LONG- TERM AND CYCLIC PLATE LOADING TESTS IN WEAK ROCKS

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1 INTRODUCTION

The rheological behaviour under long-term loading or cyclic loadings is quite important in the problems relating to concrete dam foundations, especially in weak rock masses. In situ measurements to evaluate the rheologic characteristics present considerable problems. Testing technique, set up by ISMES, and shown in Fig.1, is characterized by the following features:

- extensive loading areas ($\phi = 1$ m), to affect a large rock volume also in depth.
- Load application by, means of flat jacks, to obtain a uniform pressure distribution.
- Displacement recording at various depths, along the loading axis, by means of borehole extensometers, so as to detect possible dishomogeneities in the rock, and especially a loosened superficial layer.
- Oleopneumatic system to keep a constant load for a long time.
- Automatic data recording system.

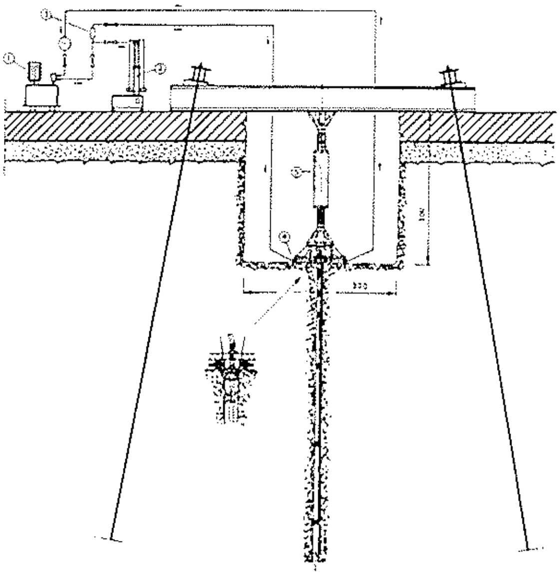

FIG. 1 - Scheme of long-term plate loading test.

2. EXPERIMENTAL RESULTS

This testing technique was applied to the study of a rock mass consisting of very jointed hard argillite (Fig.2) having characteristics somewhat varia-

FIG. 2 - The characteristics of the tested argillite: the presence of many plane joints is apparent.

ble from one side to another. The tests were carried out inside vertical shaft at increasing load levels up to a max of 1,5 MPa. Many loading cycles were performed at each load level; at each side, the test lasted about two months.

A typical load-settlement diagram, recorded at the centre of the loading plate is shown in fig.3. It is evident the downward concavity of the curve, the importance of the delayed deformation at constant load and the influence of loading cycles on the deformations. Settlement diagrams, as a function of time (Fig.4), show initially a deformation phase at constant load lasting about six days; the rate is progressively decreasing and asymptotic values of displacement were determined through linear extrapolation on the inverse time. In the subsequent unloading phase, which was maintained for about three days, both immediate and delayed recovery of part of the settlements were observed. Also in this case the final (asymptotic) value was estimated. The effect of loading cycle on deformation is quite interesting: in fact these cycles cause a marked increase in the creep rate and total displacement becomes even greater than the asymptotic limit evaluated on the basis of the initial constant loading period.

A comparison of the results obtained in the four testing areas indicates that the importance of the rheological behaviour, expressed by the ratio between the delayed and immediate settlements, decreases as the rock quantity improves (Fig.5). The above consideration applies both if rock quality is evaluated upon the unloading immediate modulus or through its seismic in situ velocity. It is also observed that the delayed recovered settlements become an increasingly greater part of the delayed settlements in the loading phase as the rock quality improves (Fig.6). In addition, the analysis of displacements in depth shows that the rheologic behaviour is more important for the superficial loosened layer (less than 1 m).

3. ANALYSIS OF THEORETICAL MODELS

In order to gain insight on field rheological behaviour, the plate loading test was analyzed for simple rheological models characterized by a reduced set of parameters; such models are composed by assembling the elements shown in Fig.7.

