Studies on Mechanisms to Decrease Earthquake Forces Applied to Buildings

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ABSTRACT

✓ Earthquake forces can hardly be controlled, but when they act upon structures and are converted to 'input' earthquake forces to the structures, it is possible to control them to some extent using appropriate media and mechanisms. The effective application of the media and mechanisms is to install them near the boundary between the structure and the soil since the earthquake forces are fed to the structures through the boundary. Mechanisms shown in this paper are designed for about and less than twenty storied R.C. buildings built on good ground, and some of the calculated results show more than a 50% decrease of input earthquake forces.

The authors point out the necessary condition for the 'Earthquake Free Mechanisms', design some of the mechanisms especially concerning to 'rocking ball systems' and 'flexible column and rod system', and check their effects through model tests and calculations. Some of the mechanisms show preferable response; flat limited response to various input frequency characteristics of excitation.

The authors conclude their study is worth doing, and some of the mechanisms are able to be applied to real structures in order to control input earthquake forces.

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SYNOPSIS

Earthquake Engineering has seen remarkable progress, but most of the problems being treated in this field are to get the characteristics of earthquakes (including the expected intensities) and to design resistable structures against the earthquakes.

The authors think that a positive attitude should be taken against the earthquake, and that, instead of accepting the input earthquake force to structures as it is, efforts should be made in order to decrease the earthquake effect through engineering methods. In this paper, some fundamental study on the Earthquake Free Mechanism are presented, and some practical mechanisms are proposed.

1. Introduction

There are various methods in aseismic design of structures, and they may be classified into two groups: (1) to make strong structures against the earthquake force, (2) to decrease the effect of the earthquake force.

Usually, these two groups of methods are compounded and result to earthquake-proof structures as a whole. In some extreme cases, their characteristics are distinctly shown. Nuclear power stations are often designed to be very strong, adopting an input earthquake force with a large safty factor, and this example belongs to the first group. Design story-shear coefficients of tall and flexible structures built on the good ground can be smaller than those of low structures of shorter natural periods, and this is a case of the second group.

The second group can be subclassified as:

(A) To keep the strain energy caused by input earthquake energy within limits.

(B) To keep the input earthquake energy itself below a level.

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In Group (A), the energy fed to structure is preferably used in the form of kinetic energy and some work not directly connected to the damage of structures. Wooden structures assembled with small pieces of members (like five-story pagodas in Japan) sometime effectively consume the input energy as work is done by friction forces between the pieces.

Many factors concern Group (B). Surrounding soils of structures decrease the input earthquake energy by their elasto-plastic behaviours. The rigid base slab of large dimensions averages and erase the peak values of the input earthquake force. Large mass of the structure on relatively soft soil confines the ground motion. In cases, when these effects are not expected, "Earthquake Free Mechanism" can be effectively applied.

"Earthquake Free Mechanism", which may be properly called "Mechanism to Decrease Input Earthquake Force" is the subject discussed in this paper.

2. Definition and Conditions of the Mechanism

"Earthquake Free Mechanism" is defined the "mechanism to be installed in a structure in order to decrease the input earthquake energy. Therefore natural phenomina like the rocking motion of rigid structures on elasto-plastic soils are not included. Some proposals have been made concerning this kind of mechanism, but very few of them have been actually applied to structures. The reason may be attributed to insufficiency of the mechanism, that should satisfy the following conditions.

i) To prevent the production of large strain energy within the structure.

ii) Not to leave permanent displacement after the earthquake.

iii) To confine the relative displacement between the structure and the ground to a certain limit.

iv) The effect of the mechanism will not be decreased by the elapse of time.

v) It is preferable, that the mechanism also absorbs the energy as mentioned in Group (A).

vi) The increase of the cost due to the installation of the mechanism to the structure should be less than the saved cost owing to the mechanism.

The authors proposed a type of buildings where flexible but high strength columns (for example high strength steel columns) were used with stoppers at or near the base story of the buildings, and attested the effect through calculation[*1], and this may be an example that satisfies the above conditions.

Generally speaking, the first condition; not to produce the large strains (strain energy) within a structure, requires that structure can be moved without a large resisting force. One method may be the installation of bearing balls between the structure and the basement. But this method can not satisfy the condition (ii) and (iii).

