



CONSTRUCTION OF E-DEFENSE (3-D FULL-SCALE EARTHQUAKE TESTING FACILITY)

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SUMMARY

The Hanshin-Awaji Earthquake (January 17, 1995) clearly demonstrated that the occurrence of very strong ground motion in the area near to the seismic fault is capable of causing severe structural damage beyond general estimation. It has emphasized the importance of earthquake engineering research into why and how structures collapse in real earthquake conditions. Considering the lessons learnt from recent earthquake disasters, National Research Institute for Earth Science and Disaster Prevention (NIED) plan to construct the 3-D Full-Scale Earthquake Testing Facility (E-Defense is the nickname of this facility), which will be able to simulate the process of destruction of structures under the condition of real strong earthquake motions. The basic performances of E-Defense are maximum loading capacity 1,200 tons, maximum velocity 200 cm/s and maximum displacement 2 m p-p for two horizontal excitations and maximum velocity 70 cm/s, maximum displacement 1 m p-p for vertical excitation to realize destructive ground motion. The construction work of E-Defense has begun at early 2000, five years after the Hanshin-Awaji Earthquake and will be completed at the beginning of 2005, ten years after that Earthquake. Now, we are conducting the construction works of the facility at the Miki-city, near Kobe-city, and the manufacturing and installing of actuators, oil-pressure supply system and other parts of shaking table by the Mitsubishi Heavy Industry Co. E-Defense is the very large scale and high performance testing facility in the world. Therefore, many researchers, which are belonging not only Japanese but also worldwide organizations, can use this facility for their researches. E-Defense should be operated the international common use. For the international research collaboration and the dissemination of research results (including test data), E-Defense Network (ED-Net) will also construct until the completion of E-Defense. ED-Net will connect, through a high performance Internet, distributed major earthquake engineering research organization. We consider that the researchers together from worldwide and research projects will determine and evaluate by the Committee. We hope that E-Defense and ED-Net will be situated to one of the cooperative research organization for the earthquake disaster mitigation in the world.

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INTRODUCTION

The Hanshin-Awaji Earthquake (Hyogoken-Nanbu Earthquake, January 17, 1995) clearly demonstrated that the occurrence of very strong ground motion in the area near to the seismic fault is capable of causing severe structural damage beyond general estimation. The destructive earthquake occurred in the worldwide in the recent years, such as Northridge earthquake (1994), Umbria-Marche earthquake (1997), Kocaeli earthquake (1999), Ji-ji earthquake (1999), El Salvador earthquake (2000), Gujarat earthquake (2001) and so on.

In order to reduce the hazards associated with large earthquakes, it is essential to improve the reliability of earthquake resistance estimations and reinforcement methods in the construction of urban and major structures. For this purpose, failure mechanisms and collapse processes of various kinds of full-scale structures must be investigated. Many types of experimental apparatus have been used for such investigations, and some of them have as large a size as possible to alleviate any difficulties arising from limitation of the model. Considering the lessons learnt from recent earthquake disasters, the National Research Institute for Earth Science and Disaster Prevention (NIED) planned to build a new three-dimensional, full-scale, earthquake testing facility, which can carry large-size soil and structure models and reproduce the processes of structural failure. This facility is expected to become a powerful tool for international collaboration in earthquake engineering research. It also requires international cooperation to successfully complete the facility and to use it effectively for engineering purposes.

Following the technical developments and surveys in earthquake engineering and related fields, the NIED began the design and construction of this new facility in the Japanese fiscal year of 1998. This paper summarizes the construction plan of E-Defense and E-Defense Network (ED-Net), which is the tool for ensure of the international collaboration and the dissemination of research results.

E-DEFENSE (3-D FULL-SCALE EARTHQUAKE TESTING FACILITY)

Based on the lessons learnt from Hanshin-Awaji earthquake, the Minister of State for Science and Technology was inquired to the Council for Aeronautics, Electronics and Other Advanced Technology, which is the one inquire organization of the Minister, for the discussion of the effective arrangement of research bases for earthquake disaster mitigation at March 29, 1996. The Council was reported to the Minister at September 3, 1997.

The report was clearly pointed out the arrangement of large-scale three-dimensional earthquake simulator facility as the core facility of research bases for earthquake disaster mitigation.

NIED initiated the project on the large-scale three-dimensional earthquake simulator facility just after the occurrence of Hanshin-Awaji earthquake. The research and development for core technology for this facility (E-Defense) was started on 1995. The fundamental concepts of this project based on the report by the Council.

The E-Defense will construct as the core facility of the research bases for earthquake disaster mitigation. Therefore, we need to clear the positions of the E-Defense.

- 1) Position of earthquake simulator for the main element of development of the "Time-Space Domain Simulation System for Earthquake Disaster.)
- 2) Position of the clearly understanding of failure mechanism of structures.
- 3) Position of the response mechanism for the request from major subject of earthquake engineering.

