building name	Description	Type of structure	Total floor area Building height
Experiment Building	Equipped with two 400-ton cranes for assembling and disassembling the main parts of the 3D Full-Scale Earthquake Testing Facility (E-Defense) and test structures	Steel structure, one-storied building	About 5,200 m^2 43 m
Operation Building	Equipped with experiment instrumentation devices and the control system unit for the centrally-operable three-dimensional shaking table	RC structure, two-storied building	About 1,300 m^2 11 m
Hydraulic Unit Building	Equipped with the hydraulic pumps, accumulators and gas-engines that provide the power source for the three-dimensional shaking table	Steel structure, two-storied building	About 4,700 m^2 21 m
Preparation Building	Facility for preparing a test structure; equipped with a 150-ton crane for assembling a test structure	Steel structure, one-storied building	About 2,200 m^2 29 m

Table 1 : Specifications of the major shaking tables in Japan

Organization (location)	Maximum Payload (tonf)	Size (m × m)	Shaking Direction	Maximum Acceleration(G)	Maximum Velocity (cm/s)	Maximum Displacement (cm)	Year of Completion
3D Full-Scale Earthquake Testing Facility (E-Defense) (Miki City, Hyogo Prefecture)	1200	20 × 15	Three-dimensional (X,Y,Z)	Horizontal: 0.9 Vertical: 1.5	Horizontal: 200 Vertical: 70	Horizontal: 100 Vertical: 50	To be completed in 2005
Tadotsu Engineering Laboratory, Nuclear Power Engineering Corporation (Tadotsu Town, Kagawa Prefecture)	1000	15 × 15	Two-dimensional (X,Y)	Horizontal: 1.84 Vertical: 0.92	Horizontal:75.0 Vertical: 37.5	Horizontal: 20 Vertical: 10	1982
National Research Institute for Earth Science and Disaster Prevention (Tsukuba City, Ibaragi Prefecture)	500	15 × 14.5	One-dimensional (X)	Horizontal: 0.5	Horizontal: 75	Horizontal: 22	Completed in 1970 Renovated in 1988
Public Works Research Institute (Tsukuba City, Ibaragi Prefecture)	300	8 × 8	Three-dimensional (X,Y,Z)	Horizontal: 2.0 Vertical: 1.0	Horizontal: 200 Vertical: 100	Horizontal: 60 Vertical: 30	1997

Source: National Research Institute for Earth Science and Disaster Prevention, an independent administrative institution of control methods for generating oscillations faithful to input signals in the electro-hydraulic servo system. Currently, the verification experiment is in progress on the shaking table.

To vibrate the total weight of nearly 2000 tons consisting of that of a test structure and that of the shaking table at a maximum displacement of ±100 cm, the horizontal actuator requires a total length of about 16 meters with the length of the three-dimensional joints added.

In the course of the development of elemental technologies using the simulated shaking table of the actuator, the performance characteristics of the actuator such as its maximum displacement and speed have been confirmed.

4-4 Problems to be studied by means of the E-Defense facility

Structures for which the improvement of earthquake resistance is needed range widely in fields such as buildings, civil engineering work, and machinery.

In the Kobe Earthquake, a great number of structures were destroyed including reinforced concrete buildings and expressway bridges that had been thought immune from destruction in an earthquake thus far imagined, with huge damage resulting from the earthquake.

The greater part of the deaths was due not to fire but to the collapse of wooden houses that had not been improved for better earthquake resistance.

Liquefaction, a phenomenon confirmed in the Niigata Earthquake 40 years ago, caused damage to roads, embankments, sewage drains, and the like. Most large urban areas of Japan are situated in alluvial plains and are therefore susceptible to liquefaction.

In the Tokachi-Oki Earthquake 2003, storage tanks were damaged due to the earthquake, with additional fire accidents caused by sloshing (liquid surface fluctuation) and long-period

