Finite element calculations of dam stability

Le calcul de la stabilité du barrage par des éléments finis

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SYNOPSIS A simple procedure for predicting embankment stability using the nodal displacements determined from finite element analyses is presented. It is applied to two large existing dams and found to be promising as an alternative approach to stability analysis.

INTRODUCTION

The application of the finite element method to analysis of stresses and movements in earth and rockfill dams has been well established over the past decade or so. Various finite element stability analysis methods have been proposed, developed and used with differing degrees of success as compared with limit equilibrium stability analysis methods. However, the use of this method in predicting the stability of dams has not received wide attention. A simple procedure for predicting embankment stability using the nodal displacements determined from non-linear finite element analyses is presented here.

REVIEW OF EXISTING FINITE ELEMENT STABILITY ANALYSIS METHODS

Three finite element stability analysis methods have been proposed and developed (1,2). The first method, F_{FE1}, is based on stress level or fraction of strength mobilised. The reciprocal of the stress level is interpreted as being equal to the value of local safety factor. It is assumed that the minor principal stress is the same at failure as for the mobilised stress state.

The second method, F_{FE2}, is based on shear stress. It uses the same definition of safety factor employed in limit equilibrium analysis procedures. The value of normal stress on the shear surface is assumed to be the same in the equilibrium and failure states.

The third method, F_{FE3}, is similar to F_{FE1} but with each local stress level weighted according to available shear strength. The assumptions of F_{FE1} and F_{FE2} are necessary for this method.

FINITE ELEMENT SAFETY FACTOR METHOD BASED ON TOTAL NODAL DISPLACEMENT (F_{δ_T})

In this method, the strength parameters, cohesion, c, and coefficient of friction, $\mu(=\tan\phi)$, of the component materials are incrementally reduced by multiplying them with a common reduction factor, N (< 1.0), and the behaviour of the total nodal displacement, δ_T, is observed. The displacements generally increase with the decrease of N and a typical plot of 1/N against δ_T is shown in Figure 1. The sharp "break-off" point where δ_T begins to increase rapidly for a small reduction of N gives the critical value of N and its reciprocal may be interpreted as the safety factor, F_{δ_T}. The interpretation can be physically explained, as a design would have a safety factor of 1/N if limiting equilibrium can be achieved with the strength parameters of the component materials at N times the design values.

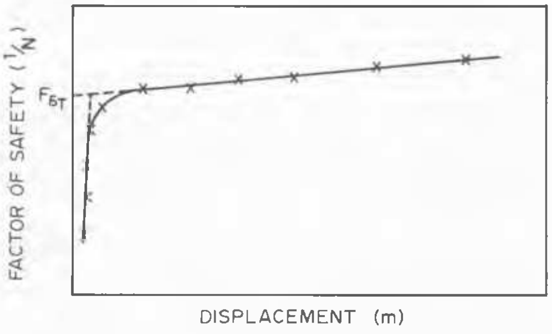

Fig.1 Behaviour of Total Nodal Displacement with the Variation of 1/N

The displacement behaviour needs to be plotted for numerous nodes within the potential failure region to indicate any possible slip surface. This can be easily detected from the displacement vector plots which define a continuous line of vectors with rather large δ_T of approximately the same magnitude and it would have a safety factor corresponding to 1/N of the corresponding plot.

Thus, unlike other definitions of safety factor, no slip surface need be assumed for the analysis. In addition, the assumptions involved in limit equilibrium methods and the various finite element safety factor methods are eliminated. However, other assumptions are employed and they are as follows:

i) the reduction of the strength parameters of a material would not affect its other properties.

ii) the rather large δ_T calculated are valid, at least until just after the sharp "break-off" point, although in the finite element analysis we are using small displacement theory.

APPLICATIONS

Analyses were carried out on Talbingo and Dartmouth Dams and the values of F_{δ_T} predicted were compared with those predicted by Bishop's simplified method, F_{LE}, and the various finite element safety factor methods. In addition, sensitivity studies were carried out on Talbingo Dam on the effect of the variation of the strength parameters of each component material on δ_T and F_{δ_T}.

Talbingo Dam

Talbingo Dam is a 162m high structure with a core which slopes moderately upstream and fairly broad transition zones as shown in Figure 2. The strength parameters of all the component materials were incrementally reduced from 100% (1/N = 1.00) to 40% (1/N = 2.50) of their design values (1). The behaviour of nodal displacement with the reduction of the parameters was observed for the nodes as shown in Figure 2. Typical nodal displacement behaviour is presented in Figure 3. The nodes generally have sharp "break-off" points in their displacement behaviour and the range of F_{δ_T} predicted is between 2.05 and 2.14.

