



Topography Induced High In-Situ Stress Under a River Valley in Himalayas - A Case Study

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ABSTRACT

The simplifying assumption that the principal stresses are vertical and horizontal with depth breaks down when the ground surface is not horizontal as in the case of valleys and the hills. Knowing the effect of topography on stress distributions is of particular interest in case of construction of superstructure like dam or construction of tunnels in mountainous regions near valley slopes. In this paper we present our experience with in-situ stress measured by hydraulic-fracturing method below a river valley located in Himalayan region. The results show very high horizontal stress below the valley with vertical stress much higher than the overburden. The rotation of maximum compressional stress direction by 90° compared to the regional stress is also another outstanding feature revealed by the test. The site conditions are simulated and analysed by numerical method taking into account two types of loading conditions viz. only gravitational loading and gravitational and tectonic loadings in which case the measured results are incorporated as input parameter. The models show that below the valley, the topography affects both gravitational and tectonic loading as reflected by the localization and enhancement of stress conditions.

1. INTRODUCTION

Locating, a superstructure like, dam and excavating an underground cavern in rugged, tectonically complex Himalayas is a challenging task which requires a proper modeling for optimum design and stability study. The in-situ stress which is an important input parameter for modeling was being measured at few of the sites in Himalayas by flat jack method. The first measurement by

hydrofracture method was taken by us (Sengupta et. al. 1991) at Lakhwar hydroelectric project on the river Yamuna in district Dehradun in Uttar Pradesh India, which is shown in Figure-1. A narrow gorge and about 200 m wide strip of trap rock presents a suitable site for the 204 m high concrete gravity dam near village Lakhwar about 80 km from Dehradun. The test location was inside a drift located 46 m below the river bed (Figure-2 and Figure-3). The results showed very high horizontal stress and deviation of horizontal stress direction from the regional, and a possible topographic affect was suspected.

Savage et. al. (1985) showed that horizontal gravity-induced tensile stresses develop along and just below the valley bottom. At depth below the valley bottom, compressive horizontal stresses concentrate due to gravitationally driven convergence of the material below the valley walls. The gravitationally induced tensile stresses below the valleys are diminished in the presence of tectonic compression and deeper below the valleys the compressive stress concentration is accentuated (Savage and Swolfs 1986). Terzaghi and Richart (1952) suggested that for a flat-lying horizontal rock mass with poisson's ratio μ , the coefficient k is equal to $\mu/(1-\mu)$. This is the result of assuming the rock mass to be an ideal homogeneous, linearly elastic, isotropic continuum under gravity and vanishing lateral displacements. Savage et. al. (1985) has given the stress state far from the ridge by assuming vanishing far-field horizontal displacements as :

$$\begin{aligned} S_x &= \mu \rho g y / (1 - \mu), \\ S_y &= \rho g y \text{ and} \\ S_{xy} &= 0 \end{aligned}$$

We tried to understand the problem by numerical modelling programme using 2D-UDEC code incorporating the topography and the above relation and also the measured results. The idea behind taking measured parameters as input to the model calculations indicate that the vertical stress and horizontal stress are influenced by the topography below the valley.

2. GEOLOGICAL ASPECTS AND TESTING PROCEDURES

The project is located in Himalayan rock formations comprising phyllites, slates, quartzites and limestones which are intruded by a number of basic trap rock bodies. The dam is located across on such intruded body of basic rock ranging in composition from dolerite to hornblende rhyolite, the maximum width of the trap rock in river section is about 300 m which is sufficient to accommodate the full main dam and a part of spillway bucket.

The hydrofracture test was conducted inside a drift 46 m below the river bed in two vertical holes and two horizontal holes. The technique is based on the

principle of sealing off a section of a borehole (unfractured) by means of two inflatable rubber packers and pressuring the isolated segment of the borehole upto a critical level (breakdown pressure P_c) by using emulsified water until a tensile fracture is induced or pre-existing fracture is opened in the rock. The pump is then immediately shut in to obtain the shut in pressure (P_{si}) which is the fluid pressure necessary and sufficient to keep the fracture open. The frac tests are followed by several refracturisation tests to determine the pressure required to reopen the induced fracture i.e., reopening pressure (P_r). The breakdown pressure (P_c), the shut in pressure (P_{si}) and reopening pressure (P_r) are directly related to the prevailing in-situ stresses. A schematic diagram for the hydrofrac experimental setup is shown in Figure-4.

3. STRESS EVALUATION PROCEDURE AND RESULTS

3.1 Calculations by Classical Method :

Out of four holes drilled for hydrofrac testing, two holes were vertical and stresses were determined from those holes by classical method (Hubbert and Wills 1957). The vertical stress (S_v) can be calculated using the relationship :

$$S_v = \rho gh$$

where ρ = density of the rock;
 g = acceleration due to gravity; and
 h = depth of overburden.