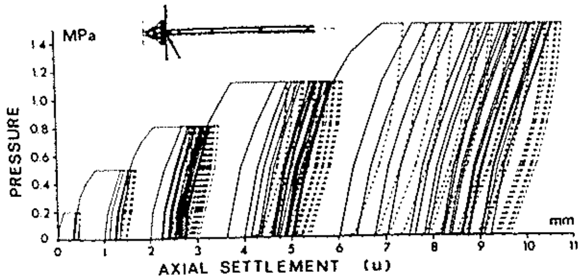

FIG.3 - Typical load settlement diagram for a point 0.07 m under the loading surface.

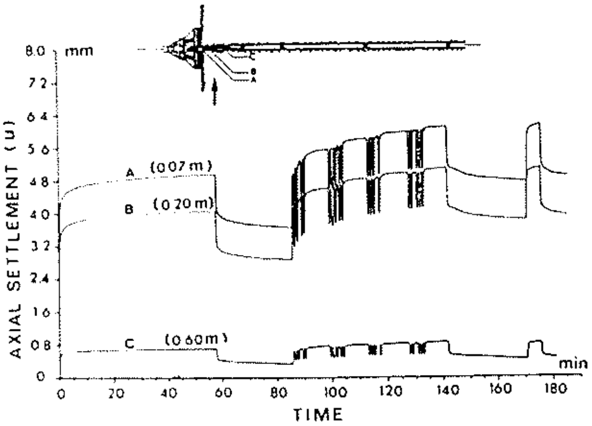

FIG. 4 - Typical plot of settlements versus time at 3 different depths under the loading surface.

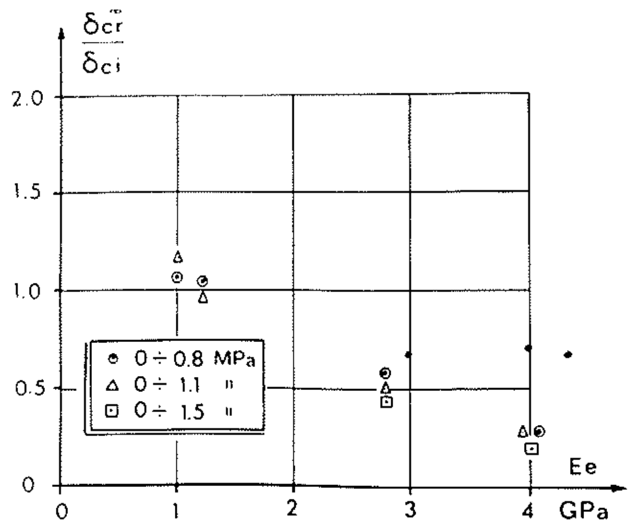

FIG. 5 - Ratios between delayed (δ_{cr}^{∞}) and immediate (δ_{ci}) settlements on loading phase as a function of the 'elastic' moduli; settlements measured at 0.07 m depth.

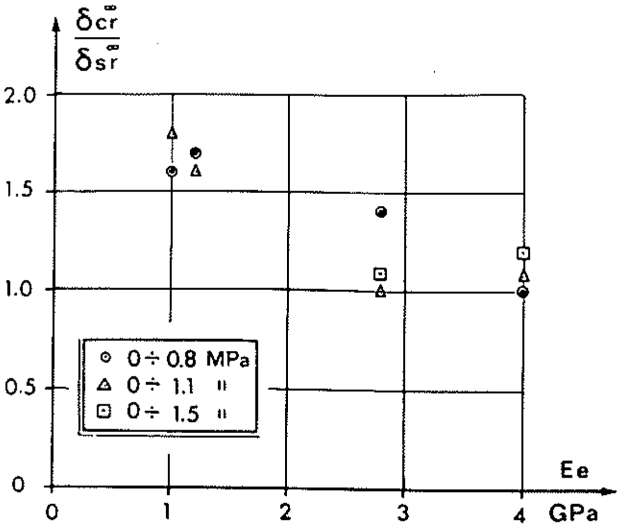

FIG. 6 - Ratios between delayed settlements in loading (δ_{cr}^{∞}) and unloading (δ_{sr}^{∞}) phases as a function of 'elastic' moduli.

