DEVELOPMENT OF ASEISMIC DESIGN AND CONSTRUCTION IN ITALY BY MEANS OF RESEARCH ON LARGE MODEL TESTS

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Introduction

The considerable seismicity of a large part of Italy confers a particular interest to the subject of aseismic construction.

Since the first years of this century the keen theoretical investigation developed on idealized structures, particularly by Danusso and Panetti, has given analysts some fundamental trends, such as the necessity to keep in mind the dynamic characteristics of the structure proper, and the possibility to attribute to the structure a correct degree of flexibility.

The knowledge of the dynamic characteristics of the actual structures, a premise necessary for the study of their behavior under seismic action, is obtained by the normal procedures indicated by the dynamic theories; but in many cases the investigation is now made with the aid of models, which give a better approximation than analytical procedures. In particular they introduce the bending characteristics with a much higher precision.

Thus, for example, the free flexural and torsional oscillations have been studied for a 400-ft reinforced concrete skyscraper (I.S.M.E.S. - 1955) now under construction in Milan for the Pirelli Co., (Figs. 1, 2 and 3); and the free and forced oscillations of the metallic support towers (700-ft high) of the high tension electrical cables across the straight of Messina (S.A.E. Co. - 1952).

A more complete investigation, which combines theoretical analysis with experience, testing the model of a structure with a minimum number of simplifying assumptions directly with an artificial earthquake in suitable scale, is being run at the I.S.M.E.S.

The first investigation was suggested last year by Ing. C. Semenza, Director of the SADE Company of Venice, for the design of a 60 m. high arched dam having a 150 m. span, to be built in the Irpino Italian pre-Alps, a zone of high seismicity.

The experimental part of this research is referred to in the last paragraph of this preliminary report.

Model and Structural Testing at ISMES

a) In order to fully appreciate the function performed by the ISMES (Experimental Institute for Models and Structures) in Bergamo (Italy), it should be noted that in Italy most of the study and research work in the field of civil engineering is done by University Institutes. Their work is largely theoretical and in the field of experimental research is confined chiefly to material testing, due also to the limited facilities and staff available for this work.

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I.S.M.E.S. is a private corporation* established for the purpose of solving with adequate financial means and freedom of movement (which, by their own structure, University Institutes do not possess) specific structural problems arising for designers and builders. Therefore, I.S.M.E.S. carries out a technical-scientific activity which is complementary to the activity which is carried out, or should be developed, in the Italian University Research Laboratories.

The experimental study of the structures by means of models has been gaining momentum in the last few years as a result of the improvement of measuring instruments, and has gained increasingly wide acceptance as an effective aid by open-minded designers and builders.

The practical usefulness comes from the fact that it is possible to work out a solution for laborious structural problems, even in the cases where calculus cannot provide sufficient assistance.

This process yields, in the design stage, valuable information making it possible to anticipate the static or dynamic behavior of the real structure (the "prototype") and, if necessary, to select from several the solution which is likely to produce the highest efficiency and the lowest construction cost. In addition to the static tests under normal load conditions, the Institute usually carries out "ultimate tests" to indicate the order of magnitude of the over-all safety factor of the prototype.

The Institute was officially established in 1951, and is being continuously developed. Among the fixed facilities now in operation, there are special structures of heavily reinforced concrete, built to contain large models of structural elements to be put through static tests, and to withstand the loads involved in the testing of the models without appreciable deformations.

One of these structures is a rectangular-base tank (Fig. 4) measuring approx. 32 x 16 ft, particularly suitable for testing model dams, and another is a circular-section tower, 32 ft interior diameter and 60-ft high, designed to hold tall models (dams built in narrow gorges, skyscrapers, cement silos,etc.), (Fig. 5). The tests on models or structural elements exerting no pushing stresses above ground levels; i.e., resting or anchored upon level ground (penstocks, floors, etc.), are conducted in a large shed-type building.