Thus with 46 m of cover, $S_v = 1.19$ MPa, with $\rho = 2.65$ gm/cc.

When horizontal fractures are formed in the vertical hole, vertical stress S_v can be computed from the relation :

$$S_v = P_{si}$$

where P_{si} = Shut-in pressure which corresponds to the normal stress acting perpendicular to the fracture.

We found at one horizon in borehole LSV (vertical hole) at a depth of 13.20 m and at two horizons in the borehole LPV at depths of 9.25 m and 10.50 m, horizontal fractures were formed. Table 1 shows the hydro-fracture data derived from two vertical boreholes.

The vertical stress measured directly in the field using the above relation is equal to 9.46 MPa, thus we were having calculated vertical stress as 1.10 MPa and measured vertical stress = 9.46 MPa. the model calculations show that there is a concentration of vertical stress below the valley which is higher than the overburden. Thus we have considered $S_v = 9.46$ MPa.

The least horizontal principal stress (S_h) was measured using the relation :

$$S_h = P_{si}$$

This relation holds good when the fracture is vertical or sub-vertical in a vertical hole.

Table I Hydrofracture Data Derived from Two Vertical Holes

Depth m	P_c MPa	P_r MPa	P_{si} MPa	θ Degree	β Degree	α Degree
LSV						
13.20	13.5	12.5	09.5	200	02	110
14.40	18.4	15.5	10.8	140	80	230
19.60	18.5	15.5	10.5	140	90	--
20.60	17.0	15.5	10.6	130	85	220
LPV						
9.25	14.5	11.0	10.0	150	00	--
10.50	13.0	11.5	08.9	110	02	200
14.40	15.0	13.9	10.8	130	88	220

where P_c = Breakdown pressure;
 P_r = Reopening pressure;
 P_{si} = Shut-in pressure;
 θ = Strike direction of the fracture (north over east);
 β = Inclination of the fracture plane (with respect to horizontal);
 α = Direction of inclination.

The maximum horizontal principal stress (S_H) was obtained from the relation:

$$S_H = 3S_h - P_r - P_o$$

Where P_o , the pore water pressure in the rock was determined from the water head in the hole. For the computation of S_H , P_r value in cycle 3 was used. Each P_r value was determined as the point on the ascending portion of the pressure time curve where slope began to deviate from that recorded in the first cycle with the flow rate kept the same as in the first cycle. A typical Pressure-Time plot is shown in Figure-5. The stress tensors as revealed by classical method are shown in Table-II.

Table II Stress Tensors Determined by Classical Method

Depth from Collar m	P _c MPa	P _r MPa	P _{si} MPa	S _H MPa	S _h MPa	S _v MPa
LSV						
13.20	13.5	12.5	09.5	--	--	9.5 *
14.40	18.4	15.5	10.8	16.9	10.8	-- #
19.60	18.5	15.5	10.5	16.0	10.5	-- #
20.60	17.0	15.5	10.6	16.3	10.6	-- #
LPV						
9.25	14.5	11.0	10.0	--	--	10.0 *
10.50	13.0	11.5	10.5	--	--	08.9 *
14.40	15.0	13.9	10.8	18.5	10.8	-- #
AVERAGE				16.93	10.67	9.46
* Horizontal Fracture						
# Vertical Fracture						
Direction of S _H from the verticle boreholes = N45° W						

3.2 Calculations from Shut-in Pressure Data

As two randomly oriented horizontal holes were involved and some pre-existing closed joints were opened, the classical method could not be used for two horizontal holes, instead a more sophisticated method namely the interpretation of measured normal stress acting across arbitrary oriented fracture plane was used. This method is based on Cornet and Valette's (1984) approach by which the magnitude and the direction stresses can be evaluated from the relation :

$$S_h = (P_{si} - n^2 S_v) / (m^2 + l^2 S_H/S_h)$$

where l, m, n, are cosines of the direction of the induced fracture plane related to the principle stress axis.

S_h = Minimum horizontal stress; P_{si} = shut-in pressure.

The calculations were done by using all shut-in pressure data derived from the measurements in the boreholes (2 horizontal and 2 vertical) by varying the ratio S_H/S_h and the strike direction of S_H in the horizontal plane. Here also vertical stress was considered as the measured one and not that determined

from the overburden. The stress tensors as calculated by the Shut-in pressure method are given in Table III.

