FAILURE CRITERIA OF ROCKFILL DAM DURING EARTHQUAKE USING NO-TENSION APPROACH

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SUMMARY

In the present paper no-tension analysis procedure has been used to predict failure criteria of rockfill dam subjected to earthquake forces. Finite element method has been used for the analysis and no-tension mathematical model has been considered to account for material non-elastic properties. Earthquake forces have been considered as pseudo static and stress redistribution is achieved in an iterative manner using no-tension models. A consistent definition of failure acceleration has been derived based on tension area developed in the dam. Failure accelerations thus obtained show a good agreement with available experimental data. Limitations of conventional elastic analysis and slip surface methods have been highlighted. The sliding of upstream surface has been observed which is generally not computed in conventional approach.

INTRODUCTION

It has been reported in the literature (Ref. 1 & 2) that the response of the rockfill dam, using elastic material properties, differs from that of prototype as obtained from the field observations and this difference has been attributed to non-elastic properties of the rockfill material. Material nonlinearity has also been considered by various authors and its influence on the response only has been reported. Further it has also been reported that pseudo-static analysis no longer gives reliable results (Ref.3) and use of dynamic analysis for predicting the behaviour of the dam has been recommended. However, the use of dynamic analysis should be reviewed critically in view of non-elastic properties of the fill. It has been reported (Ref.4) that pseudo-static analysis provides fairly comparable results to those obtained by dynamic analysis when material non-elastic properties are considered in both the analyses.

The stability of rockfill dams during earthquake has been investigated, both analytically and experimentally, by several

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authors and the limitations of the conventional methods have been reported. Yet the conventional methods find appropriate place in the design offices although they neither reflect the characteristics of the ground motion nor the dynamic properties of the material. No matter, what the limitations of the methods are, the end result is a number giving factor of safety in which the designer has his full confidence. The other methods namely pseudo-static or dynamic analysis methods using numerical analysis procedures, although versatile enough to account for variations in material properties, seismic input and the like, invariably do not finally result in a number indicating failure acceleration or factor of safety of the dam. The present paper describes an analytical procedure to account for material non-elastic properties and provides an estimate of failure acceleration and safety of the dam.

NO-TENSION MODEL

It has not yet been possible to determine accurately the nonelastic behaviour of rockfill material through laboratory tests. The data available on this is very scanty and moreover its use needs validation. Hence mathematical models called no-tension models have been used to take into account the nonelastic material properties. It is obvious from the physical visualisation of rockfill material that its capacity to withstand tension is different from that of compression. In other words the modulus of elasticity of fill is different in tension from that in compression. Therefore the tension developed in the dam body due to lateral loads gets redistributed. It is this aspect of rockfill material which has been considered in the no-tension models for the redistribution of stresses in the continuum. Using such a model, earlier studies (Ref. 5 & 6) carried out by the authors revealed the adequacy of no-tension approach yielding good results. In no-tension model, modulus of elasticity of the fill material is made to vary with the state of tensile stress in the dam. The stress redistribution is achieved through iterative cycles. A typical no-tension model used in the analysis is shown in Fig. 1. The variation in tension area with iteration cycles is shown in Fig. 2. Five cycles of iteration have been found to be adequate for convergence and a tensile stress value of 0.1 Kg/cm^2 has been permitted in the analysis. The elasticity matrix in the inclined coordinate system for plane strain case has been computed using the following relationship :

$$\left[D'\right] = C \cdot \begin{bmatrix} n(1-n\mu_2^2) & n\;{}_2(1+\mu_1) & 0 \\ n\;{}_2(1+\mu_1) & (1-\mu_1^2)) & 0 \\ 0 & 0 & m(1+\mu_1)(1-\mu_1-2n\mu_2^2) \end{bmatrix}$$

where

$$C=\frac{E_1}{(1+\mu_1)\,(1-\mu_1-2n\mu_2^2)} \;;\quad n=E_1/E_2 \;;\quad m=G_2/E_2$$

E_1, G_1, μ_1 and E_2, G_2, μ_2 are the elastic modulus, shear modulus and Poison's ratio along axes 1 and 2 respectively, the axis 1 being that for larger principal tensile stress. In the present analysis, assuming μ_1 and μ_2 to be equal, the elasticity matrix D' in inclined coordinate system is transformed to elasticity matrix D in global coordinate system using transfer matrix "T".

$$[D] = [T]\,[D']\,[T]^T$$

This is then used to compute the stiffness matrix in global coordinates.

