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# Monitoring of the Canales Dam and Its Control During Construction Period

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SYNOPSIS: This paper presents a study of the stress-deformation behaviour of the Canales Dam (Granada) during construction. The basis for this study has been the three dimensional (3D) finite elements mehod with hyperbolic material response. The analytical procedure used is presented and the study concludes with a comparative study of the results obtained from the calculation programme used and monitoring system's measurements.

## INTRODUCTION

The Canales Dam (Granada, Spain), the subject of this analysis, is an heterogeneous cross-section Dam which has limestone and slate rock fill shoulders, with a central core of clay. The transition materials are kakerite, a calcareous fragmented rock. The dam is a 155.5 metres high and the external slope is 1.7:1.

One of the main reasons for making a three dimensional model is the Dam's location in a shell offering longitudinal support on irregularly shaped di-ssymmetric and transversal slopes, Fig. 1.

Analysis was carried out in two stages, coinciding with the projet' two technical phases: First technical phase (up to elevation 910) and second technical phase up to termination of the construction (elevation 965.5), Fig. 2.

The stress-deformation study was performed using two different but complimentary methods. In the first case, a mathematical model was used by means of a three-dimensional finite elements programme simulating the process of construction of the Dam throughout successive phases of increasing loads per layer and, in the second case, the measurements taken by means of dam monitoring system equipment were analyzed. Prior adjustment of the model parameters was carried out in order to later establish a forecast of the behaviour of the Dam.

