

STABILITY OF DOWNSTREAM SLOPE OF BEAS DAM AT PONG UNDER EARTHQUAKE

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SYNOPSIS

A number of diagonal plastic gougy seams (shear zones) in clay shale bands were noted in the foundation rocks of Beas earth and rock fill dam at Pong (INDIA). Two dimensional seismic stability analysis of the dam considering the available resistance on gougy seams indicated the need for a huge amount of material as toe protection. To obtain a realistic picture, model tests were carried out on a tilting table to study the mechanism of sliding of the foundation wedges bounded by the gougy seams and the vertical rock joints together with the dam in relation to the dip and strike of the seams. Three dimensional stability analysis of the probable failure wedges were then carried out. A factor of safety more than 1.0 was seen to be available indicating no need for toe weights.

INTRODUCTION

In the construction of dams some times difficult geological conditions are encountered in the foundation or abutments which are aggravated if the areas lie in severe seismic zone. If adequate precautions are not taken to mitigate the adverse effects, the whole or parts of the dam may slide away or be seriously damaged during a major earthquake shock. In an earth and rock fill dam across Beas river at Pong a number of plastic gougy seams were noted for over a length of 900m under the downstream shell of the dam. The variation as observed in the foundations from section to section indicates that instead of the whole dam failing together there would be preferential weak zones leading to the failure of only a portion of the dam. Thus the need for a three dimensional analysis was indicated. The aim of this paper is to present the model test and analysis carried out for investigating the stability of the downstream slope of the dam.

GEOLOGY OF THE FOUNDATION

The foundation rock at the dam site consists of alternate layers of shale and sand rock. The data on geology of the area (1) indicate the presence of gougy seams (shear zones) in clay shale strata (Fig. 1). These gougy seams are reported to dip at various angles from 11 to 15 towards NE. A number of sets of joints were noted to be present in the foundation rock during geological mapping of the area and excavation at the site. These have dip at high angle to near vertical and strike towards N-S and NW-SE.

TWO DIMENSIONAL ANALYSIS

Two dimensional analysis of the dam sections at various chainage stations was carried out by wedge method to evaluate the imbalance of forces between P_a (total actuating force) and P_p (total resisting force). The following soil parameters were adopted in the analysis:

(a) Core material - effective cohesion intercept (mobilised) $C^i = 0.642$ gm/cm², effective angle of shearing resistance $\phi^i = 26.5^\circ$, unit saturated

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weight, $\gamma_{\text{sat}} = 2.158 \text{ gm/cm}^3$ and moist unit weight $\gamma_{\text{moist}} = 2.09 \text{ gm/cm}^3$;

(b) Shell and foundation rock - $C' = 0$, $\phi = 35^\circ$, $\gamma_{\text{sat}} = 2.362 \text{ gm/cm}^3$ and $\gamma_{\text{moist}} = 2.09 \text{ gm/cm}^3$;

(c) Shear zone and plastic gougy seam material - $C' = 0$, $\phi = 18^\circ$, $\gamma_{\text{sat}} = 2.362 \text{ gm/cm}^3$ and $\gamma_{\text{moist}} = 2.09 \text{ gm/cm}^3$;

(d) Seismic coefficient = 0.12; and

(e) Angle of inclination for the inter-wedge forces $\psi = 10^\circ$ and $\theta_m = \tan^{-1}(\tan \phi / \text{FOS})$.

The results are presented in Fig. 2 and show that all the sections between stations 59 and 80 are unstable and will require large toe weights to increase the resisting forces. A typical section of toe weight embankment is shown in Fig. 3.

The conventional method of three dimensional analysis is to divide the length of the dam into various segments of equal lengths with vertical planes perpendicular to the longitudinal axis and to analyse the average cross-section of each as though it were a standard two-dimensional problem. With the assumption that the two-dimensional critical surface for each segment of the dam length was contained in the most critical three-dimensional failure surface, the factor of safety is calculated as the ratio of the sum of the resisting forces to the sum of the driving forces for all the segments of the dam length. Such an analysis for the down-stream section of the dam was carried out between stations 59 and 80 (700m long), and indicated that the slope was not stable.

THREE DIMENSIONAL ANALYSIS FOR SLIDING BLOCKS

The above analysis does not take into account the failure pattern and the preferred direction of movement governed by the geological conditions of the site. Side resistances is also not properly accounted for. A three dimensional analysis was therefore required which would include the shape and size of the sliding block as well as the side resistance. To determine the size of blocks and their preferred direction of movement, small scale model tests were conducted on a tilting table as described below.

