

EARTHQUAKE ISOLATION TECHNOLOGY FOR INDUSTRIAL FACILITIES — RESEARCH, DEVELOPMENT AND APPLICATIONS IN JAPAN

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SUMMARY

In Japan earthquake isolation technology has become increasingly necessary with the growing dominance of so-called "high technology" industries and is now being used to provide effective aseismic protection for precision equipment which is of major importance in such countries. The present applications are for computer systems and semiconductor manufacturing equipment. For computers, particularly those of banks, earthquake isolation of the floors is widely used. For semiconductor manufacturing equipment, earthquake isolation has begun to be used for the components; the isolation of the floors will follow. For both applications, earthquake isolation has not yet been used for entire buildings, but is expected in the near future. Promising applications for the future include bio-technology facilities, highly automated factories and nuclear plants, especially fast breeder reactor power stations.

1. INTRODUCTION

In the last three decades research and development in earthquake engineering in Japan for industrial facilities has been devoted mainly to providing earthquake resistance by increased strength in major components of nuclear light water reactor power plants and chemical plants. Recently, however, the structure of industry in Japan has been changing rapidly. Industries oriented to so-called "high technology" are becoming dominant, where precision equipment such as computer systems and various devices for semiconductor fabrication plays the most important role. For such equipment, the traditional approach based on structural strength is of no use; fixing the components to the concrete slab of the building is usually unacceptable for practical reasons, and even when it is acceptable, strengthening of the device is often impractical or ineffective. Hence earthquake isolation technology which is capable of diminishing the force or acceleration acting on the equipment becomes necessary and is now being used. The technology is also expected to contribute to the development of fast breeder reactor power plants. Quite recently the government and electricity companies in Japan have begun to support its research and development.

In Japan earthquake isolation technology is considered to be more useful for special industrial facilities rather than for usual civil engineering structures, classified into three categories as follows:

- a) earthquake isolation technology for components;
- b) earthquake isolation technology for floors;
- c) earthquake isolation technology for entire buildings.

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Research and development in each category carried out by the author in collaboration with a number of companies is described in the following. Present and proposed uses of the technology are presented in some detail, serving to outline the present state and current trends in earthquake isolation technology in Japan.

2. PRESENT AND PROPOSED APPLICATIONS TO INDUSTRIAL FACILITIES

The main applications which have been recognised for earthquake isolation technology in its present state are computer systems and semiconductor manufacturing equipment. Future uses may include bio-technology facilities, highly automated factories and nuclear facilities.

2.1 Computer Systems/Centres

In these days when many computer systems are used to maintain various functions of society, the necessity for aseismic protection is well recognised. Components of computer systems are usually put on an elevated floor to ensure air flow for air-conditioning. Even though seismic protection is necessary in the high seismicity area of Japan, fixing them to a floor slab is not acceptable because it restricts frequent changes to the layout and frequent replacement of the system. When computer systems are subjected to strong floor motion from a destructive earthquake, components may move about, collide with each other and fall down and receive severe damage to hardware, together with possible data and software corruption. Figure 1 shows an example of such damage to a computer system observed in the Miyagi-ken-oki earthquake (1978) in Japan. Even when subjected to less severe motion, the malfunction of the system caused by the excitation of highly sensitive components, such as magnetic-disk devices, is possible. This is serious for banking systems and some control systems. To protect computer systems and maintain their operational integrity during earthquake attack, earthquake isolation of computer floors is

widespread in Japan, mainly for banking systems and also for air-traffic control and chemical process control. There are also a few examples of isolation of individual components.

Earthquake isolation of entire buildings has not been used yet for this purpose (a base isolated two-storey RC residential building has been built recently for experiments and measurements of responses to natural earthquakes). However, there are some computer centres which have several storeys of individually isolated floors and in such cases it would be more economical to isolate the entire building. It is also advantageous for isolation that buildings for computer centres are usually of low height and broad width. Therefore, for such computer centres base isolation of entire buildings will be used in future.

As society progresses to a more information-oriented one, the earthquake problem for computer systems will become more important from the point of view of computer security, and in applications such as banking systems, decentralization of computer networks should be promoted. Nevertheless the necessity for aseismic protection of individual computer systems/centres will never decrease.

2.2 Semiconductor Manufacturing Equipment/Factories

Semiconductor manufacturing equipment, in particular wafer process equipment, must have aseismic protection for the following reasons:

- (1) In wafer processing, dangerous chemicals such as hydrofluoric acid and sulphuric acid and poisonous gases such as phosphine are used. Damage to the devices containing these would injure or kill workers.
- (2) Most components of the equipment are very expensive. Damage to such components would bring the companies concerned heavy direct loss.
- (3) The companies concerned have continued vast investment every year to maintain their semiconductor business, and competition is very keen. Suspension of operation due to an earthquake would bring them costly indirect loss and, in the worst case, cause loss of their market share.

Furthermore, isolation is the most suitable form of aseismic protection for semiconductor manufacturing equipment as outlined below:

- (1) It is necessary to put components of the equipment on an elevated floor for air-cleaning and air-conditioning. As with computer systems, fixing the components firmly is not acceptable. Aseismic protection for the equipment must be provided without fixing.
- (2) The most important and most expensive precision devices such as electron-beam lithography systems and wafer

steppers are supported by air bags for isolation from ambient vibration. Although the resulting natural frequencies cause the equipment to respond excessively to seismic excitation, removing the air bags is not acceptable. Moreover, it is required to prevent not only structural damage but also loss of accuracy.

- (3) Some components contain reservoirs of dangerous acids. The reservoirs are made of brittle material such as quartz glass and vinyl chloride and are usually lidless. To protect workers and expensive equipment around them, it is important to prevent the liquid from splashing as well as the reservoirs from breaking.

Implementation to semiconductor manufacturing equipment has just started. At present isolation devices for components have begun to be used for the components containing the acids of the existing wafer process equipment. However, earthquake isolation of components alone is not enough to meet the requirements of aseismic protection. The technology for floors and for entire buildings should be developed and implemented.

2.3 Bio-Technology Facilities and Highly Automated Factories

Bio-technology laboratories, especially for genetic engineering, deal with various bacteria. They must be equipped with safety cabinets and large-scale systems to protect against "bio-hazard". Typical examples are the high-degree-of-safety laboratories which are called "P4 Facilities" in Japan, where bacteria are completely confined. For aseismic protection of these facilities, it is most important to maintain their containment function and earthquake isolation would be the most effective means for the purpose.

In machine shops, up to now it has been considered necessary only to fix machine tools to the concrete floor by anchor bolts to protect them against earthquake attack. However, automation has progressed considerably. Robots, NC machines, computers, optical fibre networks and so forth are combined with each other to form "Flexible Manufacturing Systems", "CAD/CAM" systems and "Local Area Networks". At the same time the accuracy required in each machine increases. In the future highly automated factories will need to be regarded as huge and very expensive precision machines. Furthermore, it should be noted that as the degree of automation and precision becomes higher, factories tend to be more easily damaged by an earthquake and small damage tends to cause heavier loss. In the Nippon-Kai-Chubu earthquake (1983) in Japan, it was reported that a precision machine shop in Akita-city could not resume operation quickly because of an NC machine losing accuracy. This factory, however, was not an advanced one. When modern advanced factories are attacked by such a destructive earthquake, how long will it

take them to resume operation? Highly automated factories of the future will possess vast productivity and the suspension of their operation for a long time will affect not only the companies concerned but also society; earthquake isolation probably for the entire building, will be needed.

2.4 Nuclear Facilities

At present the main factor inhibiting development of fast breeder reactor power plants is the construction cost. Even in the prototype plant "Monju" (280 MWe) under construction in Japan, the construction cost is about NZ\$5,000 million, which is nearly twice that of commercial light water reactor power plants of the 1,000 MWe class. Earthquake isolation is expected as one of the solutions of the problem.

Two types of reactor, loop-type and pool-type, have been proposed for the fast breeder reactor. Though arguments still continue, the pool-type is considered to be more suitable for large-scale commercial power plants. Strengthening its structure against earthquake attack is expensive and technically difficult and consequently earthquake isolation, particularly of the reactor building, has emerged as an alternative approach.

For this purpose, extensive research and development is needed to produce base isolation systems with extraordinarily high reliability. Experience in earthquakes of design level must be gained with similar base isolation systems in less critical structures as a precondition for accepting base isolation for nuclear power plants. Accordingly, the application to fast breeder reactor power plants will take a long time. Nevertheless, its research and development is recognised as worthy of beginning now and projects supported by the government and electricity companies have started quite recently.

3. EARTHQUAKE ISOLATION OF INDIVIDUAL EQUIPMENT

3.1 An Isolation Device for Light Equipment.

A three-dimensional earthquake isolation device has been developed for light equipment, especially semiconductor manufacturing equipment (1,2). Its structure is shown schematically in cross-section in Fig. 2. In this device, two pairs of linear motion elements crossing at right angles ensure that the table on which the equipment is mounted moves in horizontal translation without rotation, while a link mechanism provides vertical movement without tilt. Each linear motion element consists of a main rail and a thinner restraining sub-rail to prevent the equipment from stepping off the main rail. Roller bearings between them support the vertical load and side roller bearings (omitted in Fig. 2) on the side of the main rail prevent the equipment from rotation. The isolation device is equipped in each direction with coil springs to provide a restoring force, oil dampers for energy

absorption and friction dampers to fix the system in place during normal operation and provide further energy absorption. Oil dampers for each horizontal movement are installed in a direction at right angles to the movement. This enables normal car shock absorbers to follow large horizontal displacements of the device as required for earthquake isolation without exceeding their maximum stroke, and gives them nonlinear damping characteristics to produce an increasing coefficient of damping with the displacement, which is considered preferable for earthquake isolation.

Excitation tests were carried out for the application to precision equipment supported by air bags (2) using the two-dimensional, horizontal-vertical, shaking table with dimensions of 3.0 x 3.0 m at the Institute of Industrial Science, University of Tokyo. The isolation device and the equipment model used are shown in Fig. 3. The isolation device had dimensions of 2,170 x 1,600 x 397^H mm and was designed to allow a maximum displacement of ± 286 mm in each horizontal direction, and a maximum vertical displacement of ± 55 mm. The equipment model was designed to simulate the dynamic properties of an electron-beam lithography device and was almost full-scale in its size and weight. This model had two resonant frequencies of 2.4 Hz and 4.4 Hz for horizontal excitation, corresponding to rocking modes with a lower centre and an upper centre respectively, and one at 3.0 Hz for vertical excitation. The natural frequency in each horizontal direction of the isolation device plus equipment model was set to 0.276 Hz (a period of 3.62 s), and the vertical one to 1.05 Hz. The friction dampers were set by adjusting their pressure so that the isolation device would work in each direction when, roughly speaking, response accelerations of the equipment model exceeded 200 mm/s² in each horizontal direction and 300 mm/s² in the vertical direction respectively.

Various earthquake inputs were used for the two-dimensional excitation tests, including ground motion records from Hachinohe (Tokachi-oki earthquake, 1968), Tohoku University (Miyagi-ken-oki earthquake, 1978), etc. and a simulated floor response based on response accelerations of single-degree-of-freedom systems to these. Each test was done using a pair of NS and UD components or of EW and UD components.

Examples of the results are shown in Fig. 4. For each test, the response acceleration of the mass of the equipment model when isolated and non-isolated to the same input are compared. Response displacements of the isolation device are also shown together with simulation results for the isolated case to compare with the corresponding experimental results. It must be mentioned that the results when non-isolated were obtained from the results to smaller excitation, about a quarter of the amplitude, by linear scaling. This was necessary

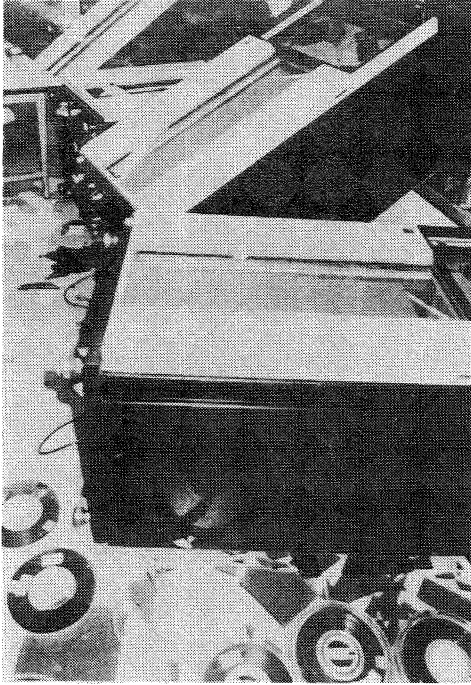


Fig. 1 An Example of Damage to a Computer System in the Miyagi-ken-oki Earthquake (1978) in Japan.

