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An experimental study of failure of a gravity dam on a jointed rock foundation

C.A.B. Pina, C.P. Costa, J.V. Lemos, J.M.P. Gomes
Dams Department, Laboratório Nacional de Engenharia Civil, P-1799 Lisboa, Portugal

ABSTRACT

A physical model of a concrete gravity dam was used in an experimental study of failure through sliding on a surface defined by two planar discontinuities. The scale model of the dam and foundation was performed in a high density material. The dam was loaded by fluid pressure on the upstream face and upward forces simulating the uplift pressure. A discussion of the experimental results and a comparison with analytical and numerical calculations are presented.

INTRODUCTION

The evaluation of the safety of concrete gravity dams usually requires the consideration of a scenario of collapse through sliding on the foundation surface, or on discontinuities in the rock mass [1]. If shearing takes place on a single planar surface, the global safety factor can be determined by simple statics calculations. If the collapse mechanism involves shearing on multiple surfaces, then numerical modelling has to be used to assess the safety margin. These numerical models must be validated and calibrated in order to be employed in design practice. Monitoring of structures provides information essentially on their behaviour under normal operating conditions. Therefore, experimental models are a very useful tool for the simulation of failure scenarios. Comparisons of physical and numerical models of discontinuous systems performed at LNEC have been reported (e.g. [2]).

Physical models made of high density materials, sometimes referred to as geomechanical models, are particularly useful, since they incorporate the dead weight loads of the structures, thus making it easier to obtain the required similitude conditions. At LNEC, materials and techniques have been developed for the application of these models to dam safety studies [3]. The present paper describes an experimental study involving a physical model of a concrete gravity under the action of water loads. Two planar discontinuities were introduced in the foundation block (Figs. 1 and 2): a horizontal joint at some depth below the dam, and an inclined joint connecting that joint to the ground surface downstream. A vertical tension joint is assumed to exist at the upstream toe of the dam.

The two discontinuities considered in the model are intended to represent existing fractures in the rock mass. These natural joints typically possess no cohesion or tensile strength, but only frictional strength, and are likely to define the preferred collapse mechanisms. The tests reported in this paper are based on a simple model, the main purpose of this work being to assess the feasibility and interest of these studies. In the continuation of the present research project, more complex joint patterns are being considered.

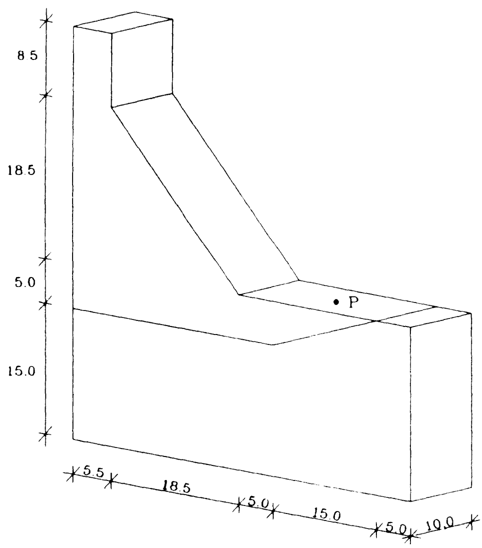

Fig. 1 - Scale model of gravity dam on jointed foundation. Dimensions in cm.

DESCRIPTION OF THE PHYSICAL MODEL

Geometry and construction of the model

The physical model represents, at a scale of 1/100, a section of a 27 m high concrete gravity dam. Fig. 1 indicates the dimensions (in cm) of the model, which has a thickness of 10 cm. Two sets of discontinuities were present in the rock mass: one set approximately horizontal, and another dipping upstream,

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at a low angle. In the scale model, only one joint from each set was selected, in order to define a simple collapse mechanism. The horizontal joint was placed at a depth of 5 m, extending for 29 m measured from the upstream face. The inclined joint, at an angle of 18.5°, extends from the end of the horizontal joint up to the ground surface. A vertical tension joint is assumed to exist at the upstream toe of the dam; the rock foundation upstream of this joint was not represented.

