13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 668

BASE ISOLATION SYSTEM SUITABLE FOR MASONRY HOUSES

Shigeya KAWAMATA[1], Naoki FUNAKI[2], Norio HORI[3], Tomomi FUJITA[4] and Norio INOUE[5]

SUMMARY

Though it is one of the most urgent subject of earthquake engineering to mitigate the disaster caused by collapse of masonry houses in developing countries of seismic area, rapid transfer of these houses into construction of modern engineering is difficult and dependence on local masonry material will prevail unchanged.

In this paper, a new form of base isolation suitable to masonry houses and apartments is proposed, where rocking pillars are utilized to support the superstructure. The rocking pillars are formed by a steel tube with concrete infill provided with spherical bearing caps at top and bottom ends. Only to settle down a caisson containing the pillar into a hole is the site execution necessary for forming an isolation foundation. Vibrational characteristics of houses built on the isolation foundation are made clear by theory and experiments. Shaking table tests are carried out using 1/4 scale specimen of the isolation foundation system having weights of 2.4 ton. Based on the result of the shaking table tests, capability of the new system to protect the masonry houses is discussed.

INTRODUCTION

In developed countries of seismic area, dwelling houses and apartment houses are built based on modern construction technique and maintain some level of seismic resistance. Recently, application of seismic control technique to these houses will conspicuously advance the level of safety and reliability against earthquake.

In contract, many people in developing countries have to live, by technical and economical reason, in traditional masonry houses of adobes, bricks and concrete blocks. The earthquake of M6.5, which took place in Iran on December 26, 2003, totally destroyed the historical city of Bam killing forty thousand people. The disaster reminds us that it is one of the most urgent subjects of earthquake engineering to improve seismic resistance of the houses in developing countries. However, it is not easy to shift the construction of these houses to the one of modern technology but dependence on local products of

[1] Professor Emeritus, Tohoku Institute of Technology, Sendai, JAPAN, E-mail: Kawamata@tohtech.ac.jp
[2] Lecturer, Tohoku Institute of Technology, Sendai, JAPAN, E-mail: funaki@tohtech.ac.jp
[3] Assistant, Tohoku University, Sendai, JAPAN, E-mail: hori@struct.archi.tohoku.ac.jp
[4] Graduated Student, Tohoku Institute of Technology, Sendai, JAPAN, E-mail: fujita@smail.tohtech.ac.jp
[5] Professor, Tohoku University, Sendai, JAPAN, E-mail: inoue@struct.archi.tohoku.ac.jp

masonry material will not be changed. A possible solution of avoiding collapse of the masonry houses is to implement base isolation devices to reduce input acceleration restricting responding stress within the shearing strength of the masonry walls. For the base isolation to be effective, the house construction should conform to the minimum requirement of providing rigid diaphragm in each floor level to avoid collapse of the masonry walls by out of plane vibration. This will be accomplished by installing supplementary RC members such as lintels and floors. Adobes are not suitable even in the case of base isolation because of their extremely poor mechanical property and alternative masonry material such as bricks is expected to be supplied. The materials and equipment of the isolation system should be supplied in low cost by means of mass production of national or international scale. The system must be so simple as to be installed in the site by non-skilled local labor.

In this paper, taking the above requirements into account, a new form of base isolation suitable to masonry houses is proposed, in which rocking pillars are utilized as bearing members. Vibration characteristics of the base isolated houses are made clear by theory and experiments. Based on the results of shaking table test of a 1/4 scale model of the isolation foundation system supporting mass of 2.5 tons, seismic capability of the masonry house built on the isolation system is discussed.

There were pioneering works of base isolation utilizing rocking elements. R. Oka [1] designed and realized base isolated RC buildings utilizing RC rocking pillars having a spherical cap at the bottom. He formed an isolation story in the basement. The superstructure was supported by rotating spherical hinges provided in the top of the pillars. In the present system, superstructure is simply placed on the spherical caps in the top of the pillars, thus larger displacement of the superstructure can be allowed. K. Matsushita and M. Izumi [2] proposed "rocking balls" of various types to support buildings. Though one of them was provided with spherical surfaces both in upper and lower halves of the body, the concept was different from the rocking pillar which corresponds to large displacement of the superstructures.

NEW FORM OF BASE ISOLATION SYSTEM FOR MASONRY HOUSES

As shown in Figs.1 and 2, in a masonry house provided with the proposed isolation system, floors are partitioned into rooms of moderate area by regularly arranged masonry bearing walls and superstructure is supported by isolation foundations installed at the intersection points of the walls. The isolation foundation consists of a rocking pillar and a RC caisson containing it. Only to settle down the caisson into a hole dug in the ground finishes site execution of the isolation foundation. The rocking pillar is formed by a steel tube provided with spherical caps at both ends, being filled with concrete. As shown in Fig.3, by making radius of curvature of the spherical caps, R, larger than half-length of the pillar, L, restoring moment occurs against rocking motion rotating around the bottom end of the pillar. Consequently the superstructure on the rocking pillar is subjected to slow lateral vibration of long period. As proved in the next section, the natural frequency of the superstructure is determined by the length L and the curvature-length ratio, R/L, independently of the mass born by the pillar. While the spherical caps can be mass produced by press process from stainless steel plate, manufacturing them as hard ceramics may be another possibility.

To maintain integrity of the superstructure during earthquake, it is required to construct the masonry walls on RC base beams and to provide RC lintels at the floor level of upper stories. These RC members combined with RC floor slabs form rigid diaphragms which prevent out of plane failure of the masonry walls. When wooden floors and roofs are inevitable, formation of lintels having diagonal bracing shown in Fig.4 is recommended. RC lintels and beams should be assembled from fabricated precast members.

In order to restrict responding displacement of the rocking pillars, it is needed to install damping device between the pillar and the caisson at their top level. As the restorability of the rocking pillars is generally very weak, excitation by wind or artificial excitation should be restrained. Dampers of hysteretic type can make triggering action for this purpose. The top end of the caisson acts as a stopper against the excessive rocking motion of the pillar and the rubber cushion is attached to relieve impulse of collision as shown in Fig.2.