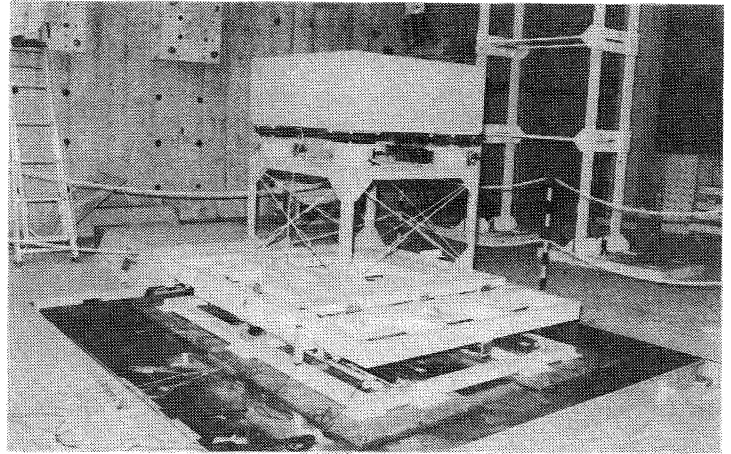


Fig. 3 Three-Dimensional Earthquake Isolation Device and an Equipment Model Supported by Air Bags used in Excitation Tests.

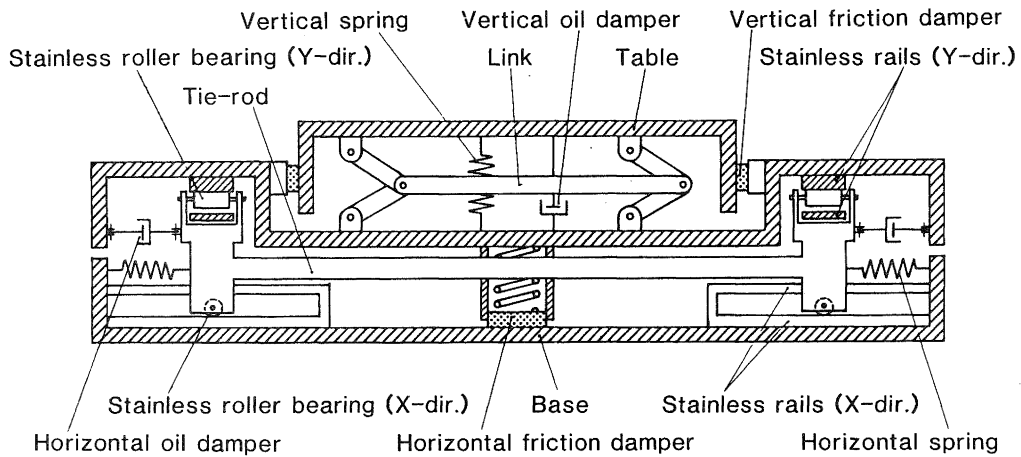


Fig. 2 Schematic Drawing of a Three-Dimensional Earthquake Isolation Device (in cross-section).

because, with the same inputs being used, the non-isolated equipment model would fail. The results in Fig. 4 are considered sufficient to apply the isolation device to the precision equipment supported by air bags. The results, however, show that the performance for vertical isolation is not as good as for horizontal isolation. This is because the vertical natural frequency of the system is not low enough for a more satisfactory performance, but it would be almost impossible to make the vertical frequency sufficiently low, e.g. 0.5 Hz, while keeping the size and cost of the isolation device acceptable.

Further isolation tests were carried out for the implementation to equipment containing reservoirs of acids, using the same shaking table and almost the same earthquake inputs mentioned above. The purpose of the tests was to examine whether the isolation device was able to prevent the reservoirs from breaking and the liquid from splashing under strong seismic excitations.

Figure 5 shows the isolation device (installed on a supporting structure) and one of the equipment models used for the tests. The dimensions of the isolation device were 3,210 x 2,110 x 415^H mm and its allowable maximum displacements were ± 250 mm in each horizontal direction and ± 50 mm in the vertical direction. This equipment model was a full-sized one of a resist stripper used in IC chip manufacture containing three lidless and unfixed glass reservoirs of hot sulphuric acid. In the tests, water was used instead of sulphuric acid. Despite the lower density of water, the sloshing was more severe because its damping is also less than that of sulphuric acid. The water in each glass reservoir had first mode natural frequencies for sloshing of 1.24 Hz in the horizontal direction and 1.85 Hz in the transverse direction. In these tests the horizontal natural frequency of the device plus equipment model was set to 0.222 Hz (a period of 4.50 s) and the vertical one to 0.932 Hz. The friction dampers were set as in the above mentioned tests.

The tests were carried out with satisfactory results. It was confirmed that the performance of the isolation device met requirements. Furthermore, at the end of the tests, the non-isolated equipment model was excited with an input used for the isolated case, with the result that the water splashed violently and the glass reservoirs fell down and broke. The isolation device has begun to be used for those components containing acids in the wafer process.

Measurement of the response of the isolation device to natural earthquakes has been done since February 1984, using the device used for the first tests mentioned above with a more simple equipment model (3). The system was installed on the second floor of a four-storey building constructed to measure soil-structure interactions during earthquakes at the Chiba Experimental Station of the Institute of Industrial Science

near Tokyo. So far the friction dampers of the device have been released so that the device will work even in weak earthquake excitation. Many records have already been obtained though they are for responses to weak floor motions whose peak accelerations are up to 610 mm/s². However, these records show that, even in such weak earthquakes, the isolation device is able to reduce the response acceleration of the equipment model to 1/5 ~ 1/4 of the floor acceleration in each horizontal direction and to 3/5 ~ 4/5 in the vertical direction. The isolation device has also begun to be used for monocrystal pullers producing monocrystals of silicon, gallium-arsenic compound, etc. for semiconductor devices. These monocrystals have the shape of a solid cylinder with a very thin neck at an end as shown in Fig. 6. The larger monocrystals have been required for improving productivity of IC devices. In the case of silicon, for example, the monocrystals produced now have diameters of about 130 ~ 150 mm and lengths of about 500 ~ 700 mm in their cylindrical bodies. In the equipment, such a monocrystal is suspended by the very thin neck with a diameter of less than 5 mm and grows longitudinally as it is pulled up very slowly from the molten material in a melting pot. The neck is easily broken even by weak earthquakes such as occur several times a year in Japan. The isolation device is used mainly to prevent a suspended monocrystal from falling in these weak but frequent earthquakes. For this purpose the isolation device was slightly modified. In place of the friction dampers, a holding system using pneumatic actuators is attached so that the isolation device is in operation during monocrystal pulling, but can be held using push-button control to allow easier operator access during the small fraction of the time this is required. Operator access is needed mainly for taking out the completed monocrystal and replenishing the material once a day. This application is the first to use isolation technology to improve productivity rather than to provide safety. Such applications seem likely to increase and become more important in the future.

Also, for the application mentioned above, an isolation device using active control may be feasible though it will be more expensive. At present the cost of a single large monocrystal for semiconductor devices is almost comparable with that of the isolation device. Therefore, if a device using active control can achieve sufficiently superior performance compared with the device used now, the additional cost will become acceptable. The author is carrying out theoretical studies and preliminary experiments for such a device in collaboration with an isolation technology company.

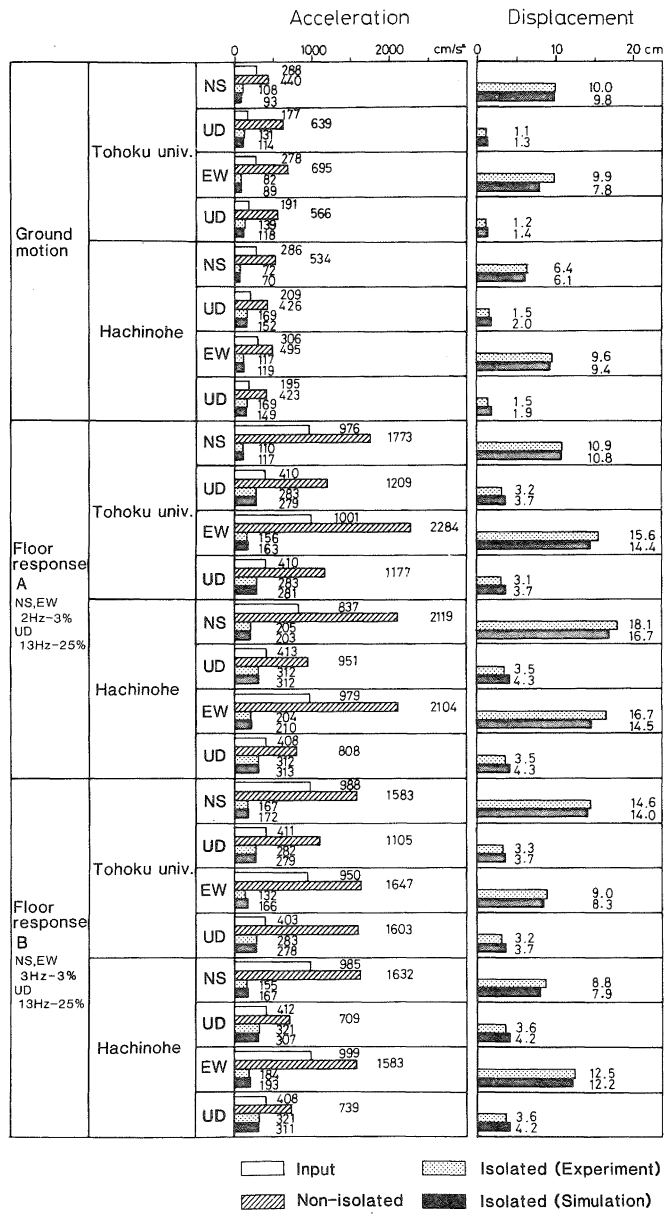


Fig. 4 Performance of the Three-Dimensional Isolation Device for the Equipment Model Supported by Air Bags.

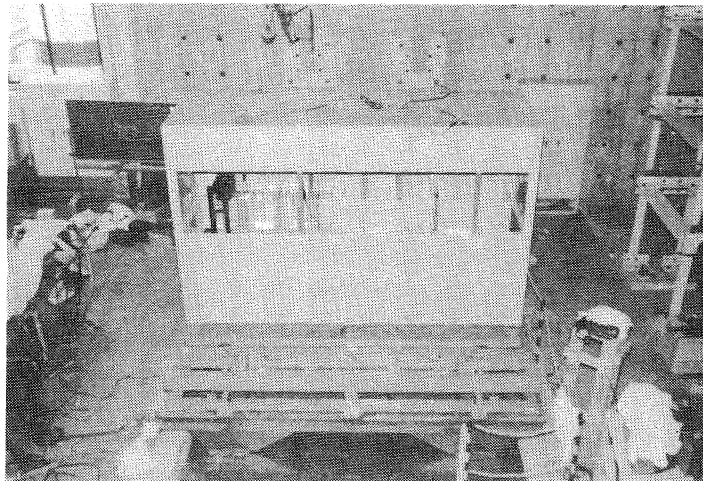


Fig. 5 Full-Sized Model of Equipment Containing Glass Reservoirs of Hot Sulphuric Acid and the Three-Dimensional Isolation Device Used in Excitation Tests.

