Effect of Seepage on Embankment Deformations Due to Water Loading

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SUMMARY. A finite element analysis is made of the movements in an embankment due to water loading, taking account of seepage through the embankment. The effects on deformations of drainage within the embankment and of a central core are investigated for an embankment resting on a rigid base. It is found that the long-term deformations due to water loading may be considerably affected by the pattern of steady state flow, and hence by the provision of drainage within the embankment. Larger horizontal movements are developed when seepage occurs than if an impermeable membrane exists on the upstream face. The modulus of the core relative to the shells also has a significant effect on movements.

1 INTRODUCTION

The finite element method has been widely used to analyse the deformations of embankments and earth and rock dams (Refs.1 & 4). Most analyses have been concerned with movements during and just after construction or with movements due to water loading. For the latter case, the water loading has generally been represented as an external applied load on the face of the embankment and little consideration appears to have been given to the effect of seepage on the deformation.

In this paper, the application of the finite element method to the determination of embankment deformations in the presence of steady state pore pressures is outlined. A series of solutions for an idealized case is then presented to illustrate the effect on deformations of drainage within the embankment and of the presence of a central core surrounded by permeable shells.

2 FINITE ELEMENT ANALYSIS

The finite element method provides a convenient method for determining numerically the stresses and displacements throughout an elastic body subject to prescribed body forces and surface tractions. Conventional finite element programs cannot be used to analyse the behaviour of a saturated soil with an elastic skeleton because of the presence of the excess pore pressure u in the stress-strain law. However an examination of the governing equation shows that the effective stress behaviour of a two-phase soil is equivalent to a single phase elastic mass in which the shear tractions are unchanged, the normal tractions at a point are decreased by an amount equal to the pore pressure at that point and the body forces are increased by the amount ($\partial u/\partial y$, $\partial u/\partial y$, $\partial u/\partial z$). Thus conventional finite element programs can be used to analyse the effective stress behaviour of two phase elastic soils provided that the pore pressure and spatial pore pressure gradient can be specified at each node point.

3 APPLICATION TO DAMS SUBJECTED TO SEEPAGE

For dams through which seepage occurs (i.e. those without an impervious upstream membrane), the prediction of deformations due to water loading requires consideration of the following factors:

(i) immediate deformations due to initial saturation of the embankment material

(ii) immediate deformations due to water loading acting as an applied load on the upstream side of the embankment

(iii) further deformations due to the establishment of steady state flow conditions within the embankment.

Deformations due to collapse on initial saturation are generally only significant in rockfill dams, particularly those in which the rockfill is dumped rather than rolled. An attempt to predict such deformations has been described by Nobari & Duncan (Ref.5). However, in many earth dams, there is evidence that little or no deformation occurs due to saturation on initial filling, even with materials compacted to average water contents as low as 3% below Standard Proctor Optimum (Ref.7). Attention herein will therefore be confined to consideration of the latter two sources of deformation listed above.

The immediate deformations of a dam due to water loading may most readily be estimated by carrying out a total stress analysis in which the water loading is considered as an applied normal force on the upstream face of the embankment and the upstream side of the foundation (provided that the upstream shell is not very permeable). The undrained deformation parameters are input into the analysis. Some parametric solutions for this case have been presented in Ref.2.

The total long-term movements due to establishment of steady state flow within the embankment, including the immediate movements, may be estimated from the effective stress analysis described earlier. The final pore pressures in the embankment may be determined from a flow net or alternative method of solution of the Laplace equation for steady state flow. The relevant initial pore pressures will be those existing in the embankment just prior to the commencement of water loading. These will depend on the magnitude of the pore pressures developed during construction and the rate of pore pressure dissipation during and after construction, up to the time that the water loading begins. Methods of predicting construction pore pressures are available (e.g. Ref.3), but measurements in several dams have shown that construction pore pressures are sensitive to the initial water content, the soil type and the amount of compaction, thus making accurate prediction of these pore pressures difficult. A numerical method for the rate of pore pressure dissipation in an embankment subsequent to construction has been proposed by Richards & Chan (Ref.6), but no reliable method is yet available for the determination of the rate of pore pressure dissipation during construction of an embankment.

