An Analysis of Stresses and Deformations in the Wide Clay Core of a Rockfill Dam

Analyse des pressions et des déformations dans l'épais noyau argileux d'un barrage en enrochement

P. ANAGNOSTI, DR.ENG., *Head of Soil Mechanics Section, Energoprojekt, Consulting Engineers, Belgrade, Yugoslavia*

SUMMARY

The problems involved in the design and construction of very high rockfill dams can be studied in the course of the erection and operation of the structures of smaller heights. The observation installations placed in the Globočica Dam in Yugoslavia have recorded some phenomena of stress concentrations and viscous flow effects in a wide clay core type rockfill structure. The behaviour of a wide clay core in a site with steep abutments can be analysed, and the conclusions derived applied to higher structures in similar site conditions. A brief description of the recorded effects is presented in the report, and the appropriate general relations of vertical, horizontal, and shear forces are derived. Some recommendations of practical measures that can be undertaken during the construction are also mentioned.

SOMMAIRE

Les problèmes relatifs à la conception et à la construction de très hauts barrages en enrochement peuvent être étudiés pendant la construction et l'opération d'ouvrages de hauteur moyenne. Les appareils de mesure installés dans le barrage de Globočica, Yougoslavie, ont révélé des phénomènes importants sur les concentrations des pressions et le fluage visqueux dans l'épais noyau argileux d'un barrage en enrochement. La distribution des pressions et des déformations dans le noyau argileux du barrage situé en vallée profonde peut être examinée, et les données ainsi recueillies peuvent être efficacement utilisées dans la construction des barrages d'une hauteur plus grande. La description précise des effets notés est exposée dans la communication, et des relations générales sont dérivées entre les forces verticales, horizontales et tangentielles. Des recommandations pratiques sont données en conclusion de l'analyse présentée.

γ, bulk density
y, vertical co-ordinate
x, horizontal co-ordinate
V, total vertical force (V_r at the boundary)
T, total shear force (T_r at the boundary)
X, total horizontal force (X_r at the boundary)
p, normal pressure at the boundary
q, tangential pressure at the boundary
P, total normal force at the boundary
Q, total tangential force at the boundary
α, angle of the slope at the boundary (abutments)
σ_x, σ_y, normal stresses
τ, shear stresses
σ_{xr}, σ_{yr}, normal stresses at the boundary
τ_r, shear stresses at the boundary
ν_0, bulk viscosity
ν_d, constant volume changes viscosity

THE ROCKFILL GLOBOČICA DAM is 90 m high and consists of two quarry run rockfill shells which support the wide vertical central rolled clay core, as shown on Fig. 1. The rock is limestone and the core is composed of several types of clayey materials and soft disintegrated schist.

The construction of the dam was started in 1960 and the completion of work is expected in 1964. The clay in the core was compacted at optimum water content, in layers

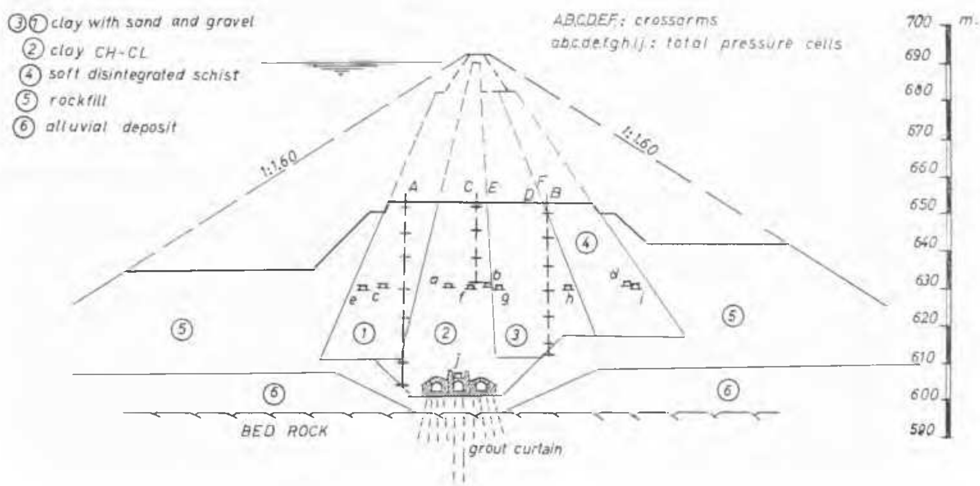

FIG. 1. Dam cross-section.

25 cm thick by sheepsfoot rollers. The disintegrated schist was compacted by a vibrating roller in 40-cm-thick layers. The rock in the supporting shells was dumped in not more than 5 m high lifts and sluiced by jets with 1:1 water to fill ratio. The transition layers in which materials from the tunnel excavation were used were compacted by the hauling equipment.