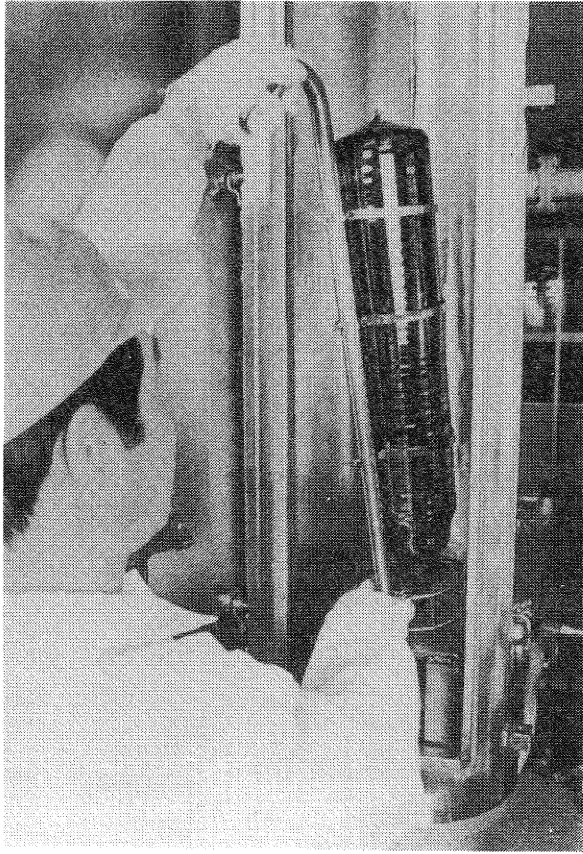


Fig. 6 A Completed Monocrystal of Silicon being taken out by an Operator (note the thin neck remaining in the equipment).

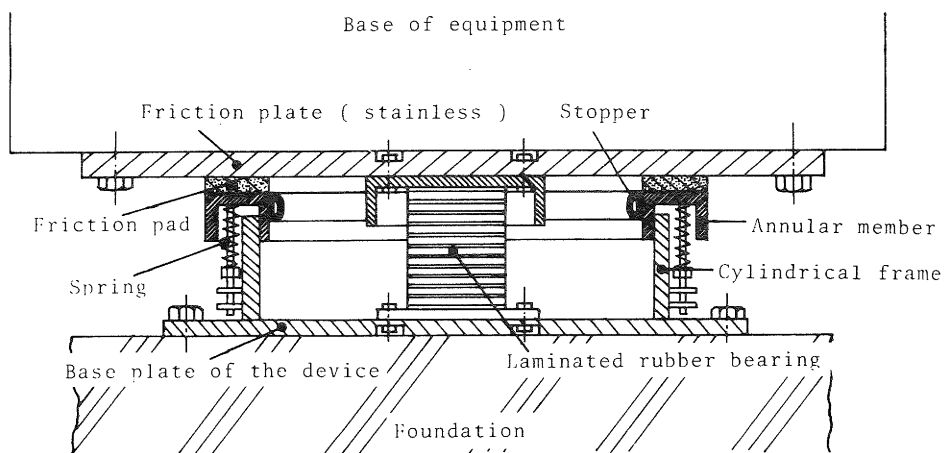


Fig. 7 Schematic Drawing of an Isolation Device for Heavy Equipment (in cross-section).

3.2 An Isolation Device for Heavy Equipment

An isolation device using a laminated rubber bearing and a friction damper has been developed for two-dimensional horizontal isolation of heavy equipment (4,5). Its structure is shown schematically in Fig. 7 and a full-sized device used for tests is shown in Fig. 8. Heavy equipment is supported using a minimum of four devices, as in Fig. 10 which shows a scale model used for excitation tests. The rubber bearing is set in the centre of the device, and its upper end is fixed by bolts to the bottom of the equipment through a cap and friction plate and its lower end to the foundation through the base plate of the device. The rubber bearing is surrounded by a cylindrical wall, on the upper end of which an annular member of an inverted U-shaped section is mounted. Several friction pads are attached on the top of the annular member. This surrounding structure functions as a friction damper. The required level of friction damping is provided by pressing the annular member with the friction pads against the friction plate by adjusting coil springs attached on the cylindrical wall. The friction damper also serves to hold the equipment in place during normal operation. Correction of the position can be done easily by releasing the friction damper. Also, the surrounding structure plays a role of a backing and fail-safe mechanism. The rubber bearing alone cannot undergo sufficient horizontal displacement without instability because of its slender shape. The surrounding structure allows the rubber bearing to accept the much larger required displacement and also limits the displacement to an allowable one. Even when the rubber bearing loses its supporting capacity for some reason, the surrounding structure can support a vertical load in place of the rubber bearing.

Full-sized devices of a rated load of 98 kN each were manufactured for tests (4). Figure 8 shows one of them, which is 1,050 mm in diameter and about 300 mm in height. The device was designed to provide a superstructure of the rated mass (10,000 kg) with a horizontal stiffness for a natural frequency of 0.5 Hz and a horizontal friction force of 8% of the rated load for the damping required. These specifications were decided through a simulation study of a single mass oscillator system isolated by the devices, supposing the devices to be used for heavy equipment to be installed on the ground. The device was also designed to have a high vertical stiffness to give the superstructure a vertical natural frequency of 19 Hz. This is to prevent the equipment from excessive rocking and vertical responses. To satisfy these specifications, rubber bearings with many layers comprising 53 natural rubber sheets of 2.5 mm thickness and 195 mm diameter bonded to steel plates were used. Dynamic tests were carried out for the complete devices, the rubber bearings alone and the friction dampers alone, using two actuators, one for exerting horizontal displacements and

the other for vertical forces. The results showed that the rubber bearings met the requirements for horizontal and vertical stiffnesses, the friction dampers using disc-brake pads for the friction pads were able to provide stable friction forces of an appropriate level and the resultant hysteresis loops of the devices were satisfactory. The tests, however, were not enough to confirm the reliability of the devices, particularly of the rubber bearings in large horizontal displacements, for which static tests were carried out. In these tests, rubber bearings with slightly different dimensions were tested, which comprised 57 natural rubber sheets of 3.5 mm thickness and 255 mm in diameter bonded to steel plates. The tests revealed that, as shown in Fig. 9, the horizontal restoring force of the rubber bearing alone for a fixed vertical load (except very small ones) increased with displacement, reached a peak value and then decreased with further displacement. Also, both the peak restoring force and the displacement at which this occurred decreased with increased constant vertical load. This behaviour has also been reported by Thomas (6) who considered the probable reason the formation of vacuoles in the rubber, and by Simo and Kelly (7) who attributed it to lifting-off of the edges of bearings which were not restrained vertically (although in the present tests the ends were bonded). In this case, it would seem that the probable reason is the geometrical nonlinearity due to large deflection of the slender bearings. Though the tests showed that the rubber bearings remained stable for a while beyond the peak, the displacement corresponding to the peak restoring force should be considered as the practical limit of displacement for a given vertical load in the case of rubber bearings alone. For the rubber bearings tested, such limits were about 180 mm for 98 kN vertical load and 130 mm for 196 kN. The rubber bearings supported by the backing mechanism of the device were also tested. Such rubber bearings could accept a displacement larger than 300 mm and their restoring forces remained almost linear up to this large displacement. Through these tests, it was verified that the devices had sufficient reliability for implementation.

Excitation tests were carried out for a scale model shown in Fig. 10 (5), using a one-dimensional shaking table of 2.0 x 1.5 m at the Institute. In this scale model, four isolation devices and a simple equipment model were scaled down by 0.44. The similarity law was used by which accelerations and frequencies in the scale model were scaled up by 1/0.44 (= 2.27), displacements and time were scaled down by 0.44, and velocities and shear strain of the rubber bearings were kept equivalent. The equipment in the scale model had a mass of 3,300 kg and natural frequencies of 5.76 Hz when non-isolated and of 1.13 Hz when isolated. This means that the full-scale equipment has a mass of 40,000 kg (10,000 kg per device) and natural frequencies of 2.53 Hz when non-isolated and of 0.5 Hz when isolated. Thus the scale model satisfied

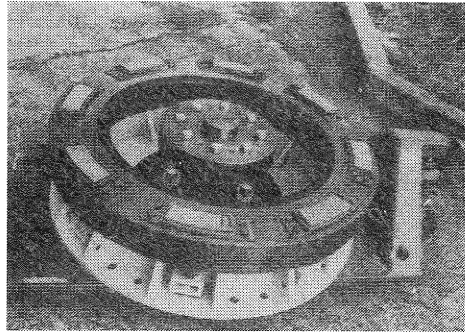


Fig. 8 Full-Sized Isolation Device of 98 kN Rated Load Used for Tests.

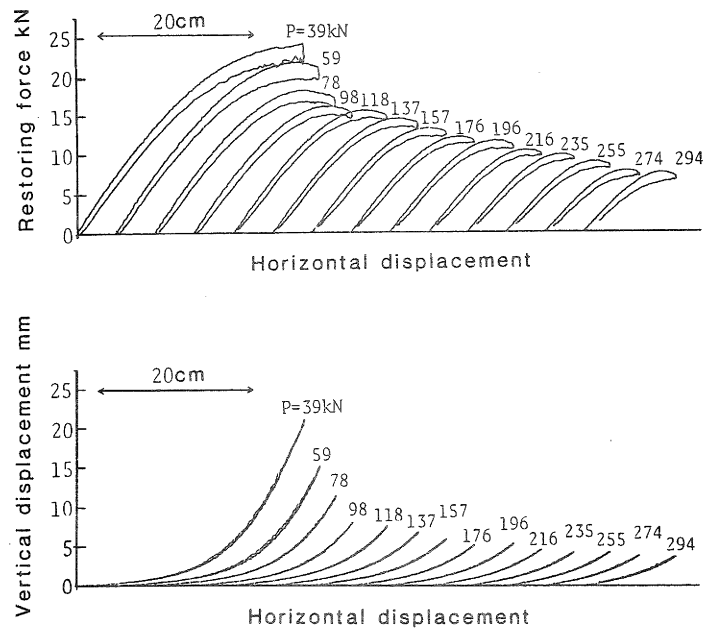


Fig. 9 Restoring Force vs Horizontal Displacement, and Height Reduction vs Horizontal Displacement for the Rubber Bearing of 98 kN Rated Load under Various Vertical Loads.

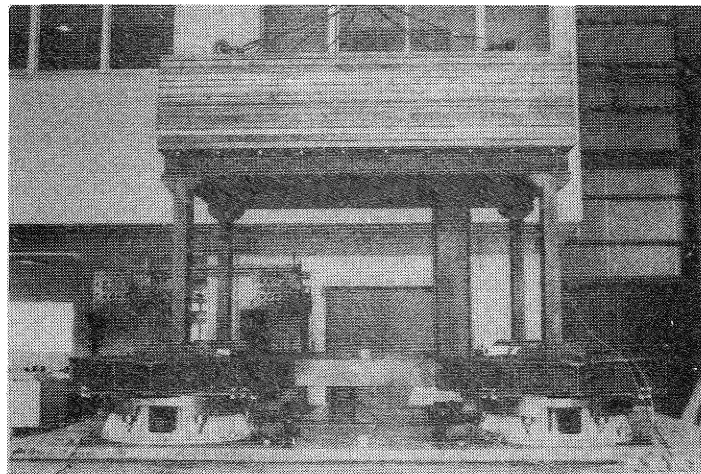


Fig. 10 Scale Model of a Simple Equipment Model Mounted on the Isolation Devices used in Excitation Tests.

well the specifications required for the isolation devices according to the similarity law. The friction dampers were also adjusted so as to satisfy the similarity law well. The results of seismic excitation tests are shown in Fig. 11. Scaled to full size, these results are interpreted as follows: For ground motions with peak accelerations of $2850 \sim 3300 \text{ mm/s}^2$, response accelerations of equipment when isolated are reduced to $1500 \sim 2200 \text{ mm/s}^2$ though for the non-isolated equipment they are amplified to $3350 \sim 9550 \text{ mm/s}^2$, and relative displacements in the isolation devices (deflections of the rubber bearings) are $14 \sim 97 \text{ mm}$. Comparing the accelerations when isolated with the corresponding values non-isolated, reductions of about $1/2 \sim 1/5$ are obtained, which are enough for some types of heavy equipment. These results also show that the response displacements when isolated are more sensitive to the dominant frequencies of the earthquakes than are the response accelerations. Another simulation study done recently by the author et al. suggests that, for earthquakes with the same peak velocity, both the response accelerations and the response displacements of isolated systems may become more independent of the variety of the earthquakes. If this can be further verified by more extensive study, it will be a useful characteristic.

The isolation device has not been implemented yet. Implementations are expected to electrical equipment of ultra-high voltage (1 MV) class which has expensive porcelain insulators of 12 m height, special equipment in auxiliary facilities of nuclear power plants such as waste disposal facilities and waste storage facilities, and so on.