The Institute has ready for use this year a set of equipment, the only one of its kind in Europe, which is used for studying with models the qualitative and quantitative effects of seismic (or, generally, vibrating) actions on building structures and dams. The seismic testing equipment include:

ISMES was established by a group of companies and contractors including: EDISON Co. of Milan, ITALCEMENTI Co. of Bergamo, ACC. FALCK Co., SADE Co. of Venice, SIP Co. of Turin, "Societa Italiana Partecipazioni Industriali",SME Co. of Naples, MONTECATINI Co., ROMANA ELETTRICITA Co., SELT-VALDARNO Co., TERNI Co., ACEA of Rome, AEM of Milan, AEM of Turin, Contractors: GIROLA, ITALSTRADE, LODIGIANI and TORNO. The scope of the Institute's work extends to experimental research on the behavior of structures, by means of tests conducted on large three-dimensional models, or on the structures themselves at the construction site.

(1) - a steel platform, measuring approx. 10 x 15 ft, in highly rigid frame, upon which is built the model-structure to be tested, complete with its foundations (see Figs. 6 and 7).

(2) - three vibration-generating units (Fig. 8) including:

(a) a composite system of a pendulum and springs (Jacobsen type) for the reproduction of shock waves;

(b) a centrifugal vibrodyne up to 10 tons (Losenhausen construction) for the reproduction of unidirectional harmonic vibrations, both vertical (b_1) and horizontal (b_2), with frequency variable from 2 to 25 Hertz;

(c) 4 electronic-controlled electro-magnetic vibrators, for the reproduction of both unidirectional and vortex-type vibrations;

(3) - equipment for recording the strains and deflections of the model during the tests.

With this equipment and using suitable casted materials, already studied and previously mentioned, it is possible to make tests on models of structures in a scale of up to 1:100 with earthquakes of an amplitude of 10 cm. and periods of the prototype from 0.2 to 2.5 sec.

Considerations of Structural Models

a) The theory of models is based on a well-known principle of similitude which states that two systems are physically similar when there exists a geometrical correspondence between the points of the two systems and the quantities of the same physical nature have a constant ratio at corresponding points. Complete physical similitude between prototype and models is reached when all the relations between the "scales" with which the model reproduces the physical quantities on which the problem depends are taken into consideration; or (if one wishes to follow the Riabucinski-Buckingham pi theorem which is fully equivalent) when dimensionless ratios which characterize the problem assume identical numerical values in model and in the prototype.

It is useful to distinguish between the case that one may wish to study on a model, separating those for which one possesses a thorough mathematical theory, from those in which this is not so. A classical example of the first case is shown by a study of the behavior of any structure made in a hemogeneous isotropic elastic material and statically determinate, as mathematics then offers the theoretically complete solution to the problem: a system of partial derivative equations in respect to the unknown functions (components of the tensor stresses).

Even though the numerical solution of such a system is often extremely laborious, as for instance in the most complex three-dimensional problems of concrete dams, the knowledge of the theory simplifies the investigation with the model, as the equations of the theory furnish a complete and precise list of the specific quantities which influence the phenomenon studied.

In particular, it should be remembered that such equations postulate the independence of the tensor of stresses from the physical and mechanical characteristics of the material (elastic modulus; yield point, etc.....) with the exception of Poisson's ratio and therefore allows us to use materials for the model which differ from those of the prototype, as applied in photoelasticity.

Without a theory and the relative equations which set out the physical problem to be studied, it is more difficult to realize a complete similitude, as naturally all the dimensionless ratios on which the phenomenon we study depend upon, may not be identified. It is in these cases that dimensional analysis becomes of use as a precious resource. Once the quantities which are present in the phenomenon are listed, it provides the independing dimensionless ratios which can be built with these quantities and thereby provides a guide to the proper use of the model to obtain satisfactory results.

