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DISCUSSION PRÉPARÉE / VORBEREITETE DISKUSSION / PREPARED DISCUSSION

Model Analysis for Structural Safety and Optimization

Analyse sur modèles de la sécurité et de l'optimisation des structures

Modelluntersuchung der Bausicherheit und -optimierung

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1.- Foreword.

a) In a short note presented at the Rio de Janeiro Congress of the IABSE in 1964 I stated that the possibility of analyzing on models, even to failure, of large structures, particularly plain or reinforced concrete structures, has long been proved by me in a great number of cases.

In fact, a model study under elastic conditions furnishes the values of the prototype stresses under working load, which is important for several reasons. Firstly, the results obtained, unaffected by the assumptions and limitations which impair the classical methods of calculation, can profitably be compared with those supplied by these methods. Secondly, it is not hard to solve on models unusual three-dimensional problems, contrary to what is the case with the conventional analytical procedures both because of extreme complexity (only partly reduced by the finite element method) and difficult mathematical schematization of accurate boundary conditions.

Extension beyond the elastic range is still always invaluable to the structural engineer as it may enable him to locate possible weak points in the design and thus assist in securing greater safety and optimization.

Models may be classified in elastic (tested within the elastic range only), structural (carried to failure) and geomechanical (when the foundation influences the structural performance).

Present trends, based on experience at ISMES, are:

- increasing emphasis on structural models;
- constant improvement of model materials to better suit the aims pursued;

- growing interest in thermal stress investigation, especially for concrete dams and reinforced (prestressed or not) concrete vessels of nuclear reactors;
- dynamic testing on large shake tables and marked concern for earthquake effects.

b) Theme I has been treated by the general reporters prof. A. M. Freudenthal and prof. J. Courbon.

In a first theoretical and critical paper regarding topic 1a, prof. Freudenthal deals with the evaluation of overall structural safety based on probabilistic criteria related to the operating loads, which seems fit for statically determinate structures only. In a second paper concerning topic 1b and also of a theoretical probabilistic nature, the same author discusses the possibility of predicting ultimate safety based on the physical properties of the materials and their influence at failure. None of the papers mentions structural model analysis.

Prof. Courbon's paper treats with topic 1c of Theme I. It concludes by mentioning, all too briefly, the great services rendered by model studies in the design of dams, thin shells and shields of nuclear reactors.

I, therefore, believe it of use to outline, the present-day possibilities of model analysis in evaluating the safety degree of large statically indeterminate structures.

c) Model investigation primarily concerns statically highly indeterminate structures and may be regarded as:

I) a modern method of stress analysis;

II) a tool for failure load evaluation.

In any case, it is possible to consider or predict the statistical dispersion of the operating loads and of the structural resistance of the prototype material.

In case II), when several models are tested, it is possible to evaluate the ultimate carrying capacity R of the structure for each type of load S, so that the model functions as a tool for determining the overall safety factor ν.

This factor may vary for each type of structure, depending on the probabilistic possibility assumed for the operating loads and the structural resistance, associated with a definite risk of failure.

Thus, for concrete dams, the loads are practically known (excepting those for earthquake-resistant design), and the uncertainties about the concrete resistance are quite small. The highly redundant type of these structures generally reduces the importance of the concrete strength dispersion. The safety factor in this case, therefore, serves rather as a coefficient of security against the insecurity of the analytical results, especially in relation to the real properties of the rock foundation.

2.- Actual possibilities of model analysis.

a) Elastic models are based on linear elasticity (Hooke's law) and, hence, a superposition of effects is allowed. They also permit to proportionately modify the loadings so as to obtain the most suitable testing conditions. In particular, it is possible to operate at strains that are amplified with respect to those required by similitude (which demands that the strains in the prototype and in the model be the same).

Elastic models, widely used in "stress-analysis", may be divided in two groups.

The first group concerns plane elastic structures, and for them the deformeter, photoelastic and Moiré methods are predominant.

Deformeters are based on the well-known reciprocal theorems (Maxwell, Betti, Müller-Breslau). Photoelasticity is a first-rate research method, most used in structural engineering laboratories. The Moiré method is primarily used in flat slab investigations.

However, it should be observed that the importance of these methods has lately decreased due to the use of computers in solving problems relating to plane elastic structures.

The second group deals with three-dimensional models. In statical tests the loading equipment is usually made up of calibrated weights or hydraulic jacks, the pistons of which react against an external rigid frame; the loads are applied to the model through wooden cork-soled pads. Strain gages, ordinarily applied to the surface of the model, are used for measuring the direction and magnitude of the principal strains.

Young's modulus and Poisson's ratio of the model material are determined as usual, the former by tensile and flexural tests and the latter by torsional tests. The material may quite differ from that of the prototype, provided it obeys Hooke's law and its Poisson's ratio is similar to that of the structure. The model then functions as a "stress computer", and its results may be compared with the theoretical ones.