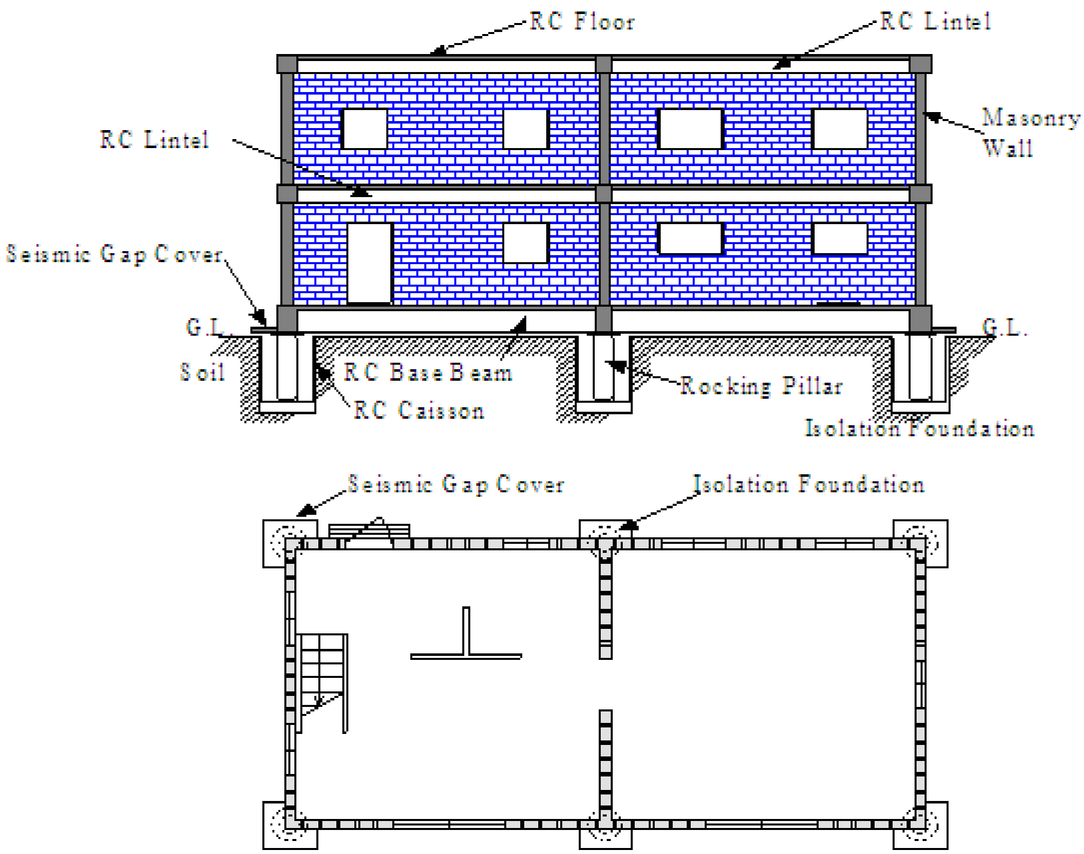


Fig.1 Plan and Section of Masonry House with Isolation Foundation

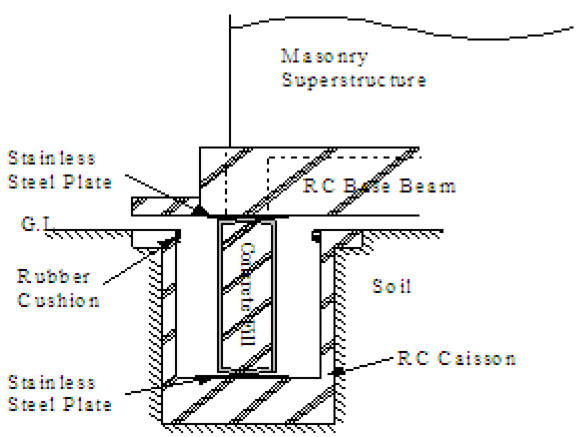


Fig.2 Scheme of Isolation Foundation

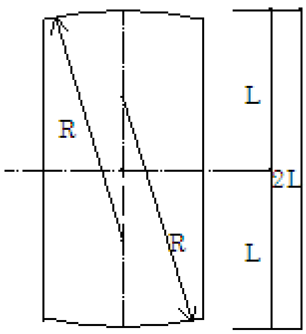


Fig.3 Geometry of Rocking Pillar

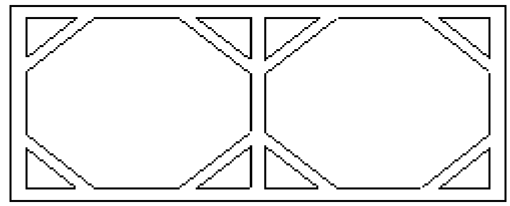


Fig.4 Plan of Diagonally Braced Lintels

VIBRATIONAL PROPERTY OF ROCKING PILLAR SYSTEM

Natural Period

Fig.5 shows the geometry of movement of the rocking pillar. When the axis of the pillar rotates by angle θ , lateral displacement of the superstructure becomes

$$x = 2L\theta \tag{1}$$

and distance of eccentricity occurring between loading point in the top cap and supporting point of the bottom cap is given by

$$e = 2(R - L)\theta \tag{2}$$

When the pillar is supporting the mass of m, moment of inertia acting on the pillar is

$$M = -m\ddot{x} \times 2L = -2mL\ddot{x} \tag{3}$$

and the restoring moment created by the load and the reaction becomes

$$\bar{M} = -mge = -2mg(R - L)\theta \tag{4}$$

Therefore, equation of motion is obtained as

$$L\ddot{x} + g(R - L)\theta = 0 \tag{5}$$

Using the relation of Eq.(1), we have

$$\ddot{x} + \frac{(R - L)g}{2L^2}x = 0 \tag{6}$$

Natural period of the single mass system governed by Eq.(6) is given as

$$T = 2\pi\sqrt{\frac{2L^2}{(R - L)g}} = 2\pi\sqrt{\frac{2L}{(R/L - 1)g}} \tag{7}$$

Eq.(7) indicates that the natural period of vibration of the structure supported by the rocking pillar system does not depend on the mass of superstructure but is determined by dimensions of the pillar, R and L. Considering a rocking pillar of prototype scale, let the parameters of R=80cm and L=70cm be assumed, then we have

$$T = 2\pi\sqrt{\frac{2 \times 70^2}{10 \times 980}} = 2\pi = 6.28\,\text{sec} \tag{8}$$

To check the validity of Eq.(7), free vibration test of a simple scale model shown in Fig.6 was carried out. The result is shown in Table 1. It is shown that Eq.(7) gave good prediction of the natural period.

