Construction Pore Pressures in Clay Cores of Dams

Pressions Interstitielles dans les Noyaux d'Argile

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SYNOPSIS: Typical construction pore pressure responses in several modern embankment dams are presented. Construction material characteristics of seven dams are given; construction pore pressure responses of these dams are compared using plots of piezometric level versus fill level. From these plots the "geometric effect" is made apparent. This effect, governed by the geometry and relative material stiffnesses of the dam, results from a progressive reduction in the acting major principal stress, as estimated by σ_1 in the dam core. The piezometric responses in different construction materials are compared according to 3 material classes: glacial drift, overconsolidated clays and residual soils (weathered igneous materials).

INTRODUCTION

Data from the systematic instrumentation of dams during the last 25 years has led to improved understanding of embankment behaviour which in turn, has contributed to reducing discrepancies between predicted and observed performances.

This paper outlines likely ranges of piezometric responses of cores during construction based on performance records of dam cores constructed of the following 3 classes of material; (a) glacial drift (b) over consolidated clays and (c) residual soils (weathered igneous material).

PARAMETERS : DEFINITIONS

In this paper the symbols u, γ and c_v are used in their universally accepted senses. The following definitions are also used:

σ_1	Major total principal stress
h_w	Piezometric equivalent height of water above cell
h_f	Height of fill above cell
H	End of construction height of fill above cell
$\bar{B}$	Pore pressure coefficient $(\bar{B} = \Delta u / \Delta \sigma_1)$
B_h	Slope of h_w versus h_f $(B_h = \Delta h_w / \Delta h_f)$ N. B. $B_h = \gamma \bar{B}$ when $\sigma_1 = \gamma h_f$
r_u	Pore pressure ratio[2] $(r_u = u / \gamma h_f)$
u_o	Pore pressure at placing (may be positive or negative)

THE BASIC PIEZOMETRIC RESPONSE CURVE

Records in which piezometric data is plotted versus time form an essential part of systematic dam performance monitoring. However, difficulties in interpretation arise during construction as such plots are being continuously affected by variations in dissipation responses and changes in the applied stress.

An alternative presentation is to plot piezometric head, h_w, versus height of fill over the cell, h_f, referred to as the piezometric response curve. Such plots facilitate the evaluation of time dependent effects and enable the comparison of different core materials and dam profile responses.

Figure 1 outlines the composition of the basic piezometric response curve. The intercept on the h_w axis, u_o, is shown as zero (atmospheric pressure). Generally u_o lies within a range extending from slightly in excess of, to much less than, atmospheric pressure. An estimate of the likely value of u_o for a particular material positions the piezometric response curve relative to the h_w axis.

Subsequent to placing core fill, the piezometric response at any level depends principally on 3 factors:

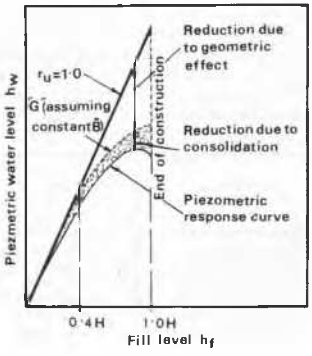

Figure 1. BASIC PIEZOMETRIC RESPONSE CURVE

(a) B̄, which relates the immediate response of pore pressure, u, to the incremental increase in the major total principal stress, σ_1

(b) Time, and

(c) The rates of construction, which include elements of (a) and (b)

For most materials, B̄ is approximately constant over the range of acting σ_1 experienced and, ignoring time dependent effects, u at any level in the core responds in direct proportion to changes in σ_1. If σ_1 increases proportionally with the height of fill, h_f, the piezometric response curve is straight, resulting in the $r_u = 1.0$ line in Figure 1. However, as previous authors have noted,[1,3,4] increases in σ_1 are not generally proportional to h_f.