4. EARTHQUAKE ISOLATION OF FLOORS

4.1 An Isolation Floor for a Computer System

At present, two types of isolation floor are used for computer systems in Japan, one of which was developed by a major construction company (8,9) and the other by the author in collaboration with a company engaged in vibration isolation technology (10-14). Figure 12 shows an early example of the latter floor, which provides isolation horizontally for the computer system of a bank. An improved version with vertical isolation portions shown in Fig. 13 may be used in future to provide more complete aseismic protection for sensitive components such as magnetic-disk devices which has been wanted by users.

The structure for horizontal isolation is as follows: A planar lattice of H-section steel beams is supported by many sets of ball bearings which can roll in any horizontal direction. On this lattice, a normal computer floor is constructed. Each set of ball bearings is put on a hardened steel plate fixed to the concrete floor which has enough area to cover the range of relative displacements of the ball bearings. Between the lattice and the concrete floor, a number of pre-tensioned spring units are installed to provide the lattice/isolation

floor with a nonlinear restoring force as shown in Fig. 15 in both directions of travel of the two principal axes of the floor. Also connected between the lattice and the concrete floor are oil dampers for horizontal motions. These are attached vertically through universal joints at both ends of each damper, as for the three-dimensional isolation device for light equipment. The non-linear restoring force is used to suppress the rotational behaviour of the floor caused by the practically unavoidable off-set between the centre of gravity and the geometrical centre, and to restore the floor to its original place after earthquakes and shifts caused by any other reason.

Excitation tests were carried out for a large-scale experimental model of the horizontal isolation floor on which an actual computer system was mounted, as shown in Fig. 14 (12). For the tests, a two-dimensional, horizontal-horizontal shaking table of $6.0 \times 6.0 \text{ m}$ was used, which belongs to a heavy industry company and has recently been converted to a three-dimensional one. The computer system used consisted of a central processing unit, a line printer, a magnetic-tape device, a magnetic-disk device, a card reader, a console panel and a CRT display. Equipment to monitor the normal function of the computer system during and after excitation was also set beside the shaking table. The isolation floor model had four pre-tensioned spring units, each of which was designed to incorporate the set of ball bearings for a compact experimental model. In Fig. 15 the nonlinear restoring force of this model is shown together with the hysteresis of the measured static friction force. Although the floor on which the computer system was mounted did not have a fixed horizontal natural frequency because of its nonlinear spring characteristics, the spring constant of 6.05 kN/m shown in Fig. 15 would give the corresponding linear system, without the nonlinearity due to pre-tension, a natural frequency of 0.227 Hz (a period of 4.40 s). However, it should be noted that the effective natural frequency of the system was higher than this value, $0.3 \sim 0.5 \text{ Hz}$ even when it had large displacements in the tests. Various excitation tests were done, including sinusoidal and seismic excitation tests each involving one-dimensional and two-dimensional excitations. Figure 16 shows the results of the two-dimensional seismic excitation tests which were the most realistic ones in the series of tests although vertical excitation was excluded. In this figure, the response accelerations measured at a point on the floor near its geometrical centre are compared with the corresponding input accelerations of the shaking table. Through the tests, it was verified that the isolation floor performed satisfactorily for implementation and its behaviour was almost pure translation for degrees of off-set expected in practical systems. Also, it was confirmed that the computer system on the isolation floor could maintain its normal function both during and after severe earthquake excitations.

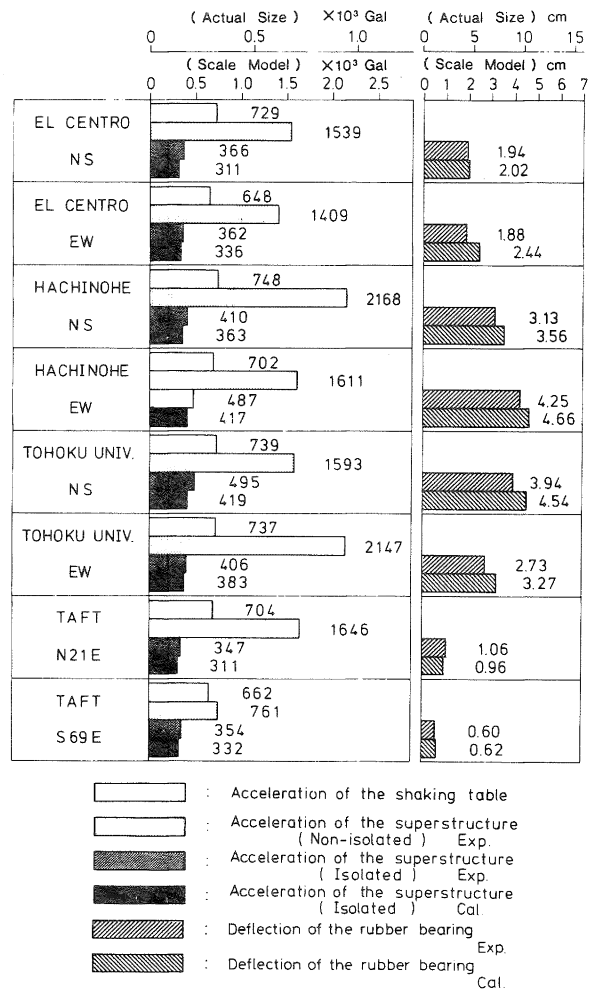


Fig. 11 Performance of the Heavy Equipment Isolation Device for the Simple Equipment Model. (Gal = 10 mm/s²).

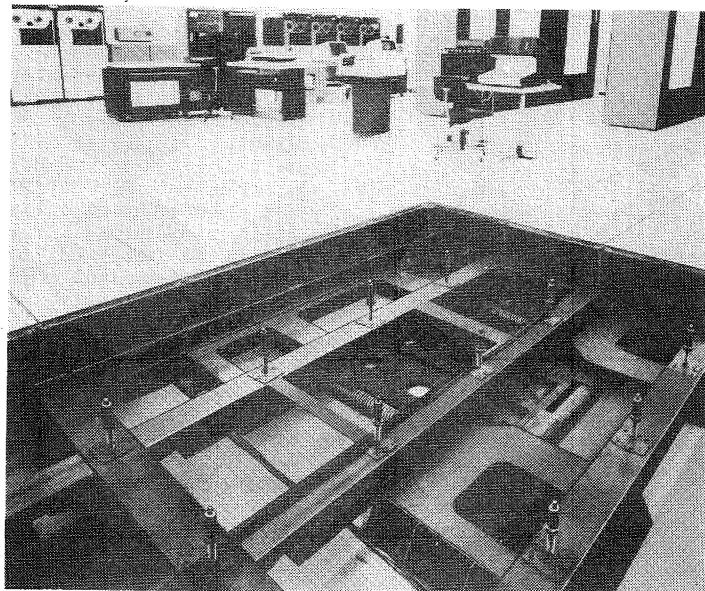


Fig. 12 An Example of the Isolation Floor Used for a Computer System of a Bank.

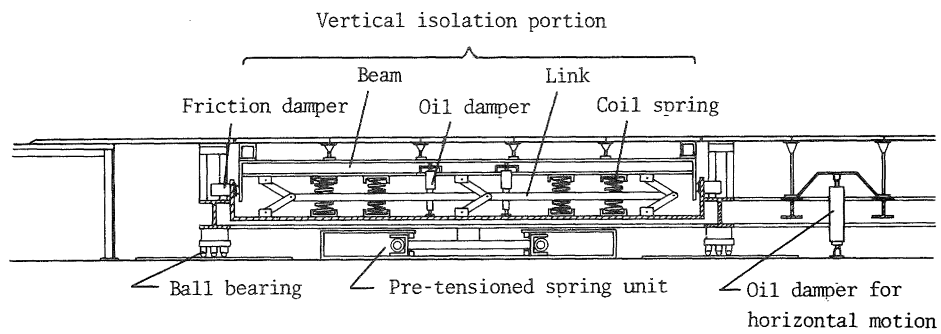


Fig. 13 Structure of an Earthquake Isolation Floor with Vertical Isolation Portions for Computer Systems.

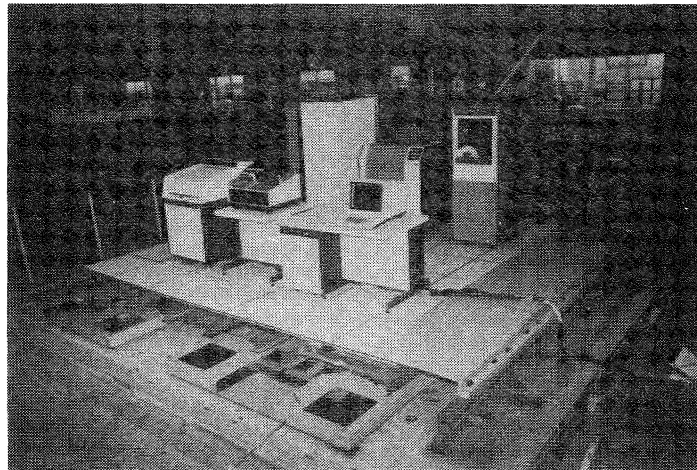


Fig. 14 Large-scale Model of the Isolation Floor and an Actual Computer System Used in Excitation Tests.

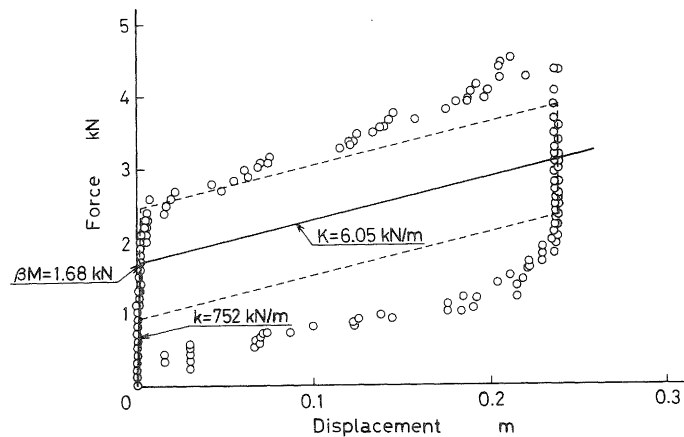


Fig. 15 Nonlinear Restoring Force due to Pre-tension and Hysteresis of Static Friction force in the Experimental Model of the Floor.

An analytical model was made considering the horizontal rotation of the floor as well as the two-dimensional horizontal translation (13). This model was proven by the experimental results mentioned above. A full-sized isolation floor shown in Fig. 17, which was almost the same as the first implemented floor of this type of isolation floor, was used as an example for the analysis. The floor had 6 pre-tensioned spring units, 36 sets of ball bearings and 8 oil dampers, and the mass of the floor plus the computer system was 48,300 kg. The spring constant of its restoring force was given a value resulting in a natural frequency of 0.167 Hz (a period of 6.0 s) in the corresponding linear system without the pre-tension, and the pre-tension force was specified to be equivalent to the inertia force when the 48,300 kg mass had an acceleration of 500 mm/s². The analysis was carried out using three components of the floor response accelerations measured on the ground floor and the 8th floor of a 9-storey combined steel and reinforced concrete frame building of Tohoku University in Sendai-city during the Miyagi-ken-oki earthquake, 1978. In this building, the large amplifications of floor response accelerations shown with broken lines in Fig. 20 were observed, particularly the NS component of the 8th floor response exceeded the acceleration of gravity. Such amplifications are recognised to be a typical example of those caused by low rise buildings up to 10 storeys or so. In Fig. 18, the behaviour of the isolation floor calculated for the 8th floor response is shown together with the input accelerations (note the different acceleration scales). Significant reductions in the response accelerations of the floor were obtained. At the same time, it was shown that the relative displacements of the floor were considerably larger. However, considering the estimated absolute displacements of the 8th floor were about 250 mm, the relative displacements of about 300 mm were reasonable. The rotation of the floor was successfully suppressed. In this analysis the vertical component of the floor response was also used to consider the varying friction force between the ball bearings and the steel plates, but this gave no influence on the results.

Furthermore, the behaviour when the floor had the components for three-dimensional isolation was investigated (14). The vertical motion of the vertical isolation components can be analysed independently of the horizontal motion of the floor because of its structure. This is verified through the analysis of the light equipment isolation device. Accordingly, a simple single-degree-of-freedom model was used for the analysis. The specifications for the vertical isolation portion were chosen to be a natural frequency of 1.0 Hz, a viscous damping of 40% critical and a friction force equivalent to 4% of the weight of the moving part including the equipment. In Fig. 19 the results of the analysis using the vertical component of the 8th floor response are shown. The reduction in acceleration was 1/2 and the displacement was very small in comparison with the

horizontal ones.