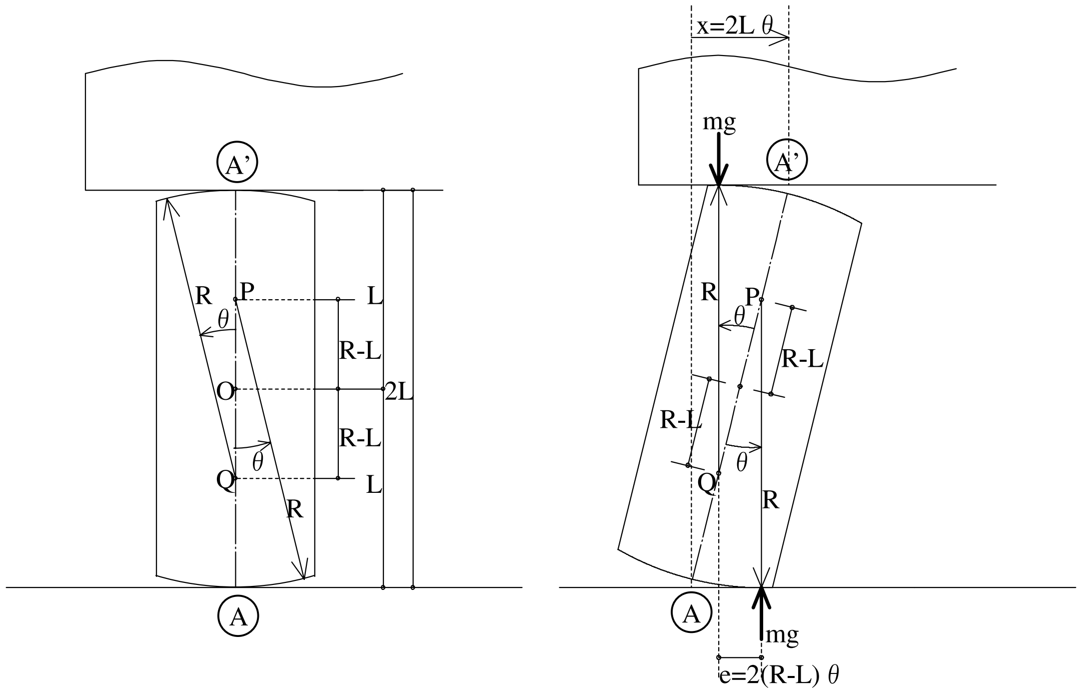


Fig.5 Movement of Rocking Pillar

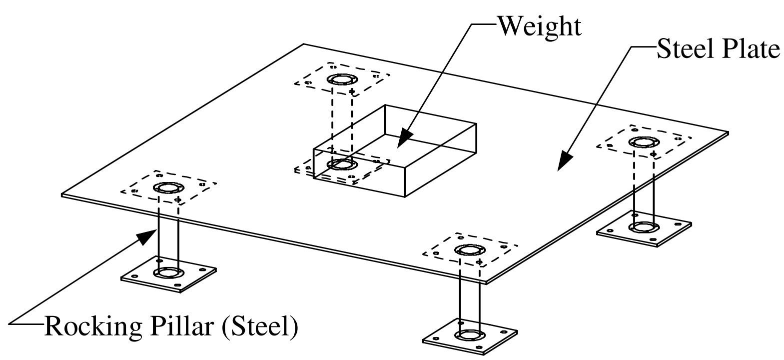


Fig.6 Model of Free Vibration Test

Table 1 Comparison of Natural Period: Theory and Test

	Pillar		Supported Mass [kg]	Natural Period [sec]	
	R [cm]	L [cm]		Test	Theory
Case1	20.0	17.0	80.5	2.70	2.78
Case2			47.0	2.63	
Case3	20.0	15.0	80.5	1.91	1.90
Case4			47.0	1.87	

Torsional Vibration

For a base isolation system utilizing laminated rubber bearings, in order to prevent response of torsional vibration, it is required to adjust the arrangement of bearings so that the center of distribution of their shearing stiffness in plane coincides with the center of gravity of the superstructure. In contrast, the present rocking pillar system is free from torsional vibration. As indicated by Eq.(4), the restoring moment of a rocking pillar is proportional to its vertical load. Therefore, the center of distributed restoring moment automatically coincides with the center of gravity of the masonry houses which are built by ordinary construction process.

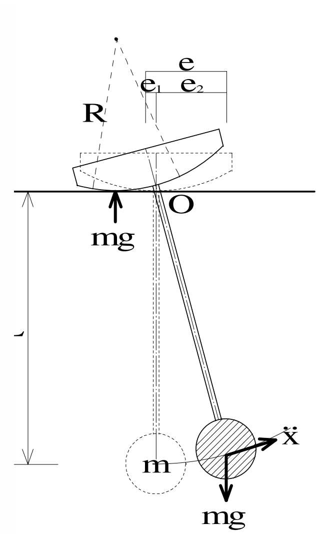
Rolling Resistance

To observe rolling resistance of the spherical bearings and its damping effect to vibration, free vibration test was carried out using a rig shown in Fig.7. A weighted pendulum was hung by a beam which was supported through spherical bearings installed at both ends. The spherical bearing shown in Fig.8 was lathed from thick stainless steel plate. The bearing was placed on a flat stainless plate so as to roll on the contact surface. The maximum load applied by the weight was 2365kg. Fig.9 shows the envelope of time history of rocking angle of the pendulum which was loaded by 1935kg weight, vibrating with the period of 2.5sec. It showed very slow damping for over 500 cycles of free vibration. Though it exhibited almost viscous type of damping, damping ratio took very small value, being below 0.1% of critical damping. Therefore, the damping caused by rolling of the bearing can be neglected compared to that of damping devices to be installed in the isolation system.

Bearing Capacity

If the rolling bearing gives rise to plastic deformation at the contact point, it will induce irregular movement of rocking vibration. The applied vertical load bringing this critical point corresponds to loading capacity of the bearing. However, the limiting load was not reached in the present test.

(a) Pendulum Rig



(b) Scheme of Pendulum

Fig.7 Rolling Test of Spherical Bearing

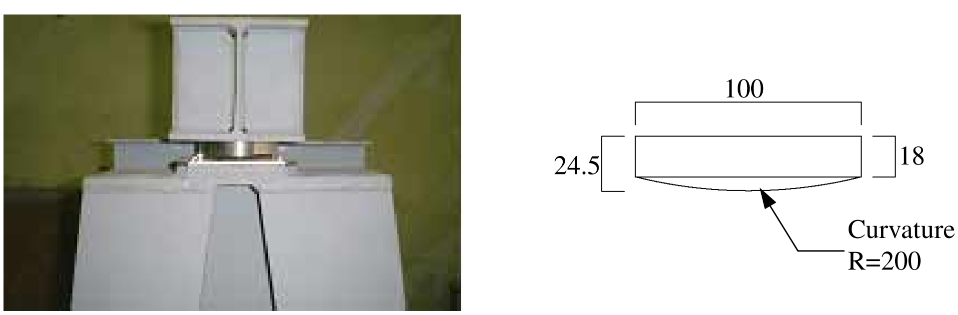


Fig.8 Spherical Bearing (unit : mm)