As dam construction above any level in the core proceeds, the increasing value of σ_1 at that level falls steadily from the straight line estimate of γh_f. Consequently the readings of a piezometer located there can be observed to diverge steadily from the straight "$r_u = 1.0$" line to a curve such as marked "G" in Figure 1.

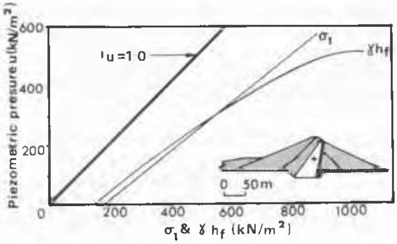

Figure 2. u versus σ_1 and γh_f

MANGLA MAIN EMBANKMENT

An example of this divergence, referred as the "geometric effect", is illustrated in Figure 2 in which a plot of the pore pressures measured in cell 117 at Mangla is given in terms of both γh_f and σ_1, measured by adjacent total pressure cells.

Superposition of time dependent effects (principally consolidation) onto the "G" curve results in further divergence, producing the "piezometric response curve". When the increasing rate of dissipation becomes equal to the decreasing rate of acting load application (due to the geometric effect) the piezometric response curve reaces a peak; thereafter h_w falls despite increasing h_f.

This paper uses the piezometric response curve to form the basis of comparison of piezometric measurements in several dam cores of different materials. For each dam data from one or two piezometers on the core centre line is used.

THE GEOMETRIC EFFECT

The geometric effect results from changes in dam loading geometry during construction. It is also affected by the use of construction materials of contrasting stiffnesses. It is accentuated in steep-sided rockfill dams and is minimal for homogeneous dams with gentle slopes.

End of construction values of σ_1 have been reported as low as $0.70\ \gamma H$ (Brianne [3]). For design purposes accurate estimates of the geometric effect call for the use of finite element techniques [4].

Comparison of the examples given demonstrates empirically the relationship between dam geometry and material stiffnesses giving rise to the geometric effect. Piezometer locations are indicated by crosses on the outline diagrams accompanying each figure and free draining materials by shading.

SUMMARY DESCRIPTIONS OF DAMS AND CORE MATERIALS STUDIED

Geographic locations, principal dimensions, and descriptions of the dams studied are summarised in Table 1. Material properties and fill placing conditions are given for each dam in Table II.

This study is facilitated by grouping the dams' core materials into 3 classes:

(a) Glacial drift

(b) Overconsolidated clays

(c) Residual soils (insitu weathered igneous materials).

Deposits of materials (a) studied generally have consistent properties with c_v in the range 5-20 m²/yr and P.I. of 10-20%.

Deposits of materials (b) generally have low c_v of less than 2 m²/yr and have more variable P.I. ranging from 25-45%. Resulting from their previous overconsolidation these materials exhibit a tendency to swell after placing.

Dam	Type	Height	Core thickness		Core material
			Base	Crest	
Brianne (Wales)	Rockfill	91 m	49	6 m (C)	Glacial Drift
Celyn (Wales)	Rockfill	54 m	17	6 m (S)	Glacial Drift
Mangla (Pakistan)	Rockfill	115 m	67	12 m (S)	Siwalik Clay
Grafham (England)	Earthfill	25 m	12	4 m (C)	Oxford Clay (reworked)
Farmoor (England)	Earthfill	12 m	5	4 m (C)	Oxford Clay
Arlington (England)	Earthfill	23 m	6	3 m (C)	Weald Clay
Lower Shing Mun (Hong Kong)	Earthfill	57 m	30	6 m (C)	Weathered Granite