For elastic models, ISMES has recently succeeded in using epoxy resins mixed with various aggregates. They permit obtaining a wide range of elastic moduli in accordance with the requirements of each case, and stress-strain relationships that are similar even when the stresses are high.

b) Structural models are best made of the same material as the prototype. This is generally possible for steel or prestressed concrete structures when suitable scale (1:4-1:20) models are used. But for very large structures, such as concrete dams, we are forced, also for economic reasons, to adopt greatly reduced scales (1:30-1:100) and hence to use model materials whose mechanical characteristics are reduced compared with those of concrete in accordance with similitude requirements.

For structural models, I have long since used special materials simulating the mechanical properties of concrete, by introducing the technique of "wet models" (with a waterproof coating) practically free of internal stresses.

The tests are then divided into two successive stages. In the first stage, called "normal load tests", the deformations are investigated for values close to similitude conditions (that is, $\varepsilon = \varepsilon'$) under loads corresponding to those of the structure in operation(°).

The second stage concerns ultimate load tests and the transition to them is gradual. The ratio of the highest actually supported load to that of the design load is generally assumed as overall "factor of safety".

This ratio can easily be referred to all the operating loads equally or differently increased following a probabilistic coefficient applied to each independent load. In the case of statically high indeterminate structures it differs from the classical ratio of ultimate to working stress, and its meaning is greater since it takes into account the bi- and triaxial strength of the material under stresses in different directions and the plastic adjustment.

One can by expedients increase on the model solely the loads which in the prototype may rise through extraordinary action. Such are wind load for skyscrapers and water pressure for dams. The horizontal loads alone may undergo increases of consequence for the stability of these structures. In setting up a model study it is, therefore, of basic importance that the factor of safety shall be evaluated as simultaneously affected by:

- loads having a fixed value (dead load);
- loads which may increase with respect to their ordinary value (wind effect);
- actions the occurrence of which is only probable (earthquake).

In practice, when the so-called "weight" of each of the above phenomena has been established, one can obtain

(°) It is advisable to secure, through repeated loading cycles, non-elastic displacements (settlement of the foundation, adjustment and opening of joints, localized plasticity) which are likely to occur since the first loading in order to obtain an elastic and uniform model performance fit for repeated measurements and controls. This permits obtaining the stresses, displacements and structural behavior of the prototype under working conditions.

the factor of safety by experimentally increasing all the loads up to the failure of the model, considering the "weight" corresponding to each type of load

Therefore, not only one but a number of factors of safety can be secured, each of which corresponds to a given set of phenomena the influence of which is to be analyzed.

c) Geomechanical models investigate structures on foundations whose equilibrium conditions may affect the safety of the structures, as is the case of dams, large bridges and power or highway tunnels.

The stability of block foundations has lately beer simulated and studied on geomechanical models the characteristics of which had conveniently been schematized on the basis of geognostic tests.

It may also be pointed out that in-situ and laboratory investigations of the geomechanical features of the rock and soil mass are increasingly used and recommended as an aid to model studies.

The models, therefore, must faithfully simulate the rock and soil conditions and its mechanical properties. The tests are usually carried to failure.

These investigations are to be considered as basic when extensive discontinuities (faults, cavities) or a pronounced anisotropy (stratifications and diaclases) are present in the rock mass, especially when sliding or least-resistance planes may develop or, more generally, when large low-strength block formations are involved.

In these models, cohesion and angle of friction must also be faithfully reproduced. The difficulty encountered in establishing the true values of the angles of friction makes it in the modeling conservative to assume reduced values which are still within the approximation allowed by field tests.

The prototype and model strains have to be the same and, therefore, the scale ratio must be reduced. The model materials then shall have high densities and low mechanical properties (i.e., very low moduli of elasticity, yield-point and ultimate loads) in order to comply with similitude.

3.- Assessment of (structural) safety at the design stage.

The adoption of model techniques is firstly of considerable importance at the design stage of structures, especially if these are statically highly indeterminate.

Structural safety can then be evaluated by modern probabilistic criteria as suggested in the Freudenthal report when:

- the expected statistical dispersion of the loads, i.e. of the external or operating forces S, is taken into consideration by determining the dimensions of the prototype on the basis of a force $\gamma_S \cdot S$ (where γ_S, the load safety factor, is >1) and adopting equivalent working forces in the model;

- the statistical dispersion of the strength σ_R of the prototype material is taken into account by assuming an ultimate load, or a yield point, equal to σ_R / γ_R (with γ_R, the rupture safety factor, >1) and comparing the highest internal stresses furnished by the model at that value.

The model then becomes a very efficient tool for a "structural analysis".

As typical examples I shall mention:

- the statical and dynamic investigations carried out on an <u>elastic model</u> of the Polcevera viaduct, of the Maracaibo bridge type, designed by prof. R. Morandi (fig. 1);
- the far more elaborate analysis, made particularly on a <u>structural model</u> carried to failure, of the new San Francisco Cathedral designed by prof. P.L.Nervi(figs.2,3);
- the study of the safety degree of the Kurobe IV Dam and its foundation (figs. 4, 5, 6).

