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World's Largest Shaking Table Takes Shape in Japan – A Summary of Construction Plan and Technical Development

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ABSTRACT

After the 1995 Great Hanshin-Awaji Earthquake Disaster in Japan, Science and Technology Agency (STA) and National Research Institute for Earth Science and Disaster Prevention (NIED) have planned construction of a new large scale shaking table as 3-D earthquake damage testing facility. The basic perfomances of this facility are maximum velocity 200cm/s and maximum displacement 200cm p-p in horizontal excitation to realize destructive ground motion. Following the basic plan, technical developments for large actuator manufacturing and verification of its perfomance was started from 1995 and completed in 1998. The construction work of the facility has begun in the fiscal 1998 and is planned to be completed at the beginning of 2005, ten years after the Great Hanshin-Awaji Earthquake Disaster. The facility is expected to be widely used for development of reinforcement of real structures and new earthquake resistant design or damage control technology through real scale dynamic collapse tests.

1 INTRODUCTION

The 1995 Great Hanshin-Awaji Earthquake Disaster in Japan clearly showed that the occurence of very strong ground motion in the area nearest to the seismic fault is capable of causing severe structural damage beyond general estimation. More than 5000 people were killed by sudden unexpected collapse of wooden houses and urban structures, especially aged structures. It has emphasized the importance of earthquake engineering research into why and how structures collapse in real conditions and how these processes could be reproduced numerically.

It is known that a big earthquake accompanied with severe disaster occur meanly once in ten years in Japan . In order to reduce the hazard due to future great eqrthquakes, it is basic measure to improve reliability of earthquake resistance estimation and reinforcement method for urban and important structures. For that, failure mechanism and collapse process of various types of real scale structures must be investigated. Many types of experimental apparatus such as shaking table have been used for static and dynamic failure mechanism research. However, research of failure mechanism and process of real scale structures during earthquake require a large and real type strong motion simulator because of the limitation of the similarity law.

Considering the lessons learnt from recent earthquake disasters and experience of using the 1-D Large Scale Shaking Table, NIED and STA have planned to build a new "3-D Full Scale Earthquake Testing Facility", which can carry large size soil and structure model and simulate the process of structural failure. After basic planning, NIED and STA have commenced the development work of shaking mechanism with very large size of hydraulic actuators in fiscal 1995 and completed perfomance tests sucessfully in 1998.

Following the above technical development and surveys in earthquake engineering and related fields, NIED and STA have begun the design and construction of this new facility in fiscal 1998. This paper summarizes the construction plan of the facility and the results of technical development work of NIED and STA during the past four years.

2 BACKGROUND

Research and development of disaster prevention in Japan are promoted based on govenmental plans, especially on "Basic Plan for Research and Development on Disaster Prevention" reported by the Prime Minister's Council of Science and Technology, and finally approved by the Prime Minister on December 1993. Based on the basic plan, STA have carried out various kinds of research and development projects on disaster prevention up to now. After the impact of the Great Hanshin-Awaji Earthquake Disaster, STA has accelerated research activity on earthquake disaster prevention.

In particular, based on the refer to the Council for Aeronautics, Electronics and Other Advanced Technology by the Minister of STA, tbe experts from various research fields have discussed on effective arrangement of research bases for earthquake disaster prevention. There were also detailed discussions on the new testing facility proposed by NIED and STA. The Council has submitted the final report to the Minister of STA at September 3, 1997. The report pointed out the role and necessity of the new testing facility as the core facility of the research bases of earthquake disaster prevention. STA and NIED are now conducting construction work following the basic concepts reported in above.

3 BASIC PLAN OF THE 3-D FULL SCALE EARTHQUAKE TESTING FACILITY

3.1 Basic Requirements for The Facility

Basic requirements to this facility are summarized as the followings. All requirements are based on effective performance of dynamic failure test in order to clear the structural damage mechanism , mode of failure and collapse process. Some of these are from the experience and lessons of the Great Hanshin-Awaji Earthquake Disaster. And some are from the experience of using the various test facilities in the past. Some of these requirement are already involved in the construction plan up to date. But other requirements are now under consideration and not in the construction work.