It seems advisable to mention these preliminary fundamentals on model theory in order to outline the difficulties that the work on models may come up against, and which are really met with, particularly in hydraulic, electric and aerodynamic research.

b) Structural investigations (and not only the most restricted elasticity problems) generally present favorable conditions since the independent fundamental quantities upon which the behavior of a structure depends are generally three: the classic "length," "mass" and "time" or three dimensionally independent quantities. These are reduced to two when only the static behavior of the structure is studied, as in this case the variable "time" is missing.

If λ and $\varkappa$ represent the ratios of similitude of the lengths and of forces respectively, the ratio is similitude ς of the stress values during the passage from prototype to the model must be:

$$\varsigma = \frac{\varkappa}{\lambda^2} \qquad (1)$$

All the other physical quantities, occuring in the problem, which have the same dimension of a stress (modulus of elasticity, yield point, ultimate stress), must have this same ratio. The materials with which the models and their foundations are built must generally conform to this same ratio ς which we will call "effectiveness ratio"*.

In the particular case of only superficial loads, with π indicating the ratio between the intensity of these loads, the required relationship will be: $\varkappa = \pi\ \lambda^2$ and π coincides with ς the latter is then independent of the scale ratio λ .

But if the stresses due to the dead weight are not negligible, and p represents the ratio of the densities then it will also be necessary that:

$$\varkappa = \rho\ \lambda^3 \qquad (2)$$

and therefore the condition, that is obtained by placing (2) into (1) must be considered. This is

$$\varsigma = \rho\ \lambda \qquad (3)$$

The difficulties increased by this requirement may justify the expedient of using large scale models and the necessity to increase the density of the model material, perhaps with artificial devices.

In the elasticity problems only and within the limits of the mentioned theory, this dependency may be avoided: so for example, photoelasticity utilizes materials for models which are quite different from those of the prototype.

In the particular case where the most important stresses are due to body forces, as for example, in dam problems (hydrostatic load and dead weight) only the relationship is required.

When it is possible to find materials to build a model and its foundations for which the conditions of invariability of ξ are met, in the sense that the "intrinsic curve" of the model material is similar to that of the prototype in the constant ratio ξ and the scale of the density ratio satisfy the relation (3), similitude may be considered attained and it may then be considered effective not only within the limits of elasticity but to the breaking point.

c) Previously, static problems alone were considered, deformations and stresses were not influenced by "time".

In reality the collapse of a structure may also depend on the time of the application of loads because of the viscosity of the materials with which it is built.

It is known from theory that, in such cases, the stresses are linearly related to the corresponding velocity of deformation through a coefficient of viscosity, which is a constant providing the material is homogeneous and isotropic. It is then necessary to add a new fundamental quantity, such as "time" for which the non-dimensional ratio μ between the viscosity coefficients must be equal $\chi \lambda^{-2} \tau$, with τ the ratio of times between the prototype and the model.

The variable "time" comes into play again when the dynamic behavior of a structure must be studied. This is of particular interest for seismic effects. In such cases, it is necessary to bear in mind that among the forces to be considered are those of gravity, and being unable, obviously, to alter the value g of the gravity acceleration in passing from the model to the prototype, one is obliged to presume that this quantity is a fixed dimensional constant. It is useful therefore to consider acceleration as a fundamental quantity instead of time. The ratio between the accelerations acting on the prototype and on the model must be equal to 1. The ratio of the times τ must then satisfy the condition:

$$\tau = \sqrt{\lambda} \qquad (4)$$

It follows that the vibrations will reproduce themselves on the model with a higher frequency: for example, on a model having a scale of 1:100 the frequencies will be ten times higher than in the prototype (Froude- similitude).

It is useful to point out that in order to satisfy relation (4) it is not possible to work a model made of the same material as the prototype, or materials which have the same density. The ratio between the density of the prototype and model materials, p, must satisfy:

$$\tau = \lambda p^{1/2} \xi^{-1/2}$$

The equations (4) and (5) are satisfied by imposing the conditions (3).

