ASEISMIC FOUNDATION SYSTEM FOR NUCLEAR POWER STATIONS

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SUMMARY

Introduction

The aseismic foundation system, as described in this paper, is a new development, which makes it possible to build standard nuclear power stations in areas exposed to strong earthquakes. By adopting proven engineering concepts in design and construction of components, great advantages are achieved in the following areas:
— safety and reliability
— efficiency
— design schedule
— cost

The need for an aseismic foundation system will arise more and more, as a large part of nuclear power station sites are located in highly seismic zones or must meet high intensity earthquake criteria due to the lack of historic data.

General concept

The principle consists in interposing a device between the buildings of the nuclear island and the foundation soil which limits the value of the horizontal acceleration in the nuclear island buildings.

The nuclear island foundations consists of a double raft with aseismic bearings interposed between the upper and lower raft. These bearings are placed on top of short concrete pedestals constructed on the lower raft. The space thus provided between the two rafts allows access to the bearings. The bearing consists of two parts:

- a block of reinforced elastomer,
- a set of friction plates such as stainless steel+bronze with lead.

Seismic response of the structures

The reinforced neoprene pad acts as a soft horizontal spring imparting a first mode of translation to the structure with the frequency of about 1 c.p.s. depending only on the characteristics of the bearing. As this first mode is predominant, the value of horizontal accelerations at each level for all buildings are almost identical. The above mentioned frequency has been selected in order to be outside the range of natural frequencies of the buildings themselves and of the frequency of the equipment.

The friction plates due to their nature and surface treatment permit to ensure a consistent value of the coefficient of friction "f" so as to limit the maximum horizontal earthquake forces to values close to $f \times g$.

Under a low level earthquake (0.15 g-0.20 g) the structure vibrates and returns to its original position.

The temporary relative displacement during such an earthquake can reach about 0.10 m. Under an earthquake of higher level (up to 0.60 g) the vibrating structure slides on the friction plates.

The complete detailed design together with experimental evidence have shown that the system is operational (this subject will be explained in detail).

The aseismic foundation system which has been developed in collaboration with Électricité de FRANCE has been approved in principle by the authorities in FRANCE and SOUTH AFRICA.

The system is going to be used at the KOEBERG Nuclear Power Plant and the specific design conditions relating to this application will be the subject of a future paper.

1. Introduction

The design of a nuclear power station requires a thorough examination of the seismic conditions of the site and its region.

In view of the risk which a nuclear accident presents for the surrounding population, it is necessary to design the vital structures, systems and components in such a way that they can resist earthquake forces of intensities well above those encountered in historic time for the region concerned.

Furthermore, in the regions where historic data are rare, it is necessary to adopt conservative criteria.

Consequently, a standard nuclear power station, which has been developed for regions where earthquake intensities are low, may not be simply reproduced in a country or in a region of high potential risk.

In fact, for earthquakes in excess of 0.20 - 0.25g horizontal acceleration, the integrity of the standard installations may no longer be ensured. In particular, relative movements between buildings may be in excess of what can be tolerated by connecting pipe lines and in addition the stability of the structures cannot be ensured.

If the buildings are given larger foundations or a complete common foundation for all the buildings, it will be necessary to reinforce their structures as well as the equipment supports. For higher accelerations, even the equipment must be strengthened or possibly extensively modified.

The creation of a standard design for high level earthquake regions in the range of 0.25 to 0.60g would therefore be prohibitively expensive.

The present system which has been developed by SPIE-BATIGNOLLES, with the collaboration of ELECTRICITE DE FRANCE, makes it possible to build a nuclear power station in a region of high seismicity, based on a standard design, for which the structures, systems and components have been developed for a country of low seismicity.

Furthermore, the present system offers a margin of safety greater than that which can be achieved with a "reinforced" solution.

2. Description of the system

The solution consists in interposing, between the buildings and the soil, a special support system which is called "aseismic bearings".

Each bearing is made of two plates named friction, or sliding plates, which can move one relative to the other (see Figure 1). The lower plate is part of a reinforced elastomer bearing pad.

During an earthquake, the horizontal accelerations of the structure cause the elastomer to deform. Then, if the horizontal forces exceed a certain value, there will be sliding between the two plates (see Figure 2).