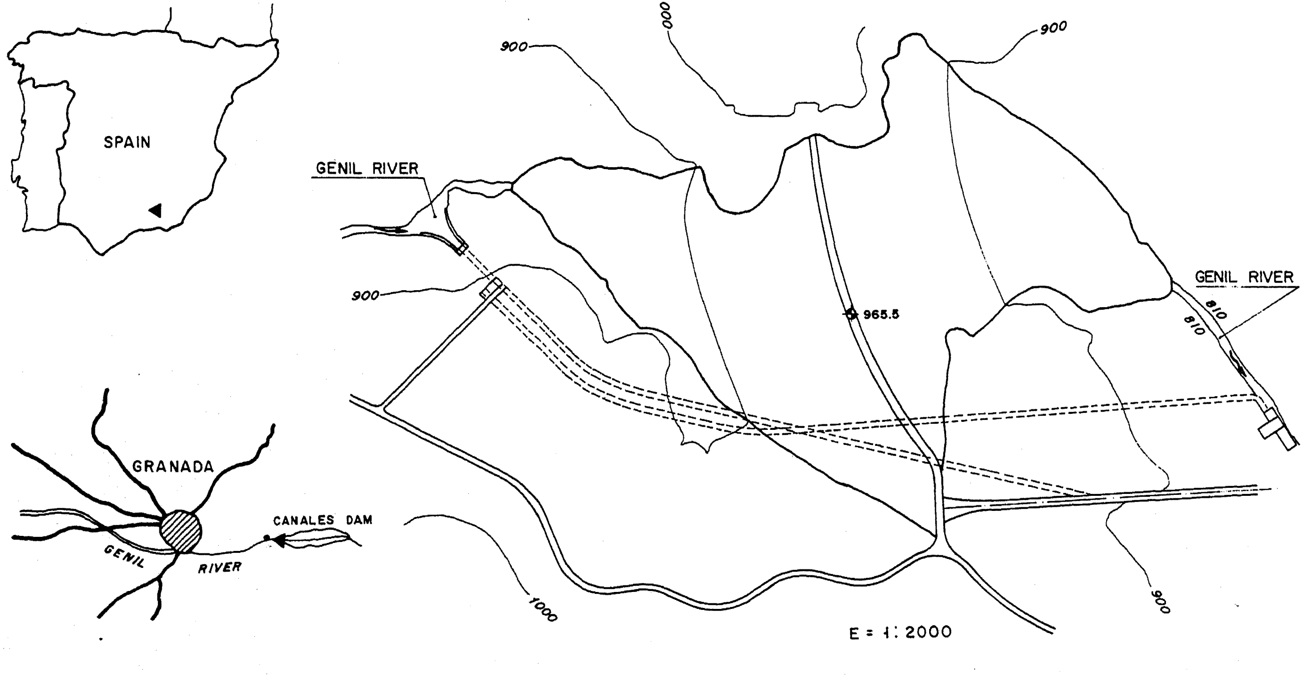


FIG.1 LOCATION MAP. PLANT OF THE DAM

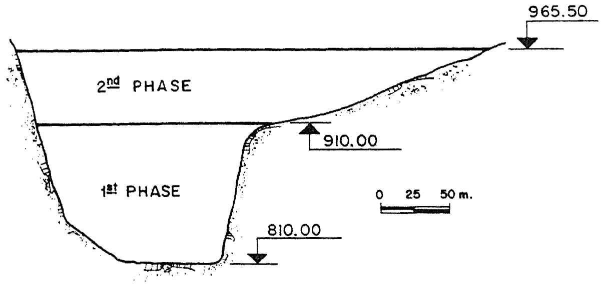


FIG. 2 LONGITUDINAL PROFILE ALONG THE DAM AXIS

## ANALYTICAL METHODOLOGY

The analytical methodology applied, is reflected in the folowing diagram, Fig. 3.

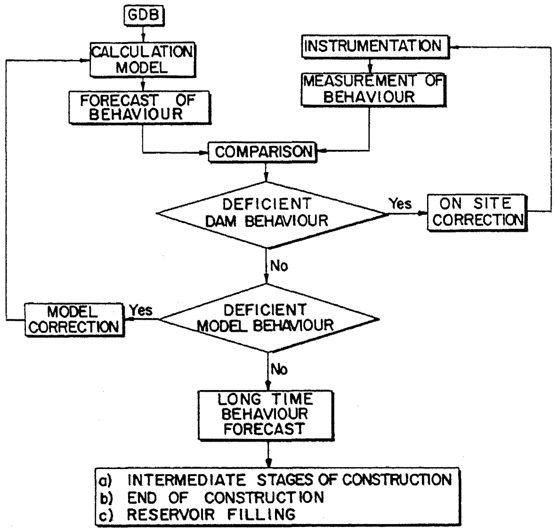


FIG. 3 METHODOLOGY

### Operation Method

The procedure has two independent inputs with a comparative phase:

1. The geotechnical data base (GDB) is used in order to obtain the calculation parameters for the mathematical model. In this respect, sampling campaigns are carried out in order to obtain the reference samples associated with each different material zone. The different tests necessary are performed under site conditions.

2. The monitoring process provides data serving as direct input to the comparison phase.

3. At the end of each of the stages foreseen in the control plan, an evaluation of the behaviour of the Dam up to that moment is performed, and the results obtained from the instrumentation are contrasted with those produced by the calculation method.

### Calculation Model

a. Computer programme. For calculation of the stresses and movements within the body of the Dam, a mathematical model has been used via a computer programme called Fespon, which was developed at the University of Purdue by Rong-Her Chen (1981) and refined in a PRIME 2655 computer. This programme is based on application of the finite elements method to three dimensional calculation and has been designed fundamentally for use in studies of the stress-deformation behaviour of earth dams.

The programme allows the construction process of the Dam to be reproduced and simulates the incorporation of new layers of material by considering the successive layers of elements. Placing a new layer is simulated on the basis of the weight on those already existing.

When the final state of the dam calculation is finished, the effect of other external agents can be introduced, for example the effect of the water during the process of reservoir filling.

The deformability modules used by the programme are variable with the level of material deformation and confinement pressure. Specifically, the stress-deformation model proposed by Kodner and Zelasco (1963) and Duncan (1970) and better known as the "hyperbolic model" is used, Fig. 4.

Each increment in load is analyzed twice. At first, using the modules obtained from the stresses existing at the beginning of the increment and then using the deformation modules obtained from the average stress values due to the initial increment analysis.