Table III Resulting Stress Field

Vertical stress	S_v	=	09.46 MPa (from Vertical Hole)
Minimum horizontal stress	S_h	=	09.47 = 0.03 MPa
Maximum horizontal stress	S_H	=	14.20 = 0.04 MPa
Direction of horizontal stress		=	N40°W
$K = S_H/S_v$		=	1.50

4. NUMERICAL ANALYSIS

The influence of the topography in the mountainous region on the stresses was investigated by numerical method. The valley at the Lakhwar dam site was formulated using computer model. Numerical analysis was performed to study the stresses at the in-situ test sites under the dam foundation. Two dimensional plane strain analysis was performed using stress analysis computer software UDEC (Universal Distinct Element Code). In this study only continuum analyses were performed. No account was taken of the tectonic or residual stresses and elastic behavior of the rock was assumed. A section along AA in Figure-2 was simulated. The rock mass was assumed to be homogeneous, isotropic and linear elastic. The material properties assumed are as follows :

1. Young's Modulus = 71 Gpa
2. Poisson's Ratio = 0.258
3. Density = 2700 Kg/m³

The model configuration considered for the analysis is shown in Figure-6. This geometry represents the cross section AA (Figure-2) across the river, parallel to the axis of the dam and nearly coinciding with the direction of the maximum horizontal stress S_H obtained from the in-situ stress measurement. Two cases of initial stress fields were assumed for the model as :

1. Stress in vertical direction (S_v) is gravitational with a gradient of 0.0265 MPa/m along the depth and the horizontal stress (S_H) is such that $K(S_H/S_v)$ is 0.35.
2. The vertical stress field is gravitational and horizontal stress is 1.7 times that of the vertical. The K value assumed here was equivalent to the value obtained from the in-situ stress measurement.

The stresses were monitored at point A as shown in Figure-6, 46 m below the river bed. The UDEC results are given in Table-4. The results of the

analyses are displayed in Figure-7 and Figure-8. The principal stress plot is shown in Figure-9. The conclusion drawn is that under the valley the vertical stress is higher than the self weight of the overlying rock and the principal stresses are oriented almost in vertical and horizontal direction. The measured value of the stresses agree reasonably with the computation in case of S_v and S_h but in case of S_H the computed value is slightly at the higher side. The relation of $S_H > S_h > S_v$ is maintained which was also observed from the measurement.

Table IV Comparison of Numerical Results with the Measured Results

Numerical results							Measured results		
Load Case	xx	yy	z(S_h)	Principal stresses			Classical method		
	MPa	MPa	MPa	S_H	S_v	Angle	S_H	S_v	S_h
				MPa	MPa	S_v & Vert.	MPa	MPa	MPa
0.35	2.8	3.5	--	2.8	3.5	2°			
1.7	20.4	9.3	10.3	20.4	10.3	1°	17.0	9.5	10.7

Remarks: xx and yy are the stresses in x and y directions.
z(S_h) is the stress-out-of-plane directions.

5. DISCUSSION

The estimation of stress field at the Lakhwar dam site is very complex in nature because of i) highly complex Himalayan tectonics ii) Strong topography effect.

The magnitude of vertical stress measured in the field found to be higher than the calculated from the overburden. This implies that the direct estimation of vertical stress holds good only when the measuring site is free from the influence of topography and residual stress. The combined effect of tectonism and gravity on the stress distribution in ridges and valleys might have caused increase in vertical stress. A plot of values of vertical stress upto a depth of 500 m show a large scatter mostly towards the higher side as compared to the average (Hoek and Brown). The high horizontal stress near the surface is common feature all over the world. Recent works carried out by Savage and Swolfs (1986) are testimony to that. The UDEC model also revealed high horizontal and vertical stress concentrations below the valley.

The direction of maximum horizontal compression S_H is N40° - 45°W. This direction is found to be not in agreement with the earthquake focal mechanism solutions for North Western Himalaya in which case it is N42°E at latitude 30°N and longitude 78°E (Khatti et. al. 1989). The composite fault plane solutions categorised the area in strike slip faulting regime viz. $S_H > S_h > S_v$.

The apparent 90° rotation of the maximum horizontal stress from the regional stress direction is more common feature in the stresses effected by topography (Haimson 1976, 1979) due to proximity of the shallow depths to the free boundaries of the surface topography.

6. CONCLUSION

We have attempted to explain the measured stresses at Lakhwar project site in Himalayas using numerical modelling. From the results, it is apparent that the measured stresses below the valley may be of tectonic origin and are affected by topography. The magnitudes and the directions of the principal stresses under a valley are influenced by topography and the resultant stress field is a complex combination of topography and tectonic stress field at considerable depth free from the influence of topography. The vertical stress in such cases can not be assumed but has to be measured. As in a vertical borehole the tendency of the newly created hydrofracture is orienting itself axially rather than transversely, it is always advisable to reopen some preexisting horizontal fractures and measure the normal stresses across such fractures to estimate the vertical stress.