The importance of promoting the strengthening and rationalization of earthquake-proof structural design is just one of the lessons from Hanshin-Awaji earthquake. Because earthquake vibrations involve three-dimensional movement, it is necessary to set up a three-dimensional earthquake simulator facility to accurately reproduce earthquake motions. To perform tests on real-size objects or large-scale models of test structures and foundations, it is desirable to have the large-scale three-dimensional shaking table. If large-scale 3-dimensional shaking table is available, tests could be performed to shed new light on the mechanism of dynamic failure using real-size structures. If a stage reached whereby design based on such discovery can be performed, this will contribute immensely to reducing earthquake disaster.

The main specification of E-Defense is shown in Table 1. The limit performance for horizontal and vertical axes is shown in Fig. 1.

Table 1: Main Specification of E-Defense

3-D Full-Scale Earthquake Testing Facility		
Payload	12MN (1200tonf)	
Size	20m × 15m	
Driving Type	Accumulator Charge Electro-Hydraulic Servo Control	
Shaking Direction	X-Y - Horizontal	Z-Vertical
Maximum Acceleration (at Maximum Loading)	>900cm/s ²	>1,500cm/s ²
Maximum Velocity	200cm/s	70cm/s
Maximum Displacement	±100cm	±50cm
Maximum Allowable Moment	Overtuming Moment 150MN·m	Yawing Moment 40MN·m

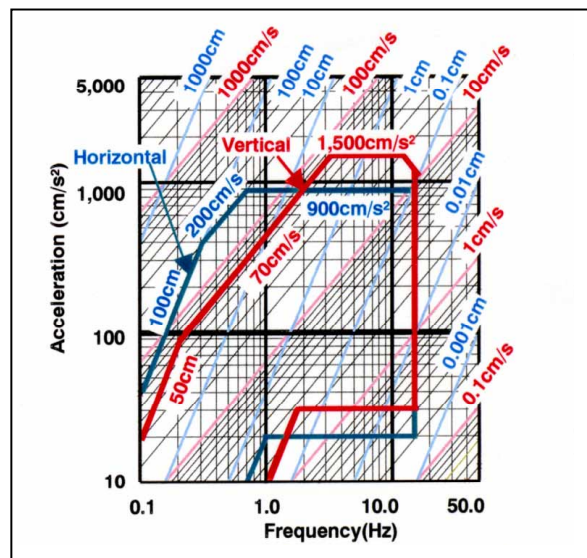


Figure 1: Limit Performance (at Maximum Payload)

TECHNICAL DEVELOPMENT OF HYDRAULIC ACTUATOR AND 3-DIMENSION LINK

TECHNICAL DEVELOPMENT OF HYDRAULIC ACTUATOR

There were four important design points of the hydraulic actuator for E-Defence. The First was to prevent the seizure caused by the bending effect due to its own weight and the large lateral load to the piston ring. The seizure results from the uneven contact and metal contact, which are caused by the inclination of the deformation of piston rod and from the lack of the lubrication by the high-speed reciprocating of piston rod under the high Hertz stress due to the large lateral load. The second was to satisfy the required capacities of the bearing system. The third was to prevent the seizure at the sealing system between the piston rod and the cylinder. The last one is to minimize the friction load occurred between a piston rod and the bearing system, and seals for the reappearance of earthquake wave.

And, to confirm the allowable errors when it was machined, manufactured and assembled is another important point. Figure 2 shows the newly developed components for the hydraulic actuator.

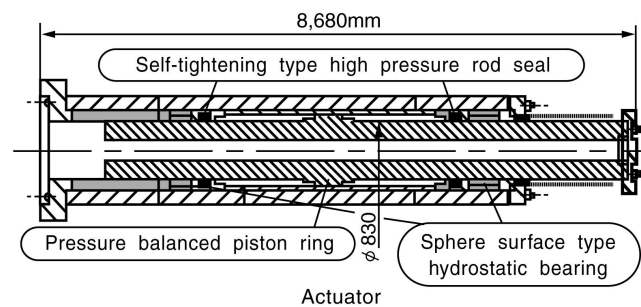


Figure 2: Newly developed components for the hydraulic actuator

Sphere Surface Type Hydrostatic Bearing.

Spherical surface type hydrostatic bearing shown at Figure 3 was developed with two special features. The one is having a sphere surface to allow the inclination of the piston rod. The other one is having the hydrostatic pressure pockets on the surface of bearing to supply high-pressure oil to satisfy the required capacity and to prevent the seizure. These features also have the purpose to minimize the friction.

The sphere surface type bearing has been applied for supporting the axis of the rotating crankshaft of an engine generally. Therefore, the design of the main dimensions was followed by it linearly without the manufacturing errors. As the result, the inclination of the piston rod of $1 \times 10^{-3} \text{ rad.}$ due to its own weight and the lateral load was able to be satisfied. The manufacturing errors were required to maintain the clearance of 0.3~0.5mm between the outer race and inner race of bearing and 0.6~0.8mm between the inner race and the piston rod when the hydrostatic method was applied. That is, in case of the piston rod, the manufacturing errors were to be 0.2mm against the diameter of 830mm. Therefore, the manufacturing process of the full-size bearing was confirmed before the start of manufacturing the prototype hydraulic actuators.