As an example, in the case of the model studies of the earthquake-effects on the Ambiesta dome dam (Fig. 9), by conforming to the requirements of these fundamental ratios, we have at the ISMES, assumed:

$\lambda = 75$ $\qquad$ $\xi = 50$ $\qquad$ $\rho = 2/3$

using for the model material a special mortar of litharge and plaster.

For determining the free vibrations of a structure it is not always necessary to satisfy (4), but simply (5). For instance, in the dynamic studies of the already mentioned Pirelli skyscraper, we have assumed for the model:

$\lambda = 15$ $\rho = \pm .65$ $\varrho = 6$

and thus result: $\tau = 7.9$

We have obtained the following results on the model (Fig. 10):

I°) max. deflection free period : $T_I = 0.59$ sec.

II°) min. deflection free period : $T_{II} = 0.48$ sec.

III°) torsional free period : $T_{III} = 0.34$ sec.

The variations of the free frequencies for the viscous damping of the material is negligible.

Structural Models for Seismic Problems

A more complex problem is posed from the necessity to reproduce with a series of reasonable experiments a complete range of probable earthquakes, in order to give the experiments a general character.

A preliminary study on seismograms has led to the identification of the values of the more frequent periods, among those with which the maximum values of the accelerations are accompanied; these dominating periods are around 1 sec. (for the zones of Italy of actual interest and for the earthquakes of greater intensities).

With regards to the stability of the construction, it must be observed that may be decisive to insist, more or less, with an earthquake of a constant frequency (or of slightly different frequencies); therefore we have considered necessary to introduce, not only the notion of the dominant frequencies but also the parameter "duration" for each frequency studies. This has been attained from the known function called seismic spectrums* - which develops the maximum values of the ratios $A/a_{o\ max}$ between the acceleration A of the structure and the forced acceleration $a_{o(t)}$ at the foot of the structure reached by structures having different natural periods T, during an earthquake of aceeleration value a_o. The envelope diagrams of the known seismic spectrums, for the different possible earthquakes are a function of the type designed in Fig. 11.

The shaded area of Fig. 11, which represents the effects of all the foreseen earthquakes, may be covered by two different types of vibrations ("civilized earthquakes"):

a) a series of damped sinusoidal motions which reproduce the individual earthquakes of the following type:

$$y = y_o e^{-st} \sin wt$$

For instance = 0.3 and with the values $T = \frac{2\pi}{\omega}$ from 0.5 to 1.5 we have obtained the maximum dynamic magnification of the order of 7 to 8.

* M. Biot - Analytical and Experimental Methods in Engineering Seismology - Trans. ASCE 1943 -

b) A series of simple sinusoidal motions $y = y_o \sin w t$, with the values of y_o suitably reduced with respect of the preceding case to account for the damping coefficients of the material used for the model under test. The object again is to obtain the maximum value of (A/a_{omax}). For instance, in the previous case: 7 to 8.

Preliminary on Seismic Tests of the Ambiesta Arch Dam

With the equipment in possession of the ISMES, up till now the following tests have been made on models of the Ambiesta dam ($\lambda = 75$):

Sinusoidal seismic vibrations: normal elastic tests for frequency variable on the model from 3 to 25 Hz; ultimate tests with a frequency reaching about 20 Hz and a forced acceleration of about 0.92 g (Fig. 12);

Undulatory seismic vibrations in the direction of the chord of the dam; normal tests for frequencies from 8 to 15 Hertz, while recording the deflections of some principal point of the structure.

Presently there is a new series of undulatory tests underway where the range of frequencies is amplified and at the end the intensity will be gradually increased till the breaking point.

Conclusion

To conclude on what has been said, it seems possible to affirm that the investigations that have already been made, illustrate the trend presently followed in Italy in the design of important aseismic projects (as the Ambiesta dam). The studies should be developed in the following steps:

a) - preliminary project from the point of view of the normal requirements of statics:

- analytical calculations;
- control of the stress distribution and of the degree of safety by means of testing on a static model;

b) - checking of the seismic action;

- preliminary investigation of the dynamic characteristics and determination of the natural periods of vibration by calculations and by testing on models.