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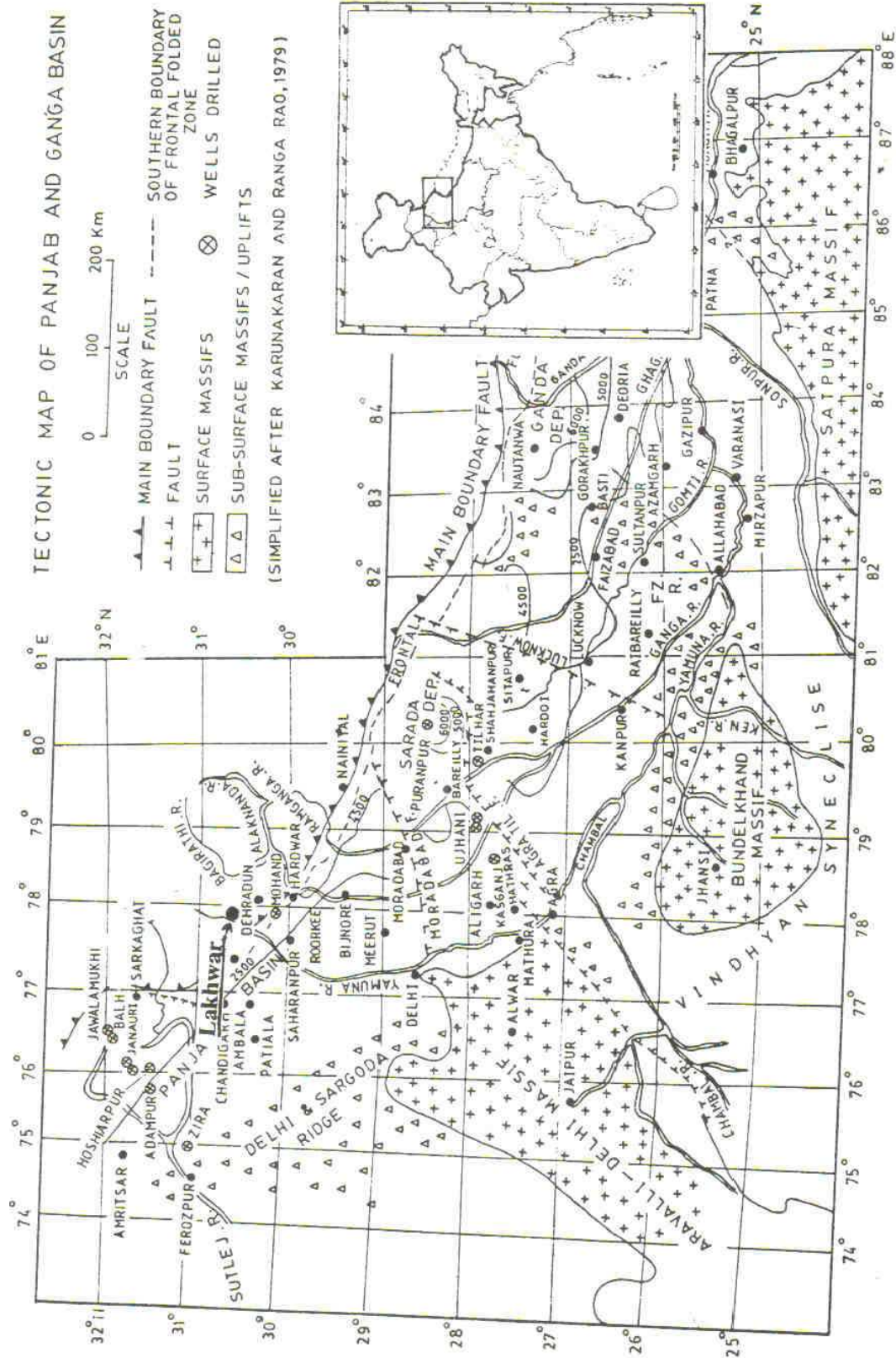


Figure 1. Location Map of Lakhwar Hydroelectric Project.

