Nonlinear Analysis of a High Rockfill Dam

L'Analyse Non-Linéaire d'un Haut Barrage en Enrochement

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SYNOPSIS Stress and deformation analysis of a 260 m high rockfill dam under reservoir full condition has been carried out by finite element method. For the analysis, nonlinear hyperbolic material model, mixed graded elements comprising parabolic elements in the core and transitions and the linear elements in the shell portion are used. Interfacial sliding has been allowed by providing nonlinear parabolic joint elements along material boundaries and the joint material constants have been determined experimentally. Two dimensional plane-strain analysis has been carried out by using residual force approach for five stages of reservoir filling for the two types of cores and a comparative study has been made.

INTRODUCTION

Finite element analysis of high rockfill dams for reservoir full condition is useful for the study of deformations and stresses within the dam section as a result of water loading. Complex movements of the core at different stages of reservoir filling have been reported in case of Infiernillo dam (1) and could be predicted by finite element analysis for Oroville dam (2). Recently possibility of detrimental leakage through cracking of the core by hydraulic fracturing has been indicated by Sherard (7) and supported by actual field observations in a number of dams. Hydraulic fracturing occurs when the hydrostatic pressure exceeds the total minor principal stress at any plane in the core of dam, provided the core material can not take up any tension. Low horizontal stresses in a dam core may occur due to stress transfer from the core to the sides.

In the conventional method the compatibility of deformations imposed by connections at the nodes along the core-filter-shell interfaces, has a tendency to magnify the load transfer effects and of giving lower values of core stresses and settlements due to side restraints. In actual practice, slippage may take place along the interfaces leading to differential settlements of the core. A realistic study of the stresses within the core would, therefore, require modification of interfacial constraints which can be achieved through provision of joint elements. The detailed finite element formulation with joint elements is given in Ref. (5) and (6).

The finite element analysis of most earth and rockfill dams has generally been carried out by using triangular elements. It has been shown that these elements yield inaccurate results due to their being inherently stiff and constant strain type especially in the region of core and transitions, where bending action and high strain gradients occur. Skermer (8) has shown the superiority of trapezoidal elements in such zones. Sharma et al (4) have suggested mixed graded elements i.e. linear elements in the shell portion and parabolic elements in the core and transitions, for greater accuracy. It has been further shown (5) that the provision of joint elements improves the stress distribution.

In order to study the effect of joint elements on the stress distribution within the dam section, the deformation of the core and the interfacial movements, a two dimensional plane strain analysis has been carried out of 260.5 m high Tehri Dam (India), section for reservoir full condition. The foundation of the dam has been assumed as rigid for the purposes of the analysis. The details of the dam with sequential analysis for end-of-construction have already been reported(5,6).

STRESS-STRAIN MODEL

The functional form as defined by Kondner's hyperbolic stress-strain model developed by Duncan and Chang and extended by Kulhawy and Duncan (3) has been used for the analysis. The values of stress-strain parameters as shown in Table 1, were used in the analysis. These are the same as used for end-of-construction, and no allowance was made for material softening on saturation for lack of adequate testing.

The effect of intermediate principal stress (σ_2) has been allowed for by taking the confining pressure for calculating the values of the elastic moduli as the average of the minor principal stress (σ_3) and intermediate principal stress (σ_2).

Table 1

Sl. No.	Parameters		Shell	Tran-sition	Core
1.	Unit weight, t/m³		1.80	1.99	1.96
2.	Cohesion, c, t/m²		-	-	1.00
3.	Friction angle, Φ, degrees		38	32	27
4.	Modulus number K		2500	3000	500
5.	Modulus exponent n		0.25	0.30	0.60
6.	Failure ratio R_f		0.76	0.76	0.90
7.	Poisson's ratio parameters				
		G	0.43	0.43	0.48
		F	0.19	0.19	0.00
		d	14.80	14.80	0.00

The hyperbolic material behaviour of the joint element as detailed in Ref.(5) has been adopted and the values of material constants given in Table 2 were determined in the laboratory by using direct shear tests (6).