3. Types of Mechanisms

There are many types of mechanisms which satisfy the necessary conditions, but they may be classified into a few groups like;

(1) Bearing Mechanism

(2) Column and Rod Mechanism

(3) Wall and Brace Mechanism

(4) Boundary Mechanism

The 'bearing mechanism' uses some kind of bearings including ball bearings, the 'column and rod mechanism' uses flexible but strong columns and rods, 'the wall and brace Mechanism' produces some kinds of 'restoring force-deflection' relations against lateral displacement and the 'boundary mechanism' provides shock absorbing materials at the boundary between the structure and the ground. They are sometimes used together.

4. Bearing Mechanism

4-1 Sample Analyses

Ball bearings inserted between two plates show remarkable effect to cut out the transmission of the energy from the ground to the structure, but they cannot produce restoring forces and both temporal and permanent displacements of the structure cannot be controlled. Bearing ball system with the restoring force is defined 'Rocking Bearing Ball' hereafter in the paper.

When the vertical motion is allowed, it is possible to design the rocking ball systems. Fig.-1 illustrates the principle of the rocking ball system. When the ground moves with large acceleration, the rocking balls are inclined and some of lateral motion is transformed into vertical motion. The model satisfies the conditions (i) - (iii) and at the same time condition (iv) and (vi), because it is very simple and the resoring force is relying on the natural force, the weight of the structure. The rough estimation of the effect of the mechanism can be calculated by solving the following equation;

$$(R_1 + R_2)\ddot{\Theta} - L\frac{d^2}{dt}(\sin\Theta) + \frac{L}{H'}g'\sin\Theta = -\ddot{Y}_0 \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

If $h \ll H'$, and $\Theta \approx \sin\Theta$, then we may put $H' \approx H+h$

$$H\ddot{\Theta} + \frac{L}{H'}g'\Theta = -\ddot{Y}_0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

Where g' is the difference of the gravity acceleration (g) and the vertical acceleration of the structure (y''). If we assume $g \approx g'$, then Eq. (2) is the simplest equation of the vibration. When we calculate the acceleration of the structure of a rigid body with the mechanisms when it is subjected El Centro 40 NS Earthquake, (Fig. - 2) the maximum acceleration decreases to 1/5 of the original. The restoring force is obtained by the moment produced by the weight of the structure and eccentric touch points with arm a in Fig.-1. The same kind of restoring forces are obtained when we design curved surfaces with different curvatures. Too large deflection between the structure and ground are not desirable for piping etc., some kind of stoppers should be provided.

In order to avoid producing impactive forces at the stoppers, curved surfaces are so designed that the mechanism has a hardening type and smooth restoring force characteristic for the large deflection.

For the small acceleration of the ground, friction force may prevent the rocking motion of the bearings. Considering the effect of the wind load, the force deflection relation is preferable rigid to some extent. As a whole, the restoring force curve shown in Fig.-3 is recommended. The clearance to the stoppers affect the size of input force.

In practical use, the rocking balls should not be rusted, and inside of the mechanism will be filled with grease and putty, which work at the same time as shock and energy absorbers. Considering these effect, many types of rocking ball mechanisms are designed, and some of them are shown in Fig.-4. These mechanisms are made of the cast steel in the same size, and the bearing capacities are adjusted by the number of the mechanism units. (Fig. 5)

4-2 Model Tests

4-2-1 Models

In order to check the effect of the mechanism, to compare the test-results to calculated results, and to estimate their effect when applied to the actural structure, model-tests were carried out. The plastic model of the mechanisms tested are No.1 - No.5 as shown in Fig.-6. The same to No.5 is also made of the cast steel. Instead of rigid structure, steel plates are used and changing the number of the piled plates, effect of the weight of the structure on the function of the mechanisms are checked.

4-2-2 Restoring Force Characteristics

Before dynamic tests were carried out, restoring force characteristics of the models, the restoring force-deflection relations were easily calculated, and the tested and calculated results compared well except at the point where the test shows some slip phenomena were accompanied. (Fig.-7) (Fig.-8 (A) - (C) shows restoring force-deflection relations of the model obtained by static tests.)