If the response of the embankment material is assumed to be elastic, two separate analyses may be carried out, one considering water loading together with the final pore pressures, and the other using the estimated initial pore pressures with the pore pressure gradients as body forces. The total deformations due to water loading may then be obtained by subtracting the movements given by the second analysis from those given by the first. The influence on the movements of the initial pore pressures (reflecting the compaction moisture content and compactive effort) may thus be examined readily. However, if the embankment material has a non-elastic response, the initial pore pressures must be input and the deformations resulting from the change to the final pore pressures then determined by an iterative procedure.

In view of the difficulties involved in estimating the pore pressures in the embankment just prior to water loading and of generalizing on their magnitude and distribution, the solutions to be presented in this paper will initially assume the initial pore pressures to be zero at all points in the embankment i.e. the change in pore pressure at any point caused by the establishment of steady flow is assumed to be equal to the final steady state pore pressure at that point. This assumption will lead to an overestimate of movement if the initial pore pressures are positive and to an underestimate if negative pore pressures exist prior to water loading.

Typical solutions showing the effects of the initial pore pressures will be presented subsequently for an idealized distribution of pore pressure prior to water loading. Since the embankment is assumed to be linearly elastic, with constant drained Young's modulus E' and Poisson's ratio ν', the movements given by this analysis may be subtracted from those for zero initial pore pressure to give the movements due to water loading.

In obtaining the solutions described herein the embankment was divided into quadrilateral elements, as shown in Fig.1. Solutions from this type of finite element idealization agreed closely with those obtained by Clough & Woodward (Ref.1).

3 SOLUTIONS FOR A HOMOGENEOUS DAM

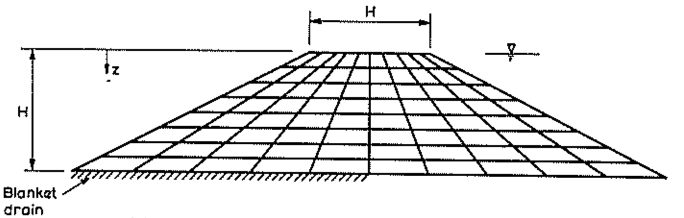
Solutions have been obtained for the homogeneous dam resting on a rigid impermeable base with a full pool (Fig.1a) for two cases:

(a) no drains within the dam

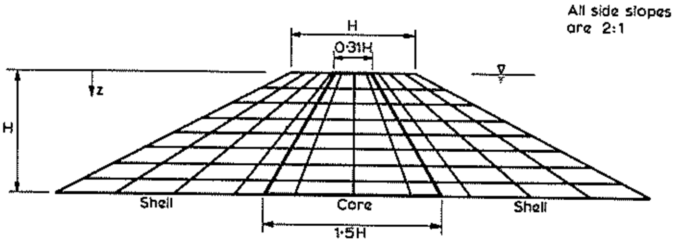
(b) a downstream horizontal blanket drain extending to the centre of the embankment.

For each case, the pore pressures for steady state flow were determined from a finite element solution of the Laplace equation.

Contours of horizontal and vertical deflections for the dam with no drain are shown in Fig.2 for Poisson's ratio ν' of the embankment of 0.4. The deflections are the total movements since water loading was commenced and include immediate deflections. The maximum movements occur near the crest. It has been found that the maximum horizontal movement is not greatly influenced by ν' but that the maximum vertical movement increases as ν' decreases. The vertical movements, which are upwards in all cases, are greater in magnitude than the horizontal movements.

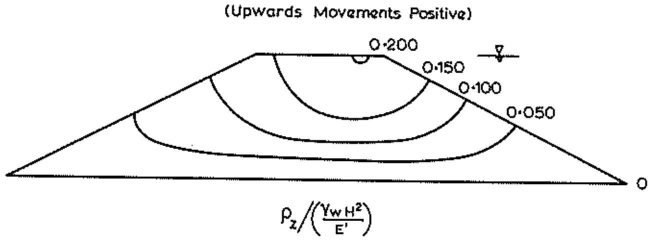


(a) Finite Element Grid For Homogeneous Embankment.