ANALYSIS

For the analysis, rockfill dam has been considered as a plane strain problem. A section at the centre of the dam perpendicular to the dam axis has been analysed and it is assumed that the response of this section will generally be true for whole of the dam but for the sections near the abutments. Finite element method has been used for the analysis. Variations in parameters like upstream and down stream slopes, core inclinations, stiffness of core relative to shell etc., have been considered. Dynamic interaction between dam and reservoir, dam and foundation has not been considered. Earthquake forces are considered as pseudo-static forces and are applied in incremental steps. Material non-elasticity has been considered using no-tension mathematical model which is a function of variation of modulus of elasticity with tension resisting capacity of rockfill material. In order to demonstrate the usefulness of notension method over elastic analysis method, elastic analysis has also been carried out. The results thus obtained have been compared with available experimental data (Ref. 7) and a consistent definition of failure acceleration has been derived.

Loads

A typical dam section has been considered for analysis. Six noded triangular and eight noded rectangular isoparametric elements have been used for descretisation. The descretised model is shown in Fig. 3. For unit thickness of the dam across the section, consistent loads due to self weight are calculated for each element. Hydrostatic loads are calculated based on depth of water in the reservoir. It has been reported in the literature (Ref.8 & 9) that the influence of presence of reservoir on the frequency of dam is negligible. Hence the hydrodynamic forces computed in normal way using Zanger's equation have been used. Uplift forces are calculated on those elements falling below the phreatic line. Consistent uplift forces are calculated on these elements for unit thickness of the dam. Seismic forces are considered as equivalent static forces using seismic coefficient. Constant horizontal acceleration along the height of the dam has been considered for the purpose of comparison of analytical results with those available experimentally wherein the acceleration throughout the height of dam model was reported to be constant. However variation of the acceleration along the height of the dam has also been considered to be in line with the reported field observations (Ref. 10) where the acceleration at the crest of the dam has been stated to be higher than that at the base. Analysis has been carried out first for reservoir empty case for comparing the results with those reported experimentally. The analysis with reservoir full has also been carried out and the results are reported.

No-Tension Analysis

In no-tension analysis, redistribution of stresses is obtained using no-tension model. To start with, fill material is assumed to be homogeneous and isotropic. Usual FEM analysis of the dam is carried out and the displacements and stresses are obtained. The principal stresses are checked for tension and modulus of elasticity is modified, along the direction of principal tensile stress, using no-tension model. The stiffness matrix thus gets modified and the analysis is carried out for second cycle. The stresses obtained are again checked for tension through no-tension model and the redistribution of stresses is obtained. This exercise is repeated for five cycles and the tension area in the dam body is computed using finally redistributed stress. Fig. 4 shows variation of percentage tension area with acceleration both for elastic and no-tension cases for a typical dam section. It is seen from this figure that the tension area abruptly increases after a certain acceleration value.

Failure Acceleration

In order to evaluate failure acceleration of a dam, the dam is subjected to various values of seismic accelerations. No-tension analysis is carried out and the percentage tension area is computed for each value of acceleration. Denoting $R(n)$ as percentage tension area at acceleration $a_{(n)}$, a parameter gradient is defined as :

$$G_{(n,n+1)} = \frac{R_{(n+1)} - R_{(n)}}{a_{(n+1)} - a_{(n)}}$$

gradient $G_{(n,n+1)}$ is a constant value for acceleration range $a_{(n)}$ to $a_{(n+1)}$. Variation of gradient with acceleration provides determination of failure acceleration which is defined as the acceleration at which the increase in gradient is maximum. Fig. 5 shows the variation of gradient with acceleration for a typical dam section.

