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SUMMARY: The study pertains to the pseudo-static stability analysis of zoned dams with geologic discontinuities in the foundation. Sequential unconstrained minimization technique in conjunction with Janbu's generalized procedure of slices has been used for finding the critical slip surface and the corresponding minimum factor of safety. The method has been found to be quite efficient in solving such problems.

INTRODUCTION

In natural and man-made slopes the slip surfaces that may develop during failure are generally non-circular regardless of whether the failure is caused by static or earthquake forces.

Due to its simplicity pseudo-static stability analysis based on limit equilibrium approach is one of the most widely used technique in computing the factor of safety of slopes under seismic conditions.

Various limit equilibrium methods of slope stability analysis have been excellently reviewed by Mostyn and Small (1987), Nash (1987) and, as such, these are not presented. Successful application of mathematical programming techniques to slope stability analysis using a general slip surface have been made (Martins, 1982; Fredlund, 1984; Mostyn and Small, 1987). Application of calculus of variation technique to slope stability problem is quite controversial (Fredlund, 1984). Even though dynamic programming (Baker, 1980) and linear programming (Munro, 1982) have successfully been applied in analysing stability of slopes they have not been widely used perhaps due to the inherent limitations of the techniques in tackling large nonlinear problems.

Intuitively or otherwise nonlinear programming has been widely used by the geotechnical engineering community in dealing with such problems.

As the efficiency of these techniques is problem oriented an attempt has been made in this paper to demonstrate the successful application of sequential unconstrained minimization technique for automated stability analysis of zoned dams. In addition the effect of earthquake forces (pseudo-static) on the stability of slopes has also been investigated.

STATEMENT OF THE PROBLEM

Fig. 1 shows the geometry the D/S slope of a zoned dam with a general potential slip surface and with the sliding mass divided into N member of slices.

For the given geometry of the dam section and soil properties, the factor of safety is a function of the shape and location of the potential slip surface. The problem is to determine the shape and location of the slip surface and the associated minimum factor of safety.

ANALYSIS

General

The pseudo-static stability analysis of the D/S slope of the dam under earthquake loading is carried out by using the generalized procedure of slices (Janbu, 1973) in conjunction with sequential unconstrained minimization technique for autosearching the critical shear surface and the corresponding minimum factor of safety without a priori restriction on the nature of the slip surface. This is achieved by minimizing the factor of safety with respect to the co-ordinates of the slip surface.

Earthquake Considerations

Stability of slopes are seriously affected by earthquakes. Earthquake accelerations caused by the ground movement induces an inertial force into the slope material providing an extra overturning moment. The vibrations due to earthquakes may result in the development of pore pressure build up in the slope and thus may cause reduction in the frictional resistance or even liquefaction. Thus the increase in the inertial force as well as the decrease in the shearing strength of the soil may cause failure if the slopes are subjected to ground movement of sufficient magnitude and duration.

In the pseudo-static stability analysis seismic effects are taken into account including a static horizontal force expressed as the product of a seismic coefficient and the weight of individual slice and acting at its centre of gravity. Seed (1973) has presented in detail the selection procedure of seismic coefficient.

As the quake actually imposes displacements rather than forces, the forces resulting from the displacements are dependent in a complicated way on