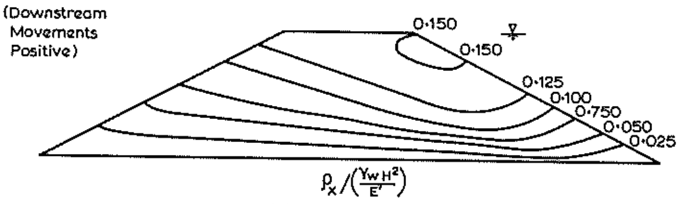


(b) Finite Element Grid For Cored Embankment.

Fig.1 Finite Element Representation of Dams



(a) Vertical Movements $\nu' = 0{\cdot}4$

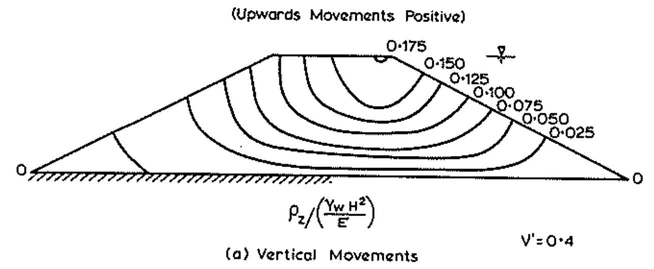


(b) Horizontal Movements

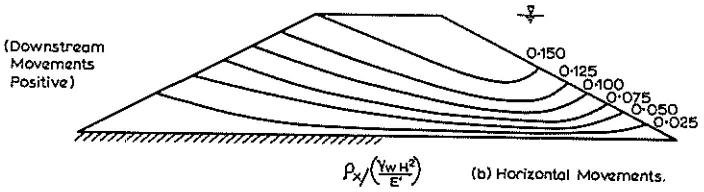
Fig.2 Contours of Final Movement. Homogeneous Dam, No Drain

Typical horizontal and vertical deflection contours for the dam with a blanket drain are shown in Fig.3 for $\nu' = 0.4$. A comparison with the corresponding contours for the dam with no drain in Fig.2 reveals that the distributions of vertical and horizontal deflection are generally not markedly affected by the presence of the drain; however, the maximum vertical movement is decreased slightly while the maximum horizontal movement is slightly increased.

Clearer illustrations of the effects of the drain are given in Fig.4 where deflection distributions with depth are plotted for the centre-line and the upstream and downstream faces.

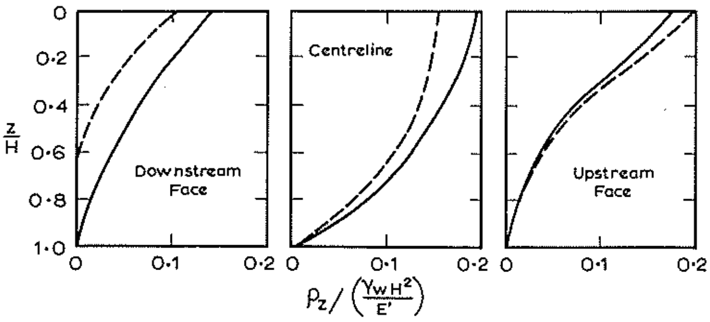


(a) Vertical Movements

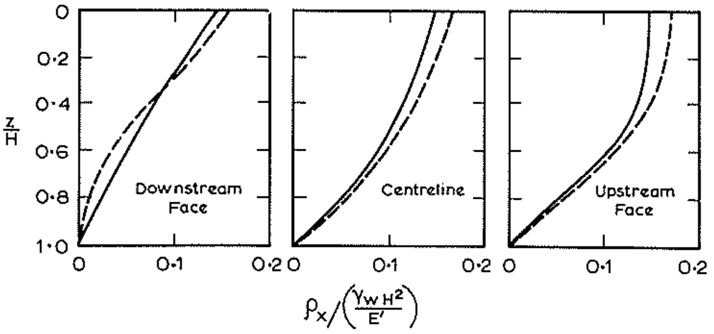


(b) Horizontal Movements.