The displacement vector plots corresponding to 1/N of 2.06, 2.11 and 2.50 are shown in Fig. 4. From the plots, it is observed that at 1/N of 2.06, no significantly large δ_T occur and there is no apparent slip surface. At 1/N of 2.11, large δ_T occur in the upstream slope of the dam and they are located in the rockfill, transition and core zones, which indicates that the resistance against slip failure is provided by all of these component materials. A slip surface becomes apparent and it is shown in Figure 4(b). At 1/N of 2.5, δ_T in the upstream slope increased in magnitude significantly with a slip surface basically similar to that for 1/N of 2.11.

From the displacement vector plot for 1/N of 2.11, a circular slip surface was assumed for stability analyses and the safety factors are presented in Table I. The results show that F_{δ_T} agrees well with F_{FE1} and F_{FE3} but to a lesser extent with F_{LE} and F_{FE2} which are slightly larger. The good to reasonable agreement between all the safety factors indicates that δ_T can be used in determining the safety factor of earth and rockfill dams and also that the assumptions made in F_{δ_T} are justifiable.

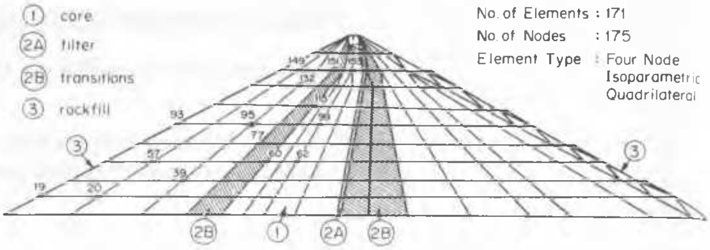

Fig.2 Nodes Observed in Talbingo Dam

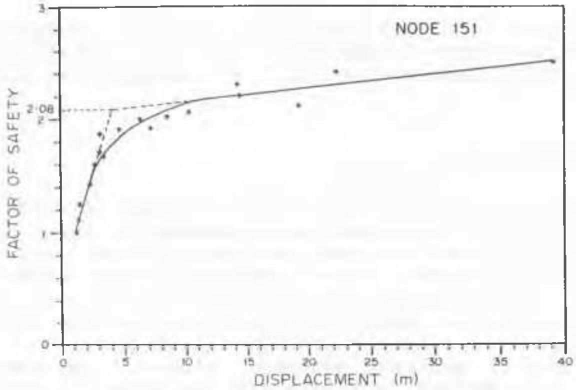

Fig.3 Nodal Displacement Behaviour

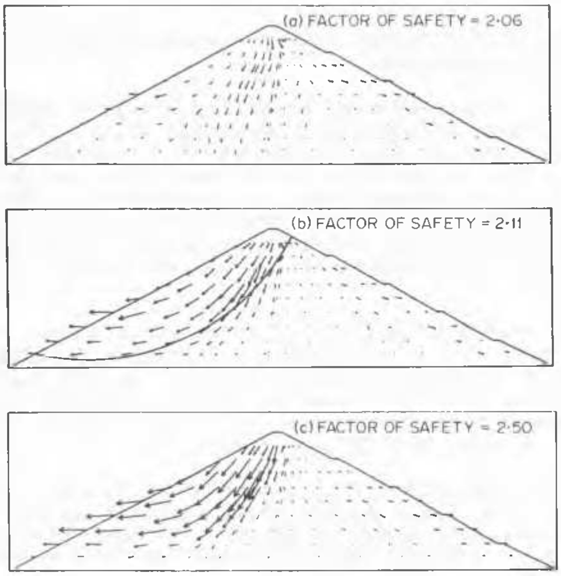

Fig.4 Displacement Vectors

A sensitivity study was carried out to observe the behaviour of δ_T as the strength parameters of each material were incrementally reduced individually. The behaviour of δ_T with the

TABLE I

Comparison of Safety Factors for Talbingo Dam

Critical circle information*			Total stress safety factors				
X(m)	Y(m)	Rad(m)	F_{FE1}	F_{FE2}	F_{FE3}	F_{LE}	F_{δ_T}
100.3	290.0	278.8	2.10	2.23	2.11	2.21	2.11

*Note: Origin of X, Y axis is the intersection point of upstream rockfill slope and embankment base.

reduction of μ' of the rockfill, transition and filter zones was observed for a number of nodes and typical behaviour is shown in Figure 5. Generally the "break-off" points were less sharp and the F_{δ_T} predicted lie between 2.11 and 2.21, slightly higher than the values corresponding to the reduction of the strength parameters of all the component materials simultaneously. The displacement vector plot corresponding to 1/N of 2.20 is shown in Figure 6 and a relatively shallow slip surface in the rockfill zone is apparent in the upstream slope.