OBSERVATION OF PRESSURES AND DEFORMATIONS

The structure was kept under close observation during the construction period. A system of electro-acoustic cells and crossarm installations were installed in order to provide check data during the construction and the operating period. The pore pressure, total pressure (Gallileo type) cells, and ordinary crossarm pipes were installed in the selected sections as shown on Fig. 2.

In steeply sloped abutments the point of special interest is the appearance of an "arching" effect in the central clay core, which should decrease the vertical stresses in the central part of the fill and increase the shear stresses. The actual shape of the abutments and locations of the observation points are shown on Fig. 3.

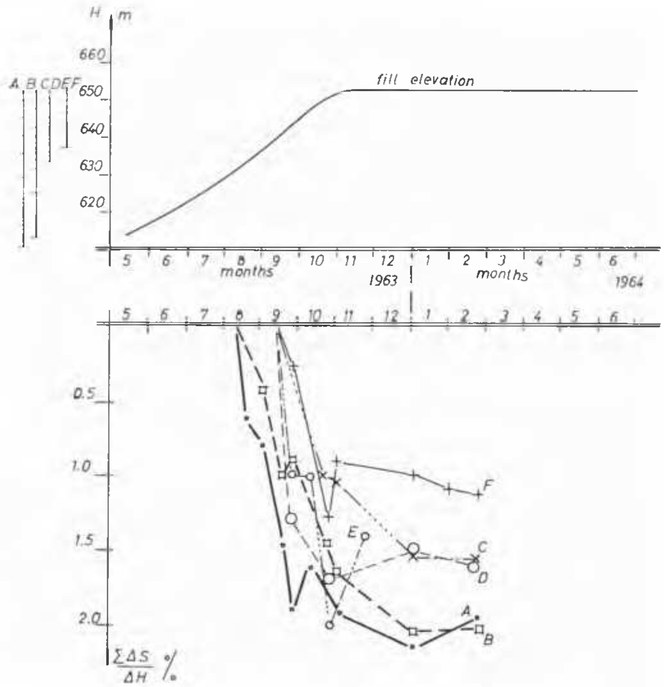

FIG. 4. Crossarm installation data.

The settlement data recorded by the crossarm installations are plotted on Fig. 4 as percentages of the thickness of the measured stratum. It can be seen that the ratio of settlement to the square of thickness in the zones close to the abutments is larger than in the central part of the clay core zone. The rates of the settlement in the central crossarm systems A and B has shown a certain time lag compared to the rate of the filling.

The data obtained by total pressure cells are presented on Fig. 5. It can be seen that a time lag in the development of the pressures exists, as well as in the release of stress under constant fill load.

The pore pressures were not recorded at the elevations where the total pressures and settlements are studied in this report. Therefore, the available results of these measurements do not interfere with the measurements and the effects described.

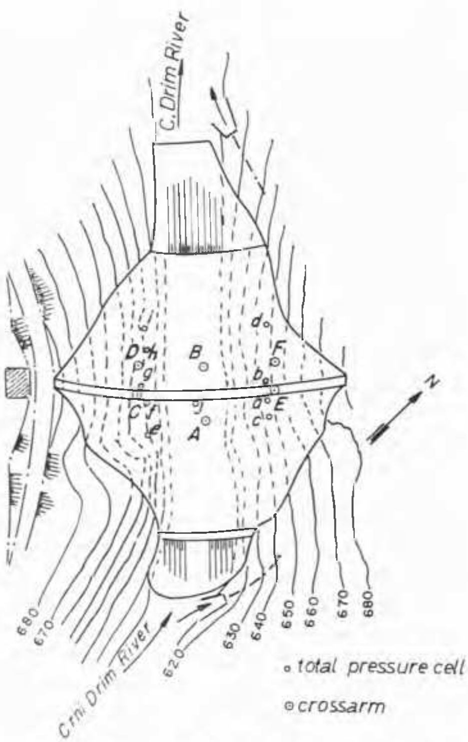

FIG. 2. Layout of dam and installations.

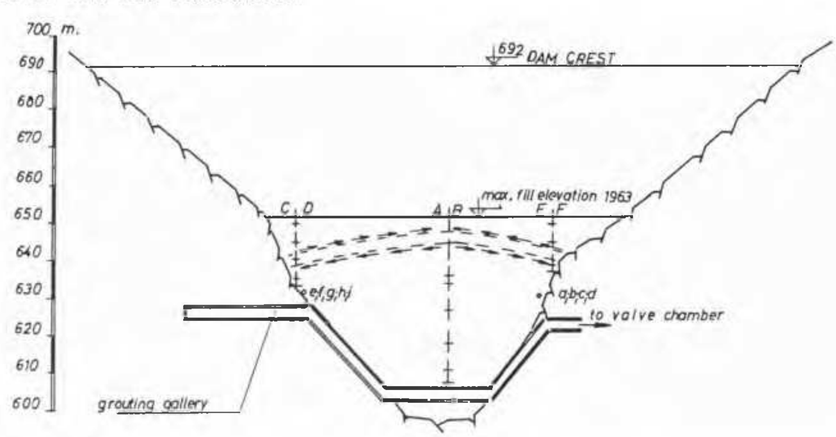

FIG. 3. Profile of dam.