Fig.3 Contours of Final Movement. Homogeneous Dam, Blanket Drain



(a) Vertical Movement (positive upwards)



(b) Vertical Movement (positive downstream)

V' = 0·4

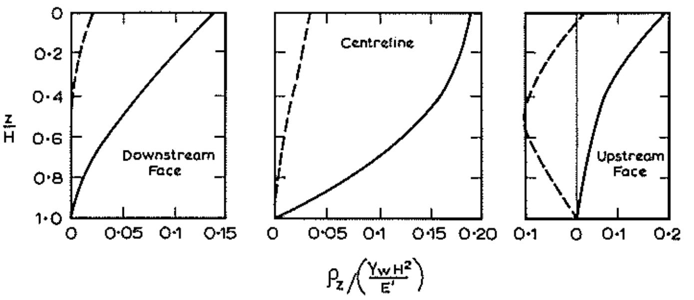
——— No drain

– – – Blanket drain

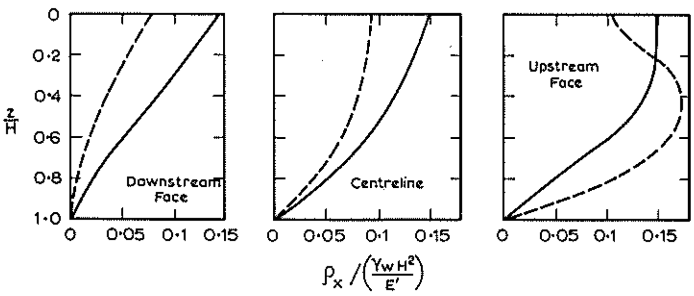
Fig.4 Effect of Drainage Blanket on Movements. Homogeneous Dam

4 EFFECT OF SEEPAGE ON EMBANKMENT DEFORMATIONS

The effect of seepage on embankment deformations may be illustrated most conveniently by comparing the long-term movements of a dam having an upstream impermeable membrane (i.e. no seepage through the dam) with those of an identical dam through which seepage occurs. Such comparisons are shown in Fig.5 for a homogeneous embankment with a full pool. Distributions of vertical and horizontal movement are plotted for the upstream face and centreline and down-stream face. Seepage tends to cause much greater upward vertical movements. The effect of seepage on horizontal movements is variable. Movements at the centre line and downstream face are increased considerably, but the movement at the upstream face is decreased except in the vicinity of the crest.



(a) Vertical Movement (positive upwards)



(b) Horizontal Movement (positive downstream)

V' = 0·4

——— Seepage through dam.

– – – Dam with Impermeable Upstream Membrane.

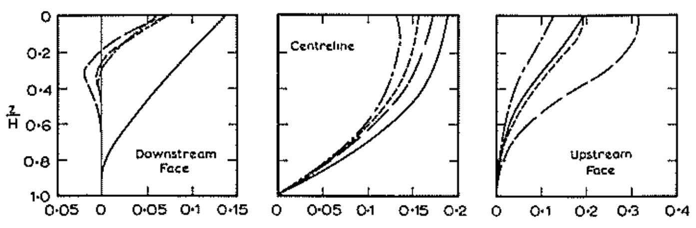
Fig.5 Effect of Seepage on Movements. Homogeneous Dam. No Drain

5 EMBANKMENT WITH CENTRAL CORE

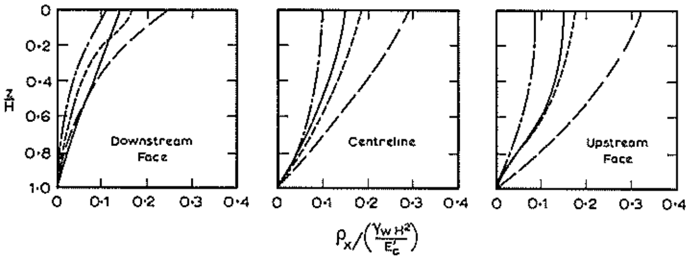
In order to examine the effects of seepage on the movements of embankments with a central core, the embankment shown in Fig.1b has been analysed. The shells are assumed to be elastic, with a constant Young's modulus E_s' and Poisson's ratio ν_s', and infinitely permeable. The core is assumed to be elastic, with drained elastic moduli E_c' and ν_c'. The position of the phreatic line and the resulting pore pressures in the core under steady flow conditions have been determined by the same numerical procedure used for the homogeneous dam.

Typical deflection profiles for the centreline and upstream and downstream faces are shown in Fig. 6 for three ratios of E_c'/E_s'. As E_c'/E_s' increases, the upward movements tend to increase along the centreline and upstream face, but the downstream face vertical movements are not greatly affected. As would be expected, the horizontal movements decrease as E_c'/E_s' increases, for a given E_s' value.