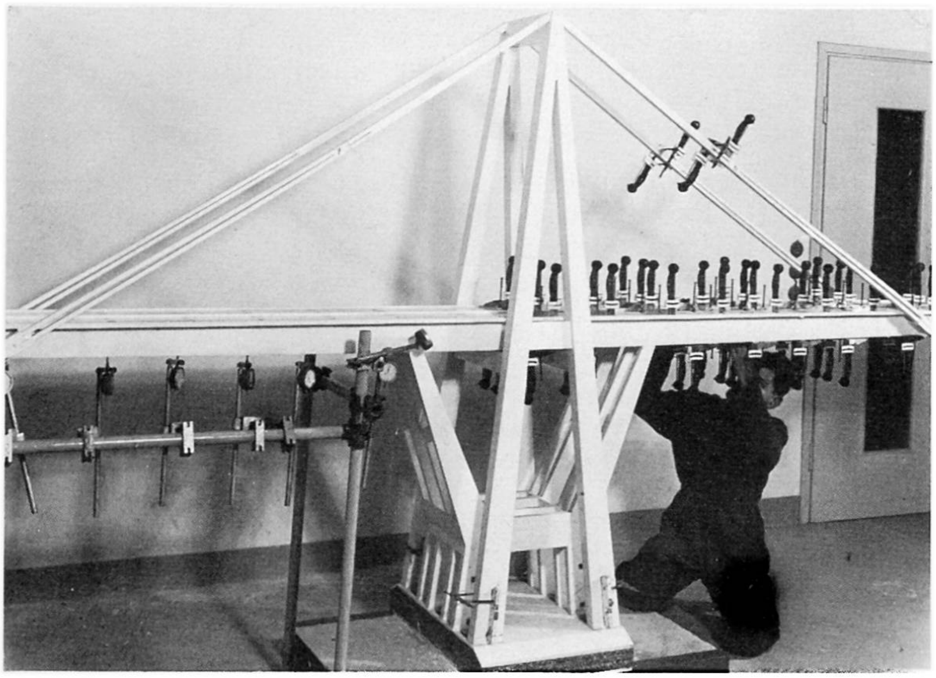


Fig. 1 Polcevera viaduct, Italy. Elastic model: Scale 1:50

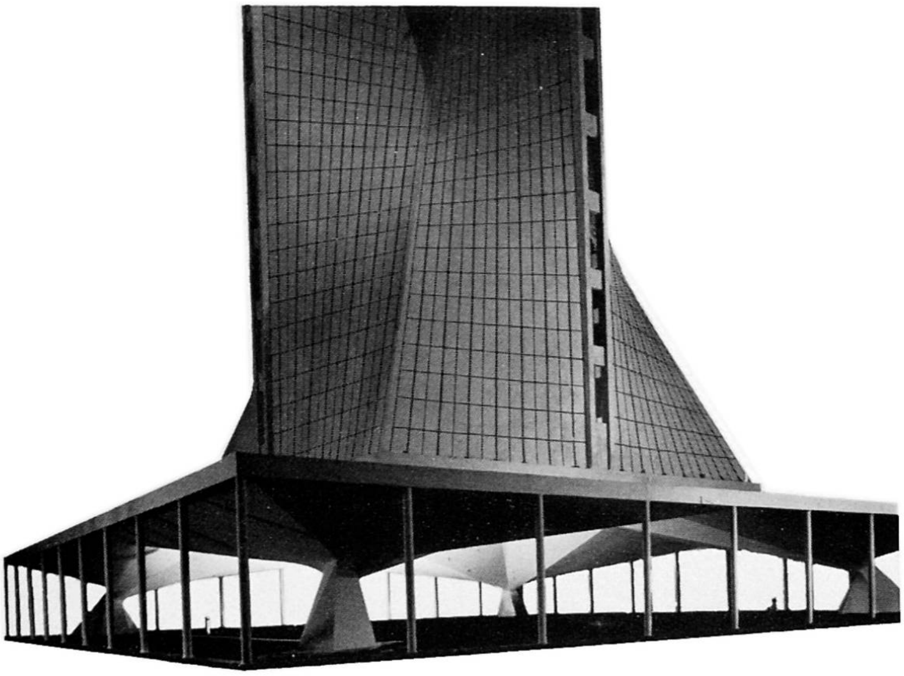


Fig. 2 San Francisco Cathedral, U.S.A.
General view of model. Scale 1:15.