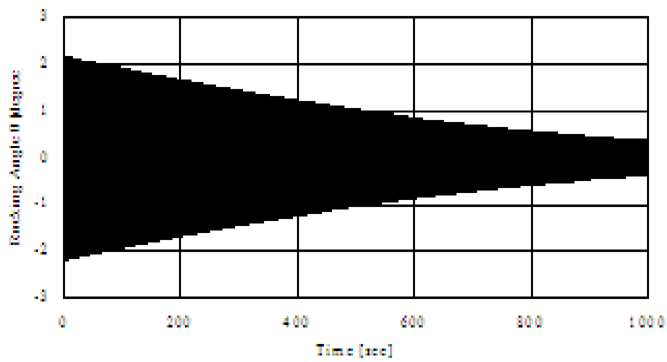
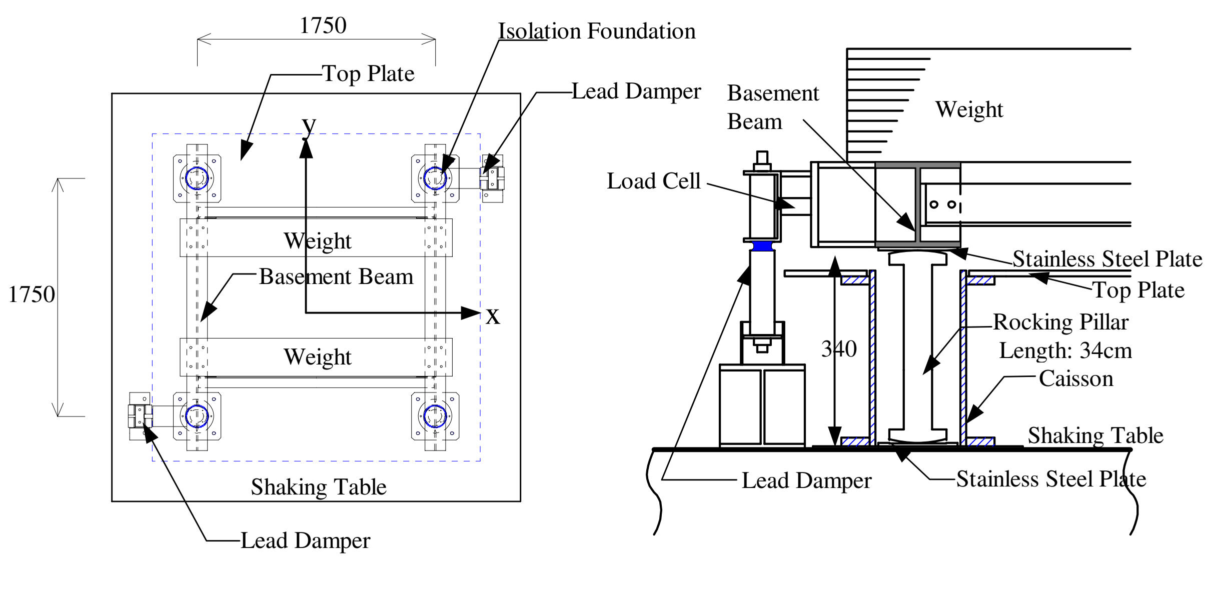


Fig.9 Envelope of Time History of Rocking Angle

VIBRATIONAL CHARACTERISTICS OF ISOLATION FOUNDATION SPECIMEN

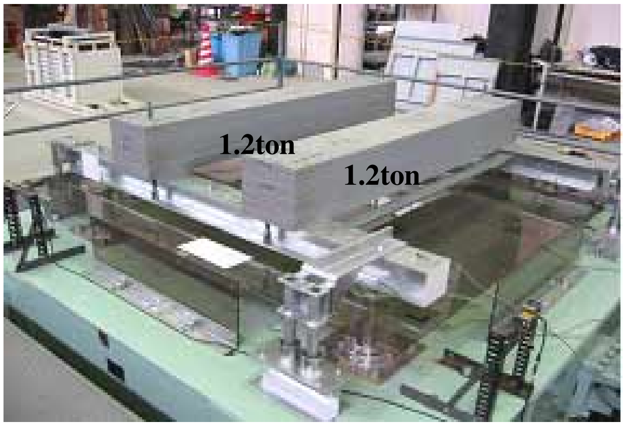
Test Apparatus

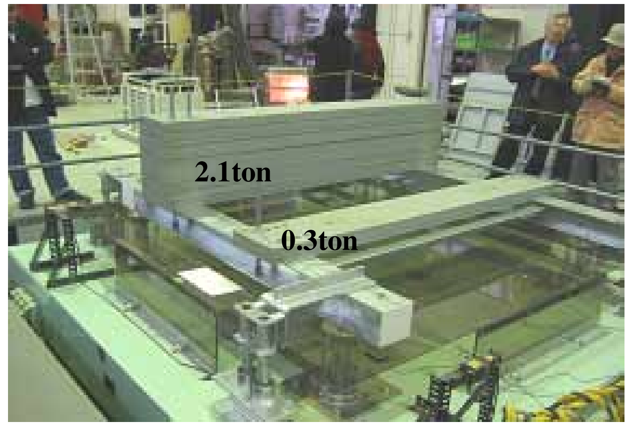
Shaking table tests were carried out with regard to the isolation foundation system using a 1/4-scale model. Fig.10 shows detail of the specimen and Fig.11, view of the apparatus mounted on a shaking table. The superstructure was composed of a raft of steel base beams and weights of steel plates mounted on it and was supported by four rocking pillars. Total mass of the weight was 2.4ton. Lead dampers were installed at two side points of the base raft. The rocking pillar of total length of 34cm was formed by steel rod provided with the top and bottom caps which were the same as the spherical bearing of R=20cm shown in Fig.8. The rocking pillar was placed on a smooth stainless steel plate of 6mm thickness, the same plate being inserted between the top of the pillar and the base beam. The caisson was fabricated from transparent acrylic tube so that the rocking pillar was visible from outside. The top stiffening rings of the caissons were connected to acrylic top plate of 10mm thickness which represents the restraint of movement of the caissons exerted by the soil. To form the weights, steel plates were piled. Tests were performed under two different types of piling: symmetric and eccentric as shown in Fig.11.



(a) Plan of Test Apparatus (b) Detail of the Base Isolation Foundation

Fig.10 Isolation Foundation Specimen (unit : mm)





(a) Symmetric Weight (b) Eccentric Weight

Fig.11 Views of Test Specimen on Shaking Table

Fig.12 shows detail of the installed lead damper. The intermediate portion of a lead rod of circular section was narrowed to form a neck portion. Upper and lower ends of the rod were encased in steel tubes. The upper tube was fixed to the end of the base beam, thus forming a fixed end of a cantilever. In the free end of he cantilever, a circular disc was provided which was encased in a steel tube leaving small gap of 1mm to allow rotation. It was intended to let the lead rod yield in bending moment occurring in the neck close to the fixed end of the cantilever. A set of the two cantilevered rods formed a damper, two sets of them being installed in the shaking table test specimen. Preliminary static loading test of single rod showed that it reached lateral load of 600N at the ultimate displacement of 35mm.

