# Some Factors Controlling the Pore Pressures set up during the Construction of Earth Dams

## De Certains Facteurs Gouvernant les Pressions Interstitielles au cours de la Construction de Barrages en Terre

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### Summary

When climatic conditions necessitate the placement of rolled earth fill on the wet side of the optimum water content, high pore pressures are set up unless drainage occurs as construction proceeds, and these pressures present a difficult stability problem.

However, if even a limited amount of drainage can occur, either naturally or as the result of special design features, it is found to result not only in a reduction of the pore pressure already set up at any stage of construction, but also in a reduction in the increment of pore pressure which would occur, under undrained conditions, when the subsequent layers of fill were placed. This cumulative effect of partial dissipation of the initial excess pore pressure makes a marked contribution to the stability during construction. In this paper its theoretical basis is discussed and its importance is illustrated by laboratory tests and field data.

### Sommaire

Lorsque les conditions climatiques exigent la mise en place d'un remblai cylindré de teneur en eau supérieure à l'optimum, il en résulte, à défaut de drainage pendant les travaux, une pression interstitielle excessive qui présente un problème difficile de stabilité.

S'il est possible cependant, de réaliser un drainage même limité, soit naturellement, soit à l'aide de dispositions techniques spéciales, il en résulte non seulement une réduction de la pression interstitielle existante, mais aussi une réduction des accroissements de pression interstitielle qui résulteraient, à défaut de drainage, de la mise en place des couches subséquentes. Cette réduction cumulative de la pression interstitielle excessive initiale contribue d'une manière certaine à la stabilité pendant la construction. La présente communication traite de la base théorique de cet effet et son importance est démontrée à l'aide d'essais en laboratoire et sur le chantier.

### Introduction

The pore pressure set up in a rolled earth fill, in the absence of drainage, depends on the placement conditions, in particular on the water content, and on the state of stress resulting from the weight of the superimposed layers.* If the placement water content is more than a few per cent in excess of the optimum, the pore pressure at any point may approach 100 per cent of the weight of the overlying fill. The actual relationship between this pore pressure ratio† and the difference between placement water content and the optimum varies with the stress range and with the soil type, and is a function of the value of the optimum water content. An example of the influence of placement water content is given in Fig. 1.

The significance, in terms of factor of safety, of a high average pore pressure throughout the cross-section is shown in Fig. 2, where the factor of safety at the end of construction is plotted against the average pore pressure around the most critical slip surface.

From Fig. 2 it is clear that, with typical slopes and values of the shear parameters $c'$ and $\phi'$, failure is likely to occur if the average pore pressure ratio $\bar{B}$ exceeds 60 per cent, except in the case of small dams. To ensure a factor of safety of 1·5, an average value of $\bar{B}$ of about 40 per cent must not be exceeded. Under unfavourable borrow pit or climatic conditions stability can thus only be ensured either (1) by using substantial zones of pervious fill (gravel or rock-fill) on either side of the impervious core or (2) if this is uneconomical or otherwise impracticable, by relying on the partial dissipation of the excess pore pressures in the impervious fill. The latter alternative may be achieved by a controlled construction rate, but in fills with a low coefficient of consolidation special drainage measures will generally be necessary.

The purpose of the present paper is to draw attention to the twofold effect of pore pressure dissipation on the residual pore pressure at the end of construction.

### The Twofold Effect of Pore Pressure Dissipation on the Final Value of the Excess Pore Pressure

If a series of increments of all-round pressure is applied in the triaxial apparatus to a compacted sample, and the resultant pore pressure changes are measured without drainage, the relationship between pore pressure $u$ and total stress $\sigma$ will be as shown in Fig. 3, curve *a*.

If, however, the load is applied in several stages (representing construction seasons) and part of the excess pore pressure is allowed to dissipate at the end of each stage before the application of the next the relationship between pore pressure and total stress is as given in Fig. 3, curve *b*. It is found, in soils compacted on the wet side of the optimum, that the increase in pore pressure in stage 2 (see Fig. 3), following dissipation, is considerably less than occurs in stage 2 when no previous dissipation has taken place. The effect continues progressively throughout the subsequent stages of construction.

The author first noticed this effect in 1953 when carrying out laboratory tests to examine the influence of pore pressure dissipation on the stability of the Usk dam. A brief theoretical analysis showed that it is the immediate consequence, in partly saturated fills, of the decrease in compressibility of the soil which occurs as the effective stress increases. From the practical point of view it means that the influence, on the final pore pressure, of even a limited amount of drainage is greatly increased.

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* The importance of construction pore pressures and of the influence of placement conditions has been emphasized in the publications of the U.S. Bureau of Reclamation (for example, BRUGGEMAN *et al.*, 1939; HILF, 1948; and WALKER and DAEHN, 1948). The influence of the state of shear has been discussed by the author in some detail elsewhere (BISHOP, 1952, 1954).