4-2-3 Forced Vibration Tests

The vibration table used for the test is of eccentric moment type shown in Fig.-9. As the models have the characteristics of the gravity pendulum, the natural period is, to some extent, proportional to the square root of the length, frequency of 2-13 cycles were used for the test, the acceleration of the vibration table at the test was in the range of (0.1 - 0.2) x $(2\pi)^2$ x $(\text{frequency})^2$ gals.

From test results, two cases, when the weight was 428 kg and 1,016 kg respectively, are shown in Fig.10.

4-3 Analyses

For high frequency vibration, the acceleration response of the structures on the mechanisms do not increase despite the increasing acceleration of the table. In some mechanism, resonance phenomena were observed and larger value of acceleration compared with that of the table were produced. This resonance phenomena is avoidable when not one, but two or three combinations of curved surfaces are used. When the resonance is going to take place, and the deflection increases, vibration characteristic changes, the large deflection makes another couple of surfaces work. Consequently, it is not difficult to design the rocking ball mechanism which an almost flat output curve against input of different frequencies. For instance type (f) and (g) of Fig.-4, are examples, where the rocking centre is gradually moved and resonance phenomena are avoided. The calculated response and the tested results compare well as shown in Fig. 11, where model No.2 with damping ratio 0.035 is used.

5 Column and Rod Mechanism

5-1 Analyses

The authors presented the results of studies concerning the flexible column at the first storey(*1). The principle and the tendency of the column and rod mechanism are the same as the analyzed results of flexible first storey systems'. It should be noted here that the behaviour of this kind of systems in the earthquake is that they move very little at the early stage of the earthquake, then gradually vibrate at the last stage of the earthquake, except when the frequency of the earthquake is very small. The acceleration and energy produced in the system with column and rod system is small, and the ratio of reduction is closely connected to the flexibility of the column. There are calculated data which show 40 % reduction of the force. Too large displacement is undesirable, as the additional moment produced by the weight of the structure gives collapse type restoring force characteristics after the deformation reaches the elastic limit(*2). Therefore, stoppers are also necessary in this system. Between the columns (or rods) and stoppers mixture of sand and gease will be used which provents the rusting and absorbs the input force and energy.

5-2 Practical Design

Fig.-12 shows an example of the mechanism where steel rods and sands are used.

Sand of 5mm in average size showed good results in the test as a damper.(*3) Fig.-13 is supported by balls, and restoring forces are taken by the steel rod erected at the centre. Fig.-14 is a kind of flexible column at the first story, and double columns are used in Fig.-15.

A structure built on the soft ground and supported by bearing piles may belong to the 'Column and Rod System'. Soft ground act as the damper, but the input earthquake forces are to some extent complicated, and not well analyzed yet.

6. Wall and Brace Mechanism

Walls and braces are usually form rigid frames, and difficult to control the rigidity. Concerning the wall, a method to control the rigidity is proposed and used in practical buildings(*4), and there is a plan to use another type of PC alls in real structures in Japan.(*5)

When a mechanism is used in a joint of the bracing, the characteristics of the restoring force may be controlled. There is a proposal, but not practically used yet.(*6)

7. Boundary Mechanism

As the earthquake energy is transmitted to the structure through the boundary. For example a structure floating on the water will be free from the earthquake shocks. But, when the cost of the construction is considered, such a mechanism is not practical. Seperation of the retaining walls and the main part of the building may be one of the method(*1). Plastic materials are inserted at the outsides of retaining walls of a building that one of the authors designed.

8. Conclusive Remarks

The results of the tests and calculation show remarkable effect of 'Earthquake Free Mechanism' on decreasing the earthquake force applied to structures.

The mechanism should satisfies the conditions shown in Chap. 2. Besides, desirable characteristics of the mechanism is to be simple, and to produce flat response against input of various frequencies. Some of the mechanism like the rocking ball type can satisfy this condition.

The strength of the mechanisms was checked and, they can be used to the real structure concering their strength.

Problem remains in the complicated ground motions in real earthquake in comparison with test conditions and calculation-assumption, and in the fact that effect of the surrounding soils to the input earthquake forces have not completely solved yet.

The most effective application of these mechanism may be to low and middle height buildings of less than 20 stories built on a good and hard soil. The flexible structure has the advantage in this ground condition, but the structure itself is not flexible unless it is designed to be so on purpose. Flexible low buildings require large interstory deflections, and usually structural details can not follow the deflection or the details should be designed with special care regardless of increase of the cost.