As applied in an actual project (see Figure 3), the station layout has been conceived such that the building structures of the Nuclear Island of a standard nuclear power plant are reproduced. The aseismic bearing system has been arranged underneath the Nuclear Island buildings in a horizontal plane between an upper and lower raft.

Approximately 1600 bearing units are placed on top of concrete pedestals located between the lower and upper raft. The space between the two rafts is accessible so that the bearings can be inspected.

The upper raft ensures the connection between all buildings concerned with nuclear safety during an earthquake and hence ensures that their movements are simultaneous. The lower raft distributes the forces over the foundation area.

Each aseismic bearing has the following dimensions: 70cm by 70cm and 13cm thick (27.50 by 27.50 and 5.12 inches thick). The uppermost plate is of stainless steel. Underneath is a bronze lead plate. These two plates together accommodate the sliding. The bronze lead plate is at the same time the upper reinforcing plate of the multilayer reinforced elastomer pad.

The nature and treatment of the friction plates is such that the coefficient of friction is ensured to remain between 0.16 and 0.18 depending on pressure and sliding speed.

The reinforced elastomer pad is 10cm (3.94 inches) high. The 0.5cm (0.2 inch) thick reinforcing steel plates, as well as the bronze lead sliding plate, are bonded to the various layers of elastomer by vulcanisation.

The elastomer pad has well defined dynamic characteristics. It has been designed to simulate the behaviour of a horizontal spring having a frequency of 1 HZ.

3. Technology

The bearing meets the following criteria:

- its properties and its ability to function remain intact during the operational life of the plant:
- the coefficient of friction, whether static or dynamic, remains constant in time over the following range of loading conditions:
  - . vertical pressure from 20 to 100 bar (280 to 1,400 lbs/in^2)
  - . speed of sliding between 0.20 m/sec (0.65 ft/sec) and 1 m/sec (3.30 ft/sec).

The following summarizes the test results obtained during design testing of the above described production bearing:

	Speed of Sliding (m per sec.)	
Vertical Pressure (bar)	0.05	1.0
20	0.18	0.18
100	0.16	0.17

After accelerated climatic ageing in accordance with American Standard MIL STD 810 C, the friction value is not significantly affected.

The reinforced elastomer pad is made in accordance with the universally known standard techniques employed in bridge bearings and other civil engineering works.

The design and functional criteria are:

- the elastomer pad must maintain its static and dynamic characteristics over the specified life span:
- the natural frequency "f" of the pad in horizontal movement is a function of dimensions and stress:

$$f = \frac{1}{2\pi}\sqrt{\frac{Gg}{\sigma e}} \qquad (1)$$

where G is the dynamic shear modulus of the elastomer, σ the average normal stress on the bearing, e the total thickness of the elastomer, and g the acceleration due to gravity.

The reinforcing plates of the bearing pad are designed to give the pad the required vertical load capacity and a high rigidity in the vertical direction.

For the type of bearing considered, the rigidity "K" is a function of the various parameters as can be seen from the following formula:

$$K = \frac{2\ G\ a^4}{(4n - 7)t^3} \qquad (2)$$

where a is the length of the side of the pad, t the thickness of the individual elastomer sheets, and n the number of elastomer sheets.

4. Analysis of the dynamic behaviour

4.1 Structure founded directly on the soil

The first mode of vibration of a structure founded on the ground is a mode of bending-rotation (frequency between 2.5 and 10 cps, depending on the type of ground). This frequency range is inside the amplification zones of the seismic response spectrum. Furthermore the accelerations increase in amplitude the higher one moves up the structure (see Figure 4).

4.2 Structure on aseismic bearing

The first mode of vibration of the same structure on aseismic bearings is an overall horizontal translation movement (frequency of 1 cps depending only on the characteristics of the bearing). This frequency is chosen far away from the structure's own frequency content in order to make this first mode preponderant. Furthermore, this frequency is outside the peaks of the response spectrum. The accelerations are almost uniform throughout (see Figure 4):

$$\forall_i \quad \gamma_i \simeq \gamma \Rightarrow F = \sum_i m_i\, \gamma_i \simeq M\gamma \qquad (3)$$

where γ_i and m_i are the acceleration and the mass of level i, F is the horizontal force at the bearing level, and M the total mass of the structure.