† The ratio of excess pore pressure to total major principal stress is conveniently expressed by the symbol $\bar{B}$. For a fuller discussion of the use of pore pressure coefficients, see SKEMPTON (1954) and BISHOP (1954).

## Theoretical Basis

The pore pressure set up by an increase in total stress under undrained conditions is a function of the relative compressibilities of the soil structure and of the fluid occupying the pore space. The solution can either be derived analytically (Bishop and Eldin, 1950) or graphically (Hilf, 1948).

The principle may be illustrated most easily by a diagram, though a numerical solution is often used in practice. In Fig. 4a, curve *I* represents the relationship between volume change and effective stress* in the soil. Curve *II* represents the relation between the volume change in the pore fluid contained in unit volume of soil and increase in pore pressure; its shape is a function of the degree of saturation and initial porosity of the soil and is discussed later.

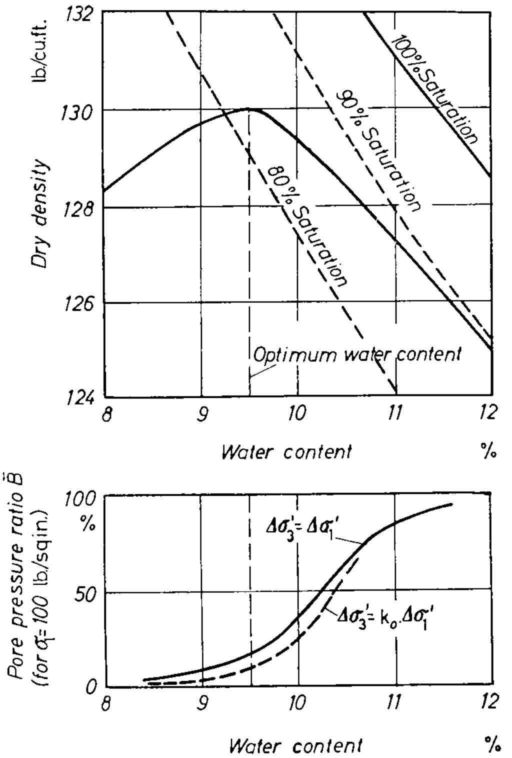


Fig. 1 The influence of placement water content on the value of the pore pressure ratio $\bar{B}$ (Usk, batch 2)

Effet de la teneur en eau lors de la mise en place sur la valeur de l'indice $\bar{B}$ de la pression interstitielle (Usk, 2$^{me}$ sélection)

In the absence of drainage, a decrease in volume $\Delta V_1$ will correspond to an increase in effective stress $(\Delta\sigma')_{01}$ and to an increase in pore pressure $(\Delta u)_{01}$ (Fig. 4a). The corresponding total stress is $(\Delta\sigma)_{01}$, where

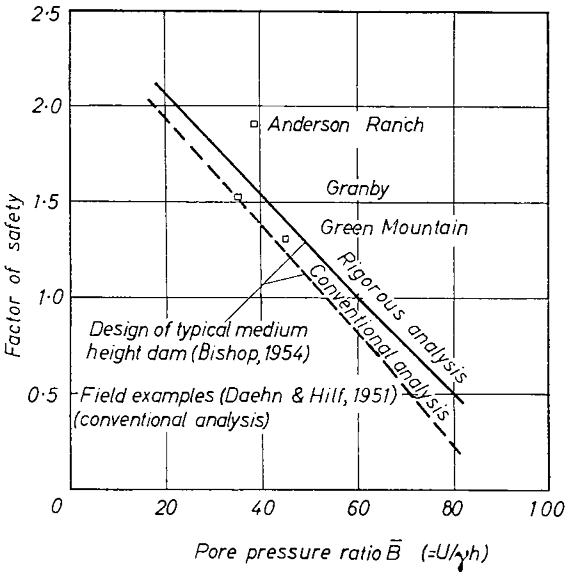
$$(\Delta\sigma)_{01} = (\Delta\sigma')_{01} + (\Delta u)_{01} \qquad \ldots. \; (1)$$

and this is represented by curve *III*. The relationship between $\Delta u$ and $\Delta\sigma$ is given by curve *IV* in Fig. 4b.

A further increment of total stress from 1 to 2 under undrained conditions leads to an increase in pore pressure $(\Delta u)_{12}$, the value of the ratio $\Delta u/\Delta\sigma$ eventually becoming unity when the pore pressure is high enough to lead to complete solution in the pore water of the air present in the soil.

If, however, full dissipation of the excess pore pressure is allowed to occur after the first increment of total stress the whole of the applied stress becomes effective, and the state of stress is represented by the points 1a on Fig. 4a and b. An increase in total stress $(\Delta\sigma)_{12}$ now applied under undrained conditions brings the sample to the state of stress indicated by 2a.

