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BY

E. PENNER

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THERMAL CONDUCTIVITY OF SATURATED LEDA CLAY

BY

E. PENNER

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THERMAL CONDUCTIVITY OF SATURATED LEDA CLAY

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E. PENNER

SYNOPSIS

The thermal conductivity of saturated remoulded Leda clay, a soil of post-glacial marine origin, increased from 5·5 to 7 B.t.u. in/sq.ft hour°F for an increase in dry density of 20 lb/cu.ft (75–95 lb/cu.ft) and decreased from 7 to 6 B.t.u. in/sq.ft hour°F for an increase of clay size particles from 39 to 60%.

The undisturbed soil appeared to have a higher thermal conductivity in the direction normal to the ground surface than in the remoulded condition, but insufficient results are available on which to base conclusions.

Extrapolating the thermal conductivity to 100% solids gave a value of 11·8 B.t.u. in/sq.ft hour°F. The use of the value for the solid fraction in De Vries's method for predicting the conductivity gave reasonable agreement with measured results.

La conductibilité calorifique d'argile de Leda remoulée saturée, sol d'origine marine de période pré-glacière, a augmenté de 5,5 à 7 unités thermiques britanniques en pieds carrés/heures/degrés Fahrenheit pour un accroissement en densité sèche de 20 livres par pied cube (75–95 livres par pied cube) et a diminué de 7 à 6 unités thermiques britanniques en pieds carrés/heures/degrés Fahrenheit pour un accroissement de dimensions des particules d'argile de 39 à 60%.

Le sol intact a révélé une conductibilité thermique plus haute dans la direction perpendiculaire à la surface du sol dans une condition remaniée, mais les résultats obtenus sont insuffisants pour en tirer des conclusions.

En extrapolant la conductibilité thermique à 100% les solides ont donné une valeur de 11,8 unités thermiques britanniques en pieds carrés/heures/degrés Fahrenheit. L'emploi de la valeur pour la fraction solide d'après la méthode De Vries pour prédire la conductibilité s'accorde raisonnablement avec les résultats relevés.

NOTATION

Symbol	*Quantity*	*Unit*
k	Composite thermal conductivity	B.t.u. in/sq.ft hour°F
k_a	Thermal conductivity of contingent medium, water or air	B.t.u. in/sq.ft hour°F
k_s	Thermal conductivity of solid inclusions	B.t.u. in/sq.ft hour°F
v_a	Volume fraction of contingent medium, water or air	dimensionless
v_s	Volume fraction of solid inclusions	dimensionless
γ_d	Dry density of soil	lb/cu.ft
g_a g_b and g_c	Particle shape factors	dimensionless

INTRODUCTION

Leda clay is a soil of post-glacial marine origin found extensively as a surficial deposit along the St Lawrence and Ottawa rivers and their tributaries (Gadd, 1956; Karrow, 1960)[1]. Because the area is fairly heavily populated and industrialized the importance of Leda clay as a foundation soil has led to many detailed studies of its mechanical and physical properties (Crawford, 1960). By comparison, only meagre information is available on its thermal properties, although these are of prime importance for the design of such public utilities as sewers and water mains for winter operation (Crawford, 1955) and for industrial installations that generate heat in the ground.

The apparatus (Fig. 1) used at present in the study of frost action (Penner, 1960) is suitable also for determining the thermal conductivity of soils. Consequently, these studies have been extended to evaluate the influence of density and mechanical composition on the thermal conductivity of saturated Leda clay, and form the basis of this Paper.

The references are given on p. 175.