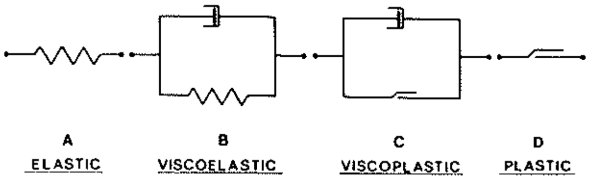

FIG. 7 - Simple elements assembled for the construction of rheological models.

The elastoviscoplastic model which is known as Bingham substance (A + C in Fig.7) was firstly investigated. It is characterized by the following parameters: the elastic modulus, the viscoplastic yield threshold, which depends upon the state of stress according to a Mohr-Coulomb law, and the viscosity, which is assumed independent on the stress or strain level.

The analyses were carried out with the finite element method, according to the technique described by Zienkiewicz et al. (1975); the mesh is shown in fig.8.

Analyses were effected with different values of the ratio, p/c, between the applied pressure and the cohesion of the rock mass which is an index of the load severity. A friction angle of 30° and a dilatancy angle of 0° were always assumed.

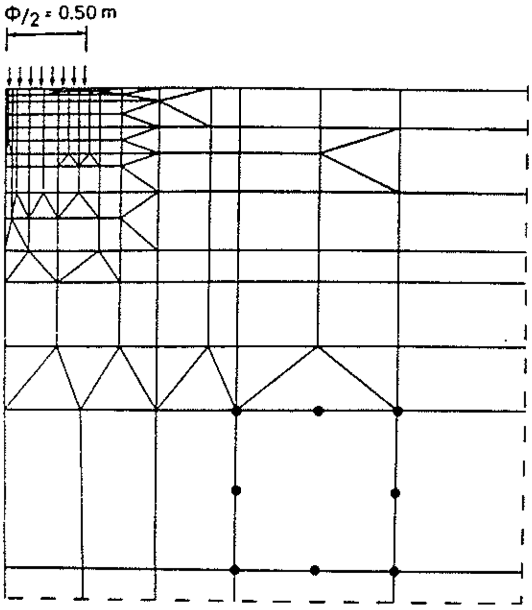

FIG. 8 - A portion of the mesh

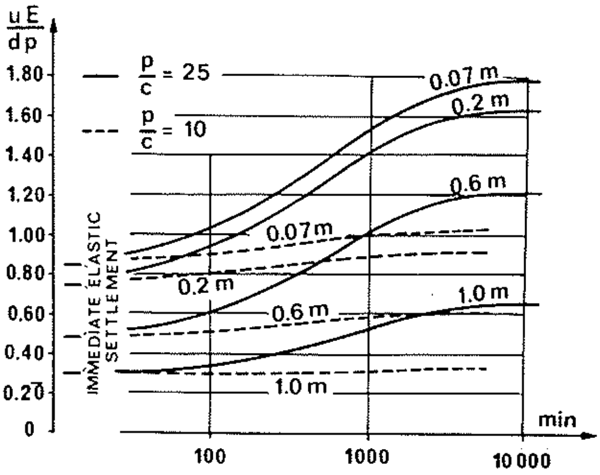

FIG. 9 - Settlements versus time obtained by the theoretical viscoplastic model for points at different depths along the loading axis and for two different loading conditions. The settlements (u) are normalized with respect to the elastic modulus E, the applied pressure p and the diameter (d) of the loading plate.

Fig.9 shows the trend of (normalized) settlements versus time in some point along the laoding axis for different values of the applied permanent load. The indicated time values corresponds to Bingham viscosity of 10^{13} poise; however, because of the logaritmic time scale, a modification of the viscosity would simply cause a shifting of the curves along the time axis. All the curves are S-shaped; if the delayed settlements are normalized with respect to the total delayed settlements, the curves of the various cases appear very similar to one another. The greatest part of the delayed settlements (between 10% and 9%) occurs within 2 time decades; an almost linear trend of the settlements versus log time is present for one time decade only. These theoretical findings are somewhat at variance with the experimental curves which show an almost linear trend for more extended range of time (Fig.10).

The relationship between settlements (immediate + delayed) and applied loads was subsequently investigated. The results obtained are also valid, with good approximation, for a material which is characterized both by immediate and delayed mechanism, the former having higher yield values (A+C+D in Fig.7).