1) 3-D earthquake motion
This is basic requirement for the new facility to simulate real ground motion. In addition, rotational motion such as rocking of floor is also required. 3-D motion may be unstable if rocking motion of the test structure and the table strongly occurs, then as possible as large allowable overturning moment has to be considered.

2) High velocity and large amplitude
The strong motion recorded at JR Takatori Station in the 1995 Hyogo-Ken-Nanbu Earthquake shows the velocity of about 170cm/s and the displacement of about

50cm in the maximum direction. In the 1994 Northridge Earthquake, ground motion larger than the velocity of 128cm/s and the displacement of 30cm are reported. Considering future great earthquakes with long duration, the new facility is needed to have the maximum perfomance of 200cm/s for velocity and ±100cm for displacement.

3) Size of test structure
In order to verify the study of failure mechanism of real structures, as possible as large test structure is required. Although technical and economical condition must be taken into account, minimum size real structures such as multi-storied building are required for future verification tests of failure process or structural control. Then, size of table is better to be equal or larger than 1-D large shaking table (15m×14.5m, the maximum test weight of 500tonf, NIED, Tsukuba) or 2-D large shaking table (15m×15m, the maximum test weight of 1000tonf, NUPEC, Tadotsu) known as verification test facility. In addition, a rectangular table is effective for building or soil movement tests. So that the table size of 20m×15m and the maximum test weight of 1200tonf have been planned for the new facility.

4) Precision control
In the range of elastic response of test structure, control method by trial excitation and input compensation is known to be fairly effective. The new facility intends mainly failure or collapse tests, and then, table motion must be robustly and precisely controled. Advanced control technique must be applied to the new facility.

5) High perfomance measurement system
Available number of measurement channels for Tsukuba 1-D large shaking table and Tadotsu 2-D large shaking tahle is 256ch and 300ch, respectively. But they are often less than required number of measurement channels. More than 900ch would be needed for the new facility. In addition, advanced measurement and data analysis technique must be applied to follow failure and collapse process of test structure.

6) Safety system
The new facility contains a large quantity of high pressure oil and gas. The shaking table moves in large range. And sometimes, test structure may fall down or go to pieces. All these conditions might cause dangerous accidents in the facility, especially around the shaking table. Safety system for human, facility components and test structure must be taken into account.

7) Effective support facility
To effectively use the new facility, test structures are required to be made in the outside of the shaking table. So that, the construction area and transfer tool are necessary. In addition, various kinds of support facility such as reaction floor, hydraulic supply for hybrid test, material and soil testing machine etc. are required for effective use.

3.2 Basic Specifications of The Facility

Table 1 shows the basic specifications of the facility. Table size planned is the world largest at this moment. Driving method is electro-hydraulic servo control system which use hydraulic pressurized oil charged in main accumulators. There are different driving method such as pure electric, explosion excitation method or liquid fuel rocket engine.

But in this project, common and traditional system is selected considering stability. Maximum acceleration 0.9G for horizontal is decided from the consideration that the facility mainly simulate ground motion rather than floor response. In addition, high velocity and large displacement are useful for floor response of high rise building and other flexible structures.

Fig.1 shows the limit perfomance of the shaking table with maximum test weight. Velocity perfomance with duration time is limitted by the number of main accumulators. In tbis project, 20 accumulator units with 1kℓ/unit are planned to be installed. Fig.2 shows tbe required accumulators for 3-D excitatin of typical strong motion records.

Table 1 Basic specifications of the shaking table

	Horizontal (X and Y)	Vertical (Z)
Table	15m × 20m	
Max. test weight	1200tonf	
Drive mechanism	Accumulator Charge/Electro- Hydraulic Servo Control	
Max. displacement	±100cm	±50cm
Max. velocity	200cm/s	70cm/s
Max. accleration (at maxmimum test weight)	0.9G	1.5G
Max. ovturning moment (at Z=1G)	≥15000tonf·m	-