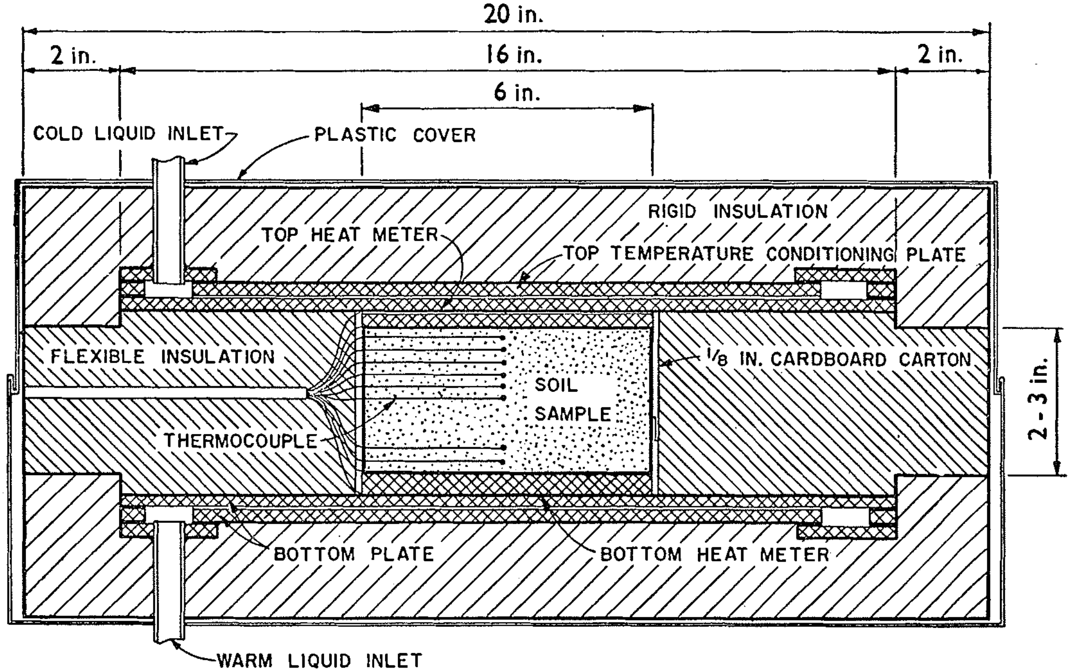

Fig. 1. Frost cell modified to measure thermal conductivity of soil (Penner 1960)

Woodside (1956) and Van Rooyn and Winterkorn (1953) have recently reviewed the applicability of equations used to predict the thermal conductivity of various materials. Their success has stimulated the Author's interest in such predictions. In addition to conduction, heat is also transferred by mass flow in unsaturated soils and results in a moisture content gradient along the axes of the temperature gradient. For these reasons the measured thermal conductivity values of unsaturated soils cannot be compared reliably with predicted values, but the measured values for saturated soils should provide a valid basis for comparison.

MINERALOGY OF LEDA CLAY IN BRIEF

A recent study of Leda clay deposits (Brydon and Patry, 1960) shows great similarity in their mineral composition, regardless of location, depth of sampling, and mechanical composition. Samples from several sites within the city of Ottawa were included in the study.

Mica, the predominant clay mineral, was well represented in the silt and sand fractions; feldspar predominated in the coarser fractions and occurred in significant amounts in the clay size range. A dissimilarity between size fractions was the increasing amount of phyllosilicate minerals with decreasing particle size. In general, quartz, feldspar, amphiboles, and mica were always represented in the clay fraction; chlorite, vermiculite, montmorillonite and mixed layered minerals were usually but not always present.

Little evidence of weathering was found in the mineralogical study of Leda clay by Brydon and Patry (1960). It is consistent with earlier conclusions (Gadd, 1956) that these sediments are composed of crushed rock. The Precambrian Shield to the north of the St Lawrence River is thought to be the area of origin of Leda clay. Sedimentation of this material is known to have taken place in salt water (probably less concentrated than sea water) during the marine invasion of the Champlain Sea (Johnson, 1917; McKay, 1949) by the water of the Atlantic.

MATERIALS AND METHODS

Sample origin and preparation

Soil was taken at a depth of from 16 to 20 ft from two excavations in Leda clay within the city limits of Ottawa for the density-thermal conductivity experiments. The mechanical composition is indicated by curve 1 in Fig. 2. All mechanical analyses were carried out according to the method outlined by the American Society for Testing Materials with some minor modifications (A.S.T.M., 1958).

As soil samples with large differences in clay size content were required in order to study the influence of mechanical composition on thermal conductivity a second excavation, more variable than the first, was sampled at several places at a depth of about 35 ft. The mechanical composition of these samples, together with a mixture from the two excavations, are indicated by curves 2, 3, and 4 of Fig. 2.

Soil from each excavation was sufficiently sensitive to permit complete remoulding and mixing at its natural moisture content. This was done mechanically with a metal paddle attached to a $\frac{1}{2}$ h.p. electric motor.