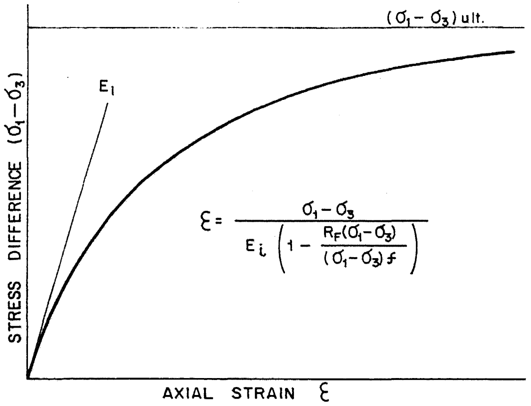


FIG. 4 HYPERBOLIC MODEL

The changes occurring in stresses, deformation and movements with each increment are added to those already existing at the beginning of each new construction stage.

The Fespon programme uses incompatible isoparametric elements in calculation, i.e. elements using interpolation functions for relationships between displacements occurring within the elements and displacements of its nodes. This gives rise to excellent flexure behaviour on the part of the element, but also produces parabolic-type incompatibilities at its limits. However, overall behaviour is better than that achieved using compatible isoparametric elements.

b. Finite element mesh. In order to carry out the study using the Fespon programme, the Dam was simulated by means of a three dimensional mesh made up of six and eight-node isoparametric elements placed such that the construction process could be reproduced by means of load increments. Simulation of the process was achieved by the placing of ten layers, recommended by Rong-Her Chen (1981), Schiffman (1977) and Marsall (1975), in order to obtain sufficient accuracy. The minimum thickness of these layers was ten metres and the maximum, 25 metres.

The remaining element magnitudes were adapted to the finite elements theory, which recommends the use of elements whose respective magnitudes are not excessively differentiated in order to achieve reliable results. In this respect, a valid ratio value should be between 1.5 and 2, transversal distribution with the Dam transversally distributed in 13 sections.

The number of elements into which the Dam was simulated was 556, with a total of 842 nodes, Fig. 5.

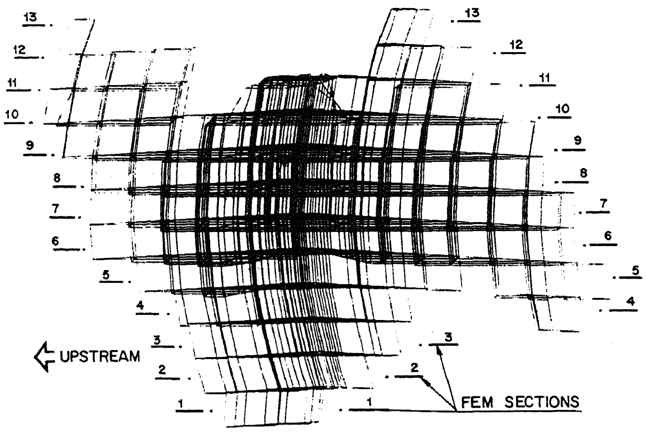
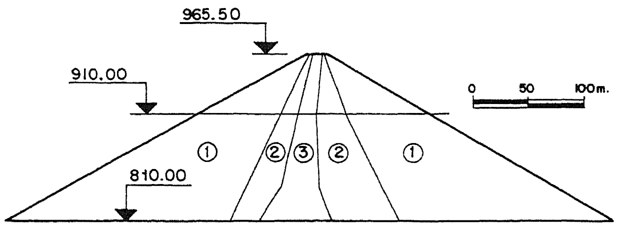


FIG. 5 DIAGRAM OF FINITE ELEMENTS MESH (FEM)

c. Materials characterization (Fig. 6). In order to determine the resistence and deformation parameters needed for calculation, the following process was used:

Study of materials characteristics based on laboratory and field tests, fundamentally tri-axial and shear tests respectively, during the first and second construction phases -estimation of basic calculation parameters- sensibility analysis of the values within the variation range, by means of the finite elements programme and comparison with the real measurements obtained from the instrumentation.