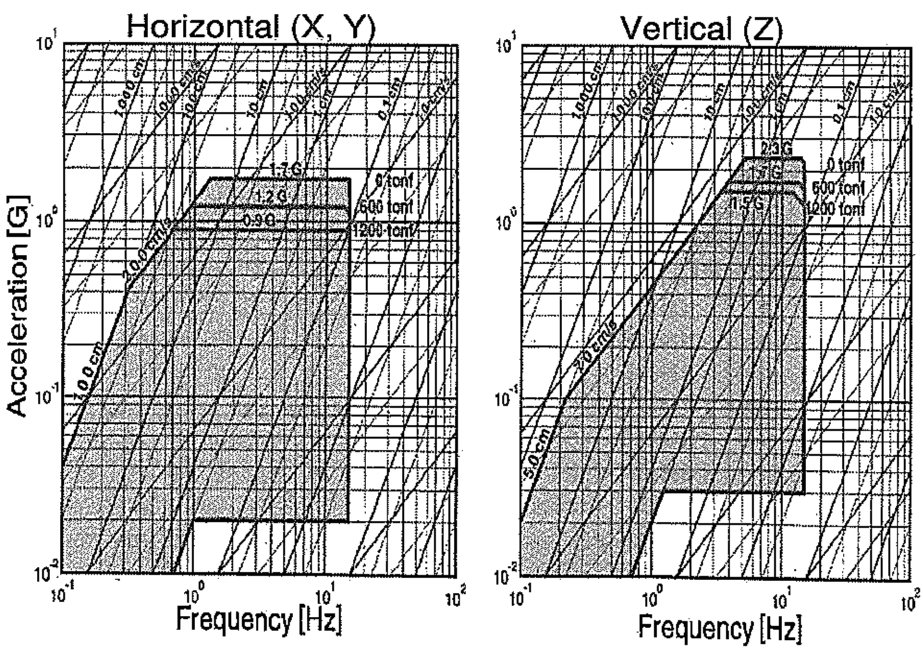

Fig.1 Limit perfomance (Test Weight = 1200 tonf)

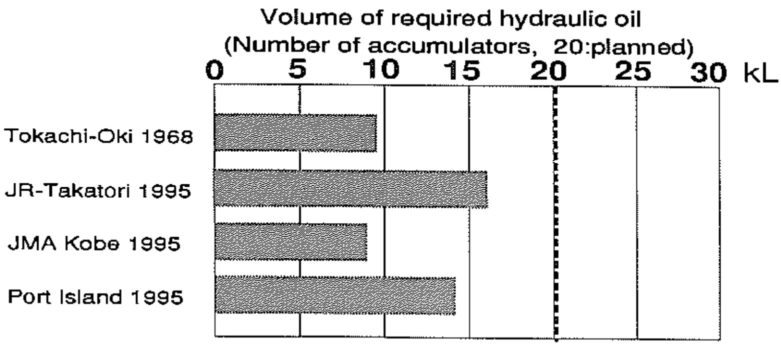

Fig.2 Required number of accumulators to simulate typical earthquake motion

Table 2 Main equipments of the facility

Item	Total Number	Specification
Table	1	20m × 15m
Hydraulic Actuator		
Horizontal (X)	5	450tonf, ±1m
Horizontal (Y)	5	450tonf, ±1m
Vertical (Z)	14	450tonf, ±0.5m
Servo valve unit (X)	15	15,000ℓ/min per unit
Servo valve unit (Y)	15	15,000ℓ/min per unit
Servo valve unit (Z)	14	15,000ℓ/min per unit
3-D Mechanical Joint	24	
Hydraulic Power Supply		
Main pump unit	4	7080ℓ/min/unit, 3175kw (Gas engin drive)
Main booster pump unit	4	7500ℓ/min/unit, 110kW
Main accumulator unit	20	1000ℓ/unit
Heat exchanger	1 set	
Oil tank	1 set	
Auxiliary pump unit	1 set	
Pipeline	1 set	
Control System	1 set	
Operation system	1 set	
Sequence controler	1 set	
Table control system	1 set	multi mode controler
Measurement System	1 set	900channels
Electric Power Supply System	1 set	22kV, 7,500kVA
Large Crane Unit	2	400tonf/50tonf per unit

3.3 Constitution of The System

The shaking system is mainly constituted by the components shown in Table 2. The components and their configuration are basically same as the past electric-hydraulic servo control shaking table systems. Fig.3 shows the main part of shaking table system.