Such analyses for the same isolation floor were also carried out using the accelerations recorded on the ground floor. The results in both cases are summarised in Fig. 20. Supposing the isolation floor is used on the 8th floor of this building, the horizontal gaps between the floor and the walls/columns will need a width of 400 mm at least. In general, this value would be the limit of the width acceptable to users. Therefore, this case could be regarded as an example showing a practical limit for application of the isolation floor.

4.2 An Isolation Floor for Semiconductor Manufacturing Equipment

For semiconductor manufacturing equipment, it is desirable to have isolation floors which are effective not only for strong earthquakes, but also for weak earthquakes and possibly even ambient vibration. The isolation for ambient vibration is important for improving the yield rate of complete IC chips. For this purpose, measures have been taken for components which especially need isolation. However, as the degree of integration in IC chips increases and patterns of circuits become more fine, more complete isolation is becoming necessary. This requires the vibration level on floors on which the equipment is mounted to be as small as possible. The requirements for isolation from weak earthquakes is for similar reasons, to make the decrease in the yield rate due to weak earthquakes as small as possible. These isolation floors will find other uses besides semiconductor manufacturing equipment, e.g. fabrication equipment for lasers and precision devices using them. Such equipment is put on elevated floors in clean rooms in which almost all particles of dust in the air (particles with diameters longer than 0.3µm) are removed. The elevated floors are much higher than those for computers, about 1.8 m high, to ensure space for air-cleaning/conditioning equipment and piping, and have frame structures of H-section steel beams and columns.

The author is now developing an isolation floor in collaboration with clean room constructors and a rubber manufacturer. Considering the requirements for the isolation floor, rubber bearings have the most suitable properties. However, if the rubber bearings to be put under the columns of the floor are designed normally, they are too slender to undergo the required displacements because the rated loads are so small. As a solution to this problem, multi-stage rubber bearings with stabilizers as shown in Fig. 21(b) were adopted and are being tested now. This type of rubber bearing has been proposed by Skinner, Bycroft and McVerry (15) in a discussion on the application of base isolation to nuclear facilities as a method for enlarging allowable displacements of rubber bearings. The multi-stage rubber bearing shown in Fig. 21(b) consisted of 32 of the rubber bearing elements, one of which is shown in Fig. 21(a).

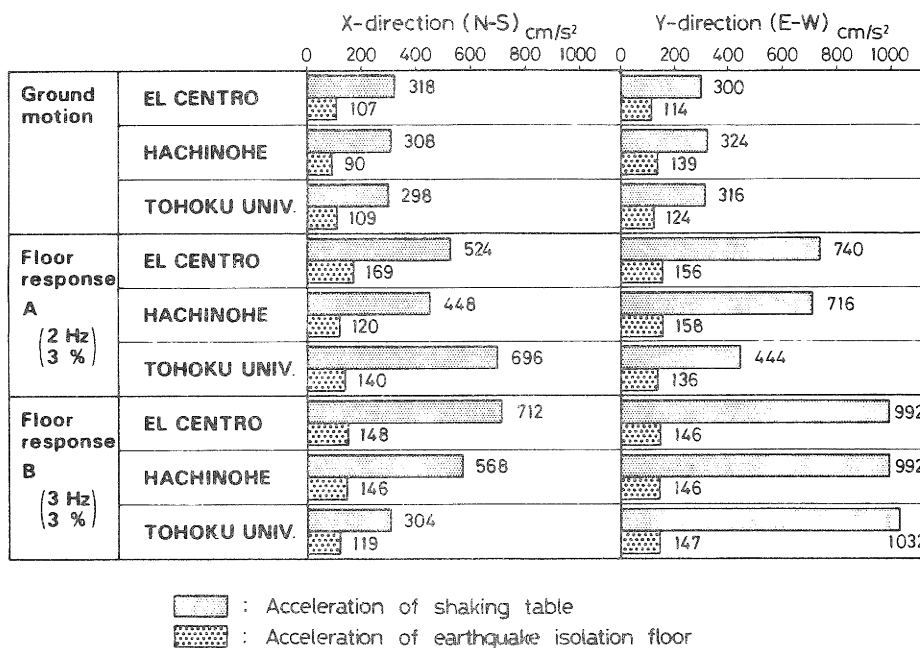


Fig. 16 Performance of the Isolation Floor in Two-Dimensional Horizontal Excitation Tests.

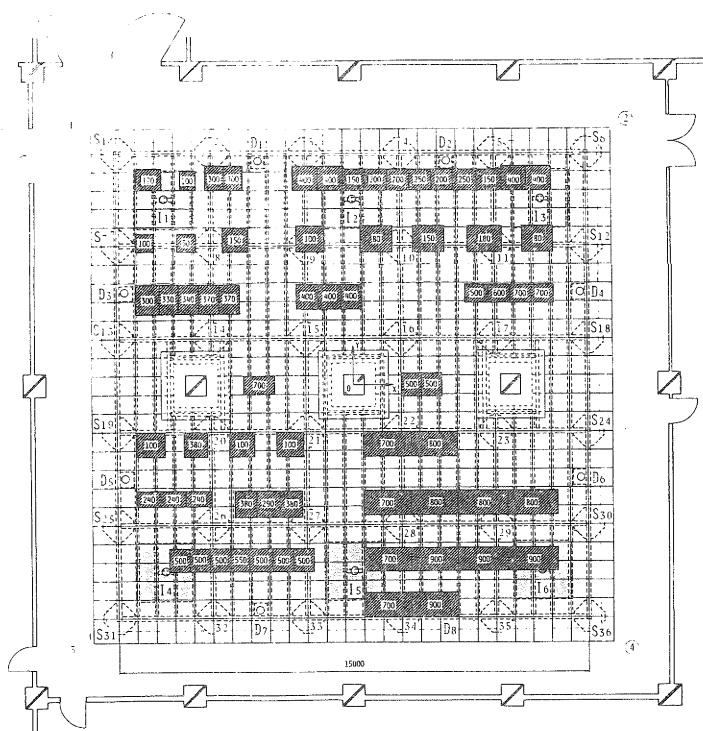


Fig. 17 Full-Sized Isolation Floor Used as an Example for Dynamic Analysis.

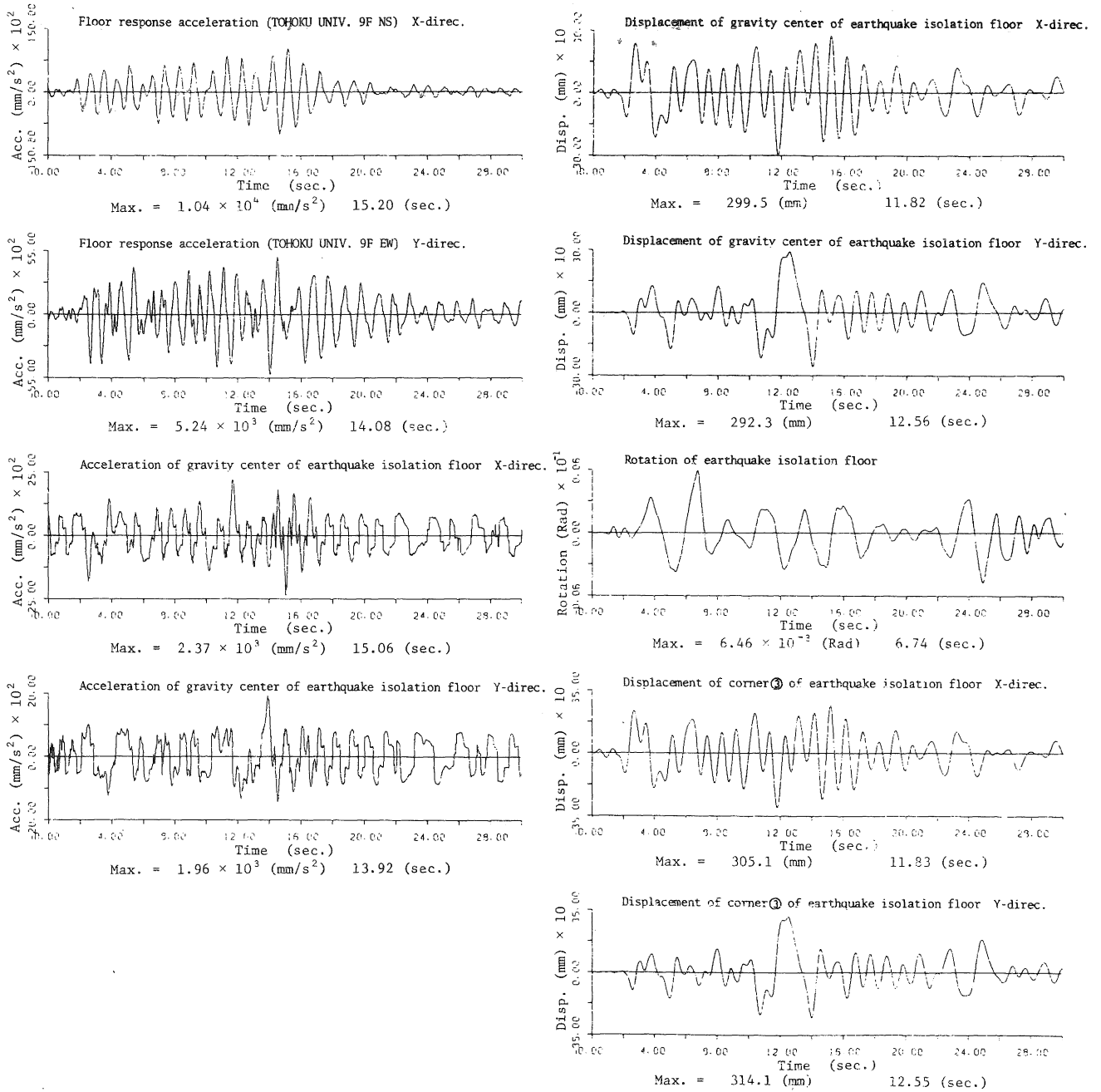


Fig. 18 Horizontal Dynamic Behaviour of the Isolation Floor Calculated using the 8th Floor Response of a 9-Storey Building Measured in the Miyagi-ken-oki Earthquake (1978).

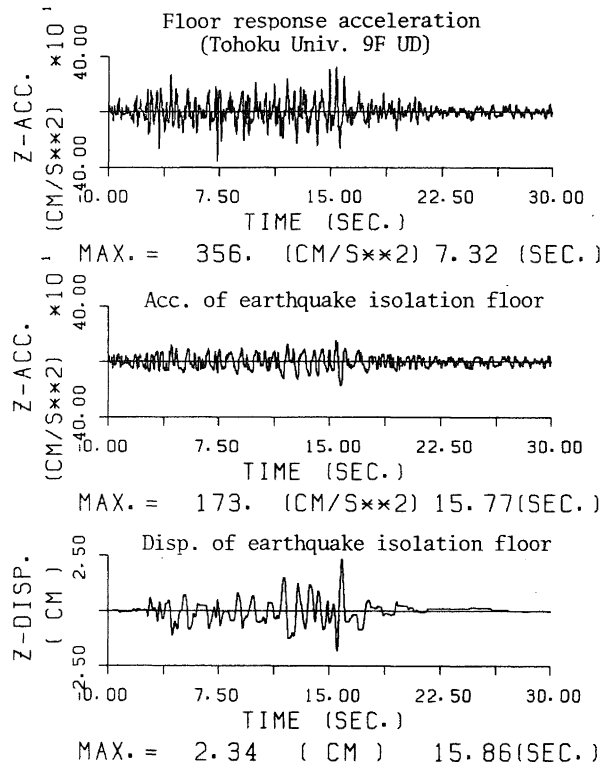


Fig. 19 Vertical Dynamic Behaviour of Three-Dimensional Isolation Portions of the Floor.