At increasing stress severity the theoretical load settlement curve (Fig.11) deviates more and more from the linear responce assuming a downward curvature, in good agreement with experimental test indications. At unloading, the behaviour is initially elastic, but, at very low loads, plastic deformations occur. A subsequent reloading to the same initial pressure causes the formation of a hysteretic loop and gives rise to higher final settlements. However, plastic deformations at unloading are quite small, campared with those that occur during the loading phase. Therefore, most of the delayed displacements which took place during in situ unloading tests, as well as a remarkable part of those develop during the loading, should be ascribed to viscoelastic mechanisms. Plastic deformations (immediate + delayed) in the experimental tests were therefore evaluated as a difference between total settlements during the loading phase and final displacements recovered on unloading. Fig.12 shows the distribution of these measured plastic settlement at various depth along the loading axis: the distribution is compared with the theoretical ones, calculated for different values of the load intensity factor p/c. The theoretical and experimental distributions are very different from one

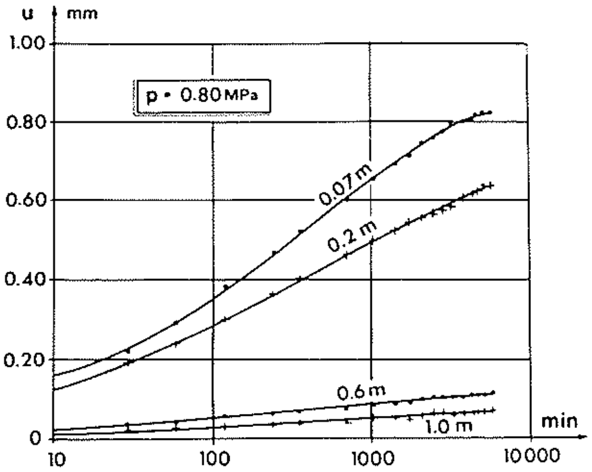

FIG. 10 - Delayed settlements versus time determined in one of the in situ tests at different depths along the loading conditions.

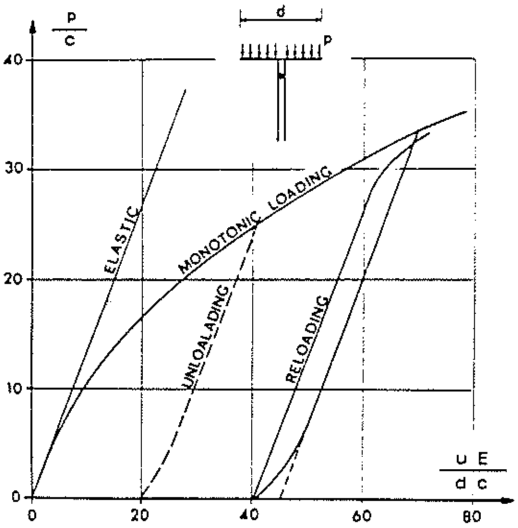

FIG. 11 - Theoretical load-settlement curve for an elastoplastic model. Settlements and loads are normalized with respect to material properties and plate diameter.

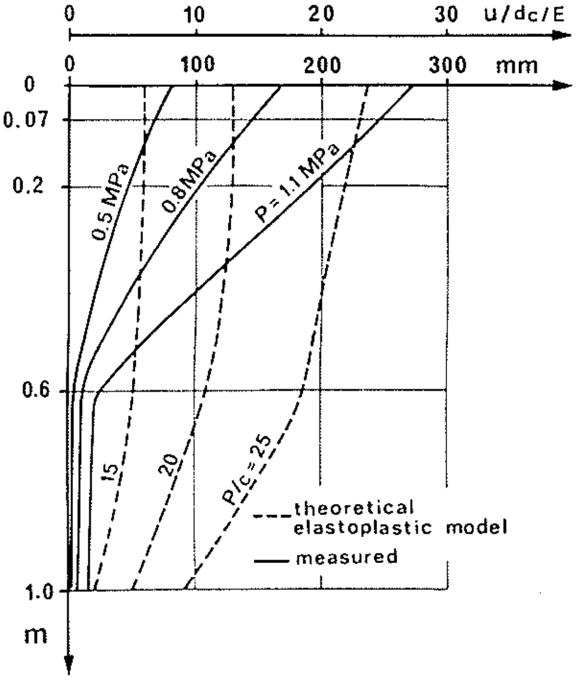

FIG.12 - Plastic settlements at various depth along the loading axis measured inone of the in situ tests (full lines); for comparison the curves predicted by the theoretical elastoplastic model are shown (dashed lines).