The hydrostatic method was applied to satisfy the required capacity of 2.8MN for the bearing system. Because it was impossible to design the bearing system base on the traditional method. According to the traditional method, the capacity of the bearing system is determined by the PV value, which was depended on the material characteristics of the bearing under a few micron oil films for lubrication. In case of the bearing system of the hydraulic actuators for E-Defense, P, that is Hertz-Stress due to the lateral load of

2.8MN, is very high, and V , that is sliding speed of 2m/sec. is also very high compared with them of the conventional hydraulic actuators.

As shown in Figure 4, the hydrostatic bearing system has some pockets to feed the high pressure of 18 MPa. The capacity of the hydrostatic bearing system is described by the following formula.

$$W = A_e (p_o - p_a) \quad (1)$$

where W = the capacity; A_e = the effective area of the bearing; $p_o - p_a$ = the pressure difference between the pressure at pockets and the pressure at clearance of the bearing system.

And the supply quantity of oil is described the following formula.

$$Q = \frac{K_B h^3 (p_o - p_a)}{\eta} \quad (2)$$

where Q = the supply quantity of the oil; K_B = the coefficient of the flow; h = the clearance of the bearing system; η = the coefficient of the oil viscosity.

Based on the above formulas, to satisfy the design capacity of 3MN, which was exceeded the required capacity, the number, the size and positions of the pockets were designed. Figure 4, the result of the investigation test using the full-sized prototype model bearings, shows that the capacity was followed with the predicted value based on the above equations. In addition, the piston rod that was floating in the oil film generated by the high-pressure oil was able to reciprocate with few frictions.

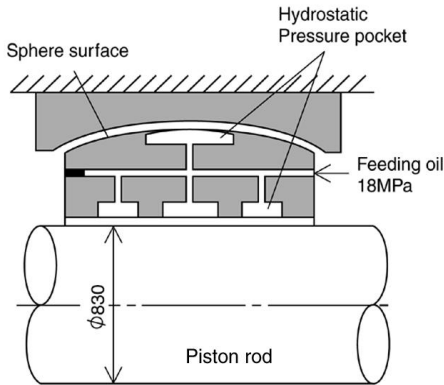


Figure 3: Sphere surface type hydraulic bearing

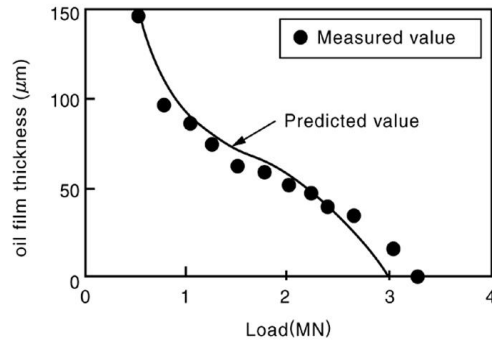


Figure 4: Result of unit investigation test

Hydraulic Pressure-Balanced Type Piston Ring

A piston ring has a purpose to tight between two cabins for the reciprocating motion of a hydraulic actuator, which is obtained by the hydraulic pressure change in both cabins alternately. Generally a conventional type piston ring, which had a simple and uniform shape or labyrinth shape, was applied. The former one prevents the leakage from a cabin by pressing the outer face of the ring to the inner surface of the cylinder. The latter one is the non-contact type, allows the small leakage and seals through the pressure losses caused by the pressure difference between two cabins. The latter one is applied for preventing the seizure and minimizing the friction losses. However, in the case of the hydraulic actuators for E-Defense, the both conventional type piston rings could not be applied, because of the following problems.

The former one has the problem of a seizure and/or an increasing the frictions by the strong contact when the piston rod reciprocates with high speed of 2m/sec. The latter one has the problem of a big leakage, because the clearance between the outside diameter of a piston ring and the inside diameter of a cylinder becomes large due to the inclination of the piston rod and the accumulations of the machining errors of a cylinder inside.

The hydraulic pressure-balanced type piston ring was developed to solve the above problems. It has the steps at the sliding surface and the piston end surface of the piston ring to reduce the working force. To determine the most suitable dimensions, 6 models of 1/8 scale, which were analyzed about the deformation, the strength, the working force and the estimated leakage quantity by FEM beforehand, were manufactured and examined. Figure 5 shows the installations of the piston rings and the comparisons of working forces on the piston ring between the conventional piston ring and the developed one. And Figure 6 shows the leakage characteristics of the developed piston ring. Here the reason of the less leakage value, which measured at the full-scale prototype hydraulic actuator, compared with the predicted value is that the predicted value is calculated under the condition of the maximum accumulations of machining errors. And the conventional sealing method, which is shown by the broken line, means the labyrinth shape piston ring