The important difference in behaviour arises from the fact that the effective stress range 1a to 2a lies on a much flatter



| Case | Height ft. | Slope | c' in clay fill lb./sq.ft. | φ' deg. |
|---|---|---|---|---|
| Design example | 145 | 2¾:1 | 350 | 37·5 |
| Green Mountain | c. 250 | 3:1 | 800 | 35 |
| Granby | c.250 | 3:1 | 1280 | 33·5 |
| Anderson Ranch | c.350 | 3½:1and3:1 | 800 | 35 |

Fig. 2 The relationship between factor of safety at the end of construction and the average pore pressure along the critical slip surface

Relation entre le coefficient de sécurité à la fin de la construction et la pression interstitielle moyenne sur la surface de glissement critique

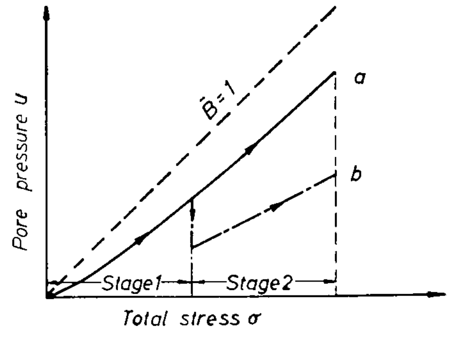


Fig. 3 The relationship between excess pore pressure and total stress (*a*) with no dissipation of pore pressure between stages 1 and 2, and (*b*) with partial dissipation of pore pressure between stages 1 and 2

Relation entre la pression interstitielle excédentaire et la contrainte totale (*a*) sans diminution de la pression interstitielle entre les phases 1 et 2, et (*b*) avec diminution partielle de la pression interstitielle entre les phases 1 et 2

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* Depending on the type of stress condition applicable, this may either be effective major principal stress or effective all-round pressure.

part of the volume change–effective stress curve (curve *I*) than the range 1 and 2, and thus corresponds to a greatly reduced compressibility. The pore pressure range, 0 to $(\Delta u)_{02a}$, in contrast, lies on a steeper part of the volume change–pore pressure curve* than the range 1 to 2 and thus corresponds to an increased compressibility of the fluid phase. The combined effects lead to the volume change–total stress curve *IIIa*, and to the pore pressure–total stress curve *IVa*, in Fig. 4b.

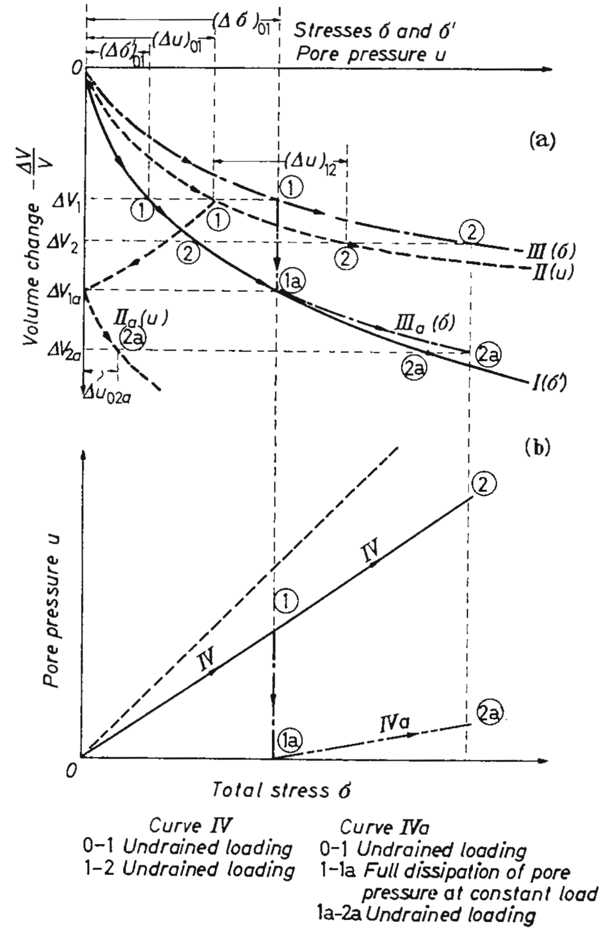

Fig. 4 Derivation of the relationship between pore pressure and total stress from the compressibilities of the soil structure and of the pore fluid: for the case of zero dissipation of pore pressure between stages 1 and 2; and for the case of full dissipation between 1 and 2

Relation entre la pression interstitielle et la contrainte totale d'après la compressibilité de la structure du sol et de l'eau interstitielle: dans le cas où il n'y a aucune diminution de la pression interstitielle entre les phases 1 et 2 et dans le cas où il y a disparition totale de la pression interstitielle entre les phases 1 et 2

The rate of increase of pore pressure with total stress $\Delta u/\Delta\sigma$ in passing from 1a to 2a is thus significantly less than in passing from 1 to 2.

