Geotechnical Investigations and Stability Analysis of Slopes at Matli Site, Uttarkashi District, Uttaranchal State, India

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ABSTRACT

The paper deals with the geotechnical investigations of slope mass, comprising rocks and overburden soils, which failed along the state highway (SH-53) near village Matli in the Uttarkashi district of Garhwal Himalaya, India. The site was taken up for detailed investigations which included topographical, geological, geomorphological, morphometric, geotechnical, instrumentation and monitoring studies. The present paper aims to discuss the results of geotechnical investigations of the slope materials viz. point load and uniaxial compressive strength of the various rocks exposed at the affected site, grain size analysis including hydrometer analysis, bulk density, water content, liquid and plastic limits, cohesive strength and friction angle of the overlying soil mass in the failed area.

The paper also discusses the use of geotechnical parameters obtained from the above study in interpreting the stability of slopes under varying conditions of pore water pressure and ground accelerations due to seismic activity. It concludes that the geotechnical investigations of slope mass at problematic sites can be effectively used to understand the nature and behaviour of slopes under different conditions of pore water pressure and ground accelerations. The stability analysis of slopes using geotechnical parameters can also help in interpreting the potential slip surfaces under specific geo-environmental conditions, i.e. given pore pressures and seismic accelerations. The effects of changing pore water pressures and seismic accelerations are very obvious from the results of this study.

Keywords: Geotechnical, Stability Analysis, Slip Surfaces, Pore Water Pressure, and Seismic Acceleration

1.0 INTRODUCTION

The hill slopes near village Matli constitute the most problematic failed slope (Fig. 1) along the state highway 53. The site located at a distance of 139.8 km from Rishikesh, on a sharp bend on the right bank of the river Bhagirathi is significant from techno-economic and socio-ecological point of view and has been selected in consultation with Border Roads Organisation (BRO) for detailed investigations and field monitoring in order to understand the nature and behaviour of these slopes and to suggest appropriate remedial measures.

The detailed investigations included collection of data and information available prior to taking up the present studies, history and recurrences of failure, topographical, geological, geomorphological, morphometric, geotechnical, instrumentation and monitoring studies. But the present paper discusses mainly the geotechnical investigations carried for this site and the use of geotechnical data in analysing the stability of slopes. The other parts of this study have been discussed in detail in Mehrotra, Parkash and Dharmaraju (1996), Parkash (1998) and Parkash & Awasthi (2001).

2.0 HISTORY OF SLOPE FAILURE AT MATLI

The records maintained in the office of the BRO indicate that the first failure occurred at this site on October 23, 1984, when a large chunk of hill slope mass slided down towards the road side. As per the local people, after an electric pole was taken out of its place from the hill slope, a local depression thus created, became the site for accumulation of rainwater. In this zone, the accumulated water seeped through the hill mass which failed ultimately. Since then, the slopes fail frequently mainly during the rains. So far, it has failed more than 87 times. The slide area has increased its dimension every monsoon and it became highly risky and dangerous for the passers by, plying vehicles and the residents staying on the downhill side of the slope. The recurring event caused huge damage to the road and resulted in traffic disruption along the only highway reaching Uttarkashi. The slided debris also damaged the vegetative cover of the slopes on the downhill side. Though a retaining wall was constructed by BRO in 1986 to prevent this failure, it could not serve the purpose. Hence, the present investigations were called for understanding the phenomena of failure and suggesting appropriate remedies.

3.0 GEOTECHNICAL INVESTIGATIONS

In order to assess the stability of slopes at Matli site (Fig. 1), an evaluation of the geotechnical properties of the slope materials in field conditions is necessary. Investigations have been made in the field as well as in the laboratory. The rock and soil samples (both disturbed and undisturbed) have been collected from the site for laboratory testing. The locations of these samples are shown in Fig. 2. The geotechnical parameters viz. uniaxial compressive strength of the rocks, grain size distribution of soils, Atterberg's limits of soils, bulk density, water content and shear strength of soils have been studied from these samples and the results are presented in Tables 1 and 2.

The strength of slope mass determines the stability of slope. It depends mainly on cohesion and friction. Cohesion is the internal molecular attraction which resists the rupture or shear of a material and friction is due to resistance of grains to sliding over each other and is characteristic of coarser soils. The strength of slope mass depends on grading, surface texture of the particles, degree of compaction, water content and the load to which it is subjected. It is reduced in the presence of a lubricant such as water. The strength of non-cohesive soils depends entirely on internal friction. Direct shear tests on the undisturbed soil samples (four in number) have been performed under unconsolidated - undrained conditions. The tests have been carried out under normal loads varying from 10kN/m^2 to 40 kN/m^2. The results are presented in Table 2 and the plots are shown in fig. 6 a-d. It may be observed that the soils exhibit variability in strength characteristics with the value of cohesion varying from 14 kN/m^2 to 23kN/m^2 with an average of 18.75 kN/m^2, and the angle of internal friction varying from 30° to 38° with average friction angle of 34°. The variations in cohesion and friction of soils may be attributed to the variations in grain size and shape. The coarser soils have greater friction angle whereas the finer soils possess higher cohesion. The data obtained from geotechnical investigations of soil and rock samples has been used for slope stability analysis of this site as discussed below.