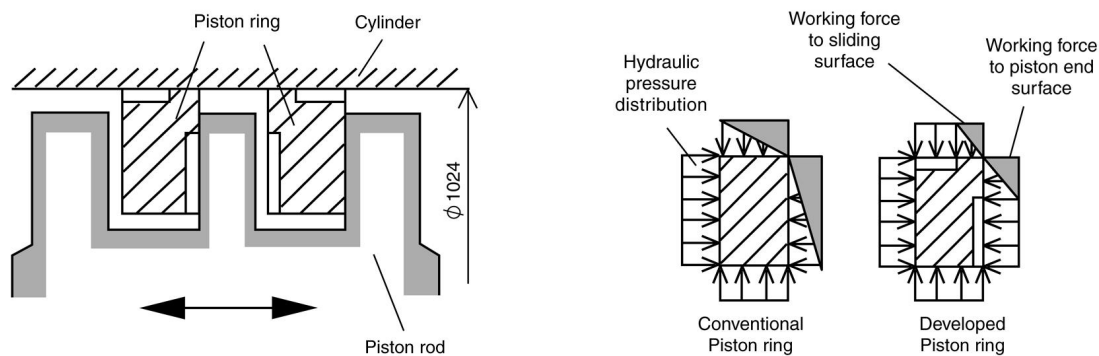


Figure 5: Pressure –Balanced Piston Ring

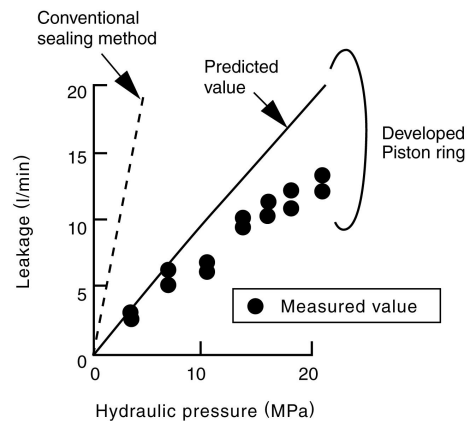


Figure 6: Leakage Characteristics

Self-Tightening Type High-Pressure Rod Seal

In order to prevent the leakage from the cabins of the cylinder to outside, the rod seals are installed at the both ends of the reciprocating range. The elastic and contact type seals, O-ring and V-ring are generally

used for the rod seals. However, those type seals are not suitable for a hydraulic actuator working under high-speed condition, because they have the problems of the large frictions and the wear in short time. Therefore, the floating type metallic seal ring, which is made of the copper or brass, is applied instead of an elastic type seal. The conventional floating type metallic seal ring minimizes the leakage by the resistance when the oil passes through the minute clearance between the inner face of seal and the outer face of the piston rod. Therefore, it is very important to be clearance under the any conditions; otherwise the seizure occurs between the seal and the piston rod. In case of a floating seals for a small size actuator, since the shrinkage of the seal ring caused by the oil pressure difference between the outer face and inner face of ring is negligible small, it does not affect the clearance.

However, it became clear not to secure the clearance at the hydraulic pressure of 14MPa, as the result of the FEM analysis when it was designed according to the design process of the conventional floating metallic seal, because of the physical size effect of the seal.

As shown at Figure7, the new floating type metallic seal was designed to secure the clearance by the asymmetrical deformation, which was occurred by the existence of the steps at the inner surface and the side surface. The shape and the dimensions of the seal and steps were designed to keep the clearance of $50\ \mu\text{m}$ based on the results of the FEM analysis of the various cases. Figure 8 shows the comparison of the clearance at the transition of the hydraulic pressure between the conventional designed seal and the new type seal. And, Figure 9 shows the leakage characteristics of the new type floating metallic seal.