Figure 4 : Shaking table and actuator system

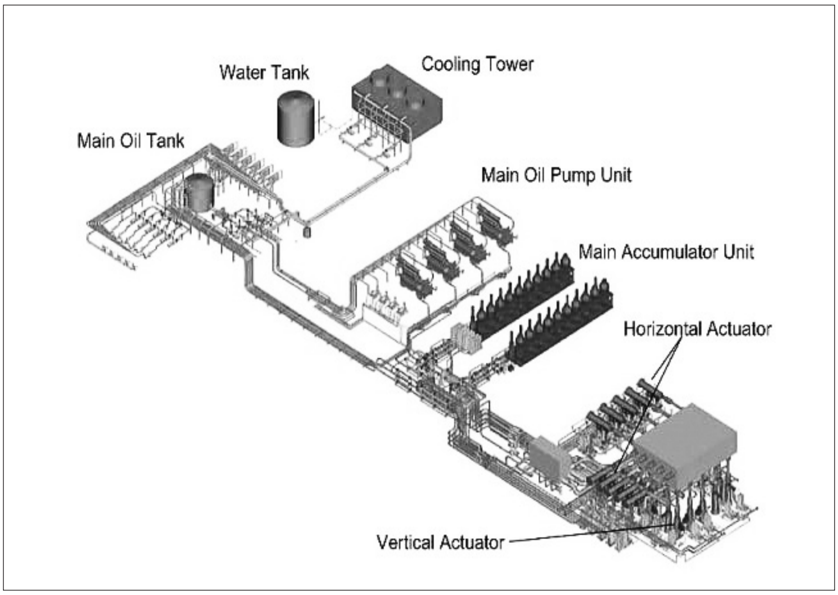
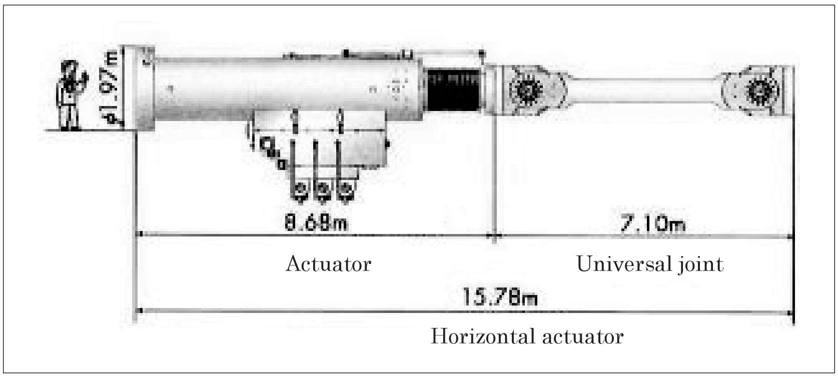


Figure 5 : A schematic diagram of a horizontal actuator



seismic motion.

For the structures mentioned below, the use of the E-Defense facility will allow us to verify the process of their collapse as well as the relevant earthquake resistance technology at full scale and in three-dimensional motion:

(i) To reproduce the process of collapse of a reinforced concrete structure by an earthquake to estimate the damage;
(ii) To reproduce the process of collapse of a bridge by an earthquake to develop and verify new reinforcement technologies;
(iii) To reproduce how industrial facilities like dangerous article storage tanks behave during an earthquake to verify their earthquake resistance;
(iv) To reproduce liquefaction using the ground model created in a special box to assess damage; and
(v) To contribute to the assessment of overall safety of a housing environment and to the development of new earthquake resistance technologies by performing shaking experiments covering the ground, foundation, furniture, and domestic equipment for various types of wooden housing.

4-5 Execution plan (a five-year plan)

The performance test on the 24 actuators of the E-Defense facility has been finished. In May, the 750-ton-weighing shaking table was hoisted using two 400-ton cranes to be installed in the pit. With the joint connection work and the connection of the shaking table with the actuators finished, the facility has been put to test runs and adjustment since July; it will be completed in the coming spring.

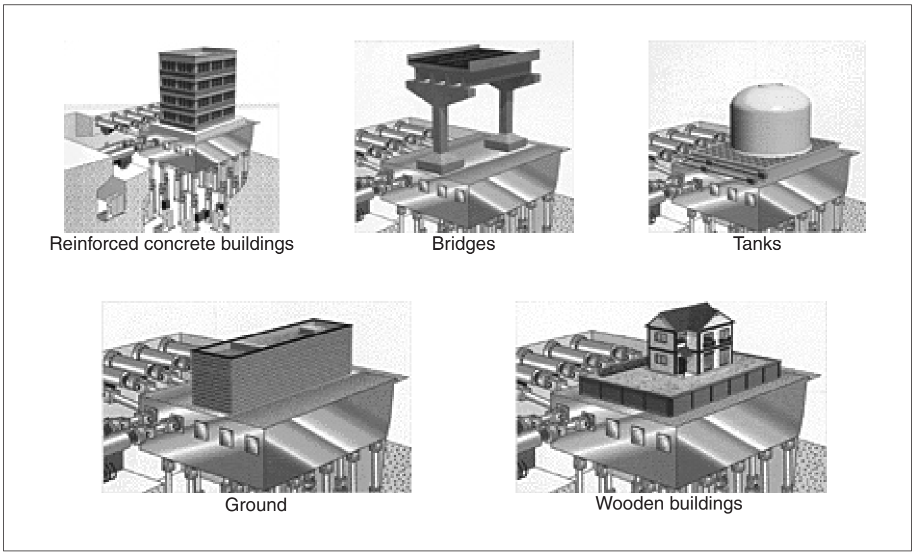
For the two years beginning in 2005, the experiments for the Special Project for Earthquake Disaster Mitigation in Urban Areas are planned, with earthquake resistance experiments on reinforced concrete buildings, wooden buildings, and foundation ground being scheduled.