Notes : (S)... Upstream sloping core (C)... Symmetrical centrally situated core

TABLE I: SUMMARY DESCRIPTIONS OF DAMS AND MATERIAL TYPES

DAM	Atterberg limits		Proctor density test		Placed		C_v m^2/yr	r_u at E.O.C. (max)
	P.L. (%)	L.L. (%)	Max density γd (T/m³)	Optimum M.C. (%)	γd (T/m³)	M.C. (%)		
Brianne	15-20	25-30	2.11	10.8	2.12	11.2	15-20	0.63
Celyn	18	32	2.07	12.3	2.12	12.4	3-6	0.42
Mangla	18	40	1.87	15.0	1.91	15.0	10-70	0.48
Grafham	20	58	1.71	19.5	1.69	20.5	0.1-0.4	0.50
Farmoor	23	63	1.60	23.6	1.55	25.2	0.1-0.4	0.10
Arlington	23-28	45-75	1.61	22.0	1.61	23.0	1-2	0.50
Lower Shing Mun	32	57	1.72	18.5	1.63	21.2	10-100	0.27

TABLE II: MATERIAL PROPERTIES, PLACING CONDITIONS AND END OF CONSTRUCTION PORE PRESSURES FOR DAM CORES STUDIED

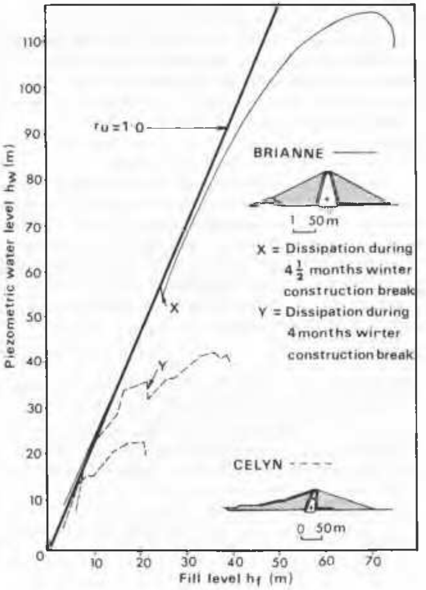

Figure 3: BRIANNE AND CELYN

Deposits of materials (c) often have considerably variable properties, even within one site, reflecting the degree of weathering of the parent rock which was granite in the example given. C_v is variable, lying in the range 10-100 m^2/yr and these materials typically have P.I. in the range 18-38%.

PERFORMANCES OF GLACIAL DRIFT CORES FIGURE 3.

Observed piezometric response curves for these materials have a similar form to the basic curve. In each material u_o was close to atmospheric pressure (slightly above in Brianne, slightly below in Celyn). Initially B_h was 1.0γ. Dissipation was slight (see detail of reduction in h_w during the winter breaks) so the response curves do not diverge much from the "G" curves. These dam cores showed maximum values of piezometric height attained before the end of construction. The geometric effect becomes apparent at values of h_f between 0.40H (Celyn) and 0.50H (Brianne).

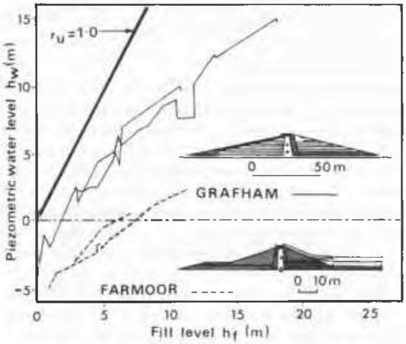

Figure 4: FARMOOR AND GRAFHAM

Maximum values of h_w were reached at values of h_f between 0.85H (Celyn) and 0.90H (Brianne), and by the end of construction values of r_u for each dam were 0.42 (Celyn) and 0.63 (Brianne).

In contrast to Brianne and Celyn (both rockfill) Cow Green* and Derwent+, earthfill dams of drift material, both responded to construction with roughly constant B_h values of 0.90γ and 0.75γ respectively. By the end of construction the reduction in h_w due to the geometric effect was of the order of 5-10% and maximum r_u values were 0.70 (Cow Green) and 0.75 (Derwent).