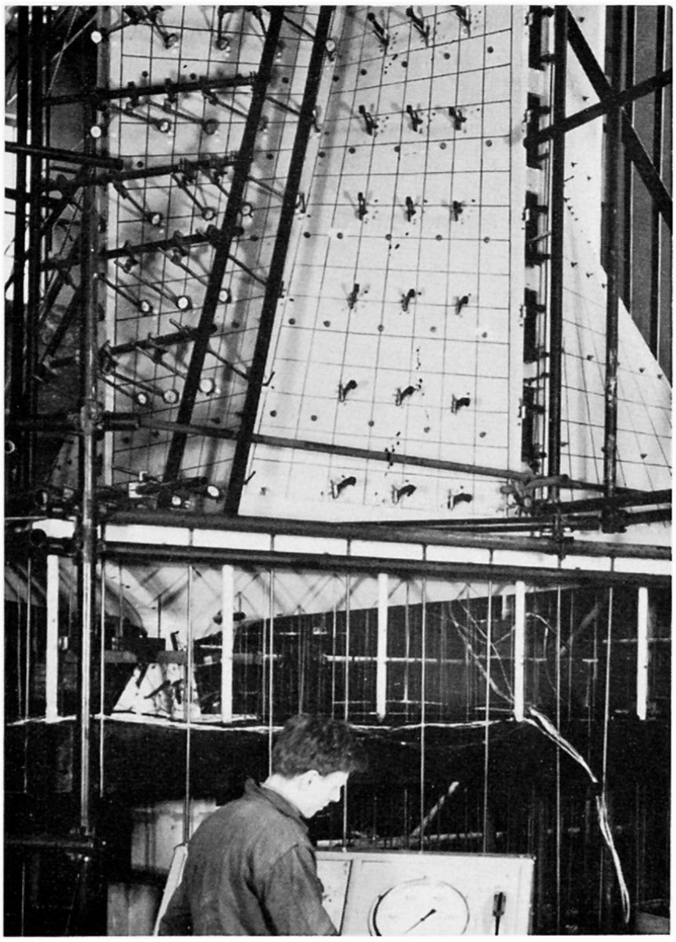
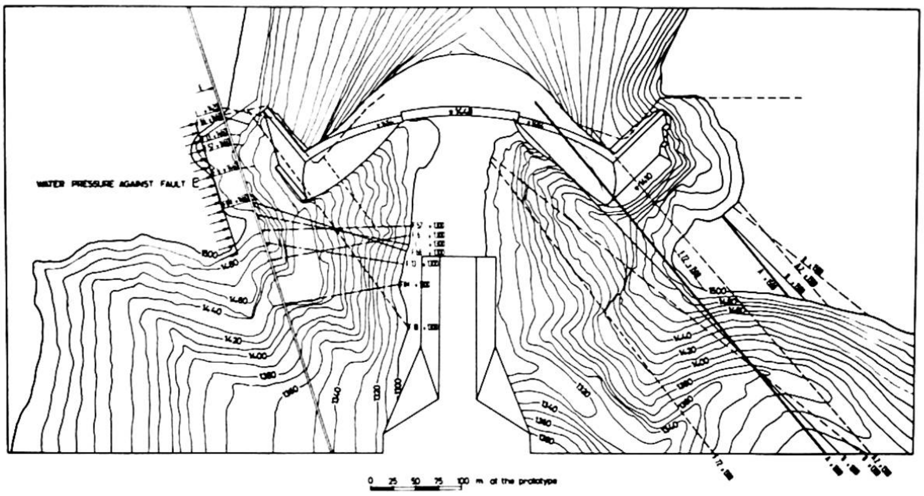


Fig. 3 San Francisco Cathedral.
Structural model under failure tests.



CHARACTERISTIC DATA FOR ACTUAL FAULTS

RIGHT BANK				
FAULT	THICKNESS m	COHESION kg cm^{-2}	FRICTION ANGLE φ	MODULUS OF ELASTICITY
E	2.00	2.00	40°	4000 kg cm^{-2}
F 6	0.40	2.00	25°	1000 ·
F1M	0.40	2.00	25°	1000 ·
F 57	0.40	2.00	25°	1000 ·
F 18	0.25	2.00	25°	1000 ·
I	0.25	2.00	25°	1000 ·
F 13	0.25	2.00	25°	1000 ·
F 65	0.25	2.00	25°	1000 ·

LEFT BANK				
FAULT	THICKNESS m	COHESION kg cm^{-2}	FRICTION ANGLE φ	MODULUS OF ELASTICITY
A	1.00	0.15	8°	1000 kg cm^{-2}
A 2	0.40	0.40	10°	1000 ·
B	0.40	0.40	10°	1000 ·
D	0.40	0.40	10°	1000 ·
F 72	0.40	0.40	10°	1000 ·

Fig.4 Kurobe IV Dam, Japan.
General Layout of geomechanical model.