- application of the different types of seismic action, for which it may be foreseen that the structure moves solidly with the ground. A static calculation foresees the resolution of the earthquake effects into static forces;

c) - control by means of suitable models of the effects of the various seismic actions and especially those for which it is possible to foresee a dynamic magnification.

Lastly, an experimental determination on the model of the degree of safety, for the case that appeared most dangerous to the stability of the structure.

DEVELOPMENT OF ASEISMIC CONSTRUCTION

CAPTIONS FOR FIGURES

Fig. 1 - Comparison between the prototype designs and the model designs of the new reinforced concrete skyscraper of the Pirelli Co. Milano (Italy).

Fig. 2 - General view of the model (λ = 15) and of the equipment for static loading of the skyscraper Pirelli, placed in the great experimental tower of the ISMES Bergamo (Italy).

Fig. 3 - A particular view of the model of the Pirelli's skyscraper.

Fig. 4 - Rectangular-base tank of the ISMES especially used for testing large models of arch dams.

Fig. 5 - The experimental great circular tower in heavy reinforced concrete of the ISMES.

Fig. 6 - The steel vibrating-table of the ISMES.

Fig. 7 - A view of some of the equipments used for the seismic tests by means of the vibrating table.

Fig. 8 - The three types of vibration generating units applied to the steel platform used for seismic tests (ISMES).

Fig. 9 - The model of Ambiesta dome dam (λ = 75) ready for the seismic tests.

Fig. 10 - Typical records obtained in testing the free vibrations of the skyscraper model of the Pirelli Co.

Fig. 11 - The envelopes of the seismic spectrums.

Fig. 12 - Model of Ambiesta arch dam after the ultimate tests, with vertical seismic vibrations.