If, as is more usual in practice, only partial dissipation of the excess pore pressure occurs at the end of stage 1 before the next increment of total stress is applied, a similar argument applies, and an intermediate value for the pore pressure ratio $\Delta u/\Delta\sigma$ is obtained (Fig. 5a and b).

## Numerical Solution

This is based on the assumption that the difference between pressure in the air and water in the pore space may be neglected as small compared with other stress changes, and that the principle of effective stress can thus be applied in its simplest form to partly saturated soil. The steps are outlined below.

*Volume change–effective stress relationship*—This is obtained either from undrained tests with pore pressure measurement or from drained tests using an appropriate stress ratio.

*Volume change–pore pressure relationship*—This can be deduced, at each stage, from Boyle's law and Henry's law of solubility. Let $V_v$ denote the initial volume of voids in a volume $V_0$ of soil; $S_0$ the initial degree of saturation; H Henry's coefficient of solubility (= 0·02 volumes of air per unit volume of water, approximately, at usual temperatures); $p_0$ initial pressure (absolute) in the pore space.

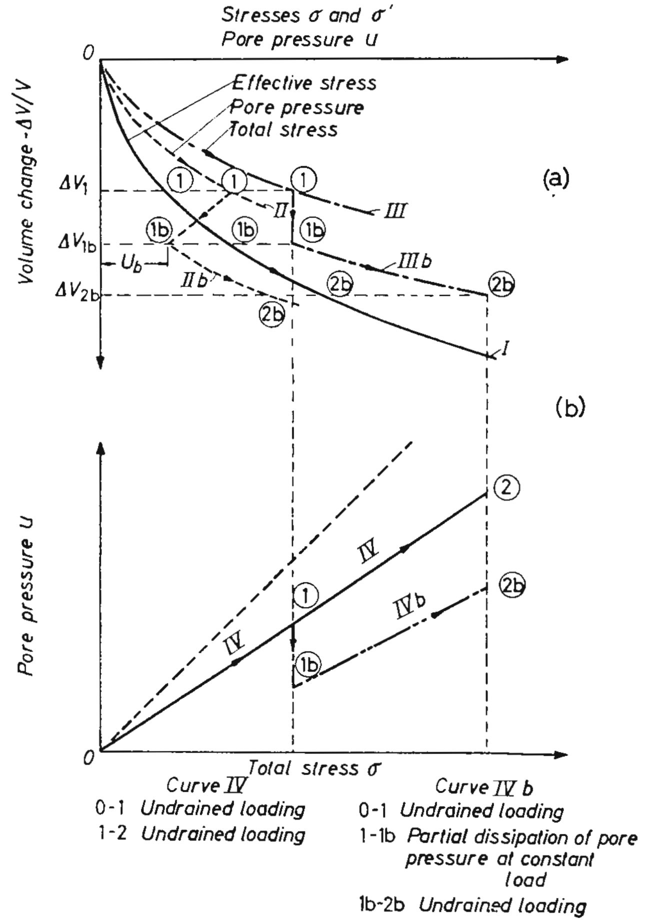

Fig. 5 Derivation of the relationship between pore pressure and total stress for the case of partial dissipation of pore pressure between stages 1 and 2

Relation entre la pression interstitielle et la contrainte totale dans le cas de diminution partielle de la pression interstitielle entre les phases 1 et 2

The initial volume of free air is thus $(1 - S_0)V_v$ and of dissolved air $S_0 . V_v . \mathrm{H}$. Hence the total volume of air at $p_0$

$$= V_v.(1 - S_0 + S_0\mathrm{H}) \quad \ldots . (2)$$

At a new pressure $p$ (absolute), this becomes

$$V_v.(1 - S_0 + S_0\mathrm{H}).p_0/p \quad \ldots . (3)$$

The volume of dissolved air at this new pressure is again $S_0 . V_v . \mathrm{H}$, and hence the free air volume is

$$V_v.(1 - S_0 + S_0\mathrm{H}).p_0/p - S_0 . V_v . \mathrm{H} \quad \ldots . (4)$$

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* The shape of this curve, now represented by *IIa* is slightly modified by the small change in porosity of the soil.

The volume change in the pore fluid, neglecting the compressibility of the water itself, is due to the change in volume of the free air. Hence

$$\Delta V = V_v\{(1 - S_0 + S_0 \mathrm{H}).p_0/p - S_0\mathrm{H} - (1 - S_0)\}$$

or

$$\Delta V/V_v = (p_0/p - 1)(1 - S_0 + S_0\mathrm{H}) \quad \ldots . \; (5)$$

To calculate the increase in pore pressure corresponding to a given volume change in stage 1, $p_0$ is taken as atmospheric pressure and thus $\Delta u = p - p_0$. If $n_0$ denotes the initial porosity, $V_v = n_0 . V_0$; and equation 5 can be rearranged in the form

$$\Delta u = p_0 . \frac{-\dfrac{\Delta V}{V_0}}{\dfrac{\Delta V}{V_0} + n_0(1 - S_0 + S_0\mathrm{H})} \quad \ldots . \; (6)$$