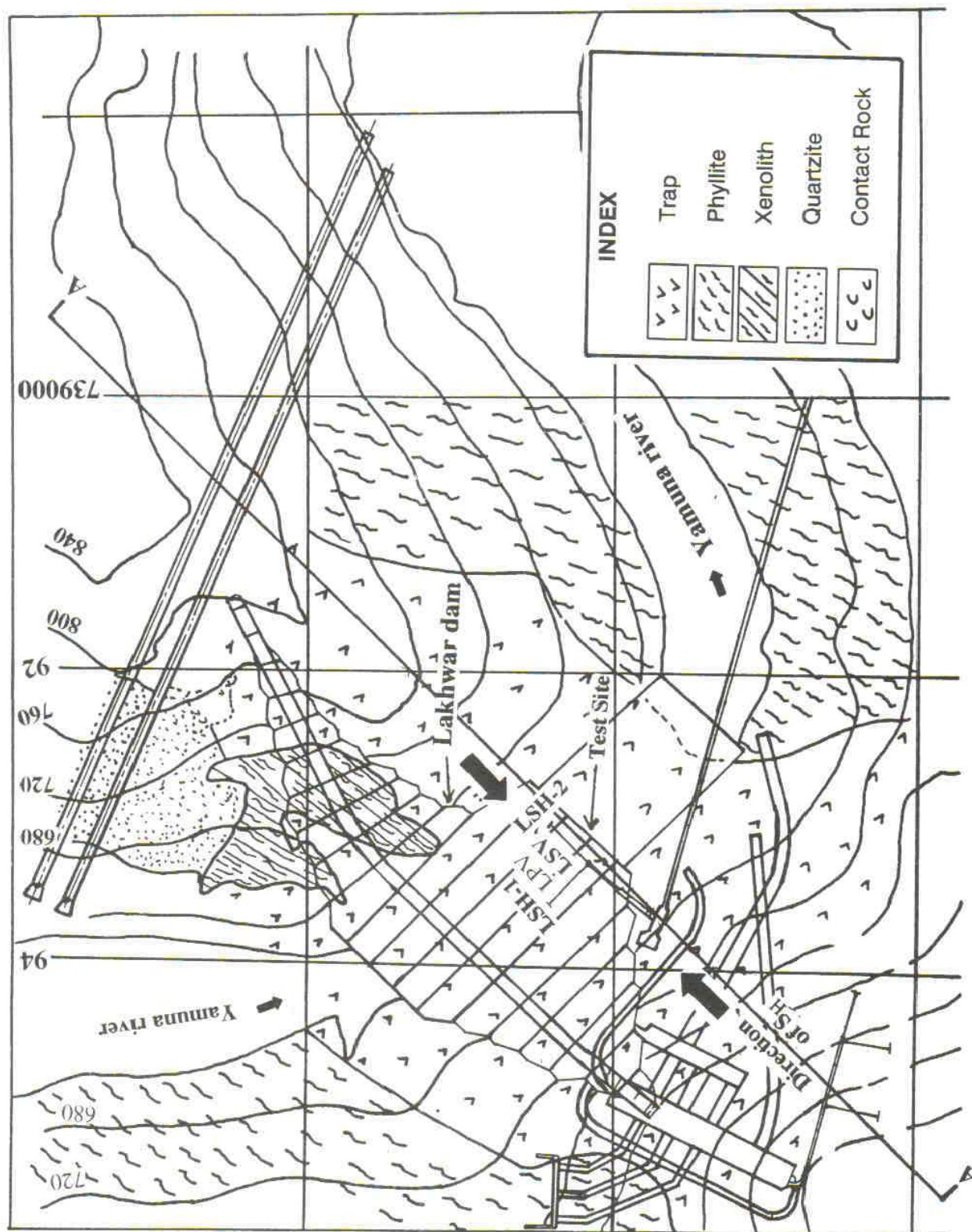


Figure 2. Geological plan showing section A-A used for the numerical modelling.