The earthquake intensity may be less than 500 gals(*7), and the clearance to the stopper will be designed against this value. And still the input earthquake force transmitted through the mechanisms is much less than 200 gals for the same earthquakes.

Results of earthquake response calculation and recorded data shows about 3 times multiplication of the acceleration at the top of the building of middle height in comparison to the input acceleration at the base. The calculated responses of structures with 'Earthquake Free Mechanism' show small values of response even at the top of the building.

Therefore studies on this kind of mechanism aimed to aseismic design of low and middle height buildings is worth doing, and the authors believe that is a positive attitude of engineers against earthquake forces.

Acknowledgement

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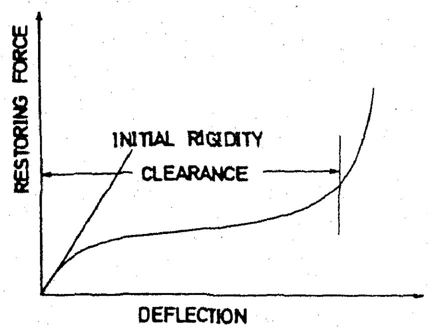


Fig. 3 Desirable Restoring Force Characteristics

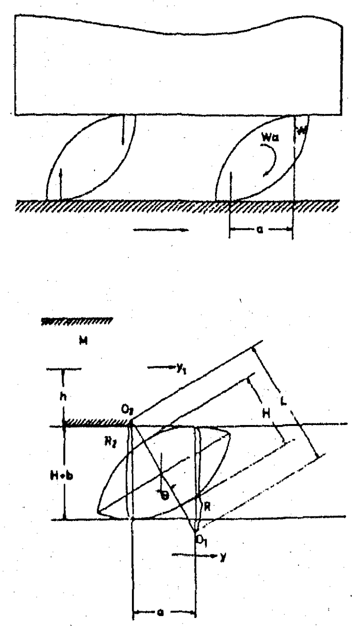


Fig.1 Principle of Rocking Ball System

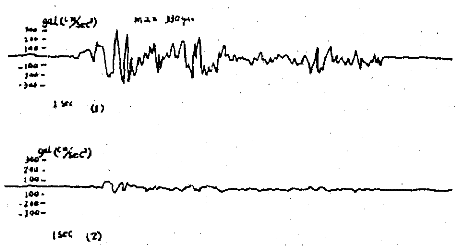


Fig. 2 Comparison of Ground-Acceleration with Response Acceleration of a Structure with Rocking Ball System