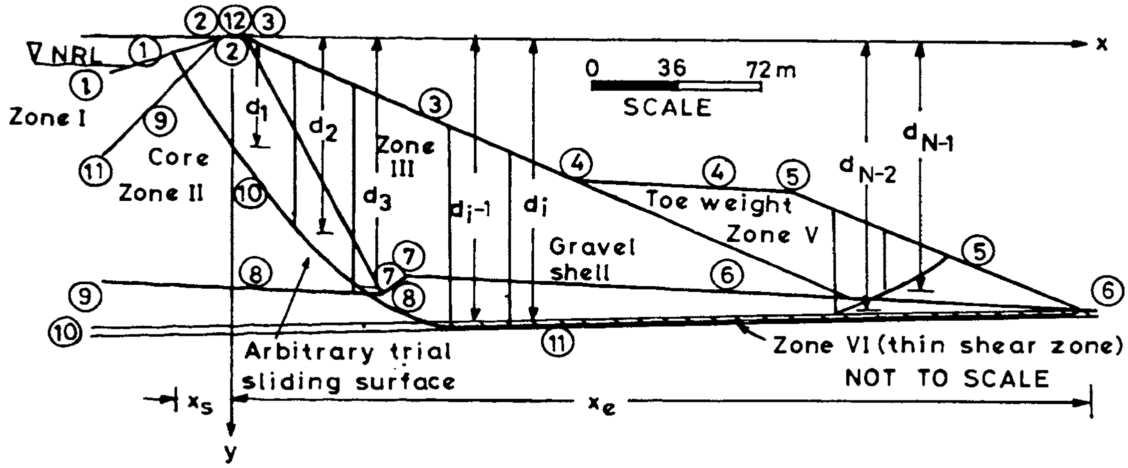

Fig. 1 Idealized Section of a Zoned Dam with the Potential Sliding Mass Divided into Slices.

dynamic stress-strain relationship of the embankment material. Hence the application of the pseudo-static method to analyse the semismic stability of slopes is quite controversial. There is a belief that the method should not be used under any circumstances as it cannot take into account the cyclic nature of forces applied to the slope. However, review of literature to (Mostyn and Small, 1987) suggest that the seismic coefficient method may be suitable for stability analysis of slopes in soils which show no significant loss of strength due to earthquake shaking (usually clayey soils, dry sands and some very dense cohesionless soils).

Design Variables and Objective Function

Referring to the Fig. 1 for a fixed number of slices the elements of the design vector are chosen as follows:

$$\bar{D}^T = (d_1, d_2, d_3, \ldots, d_{N-1}, x_s, x_e) \qquad (1a)$$

writing $d_N = x_s$ and $d_{N+1} = x_e$ one obtains

$$D^T = (d_1, d_2, d_3, \ldots, d_{N+1}) \qquad (1b)$$

So the total number of design variables are N+1.

The objective function is the factor of safety and for any given slip surface it is computed by using the Janbu's generalized procedure of slices (Janbu, 1973). The factor of safety can be written in terms of the design vectors as

$$F = f(\bar{D}) \qquad (2)$$

Constraints

To ensure the acceptibility of the potential slip surface the following constraints are imposed.

1. The curvature of the slip surface should be concave upward. This requires

$$d_{i+1} - 2d_i + d_{i-1} \leq 0 \qquad (3)$$

2. The slip surface should be within the cross-section of the dam. This requires

$$h_i - d_i \leq 0 \qquad (4.$$

where h_i is the y co-ordinate of the intersection point of the top boundary line of the dam section with the vertical line drawr through the point whose y co-ordinate is d_i; i varies from 1 to N-1.

So the problem is one of (N+1) design variables and (2N-2) side constraints.

Slices, Width of Slices and Zoning

The encircled key points defining the idealized dam section as shown in Fig. 1 are numbered in order. The lines joining the different key points are also numbered; such numbers are marke by semicircles.

Once the dam geometry is defined by the co-ordinates of the key points, the coefficients of each straight line defining the dam section can be generated on the computer.

The optimal number of slices are to be obtained by a trade off study of computational efficiency and the cost involved. In the present study 24 m slice width has been found to be very satis factory.

Correctness of the weight calculations of the slices by the developed computer program (Basudhar et.al., 1988) has been ensured for different potential slip surface, position of slip surface and comparing the results with manually computed values. The details are reported by Babu (1986) and are not reported here.

Existence of Thin Shear Plane in the Dam Foundation

If very thin shear zone is present in the foundation, while searching for the critical slip surface there is a possibility that the surface may lift off from this weak zone ultimately converging to a solution which is much higher than the critical one. This possibility is safeguarded by choosing the initial trial shear surface to lie mostly along the shear zone and also by arbitrarily increasing the shear zone thickness. It has been observed that the critical shear surface does not move much from the actual shear ane and, as such, the results are not affected gnificantly and the technique can be adopted th confidence.

timization Formulation

ıe problem of finding the critical slip surface ıd the corresponding minimum factor of safety - stated as a mathematical programming problem ; follows.