Monitoring System



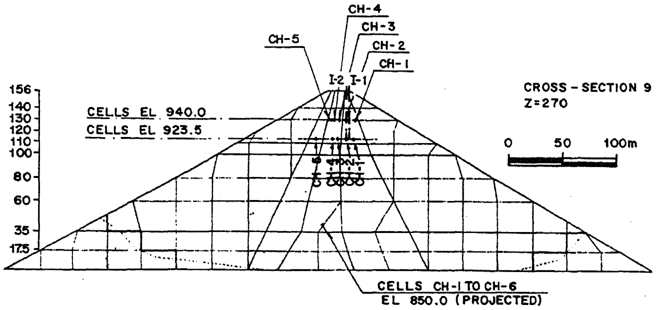
| MATERIALS | HYPERBOLIC MODEL PARAMETERS | | | | |
|---|---|---|---|---|---|
| | K | n | $R_f$ | C Kg/cm² | φ(°) |
| ① ROCK FILL SHOULDERS | 500 | 0.50 | 0.8 | 0.2 | 38 |
| ② KAKERITE TRANSITION ZONE | 400 | 0.55 | 0.8 | 0.2 | 36 |
| ③ CLAY CORE | 150 | 0.60 | 0.83 | 0.2 | 23 |

FIG.6 TYPICAL DAM CROSS-SECTION

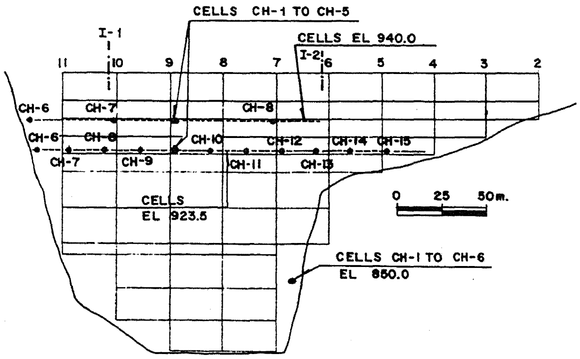
In this study, the values obtained from the hydraulic settlement cells and horizontal displacement measuring inclinometers have been taken into account, Fig. 7.

The cells are located on three levels at elevations 850.0, 923.5 and 940.0

Inclinometers I1 and I2 are located in the vicinity of the left and right hand banks respectively.



a) TRANSVERSAL CROSS-SECTION



b) LONGITUDINAL SECTION

FIG. 7 LOCATION OF SETTLEMENT CELLS AND INCLINOMETERS

## RESULTS ANALYSIS

### General

Before analyzing the stress-deformation state results for the Dam, the following observations on the calculations carried out should be taken into account:

- The methodology used during discretization of the dam's body, involve some problems of accuracy, due to:

1. Sudden changes in geometry and typology of the elements, conditioned by the relative location of the materials, contact with the bed rock and outer slopes.

2. Contact in steps on the right hand bank and vertical contact on the left.

3. Size of the elements, especially in the bottom of the Dam.

- The Fespon program, after each incremental layer made nule displacements in the top nodes, wich simulate the fact that the end of construction has really happened at crown level.

- The non-deformability of the foundation in order to simplify the element mesh, leads to small errors given the high degree of relationship between the deformation modules of the rock and the materials used in the Dam.

- It should be pointed out that when comparing the readings from the instruments with the model, we have taken into account the fact that the measurements obtained from the cells corresponding to a given height of dam above the cell, including an initial and immediate settlement which occurs when the overload is increased, and a second long-time consolidation settlement process due to readjustment of the material particles, which is a function of the friction of the solid framework and the viscosity of the water surrounding the surfaces in contact. The rate of this last deformation reduces with time and finally reaches zero on termination of the phenomenon, when a certain solidification of the material occurs.

The model calculates final deformations while the readings taken during construction do not reflect the total deferred consolidation. This means that in comparing the model and data from instruments, the deformations corresponding to settlement time curve asyntotic values must be considered. Given the shape of these curves, this has not meant increments above 10% with respect to previous readings recorded for a given elevation.