The coefficient of friction limits the force F:

$$F \leqslant f.M.g \qquad (4)$$

where f is the coefficient of friction and g the gravity.

Therefore, from (3) and (4):

$$\gamma \leqslant f.g$$

The acceleration is uniform and limited by the value of the coefficient of friction.

4.3 Structure on Neoprene alone

Relationship (3) remains: the accelerations are uniform. As the force F is not limited, the accelerations depend on the earthquake level.

4.4 Structure on friction alone

Relationship (4) remains, but the accelerations are not uniform:

$$\sum_i m_i\, \gamma_i \leqslant f.M.g$$

Only the sum is limited and $\gamma_i > f.g$ can be had: the structure flexes before it slides.

5. Mathematical study

5.1 Mathematical formulation of the aseismic bearing

Vertically, the bearing is an elastic spring Kv associated to a dash-pot Cv. Horizontally, the model is represented in Figure 5. In order to simplify the equations, the rotational spring is here neglected.

5.1.1 Non-sliding phase

$$F_{ij}(t) = K_{ij}\ (x_j - x_i - \delta_{ij}) + C_{ij}\ (\dot{x}_j - \dot{x}_i) \qquad (5)$$

where F_{ij} is the horizontal force in the (i-j) bearing, K_{ij} and C_{ij} are the stiffness and the damping of the neoprene, x_i, $\dot{x}_i$, x_j, $\dot{x}_j$ are the horizontal displacements and velocities of nodes i and j, δ_{ij} is the relative displacement between the two friction plates. The maximum force the spring can withstand is:

$$Q_{ij}(t) = f.(P_{ij}-R_{ij}(t)) \qquad (6)$$

where f is the coefficient of friction, P_{ij} is the static weight on this pad and $R_{ij}(t)$ the dynamic vertical force.

$$R_{ij}(t) = K_v(y_j-y_i) + C_v(\dot{y}_j-\dot{y}_i) \qquad (7)$$

where y_i, $\dot{y}_i$, y_j, $\dot{y}_j$ are the vertical displacements and velocities of nodes i and j. These displacements are due to the vertical earthquake and by the horizontal-vertical coupling in the structure. When $F_{ij}(t)$ becomes greater than $Q_{ij}(t)$, the sliding starts.

5.1.2 Sliding Phase

$$\left\{\begin{array}{l} F_{ij}(t) = K_{ij}(x_j-x_i-\delta_{ij}(t) + C_{ij}(\dot{x}_j-\dot{x}_i-\dot{\delta}_{ij}(t)) \\ \\ F_{ij}(t) = f.(P_{ij}-R_{ij}(t)) \end{array}\right. \qquad (8)$$

This supplementary equation permits computation of $\delta_{ij}(t)$. The end of the sliding occurs when $\dot{\delta}_{ij}(t)$ changes its sign.

5.2 Calculation on computer

The introduction of this special connection, which represents a friction pad, can be made in any dynamic computer code based on a step by step integration of the equations.

5.2.1 Simplified approach

It can be carried out by taking into account a reactor building idealized as a lumped mass system of 7 nodes and one pad, submitted to El Centro 1940 quake scaled at 0.15g, 0.30g and 0.60g. Ground is modelled by means of springs and dash-pots calculated according to Deleuze Theory [1] . Some maximum accelerations are given in Figure 4. Curves showing relative displacement of the two rafts and sliding versus time are given in Figure 6. These computations show that the reactor building almost behaves like a one-degree-of-freedom oscillator. Conclusions on detailed analyses are summarized hereafter.

5.2.2 Effect of modelling

Different calculations carried out under El Centro 0.6g quake, with a coefficient of friction of 0.2, making the number of nodes vary, show that a simplified and a sophisticated model give almost the same results (variations of 0.02g at the top). On the contrary, a detailed model is necessary in case of classical design (variations of 0.25g at the top).

5.2.3 Effect of soil stiffness

Different calculations carried out under El Centro 0.6g quake with 0.2 coefficient of friction for different grounds (Dynamic Young Modulus between 10,000 bars and 40,000 bars) show that soil characteristics are not very important (variations of 0.04g at the top). On the contrary, in case of foundation on soil, these characteristics are of major importance (variations of 0.7g at the top).