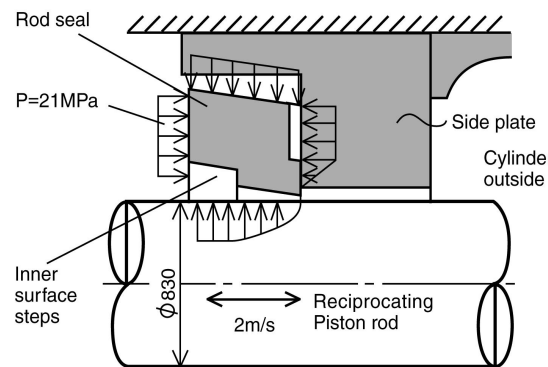


Figure 7: Cross Section of the New Floating Type Metallic Seal

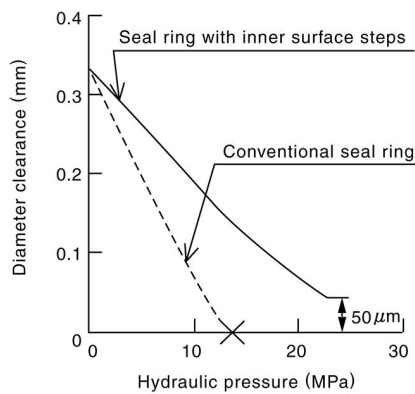


Figure 8: Comparison between the Hydraulic Pressure and the clearance

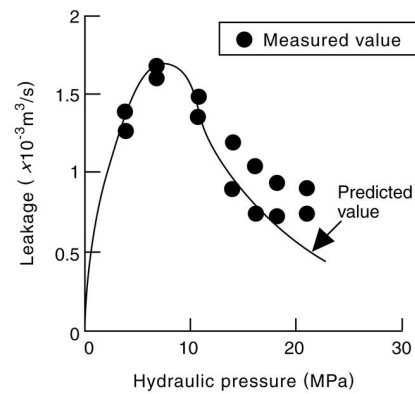


Figure 9: Leakage Characteristics of the New Floating Metallic Type Seal

Technical Development for Three-Dimension Link

The three-dimension link was newly developed and designed for E-Defence. It has the 570mm diameter spherical inner rings at both sides, which can freely rotate within ± 12 degrees and the clearance adjustment function between the outer ring and inner ring of the bearings by the taper ring. And to satisfy the required design capacity of 3.5MN, the hydrostatic bearing method was applied. Figure 10 shows the outline of the newly developed three-dimension link. Figure 11 shows the detail cross section drawing of the sphere surface hydrostatic bearing with clearance-adjusting function.

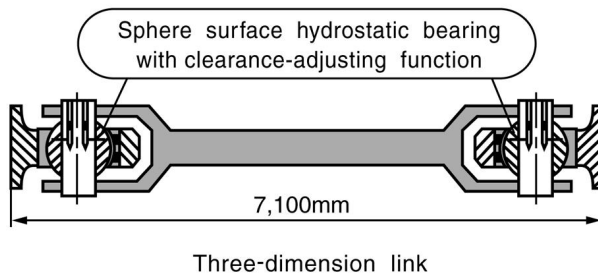


Figure 10: Outline of Three-Dimension Link

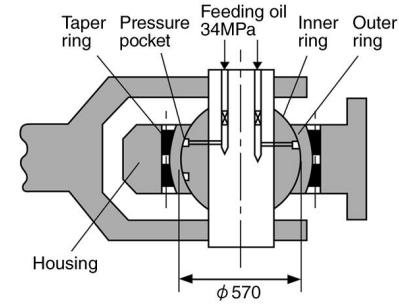


Figure 11: Detail Cross Section of Bearing

The spherical inner ring of the bearing has the hydrostatic pressure pockets. The capacity of the bearing is determined by the hydraulic oil pressure, which is fed to the hydrostatic pockets. As the result of the basic studying, the oil pressure of 34Mpa has to be fed to satisfy the required design capacity of 3.5MN. Since the feed pressure is very high, the numbers, the locations and the dimensions of the pockets have to be considered about the uneven contact which is caused by the deformations of the bearing housing under the high pressure condition. Therefore, those specifications of the pockets were determined based on the deformation analysis by FEM, which was performed based on the following formulas.

$$\delta = \sum_1^n \left(\frac{P_n}{34} \right) \delta_n(\theta) \quad (3)$$

where δ = the deformation value of the housing at the location of the pocket; P_n = the hydrostatic pressure of the pocket; $\delta_n(\theta)$ = the basic deformation value, which is analyzed under the condition of the individual hydrostatic pressure of one pocket; θ = the angle at the location of the pocket.

The one of the important purpose of the three-dimension link is to transmit the displacement to the shaking table linearly besides the transmission of the load from the hydraulic actuator. The non-linear transmission, which results from the unsuitable clearance between the inner ring and the outer ring, obstructs the reappearance of the earthquake wave. Therefore, the clearance-adjustment function, which consists of the two taper rings between the housing and the outer ring at both sides, was applied. The clearance can be adjusted by tightening or loosening the taper rings to the most suitable condition of the earthquake wave reappearance.

As a result of the combination of the above-mentioned technologies, the loading capacity of 3.5MN that was confirmed by the full-scale unit test of the bearings could be achieved at the both compression and tension directions as shown in Figure 12.

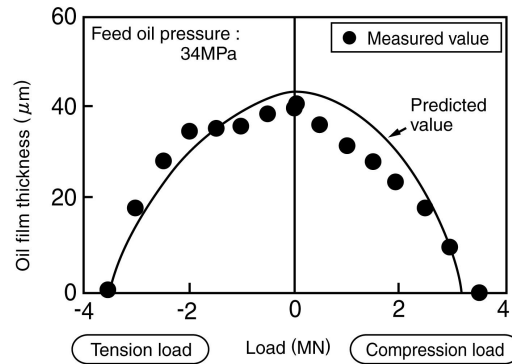


Figure 12: Lording Capacity of Bearing

Test Result

The important points at the designing and the manufacturing of the hydraulic actuator, three-dimension link and so on for E-Defence were that the specifications of the maximum speed and the stroke for the hydraulic actuator and the capacity for the three-dimension link, and the physical size due to their specifications could not be extrapolated base on the experiences of the designing and the manufacturing of them. Therefore, the verification of the manufacturing, the assembling, the installing processes and the mechanical performances under the exciting condition of their full-sizes were necessary in advance the practical use, to say nothing of the approach by the theoretical method and/or the computer-simulation.