The model is shown in Fig. 2. It was cast in two separate blocks, separated by the two joints. The blocks were then assembled, and the bottom block was included in a concrete tank.

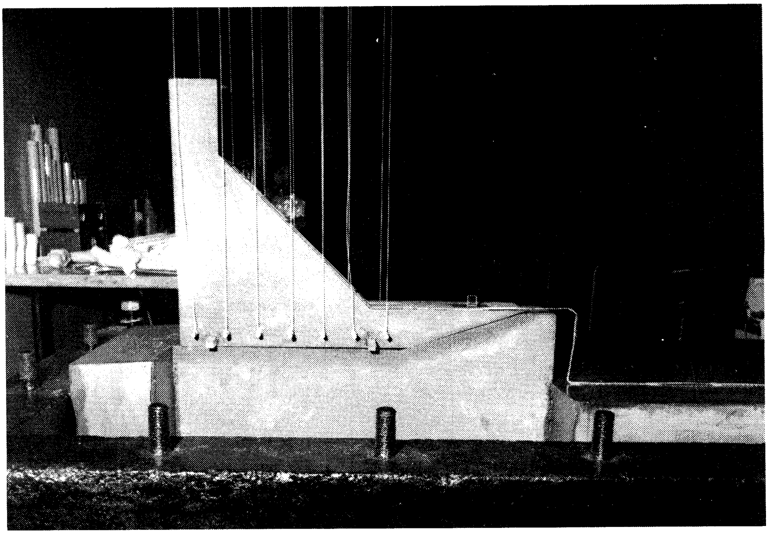

Fig. 2 - View of model (after test).

Mechanical properties of the model material

The high density material, used for the dam and the rock mass, is composed of the following materials, in the weight proportion indicated:

Ilmenite sand	5.880 N
Red lead powder	2.940 N
Water	1.225 N
Plaster	0.735 N

Six prisms of the model material, with dimensions 6x6x18 cm, were cast in the same conditions as the two model blocks, in order to determine the mechanical properties. The average unit weight was 31.80 kN/m^3, with a standard deviation of 0.163 kN/m^3. Previous tests have shown that this type of material has an Young's modulus of about 1.6 GPa, and uniaxial compressive strength of 3 MPa [4].

In order to determine the friction angle of the joints, sliding tests were performed with pairs of prisms: the bottom prism was fixed, and the top prism was pulled until sliding occurred. The normal stress on the joints was thus due only to the weight of the top prism. Four tests were executed for each of 4 pairs of prisms. The mean friction angle of the 16 tests was 34.1°,and the standard deviation was 3.1°. As these results show a significant dispersion of frictional resistance, it was decided to perform sliding tests using the actual model. The top block was pulled upstream, and the horizontal forced which produced sliding was measured. Assuming an average normal stress given by the top block weight divided by the area of the horizontal joint, friction angles of 31.3° and 32.6° were obtained in 2 tests.

Similitude conditions

Since only frictional strength on the joints is of importance for the present collapse mechanism, and no failure of the intact material was to be simulated, the selected model material stiffness and strength are higher than the similitude conditions would require, which facilitates the handling of the model.

The forces to be represented in the test are the dead weight and water load. In order to obtain the correct force relations, given the model material density of 31.8 kN/m^3, and a concrete density of 24.0 kN/m^3, the fluid acting on the upstream face must have a density of 13.25 kN/m^3.

Loading system

The hydrostatic pressure on the upstream face was applied by means of a solution of zinc chloride, with the above given density. This fluid was contained in a rubber bag, which was in perfect contact with the model face, and was supported by a box rigidly connect to the concrete tank (Fig. 3).