Model Test: A trapezoidal tilting box (42.5cm wide, 21cm high, 38cm long at base and 60cm long at top) was made with transparent sides and tilt tests were conducted on a small scale model. The main purpose of the model test was to observe qualitatively the effect of the gougy seams present in the foundation on the geometry of the failure pattern on the downstream shell as well as on the direction of slipping of the rock mass. Since only a pseudo-static analysis was proposed for computing the seismic stability of the dam and since it was felt that the most critical direction of the inertia forces is usually at right angle to the longitudinal axis of the dam, tilting in a plane perpendicular to this axis was resorted to. Also, taking into account the daylighting of the gougy seams, only the portion of the dam between stations 59 to 80 was represented in the model. So as to have the largest possible scale ratio, the upstream shell was not represented and only the foundations and half of the dam section was scaled. The angle of internal friction of the shell material, foundation rock and the

gougy seams were represented in the model. Sand compacted to the desired densities was used to represent the shell as well as the foundation rocks. Borax powder in between two cellophane sheets giving the desired friction coefficient was used to represent the gougy seams. The model test indicated that the movement was initiated and the wedges after separation along the joints got displaced in the direction of the strike of the gougy seams. Thus the preferred direction of movement of the foundation rock wedges bounded by the joints and the gougy seams turned out along the strike of the seams.

Analysis: Besides the size and preferred direction of movement as determined by model tests the following assumption were made in the three-dimensional stability analysis:

- (a) At-rest earth pressure prevails to provide resistance on the sides of the wedges and when the wedges slides, no lateral expansion of the soil occurs along the axis of the dam. (The condition of instant failure is indicated by factor of safety greater than unity which means there will be no lateral expansion).
- (b) Passive pressure at the toe from the foundation rock is negligible. (An assumption on the safe side).

The stability of the down-stream slope of the dam together with the foundation blocks was analysed for three wedges of 183m, 90m and 123m length in river bed portion. The spacing of gougy seams as shown in Fig. 1 controls the width of these wedges. A combined wedge of 396m length was also analysed assuming that all the three wedges slide together.

In this analysis, the surface between active and passive wedge is considered vertical. From model tests and detailed analyses (3,4), it has been concluded that if a sliding wedge analysis is made using vertical boundary between the wedges and if the angle of internal friction of the shell material is determined by triaxial compression test, the assumption that inter-wedge forces are inclined at ϕ_m (The mobilised angle of internal friction of the shell material) to the horizontal leads to the best evaluation of the factor of safety. Thus for this analysis inter wedge forces were assumed to be inclined at ' ϕ_m '. Alternatively the inclination was also assumed as 10° which gave more conservative values. The results of this analysis are given in Table 1 which show that a stable condition of the downstream slope of the dam really exists. A further analysis of the wedges as identified by the model tests and the analysis described was carried out for its possible slipping in a direction perpendicular to the dam axis as against slip in the strike direction. The results of this analysis are also listed in Table 1.

DISCUSSION

It is very well known that two-dimensional analysis of the stability of embankments leads to conservative results. However this study indicates that even the conventional three dimensional analysis gives conservative results for the cases where the failure pattern in the embankment is essentially controlled by the foundation characteristics and where the assumption of 'uniform' conditions in the dam may not be realistic. It is the usual practice to assume the direction of least resistance to sliding as the one normal to the longitudinal axis of the dam. The analysis here is a pointer

to the fact that once the critical wedge is identified, the direction of least resistance also should be determined so as to get rational results and not to overestimate the stability of the dam.

Since pseudo static method has been employed in this study, no information regarding possible magnitude of downstream movement of the dam during an earthquake has been obtained. Lack of information regarding the dynamic strength of the gougy seam material is the main reason for this. Provided that the earthquake strength of this material is similar to its static strength and also that the pore pressures in the clay core are not much affected by the earthquake waves, the concept of "yield acceleration" for the dam and "damage potential" of the earthquake shock could have been utilised for obtaining the important parameter - the earthquake induced displacements. If the two conditions already stated are not satisfied, a total stress analysis supplemented by a large number of laboratory tests alone can provide the answer. However, inspite the recent advances in computing the displacements in embankments due to earthquake shocks, the pseudo-static analysis continues to be used and has been considered as a reliable tool to compare the design adequacy of different sections. The absolute safety or otherwise of the dam cannot at present be foretold in view of the lack of data regarding the behaviour of well designed embankment dams subjected to severe earthquakes. This paper therefore highlights the importance of considering the probable failure pattern in obtaining realistic factors of safety from pseudo-static analysis.