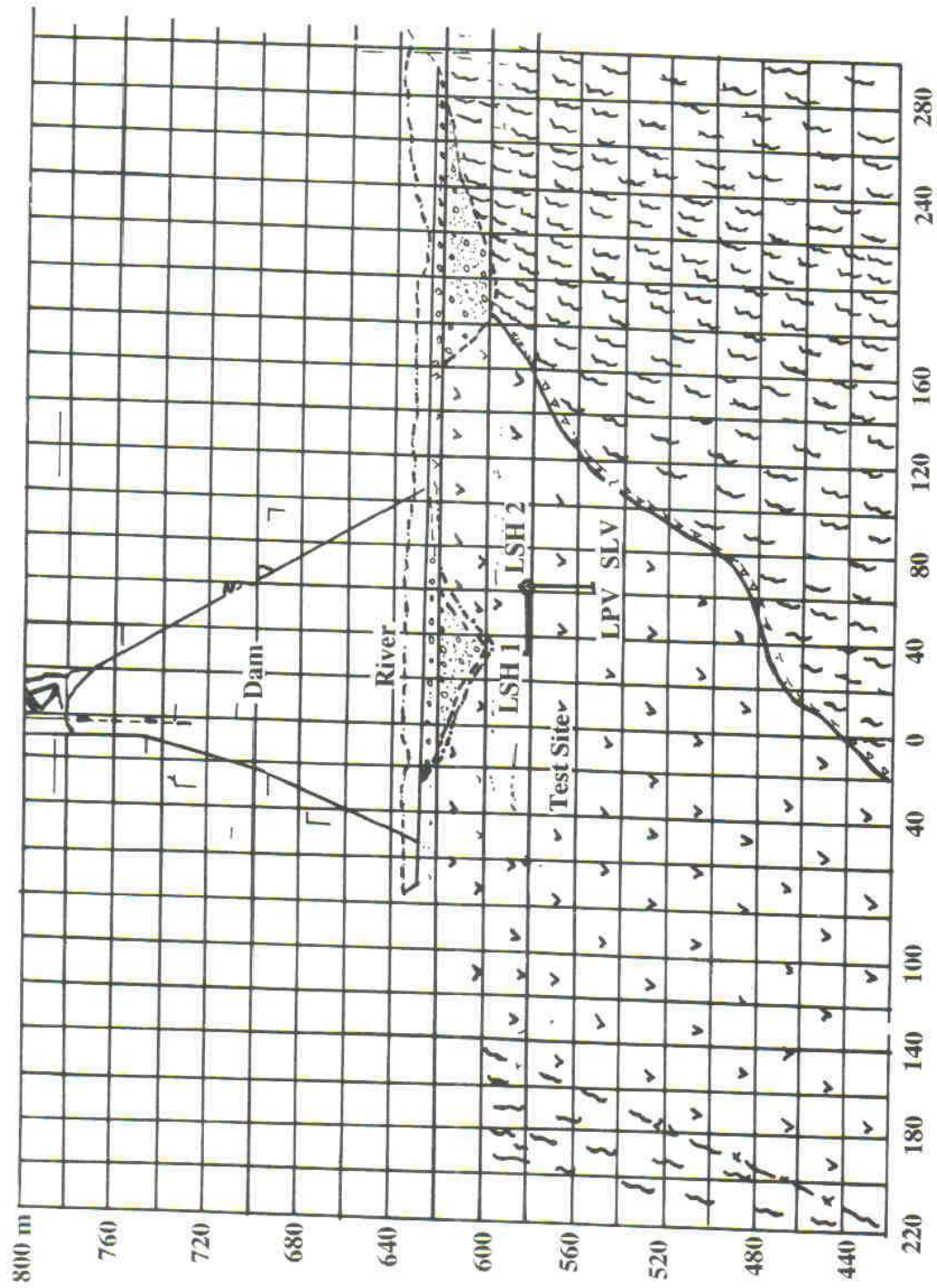


Figure 3. Location of the test site.