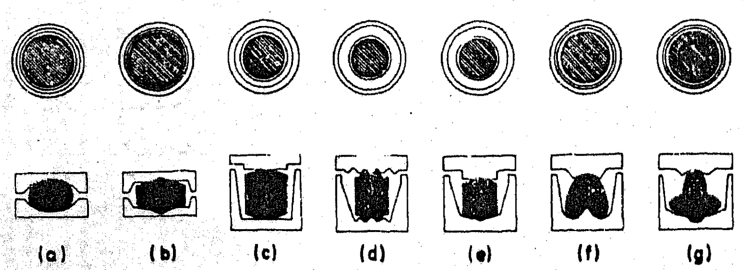


Fig. 4 Examples of Rocking Ball Mechanisms

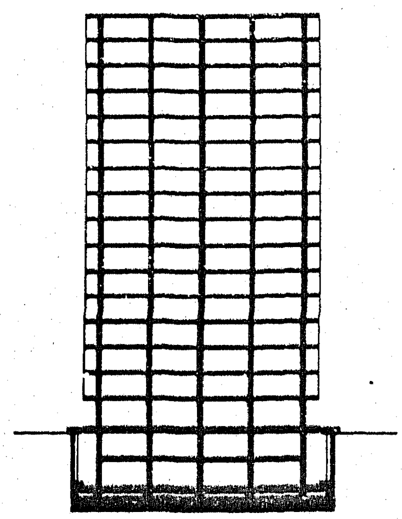


Fig. 5 Installation of Rockng Ball System

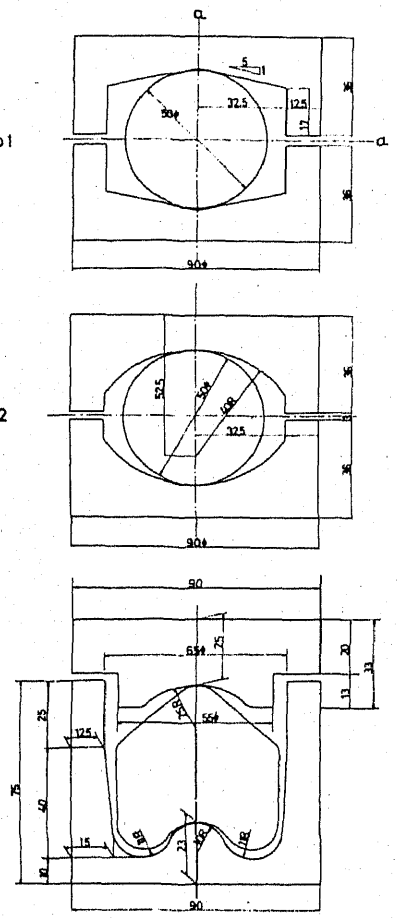


Fig. 6 Test Model

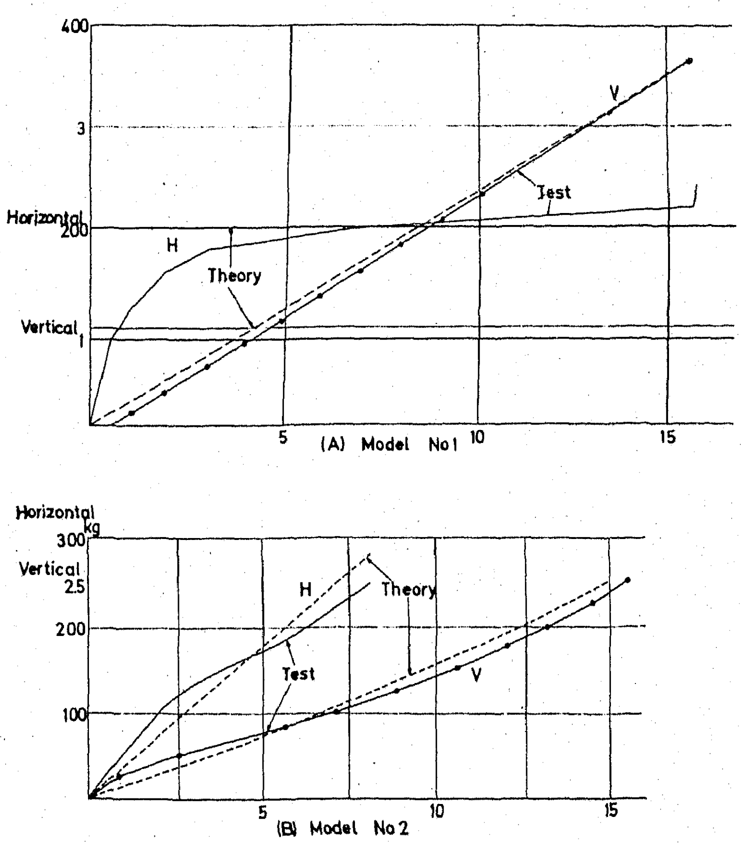


Fig. 7 Comparison of Calculated and Measured Relations of Restoring Force and Deflection