another; in the latter the plastic irreversible deformation take place just below the loading surface (less than 0.5 diameters), whereas the theoretical model indicates that plastic strains mainly occur at a depth of about 1 diameter.

The theoretical behaviour of a viscoelastic material (A+B in Fig.7) was subsequently analyzed. It is well-known that the immediate and the final (asymptotic) settlements can be obtained by the usual elastic solution computed, respectively, by element A deformability and by an effective deformability obtained by summing up Hookean part of element A and B. The transient solution can be easily obtained by applying Laplace transform theory to the elastic solution (Jaeger & Cook, 1969).

It should be noted that the viscoelastic behaviour may concern either the deviatoric stress component or the hydrostatic component or both. Some results are shown in Fig.13; also in this case, the settlements versus log time curves are S-shaped and the delayed settlements are almost complete within 2 time decades. The experimental data for unloading conditions (Fig.14) do not fully agree with the theoretical predictions, because they show an almost linear trend for a more extended time range.

The settlements recovered in the unloading phase (immediate+delayed) are compared with the theoretical solution for a homogeneous elastic medium (Fig. 15). Obviously a large part of the settlements is caused by the deformation of the surface layer. The experimental results can be explained by from a two-layer medium model: the deformability of the surface layer being about 3 times greater than that of the underlying rock mass (Fig. 16). This greater deformability obviously arises from the loosening of the rock which could not be fully avoided during the preparation of tests.

However, this distribution of plastic

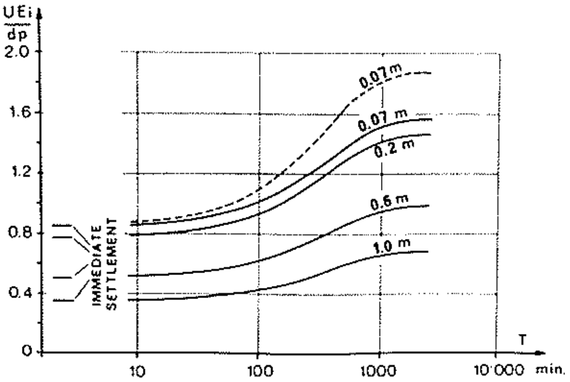

FIG. 13 - Normalized settlements versus time obtained by the theoretical viscoelastic model at different depth along the loading axis: viscoelastic behaviour concerns the deviatoric component (full lines) or both deviatoric and hydrostatic components (dashed line).

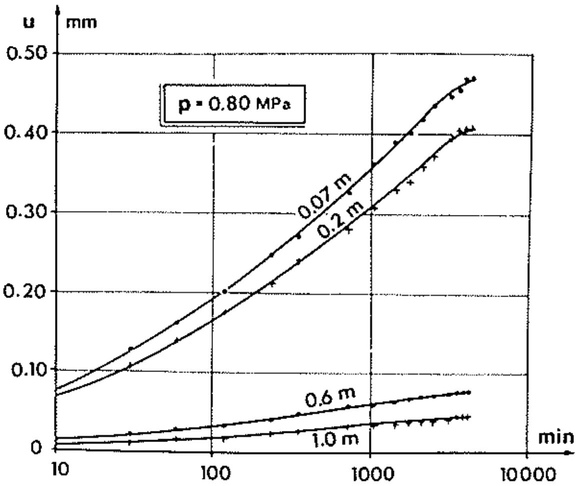

FIG. 14 - Delayed settlements versus time determined in one of the in situ tests at different depths along the loading axis in unloading conditions.