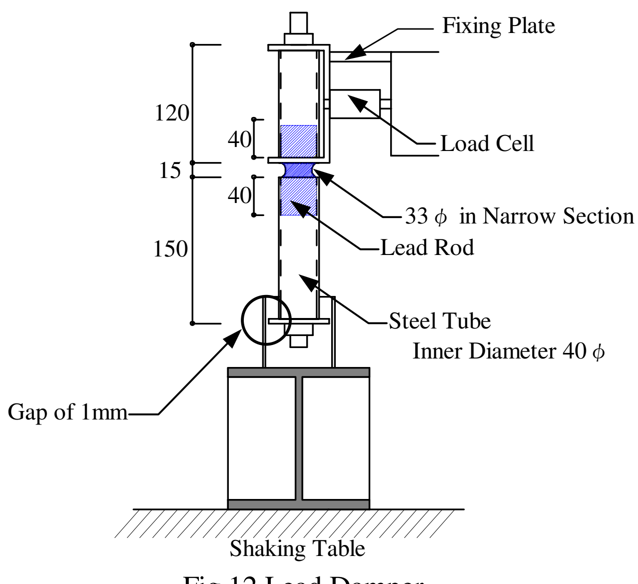
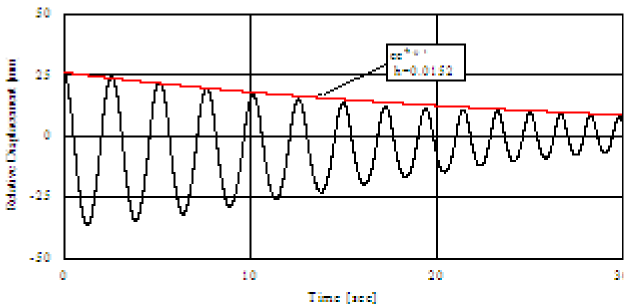


Fig.12 Lead Damper

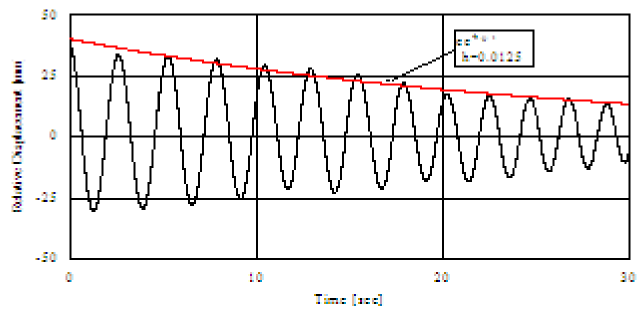
Natural Period and Damping

The specimen was subjected to free vibration test through excitation by man power. Time histories of relative displacement are shown in Fig.13 for the cases of damped and undamped, symmetric weight and eccentric one. Natural frequency and damping ratio estimated are presented in Table 2. The natural frequency took values similar to the theoretical one shown in Table 1 for the cases without the damper. For damped cases, the natural frequency took far shorter value because of the stiffness of the dampers, which would be excepted to play role of trigger against excitation by wind. It can be seen that provision of the dampers largely increased damping ratio.

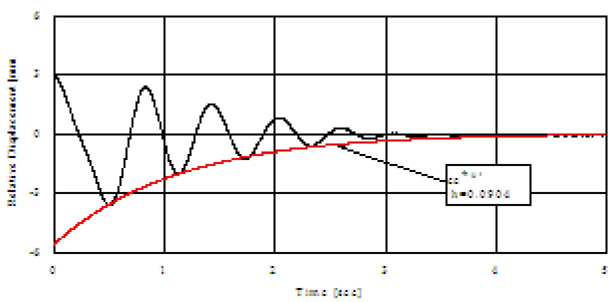
In the cases of eccentric weight, the specimen without the damper exhibited vibration accompanying torsional mode. However, the torsional vibration did not take place for the cases having dampers even though arrangement of the weight was eccentric.



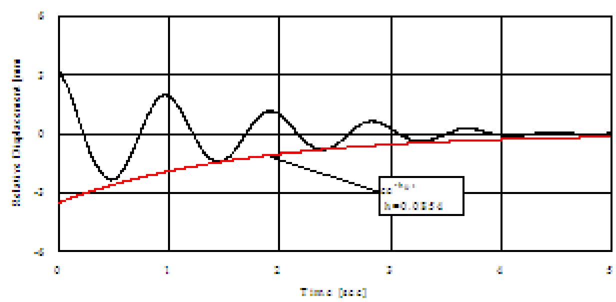
(a) Without Damper, Symmetric Weight



(b) Without Damper, Eccentric Weight



(c) With Dampers, Symmetric Weight



(d) With Dampers, Eccentric Weight

Fig.13 Free Vibration Time Histories of Relative Displacement

Table 2 Natural Period and Damping Ratio

	Weight	Natural Period [sec]	Damping Ratio [%]
Without Damper	Symmetric	2.52	1.52
	Eccentric	2.59	1.25
With Dampers	Symmetric	0.63	9.04
	Eccentric	0.92	8.54

RESPONSE TO EARTHQUAKE WAVE INPUT

Test Cases

To observe earthquake response characteristics of the isolation foundation specimen, recorded earthquake waves were input to the shaking table. Table 3 shows the input waves and their maximum acceleration. Time axis of the ground acceleration records was compressed into 1/2 of the original considering that the specimen was 1/4 scaled model. The tests were carried put under one-directional and two-directional inputs, El Centro NS and Hachinohe EW components were used for the one-directional excitation.

The specimen was tested under different conditions; damped and undamped, symmetric weight and eccentric weight.

Table 3 Input Earthquake Wave

	Direction	Maximum Acceleration [gal]	Time Axis
El Centro	NS	341.7	Compressed into 1/2 of original
	EW	210.1	
Hachnohe	EW	182.9	
	NS	225.0	

Test Result

As representative test results obtained by the excitation of the maximum inputs, response to El Centro wave is presented. Diagrams of the response parameters for typical test cases are presented in Figs. 14-18. Table 4 shows comparison of the maximum response parameters of each case.

Table 4 Response to Earthquake Input of El Centro Wave

Exciting Direction	Condition of Specimen		Maximum Acceleration		Amplification Factor of Acceleration	Max. Relative Displacement [mm]	Max. Load of a Damper [N]	Max. Torsional Angle [degree]	Figures for Diagrams
	Weight	Damper	Shaking Table [gal]	Test Frame [gal]					
One Direction	Symmetric	Undamped	218.8	33.8	0.15	24.3	-	0.368	Fig. 14
One Direction	Symmetric	Damped	209.3	37.5	0.18	7.03	408.3	0.137	Fig. 15
One Direction	Eccentric	Undamped	219.2	46.6	0.21	25.3	-	0.423	-
One Direction	Eccentric	Damped	208.5	35.9	0.17	8.85	433.8	0.221	Fig. 16
Two Direction	Eccentric	Undamped	154.0	26.8	0.17	24.1	-	0.744	Fig. 17
			251.6	32.6	0.13	26.3			
Two Direction	Eccentric	Damped	148.6	24.3	0.16	6.68	327.7	0.159	Fig. 18
			95.7	20.8	0.22	2.78			

Discussion

In all cases, the responding acceleration was largely decreased from the one of shaking table, the range of amplification factors being 0.13 - 0.22.

In the cases without damper, displacement of the specimen relative to the shaking table was large because of the extremely weak restorability of the foundation system. This was one of the reasons of the relatively low level of the maximum input acceleration of the tests. The responding displacement was drastically decreased by providing the lead dampers. Though torsional vibration was stimulated to some intensity in the undamped case, it was also restricted by the dampers. The lead dampers installed in specimen experienced disorder, bond between the lead rod and the encasing tube being loosened after cycles of plastic deformation. This was another reason of the limited intensity of the input acceleration.