4.0 SLOPE STABILITY ANALYSIS

The main objective of the stability analysis is to evaluate the factor of safety of the slopes compatible with the existing field conditions along the critical slip surface. The slip surface or failure surface develops along the path of least shear resistance and is represented by the one for which the factor of safety is the least.

The factor of safety is defined as the ratio of the resisting forces and the driving force:

$$\text{Factor of Safety} = \frac{\text{Resisting Force}}{\text{Driving Force}}$$

At Matli site, the slope material is highly weathered, jointed and fractured which clearly indicates that the failure surface may tend to follow a circular path. The stability analysis of this site has been carried out using a computer program, which is based on Bishop's simplified method of slices. An attempt has also been made to consider the seismic accelerations and pore water pressures on the stability of slopes.

The input data for the program includes coordinates of slope profile, thickness of overburden, cohesion, angle of internal friction, unit weight of soil, unit weight of water, pore pressure ratio, maximum possible magnitude of the earthquake expected and seismic coefficients in terms of horizontal and vertical accelerations of the ground motion. The data obtained from the geotechnical analysis of the slope mass at the site has been used for stability analysis in this section. Since the pore pressures could not be measured in the field, assumed values of pore pressure ratios have been considered for the purpose of stability analysis. Similarly, the seismic coefficient (which is considered equivalent to the component of horizontal acceleration in ground motion), based on past experience is assumed to vary from 0.0 to 0.1 g.

The input parameters used were:-

Cohesion of soil	- 19 kN/m^2
Friction Angle	- 34°
Unit weight of soil	- 24 kN/m^2
Unit weight of water	- 10.0 kN/m^2
Overburden thickness	- 1 m (for western profiles) 1.5 m (for central & eastern profiles)
Depth of Tension Crack	- Nil (for western profile) - 0.25 m (for central & eastern profiles)
Pore Pressure Ratio	- 0.00, 0.10, 0.20, 0.30, 0.40, 0.50
Max. Magnitude of earthquake expected	- 8
Horizontal Ground Acceleration	- 0.00, 0.05, 0.10
Vertical ground Acceleration	- 0.00, 0.025, 0.05

Three cross-sections (Fig 7) of the failed site in the eastern, central and western parts have been considered for stability evaluation in the present case. The results are presented in Table 3. The Table shows the variations in the values of factor of safety with changes in pore pressure ratios and seismic coefficients for different profiles. It has been observed that the factor of safety varies between 1.1875 and 0.275. The slip surfaces for the three profiles at minimum water content with minimum ground accelerations as well as in the extreme conditions when the water content and ground accelerations are maximum, have been shown in the Fig. 8 a-f. An attempt has also been made to know the variations in the factor of safety with changes in pore pressure ratios at different seismic coefficients along these profiles. It can be observed from these figures that the site is stable only in dry conditions when there is no ground acceleration. An increase in water content even by 10% makes the slopes unstable. The results also indicate that the western profile has the lowest factor of safety compared to central and eastern profiles.

5.0 CONCLUSIONS

The present study indicates that the geotechnical investigations of slope materials can help in better understanding of the nature of stability conditions. The geotechnical data, thus, obtained can also be used for stability analysis of these slopes under varying conditions of pore water pressures and ground accelerations.

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Table1- Physical Properties of Disturbed Soil Samples from Matli Site

S. No.	Location of Soil Sample	Field Water Content	Grain Size Analysis (in % passing)					Atterberg's Limits		Soil Classification
			Dry/ Wet	Gravel	Sand	Silt	Clay	LL	PI	
1	S1	15.83	Wet	24.0	33.0	39.7	3.3	18	NP	SM
			Dry	26.0	35.0	37.79	1.21			
2	S2	14.05	Wet	20.0	39.0	36.6	4.4	20	3	SM
			Dry	21.0	40.0	38.0	1.0			
3	S3	15.26	Wet	26.0	40.0	32.3	1.7	26	5	SM-SC
			Dry	28.0	44.0	27.1	0.9			
4	S4	20.49	Wet	22.0	38.0	38.2	1.8	21	3	SM
			Dry	23.0	41.0	35.46	0.54			
5	S5	14.81	Wet	25.0	34.0	37.5	3.5	22	4	SM-SC
			Dry	27.8	35.0	34.5	2.7			
6	S6	13.34	Wet	24.0	35.0	37.71	3.29	24	5	SM-SC
			Dry	28.0	36.0	34.85	1.15			

Notations: SM- Sandy Silt, SM-SC = Sandy Clayey Silt, LL - Liquid Limit, PI - Plasticity Index, NP - Non-Plastic

Table 2 - Direct Shear Test Results of Undisturbed Soil Samples

S. No.	Location of Soil Sample	Type of Soil	Bulk Density (Tonne/m^3)	Water Content (%)	Normal Load (kN/m^2)	Shear Stress (kN/m^2)	Cohesion (kN/m^2)	Angle of Friction
1	Left Flank of the slope failure	Yellowish sand, poorly graded	2.33	12.05	10	22.0	14	38°
			2.25	18.49	20	29.5		
			2.416	14.06	30	37.5		
			2.33	14.63	40	45.5		
2	Central portion of the slope failure	Green colored, very poorly graded Gravelly sand	2.537	10.44	10	28.5	23	30°
			2.247	9.33	20	34.0		
			2.258	5.62	30	40.0		
			2.537	8.07	40	45.5		
3	Right Flank of the Slope failure	Green colored, very poorly graded Gravelly sand	2.537	8.456	10	25.0	18	35°
			2.548	9.53	20	32.0		
			2.515	5.86	30	39.0		
			2.209	7.38	40	46.0		
4	Central Portion of the Slope Failure	Green colored, very poorly graded Gravelly sand	2.540	11.65	10	26.0	20	32°
			2.304	12.30	20	32.5		
			2.289	14.05	30	38.5		
			2.431	12.14	40	45.0		