PERFORMANCES OF OVERCONSOLIDATED CLAY CORES - FIGURE 4 AND 5

The two Oxford Clay dams (Grafham and Farmoor, Figure 4, show similar characteristic responses. In each case u_o was negative and although isolated piezometers showed apparently no response, in general responses to construction were roughly constant with a B_h of 0.40γ to 0.60γ.

* Atterberg limits[7]: P.L. 13% to 18%; L.L. 30% to 50%
C_v - 1 to 3 m^3/yr

\+ Atterberg limits[5]: P.L. 16% L.L. 35%; C_v = 2 to 4 m^2/yr

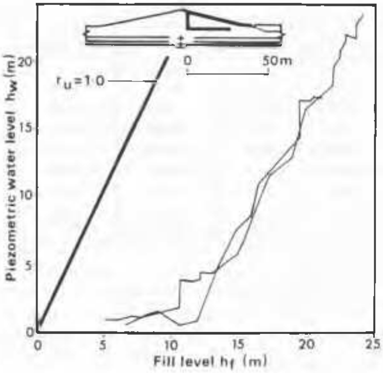

Figure 5: ARLINGTON

Dissipation was negligible. Indeed owing to their low values of c_v these materials may have continued swelling for some time. The geometries of these dams, fairly flat slopes, with similar stiffness of core and shoulders are such that the geometric effect was little. The slight deviation of the curves from their mean B_h at values of h_f between 0.70 and 0.80H may be attributable to geometry. Highest values of end of construction pore pressure rations were r_u = 0.50 (Grafham) and r_u = 1.10 (Farmoor).

Data from Arlington, constructed of Weald Clay, gives different response curves. The pore pressure u_o was close to zero (generally negative); B_h increased steadily from a low initial value (0 to 0.3 γ) until becoming at 1.0 γ. Piezometers in the lower part of the dam showed very similar responses, each reaching B_h = 1.0 γ after about 13m of fill had been placed over it. The highest end of construction pore pressure ratio was r_u = 0.50.

PERFORMANCES OF RESIDUAL SOIL CORES FIGURE 6

The high values of c_v (10 to 100 m^2/year) make consolidation the controlling factor in pore pressure generation in dams constructed of these materials. Generally, the piezometric levels remained roughly at u_o (see line (1)). In Lower Shing Mun one piezometer nearest the base of core responded as shown by (2) in the figure, developing a maximum piezometer head of h_w = 24m. The rate of pore pressure dissipation can be judged by a drop of 5 m in h_w during a one month construction break. For most dams constructed of these materials the pore pressure response lay within the limits of (1) and (2) in Figure 6 with B_h = 0. Highest end of construction pore pressure ratio was r_u = 0.27.

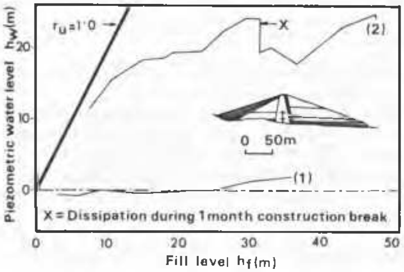

Figure 6: LOWER SHING MUN

CONCLUSIONS

For the purposes of comparing pore pressure generation in the cores of dams during construction, plots of piezometric height, h_w, versus fill height, h_f, are particularly valuable.

From such plots the "geometric effect" is made apparent. This effect, observed in Mangla and Brianne dams, results in a reduction of the principal stresses (and hence pore pressures) acting in dam cores during construction. It is most noticeable in dams with steep sided rockfill shoulders where, at the end of construction, values of σ_1 may amount to only 0.70γh_f. In flat, homogeneous dams this effect is less apparent, reducing σ_1 to between 0.90 - 0.95γ h_f.

Assuming σ_1 in a dam core to be equal to γh_f can therefore result in overestimating pore pressures during design. The examples studied in this paper serve to give the patterns of response for a wide range of core fill materials used in dam construction and may, together with laboratory test results, aid the prediction and interpretation of construction pore pressures in embankments.

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