CONCLUSION

This study shows that a two dimensional analysis gives rather conservative results compared to the three-dimensional analysis which takes into account the true mechanism of the failure. In a realistic analysis for the problem as at Beas, one should consider the shape and size of the foundation wedge bounded by geological discontinuities consisting of gougy seams, joints, shear zones, etc., along which the wedges could separate out and move, and also evaluate the probable direction of movement of the wedges. The pseudo static analysis as reported here is felt to be a reasonable procedure to evaluate the seismic stability of the embankment.

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TABLE 1
FACTOR OF SAFETY FOR DIFFERENT WEDGES

Assumed Wedge	WEDGES 3(183m)		WEDGE 2(90m)		WEDGE 1(123m)		COMBINED WEDGE (396m)	
	=10°	=φ _m	=10°	=φ _m	=10°	=φ _m	=10°	=φ _m
from Model test	1.100	1.156	1.236	1.334	1.201	1.294	1.112	1.216
normal to dam axis	1.144	1.303	1.386	1.454	1.268	1.430	1.164	1.320

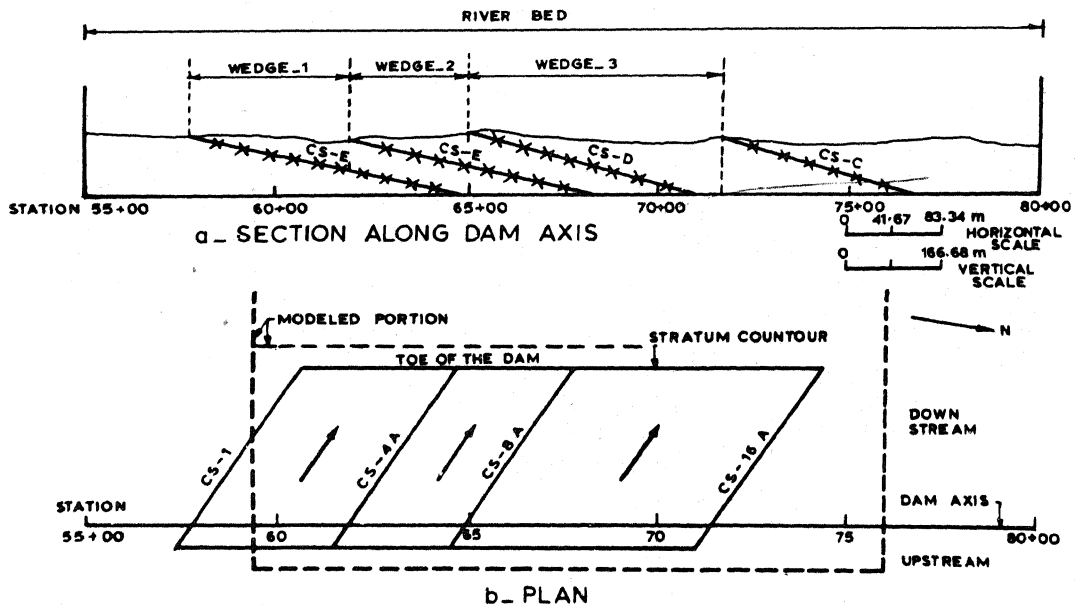


FIG. 1 - GENERALISED GEOLOGICAL SECTION AND PLAN SHOWING PREFERRED MOVEMENT DIRECTION OF THE WEDGES

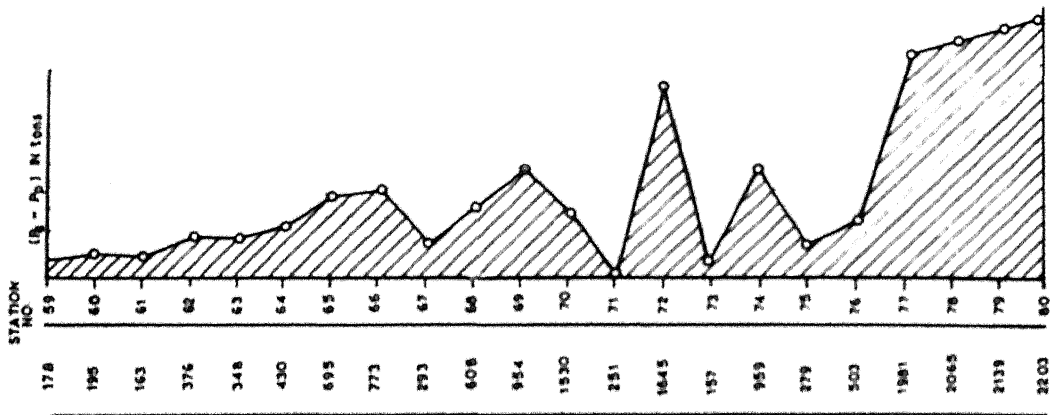


FIG. 2 - EXCESS OF ACTUATING FORCES OVER RESISTING FORCES AT VARIOUS STATIONS BASED ON TWO DIMENSIONAL ANALYSIS

0 100 200 ft
SCALE

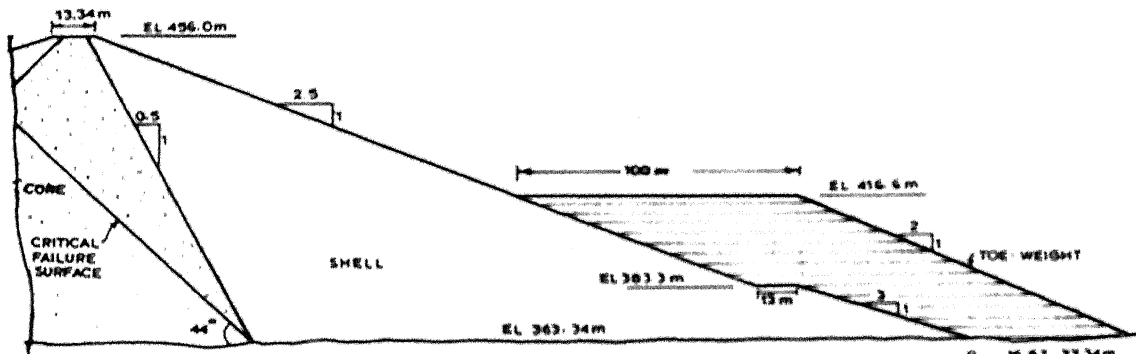


FIG. 3 - SECTION SHOWING DOWN STREAM TOE WEIGHT REQUIRED FOR STABILITY OF DAM BASED ON TWO DIMENSIONAL ANALYSIS

0 16.67 33.34m
SCALE

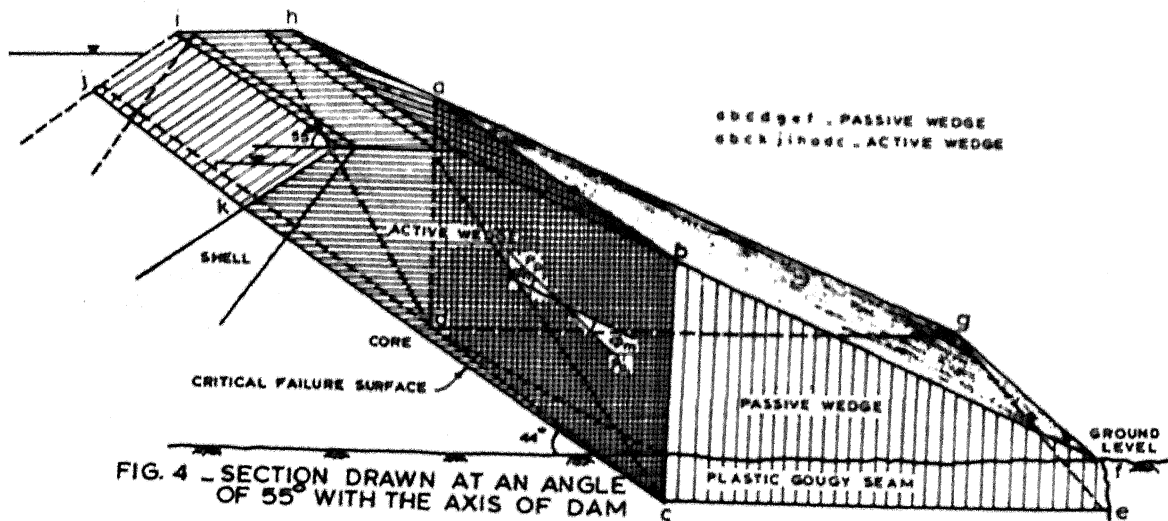


FIG. 4 - SECTION DRAWN AT AN ANGLE OF 55° WITH THE AXIS OF DAM