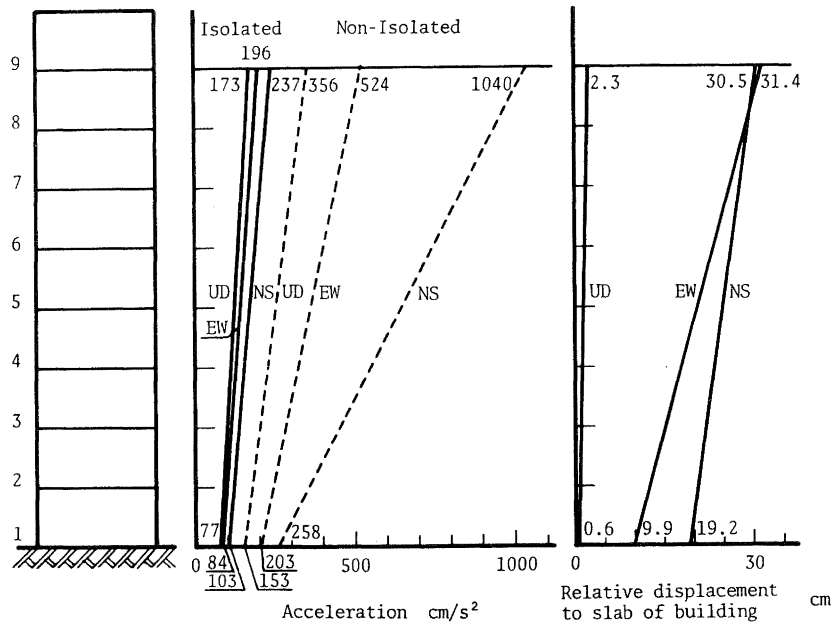


Fig. 20 Performance of the Isolation Floor Calculated for the Floor Responses Measured in the Miyagi-ken-oki Earthquake.

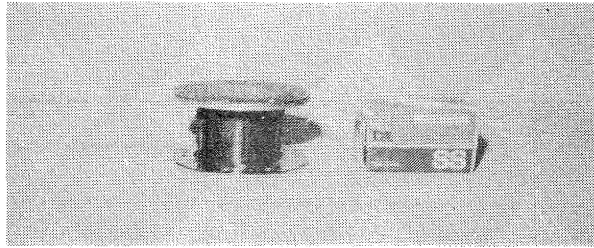


Fig. 21 A Multi-Stage Rubber Bearing Tested for an Isolation Floor for Semiconductor Manufacturing Equipment.
(a) Laminated Rubber Bearing Element.
(b) Complete Rubber Bearing.

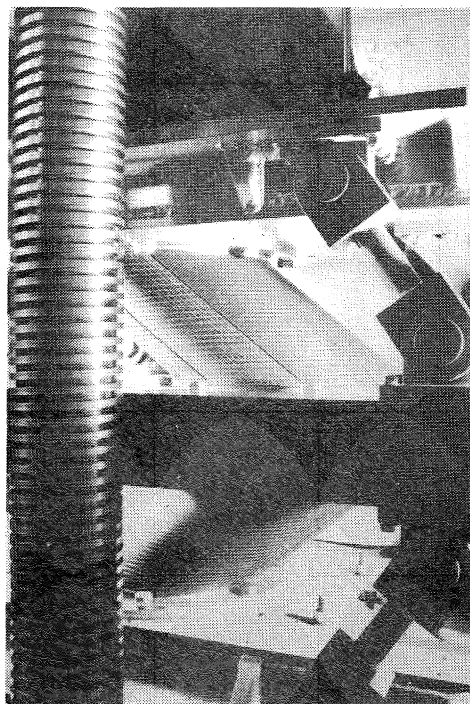
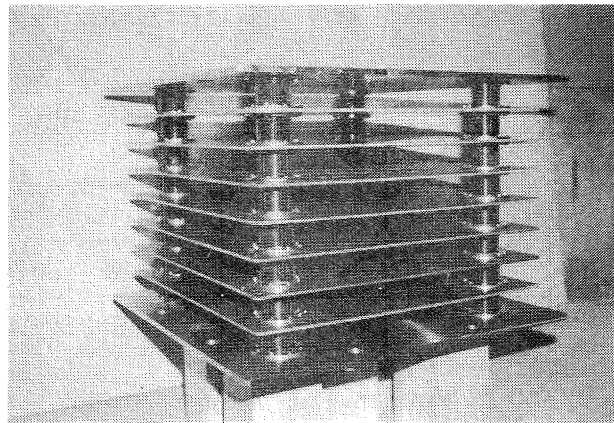


Fig. 22 Rubber Bearings of 490 kN Rated Load in Static Tests.

The complete rubber bearing was designed to provide the rated mass of 3,000 kg with stiffnesses corresponding to a horizontal natural frequency of 0.4 Hz and a vertical one of 12 Hz. Each rubber bearing element comprised 37 rubber sheets of 0.5 mm thickness and 40 mm diameter bonded to steel plates. The test results obtained up to now show that these multi-stage rubber bearings are feasible to use for these isolation floors. This work is the first step in the development. The development of a vertical isolation mechanism is being undertaken, and various tests including excitation tests of a large-scale model of the floor will follow.

5. EARTHQUAKE ISOLATION OF ENTIRE BUILDINGS

In general, earthquake isolation technology for industrial facilities is more attractive for floors rather than for components, and even more so for entire buildings, because there are fewer boundaries between isolated and non-isolated portions at which the relative displacements must be accommodated. Particularly in the case of the isolation of entire buildings, equipment can be installed in the normal manner, which is a great advantage in practical cases. For present uses and those in the near future such as computer systems and semiconductor manufacturing equipment, the isolation of floors may be still the main approach with the isolation of entire buildings used for special cases. However, for a number of uses expected in the future, the isolation of entire buildings will play the main role.

5.1 Rubber Bearings

In Japan, as well as in New Zealand (16), it is well recognised that energy absorption is an indispensable factor for base isolation systems. So far, however, research and development has been devoted mainly to rubber bearings rather than energy absorbing devices. This is because, in Japan, rubber bearings are considered to be more essential to the isolation of buildings, while they have scarcely been used for bridge bearings or any other uses.

A series of static tests have been carried out for rubber bearings of rated loads of 490 kN, 980 kN and 2,450 kN in collaboration with a major rubber manufacturer. The bearings of 490 kN rated load were tested first. These bearings comprising 30 natural rubber sheets of 5 mm thickness and 440 mm diameter bonded to steel plates were designed to provide the 50,000 kg rated mass with a horizontal natural frequency of 0.5 Hz and a vertical one of 17 Hz. Both end planes of the laminated rubbers were bonded to thick steel plates for fixing by bolts. As shown in Fig. 22, the tests were done using test apparatus which exerted vertical loads and horizontal displacements on a pair of the bearings while keeping both end surfaces of each bearing parallel by a link mechanism. Figure 22 also shows that the bearings could be stable under conditions of a 1,960 kN vertical load (4 times the rated load) and a 294 mm displacement

(about 3/4 times the diameter), which was the maximum stroke in the test apparatus. Figure 23 shows the horizontal restoring forces of the bearing for displacements up to 200 mm under various constant vertical loads, P , together with the decreases in its height measured simultaneously. The horizontal stiffness of the bearing considerably decreased with increased vertical load; under a fixed vertical load, it was roughly linear for displacement, although it slightly softened with displacement and then slightly hardened with further displacement. This nonlinear behaviour seems to imply that, in these thickset bearings bonded at both ends, the material nonlinearity of the rubber causing hardening of the stiffness became dominant with displacement rather than the geometrical nonlinearity which caused softening. Also it suggests that, if the displacement had continued to increase, the stiffness would increasingly harden and finally vacuoles and breaks would be formed in the rubber. From the results shown in Fig. 23, the vertical restoring forces of the bearing for vertical displacements (decreases in the height) under various fixed horizontal displacements, X , were derived, as shown in Fig. 24. The vertical stiffness of the bearing considerably decreased with horizontal displacement. This relationship was caused by the decreased overlapping area of the upper and lower end planes of the laminated rubber which substantially supported the vertical load. These tests confirmed that the bearings met the requirements satisfactorily. The bearings are being used for a base isolated structure for measuring responses to natural earthquakes as shown in Fig. 31.

Bearings with rated loads of 980 kN and 2,450 kN have been tested recently, using a test rig which was designed for bearings with rated load of up to 4,900 kN (Fig. 25(b)) and a large-scale test machine with a vertical load capacity of 19,600 kN which belongs to the Faculty of Engineering, University of Tokyo (Fig. 25(a)). The tests included exerting horizontal displacements of up to 400 mm for the 980 kN bearings and 500 mm for the 2,450 kN bearings under fixed vertical loads up to twice the rated loads. For both bearings, the horizontal and vertical stiffnesses satisfied the specifications well, and the sustainable displacements were large enough for implementation. Nonlinear behaviour of the horizontal stiffness was observed in these tests also because both the top and the bottom of the bearings were bonded. In the tests of the 980 kN bearings, the vertical load distributions across the top plate under various horizontal displacements were measured, showing that they were always concentrated into the overlapping area of the upper and lower end planes.

For rubber bearings which are bonded at both ends, it is very important to provide the largest possible range of displacement which can be achieved without the formation of vacuoles and breaks in the rubber by careful design of the dimensions of the bearings. Such design

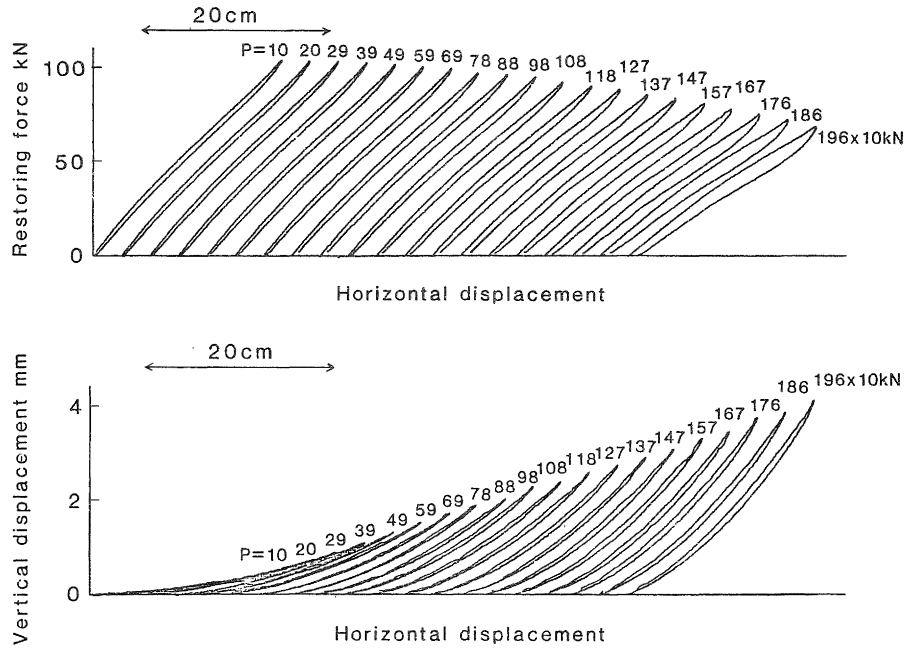


Fig. 23 Restoring Force vs Horizontal Displacement, and Height Reduction vs Horizontal Displacement for the 490 kN Rubber Bearing Under Various Vertical Loads.

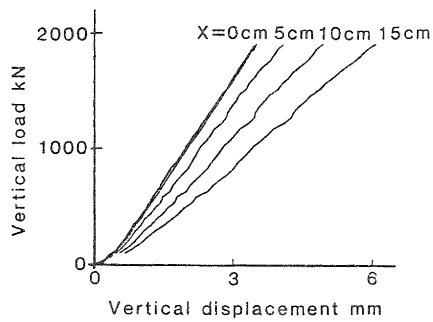


Fig. 24 Vertical Restoring Force vs Vertical Displacement for the 490 kN Rubber Bearing Under Various Fixed Horizontal Displacements.

will lead to bearings of larger diameter and height, and inevitably more layers, within the range of feasible and economic bearings satisfying the requirements for horizontal and vertical stiffnesses. For these larger bearings the vertical stiffnesses will also become less sensitive to their horizontal displacements. However, for the present, this design is not well based on quantitative understanding of non-linear behaviour of the horizontal restoring force. The development of analytical methods for this purpose is the most important subject in the future.