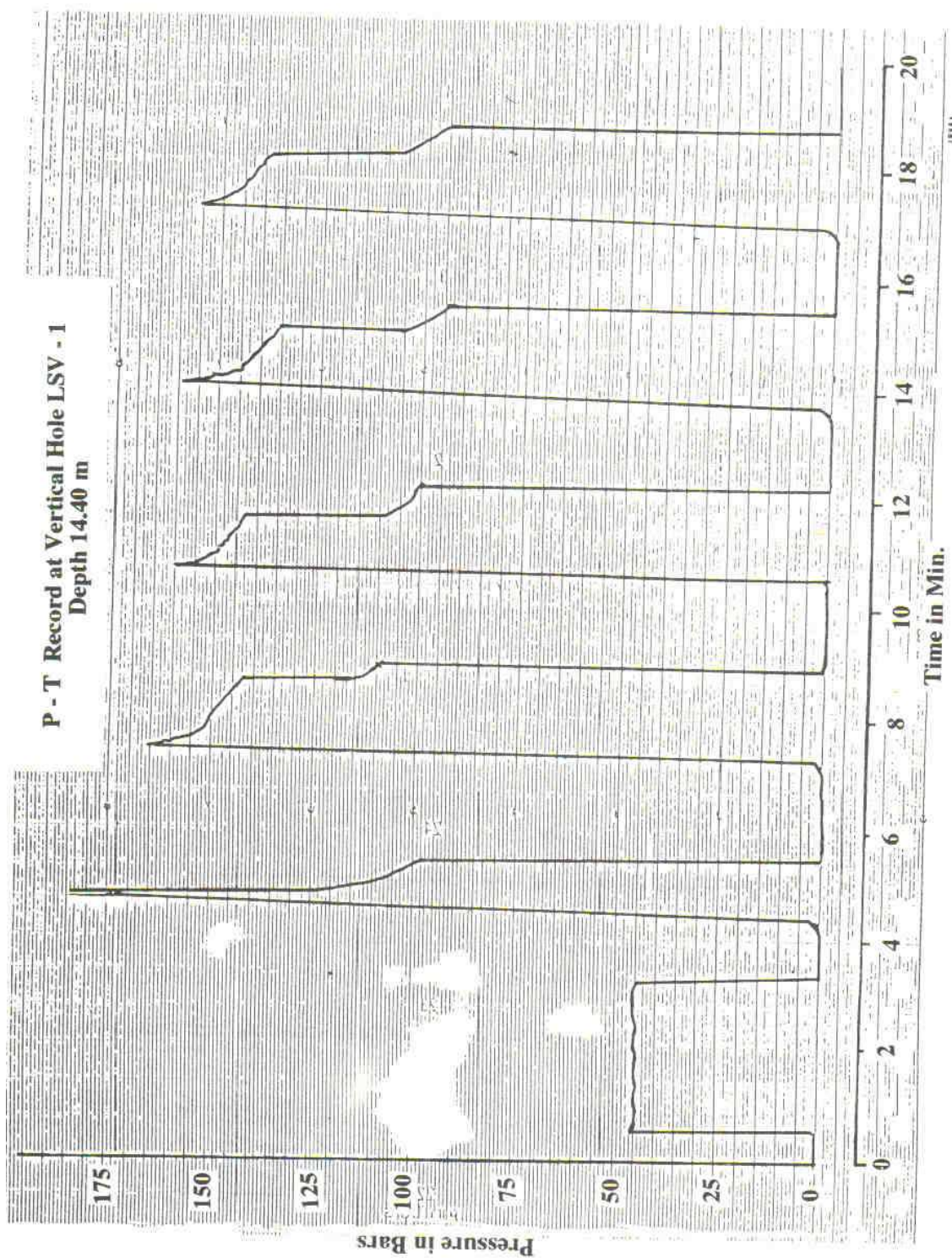


Figure 5. Typical P-T curve.