In spite of the above limitation, it was observed by the tests of various levels of input acceleration that the amplification factor became the smaller for the higher level of input. Therefore, the capability of the proposed system can be taken optimistic for the purpose of preventing collapse of masonry houses.

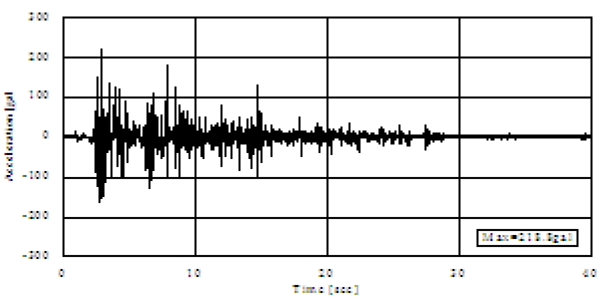
CONCLUSION

A new form of base isolation suitable to masonry houses and apartments was proposed. In the proposed system, a superstructure is supported by rocking pillars encased in RC caissons. The rocking pillars having spherical caps in both ends are mass produced from steel tubes being filled with concrete. Settling down the caisson into a hole dug in the ground simply forms an isolation foundation. The houses on the isolation foundations have very long period of oscillation determined by the geometry of the rocking pillar independently of their mass and free from torsional vibration. Therefore, no calculation of mechanics in design nor any skilled labor in execution is needed.

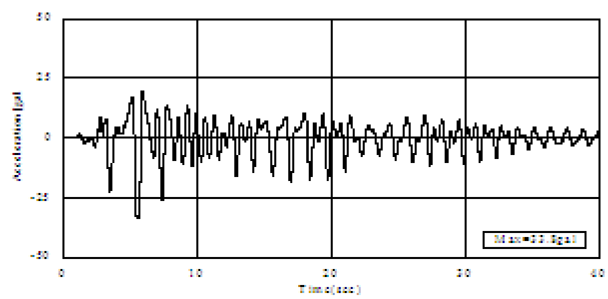
The fundamental vibrational property of the isolation foundation system was made clear based on theory and experiment. Results of shaking table tests conducted on 1/4 scale model specimen indicated promising capability toward the realization of base isolated masonry construction.

REFERENCES

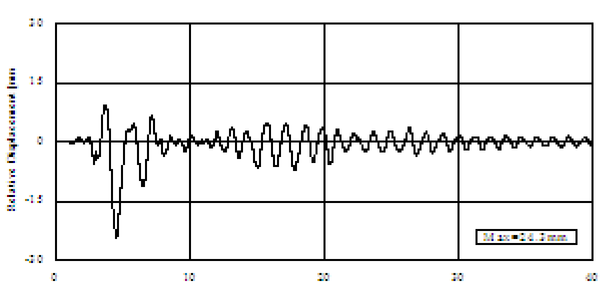
1. Oka R. "Base Isolation Device for Structures", Japanese Patent, No.95076, 1932
2. Matsushita K, Izumi M. "Studies on Mechanisms to Decrease Earthquake Forces Applied to Buildings", Proceedings of the 4th World Conference on Earthquake Engineering, Tokyo, Vol.2, 118-129, 1969



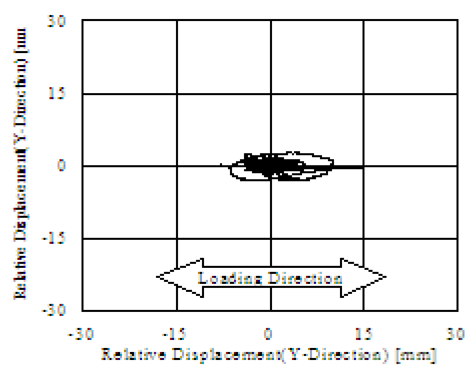
(a) Acceleration of Shaking Table



(b) Acceleration of Test Specimen

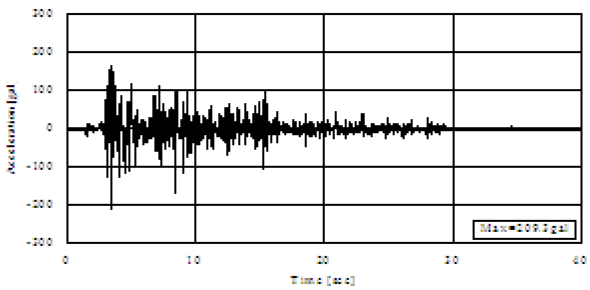


(c) Relative Displacement of Test Specimen

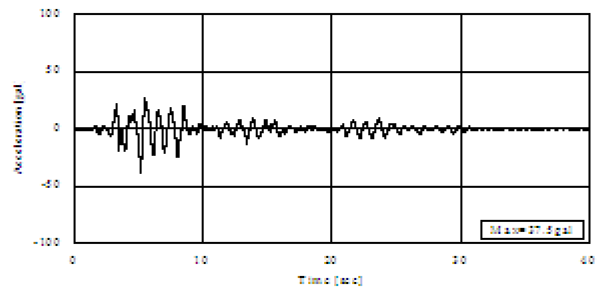


(d) Displacement Orbit of Test Specimen

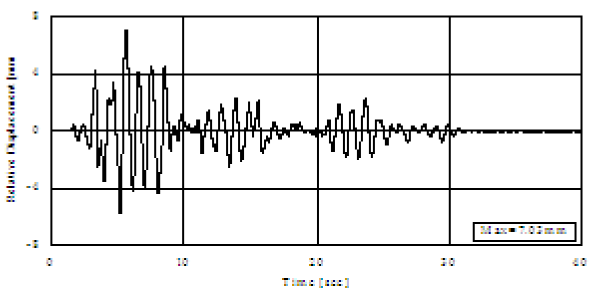
Fig.14 Response to Excitation of Earthquake Wave Input
EL Centro NS, 1/2 Time Axis, One Directional, Symmetric Weight, Without Damper