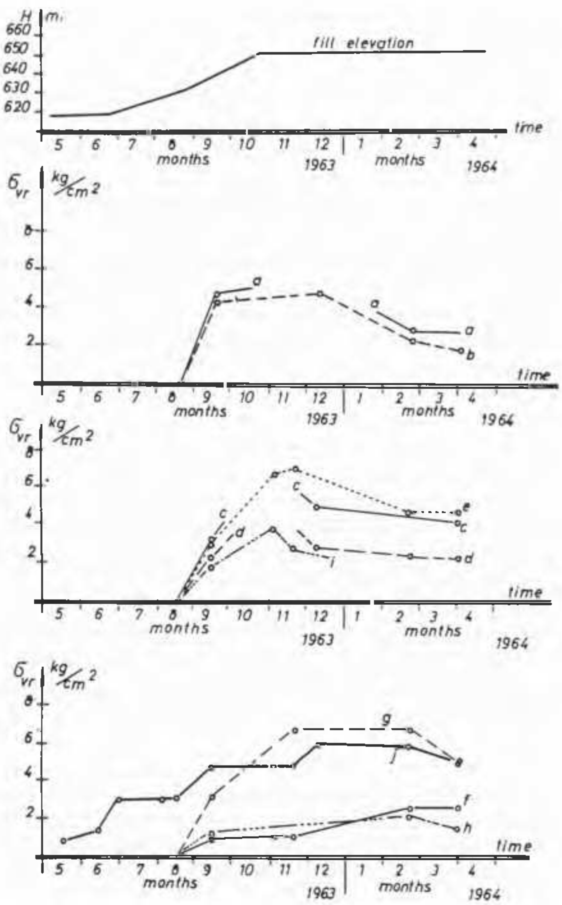

FIG. 5. Total pressure cell data.

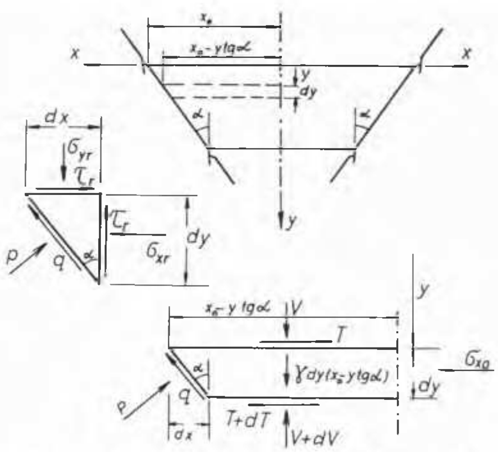

FIG. 6. Directions and relations of stresses.

DISCUSSION

The data presented allow the study of two main effects: arching and viscous flow. The first is caused by the shape of the abutments and the second by the physical properties of the clayey materials.

Assuming a symmetric wedge subjected to an arching action as shown on Fig. 6, the following equilibrium equations can be established:

$$\left.\begin{aligned} \gamma\cdot dy(x_0 - y\tan\alpha) &= dV + pdx + qdy \\ pdy - qdx &= dT + \sigma_{x0}\cdot dy \end{aligned}\right\} \quad (1)$$

which lead to:

$$\left.\begin{aligned} V &= \gamma(x_0 y - \tfrac{1}{2}y^2\tan\alpha) - P\tan\alpha - Q \\ T &= P - \tan\alpha Q - X_0 \end{aligned}\right\} \quad (2)$$

where $P = \int p\cdot dx$ (total normal force at the boundary); $Q = \int q\cdot dy$ (total tangential force at the boundary); $X_0 = \int \sigma_{x0}\cdot dy$ (total normal force at the centre line).

The boundary conditions lead to:

$$\left.\begin{aligned} p - q\tan\alpha &= \sigma_{xr} - \tau_r\tan\alpha \\ p\tan\alpha + q &= \sigma_{yr}\tan\alpha - \tau_r. \end{aligned}\right\} \quad (3)$$

Integrating along the boundary, the following is obtained:

$$\left.\begin{aligned} P - Q\tan\alpha &= X_r - T_r\tan\alpha \\ P\tan\alpha + Q &= V_r\tan\alpha - T_r \end{aligned}\right\} \quad (4)$$

where

$$\left.\begin{aligned} X_r &= \int_0^y \sigma_{xr} dy \\ V_r &= \int_0^y \sigma_{yr} dy \\ T_r &= \int_0^y \tau_r dy. \end{aligned}\right\} \quad (5)$$

From Eqs 2 and 4 the following conclusions can be derived: (1) The total vertical force, that is average vertical stress, at the arbitrary chosen depth y decreases when boundary forces P and Q increase and angle α increases. (2) The force P is proportional to the boundary forces V_r and X_r, that is to the stress concentration along the boundary. (3) The force V_r, that is the stress concentration along the boundary, decreases when the lateral force X_r increases, and consequently shear force T_r and Q decrease.