Table 3 - Factor of Safety along selected profiles at Different Pore Pressure Ratios and Seismic Coefficients

Factor of safety									
Pore Pressure Ratio	Seismic Coefficients of Profile AA' (Eastern Profile)			Seismic Coefficients of Profile BB' (Central Profile)			Seismic Coefficients of Profile CC' (Western Profile)		
	0.00	0.05	0.10	0.00	0.05	0.10	0.00	0.05	0.10
0.0	1.1875	1.037	0.983	1.128	1.022	0.931	1.072	0.978	0.897
0.1	0.996	0.897	0.856	0.980	0.885	0.802	0.906	0.821	0.747
0.2	0.846	0.758	0.682	0.832	0.748	0.674	0.763	0.688	0.623
0.3	0.697	0.620	0.553	0.686	0.612	0.548	0.623	0.623	0.502
0.4	0.550	0.483	0.426	0.543	0.479	0.425	0.487	0.432	0.385
0.5	0.405	0.350	0.302	0.403	0.350	0.306	0.357	0.313	0.275

Fig. 1 - Panoramic view of problematic slope at Matli site

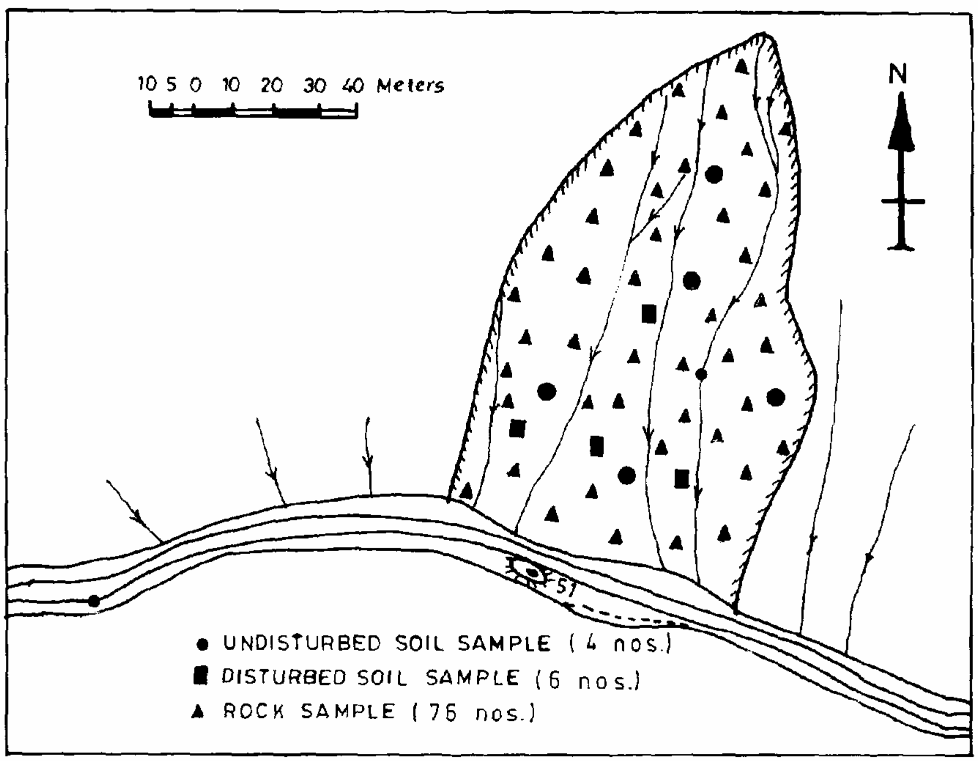
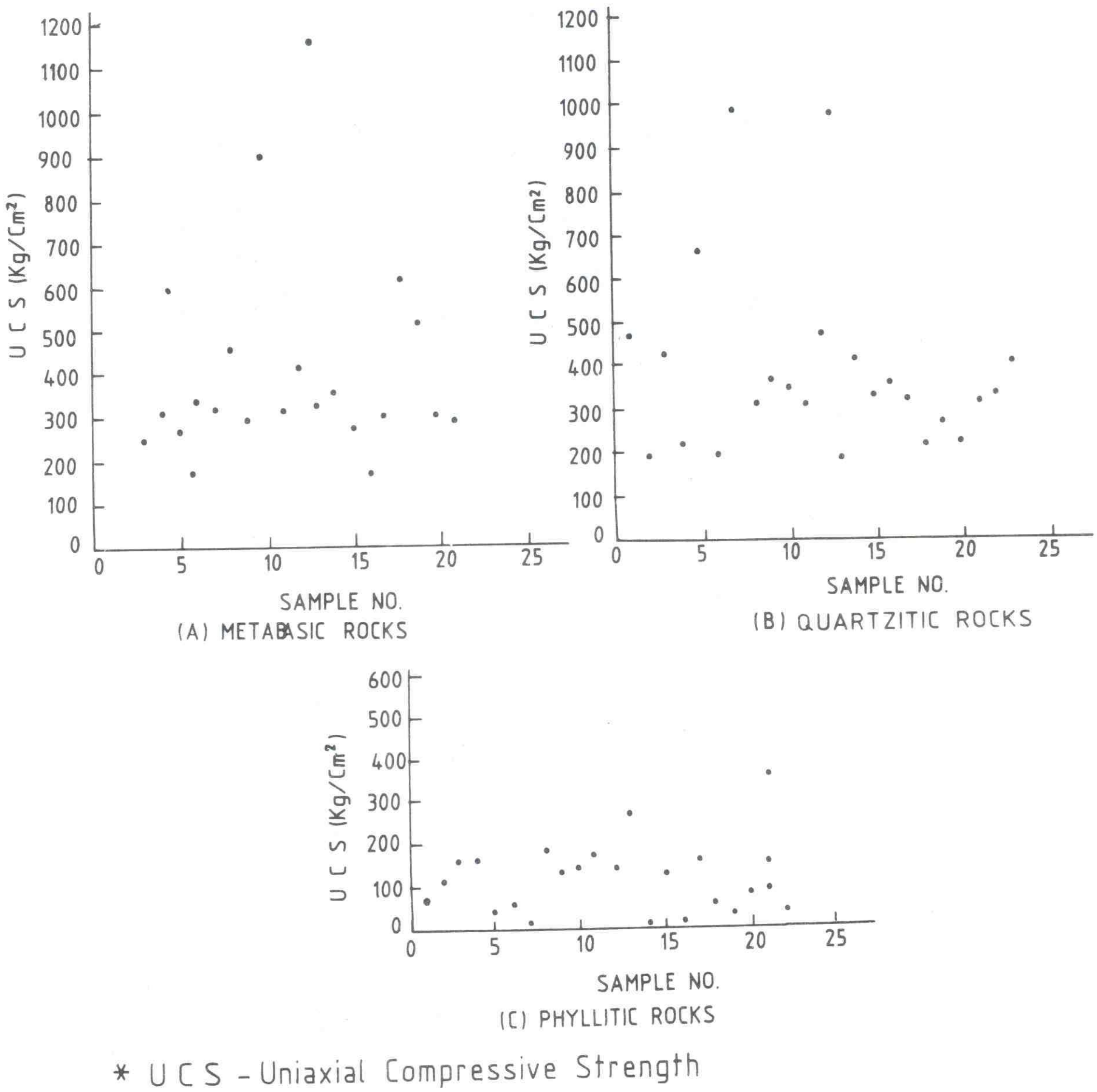
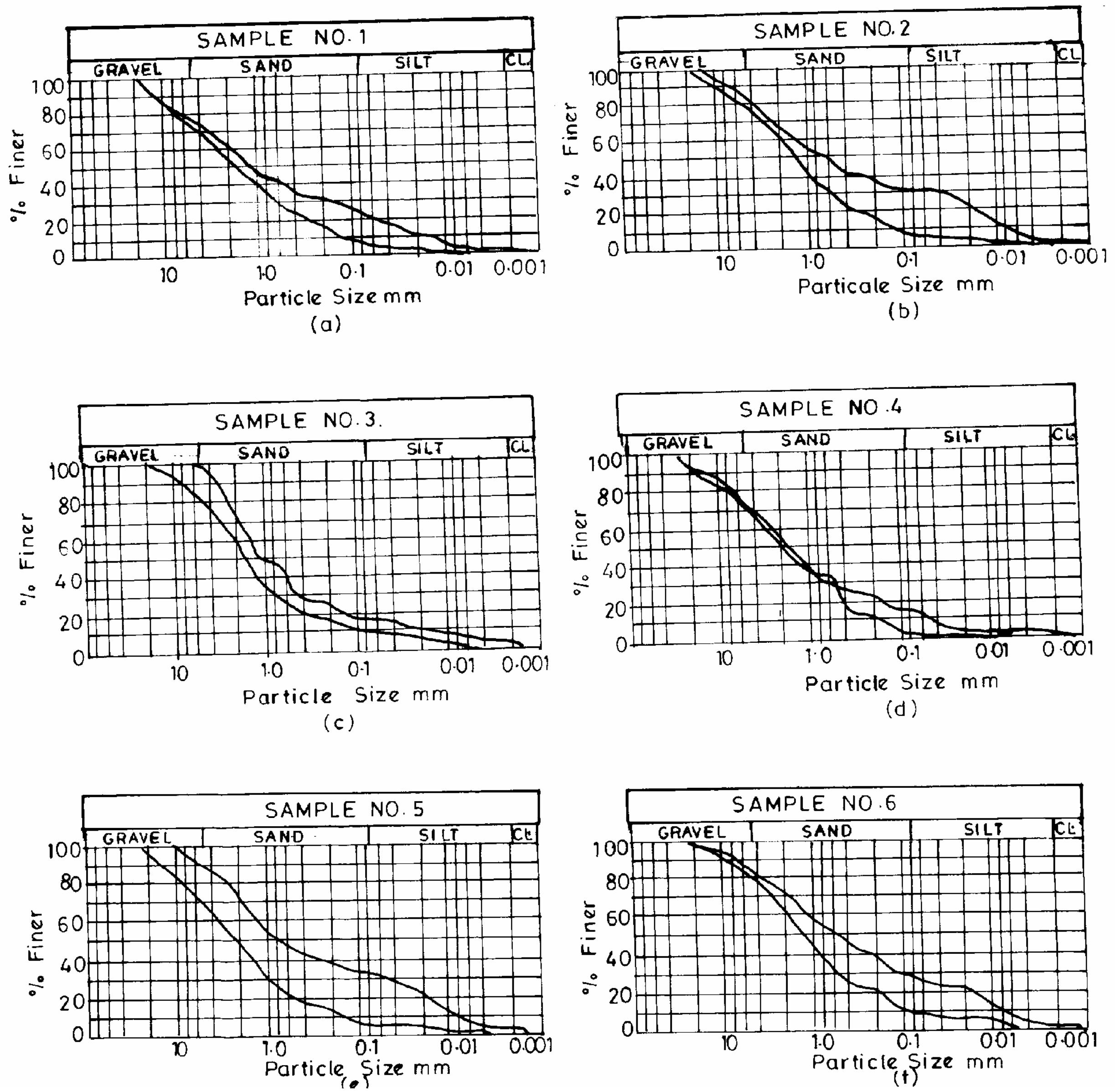