5.2.4 Effect of vertical solicitations

A very detailed analysis shows that the vertical accelerations do not affect greatly the general behaviour of the sliding. The major reasons are:

- Neoprene has a high value of vertical stiffness so that there is no amplification of the vertical movement
- the first mode of vertical vibration is above 5 cps such that the variations of the "apparent weight" are quick compared to the 1 cps horizontal movement.

5.2.5 Differential behaviour of the bearings

The fact of taking into account many independent pads, placed on the lower raft which in turn is put on a purely elastic soil, does not modify the general dynamic behaviour and the distribution of the accelerations throughout the structure.

5.2.6 Soil-structure interaction

Taking into account soil-structure interaction phenomena depends obviously on the characteristics of the ground and on the relative stiffness of the two rafts. Studies taking into account possible plastification phenomena in the soil confirm and validate the simplified studies.

5.2.7 Miscellaneous

Parasitic rotations about a vertical axis due to:

- dynamic eccentricity
- uneven distribution of the coefficient of friction
- travelling shear wave (Love wave) [2]

have been studied. Induced rotations under 0.6g El Centro quake are lower than 4 10^{-4}rd. Flexure due to the passing Rayleigh wave gives relative vertical displacements between the two rafts lower than 0.10 mm.

5.3 Maximum sliding amplitude

The dimensioning of the friction pads depends essentially on their maximum relative movements and therefore on the earthquake level. Consequently a relationship between the earthquake level and the maximum sliding was established. This relationship has been obtained by compiling all the parametric studies already performed. Therefore this relationship takes into account different ranges of parameters (coefficient of friction ...) (see Figure 7). The maximum relative displacement of the raft can be obtained by adding the Neoprene distortion.

6. Experimental test on shaking table

A series of tests had been carried out by the Commissariat ā l'Energie Atomique (CEA) on a concrete structure (14.5t) representing a 1/10th scaled reactor building and placed on 4 aseismic bearings (10cm x 10cm). The horizontal solicitations have simulated many earthquakes (as El Centro 0.6g).

The good correlations obtained between experience and computations for the accelerations as well as for the displacements, show the exactness of the theory and the validity of the computer code (see Figures 8 and 9). In addition, the reproduction of the test made (70 earthquakes on the whole) shows the good behaviour of the supports and the general reliability of the system.

7. Safety

The examination of the aseismic bearing system from a safety point of view leads to the following two main questions:

- does the system guarantee satisfactory performance during the life span of the plant?

- does the present system offer a safety margin at least as high as that given by a "reinforced" design?

The analysis of safe permanence criteria of the plant involves a thorough knowledge of the bearing materials, their characteristics as well as their durability.

Results of theoretical and experimental research, together with field experience obtained over 30 years of use of these materials, provide the answer to the first question.

Furthermore, the station layout permits, if necessary, all the bearings to be in an accessible space where they can be readily inspected and, if need be, removed and replaced at any time during the station life without in any way interfering with the operation of the plant.

Concerning the question whether the aseismic bearing system presents a safety margin at least equivalent to that given by a "reinforced" design, it is necessary to examine which features determine the safety of a nuclear power station. Regarding a "reinforced" design, the safety of the plant depends on:

- the intensity of the earthquake forces
- the dynamic behaviour of the soil under the station
- the soil-structure interaction

The aseismic bearing system offers definite advantages:

- elimination of risk of horizontal earthquake accelerations in excess of the design acceleration
- the dynamic behaviour of the structure is more readily predictable since it only depends on the known characteristics of the bearings and their constituent materials.

Although much progress has been achieved in recent years in the field of mathematical treatment of soil-structure interaction, and in spite of scientific advances in soil mechanics, the structural behaviour of bearings can obviously be predicted more precisely than the behaviour of soil.

Finally, it stands to reason that the reproduction of proven designs, general arrangement structures, systems and components from standardised power plants provides in itself an additional margin of safety and reliability.

The aseismic bearing system has been successfully submitted to the French and South African authorities for approval of the general principle of the system.