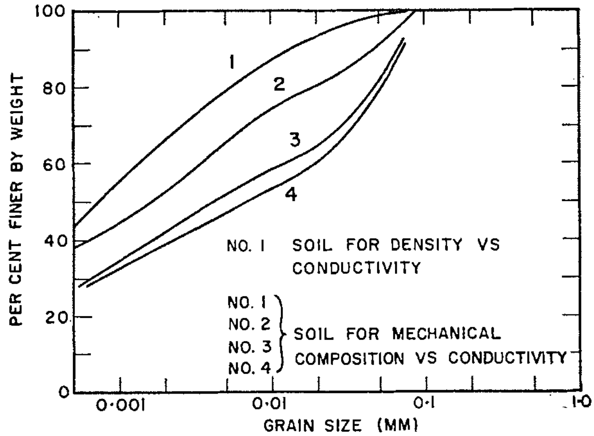

Fig. 2. Grain size distribution curves

Soil specimens for thermal conductivity measurements were prepared at various densities by using different consolidation pressures. A 6-in.-diam. mould was filled to a height of 4 in. with remoulded soil. Loading was applied in stages in a heavy-duty consolidation frame by doubling the load each day until the desired density was achieved. (The highest load used was about 21 tons/sq.ft on a 6-in.-diam. mould.) After the soil had reached the required consolidation, a 2-in.-long specimen was cut, the length required for the apparatus.

Heat flow and temperature measurements

In order to determine thermal conductivity, heat flow meters were used to measure the steady heat flow through a soil specimen sandwiched between two constant-temperature plates. This type of apparatus has been used in vapour flow studies (Hutcheon and Paxton, 1952; Woodside and DeBruyn, 1959; Woodside and Cliffe, 1959) and as an alternative to the well-known properly guarded hot plate technique for determining the thermal conductivity of building materials (Verschoor and Wilber, 1954). Heat flow meters were placed in thermal series at opposite ends of the soil specimen. The values at which the e.m.f. output of the two meters became constant were used in determining the average thermal conductivity of the soil.

Calibration of the heat flow meters was carried out in the same apparatus with a 2-in.-thick slab of rubber of known thermal conductivity; it had previously been determined by the guarded hot plate.

Copper-constantan thermocouples (30-gauge) placed $\frac{1}{4}$ in. apart in the soil specimen served to determine the thermal gradient. Each thermocouple was placed along the isothermal plane of the specimen in pre-drilled tight-fitting holes 2 in. deep. The thermal gradient at constant heat flow varied a little between different runs, but on an average it was 1·9°F/in. The cold side of the specimen was maintained at approximately 32°F in preparation for the frost-heaving experiments that followed. By keeping the thermal gradient reasonably small, but consistent with the general accuracy of the experiment, the recording of heat flow and temperature could be accommodated by the same recording potentiometer.

EXPERIMENTAL RESULTS

Dry density versus thermal conductivity, k

The density, moisture content, and per cent saturation value of the soil specimen used in the density-thermal conductivity experiments are given in Table 1. The calculated percentage saturation based on the determined specific gravity of the soil and specimen dimensions

Table 1

Dry density *versus* thermal conductivity experiments for remoulded samples of Leda clay (66.4% clay size)

Dry density: lb/cu.ft	Moisture content (per cent by weight)	Saturation (calculated): per cent
74·92	47·6	99·6
86·15	36·6	99·2
87·40	35·9	97·3
88·03	34·2	96·9
89·27	34·8	101·5
90·84	4 × Exp. series	
95·83	29·1	98·8

shows some variation from the measured values. The method of remoulding resulted in the inclusions of some air pockets and this would explain all the deviations except one, where the calculated percentage saturation exceeded 100%. However, it was assumed that thermal conductivity was not seriously affected by the small divergences from perfect saturation.

The average thermal conductivity based on the readings of the two heat flow meters is plotted in Fig. 3 as a function of dry density. Assuming saturated conditions, a higher thermal conductivity may be anticipated as the density is increased from the difference between the conductivity of soil solids and water. Others have shown this experimentally; Kersten (1949) found the following general relationship applied:

$$k = A10B\gamma_d$$

where A and B are constants, k is the composite thermal conductivity, and γ_d the dry density. This relationship is quite different from the one Woodside and DeBruyn (1959) found for Leda clay for the air dry state and from that which the Author found for the saturated state (Fig. 3).