Factor Of Safety

Slip surfaces both on the upstream and downstream sides of the dam section are assumed in normal way. The elements through which the slip circle passes are identified. Based on the stress distribution, the normal and tangantial component of the stresses are computed for each segment of the slip surface passing through the respective elements. Using these normal and tangantial components of the stresses and the corresponding values of angle of internal friction and cohesion, the forces causing sliding and resisting sliding are computed for each sub-segment length. The summation is carried over along the entire slip surface to arrive at the overall values of the forces and the factor of safety is then computed as the ratio of forces resisting sliding to those causing sliding. The results thus obtained were compared with those computed by conventional method for slip surfaces on downstream sides alone and indicated a good agreement. However for slip surfaces on upstream sides factor of safety values less than unity have been obtained by FEM method. This, however, could not be predicted by conventional approach.

RESULTS

Failure accelerations have been computed for various dam sections having different upstream and downstream slopes for reservoir empty case using constant acceleration along the height of the dam. The failure accelerations, both for elastic and no-tension analyses have been compared with available experimental results (Ref. 7) and have been shown in Fig. 6. It is seen that no-tension analysis results show a good agreement with experimental results. Elastic analysis provides under estimation of the failure accelerations. This demonstrates the distinct advantage of no-tension analysis over elastic analysis and also validates the no-tension approach.

Analysis of a dam section for reservoir full condition has been carried out for inclined and vertical core. Cases of hard core and soft core relative to fill material have also been analysed. Further the analysis has also been carried out considering variation of acceleration along the height of dam. Fig. 7 shows gradient versus acceleration plots wherein the failure acceleration in each case has been shown by thick dark line. Failure acceleration for reservoir full case is about 55% of that for reservoir empty case. This also is in good agreement with available experimental results (Ref. 7) wherein this number is 60%. It is also seen from Fig. 7 that failure acceleration for inclined core is 25% higher than that of vertical core. It is also found that for variation in acceleration along the height of the dam, the failure accelerations at the crest level remains same as that for constant acceleration.

Factor of safety values of a typical dam section along slip surfaces both on upstream and downstream sides, as shown in Fig. 3, have been computed for different core cases and are tabulated in Table 1. It is seen from this table that factor of safety for some upstream surfaces have a tendency to approach unity for all core cases but for inclined hard core where it is less than unity for acceleration value of 0.15g which is even less than computed failure acceleration. This clearly indicates that evaluation of factor of safety for upstream face must also be done.

CONCLUSIONS

From the results of the study, the following general conclusions are drawn:

1. No-tension approach provides distinct advantages over elastic analysis approach and its use has been validated.
2. It overcomes the shortcomings of conventional approach and provides evaluation of failure acceleration and factor of safety.
3. No-tension model can appropriately account for non-elastic properties of rockfill material.
4. Inclined core indicates better behaviour than vertical core.
5. It is a must to evaluate factor of safety of the upstream surface which is generally not considered in conventional method.
6. Pseudo-static no-tension analysis provides reasonably good results. However, use of dynamic analysis with elastic material properties needs critical review as the fill material is primarily non-elastic.

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Table - 1

Factor Of Safety For Different Core Cases

(Dam Slope 1:2.0, Reservoir Full, Variable Acceleration 0.15g)

($E_{\text{hard core}} = 1.06\ E_{\text{shell}}$, $E_{\text{soft core}} = 0.94\ E_{\text{shell}}$)

Core Cases	Analysis	Slip Surfaces					
		1	2	3	4	5	6
Vertical Core-Hard	Elastic Analysis	1.54	1.65	1.51	1.21	1.67	4.58
-Soft		1.55	1.69	1.51	0.93	1.99	4.47
Inclined Core-Hard		1.57	1.68	1.52	0.91	2.04	4.33
-Soft		1.54	1.68	1.51	0.92	2.05	4.30
Vertical Core-Hard	No Tension Analysis	1.50	1.66	1.51	1.15	1.92	4.16
-Soft		1.48	1.68	1.51	1.03	1.66	4.64
Inclined Core-Hard		1.63	1.69	1.53	0.89	1.80	4.72
-Soft		1.54	1.67	1.52	1.37	2.36	4.54