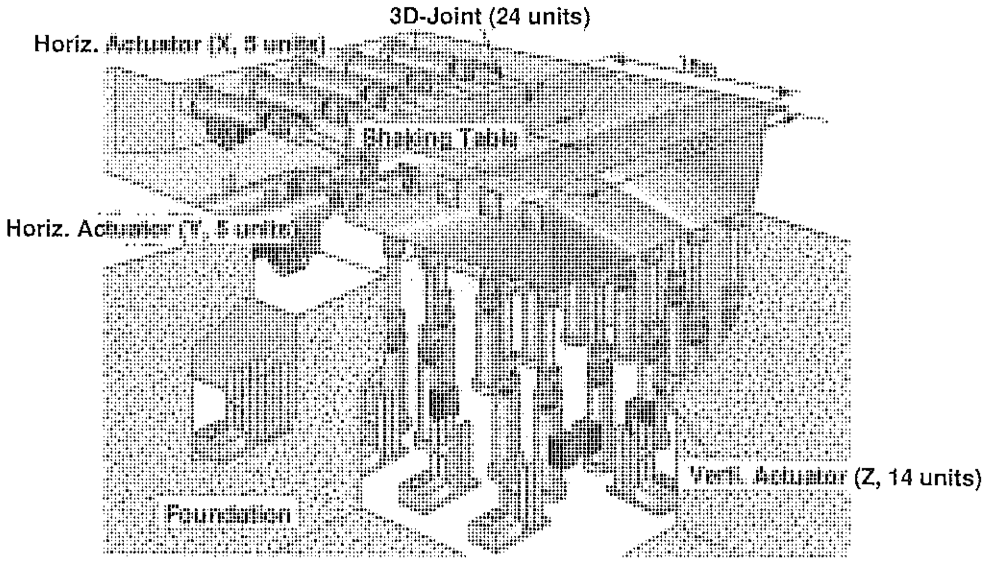

Fig.3 Main part of shaking table system

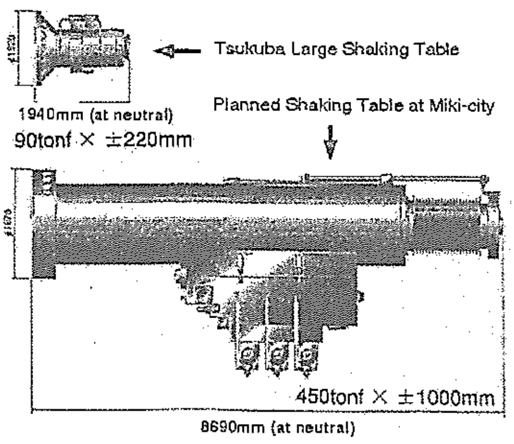

Fig.4 Comparison of horizontal actuator of Tsukuba and the planned new facility

4 TECHNICAL DEVELOPMENT AND VERIFICATION TEST OF LARGE ACTUATOR SYSTEM

4.1 Objectives

Basic technology to make shaking table has been established through development and construction of various scale shaking tables in the past years. However, the facility in this project requires large scale shaking actuators beyond those of the past facilities (Fig.4). Then some technical developments in order to realize stable motion of large actuators were needed. Furthermore, perfomance of 3-D smooth motion of large shaking mechanism using joint system were also needed to be verified. This technical development and verification tests started at 1995 and sucessfully completed at the end of 1998.

4.2 Technical Development of Basic Components

Typical developments related mechanical components are summarized as follows:

1) Bearing system for actuator piston
   Hydraulic actuators to realize large amplitude and high power requires long piston and cylinder in its mechanism. Then bending effect of piston due to self weight and dynamic lateral load become not to be negligible. Although bending of piston is small, it may cause seizure and failure of piston if it is supported by traditional bearing. In addition, it may increase friction between piston and bearing and give bad effects on table perfomance such as acceleration wave distortion. To solve this problem, a new bearing system with spherical hydrostatic sliding is adopted to support piston (Fig.5). This bearing system has made possible to follow piston deformation and reduce friction to near zero at support position.

2) High pressure seal mechanism
   At the piston land between both chambers of cylinder, a new type piston ring seal has been applied in place of traditional labyrinth seal. This was found to act as effective seal and reduce friction and oil leak between both chambers for long scale actuator. And further, non-contact high pressure oil seal using hydraulic force balance was adopted to prevent leak to the outside from the cylinder chamber considering piston deformation.