The results in Fig. 3 were statistically analysed; the linear regression equation is:

$$k = 0{\cdot}92 + 0{\cdot}062\gamma_d$$

where k is the composite thermal conductivity and γ_d the dry density. The coefficient of correlation, 0·97, was shown to be highly significant statistically.

Mechanical composition versus thermal conductivity, k

The influence of mechanical composition on the thermal conductivity of Leda clay was shown by comparing four samples with different percentages of clay and silt size particles. The thermal conductivity values were adjusted to give a density of 80 lb/cu.ft by assuming that the slope shown in Fig. 3 applied. The resultant curve is given in Fig. 4.

The influence of texture appears to be much less marked than the influence of density

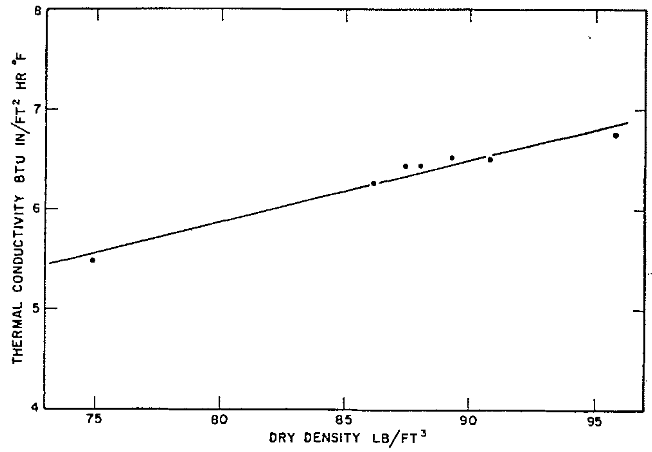

Fig. 3. Measured thermal conductivity versus dry density for saturated Leda clay

within the range studied; the reduction in k is about 15% for an increase of 50% in clay content fraction.

Shown also in Fig. 4 are two k values determined in the direction normal to the ground surface on specimens of natural structure. These laboratory-determined values are slightly higher than those for remoulded material. Pearce and Gold (1959) estimated a k value for Leda clay at Ottawa by applying the theory of periodic heat flow in a homogeneous body to measured soil temperatures and heat flow in the field. The value determined by this technique was considered a type of average for the year, and the agreement between laboratory-determined k values for the natural structure and that given by Pearce and Gold is quite good (Fig. 4). This may be fortuitous because the temperatures were measured only to a depth of 3 ft, and freezing and thawing was not included in the calculation. There were differences also between the laboratory samples and field soil regarding moisture saturation. Saturated conditions in this area exist only periodically in the summer; in the fall, the water-table may rise to the surface of the ground.

CALCULATED THERMAL CONDUCTIVITIES

Good agreement was obtained between measured and calculated thermal conductivities for 20/30 Ottawa sand and powdered flint (Woodside and Cliffe, 1959). Earlier, De Vries (1952), using the same method of calculation, compared it with the measured thermal conductivities of soils reported in the literature (Smith and Byers, 1938; Kersten, 1949). The method of De Vries, proposed originally by Eucken (1932), appeared promising for a wide range of soils, densities, and moisture contents. For air dried soils the calculated values were on the low side and a factor of 1·25 was required to increase calculated values to the measured k values. At high moisture contents the calculated values were high compared to Kersten's measured values.

These calculations may be made for any soil, provided that the volume fraction and thermal conductivity of the components of the system are known. In the present case the system consists of soil solids and water. A factor for the effective shape of the particles is also involved in the solution. De Vries used an average value based on vapour diffusion work (Penman, 1940). The thermal conductivity, k, is calculated from the equations:

$$k = \frac{k_a v_a + k_s v_s F}{v_a + v_s F}$$

$$F = \tfrac{1}{3} \sum_{a,b,c} \frac{1}{1 + \left(\frac{k_s}{k_a} - 1\right) g_a} \quad \text{and} \quad \sum_{a,b,c} g_a = 1$$

where

k_a = thermal conductivity of the contingent medium, air or water
k_s = thermal conductivity of the solid inclusions
v_a = volume fraction of air or water
v_s = volume fraction of solids
$\left.\begin{matrix} g_a \\ g_b \\ g_c \end{matrix}\right\}$ = shape factors.