8. Conclusion

The potential field of application of the system is wide since, in addition to the added safety and reliability, the reproduction of a standard design of structures, systems and components as developed for a series of standard plants, offers further important advantages:

- efficiency
- reduced design time
- economy in design, equipment and field work

Based on a number of designs carried out under different economic situations, it appears that the system is competitive above 0,25g, and the advantages increase rapidly with increase in seismic intensity.

The system is presently being applied in the Republic of South Africa for the Koeberg Nuclear Power Plant.

In this manner and in spite of high earthquake forces (0.3g), the design of a standard EDF power station can be reproduced.

Other applications are presently at the design stage both in France and Iran.

The system can also be used for other structures such as apartment buildings and industrial buildings built in high risk seismic areas, or otherwise submitted to violent dynamic action (explosion ...).

References

[1] DELEUZE, G., "Réponse à un mouvement sismique d'un édifice posé sur un sol elastique," Annales de l'ITBTP No. 234 de juin 1967.

[2] WOLF, John P., "Seismic response due to travelling shear wave including soil-structure interaction with base mat uplift," Specialist meeting on the anti-seismic design of nuclear installations, OECD Headquarters, Paris, 1st-3rd December 1975.

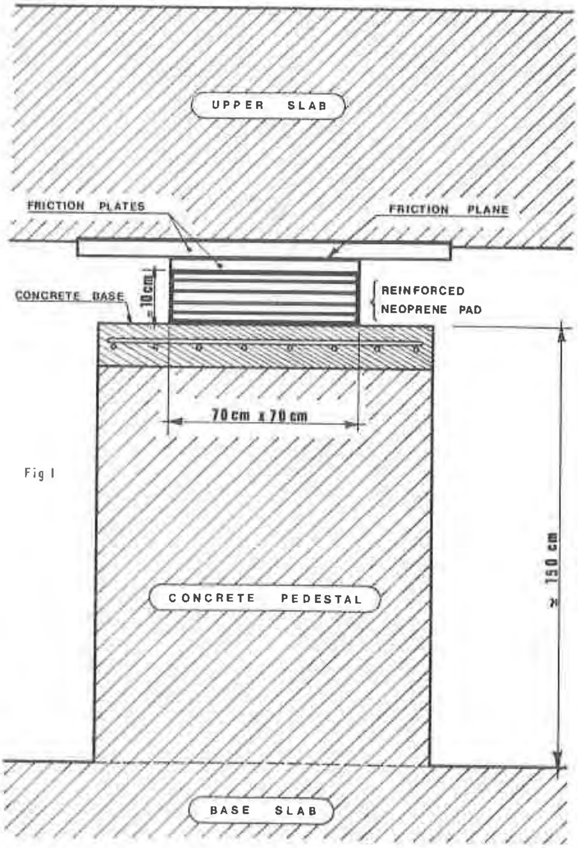


Fig I

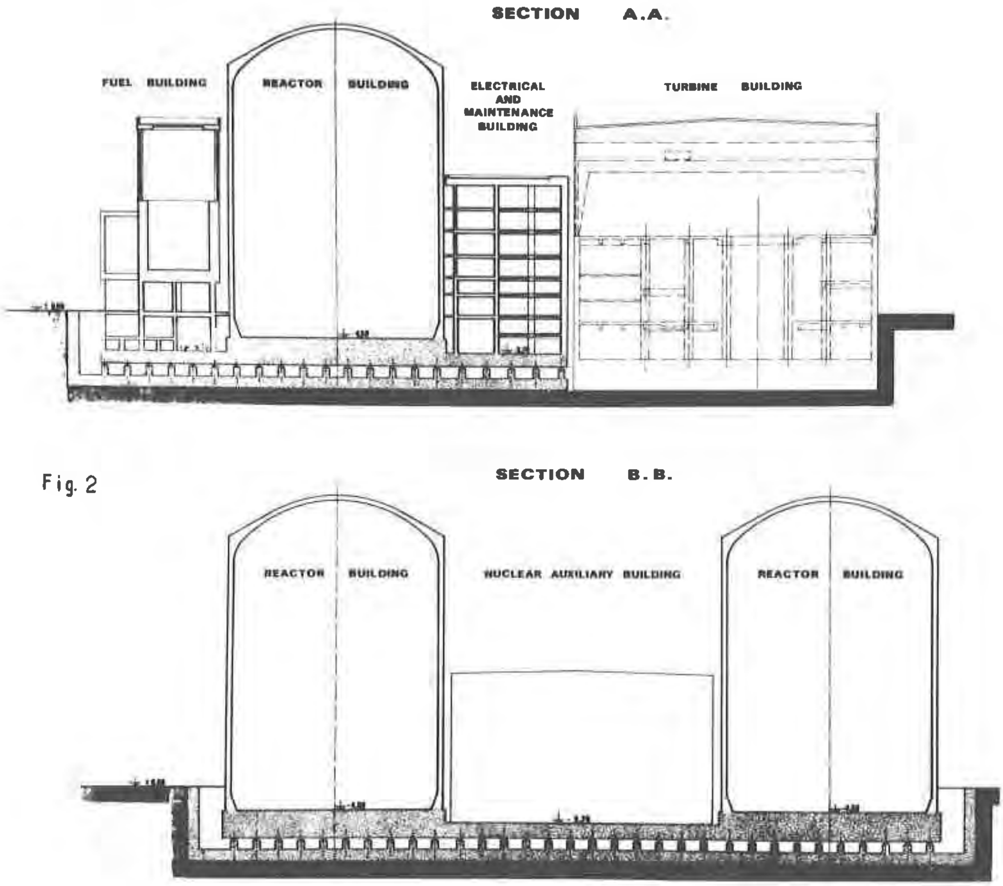
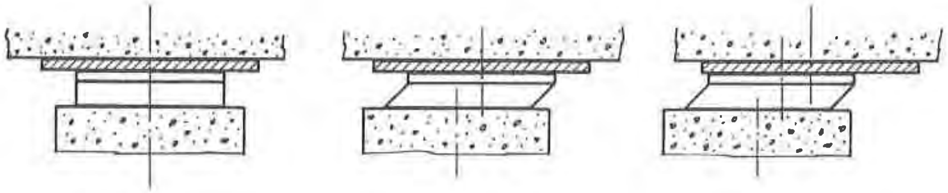


Fig. 2

DYNAMIC BEHAVIOUR OF THE ASEISMIC BEARING



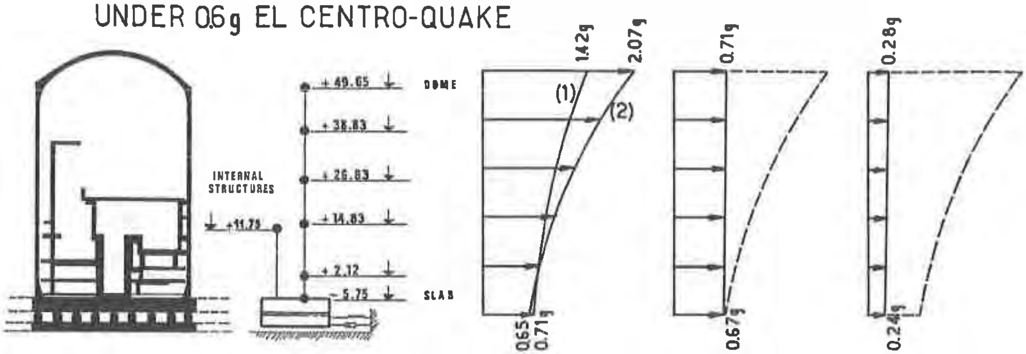
INITIAL

DISTORTION

DISTORTION + SLIDING

Fig. 3

REPARTITION OF ACCELERATIONS FOR REACTOR BUILDING UNDER 0.6g EL CENTRO-QUAKE



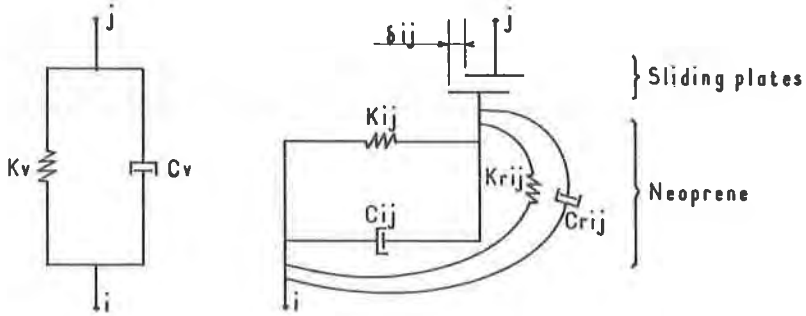
ON ELASTIC SOIL
(1) E = 10 000 bars
(2) E = 40 000 bars