.nd the design vector $\bar{D}_m$ such that $F = f(\bar{D}_m)$ is ıe minimum of $f(\bar{D})$ subject to

$$.(\bar{D}_m) \leq 0; \quad j = 1,2,...,M$$

ıere M is the total number of constraints.

inimization Procedure

ıe sequential unconstrained minimization techique using the interior penalty function formlation in combination with Powell's multidimenional search and quadratic fit for finding the inimizing steps, has been used. The basic obect of the penalty function method is to convrt the original constrained problem into one f unconstrained minimization by blending the onstraints into a composite function (Ψ). The etailed background of these methods are available in standard textbooks on optimization (Rao, 984).

or problems with inequality constraints only, he Ψ-function is defined as:

$$(\bar{D}, r_k) = F(\bar{D}) - r_k \sum_{j=1}^{M} \frac{1}{g_j(\bar{D})}$$

ʋhere F is to be minimized over all $\bar{D}$, satisfying

$$;_j(\bar{D}) \leq 0; \quad j = 1,2,...,M$$

ʻhe penalty parameter r_k is made successively smaller in order to obtain the constrained miniᴨum of F.

ʔESULTS AND DISCUSSIONS

The following design parameters are used in the analysis:

Unit weight:	Core	20.4 KN/m^3
	Shell	24 KN/m^3
	Toe-weight	24 KN/m^3

Angle of shearing resistance (ϕ'):

Core	26.5^o
Shell and toe-weight	35^o
Shear zone	18^o

Effective cohesion (C'):

Core	0, 20, 40KPa
Shell and toe-weight	0
Shear zone	0

Pore pressure ratio (r_u): 0.3, 0.4, 0.5

Seismic coefficient (α_g): 0, 0.05, 0.1, 0.12

Numerical results have been obtained by using DEC 1090 system and the SUMSTAB package (Basudhar et.al., 1988).

Typical results with three different initial trial surface is presented in Table 1. The table

TABLE 1. Factors of Safety for c' = 20 KPa

α_g in %	r_u	F_{avg}	Set 1 F_{st}	Set 1 F_{min}	Set 2 F_{st}	Set 2 F_{min}	Set 3 F_{st}	Set 3 F_{min}
0.0		1.522	1.829	1.512	1.622	1.497	1.741	1.559
5.0	0.3	1.193	1.299	1.204	1.262	1.164	1.407	1.212
10.0		0.982	1.043	0.996	1.026	0.952	1.143	0.999
12.0		0.919	0.968	0.929	0.931	0.899	1.038	0.930
0.0		1.268	1.412	1.267	1.347	1.247	1.501	1.290
5.0	0.4	0.996	1.068	1.001	1.047	0.973	1.165	1.014
10.0		0.823	0.863	0.830	0.835	0.804	0.929	0.835
12.0		0.761	0.783	0.753	0.778	0.753	0.866	0.777
0.0		1.012	1.105	1.009	1.079	0.995	1.199	1.034
5.0	0.5	0.806	0.852	0.813	0.839	0.787	0.931	0.819
10.0		0.663	0.679	0.666	0.675	0.648	0.749	0.675
12.0		0.615	0.632	0.609	0.629	0.604	0.698	0.631

F_{st} = Starting factor of safety
F_{min} = Critical factor of safety
F_{avg} = Average of the critical factors of safety values.

shows that the initial starting point design vector has marginal influence on the numerical scheme. Similar results have been obtained for other values of C'. The average of the critical factor of safety for three input surfaces in each case is calculated and is shown in these tables.

The influence of the number of function evaluation and the penalty parameter (r_k) on the solution has been studied. It has been found that as the number of function evaluation increases the objective function (F) and the composite function (Ψ) converge to the same value. This signifies that the solution scheme is quite efficient in locating the minimum factor of safety under the imposed design constraints. Similar observations have also been made for the decreasing sequence of the penalty parameter (see Basudhar et.al., 1988).

Fig. 2 shows the plot of the minimum factor of safety with pore pressure parameter (r_u) for different seismic coefficient and cohesion value. It will be seen from the figure that the factor of safety is linearly related to the pore pressure ratio for various values of the effective cohesion and horizontal acceleration. Bishop and Morgenstern (1960), without considering earthquake forces, have used a linear relationship of the following form:

$$F = m - n \, r_u$$

where m is the value of F for $r_u = 0$ and n is the slope of the F vs. r_u straight line. The validity of the above relation for slopes subjected to earthquake forces has been checked over a wide range of values for horizontal acceleration.