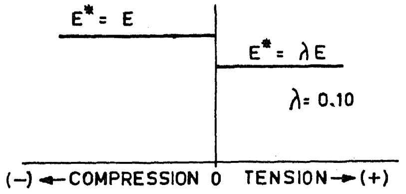

FIG. 1 NO-TENSION MODEL

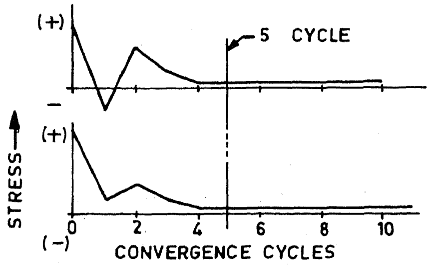

FIG. 2 CONVERGENCE OF TENSILE STRESS

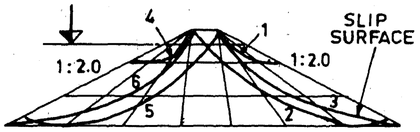

FIG. 3 A TYPICAL DAM SECTION

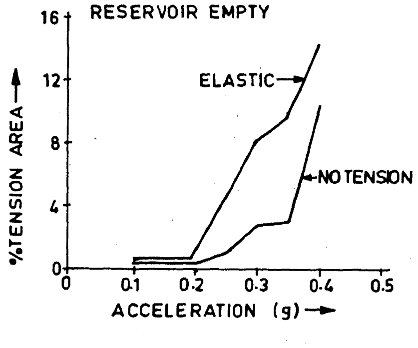

FIG. 4 TENSION AREA Vs. ACCELERATION

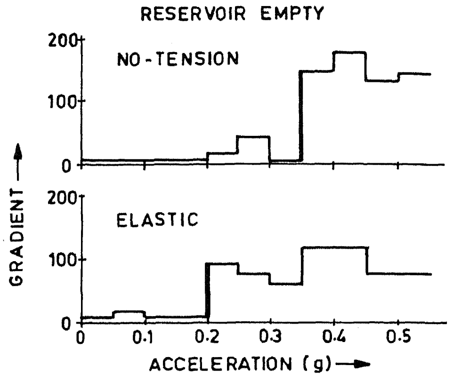

FIG. 5 GRADIENT Vs. ACCELERATION

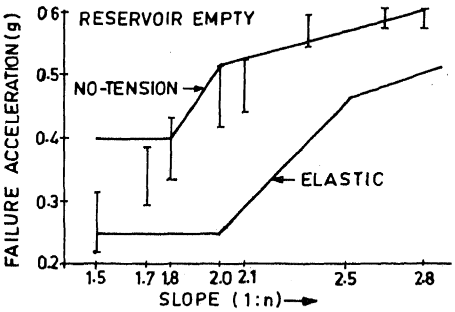

FIG. 6 FAILURE ACCELERATION Vs. SLOPE

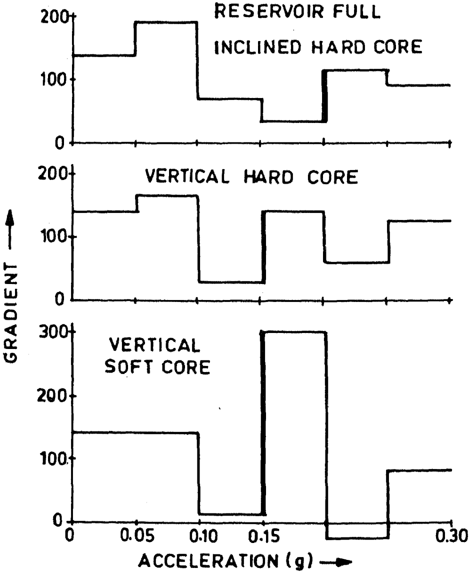

FIG.7 GRADIENT Vs. ACCELERATION