Table 2

Sl. No.	Parameters	Interfaces	
		Shell Filter	Filter Core
1.	Adhesion, c_a, t/m²	0	1.3
2.	Stiffness constant k_j	4500	6500
3.	Exponent n'	0.72	0.3
4.	Failure ratio R_f	0.85	0.90
5.	Angle of adhesion δ', degrees	39	29

The normal stiffness k_{nt} was kept constant 50,000 t/m³ for the top layer. Since the stiffness is a function of confining pressure, the value of k_{nt} was arbitrarily increased for lower layers at the rate of 50,000 t/m³ for each layer below. If the element failed in shear, k_{st} was set equal to 0.4 t/m³, and if it developed tensile stress, both k_{st} and k_{nt} were set equal to 0.2 t/m³.

NONLINEAR ANALYSIS

The dam sections were discretized into seven layers to simulate sequential construction and were further subdivided into 115 elements each for the vertical and the inclined core sections. Nonlinear stress analyses were carried out for the water load applied on the upstream face of the core. The shell and the upstream transition were treated as submerged. The maximum reservoir level was divided into five increments. Stresses and deformations obtained in the analysis for the end-of-construction condition were assumed as initial stresses (5). The stress strain relationships were satisfied and iterations were carried out by computing the residuals and liquidating them in order to maintain the equilibrium by residual force approach (5).

RESULTS AND DISCUSSIONS

1. Displacements: Horizontal and vertical displacements were computed at the nodes within the dam section for both the core sections and are shown in Figs. 1 and 2. The maximum horizontal displacements occur at the top and are 1.4 m and 1.2 m for vertical and inclined cores respectively. Maximum vertical displacements of 0.87 m and 0.93 m, however, occur at 0.66 H for vertical and inclined cores respectively. Although the general pattern is similar for the two cores, horizontal displacements are higher in the core and downstream shell for the vertical core section, whereas the vertical displacements are higher for the inclined core section. Horizontal and vertical displacements along the centre line of the core have also been shown.

2. Stresses: Horizontal and vertical total stresses were computed within the dam section at Gaussian points. Distribution of σ_x at three horizontal sections has been shown in Fig. 3, and the stresses obtained in the analysis for the end-of-construction condition have also been shown for comparison. It is seen that as a result of water loading the horizontal stresses have reduced in the upstream shell and transition, whereas these have increased considerably in the downstream transition and shell. Similarly a comparative distribution of vertical stresses has been shown in Fig. 4. It can be seen that in general the stresses have reduced in the upstream shell and transition, and increased in the core portion, while those in the downstream shell do not show much change. The general reduction of stresses in the upstream shell and transition may be attributed to buoyancy effects and application of the water load on the core face, which presses it towards the downstream and relieves the upstream portion.

Fig. 5 gives a plot of vertical and horizontal stresses along the central line of the core for the two sections. The hydrostatic pressure line ($\gamma_w h$) as well as the total vertical load line ($\gamma_c h$) are shown for comparison. The σ_y line lies within the $\gamma_c h$ - line indicating transfer of stresses to the transitions and shells. The σ_x values are seen to be larger than the hydrostatic pressure throughout the height of the core, thus indicating safety against likelihood of hydraulic fracturing. It may be pointed out that the horizontal stresses along the central line of the core obtained for the end-of-construction condition, were lesser than the hydrostatic pressures in considerable height of the core (see figure) but filling of the reservoir has resulted in increase of the σ_x to safe values.

ALL VALUES ARE IN METRES

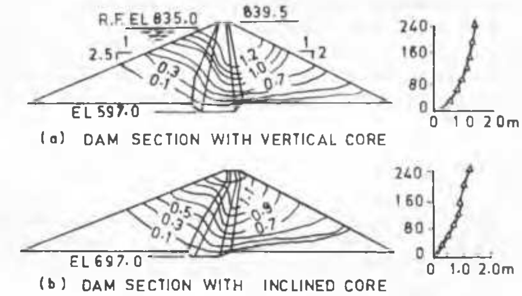

FIG.1-CONTOURS OF HORIZONTAL DISPLACEMENTS.