It should be noted that a decrease in volume corresponds to a negative value of $\Delta V$, and thus gives a positive value of $\Delta u$. It should also be noted that this equation only holds while free

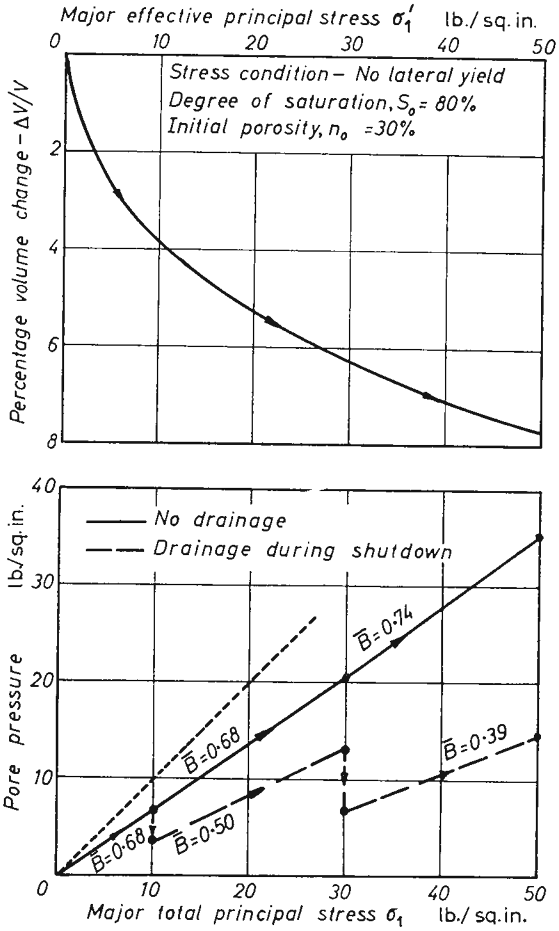

Fig. 6 Result of typical calculation with 50 per cent dissipation of pore pressure between each loading stage, compared with zero dissipation case

Résultat d'un calcul typique avec une diminution de 50 pour-cent de la pression interstitielle entre chaque phase du chargement, comparé avec le cas où il n'y aurait diminution

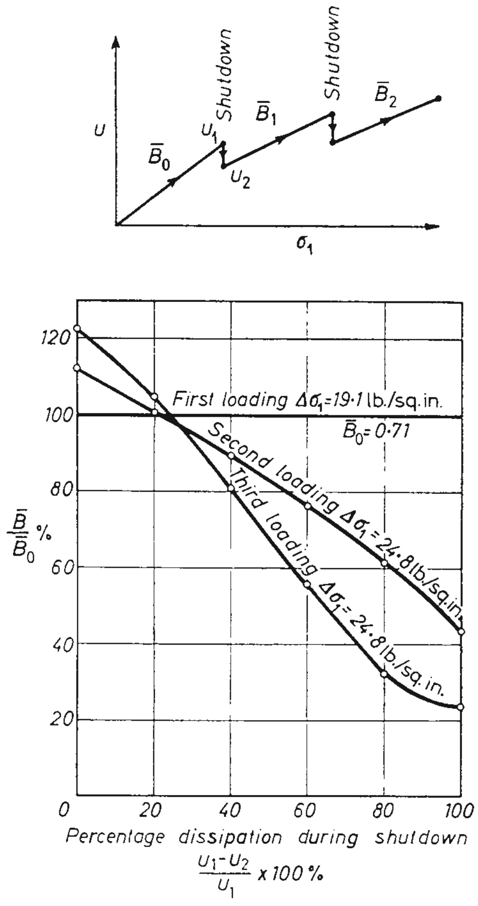

Fig. 7 Influence on pore pressure ratio $\bar{B}$ of percentage dissipation during shut-down (loading stages assumed to be undrained): analytical solution

Effet sur le rapport $\bar{B}$ de la pression interstitielle d'une pourcentage de diminution pendant l'interruption du travail (en supposant que les phases de chargement ne sont pas drainées)

Table 1

a

Stage (1). Undrained loading, 0–25 lb./sq. in.