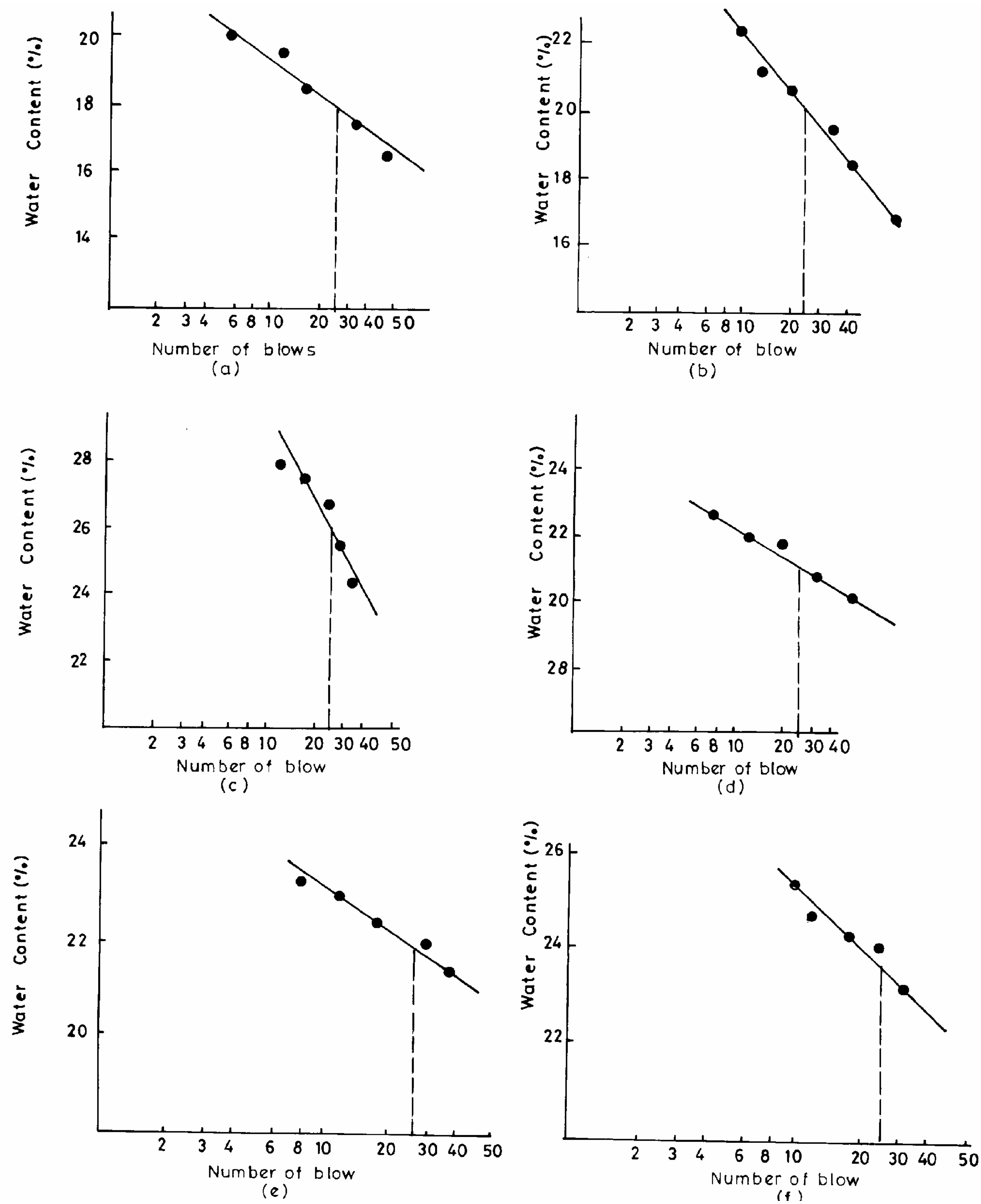
Fig. 2 - Locations of samples at Matli site