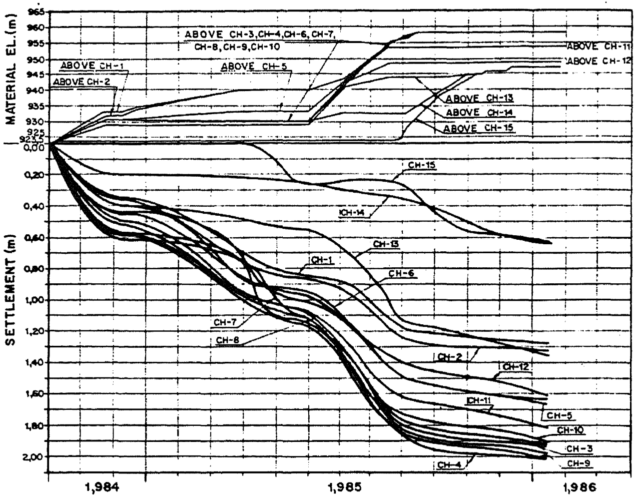
- A run was also performed without including the right hand part of the Dam above elevation 920, whose construction did not begin until the height of the central part of the Dam was at elevation 955. The results obtained have been very similar to those corresponding to the overall Dam, with maximun deviations of 10% or less with respect both to displacements and stresses.

### Model Monitoring System Contrast. End of Construction

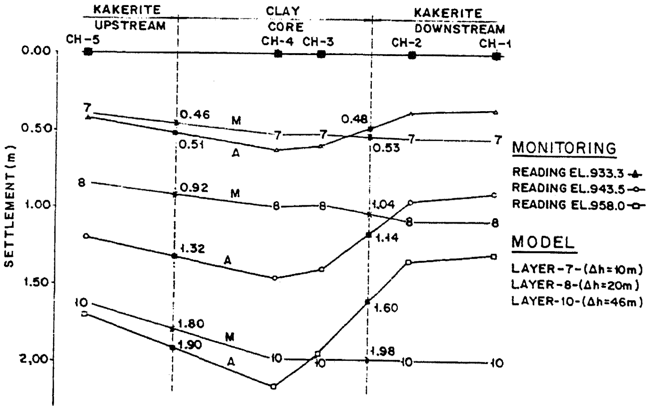
a. Hidraulic cells.

Comparison between monitoring system and model adjustment were performed during the period between installation of the cells at elevation 923.5 (2nd October, 1984) and practically the end of the construction period with the Dam at elevation 958.0 on the 17th January, 1986.

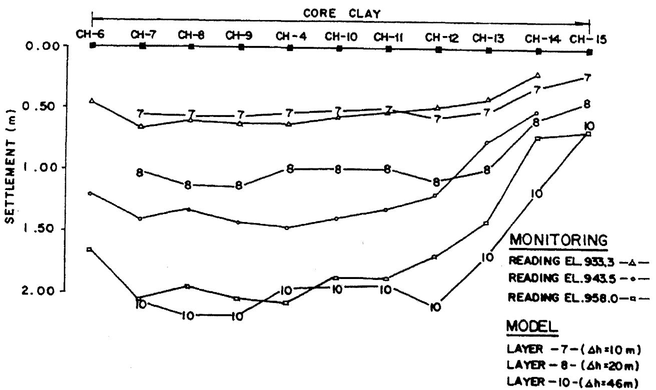
- Elevation 923.5, Fig. 8. Contrasts were carried