The uplift pressure along the horizontal joint was simulated by concentrated forces applied to the upper block. For this purpose, seven copper rods, crossing the block thickness, were located above the horizontal joint. Each rod was loaded by means of two wires, one on each side of the model, connected to a pulley system attached to a metal structure located above the model (Fig. 3). It was assumed that the uplift pressure followed a triangular diagram, varying linearly from the maximum value at the upstream face of the model, to zero at the end of horizontal joint. The weights applied to the wires were calculated accordingly. No uplift pressure was applied on the inclined joint.

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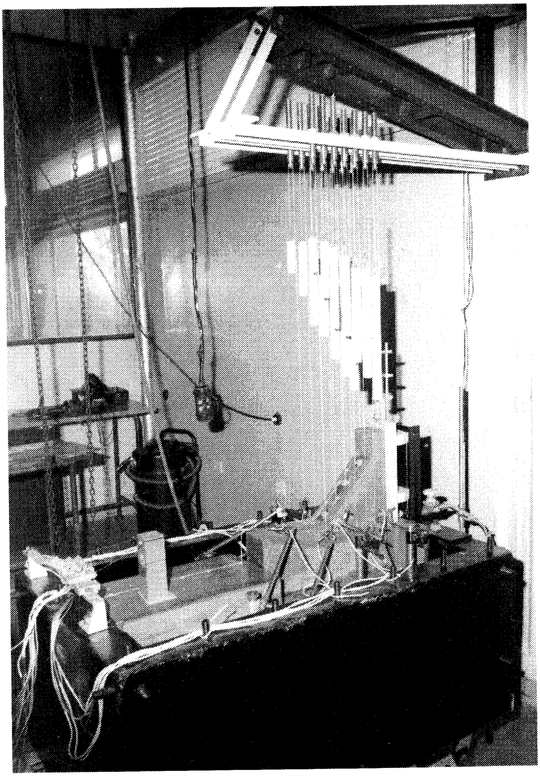

Fig. 3 - View of scale model and systems to apply fluid pressure and uplift forces.

TESTING SEQUENCE AND MEASUREMENTS

The failure was induced by progressively raising the fluid level upstream, above the dam crest. This can be view as the possible action of a wave overtopping the dam. Two types of tests were performed, depending on the uplift conditions assumed:
(i) Test 1 : No uplift pressure.
(ii) Test 2 : Constant uplift pressure, corresponding to the water level at the dam crest. This condition simulates a rapid overtopping of the dam, which does not allow the penetration of the water pressure along the horizontal joint.

Horizontal and vertical displacements of 5 points were monitored during the tests. The measurements were performed with induction deflectometers Peekel type B60. Fig. 4 shows the evolution of the horizontal displacement of the top block with the water level for the 2 tests. The plot of vertical displacement of a point of the top block at the ground surface downstream is displayed in Fig. 5.

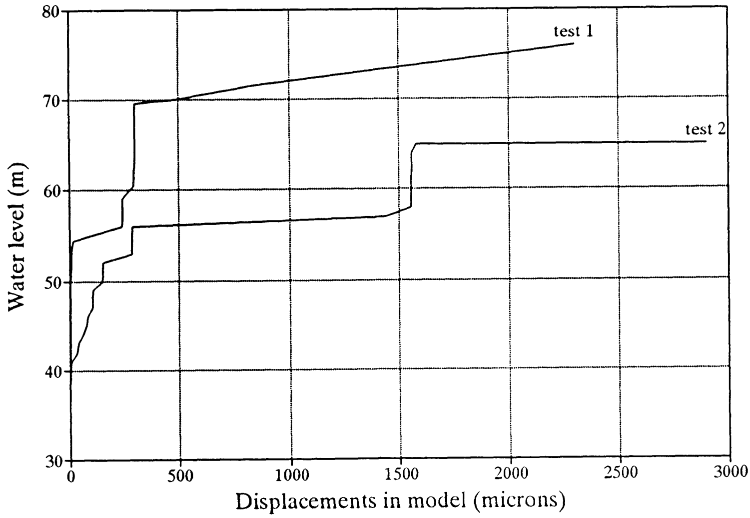

Fig. 4 - Evolution of horizontal displacement of top block with water level.