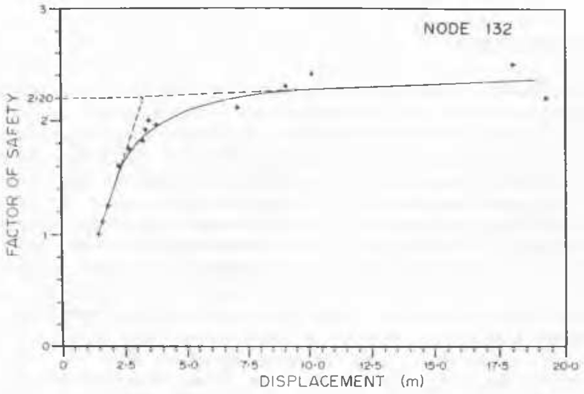

Fig. 5 Nodal Displacement Behaviour (reduction of μ' of rockfill, transition and filter materials)

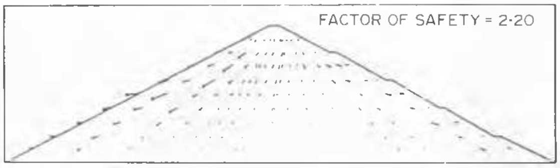

Fig. 6 Displacement Vectors (reduction of μ' of rockfill, transition and filter materials)

The behaviour of δ_T with the individual reduction of μ and c of the core material was observed for a number of nodes and their typical behaviour is shown in Figures 7 and 8 respectively. The plots show that δ_T increases gradually with the reduction of the strength parameters without any "break-off" point. This indicates that the stability of the dam is not sensitive to the reduction of μ and c of the core material individually.

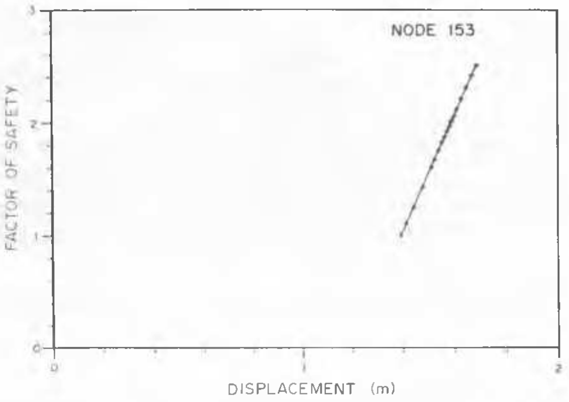

Fig.7 Nodal Displacement Behaviour (reduction of μ core material)

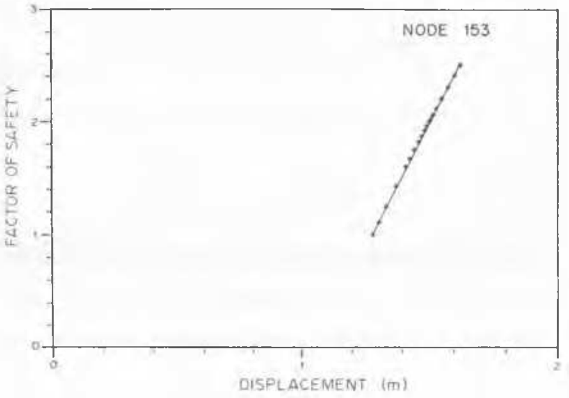

Fig. 8 Nodal Displacement Behaviour (reduction of c of core material)

The sensitivity study provides us with information as to which strength parameters of the component materials are significant for the stability of a dam and therefore which materials need to be most carefully tested in the laboratory and controlled in the field.

Dartmouth Dam

The dam stands at an enormous height of 180m with a central vertical core and fairly thin filter zones, as shown in Figure 9. The strength parameters of all the component materials were incrementally reduced from 100% (1/N = 1.00) to 47.5% (1/N = 2.11) of their design values (1). The behaviour of nodal displacement with reduction of the parameters was observed for a number of nodes as shown in Figure 9. The typical displacement behaviour of these nodes is presented in Figure 10.