Preparatory research, planned in view of the E-Defense-based full scale experiment to be started in Fiscal 2005, has been in progress using the existing shaking table since Fiscal 2002.

(i) Experiments on reinforced concrete buildings

- Experiment on the collapse of a one-third-scale reinforced concrete building on a large-scale shaking table (December 2003)
- Experiment for verifying the vibration-migrating performance of a one-half-scale four-storied model building built according to a new construction method enabling easy assembling and disassembling (February 2004)
- Experiment for clarifying the dynamic collapse

Figure 6 : Structures for which the process of collapse and earthquake resistance technology can be verified on the E-Defense facility



mechanism of an earthquake-resisting wall frame structure (scheduled in September 2004)

(ii) Experiments on ground and foundations

- Experiment on the liquefaction and lateral flow of ground arising from a sheared slope soil layer (July 2004)

(iii) Experiments on wooden buildings

- Experiment on the collapse of a wooden building using the shaking table (March 2003)
- Experiment on the collapse of a two-storied wooden building (March 2004)

Earthquake resistance designs and design standards for structures have undergone revisions and reforms repeatedly after large-scale earthquakes.

According to our plan, the findings obtained from the experiments carried out using the existing shaking tables will be reflected in the development of design methods for building and civil engineering structure foundations and of computer simulation programs. In this way, the findings will be fully used in the experiments on collapse scheduled for the E-Defense facility and thereby contribute to earthquake-related estimations.

It is impossible to predict the entire process from the destruction to the collapse of a building by computer simulation. To establish methods of design or reinforcement of structures immune from total collapse to protect human lives from earthquakes, it is necessary to record and analyze the process of collapse of a full-scale structure shaken three-dimensionally on a shaking table.

4-6 Usage patterns for the E-Defense facility

According to the current plan, the E-Defense facility will be owned by a research institution like an independent administrative organization and used in the same manner as existing large-scale research facilities that external organizations are allowed to use.

Three types of usage pattern are available: self-action-based research, joint research, and consigned research. A joint research work is conducted by a domestic or overseas research organization in cooperation with the National Research Institute for Earth Science and Disaster Prevention, with the usage charge split between the former and the latter; the usage charge for a consigned research work is fully borne by the consignor.

In the future, usage charges will be determined on the basis of the expenses necessary to operate and maintain the shaking table and the related facilities.

Applications for usage, to be solicited on the

Table 2 : Special Project for Earthquake Disaster Mitigation in Urban Areas

	Fiscal 2002 to Fiscal 2004	Fiscal 2005 to Fiscal 2006
Experiments on reinforced concrete buildings	Preparatory research 1. Clarification of destruction mechanisms using the existing shaking tables 2. Development of a numerical simulation system 3. Formulation of a full-scale experiment plan	Full-scale destruction experiments Fiscal 2005 Comparison between the new and the old design guidelines Fiscal 2006 Earthquake-resistant reinforcement
Experiments on ground and foundations	Preparatory research 1. Earthquake resistance of ground-pile foundations 2. Earthquake resistance of lateral flow 3. Assessment of three-dimensional behavior 4. Experiment plans and preparation/arrangement of facilities	Experiments on the destruction of pile foundations by an earthquake Liquefied ground and non-liquefaction Clarification of the destruction mechanism of pile foundations Experiments on the lateral flow of bulkheads Establishment of design methods
Experiments on wooden buildings	Preparatory research 1. Observation of earthquake responses 2. Numerical simulation 3. Experiment on collapse 4. Tests on structural elements and investigation of their strength	Determination of earthquake resistance strength and verification of the effect of earthquake-resistant reinforcement • About-30-year-old dwellings • Town houses (build by traditional construction methods) • Group of stores and large-scale stores

homepage of the National Research Institute for Earth Science and Disaster Prevention, will be reviewed by the Committee on the Utilization of the E-Defense to determine whether an application is to be approved and how long the facility is allowed to be used for the purpose of such an application.