a) READINGS FROM CELLS EL. 923.5



b ) CONTRAST IN TRANSVERSAL CROSS-SECTION



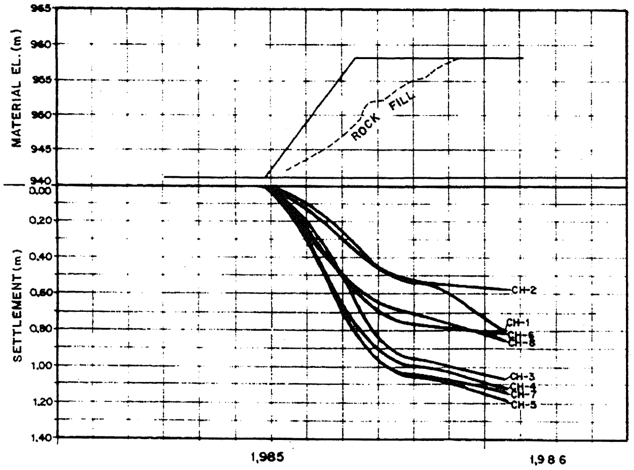
c/ CONTRAST IN LONGITUDINAL-SECTION

Fig. 8 CELLS EL. 923.5 MODEL-MONITORING SISTEM CONTRAST out in two directions perpendicular and parallel to the axis of the Dam by means of cells CH1 to CH5 and CH6 to CH15.

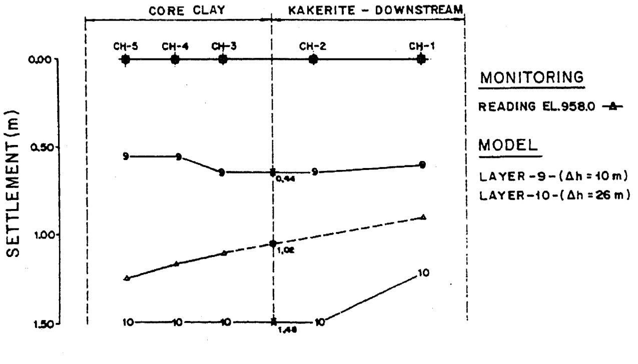
In the transversal cross-section, where the significant comparison values are those corresponding to the Dam core-kakerite contact points, the most significant points of contrast are the following:

1. For an overload of 10m, contrast is good with deviations below 10%.

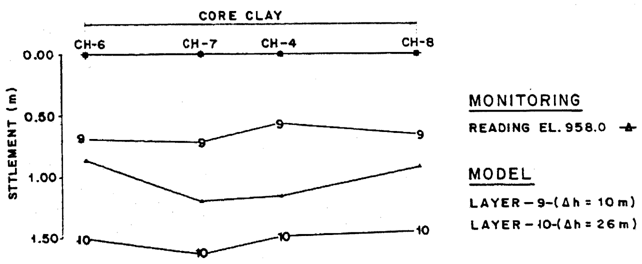
2. For an overload of 20m, the above values are maintained downstream, while upstream the deviation reaches 30%.



a) READINGS FROM CELLS EL. 940.0



b) CONTRAST IN TRANSVERSAL CROSS-SECTION



c) CONTRAST IN LONGITUDINAL-SECTION CORE CLAY

Fig. 9. CELLS EL.940.0 MODEL-MONITORING SYSTEM CONTRAST

3. With regard to the final phase of reading, with a difference in overload ratio of 0.75, the direction of contrast established in point b. is inverted, giving a total maximum deviation of 24% which, following application of the above ratio, is reduced to 20%.

With respect to the longitudinal section the contrast is analogous to that established above, with a maximun deviation of 30% corresponding to an overload of 20m.

- Elevation 940, Fig. 9. Contrast was performed with the Dam at elevation 958, 18m above the cells.

On the basis of the results, it is estimated that on termination of construction of the Dam, the deviations with respect to the model will be below 20%.

b. Inclinometers

The readings recorded have given displacements for upstream and left hand-limit orientations on the order of 15 centimetres in both directions. The results obtained from the models, give values of around 10 cm upstream and practically nil in the perpendicular direction.