5.2 Base Isolation Systems Suitable for Industrial Facilities

Base isolation systems for industrial facilities should perform satisfactorily not only for the buildings themselves but also for the equipment of concern in them. Accordingly energy absorbing devices used for base isolation systems should be evaluated mainly from this viewpoint. To investigate such performance of base isolation systems using various types of energy absorption and to find the most suitable systems for various industrial facilities, fundamental study, including excitation tests of a scale model, is being carried out in collaboration with a major company engaged in the design of nuclear power reactors and in semiconductor manufacturing, etc. Figure 26 shows a 0.3 scale model of a supposed two-storey steel-frame building with a mass of 211,000 kg supported by four of the 490 kN rubber bearing previously mentioned. The 5,700 kg superstructure in the scale model had natural frequencies of 13.3 Hz and 28.5 Hz when non-isolated, which corresponded to 4.0 Hz and 8.5 Hz respectively in the full scale building. The natural frequencies of the base-isolated building are shown in Fig. 27 for both the scale model (fm) and the full-scale system (fa), together with the mode shapes. These theoretical results were derived from a four-degree-of-freedom model including the rocking motion. In this scale model, the first natural frequency was slightly higher than the intended value which corresponded to 0.5 Hz in full scale. Also, its vertical natural frequency of 33.3 Hz, corresponding to 10.0 Hz in full scale, was considerably lower than the target value of 17 Hz in full scale, which was caused by the decreased compression stress in the scaled-down rubber bearings. Particularly the factor of the lower vertical natural frequency needs to be considered in interpretation of the test results.

Base isolation systems using viscous dampers alone, friction dampers alone and both types of damper were tested. The friction damper used for the tests was installed under the superstructure and produced the required horizontal friction force by pressing a friction pad of special alloy through a coil spring against a stainless steel plate on the bottom of the superstructure. In the tests, two of the friction dampers were used; the resultant friction force was set to be equivalent to the inertia force when the 5,700 kg mass of the model had an acceleration of 0.15 g

for the case using friction dampers alone or of 0.07 g for the case using both dampers. These values corresponded to an inertia force in the full-scale system of the 211,000 kg mass having an acceleration of 0.045 g or 0.021 g. Two oil dampers of the normal type gave the system viscous damping of 11% critical for both cases of viscous dampers alone and combined viscous and friction dampers. These specifications were adopted as examples.

The two-dimensional, horizontal-vertical, seismic excitation tests produced the results shown in Fig. 28. For all combinations of types of dampers and cases of excitation, the horizontal and vertical response accelerations of the superstructure when isolated and when non-isolated are compared. The response displacements in the rubber bearings are also shown. The values in Fig. 28 can be scaled to full size by multiplying by 0.3 for acceleration and $1/0.3$ ($= 3.33$) for displacement.

To evaluate the performance of the base isolation systems/dampers for equipment, it is necessary to examine the floor response spectra. The floor spectra for three types of damper with the El Centro NS-UD input are given in Fig. 29 and those for the Akita NS-UD input (the Nippon-Kai-Chubu earthquake, 1983) are given in Fig. 30, including the spectra obtained by analysis for reference. The El Centro case is considered to be a typical example of earthquake ground motions containing mainly higher frequency components, and the Akita case a typical example of those having lower dominant frequencies.

The oil dampers used probably did not work well for the 3rd mode vibration of the scale model with its 29.8 Hz frequency because the displacement amplitudes were too small. This presumption is supported by the analytical results in Fig. 29 derived from an analytical model which had previously been proved to be valid. This means, at the same time, that, even in full-scale systems, viscous dampers must respond to small amplitude vibrations in order to control the responses of higher order modes which are important to equipment at the base of buildings. This applies to all types of damper. Viscous dampers which can respond to such small amplitude motion will have a better performance than other dampers in the range of higher frequencies; therefore they will achieve superior performance even for equipment to earthquakes of the El Centro type as shown in Fig. 29. However, viscous dampers seem to be unsuitable to earthquakes of the Akita type as shown in Fig. 28 and Fig. 30. By using viscous dampers of a larger capacity, it may be possible to improve the performance in a frequency range around the first natural frequencies of base-isolated buildings, but such improvement would not be easy to achieve because of their linear vibration characteristics.

For friction dampers, roughly speaking, the inverse properties apply. The friction dampers used in the tests could be effective even for vibrations

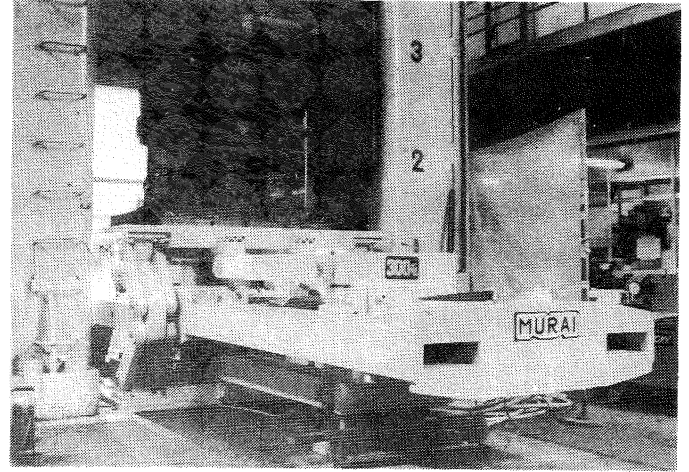
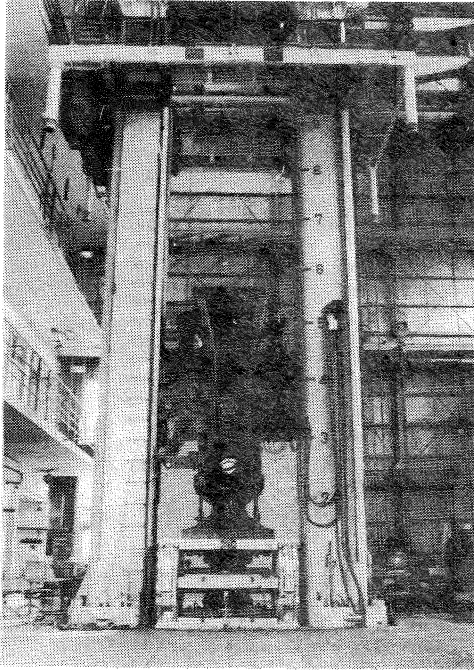


Fig. 25 Test Apparatus for Rubber Bearings with Large Load Capacities.
 (a) Large-Scale Test Machine with 19,600 kN Vertical Load Capacity.
 (b) Test Rig for Bearings with Rates Load of up to 4,900 kN.

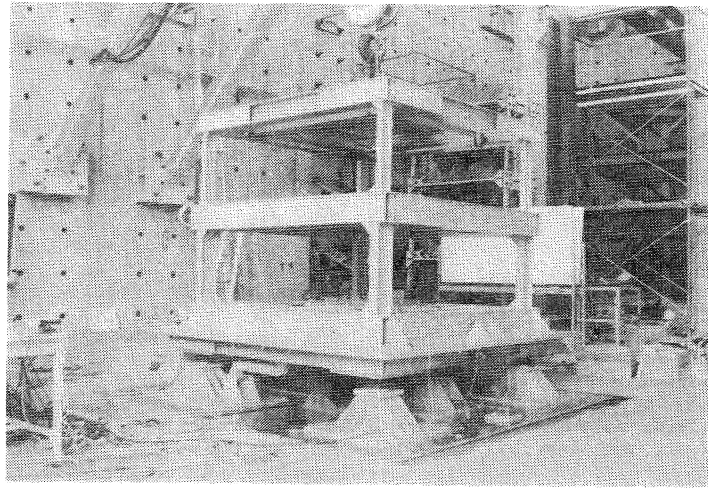


Fig. 26 Scale Model of a Base-Isolated Building used in Excitation Tests.

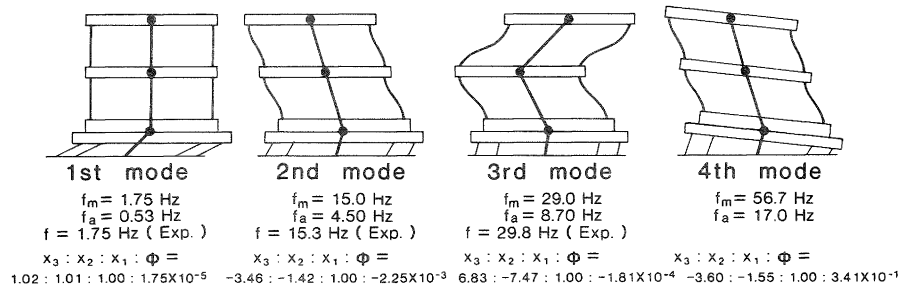


Fig. 27 Natural frequencies and mode shapes of the Base-Isolated Building.

with very small amplitudes, which can be shown by the good agreement between the experimental and analytical results shown in Figs. 29 and 30. Consequently, it is expected that a combination of viscous dampers and friction dampers, each with an optimal capacity, may result in the most desirable dampers effective in all ranges of frequency. Some such improvement was observed in the results of the combination tested, shown in Figs. 29 and 30. Analytical study to examine the various combinations is now being done.

Furthermore, hysteretic dampers should be considered, including a combination with viscous dampers. Lead-rubber bearings (17), extrusion energy absorbers (18) and other hysteretic dampers (19) developed in New Zealand are the most suitable devices for this purpose.

A practical viscous damper for base isolation has been jointly developed by a major construction company and a damper manufacturer, and is being used for a base isolated structure built for research purposes by the construction company (Fig. 31)(20). This damper produces a damping force by shearing a special viscous material which has been used for bridge dampers between two parallel horizontal plates, which is effective even for small amplitude vibrations. The base isolation system being used for the structure consists of 9 or the 490 kN rubber bearings mentioned previously, and 6 of the two-dimensional horizontal viscous dampers. The superstructure which is a coal silo for another experiment does not represent an intended use of the base isolation system. For this base-isolated structure, regular free vibration tests and measurements of the responses to natural earthquakes have been done. Another major construction company has done static tests of rubber bearings and excitation tests of a base isolation system using a simple type of steel hysteretic damper (21). The company has undertaken work for the implementation of a base isolation system to its own new building.

Base isolation systems for industrial facilities may become slightly expensive in order to perform satisfactorily for both the building and equipment, but this could be acceptable. For example, in current nuclear power plants in Japan, the construction cost of buildings, including a reactor building and a turbine building, is normally about 5%, at most 10%, of the total construction cost. The rest is for equipment. This applies to fast breeder reactor power plants. Therefore, with a significant improvement in aseismic protection for equipment being achieved by a base isolation system, the decrease in cost due to it will not only compensate for a possible increase in construction cost for the base-isolated building, but also bring a decrease in the total cost. Also, in semiconductor manufacturing factories and other uses expected in the future, the cost of the entire equipment of concern will be far bigger than that of the building containing it. Insurance against earthquake of such equipment is not available in Japan, so if the cost to

replace earthquake losses is taken into account, the reduction in repair cost will be enough to allow base isolation of the building.

Recently in Japan a number of companies engaged in the nuclear power plant industry and building construction, have begun research and development for earthquake isolation of buildings. The projects supported by the government and electricity companies will stimulate the research and development. Excitation tests will be carried out for very large-scale models of base-isolated reactor buildings, using a two-dimensional, horizontal-vertical shaking table at Tadotsu Engineering Laboratory, Nuclear Power Engineering Test Centre (Fig. 32). This shaking table has been used for a series of seismic proving tests for major components of nuclear power plants since its construction in 1982. The main specifications are as follows:

Max. loading capacity	: 1,000 ton.
Table size	: 15 m x 15 m.
Max. acceleration:	
Horizontal	: 2.72 g (500 ton), 1.84 g (1,000 ton).
Vertical	: 1.36 g (500 ton), 0.92 g (1,000 ton).
Max. velocity:	
Horizontal	: 750 mm/s
Vertical	: 375 mm/s
Max. displacement:	
Horizontal	: ± 200 mm
Vertical	: ± 100 mm

6. CONCLUDING REMARKS

Various equipment will appear in the future to apply more advanced science and technology in industry. Such equipment will probably achieve extremely microscopic operation and/or function under extreme conditions in temperature, pressure, magnetism, etc; at the same time it will have delicate mechanisms with accuracy of the highest degree and/or fragile structures comprising materials exposed to various extremely severe circumstances. It will be more difficult for advanced equipment in the future to satisfy earthquake resistance requirements by its own structure alone. For example, nuclear fusion reactors expected as power reactors in the 21st century will have huge super-conduction magnet coils cooled by liquid helium which will need to be supported by a single FRP cylindrical column at the centre. It is considered that earthquake isolation will be indispensable to large-scale reactors/plants in Japan. The author and a major company engaged in the design of nuclear fusion reactors have already jointly undertaken a preliminary study. It must be emphasized that earthquake isolation technology is expected to become even more indispensable in the future for many industrial facilities.