Figs. 3 (A to C) - Uniaxial compressive strength of rock samples from Matli site



Figs. 4 (a to f) - Grain size distribution curves of soils at Matli site



Figs. 5 (a to f) - Flow curves of soils at Matli site

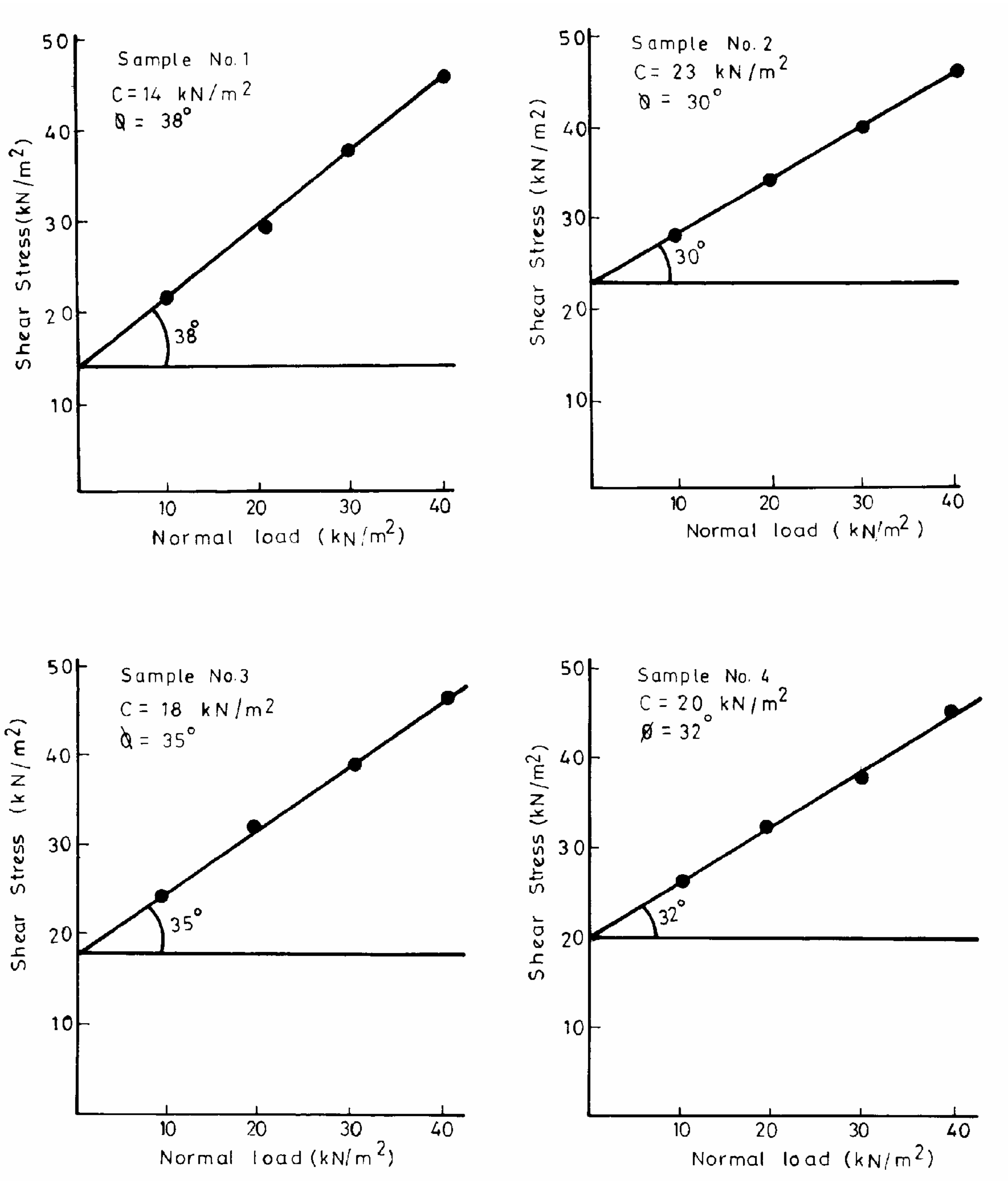


Fig. 6 - Direct shear test of undisturbed soil samples

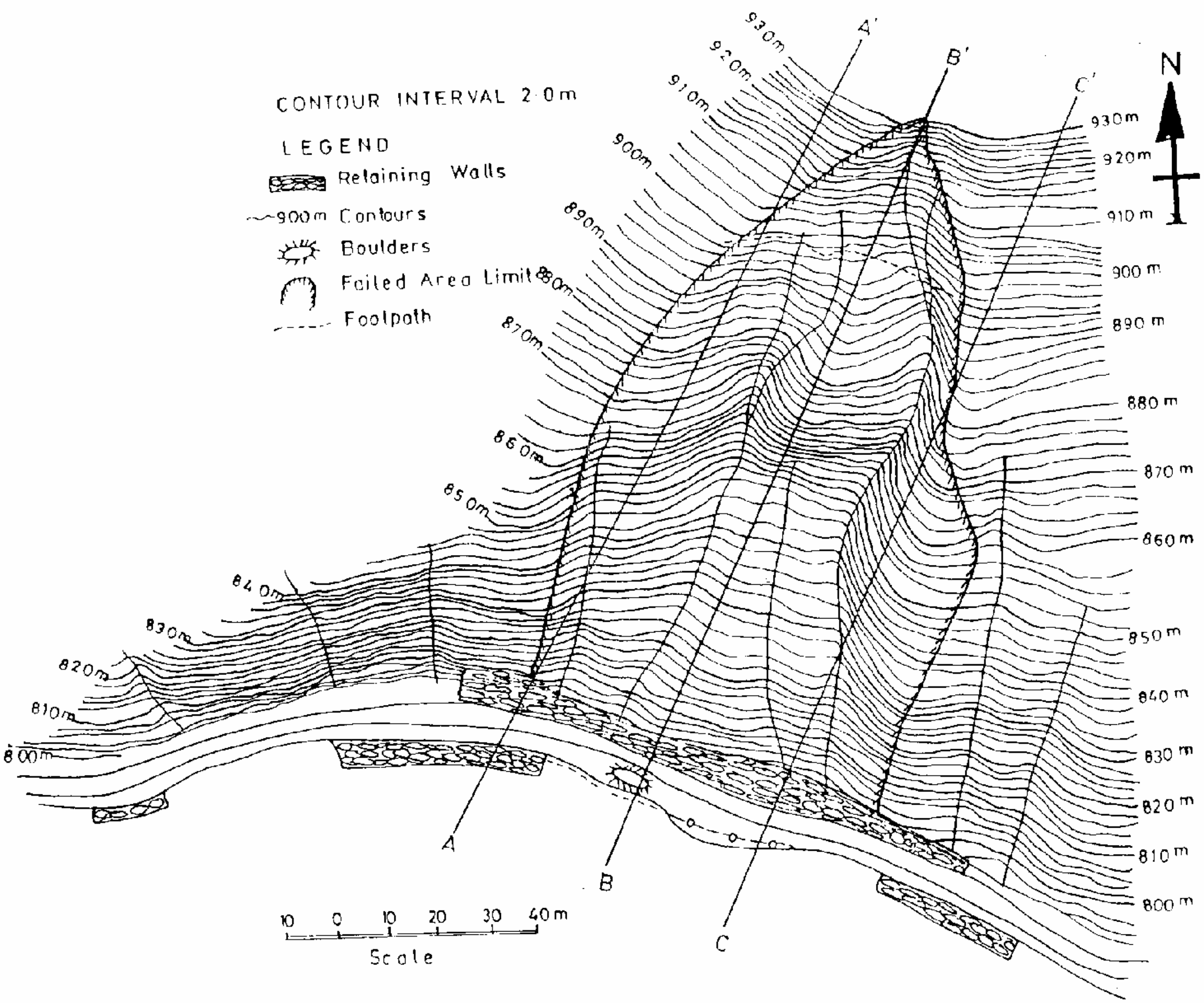
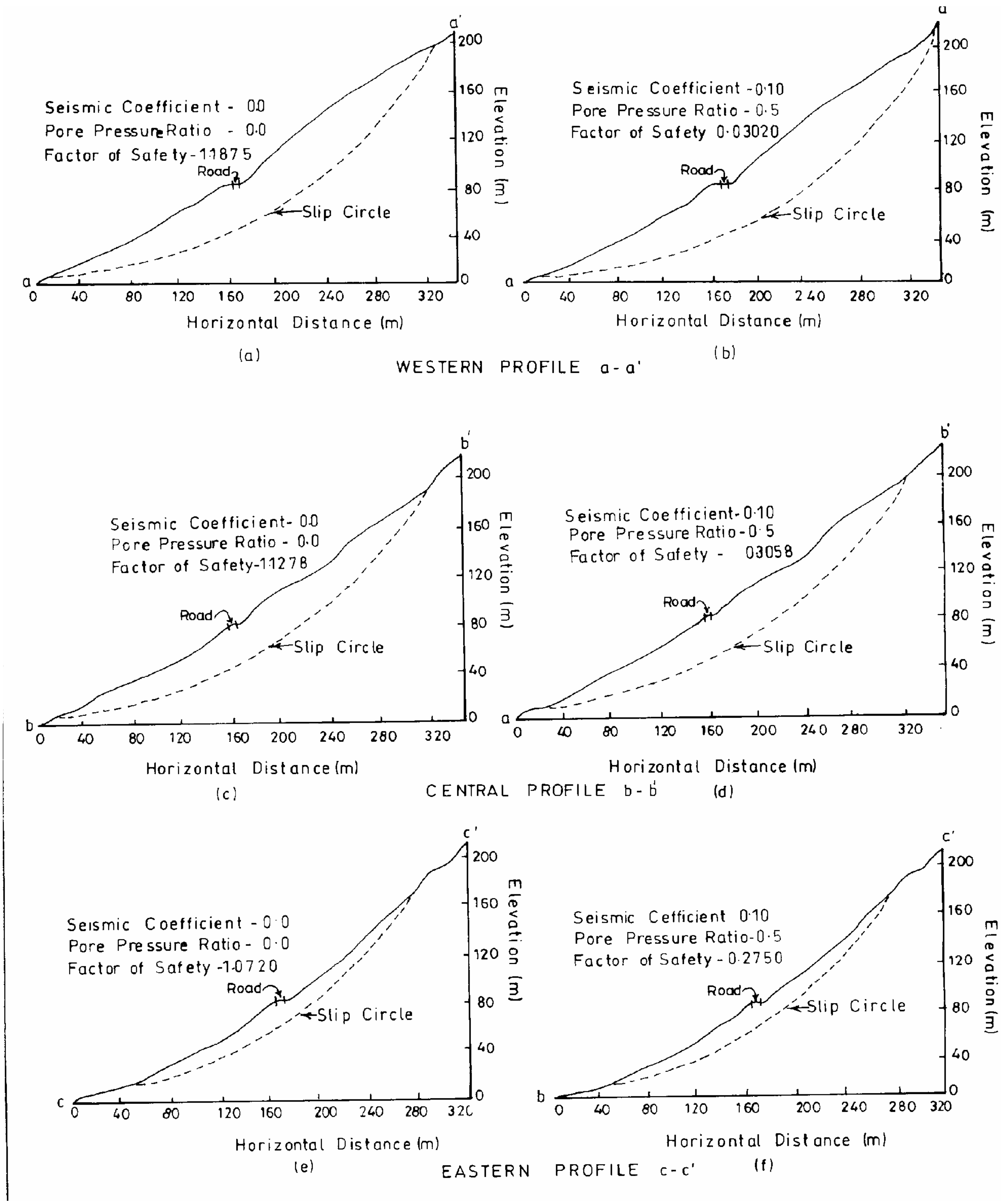