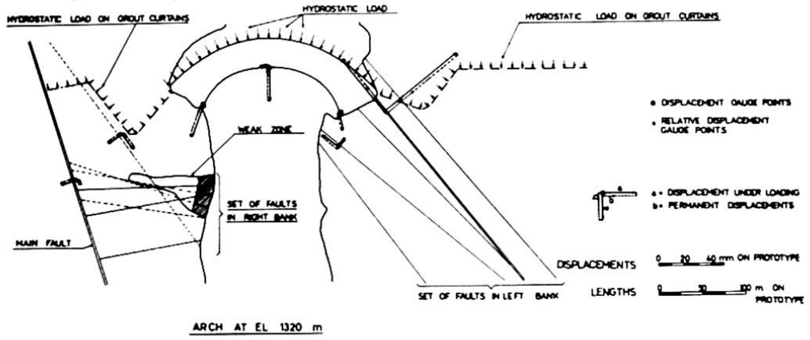


Fig.5 Kurobe IV Dam. Displacements recorded at a horizontal section (el. 1320 m).

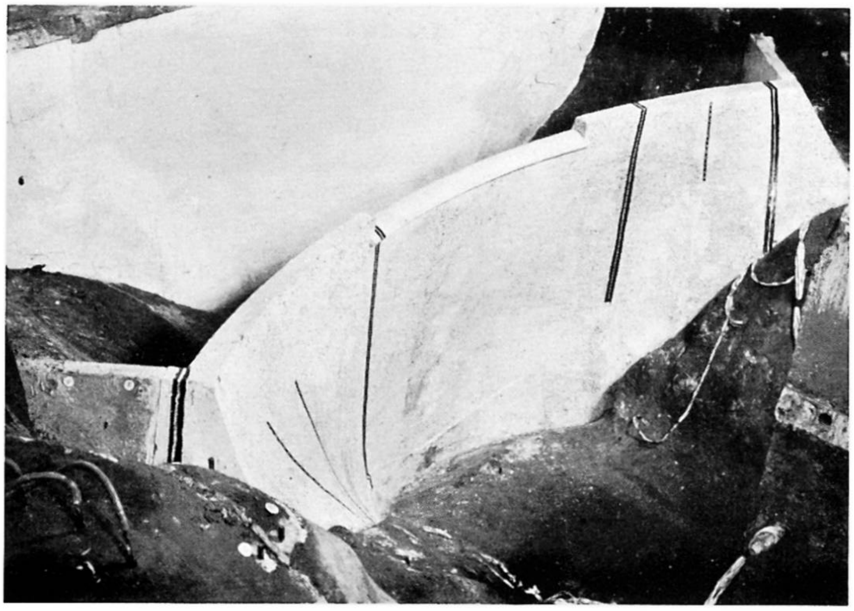


Fig.6 Kurobe IV Dal. Structural model at failure, showing the opening of joints.

4.- Evaluation of the safety degree of an already existing structure.

Models may be of great assistance not only when structures are being designed but also when the stability and safety degree of erected works are being checked. This is particularly true when verifying large structures which have undergone statical conditions unpredicted or unpredictable at the design stage.

Here, too, I shall briefly illustrate some examples in which testing on models has yielded highly significant and conclusive results, with particular regard to the safety degree of the structure.

After a few years of operation, extensive subhorizontal microcracks were found at the upstream face of a large arch-gravity dam completed in 1958. The influence of these cracks on the structural performance and safety of the dam at full reservoir has been investigated on a large structural model in which the number and pattern of the microcracks had faithfully been reproduced (figs. 7, 8).

Interesting tests were also conducted on a 1:4 scale model to verify the compression safety degree of the main columns of the Cathedral in Milan (fig. 9). The two materials (Candoglio and Serizzo marbles), of highly different moduli of elasticity, and the geometry of the individual blocks were identical with those of the prototype (fig. 10). The pattern of the stresses in the masonry dome carrying the main spire of the Cathedral has then been analyzed on a large elastic model (fig. 11).

The effect of the horizontally stratified bedrock anisotropy on the stability of a recently constructed dam was investigated by means of geomechanical models. The various expedients devised to raise the safety degree of the dam-foundation unit were also examined (fig. 12).

Finally, the model tests carried out for the double-curvature arch Vajont Dam should be mentioned. As is known, this dam has brilliantly withstood the extraordinary sliding of Mount Toc into the partly filled reservoir and is now sustaining the enormous asymmetric mass of slide material (fig. 13). After the disaster, model studies were conducted to determine the safety degree of this imposing structure under the present exceptional live load (fig. 14).

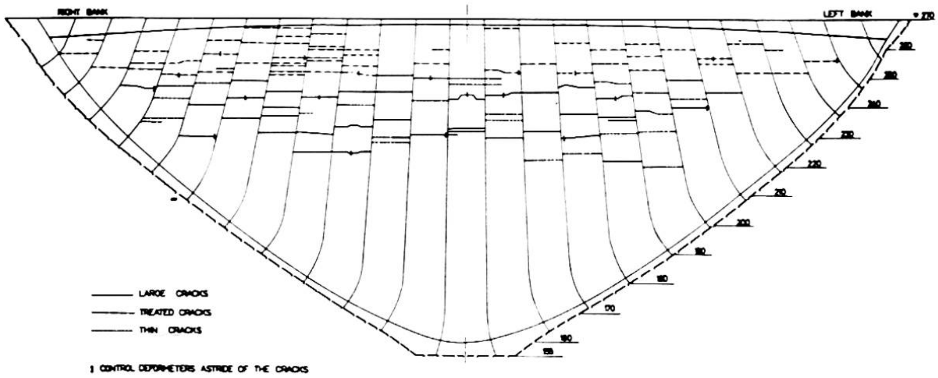


Fig. 7 Flumendosa Dam, Italy. Microcracks on upstream face of model.