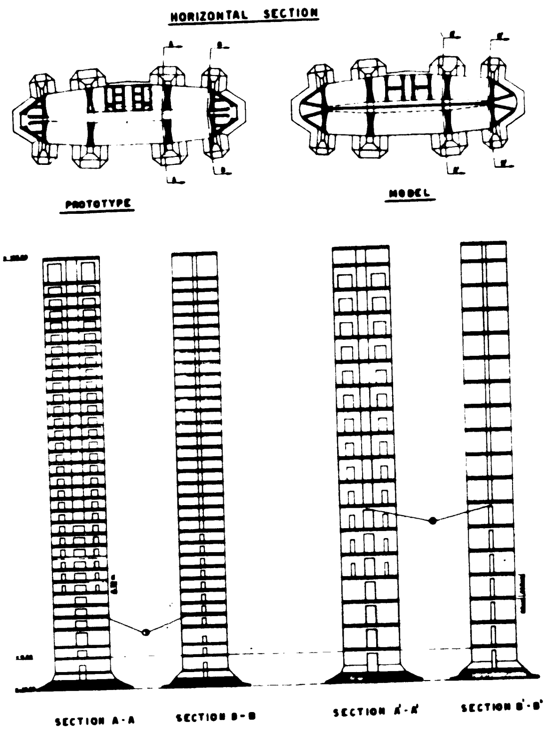

Fig. 1

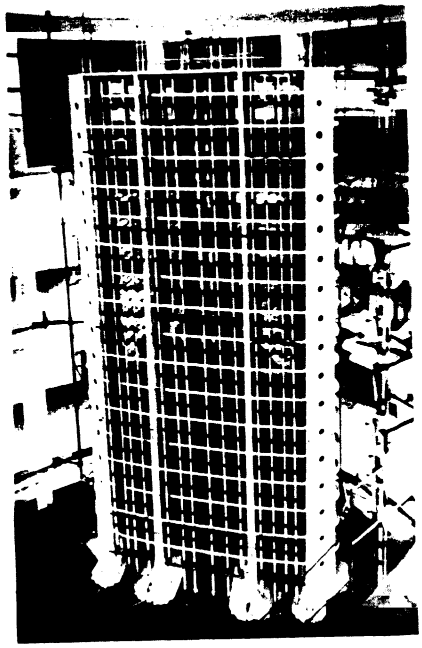

Fig. 2

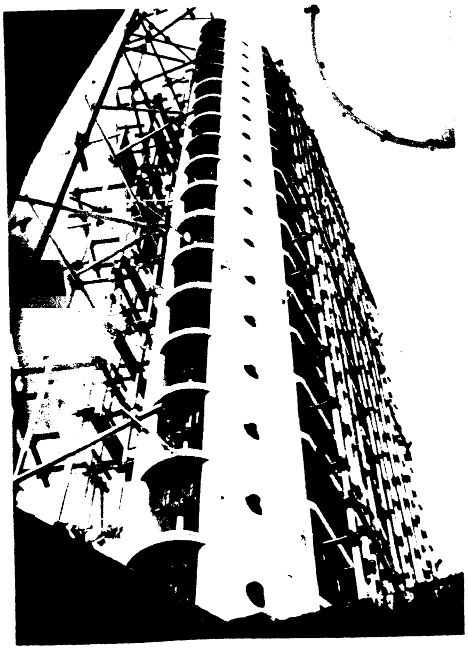

Fig. 3

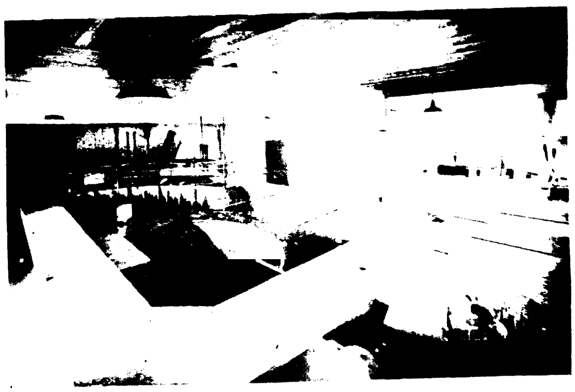