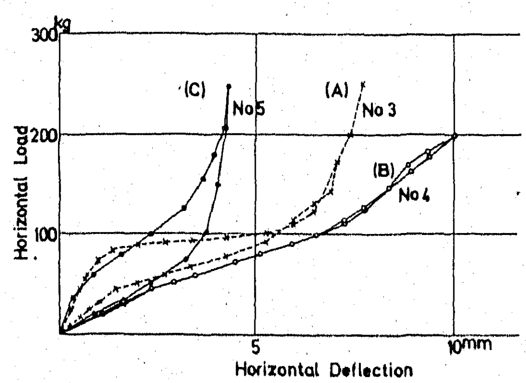


Fig. 8 Measured Restoring Force Characteristics

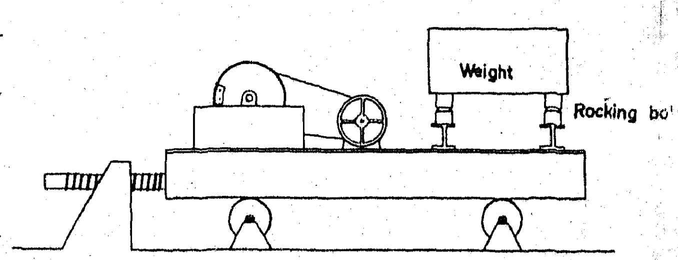
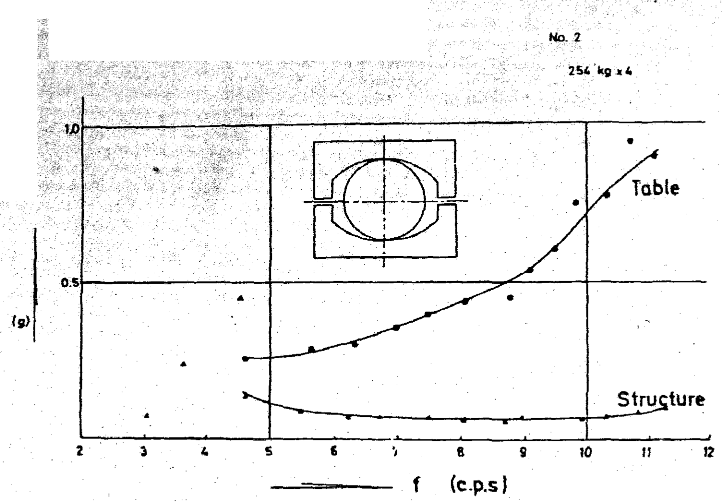
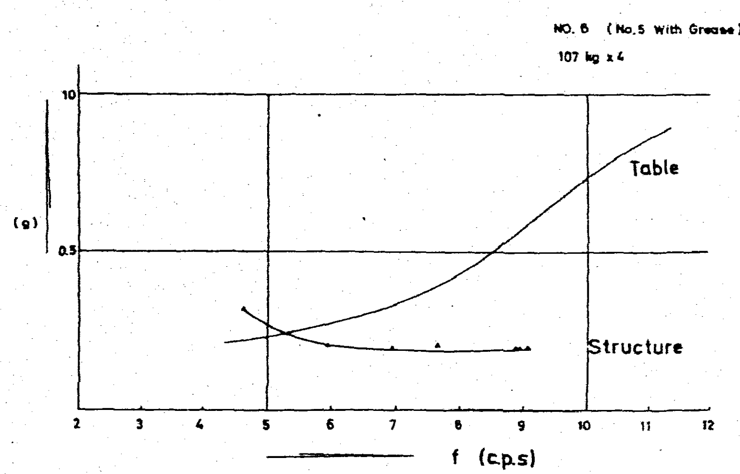


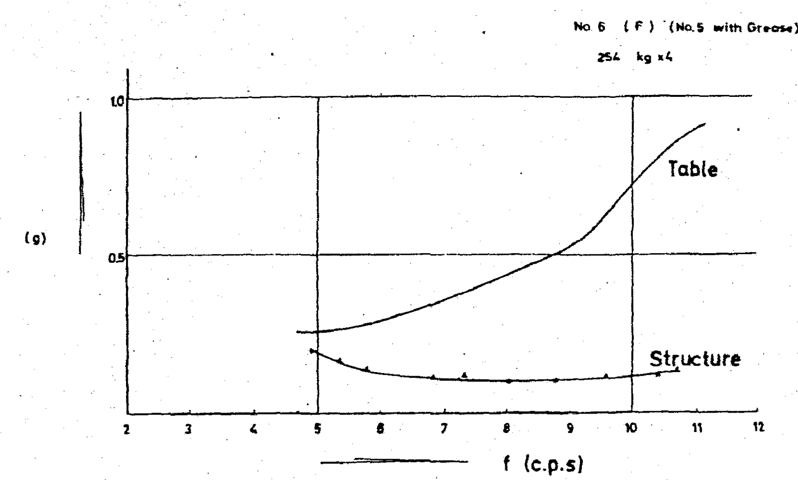
Fig. 9 Vibration Table



(A)



(B)



(C)