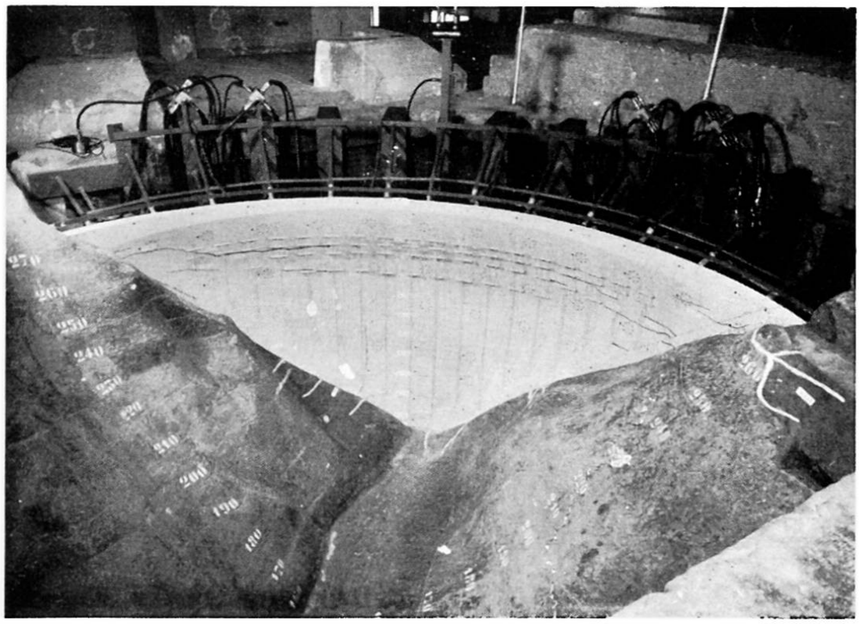


Fig. 8 Flumendosa Dam. Downstream view of model under test.

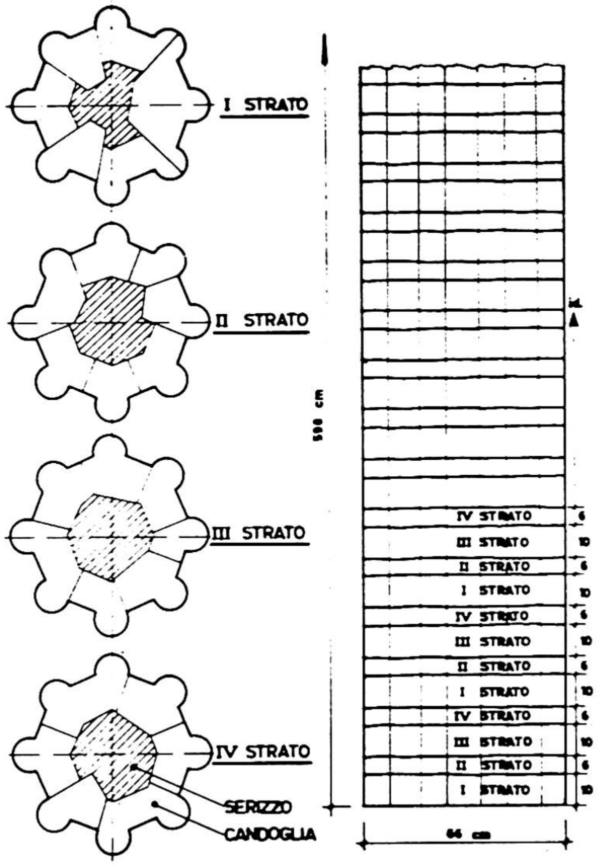


Fig. 10 Milan Cathedral. Cross-sections of columns.