The nodes generally have a sharp "break-off" point in their displacement behaviour and the range of F_{δ_T} predicted is between 1.88 and 1.93. The displacement vector plots corresponding to 1/N of 1.87, 1.92 and 2.00 are shown in Figure 11. The plots show that at 1/N of 1.87, no significantly large δ_T occur and there

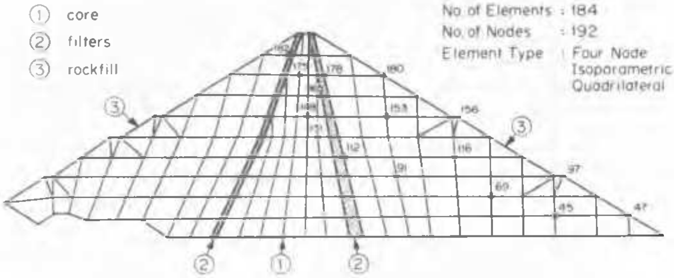

Figure 9 Nodes Observed in Dartmouth Dam

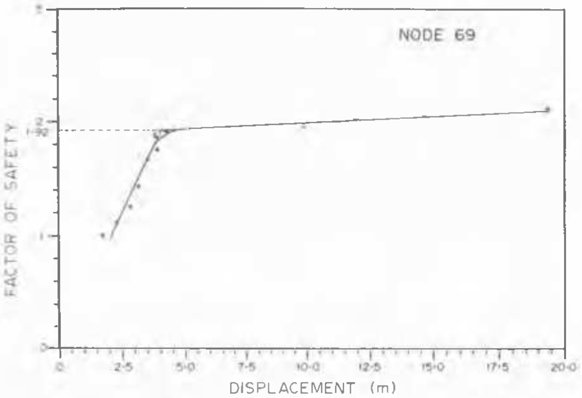

Figure 10 Nodal Displacement Behaviour

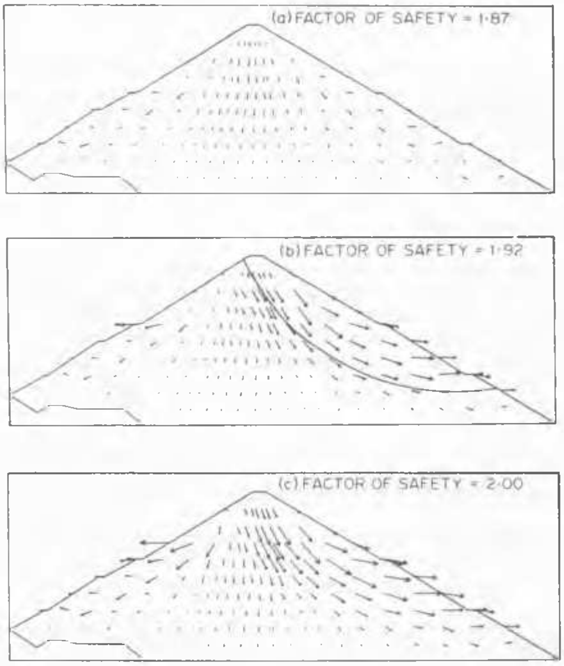

Figure 11 Displacement Vectors

is no apparent slip surface At 1/N of 1.92, large δ_T occur in the downstream slope of the dam and a slip surface is apparent, as shown in Figure 11(b). At 1/N of 2.00, δ_T in the downstream slope increase in magnitude significantly with a slip surface similar to that for 1/N of 1.92.

From the displacement vector plot for 1/N of 1.92, a circular slip surface was assumed, to obtain the safety factors presented in Table II. The results show that F_{δ_T} again agrees well with F_{FE1} and F_{FE3} but to a lesser extent with F_{LE} and F_{FE2} which are slightly larger.

TABLE II

Comparison of Safety Factors for Dartmouth Dam

Critical circle information*			Total stress safety factors				
X(m)	Y(m)	Rad(m)	F_{FE1}	F_{FE2}	F_{FE3}	F_{LE}	F_{δ_T}
539.6	294.3	259.8	1.96	2.18	1.91	2.13	1.92

CONCLUSIONS

A stability analysis method, based on the nodal displacements of embankments calculated using non-linear finite element methods was presented and discussed. It was applied to Talbingo and Dartmouth Dams and the results showed that it is promising as an alternative approach to the stability analysis of earth and rockfill dams. The main advantage of this method is that no failure surface need be assumed for the analysis. In addition, the assumptions involved in the limit equilibrium methods and the various other finite element definitions are eliminated. However, other assumptions are employed, although they are less restrictive. The method also indicates clearly which material strength parameters are significant for the stablity of a dam.

REFERENCES

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2. Kulhawy, F.H., Duncan, J.M. and Seed, H.B. (1969). Finite Element Analysis of Stresses and Movements in Embankments during Construction. Report TE 69-4, University of California, Berkeley.