NEOPRENE

ASEISMIC BEARING
f = 0.2

Fig. 4

REPRESENTATION OF THE ASEISMIC BEARING



VERTICAL

HORIZONTAL

Fig. 5

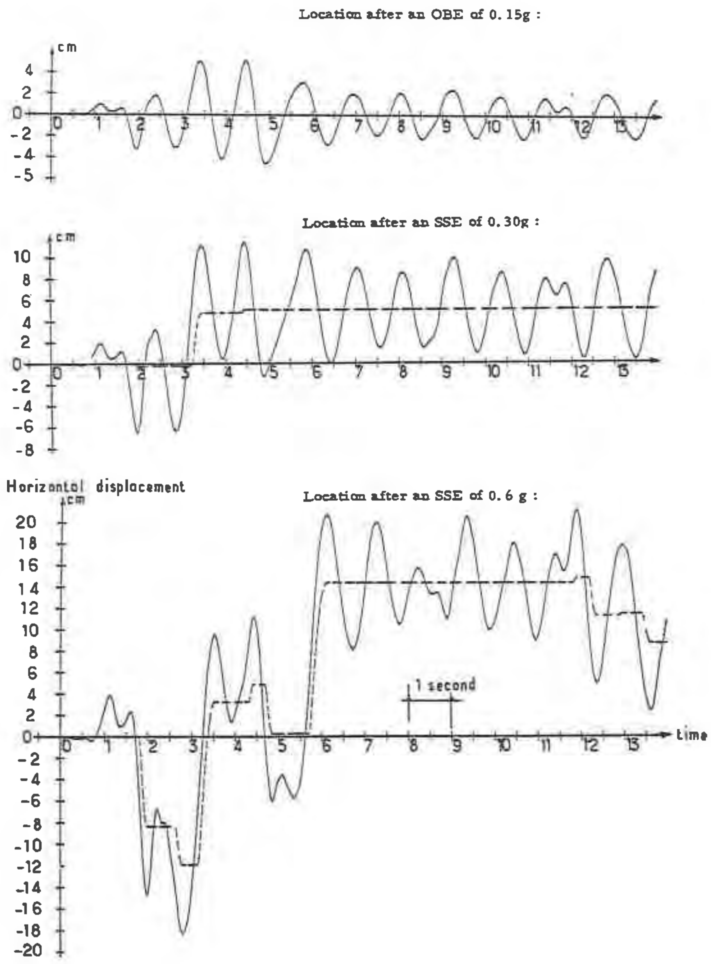
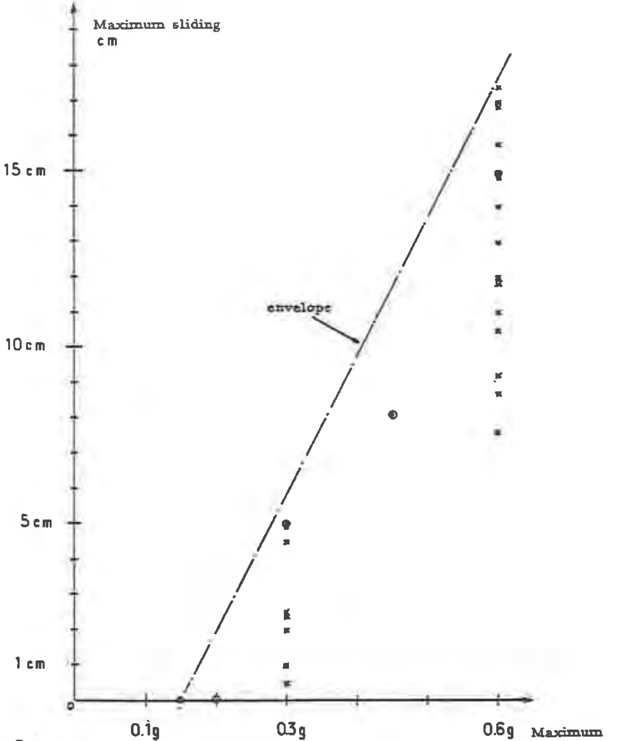


Fig. 6

Relat[illegible] between the maximum sliding and the earthquake level



⊙ = obtained with the accelerogramme El Centro N - S

coefficient of friction = 0.2 neoprene : G = 15 bars

ν = 5%

Fig. 7

Mock-up subjected to El Centro N-S 0,6g :
Comparison between recorded and computed absolute accelerations of the mock-up.