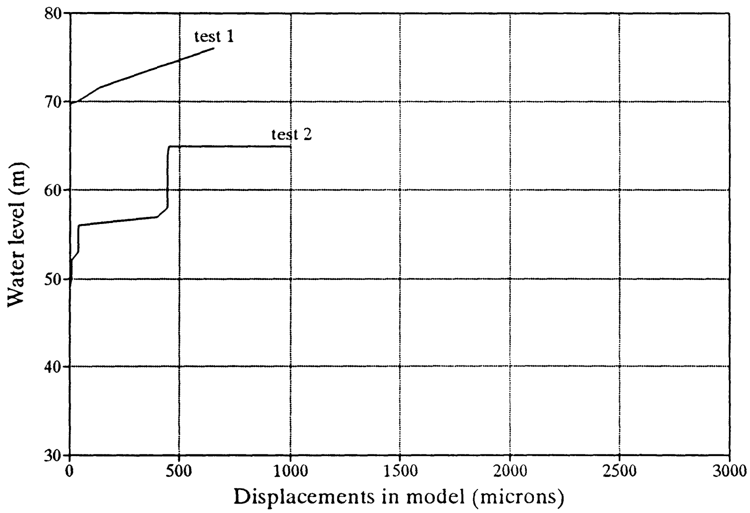

Fig. 5 - Evolution of vertical displacement of point P (in Fig. 1) with water level.

DISCUSSION OF RESULTS

The most likely failure mode of the system involves sliding on the two discontinuities. As the top block starts riding up the inclined joint, there will be only two small areas of contact between the two blocks, around points A and B, shown in Fig. 6. It can then be assumed that, as sliding occurs, the reaction forces at these two points are inclined at an angle ϕ to the normal of each surface, ϕ being the friction angle. Then, simple statics calculations can be used to decompose the resultant of the forces applied by the top block on the bottom block along these two lines of action, and the angle ϕ can be determined, from the following equation:

$$(\tan\phi)^2[-R_{Av}\tan\beta]+(\tan\phi)[R_{Av}+R_{Bv}+F_h\tan\beta]+[-F_h+R_{Bv}\tan\beta]=0$$

where F_h is the horizontal component of the resultant of the forces exerted by the top block on the bottom block, R_{Bv} and R_{Av} are the vertical components of the reactions at A and B respectivelly, and ß is the angle of the inclined joint with the horizontal.

A second failure mode is possible if the line of action of resultant force intersects the inclined joint. Then, sliding would take place along this joint only, and no contact would exist on the horizontal joint. Table 1 shows the results obtained by these calculations. For each test, the table gives the water level required to cause failure for 3 values of the friction angle.

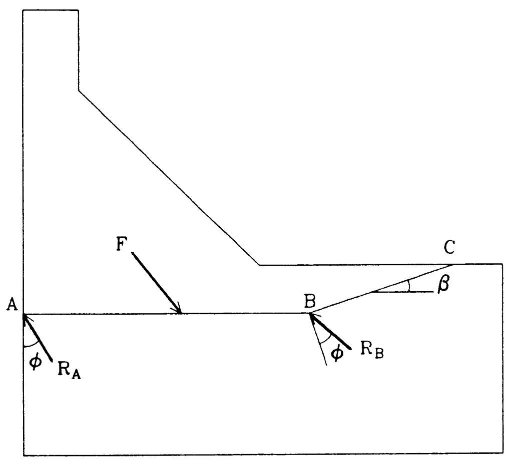

Fig. 6 - Diagram of forces assumed in analytical calculations.

Numerical simulations were also performed with the discrete element code UDEC [5]. The 2 blocks were assumed to be deformable, with an elastic behaviour. The joints were assumed to follow a Coulomb friction law, and were discretized into 14 contact points. The results of these computations were in agreement with the table obtained by the simplified analytical calculations, namely the predicted failure modes.