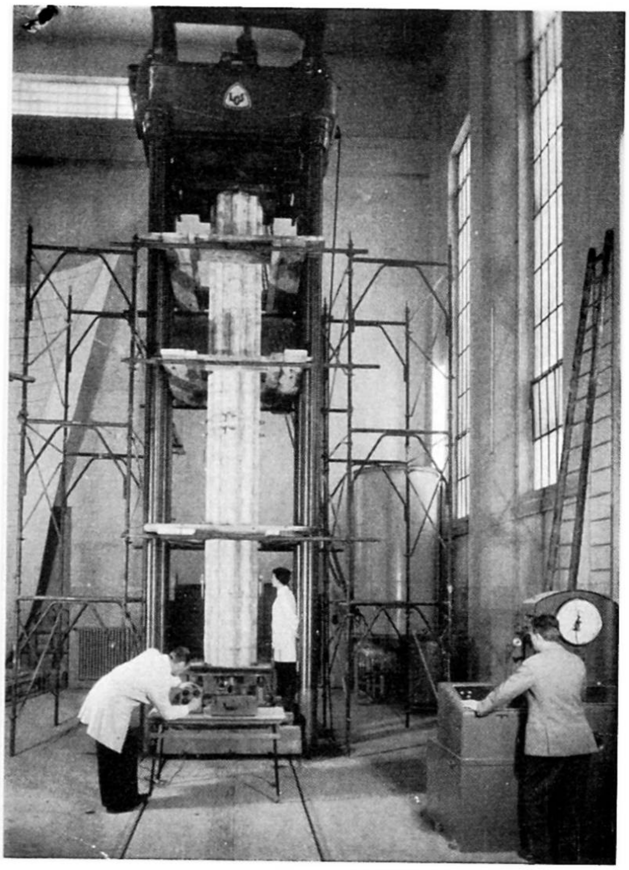


Fig. 9 Milan Cathedral. Model of column under test. Scale 1:4.

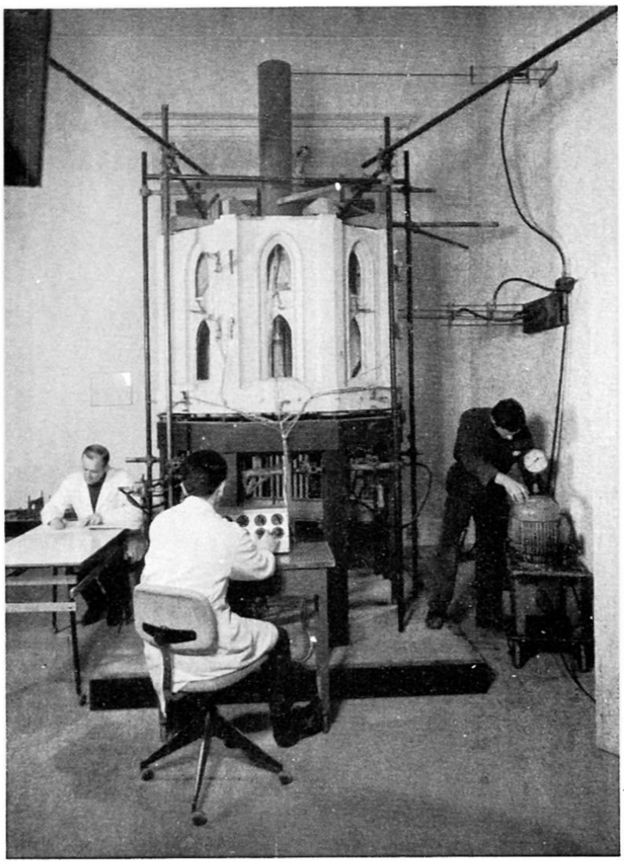


Fig. 11 Milan Cathedral. Elastic model of masonry dome.

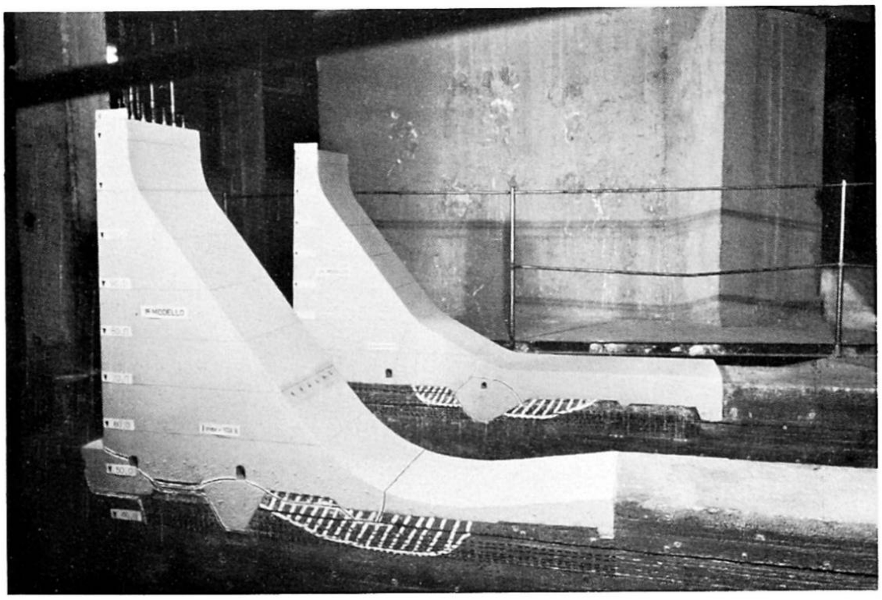


Fig. 12 Mequinenza Dam, Spain. Plane model on geomechanical foundation.