| $-\frac{\Delta v}{V_0}$ % | $\Delta\sigma'$ lb./sq. in. | $\Delta u$ lb./sq. in. | $\Delta\sigma$ lb./sq. in. | $\bar{B} = \frac{\Delta u}{\Delta\sigma}$ |
|---|---|---|---|---|
| 0 | 0 | 0 | 0 | — |
| 2 | 3·2 | 6·3 | 9·5 | 0·66 |
| 3·4 | 8·2 | 16·8 | 25·0 | 0·67 |

b

Stage (2). Undrained loading, 25–50 lb./sq. in., after dissipation of stage (1) pore pressure from 16·8 lb./sq. in. to 8·4 lb./sq. in. The starting value of the effective stress $(\Delta\sigma')_{1b}$ = 25·0 − 8·4 = 16·6 lb./sq. in., giving a value of $-\Delta V_{1b}/V_0$ = 4·8 per cent

| $-\frac{\Delta V}{V_0}$ % | $\Delta\sigma'$ lb./sq. in. | $-\frac{\Delta V_{12}}{V_0}$ % | $(\Delta\sigma')_{12}$ lb./sq. in. | $(\Delta u)_{12}$ lb./sq. in. | $(\Delta\sigma)_{12}$ lb./sq. in. | $\bar{B} = \frac{\Delta u}{\Delta\sigma}$ |
|---|---|---|---|---|---|---|
| 4·8 | 16·6 | 0 | 0 | 0 | 0 | — |
| 5·6 | 23·4 | 0·8 | 6·8 | 6·4 | 13·2 | 0·48 |
| 6·13 | 28·6 | 1·33 | 12·0 | 13·0 | 25·0 | 0·52 |

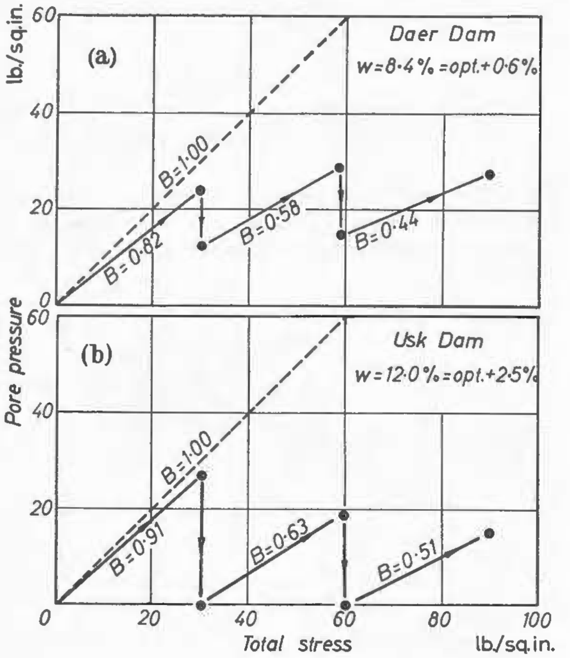

Fig. 8 The results of two laboratory tests on material compacted at a water content above the optimum: (a) with 50 per cent dissipation of excess pore pressure between loading stages and (b) with 100 per cent dissipation between loading stages

Résultats de deux essais faits en laboratoire sur un matériau compacté à une teneur en eau supérieure à optimum (a) avec une diminution de 50 pour cent de la pression interstitielle excédentaire entre les phases due chargement et (b) avec une diminution de 100 pour cent entre les phases de chargements

air is present, i.e. until the volume change $-\Delta V/V_v$ is equal to $n_0(1 - S_0)$, or from equation 6, until

$$\Delta u = p_0 \cdot \frac{(1 - S_0)}{S_0 . \mathrm{H}} \qquad \dots\dots (7)$$

*Increase in pore pressure due to an applied stress with zero drainage*—A series of values of $\Delta V/V_0$ are then chosen and the corresponding values of $\Delta u$ and $\Delta\sigma'$ are obtained from equation 6 and from the volume change–effective stress curve respectively. The results may be tabulated as in Table 1, the last columns giving $\Delta\sigma (= \Delta u + \Delta\sigma')$ and the ratio $\Delta u/\Delta\sigma$. The process is carried on until the required value of $\Delta\sigma$ is reached, or until the saturation limit $-\Delta V/V_0 = n_0(1 - S_0)$ is reached. Above this limit $\delta u = \delta\sigma$.

*Effect of dissipation of pore pressure on degree of saturation*—In general the pore pressure will not dissipate completely after each stage of loading, but will drop from the value $(\Delta u)_1$ at the end of stage 1 to a value $u_b$, as shown in Fig. 5a, and this will form the initial condition for the next stage of loading.* Expressing this initial pore pressure as $p_{0b}$ in absolute units, we can again use equation 6 provided the values of $S_0$ and $n_0$ are recalculated.

During the loading stage, under undrained conditions, the degree of saturation $S$ at any absolute pressure $p$ in the pore space can be calculated from equation 5. After a change $\Delta V$ in the volume of the voids has occurred,

$$S = \frac{\text{vol. of water}}{\text{vol. of voids}} = \frac{S_0 . V_v}{V_v + \Delta V} = \frac{S_0}{1 + \dfrac{\Delta V}{V_v}} \qquad \dots\dots (8)$$

Substituting from equation 5, this becomes

$$S = \frac{S_0}{1 + (p_0/p - 1)\{1 - S_0 + S_0\mathrm{H}\}} \qquad \dots\dots (9)$$

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* Since the total stress is constant between the two loading stages, the effective stress increases by an amount equal to the drop in pore pressure, and the volume change thus increases to $\Delta V_{1b}$ (Fig. 5a).