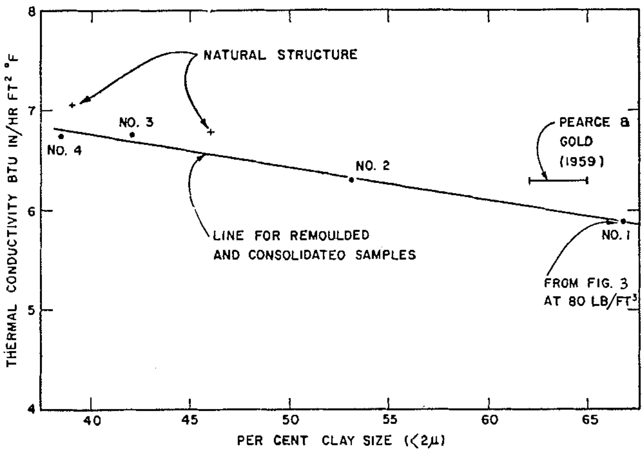

Fig. 4. Thermal conductivity versus per cent clay size (<2 microns) for saturated Leda clay at 80 lb/ft.³

The value for g_a and g_b, selected according to De Vries's method, for a two-phase medium both equal 0·125 and $g_c = 0{\cdot}75$. The "effective particle shape" of the solid corresponds to a flattened ellipsoid of revolution with a ratio of 1:5 between the short and long axes.

Woodside and DeBruyn (1959), using De Vries's value of 20·3 B.t.u. in/sq. ft hour°F for k_s, 0·18 for k_a and the above particle shape factors, calculated too low a value for air-dry Leda clay. These results are plotted in Fig. 5, together with the measured values. For the saturated state, using the same shape factor and k_s, but 3·83 for k_a (the thermal conductivity of water at 32°F), gives high results compared with measured values. This is in agreement with some divergencies observed by De Vries, i.e. the calculated conductivities were too high in the wet state and too low in the dry state.

Recognizing the difficulty in calculating a value for k_s from the mineralogy of the soil and assumed orientations, one approach is to extrapolate the thermal conductivity curve in Fig. 3 to 100% solids. This gives k_s a value of 11·8, assuming the straight line extrapolation is valid. Substituting this value for k_s gives better agreement between calculated and measured values in the saturated state and only slightly reduces the calculated air-dry conductivities.

DISCUSSION AND CONCLUSIONS

The thermal conductivity of two undisturbed samples had a higher k_s, as did earlier field results (Pearce and Gold, 1959), than the values determined for the remoulded soil. An explanation is suggested that it is based on the natural structure in undisturbed Leda clay and the anisotropic thermal conductivity of minerals such as mica. The k_s value along the planes of cleavage of mica has been shown to be ten times greater than that across the planes (Goldschmidt and Bowley, 1960). Undisturbed Leda clay has a flocculated structure (Warkentin and Bozozuk, 1960); when remoulded and compressed the clay particles assume positions which form a parallel arrangement of the two long axes of the platelets normal to the direction of consolidation. The thermal conductivities of soil containing this structural arrangement, measured in the same direction as the applied pressure, would be expected to be less than

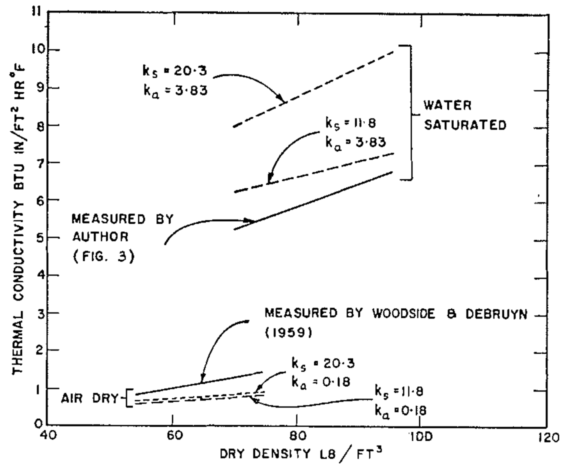

Fig. 5. Measured and calculated thermal conductivity values for air-dry and saturated Leda clay

those for the naturally occurring flocculated structure. Supporting evidence still is insufficient and further work is being planned; however, there is the suggestion that the thermal conductivity determined on remoulded samples of Leda clay is lower than that of the natural soil.