Type			NS El Centro EW		NS Taft EW		NS Hachinohe EW		NS Akita EW			
	Rubber bearing + Friction damper	Horizontal										
Vertical			$\bar{F}_k = 0.15$	m_3 acc. (cm/s ²)	842 (726)	764 (689)	752 (676)	821 (634)	556 (717)	605 (652)	396 (483)	392 (565)
			$\zeta_D = 0.0$	m_2 acc. (cm/s ²)	711 (612)	701 (553)	585 (719)	731 (642)	541 (638)	578 (577)	389 (364)	404 (471)
			m_1 acc. (cm/s ²)	703	721	601	726	558	601	428	435	
			Input acc. (cm/s ²)	474	523	405	466	533	528	371	366	
Rubber bearing + Friction damper + Oil damper	Horizontal											
		Vertical	$\bar{F}_k = 0.07$	m_3 acc. (cm/s ²)	865 (740)	835 (653)	758 (794)	917 (713)	568 (664)	554 (630)	388 (488)	390 (604)
			$\zeta_D = 0.113$	m_2 acc. (cm/s ²)	638 (624)	638 (525)	608 (849)	606 (722)	558 (591)	562 (558)	379 (367)	383 (503)
			m_1 acc. (cm/s ²)	743	764	679	827	574	580	405	394	
			Input acc. (cm/s ²)	483	496	480	524	493	511	375	391	
Rubber bearing + Oil damper	Horizontal											
		Vertical	$\bar{F}_k = 0.0$	m_3 acc. (cm/s ²)	1158 (778)	1181 (613)	1180 (855)	1229 (741)	505 (555)	506 (504)	348 (398)	350 (459)
			$\zeta_D = 0.113$	m_2 acc. (cm/s ²)	1052 (656)	1022 (492)	814 (911)	965 (750)	454 (494)	456 (446)	354 (300)	333 (382)
			m_1 acc. (cm/s ²)	978	959	790	925	461	460	342	327	
			Input acc. (cm/s ²)	508	465	513	545	412	408	306	297	

Fig. 28 Test Results for Base Isolation Systems Using Viscous Dampers Alone, Friction Dampers Alone and both types of Damper. Dotted lines and values in brackets are for non-isolated case. When non-isolated, m_1 is fixed to shaking table; acceleration of m_1 and input are then identical.

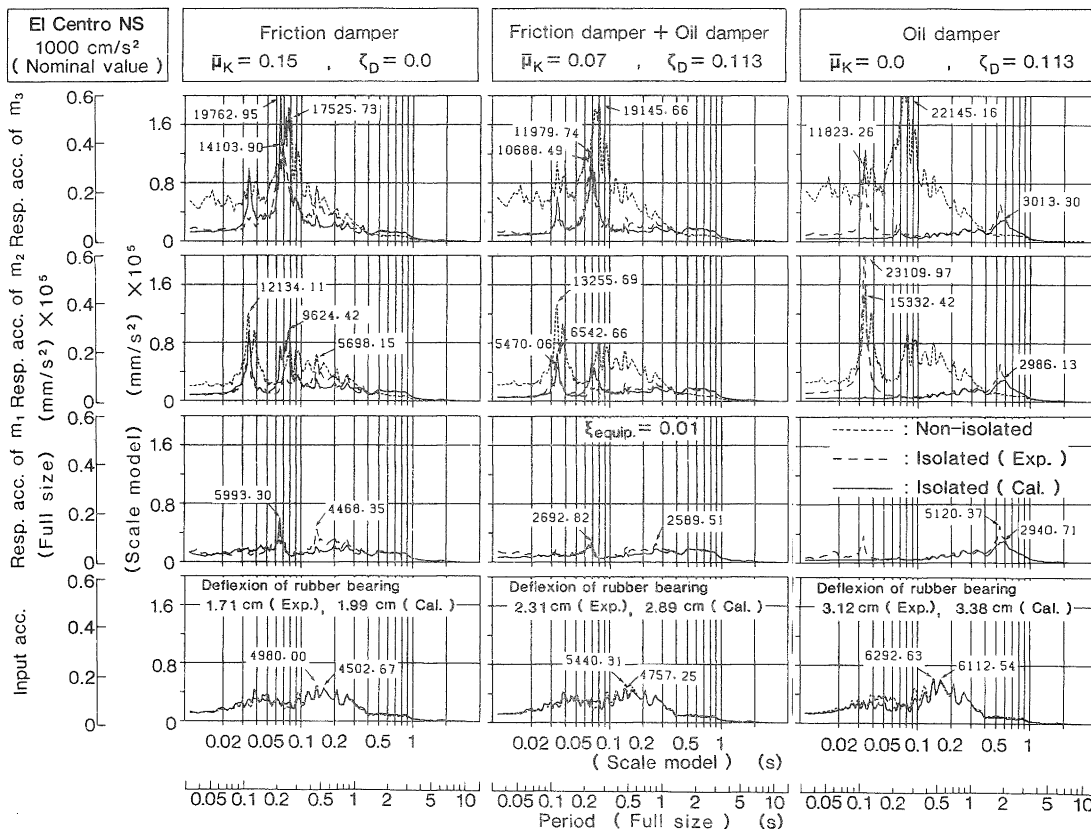


Fig. 29 Floor Response Spectra for Three Types of Damper in the Case of the El Centro NS-UD Input.

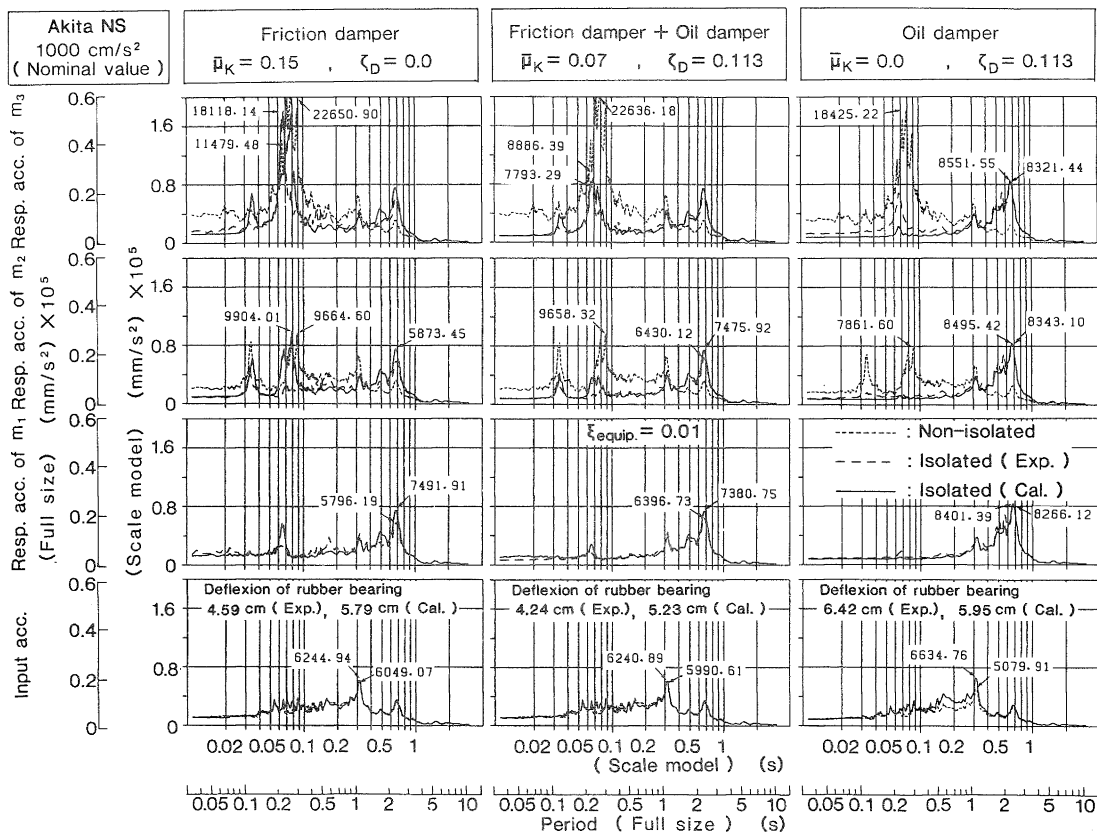


Fig. 30 Floor Response Spectra for Three Types of Damper in the Case of Akita NS-UD Input.

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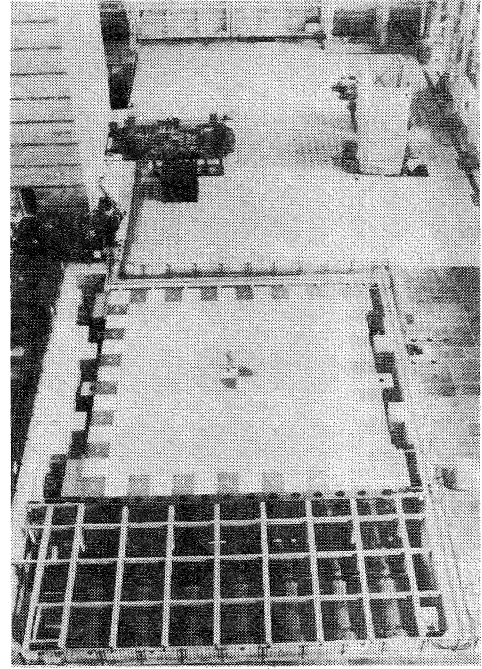


Fig. 32 Very Large-Scale Shaking Table being used for Seismic Proving Tests for Major Components of Nuclear Power Plants at Tadotsu.

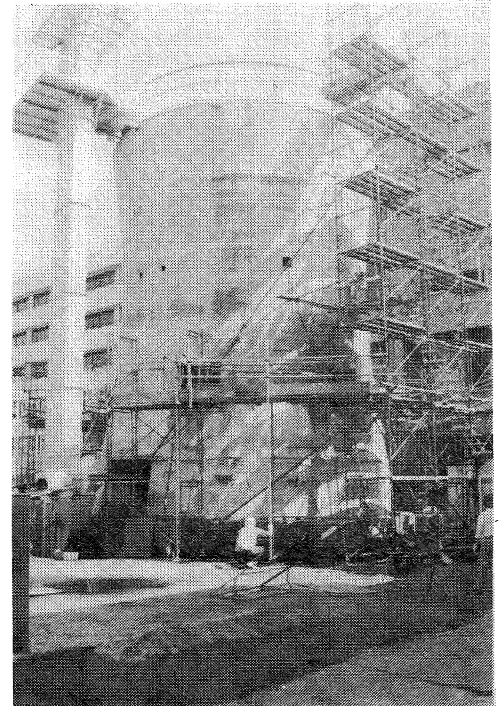
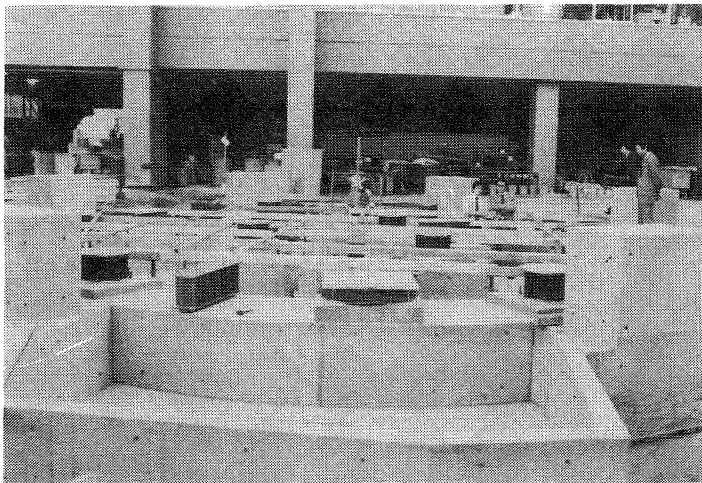


Fig. 31 A Base-Isolated Structure Built for Research Purposes by a Private Construction Company.
 (a) 490 kN Rubber Bearings and Two-Dimensional Horizontal Viscous Dampers installed on the Foundation.
 (b) Complete Base-Isolated Structure.