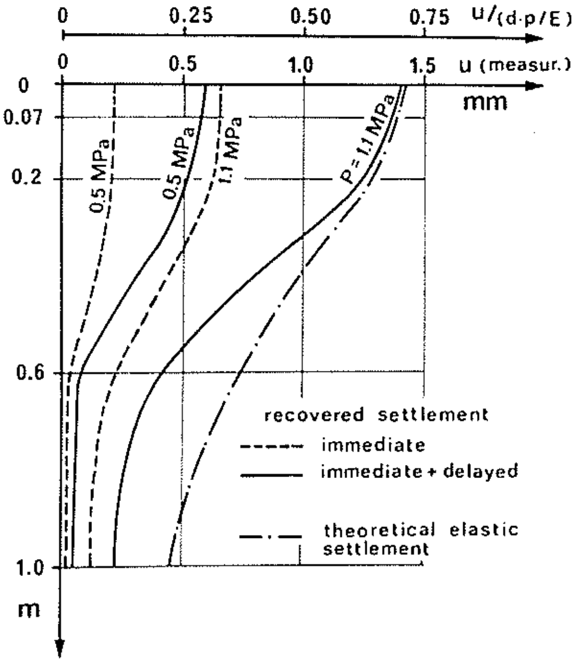

FIG. 15 - Recovered elastic settlements measured in situ compared with the theoretical trend for a homogeneous medium.

deformation shown in Fig.12 cannot be only ascribed to a dishomogeneity of elastic properties. Surface layer must have strength characteristics much lower those that of the underlying rock and probably plastic deformations cannot be ascribed to the deviatoric stress component only.

4 CONCLUSIONS

Some phenomena, recorded in the experimental tests, can be qualitatively explained by simple theoretical models. The rheologic behaviour of the tested material presents viscoplastic and viscoelastic components. The latter justifies delayed deformations at the unloading, which are much higher than those forecast by a viscoplastic model only.

Deformation trend versus time could be justified by the presence of several rheological elements with different time constants.

The distribution of immediate and delayed settlements indicates that the behaviour of the rock mass under the plate is not homogeneous, and exhibits a marked decrease of the stiffness and strength of the surface layer, notwithstanding the care applied in the preparation of the test. The increase in creep rate caused by load cycling is in agreement, at least from a qualitative standpoint, with the theoretical behaviour of a viscoplastic material.

The difficulty of accurate theoretical modeling of the surface layer emphasizes the importance of measuring the deformations at various depths, as achieved by the proposed experimental technique. Moreover this behaviour of the undisturbed rock is the most relevant information for design purposes. Hence in practice it is reasonable to use a simplified modelling of the surface layer such that the load is accurately transmitted from the plate to the deeper material although the deformation of the surface layer is not adequately described.

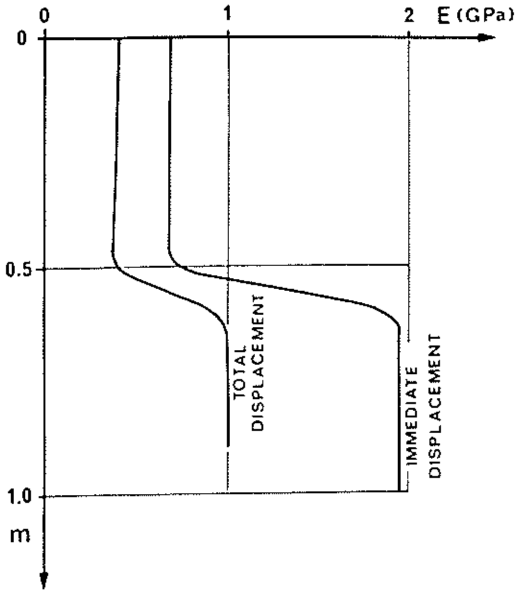

FIG. 16 - Deformability characteristics of the rock mass under the loading plate determined on the basis of the measured recovered elastic settlements.

5. REFERENCES

Zienkiewicz O.C. & Cormeau I.C. - Visco-plasticity-plasticity and creep in elastic solids. A unified numerical solution approach. Int. Jnl. Num. Meth. Engng 8, 821-841.

Jaeger G., Cook G.W., Rock Mechanics Methuen & Co LDT - London.