Deformations

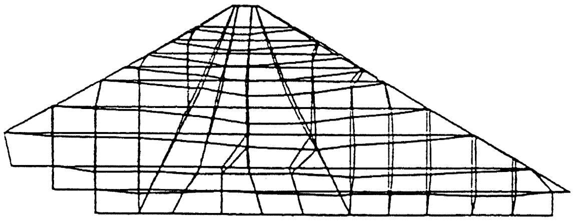
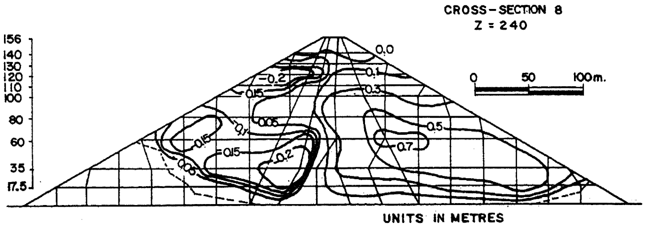
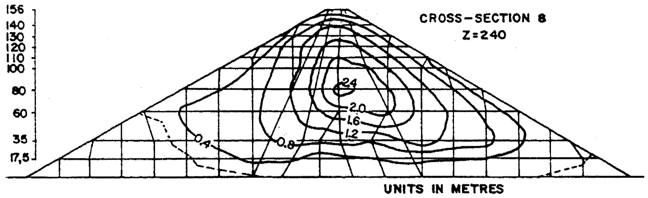


Fig. 10 DEFORMED TYPE TRANSVERSAL CROSS-SECTION



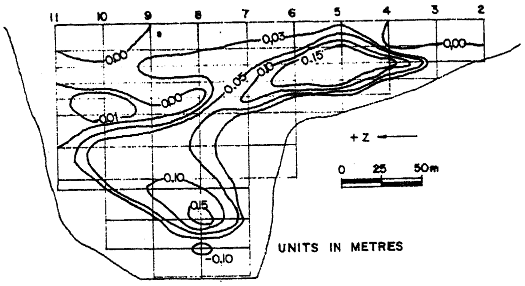
a) ISO-LINES FOR HORIZONTAL MOVEMENTS X



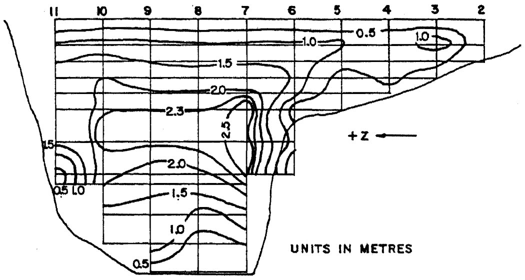
b) SETTLEMENT ISO-LINES

Fig. 11 TRANSVERSAL CROSS-SECTION. MOVEMENTS

In order to obtain an overall idea of the behaviour of the Dam at the end of construction time, a deformation diagram of the central section of the Dam has been drawn, Fig. 10. along with the vertical and horizontal iso-displacements lines and a longitudinal cross-section along the axis of the core, Figs. 11 and 12.



a) ISO-LINES FOR HORIZONTAL MOVEMENTS z



b) SETTLEMENT ISO-LINES

Fig. 12 LONGITUDINAL CROSS-SECTION. MOVEMENTS

## Stresses

In general terms, stresses tend to show a parallel orientation with respect to the slopes and material change surfaces.

The range of maximun stress has varied between 20 and 30 kg/cm$^2$ with the exception of certain elements at the contact points between the core and kakerite and Dam foundation in the higher sections and in others having singular geometries.

There are almost no elements in tension and only a small group of triangular elements and other elements located at the upstream point of contact between the rock fill and the kakerite have been plasticised, possibly due to excessive stresses arising as a result of the high degree of deformability of the clays in this area.

## CONCLUSIONS

The analysis carried out shows general deviations between the model and data measured of between 10 and 20% over absolute values of between 1 and 2 metres.

The maximum settlement is 2.45 metres, wich implies 1.6% of the total height of the Dam.

Horizontal movements maintain the tendency of the Dam to open under its ovn weight, with values of 20 and 60 centimetres upstream and downstream respectively.

The normal range of maximum stresses is between 20 and 30 kp/cm$^2$ except in the case of certain elements in contact with the foundation and located below the maximum Dam heights.

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