Fig. 7 - Map showing longitudinal section lines for stability analysis



Figs. 8 (a to f) - Potential slip surfaces along different profiles at Matli site

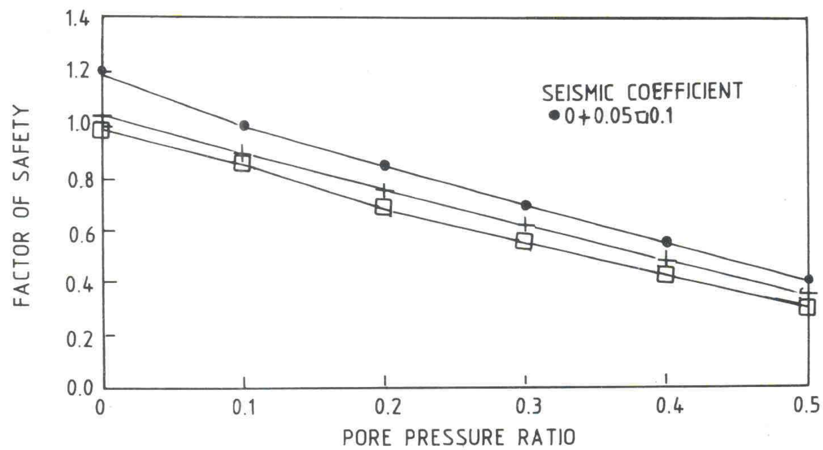


Fig. 9a - Factor of safety versus pore pressure ratio along profile AA'

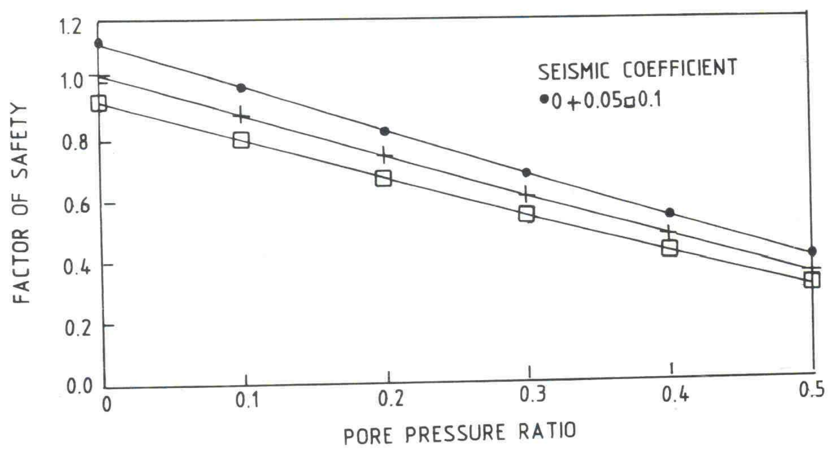


Fig. 9b - Factor of safety versus pore pressure ratio along profile BB'

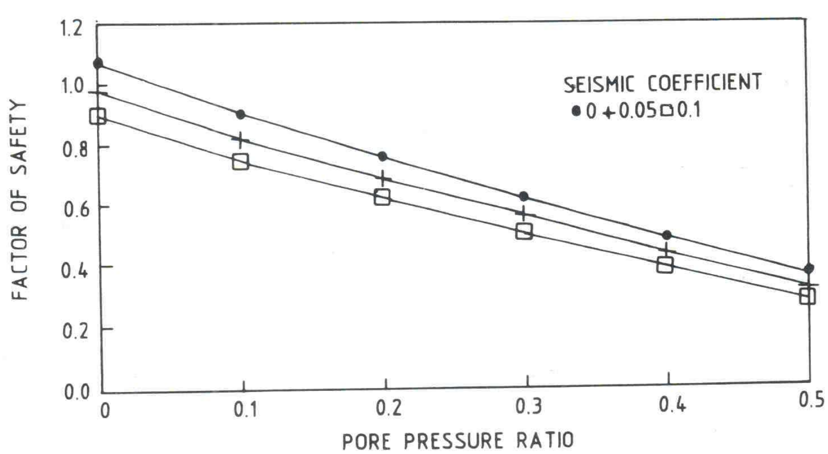


Fig. 9c - Factor of safety versus pore pressure ratio along profile CC'