Fig. 4

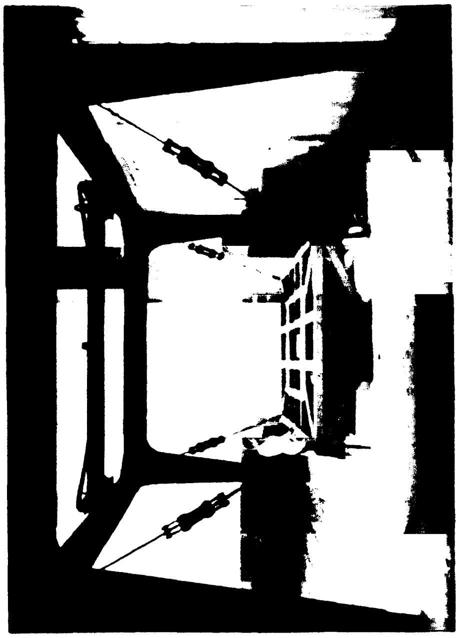

Fig. 6

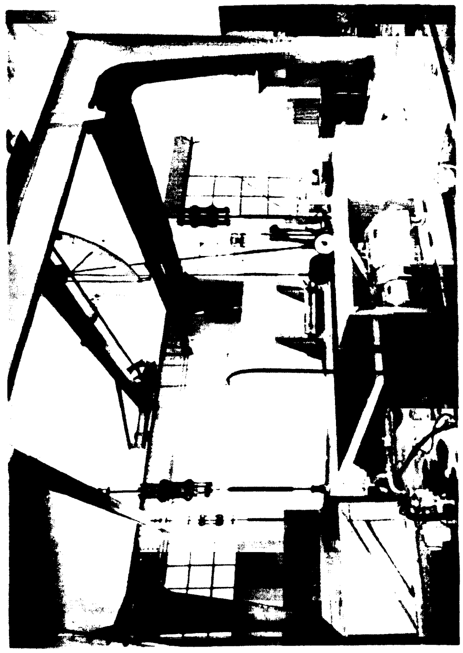

Fig. 7

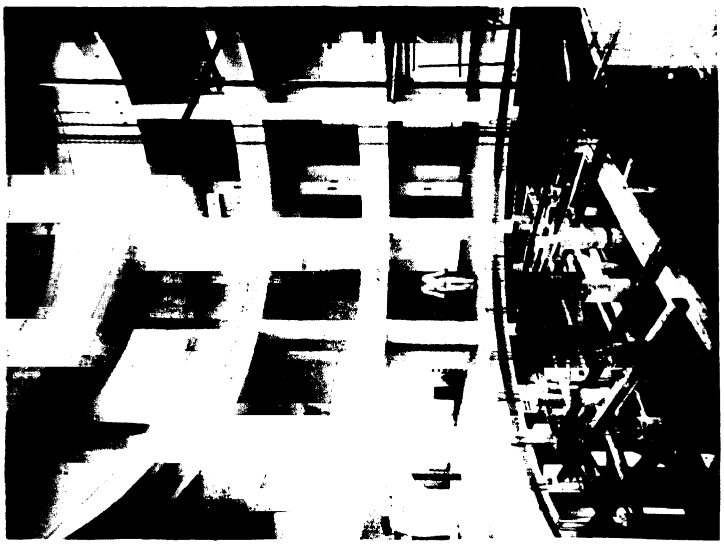