It is also observed that for a given r_u, the factor of safety decreases with increasing horizontal acceleration. The rate of decrease for a given r_u depends on the range of values of horizontal acceleration under consideration. Also for all values

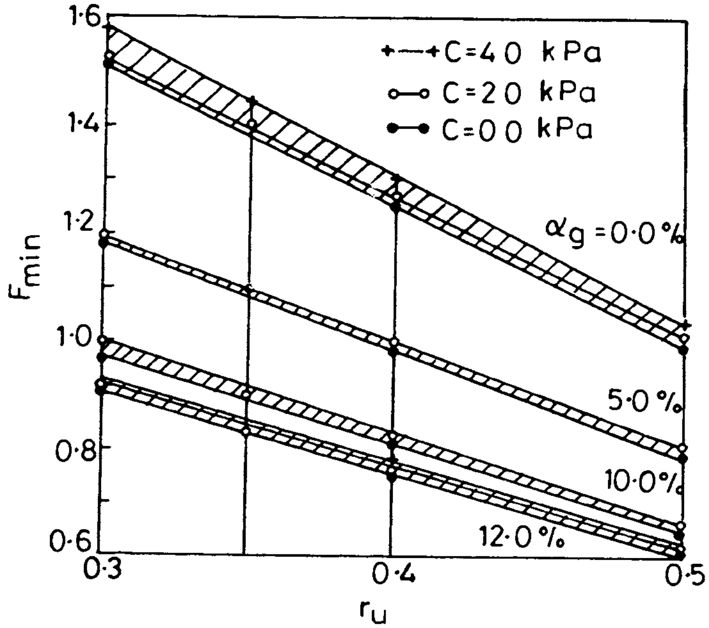

Fig. 2 F_{min} Versus r_u Relationship.

of horizontal acceleration greater than zero, the magnitude of the effective cohesion does not seem to have any significant influence on the factor of safety. This observation is to be viewed in the light of the fact that for the dam section as shown in Fig. 1 the major portion of the slip surface is controlled by the shear zone with C'=0.

The linear relationship enables to interpolate/extrapolate for values of F under different condition of pore water pressure and earthquake loading. Fig. 3 shows the variation of coefficients m and n with horizontal acceleration which allows computation of factor of safety for any particular value of α_g.

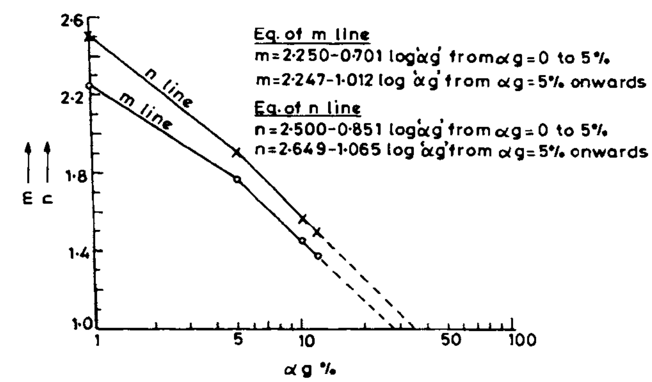

Fig. 3 'm' and 'n' Versus α_g Relationship.

For gravity forces in excess of 5%, the magnitude of pore water pressures governs the factor of safety; the effect of C' value for the core material being only marginal. The result is in accordance with the general practice to control pore water pressures through efficient drainage measures in dams subjected to earthquake forces. As such the results shown in Figs. 2 and 3 can be useful aid to decision making in design and construction of dams.

CONCLUSIONS

Sequential unconstrained minimization techniqu is quite efficient in location the generalized critical non-circular slip surface without a priori assumption regarding its shape. For di ferent C', r_u and α_g values the relationships between F_{min} and r_u is linear. For higher gra ity values the magnitude of C' does not signif cantly change the factor of safety for the dam under investigation. It has also been seen tha for gravity values greater than 5%, for every increase in the gravity value by a factor of 2 the factor of safety is reduced by 20%. Such a chart is quite useful for design purposes. Th developed method of analysis is quite effectiv with respect to speed, accuracy and economy.

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