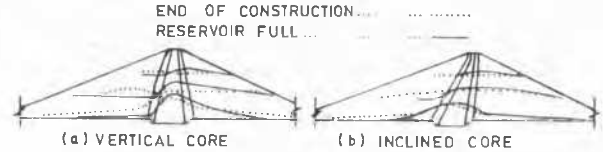

FIG.3-DISTRIBUTION OF σ_x

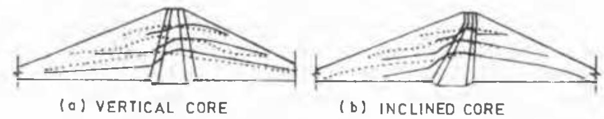

FIG.4-DISTRIBUTION OF σ_y.

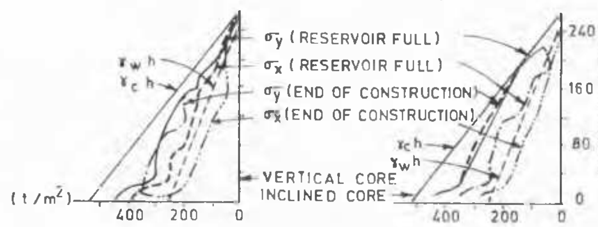

FIG.5-DISTRIBUTION OF σ_x AND σ_y ALONG ℄ OF CORE.

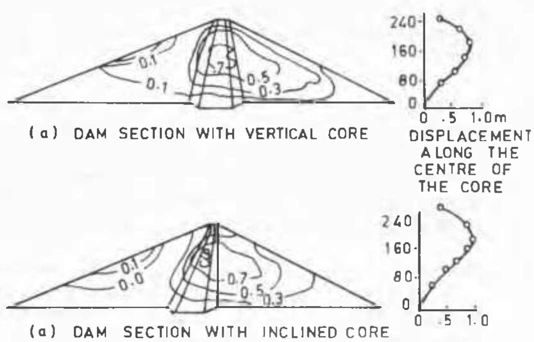

FIG.2-CONTOURS OF SETTLEMENTS.

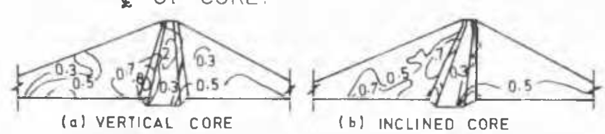

FIG.6-DISTRIBUTION OF MOBILIZATION FACTORS.

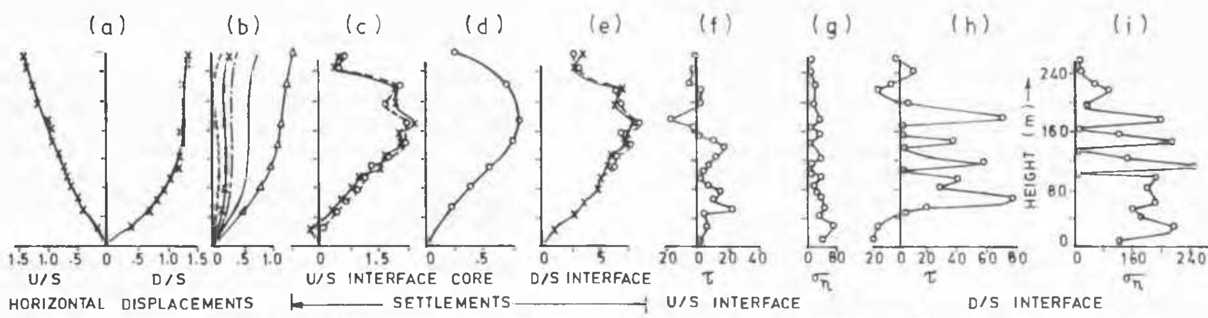

FIG.7-STRESSES AND MOVEMENTS ALONG FILTER CORE INTERFACES VERTICAL CORE.