The eight prototype actuators and three-dimension links, into which the newly developed components were integrated were manufactured, assembled and installed as the test facility to verify the performance, namely the maximum speed, maximum displacement and so on. The verification tests were started in 1995 and successfully completed at the end of 1998.

Figure 13 shows the result of maximum speed test. Here the reason why the wave-shape is not orderly sinusoidal wave is due to the capacity of the hydraulic equipment of the test facility.

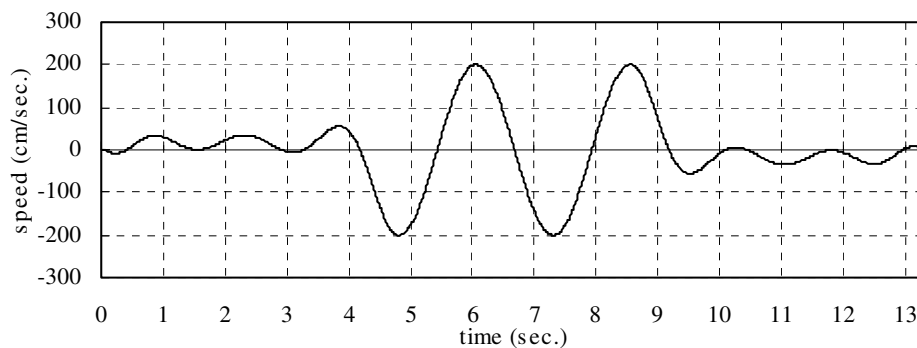


Figure 13: Test Result of the Maximum Speed

Figure 14 shows the result of maximum displacement test.

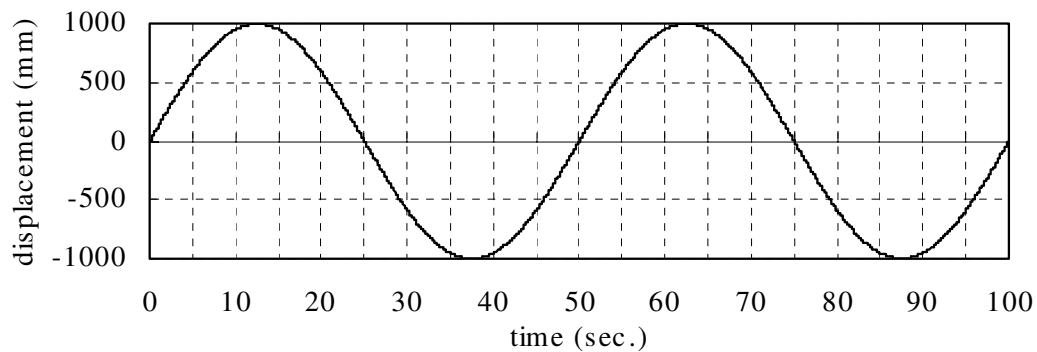


Figure 14: Test Result of the Maximum Displacement

After completion of the all tests, all parts were disassembled to investigate the durability, the wear in the sliding parts, the effects due to the manufacturing and the machining errors and so on. Those were satisfied the mechanical requirements absolutely.

CONSTRUCTION AND MANUFACTURING OF E-DEFENSE

NIED have commenced the development work of shaking mechanism with very large size of hydraulic actuators in fiscal year 1995 and completed performance tests successfully in 1998. Following the above technical development and surveys in earthquake engineering and related fields, NIED have began the design and construction of E-Defense in 1998.

Figure 15 shows the drawing bird eye view of E-Defense. We will construct several buildings, such as laboratory building, measurement and control building, hydraulic oil unit building, preparation building and so on. The 3-dimensional shaking table will be installed in the laboratory building. Hydraulic oil will be supplied to shaking table by pipelines via underground culvert. The reaction foundation (shaking table foundation) has weight of about 2 GN (200,000 tonf) and set to the bedrock directly.

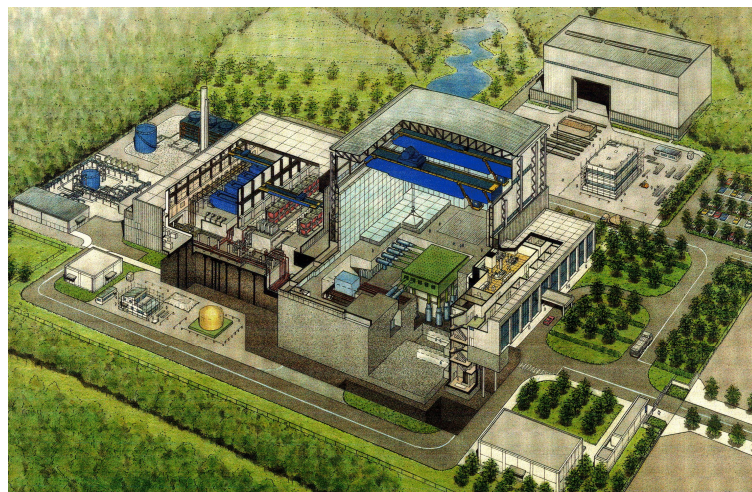


Figure15: Layout of E-Defense

The construction work has begun in 1998 and will be completed at the beginning of 2005. The new facility will start to operate at the 10 years after the Hanshin-Awaji earthquake. The E-Defense is constructed in “Miki Earthquake Disaster memorial Park (tentative name)”, which is being constructed in Miki city, on the north of Kobe city. The construction of shaking table foundation was started at the construction site in January 2000. Figure 16 shows the aerial photograph of the site before the construction work.