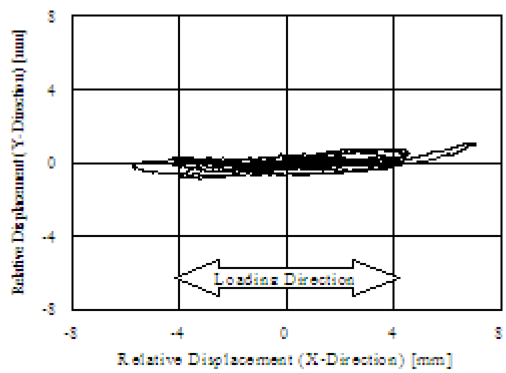
(a) Acceleration of Shaking Table



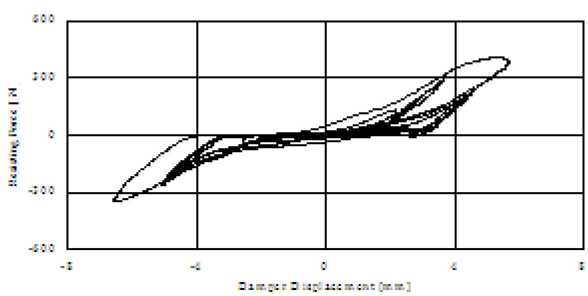
(b) Acceleration of Test Specimen



(c) Relative Displacement of Test Specimen

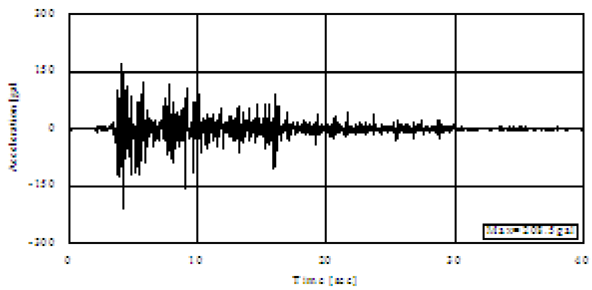


(d) Displacement Orbit of Test Specimen

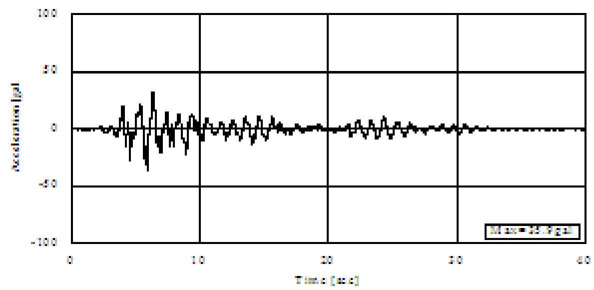


(e) Hysteresis Loop of Lead Damper

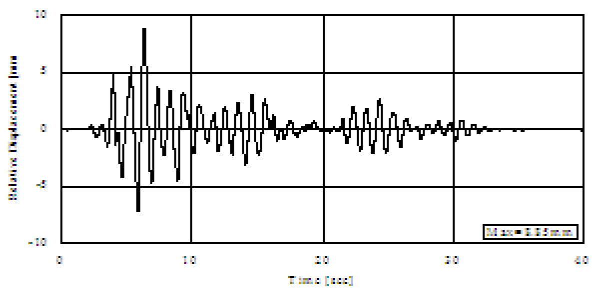
Fig.15 Response to Excitation of Earthquake Wave Input
EL Centro NS, 1/2 Time Axis, One Directional, Symmetric Weight, With Dampers



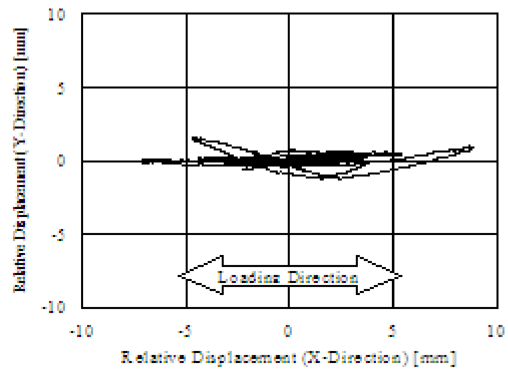
(a) Acceleration of Shaking Table



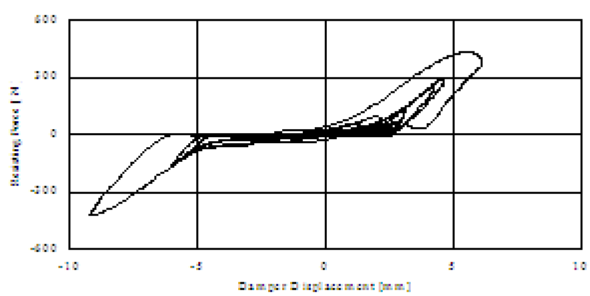
(b) Acceleration of Test Specimen



(c) Relative Displacement of Test Specimen



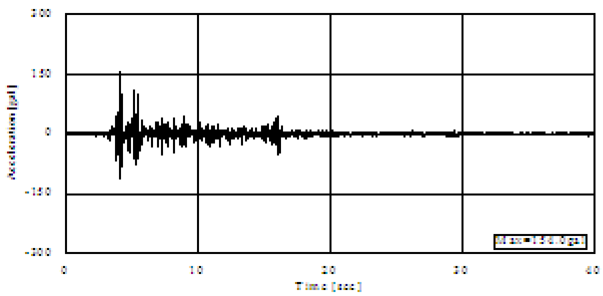
(d) Displacement Orbit of Test Specimen



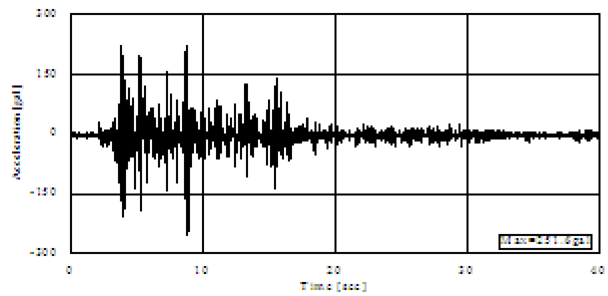
(e) Hysteresis Loop of Lead Damper

Fig.16 Response to Excitation of Earthquake Wave Input

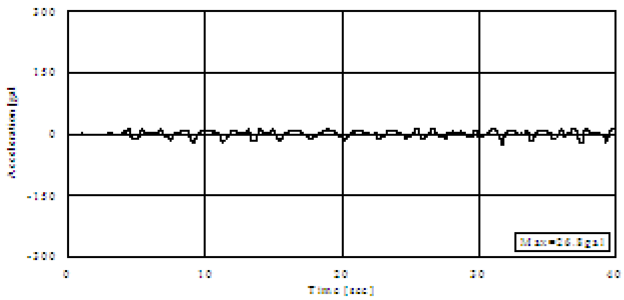
EL Centro NS, 1/2 Time Axis, One Directional, Eccentric Weight, With Dampers



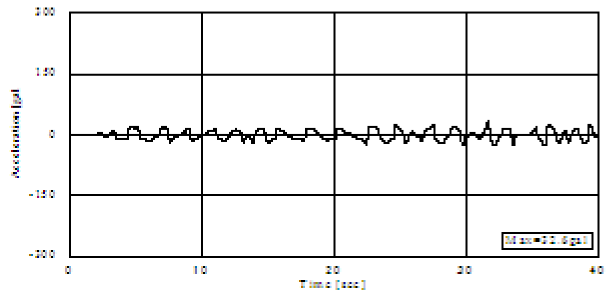
(a) Acceleration of Shaking Table (X-Direction)



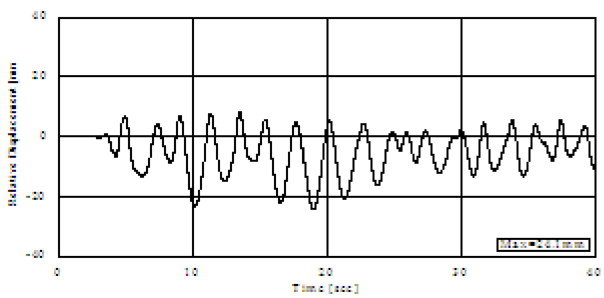
(b) Acceleration of Shaking Table (Y-Direction)