Fig. 10 Test-Results

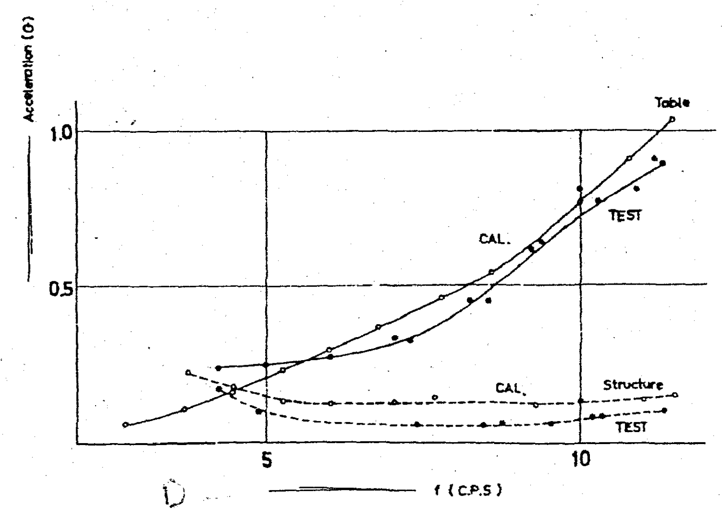


Fig. 11 Comparison of Test-Data with Calculated Results

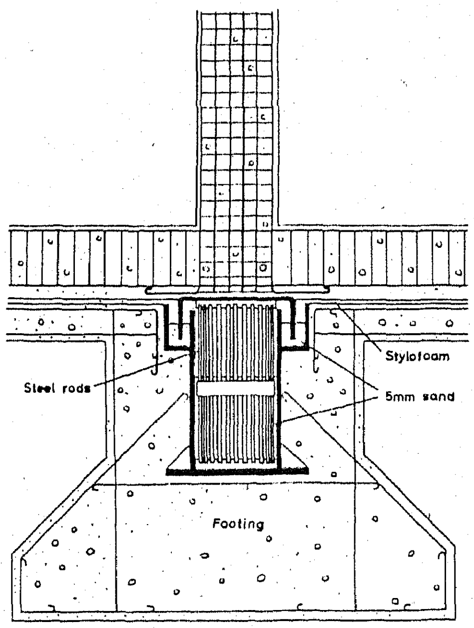


Fig. 12 Example of Rod Mechanism

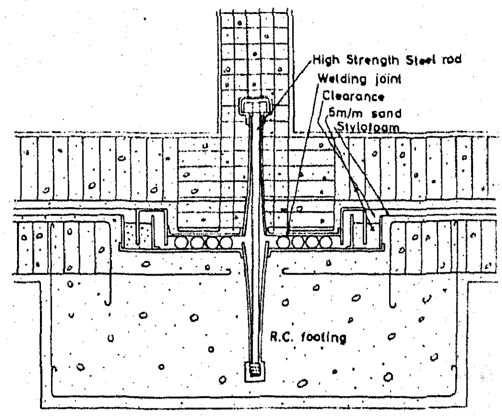


Fig. 13 Example of Rod Mechanism
with Bearing Balls

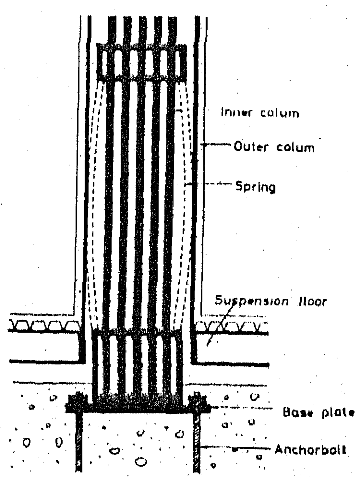


Fig. 14 Example of Flexible
Column System

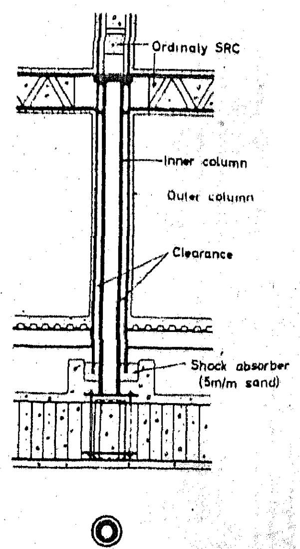


Fig. 15 Double Column System