Fig. 5

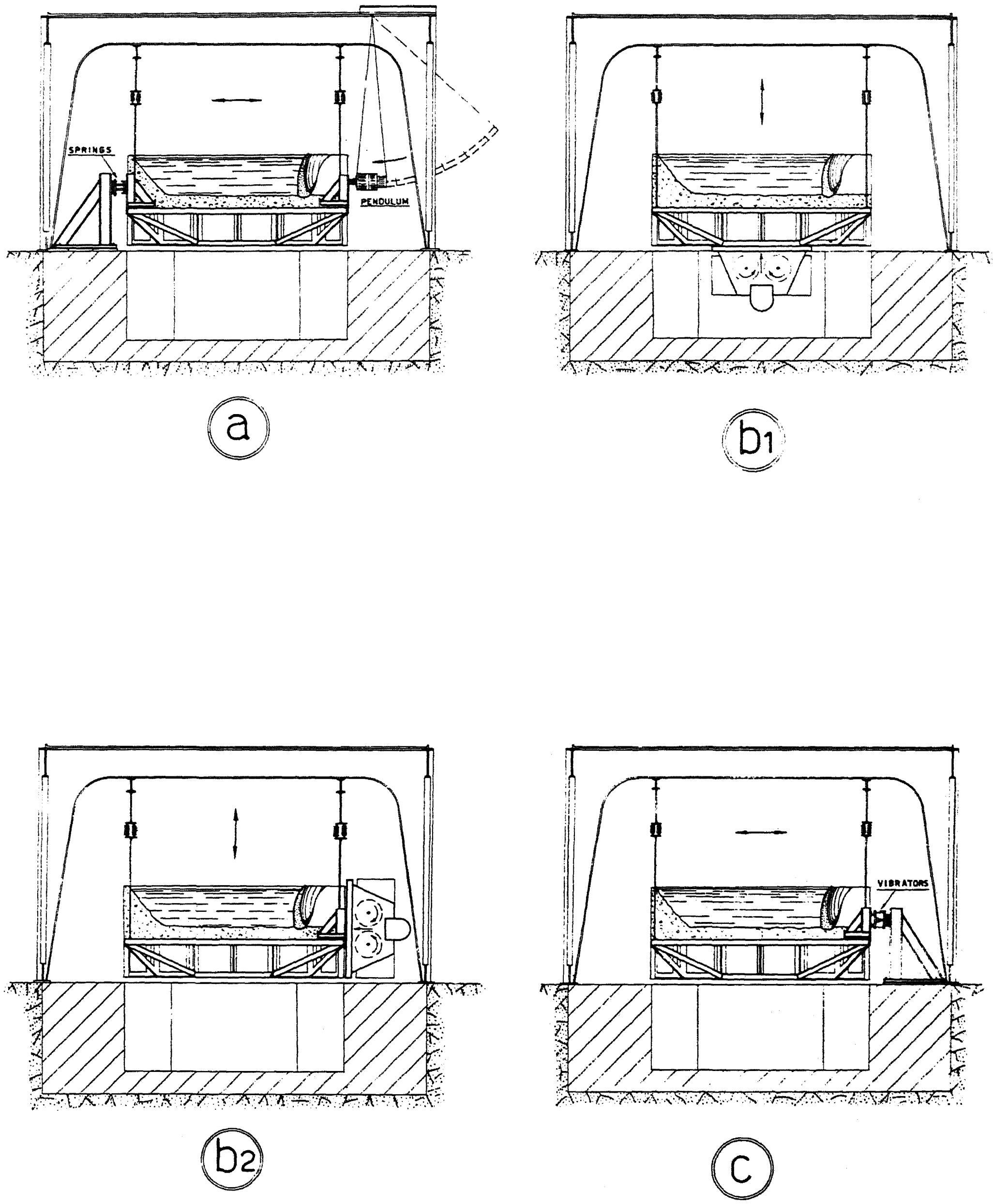

Fig. 8

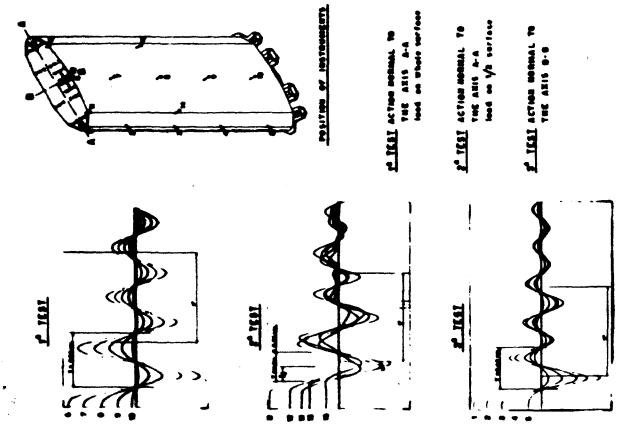

Fig. 10

Fig. 12

Fig. 9

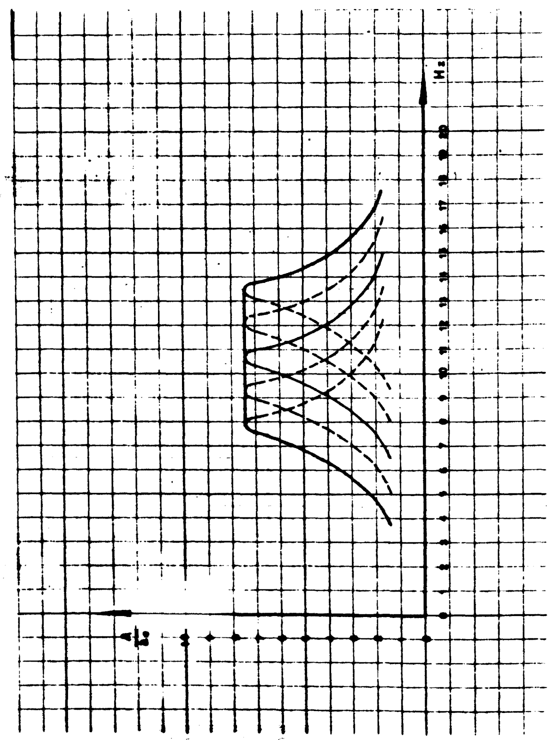

Fig. 11