Figure 16: Construction Site (January 17, 2000)

Figure 17 shows the scene of the first concrete casting for the foundation. The D51 (diameter 51 mm) reinforcing bars were used for the foundation, such as the foundation for Nuclear Power Plant. Figure 18 is the recent construction condition.



Figure 17: First Concrete Casting (June 20, 2000)



Figure 18: Recent Construction Condition

The installation of piping system, actuators, pumping units and accumulator units were started in 2000. Figs. 19– 21 are shown the installed condition of actuators, pumping units, accumulator units and the recent construction condition of buildings, respectively.

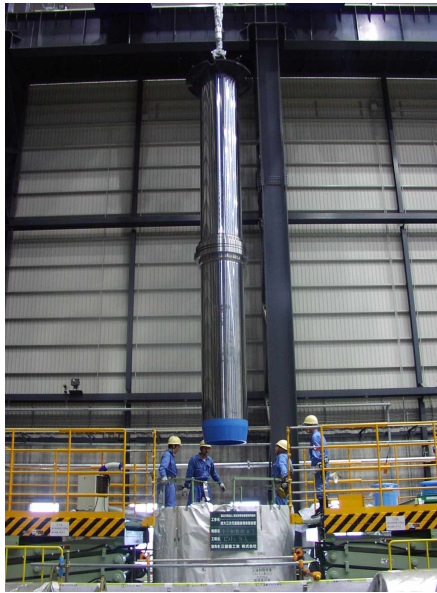


Figure 19: Assembling of Actuator



Figure 20: Installation of V-Actuators



Figure 21: Installation of H-Actuator

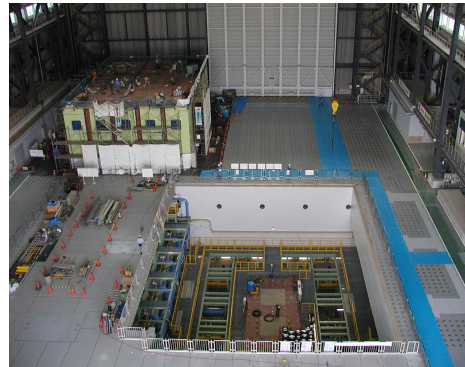


Figure 22: Recent Condition

CONTROL AND MEASURING SYSTEMS

The control system of shaking table and measuring system are key functions of the facility. We are currently arranging these systems.

The control model is composed 2 step systems, basic control system and Application control system. The basic control system is used for the safety control of shaking table, which is composed TVC (Three Variable Control) technique. Application control system is used for the more accuracy control of shaking table. The researcher can insert the own control technique to the control system. Fig. 23 shows the block diagram of control system.

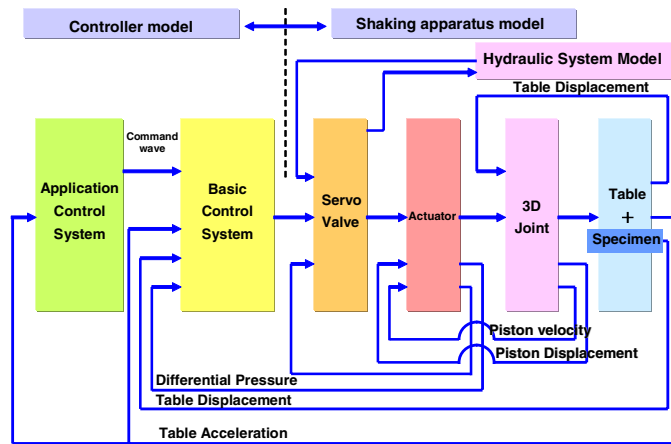


Figure 23: Block Diagram of Control System

The E-Defense is the large scale testing facility, therefore, the researcher, who use this facility, want get a lot of data during test. We will install 960 measuring channels. We have 440 channels of the sensor for control signal. The 64 channels within these 440 channels are able to record the measuring system. The 896 channels of the sensor for measurement are installed for the research purpose. Fig. 24 shows the block diagram of measuring system.