Also shown in Fig.6 are solutions for a homogeneous dam in which the core and shell are of the same material (Fig.4). This case differs from that of a dam with a core because of the difference in the steady state flow pattern between the two cases. The deflections for the homogeneous dam generally do not differ significantly for the core dam having $E_c'/E_s' = 1$. The difference is most marked at the downstream face and the centreline, where the differences in the final stready state pore pressures are greatest. These solutions again illustrate the influence of the final steady state pore pressures on the long-term movements of a dam subjected to seepage.



(a) Vertical Movement (positive upwards)



(b) Horizontal Movement (positive downwards)

$\nu'_c = \nu'_s = 0.4$

—·— Cored dam $E'_c/E'_s = 0.5$
------- Cored dam $E'_c/E'_s = 1.0$
— — — Cored dam $E'_c/E'_s = 2.0$
——— Homogeneous dam

Fig.6 Effect of Central Core on Movements

6 EFFECT OF INITIAL PORE PRESSURES

To examine the effect on deformations of initial pore pressures existing in the embankment prior to water loading, an analysis was carried out using an idealized distribution of initial pore pressure u_o given by

$$u_o = \bar{B}\gamma h \qquad (1)$$

where $\bar{B}$ = pore pressure coefficient, γ = bulk unit weight of soil, h = height of soil above a point.

The resulting pore pressure gradients were treated as body forces, and $\bar{B}$ was assumed to be constant throughout the embankment. Contours of dimensionless vertical and horizontal movement are shown in Fig.7 for a homogeneous embankment. The magnitude of the actual movement will depend on the value of $\bar{B}\gamma$. As mentioned previously, provided that linear soil response is assumed, the movements due to water loading may be obtained by subtracting the movements as given by Fig.7, from the movements determined when the water loading acts in conjunction with the final pore pressures (i.e. when zero initial pore pressures are assumed).

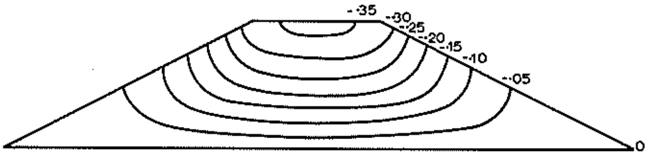
7 CONCLUSIONS

It has been shown that the consideration of flow through an embankment can lead to considerable differences in theoretical long-term movements due to water loading as compared with the case of a perfectly impervious embankment. The long-term movements are dependent on the final steady state flow pattern developed within the embankment. Thus, the provision of a drainage blanket or the presence of a core between pervious outer shells, may result in considerably different movements as compared with those developed in a homogeneous dam with no drain.

Although only one embankment geometry has been considered and general conclusions regarding the effects of seepage on embankment movements cannot be made, it is obvious that there is a tendency for larger upward vertical movements and larger downstream horizontal movements to occur as compared with the case where no seepage through the dam is concerned. The provision of an upstream impermeable facing on the embankment may therefore be advantageous from the point of view of long-term movements, as well as for its primary purpose of seepage control.

The solutions presented herein are idealized and do not take account of such factors as the movements due to initial saturation, the non-elastic and nonlinear stress-strain response of the embankment material and the rate of development of long-term movements. However, provided appropriate formulations of material behaviour can be made, incremental analyses incorporating these factors may be carried out using the approach described in the paper.

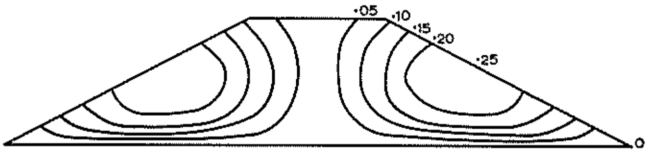
(Upwards Movements Positive)



(a) Vertical Movements - Contours of $\rho_z/\left(\frac{\bar{B}\gamma H^2}{E'}\right)$

$\nu' = 0.4$

(Outwards Movements Positive)



(b) Horizontal Movements - Contours of $\rho_x/\left(\frac{\bar{B}\gamma H^2}{E'}\right)$

Fig.7 Contours of Movement Arising from Initial Pore Pressures Prior to Water Loading

8 ACKNOWLEDGEMENTS

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