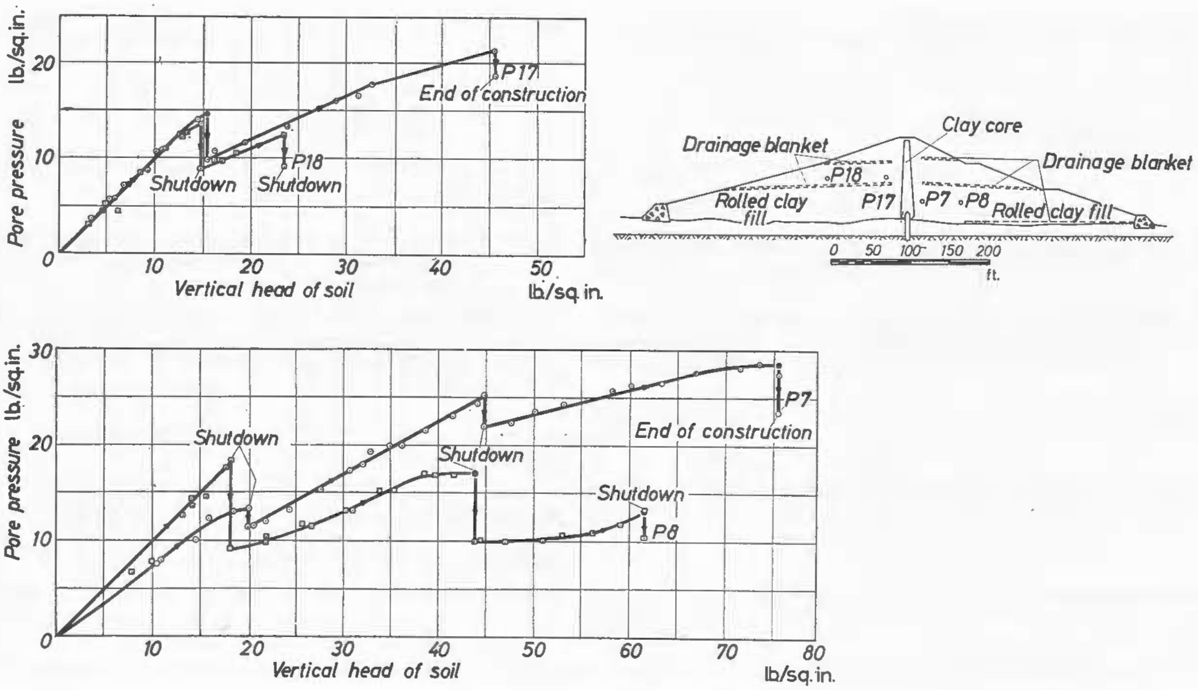

Fig. 9 Field measurements of pore pressure from the Usk dam, showing the influence of pore pressure dissipation ($\sigma_1$ is approximately equal to the vertical head of soil)

Mesures faites sur le chantier de la pression interstitielle du barrage d'Usk, montrant l'influence de la diminution de la pression interstitielle ($\sigma_1$ est à peu près égal à la charge verticale du sol)

The degree of saturation is thus a function only of the initial value $S_0$ and of the change in pore pressure.

If, during the dissipation stage, the mixture of air and water leaving the sample has the same proportions by weight as that remaining in it, equation 9 will continue to hold. For soils containing relatively little free air this assumption would appear likely to err on the safe side since the air bubbles will find difficulty in moving. In relatively dry soils the opposite tendency would be expected. Laboratory measurements of degree of saturation, which are of necessity indirect, indicate that the residual degree of saturation tends to be slightly higher than expected. This may be due to delay in the evolution of dissolved air when the pore pressure drops at the rate usual in a laboratory test.

For practical purposes equation 9 may be accepted, and the new degree of saturation $S_{0b}$ is obtained by substituting $p_{0b}$ for $p$. The new volume of voids is $V_v + \Delta V_{1b}$. As all the volume changes in the soil are expressed in terms of its initial volume $V_0$, the new value of the porosity to be used in equation 6 must also be expressed as a function of $V_0$, i.e.

$$n_{0b} = \frac{V_v + \Delta V_{1b}}{V_0} = n_0 + \frac{\Delta V_{1b}}{V_0} \quad \ldots . \ (10)$$

*Undrained pore pressure increment in second stage*—The increment of pore pressure under undrained conditions can now be calculated for changes in volume from $\Delta V_{1b}$ to $\Delta V_{2b}$ and is represented by curve *IIb* in Fig. 5. From this curve, and the relationship between volume change and effective stress (curve *I*), is obtained the new relationship between volume change and total stress (curve *IIIb*), and between pore pressure and total stress (Fig. 5b). Subsequent stages are calculated in the same way. The steps are outlined in Table 1b.