Table 1 - Analytical estimate of water level at failure for 3 values of friction angle

Test	Friction angle (°)	Water level (m)
1	30.0	56.7
	31.0	58.9
	32.0	61.2
2	30.0	40.9
	31.0	42.2
	32.0	43.6

The curve concerning test 1 in Fig. 4 shows a first episode of slip at a water level of 56 m, which in the analytical calculations would imply a friction angle of 30°. For test 2, the initial sliding is not well defined, and a kind of stick-slip behaviour can be noticed starting at a water level of about 40 m. This also agrees with the analytical table, for the same angle of 30°. This indicates that the effective friction angle in these experiments may be lower than the value of 32° that had been obtained in the initial test where the top block was pulled horizontally upstream, a situation in which full contact along the horizontal joint was achieved. It can also be conjectured that wear on the joints surfaces caused by the successive tests reduced the friction angle.

CONCLUSIONS

The experiment reported was mainly intended to assess the feasibility of performing physical models in high density materials to represent discontinuous systems, such as jointed rock foundations. The results obtained show that it is possible to execute such tests, and that they can be of practical value as a means to validate and calibrate numerical techniques. The model used in the present work allowed only a simple failure mechanism of sliding on two discontinuities. Experiments with more complex systems are currently under

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way at LNEC. In these models, more joints are included, forming a system of blocks in the foundation (Fig. 7).

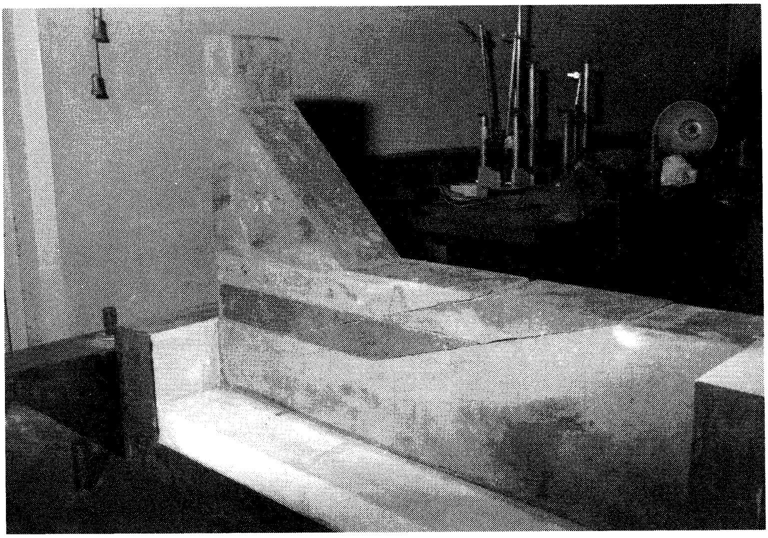

Fig. 7 - Model of gravity dam with multiple discontinuities in the foundation.

REFERENCES

1. Rocha, M. 'Analysis and design of the foundations of concrete dams' Proc. International Symposium on Rock Mechanics Applied to Dam Foundations, Rio de Janeiro, 1978.
2. Lemos, J.V. 'A comparison of numerical and physical models of a blocky medium' Proc. Int. Conf. on Mechanics of Jointed and Faulted Rock, Vienna, pp. 509-514, 1990.
3. Azevedo, M.C., Ferreira, M.J.E. and Costa, C.P. 'The use of geomechanical physical models at LNEC' Proc. Conferência Ibero-Americana sobre Aproveitamentos Hidráulicos, 1987.
4. Silveira, A.F., Azevedo, M.C., Ferreira, M.J.E. and Costa, C.P. 'High density and low strength materials for geomechanical models' Proc. International Colloquium on Physical Geomechanical Models, Bergamo, 1979.
5. UDEC - Universal Distinct Element Code, User's Manual (Version 1.7), Itasca Consulting Group, Minneapolis, 1991.