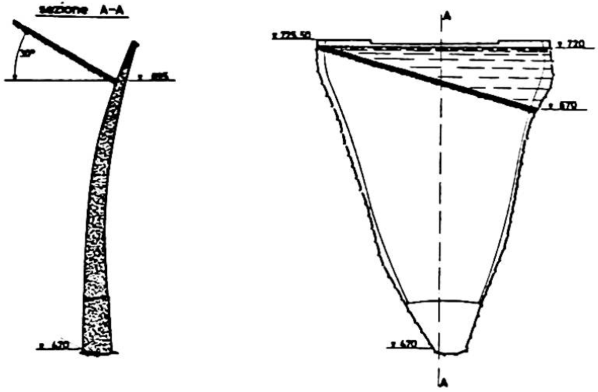


Fig. 13 Vajont Dam. Asymmetric slide material acting on upstream face.

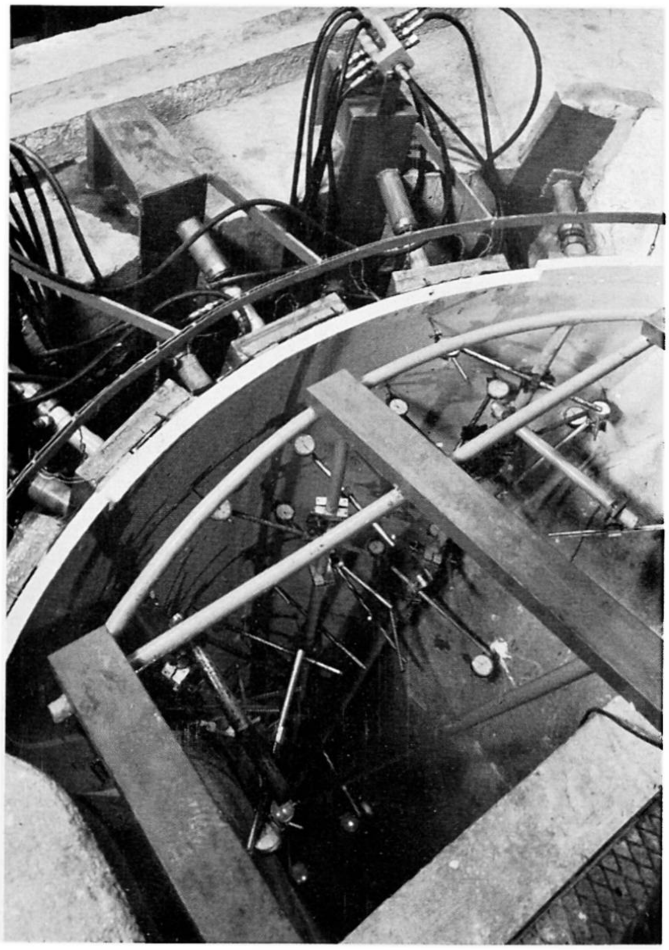


Fig. 14 Vajont Dam. Model under asymmetric load test.

5.- Conclusions.

It is believed that the above brief outline has clearly shown the contribution given, and which can be given, by testing on models when evaluating the safety degree of a structure at its design stage and after construction.

When it is assumed, in accordance with modern trends, that a rational determination of safety involves the adoption of an acceptable risk of failure, a design procedure for uniform safety, and hence optimization, can be based on structural model investigation.

Finally, the arduous problem of structural reliability of statically indeterminate structures, related to the failure mechanisms depending on the consecutive loads mentioned also by prof. Freudenthal at the end of his paper, can satisfactorily be solved through a judicious adoption of the present model test technique.

SUMMARY

After a short introduction the paper outlines the actual possibilities of evaluating the safety degree of a structure by testing elastic, structural and geomechanical models.

The evaluation may concern: 1)structural safety at the design stage; 2) safety degree of an existent structure and of one operating under extraordinary conditions.

The importance of model investigation particularly for the optimization of statically highly indeterminate structures is then emphasized.

RÉSUMÉ

Après quelques mots d'introduction le rapport sousligne les possibilités actuelles données par les differents types de modèles(elastiques,structureaux,géomechaniques)pour l'analyse de la sécurité dea grandes structures.

On considère après:1) l'examen du coefficient de securité dans la phase du projet de l'ouvrage; 2)l'evaluatior du dégré de securité d'un ouvrage dejà achevé ou soumis à des actions exceptionelles.

Le rapport termine en soulignant les possibilités des modèles surtout pour l'étude et l'optimization des structures hautement hyperstatiques.

ZUSAMMENFASSUNG

Nach einer kurzen Einleitung werden die wirklichen Möglichkeiten einer Untersuchung des Sicherheitskoeffizienten eines Bauwerkes an elastischen, strukturellen und geomechanischen Modellen beschrieben.

Der untersuchte Sicherheitskoeffizient kann sich auf den Entwurf, ein bestehendes oder ein unter ausserordentlichen Verhältnissen befindliches Werk beziehen.

Die Wichtigkeit der Modelluntersuchungen für die Optimisierung statisch hochunbestimmter Werke wird nachdem besonders unterstrichen.