3) High flow rate servo valve
   In order to realize table velocity 200cm/s, about 45000ℓ/min flow rate is needed for one horizontal actuator. So that a new servo valve with 15000ℓ/min flow rate was developed. Three servo valves are equiped for one horizontal actuator and one for vertical actuator.

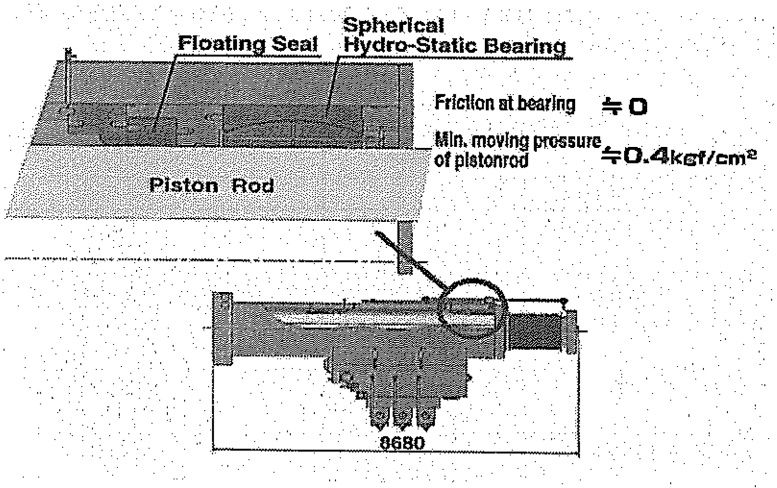

Fig.5 Horizontal actuator and its bearing mechanism

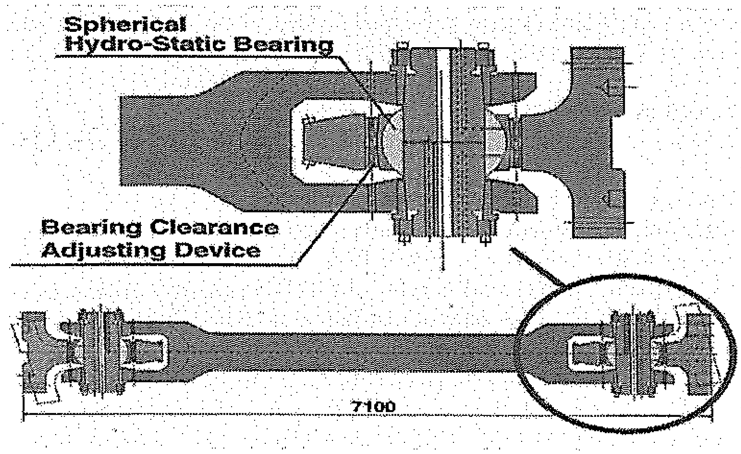

Fig.6 Large 3-D mechnidal joint with high pressure spherical bearing

4) Large mechanical 3-D joint
A 3-D joint is needed between actuator and table. The joint must satisfy requirement of 3-D flexible motion and force transmission without friction. For the planned facility a new spherical hydraulic bearing with high pressure forced-feed lubrication has been adopted in place of traditional grease lubrication (Fig.6). These joints acted as effective components in the verification test.

4.3 Setup of the Large Actuator Test System

In order to verify actuator perfomance as a 3-D system, a large actuator test system was designed and constructed parallel witb components development. Table 3 shows main specifications of the test system, and Table 4 shows the constitution of the test system. The table (6m $\times$ 6m) was made only for this verification test. However, main equipments like as actuators and joints are planned to be used for the main plan through necessary improvement. Main hydraulic pumps are driven by engine in place of electric motor. Photo.1 shows main part of tbe test system.

Table 3 Main specifications for the large actuator test system

Item	Sub item	Specification
Max. test weight		50 tonf
Vibration direction	Translation	x,y,z
	Rotation	x-,y-,z-axes
Drive method	Accumulator Charge/ Electro-Hydraulic Servo Control	
Max. displacement	Horizontal (x,y)	±100 cm
	Vertical (z)	± 50 cm
Max. velocity	Horizontal (x,y)	200 cm/s
	Vertical (z)	70 cm/s
Max. acceleration	Horizontal (x,y)	0.4G *
	Vertical (z)	0.4G *

* This is decided by limitted strength of reaction wall.