## Typical Results

*From calculations*—In Fig. 6 the results are given of a calculation in which 50 per cent of the excess pore pressure present at the end of each construction season is assumed to have dissipated before the next layer of fill is placed. The ratio $\bar{B} = \Delta u/\Delta\sigma_1$ is given for each stage, and is compared with the value which would have resulted if no dissipation had occurred. It will be seen that in the second stage the value of $\bar{B}$ is 74 per cent of the value not preceded by dissipation, and in the third stage only 53 per cent. In the field, however, it is only possible to compare the value of $\bar{B}$ in the later stages with that measured in the first. A comparison of calculated values is made in Fig. 7, for a range of dissipation values, and the marked effect on the value of $\bar{B}$ during subsequent stages can be seen.

*From tests in the triaxial apparatus*—The results of two tests on samples compacted on the wet side of the optimum water content are given in Fig. 8, equal all-round pressure being used. In each case the value of $B$ in the third stage is between 50 and 60 per cent of its initial value.

*From an earth fill under construction*—In Fig. 9 the results are given of field measurements of pore pressure at four points in the fill of the Usk dam. The pore pressure in each case is plotted against the total major principal stress. The decrease in the value of $\bar{B}$ after partial dissipation of pore pressure is clearly marked, and in fact exceeded the predicted drop. This probably represents the additional influence both of the change in the state of shear as construction proceeds, and of the continuation of dissipation during the construction periods as well as during shut-down.

The influence of the amount of dissipation in the preceding stage on the subsequent value of $\bar{B}$ is illustrated in Fig. 10, where the results from eleven piezometers are given.

## Conclusions

The effect of consolidation in a layer of partly saturated fill is not only to reduce the excess pore pressure already set up but also to reduce the magnitude of the pore pressure set up, under undrained conditions, by each subsequent increment of load. This is an important factor in determining the effectiveness of natural or artificial drainage of the fill. Its theoretical basis is discussed, and its practical importance is illustrated by laboratory tests, and field results from a recently completed earth dam.

*The experimental work was carried out in the Civil Engineering Department of Imperial College and the author wishes to acknowledge the assistance of Mr B. Kjaernsli, Mr A. J. Watt, and Mr D. W. Lamb. The field piezometers were installed by Mr A. Penman and the author is indebted to the Engineer and Manager, Swansea Corporation, the Daer Water Board and Messrs Binnie, Deacon & Gourley for permission to publish these results, together with the laboratory results from the Usk and Daer dams. Mr C. Kenney has also given valuable assistance, particularly with respect to the numerical solutions.*

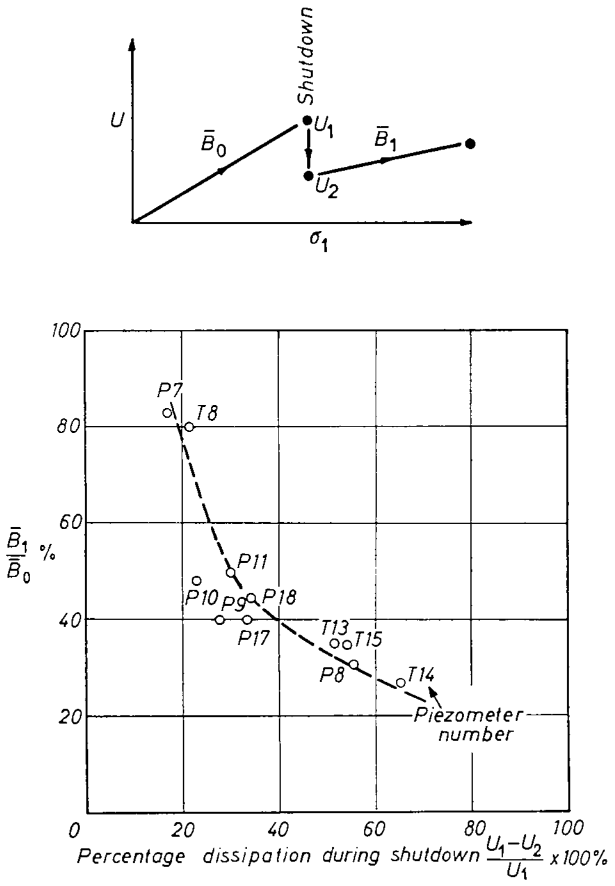

Fig. 10 Influence on pore pressure ratio $\bar{B}$ of percentage dissipation during shut-down (neglecting dissipation during loading stages): from field measurements on the Usk dam)

Effet sur l'indice $\bar{B}$ de la pression interstitielle d'un pourcentage de disparition pendant l'interruption du travail (négligeant toute disparition pendant les phases du chargement): d'après des mesures sur place au barrage d'Usk

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