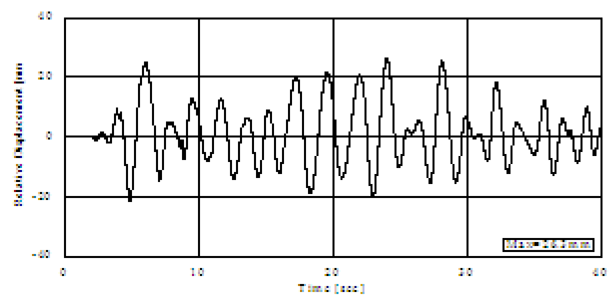
(c) Acceleration of Test Specimen (X)



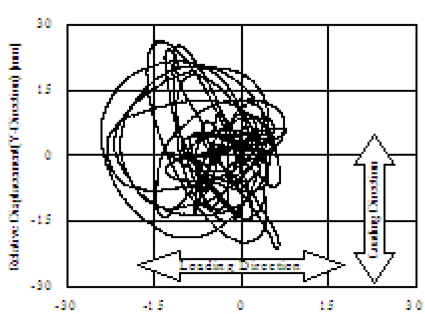
(d) Acceleration of Test Specimen (Y)



(e) Relative Displacement of Test Specimen (X)

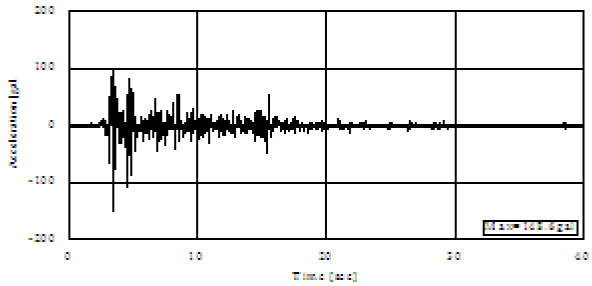


(f) Relative Displacement of Test Specimen (Y)

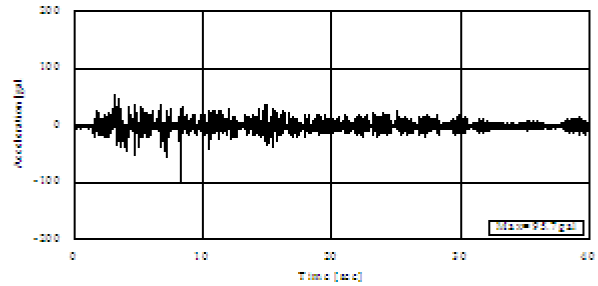


(g) Displacement Orbit of Test Specimen

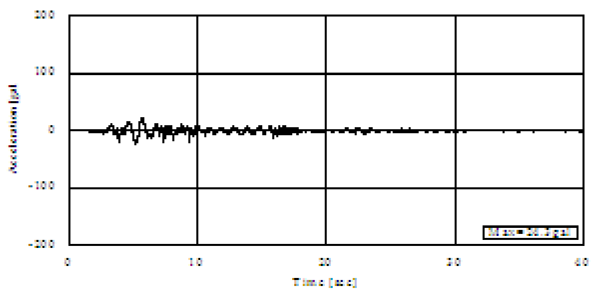
Fig.17 Response to Excitation of Earthquake Wave Input
EL Centro, 1/2 Time Axis, Two Directional, Eccentric Weight, Without Damper



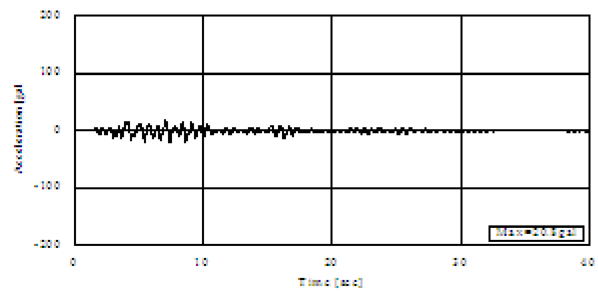
(a) Acceleration of Shaking Table (X-Direction)



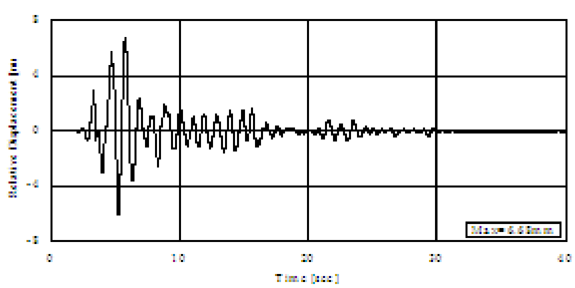
(b) Acceleration of Shaking Table (Y-Direction)



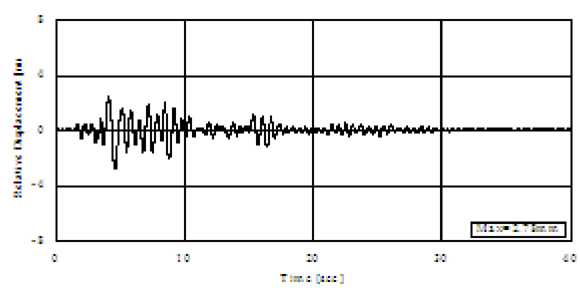
(c) Acceleration of Test Specimen (X)



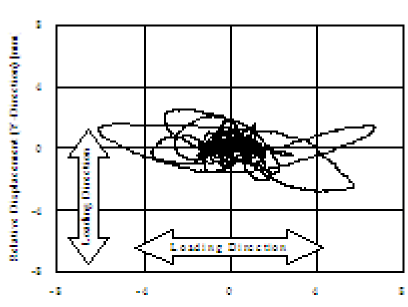
(d) Acceleration of Test Specimen (Y)



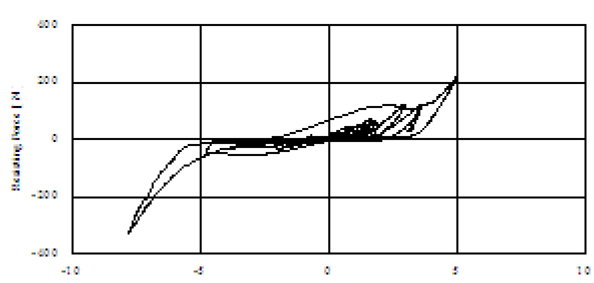
(e) Relative Displacement of Test Specimen (X)



(f) Relative Displacement of Test Specimen (Y)



(g) Displacement Orbit of Test Specimen



(e) Hysteresis Loop of Lead Damper

Fig.18 Response of Base Isolation System to Excitation of Earthquake
EL Centro, 1/2 Time Axis, Two Directional, Eccentric Weight, With Dampers