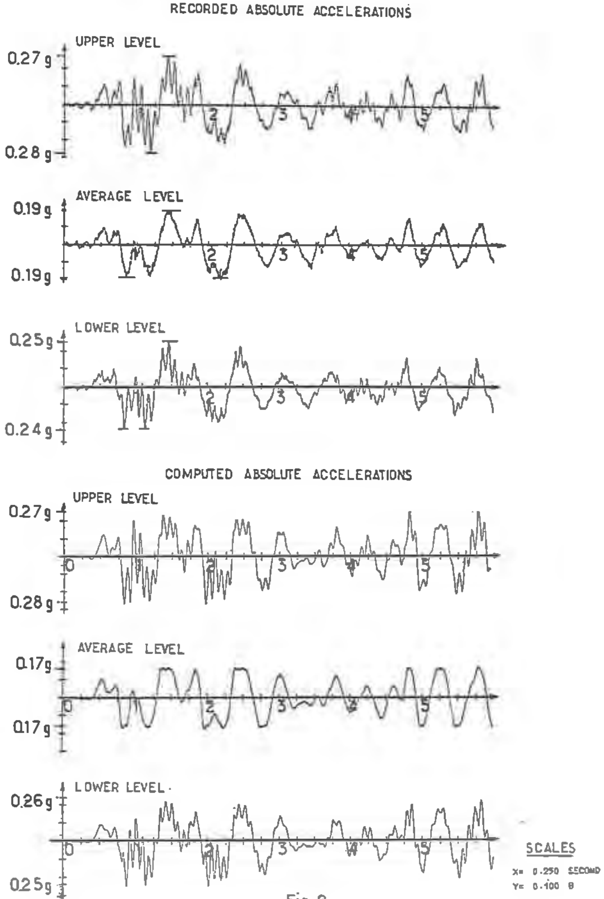


Fig. 8

Mock-up subjected to El Centro N-S 0,6g :
Comparison between recorded and computed displacements of the mock-up

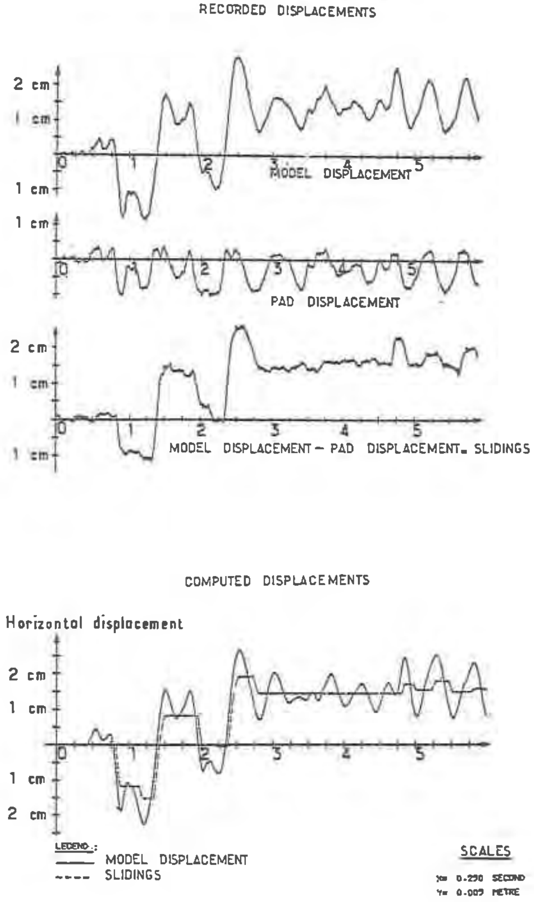


Fig 9