Table 4 Main equipments for the large actuator test system

Name	Number	Specification
Table	1	6m × 6m, 45 tonf
Horizontal actuator(x)	2	Max. disp. ±100cm (with 3 Servo valves)
Horizontal actuator(y)	2	ditto
Vertical actuator(z)	4	Max. disp. ± 50cm (with 1 Servo valves)
Servo valve unit	16	15000ℓ/min/unit
3-D joint	8	Rot. angle ±12° and ±4°
Hydraulic supply system	1 set	
Controler	1 set	

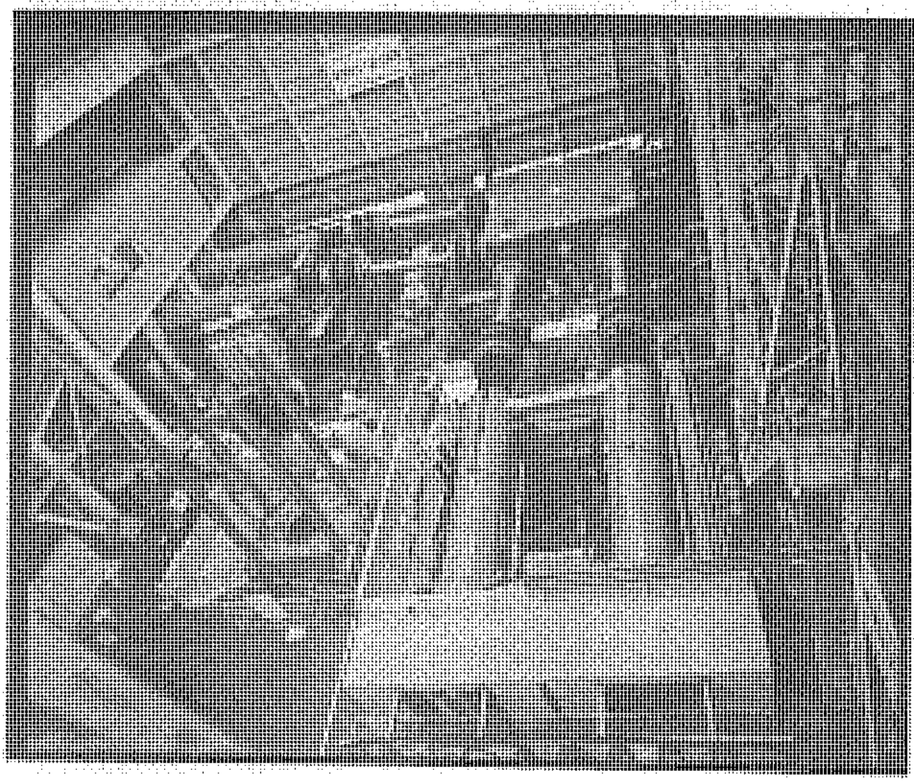

Photo.1 Main part of large actuator test system

4.4 Results of the Verification Test

After each component test, three types of verification tests for shaking performance have been conducted. In the first stage of the tests, basic perfomance on displacement, velocity and acceleration were verified with table only. In addition, other mechanical perfomance such as the oil leak, friction etc. were examined. At the second stage, frequency response test, oil column resonance test, cross talk control tests etc. were performed with and without additional test weight 50tonf. At the final stage, with an elastic test model on the shaking table, dynamic property tests such as control of interaction between the shaking system and the test structure were conducted.