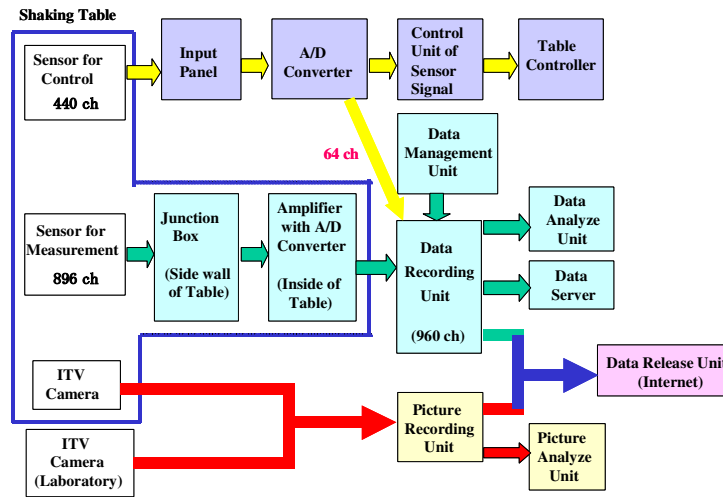


Figure 24: Measuring System of E-Defense

MANAGEMENT MECHANIZM

For the management of E-Defense, we are thinking about following management mechanism as shown in Figure 25. We will establish the Hyogo branch (tentative name) for the operation of facility and conducting the research works. But, by the limitation of number of regular staffs, we will establish the Supporting Company, such as outsourcing mechanism. This Supporting Company is functioned to conduct the smoothly operation of facility cooperate with the staffs of Hyogo branch.

We established one council and one committee for more effective management and operation of facility. The Advistoy Council is organized by the representatives from government, academic and private sectors.

Dr. S. Ito, President, Research Institute for Urban Disaster Mitigation, is chaired the Council. 18 members were nominated. This council will discuss the medium and long term management plan and more effective management of facility.

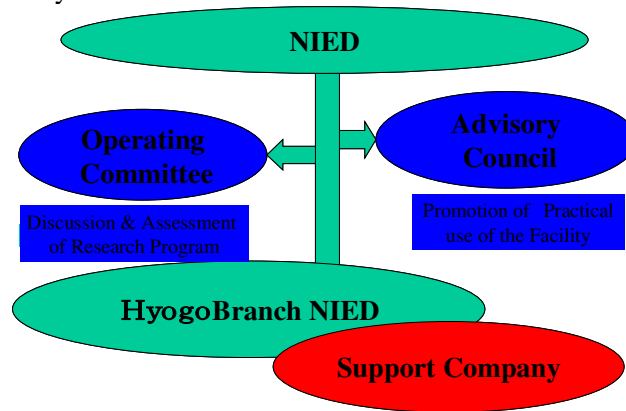


Figure 25: Organization for Operation of E-Defense

The Operating Committee is organized by the active researchers from various fields of earthquake engineering. Prof. K. Kawashima, Tokyo Institute of Technology is chaired this committee. 19 members were nominated. This committee will discuss the research plan and research results by using this facility.

EARTHQUAKE ENGINEERING COLLABORATION

E-Defense should be operated the international common use. To ensure the international common use and disseminate the test results, we will construct and install the E-Defense Network (ED-Net). The ED-Net has 2 major functions: The one is the connection tool between E-Defense in Miki and the Super Computer in Tsukuba. The other one is the connection tool between NIED and the other organization, such as research institute, university, private sector and so on. This function is not only limited to domestic, but also international manner.

We will install the tele-observation and tele-discussion capabilities, but not install the tele-operation function. Because, conducting of shaking table test, especially failure test, has very delicate and dangerous factors. Therefore, the operation of shaking table will limit by the shaking table administrator, who is the specialist of operation. Figure 26 shows the schematic image of ED-Net.

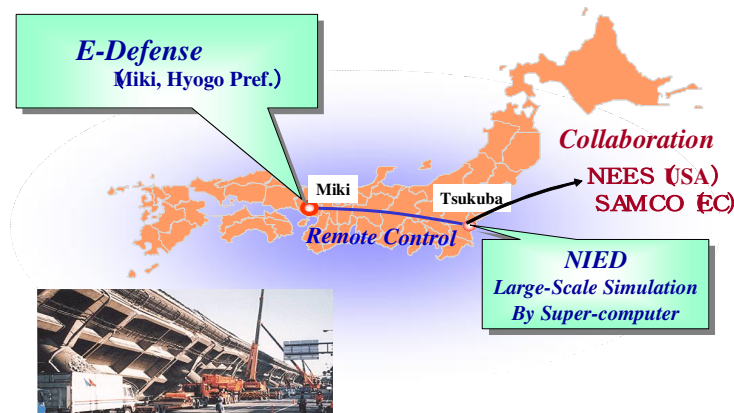


Figure 26: Schematic Image of ED-Net

CONCLUDING REMARKS

Based on the lessons learnt from Hanshin-Awaji earthquake, we, NIED, need more research to understand the failure mechanism of different kind of structures during earthquake. For this research needs, we began the construction project of E-Defense (3-D Full-Scale Earthquake Testing Facility) and ED-Net (E-Defense Network). After completion, these tools will be perfectly opened to international use.

We strongly hope that these tools are contributed to the dramatic progress of the earthquake engineering research, especially the understanding of structural failure mechanism, the progress of the earthquake resistant design of structures and the evaluation/reevaluation of structural performance during earthquake, by the coordination and collaboration research works in the worldwide bases.

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