In general, the k values measured for Leda clay are lower than those for similar fine-grained soils reported by Kersten (1949). In part, the difference can be attributed to the high clay content of Leda clay, but the influence of mineral type is believed to be of greater significance. Brydon and Patry (1960) found the major portion of the sand and silt fraction to consist of feldspars, which have a conductivity one-third that of quartz. Mica, the predominant clay mineral, was also contained in appreciable amounts in the larger fractions. The k value for mica across the planes of cleavage is about 3·5 B.t.u. in/sq.ft hour°F. This is similar to the value for water, so that the relatively low thermal conductivity of Leda clay is not surprising.

The k values reported here were measured on soil samples from a relatively small area, but the similarity in mineral composition of the Champlain Sea deposit, taken from widely separated areas and differing as it does in mechanical composition, indicates that the results may apply more generally than was originally anticipated.

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CORRESPONDENCE

The Secretary,
The Institution of Civil Engineers.

CONTROL OF SEEPAGE THROUGH FOUNDATIONS AND ABUTMENTS OF DAMS

DEAR SIR,

I read recently the very important article by Professor A. Casagrande on "Control of seepage through foundations and abutments of dams" (First Rankine Lecture) published in *Géotechnique* (11 : 3 : 159–182). The cases described, in which the primary importance of the geological factors in the stability of the foundations and abutments is emphasized, deserve the careful attention of all those connected with dams. The considerations about the non-effectiveness of the ordinary single-lined grout curtains and the need for much wider curtains also seems very important. This was our point of view in the case of some difficult foundations of arch dams built in Portugal, which are behaving very normally, as can be fully proved by the large amount of data collected from their systematic observation.

It is interesting to refer the case of Odeaxere dam, a thin arch, founded in altered and decompressed formations of schists and greywackes, especially in the right abutment where clay could be found in many seams. The conditions were such that the modulus of elasticity of the foundation considered in the computations of the arch was 5,000 kg cm^{-2} and that the maximum stress allowed in the upper part of the right bank was only 4 kg cm^{-2}. The design called for a wide concrete base for the support of the arch. The dam has now been under operation for 4 years. In this case a three-lined grout curtain and a chemical treatment for the removal of the clay from the seams were used. The operations appear quite successful as the cores obtained from borings made after grouting show continuity and bond of the schist and the grout and a reasonable strength of the bond. Besides the grouting curtains, the right bank of the foundation was provided with a line of drain holes placed in a vertical plane just downstream of the dam for the complete drainage of the bank. In the left bank the drainage is secured by a horizontal drain hole near the bottom of the valley. This drainage is being observed and is behaving very satisfactorily.

In the case of another dam in Angola, a very large and wide arch, the foundation presented numerous problems due to the presence of faults, clay seams, and also altered rock. There are numerous geological details which were carefully investigated through the opening of galleries, geophysical methods, geotechnical tests of various kinds, etc. The drainage is secured in the foundations by two longitudinal galleries at about 15 m distance from the surface of the foundation. One of the galleries is upstream and the other downstream. All the bulb of pressure in the foundation is being grouted and this will be tested by taking cores containing pieces of rock separated by grout or even residual clay. Double core barrels of large diameters are being used and a programme of shear tests of the cores obtained is under way. In this complicated case we do not think any problem of safety was overlooked.

Also in this instance, as well as in another case of a dam under construction in a site of very deformable rock, steel reinforcements are being placed along the foundation in the socket of the arch in order to resist the tensile stresses that in such cases develop downstream near the foundation and parallel to it. Such tensile stresses were carefully investigated in models in which the deformability of the rock and the major geological details were reproduced. The investigations included measurements in the elastic range using strain-gauges, brittle lacquers, etc., and final rupture tests for the determination of the overall safety factor (both of the foundation and of the arch) of the undertaking.

As said above, some of the Portuguese arch dams under operation are located in poor rock