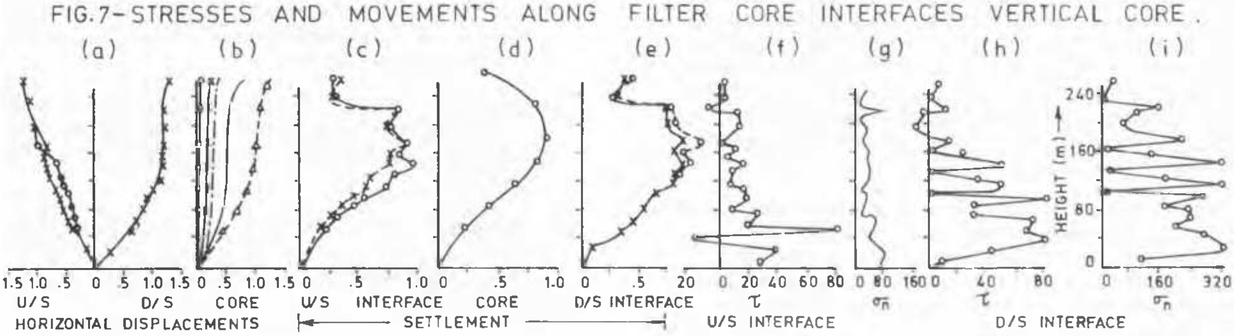

FIG.8-STRESSES AND MOVEMENTS ALONG FILTER-CORE INTERFACES - INCLINED CORE.

(a) ALONG CORE-FILTER INTERFACE.
(b) ALONG CENTRE LINE OF CORE.
(c) ALONG U/S CORE-FILTER INTERFACE.
(d) ALONG CENTRE LINE OF CORE.
(e) ALONG D/S INTERFACE.
(f) τ ALONG U/S INTERFACE.
(g) σ_n ALONG U/S INTERFACE.
(h) τ ALONG D/S INTERFACE.
(i) σ_n ALONG D/S INTERFACE.

3. Mobilization Factors : The mobilization factors, (m) defined as the ratio of developed deviatoric stress at a point to the deviatoric stress at failure, were worked out at Gaussian points and are plotted in Fig. 6. The figure shows that in the section with both the cores, a mobilization factor of unity indicating material failure, is obtained in the upstream transition, although the affected area is larger in the case of vertical core. The maximum value of mobilization factor in the transition portion obtained in the analysis for the end-of-construction condition was 0.8, which has increased to unity as a result of water loading. In the downstream portion the value of m has shown reduction except in the portion of the transition near the base where it has increased to 0.8 from a value of 0.6 under end-of-construction condition.

4. Displacements and Stresses along Interfaces : Figs. 7 and 8 show the differential displacements along the interfaces for both the cores. It is seen from the figures that although marked differential settlement is observable along the downstream core-filter-interface, there is no separation in both the cores. On the upstream core-filter interface both separation as well as differential settlements are observed.

Shear and normal stress distributions along the interfaces have also been shown in the figures. The shear and normal stresses as obtained have shown reduction on the upstream interface and increase on the downstream interface due to downstream displacement on the core on water loading. The oscillatory trend of the distribution (including zero value) is indicative of discontinuous contact along the material interfaces.

CONCLUSIONS

1. The finite element analyses of 260.5 m high Tehri Dam under reservoir full condition have indicated higher horizontal displacements in the section with vertical core, whereas higher vertical displacements are obtained in the section with inclined core. The maximum vertical displacement in the section with both the cores has been observed to occur at 0.66 H.

2. The water loading of the core resulted in increased horizontal and vertical stresses in the downstream shell and the core. Increase in the vertical stresses is, however, mainly confined to the core in case of inclined core.

3. The water loading causes increased horizontal and vertical stresses in the core. The horizontal stresses are found to be higher than the hydrostatic pressures all through the height, thus indicating safety against likelihood of hydraulic fracturing.

4. Separation has been observed on the upstream core-filter interface in the section with both the cores as a result of water loading, while no separation is indicated along the downstream material interfaces. Mobilization factor equal to unity indicating material failure has also been observed in the upstream transition for both the cores.

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