Fig.7 shows the test records of the maximum velocity verification test without test

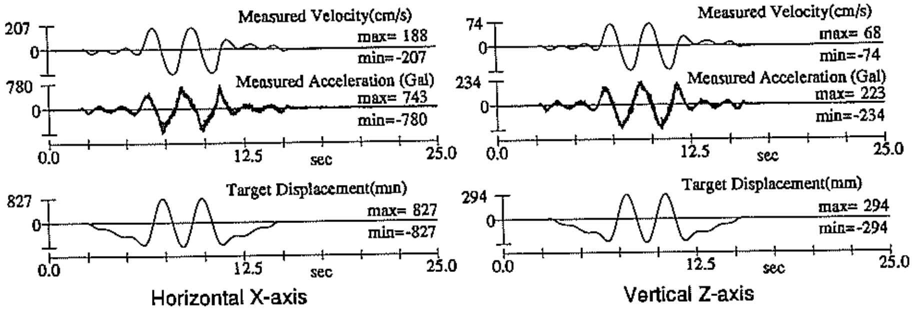

Fig.7 Table response at maximum velocity excitation test

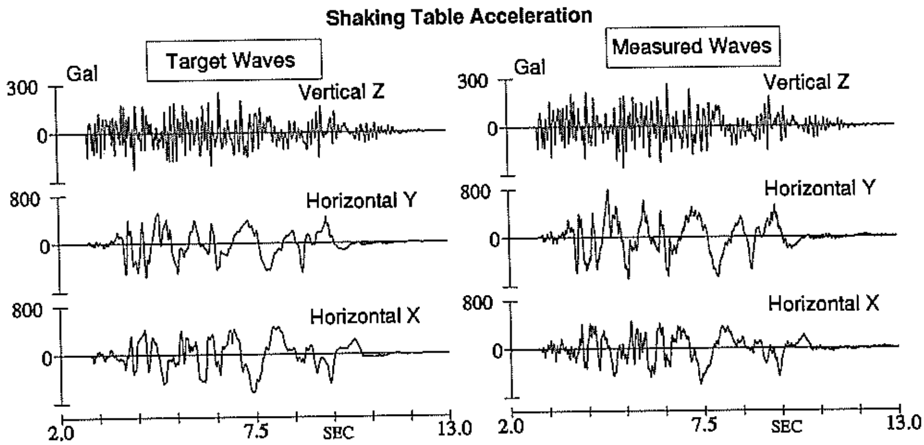

Fig.8 Comparison of acceleration waves at earthquake wave excitation test

weight. Because of the limitation of hydraulic flow supply, two cycle sinusoidal wave was used. Fig.8 shows the results of the earthquake wave excitation test with no test weight. In this test, main part of the strong motion recorded by JR alarm seismometer at Takatori Station in Kobe City was used (ID-No.T065, Ref.1). Although this test was performed without best tuning of controler, target and measured waves show fairly good agreement.

From these verification tests, it was found that developed large actuators are capable to be applied to the main plan of the 3-D Full Scale Earthquake Testing Facility. Though, some technical items such as advanced control method effective for large scale collapse tests are remained to be developed .

5 CONSTRUCTION OF THE 3-D FULL SCALE EARTHQUAKE TESTING FACILITY

5.1 Construction

The construction work has begun in fiscal 1998 and will end at the beginning of 2005. The new facility will start to work 10 years after the 1995 Great Hanshin-Awaji Earthquake Disaster. The first stage of construction will be manufacturing mechanical and hydraulic components, design of foundation and building and ground preparation.

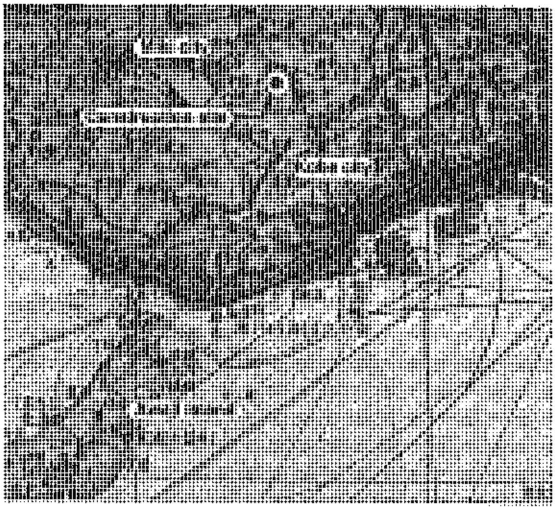

Fig.9 Construction site of the facility (Miki City on the North of Kobe City)