Invitations for the application of use of the facility will start in Fiscal 2006 to prepare for the use by external organizations to be started in Fiscal 2007 when the current five-year program is expected to be completed.

4-7 Framework for the management of the E-Defense facility and international cooperation

In June, the Network of Science and Technology experts conducted a questionnaire survey concerning the use of the facilities such as the World's Largest Third-Generation Synchrotron Radiation Facility (Spring-8) and the Earth Simulator, facilities that are unique to Japan or best-performing in the world such as the E-Defense facility. The survey collected various opinions toward the widely open, maximized utilization of the functions of such facilities, summarizing them as follows: (i) dissemination of information on the facility; (ii) establishment of a system allowing easy access to the facility; (iii) enhancement of a supporting framework; and (iv) protection of results obtained using the facility.

The homepage of the National Research Institute for Earth Science and Disaster Prevention has publicized the outline of the E-Defense facility and the progress of its construction work; in the future, the homepage will publicize the data of experiments obtained using the facility and the results of experiments using the facility in the form of reports on research experiments. Further improvement of the environment for the usage by external research organizations will promise the E-Defense's contribution to dramatic improvement of earthquake resistance of buildings.

A plan is under study to run the E-Defense facility as an internationally shared facility that is open for access domestically and internationally alike. In addition, the E-Defense facility will be used to promote and support new experiments and research works under the cooperation of researchers both in Japan and abroad.

In 2002, a management conference and a committee on the utilization of the facility were created. The National Research Institute for Earth Science and Disaster Prevention will set up the Research Center for Earthquake Resistance Engineering (provisional name) prior to the start of the operation of the facility with the aim of carrying out research into improvement of earthquake resistance of structures by using the shaking table and of managing the operation of the facility.

(1) Management Conference forthe 3-D Full-Scale Earthquake Testing Facility

The conference was created with the aim of obtaining advice and guidance on the management of the E-Defense facility from 18 members representing the industrial, governmental, and academic sectors:

(i) Management of the E-Defense facility; and
(ii) Promotion of utilization of the E-Defense facility and medium-to-long term plans for the utilization of the facility

(2) Committee on the Utilization of the 3-D Full-Scale Earthquake Testing Facility

The committee was created with the aim of having 19 people of experience or academic standing formulate experiment programs and coordinate with related organizations:

(i) Programs for experiments using the E-Defense facility; and
(ii) Preparatory research for experiments on full-scale destruction.

(3) Conference on Japan-US joint research into disaster prevention against earthquakes using the shaking table

The conference consists of members of the four organizations below: the Ministry of Education, Culture, Sports, Science and Technology and the National Research Institute for Earth Science and Disaster Prevention, an independent administrative institution, on the Japan side and the National Science Foundation and the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES Program) on the US side. The conference will take up subjects such as the verification of results of E-Defense-based full-scale experiments by means of those based on computer simulation to discuss how to dramatically advance research into disaster prevention against earthquake. In April this year, a basic agreement was reached to explore a new direction of research into earthquake resistance by integrating computer-simulation-based research with E-Defense-based full-scale experiments.

5 Conclusions

The idea of a “minimized disaster” has been proposed meaning that efforts should be made to minimize a disaster to avoid a catastrophic one, though it is impossible to prevent a disaster completely by means of hardware measures.

The improvement in the performance of concrete and reinforcing bars has probably made it technically feasible to build a building immune from collapse. However, it is impossible to design and rebuild all buildings so that they may be free from destruction. The world trend is toward performance design specifying allowable damage corresponding to the strength level of earthquake motion.

To avoid catastrophic damage caused by an earthquake and protect human life even if a certain degree of damage is unavoidable, it is necessary to clarify the process of collapse of buildings (why, how, and to what extent buildings collapse). The role that E-Defense is expected to play is to realize the collapse of a full-scale structure on a shaking table, and thereby contribute to the designing of structures not susceptible to catastrophic damage.

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