The measured values of $\Sigma\Delta S$ (presented on Fig. 4) divided by $(\Delta H)^2$ give the following values:

Crossarm:	A	B	C	D	E	F
$\sum \Delta S/(\Delta H)^2$ [cm/m²]	0.064	0.065	0.083	0.124	0.140	0.090

The values $\Sigma\Delta S/(\Delta H)^2$ are proportional to the pressures which cause the settlements, assuming a linear distribution of the pressures with depth. It will be noticed that at the

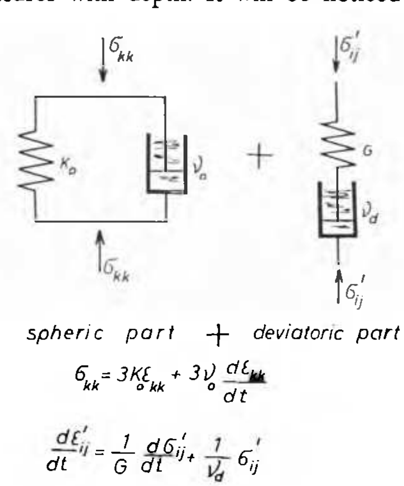

FIG. 7. Rheological model applied.

abutments the values of $\Sigma\Delta S/(\Delta H)^2$ are in general larger than in the central section where crossarms A and B were placed.

Viscous effects are manifested as the time lag of the development of vertical pressures during the initial time period of the full constant fill load. The next time period is characterized by a decrease of these pressures. In some previous work a suitable rheological model of viscoelastic type has been used in explaining the triaxial compression test results. This model is shown on Fig. 7.

Using the model mentioned some of the measured effects can be easily explained. The time lag in the recorded settlements is caused by the spherical viscosity (viscosity of the volume changes) as well as by the deviatoric viscosity (viscosity of the constant volume changes) which causes the lateral displacements of the clay core zone. The time lag in the measured stresses can be caused by creep phenomena and a change of the shear stress intensity. The immediate fill load is transmitted through the fill without volume changes, that is with shear stresses corresponding to an elastic state of stress and strain. The viscoelastic volume changes and deformations can cause the stress concentration at the abutments and development of the larger shear stresses. Later, the creep shear deformations can cause the decrease in shear stresses and increase in lateral pressures. Therefore, the drop in stress concentration at the abutments can be also explained.

A detailed study of all mentioned phenomena as well as the relations of the measured stresses and the fill weight will require more data and a particular theoretical approach to the problem in question. To date it is possible to express only the general relations and effects.

CONCLUSIONS

In present design practice, projects with dams of 250 to 300 m height of the rockfill type are to be expected. In order to provide a sound engineering background for the design of such structures comprehensive measurements on existing structures should be carried out. A number of problems have been raised in connection with design and construction of very high rockfill dams. One of them is the behaviour of the clay core of dams constructed in steep canyons. The measurements recorded in the Globočica Dam can be useful regarding the change of stresses in time and its distribution in space for a wide clay core placed in a steep canyon. Based on the analysis already carried out, some measures can be pointed out which would provide more satisfactory stress conditions in such a clay core and would thus minimize the potential danger of cracking which can cause seepage and erosion of the core. The friction in the contact zone of the fill with abutments should be minimized as much as is practical, by using the most plastic clay available in the zone, or by increasing the placing moisture content in this part of the fill. The undesirable lateral displacements of the clay core zone under constant or increasing load can be minimized by compaction of the adjacent fill zone to the maximum practical degree. This will provide the highest possible passive resistance of the supporting zone with the smallest required movement of the supporting fill. It is obvious that a detailed study of the viscous flow phenomena will require further laboratory testing on the clayey materials and new theories, before firm quantitative solutions will be attained.

REFERENCES

ANAGNOSTI, P. (1963). Stresses, deformations and pore pressure in triaxial test obtained by a suitable rheological model. *Proc. Fourth European Conference on Soil Mechanics and Foundation Engineering.* (Wiesbaden).

NONVEILLER, E., and ANAGNOSTI, P. (1961). Stresses and deformations in cores of rockfill dams. *Proc. Fifth International Conference on Soil Mechanics and Foundation Engineering* (Paris).