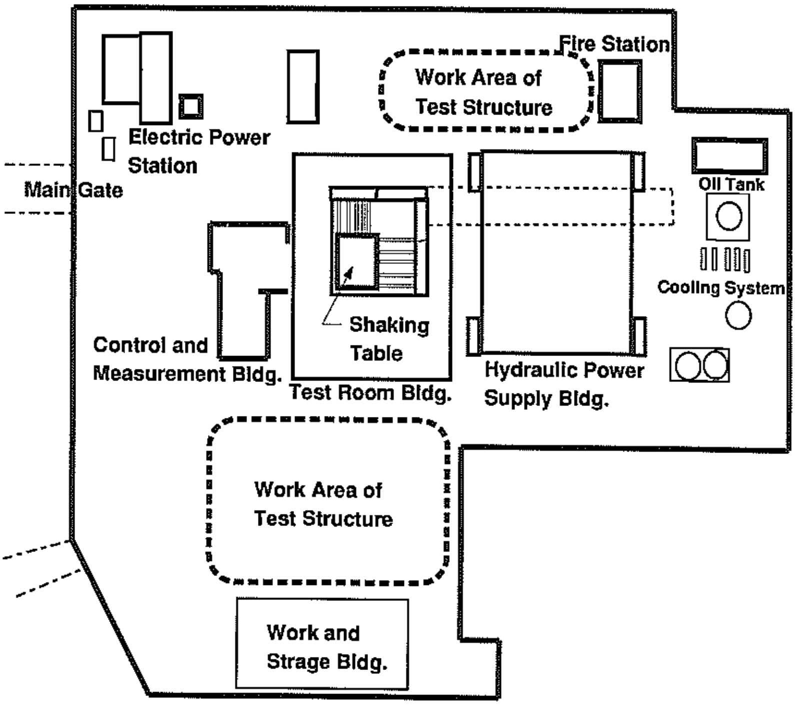

Fig.10 General layout plan of the facility

Construction site is decided as Miki City on the north of Kobe City of Hyogo Prefecture (Fig.9). The design of layout is now under way. The outline is shown in Fig.10. Test Room Building, Control and Measurement Building and Hydraulic Power Supply Building are main structures. Hydrulic power oil are supplied to Test Room Building by pipelines via underground culvert.The reaction foundation has weight of about

210,000tonf and will be connected to the bed rock without pile. In the design of the foundation and the buildings, assesments of influence to the envirenment such as ground vibration are intended to be investigated.

The main works of second construction stage are to build foundation and structures, to assemble and equip large actuators and hydraulic components including pipelines. The final stage works are flashing of hydraulic system, various types of perfomance tests and the final verification test.

5.2 Use and Operation of The Facility

This facility is expected to be used as a powerful tool in earthquake engineering research for structural failure and structural control. For utilization and operation of the facility, the Council descrihed in the previous section has given basic concepts. In parallel, task team on use plan of the facility organized by STA has preliminarily investigated the request and requirement to use the new facility and reported about a hundred of test requests in 6 type of research fields.

After that, STA has organized a task committee to concretely investigate use and management of the facility. This committee is discussing on test subject and effective use of the facility based on the above basic concepts and preliminary investigations. At the present stage, the following 22 test projects are proposed in this committee.

1) Related to Building : 7 subjects (ex: wooden house on the ground)

2) Related to Public Works : 8 subjects (ex: bridge pier, pile in liquefaction soil)

3) Related to Mechanical System : 5 subjects (ex: tank, active components)

4) Others : 2 subjects (ex: estimation test of fragility curve)

STA and NIED will continue to investigate like above and establish use plan and management system of the facility. Research work using this facility in future will be conducted hy international cooperation as well as national cooperation.

6 CONCLUSION

Construction plan and technical development for the 3-D Full Scale Earthquake Testing Facility are successfully progressed hy effetive discussions and supports of many experts in earthquake engineering research and related fields. There must be more developing and investigation of tecbnical problem and test projects for future fruitful use of the facility.

ACKNOWLEDGMENT

Technical investigations for the new facility construction plan have been performed by much helps and valuable suggestions of so many specialists of earthquake engineering and related fields. The authors are so much grateful to them.

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[1] NAKAMURA, Yutaka; "Waveform and its Analysis of the 1995 Hyogo-Ken-Nanbu Earthquake", JR Earthquake Information No.23c, Feb. 1995, Railway Technical Research Institute.