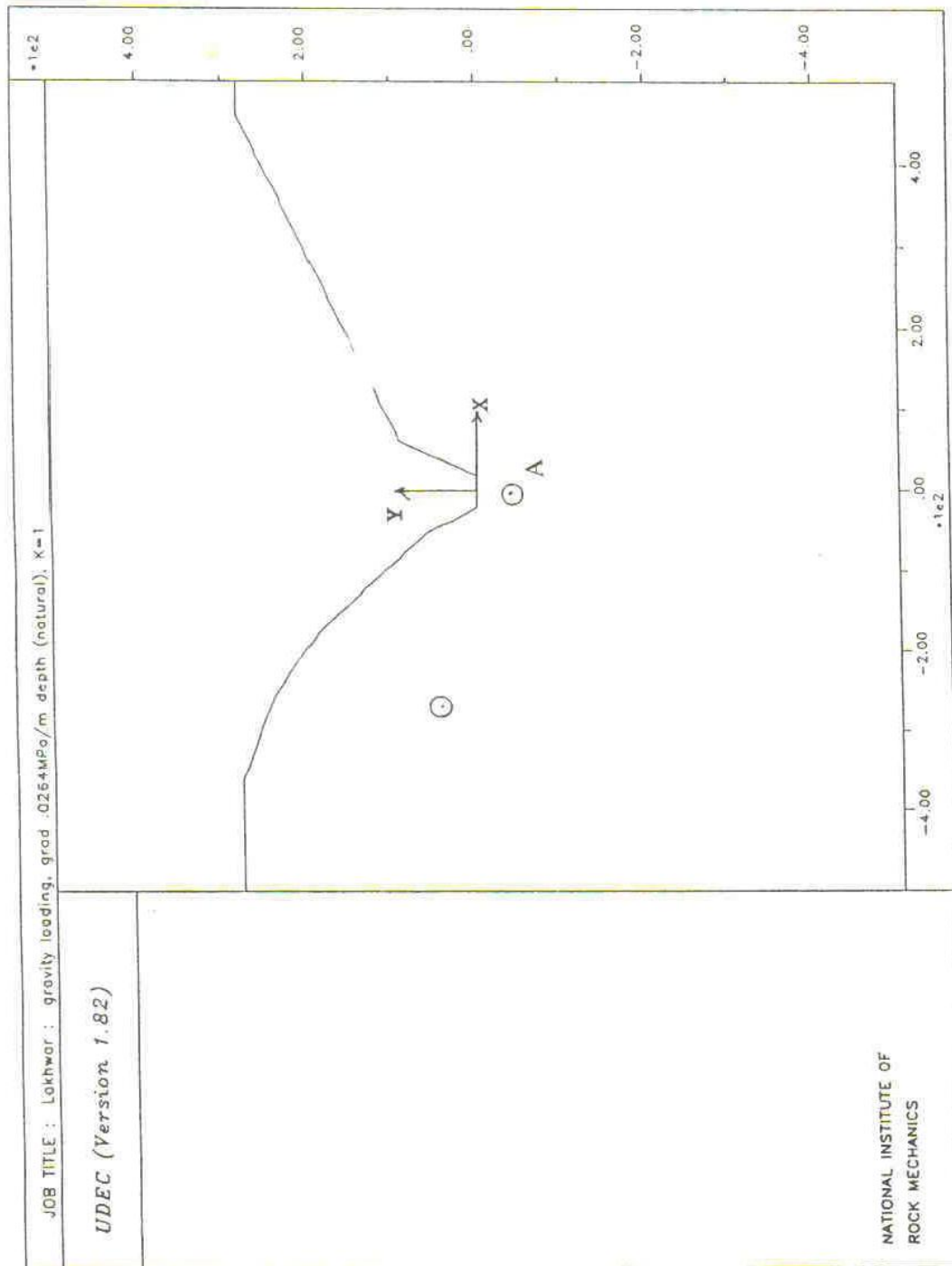


Figure 6. Model geometry along section A-A.

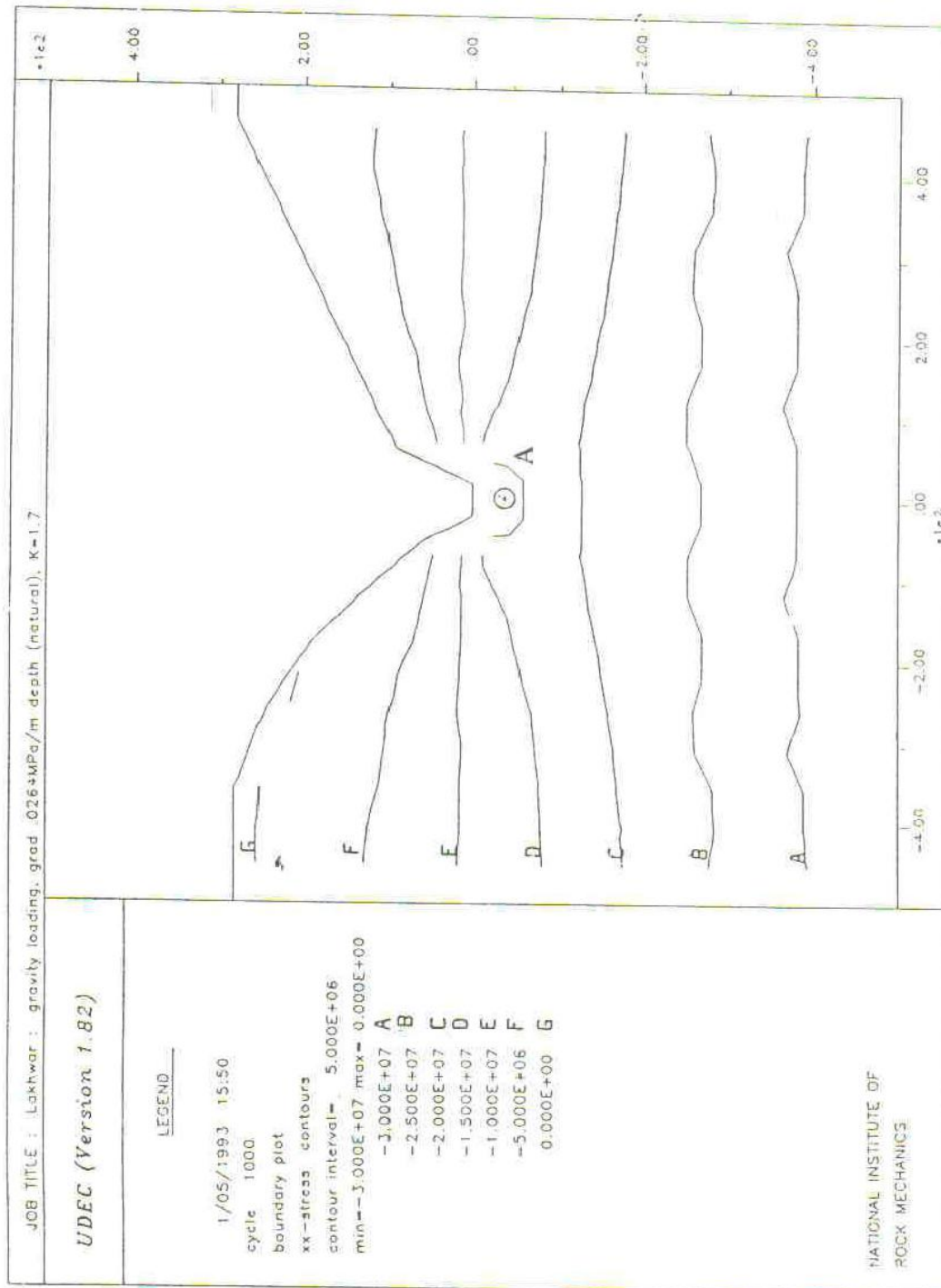


Figure 7. Horizontal stress Contours near the valley for the load case 1.7.

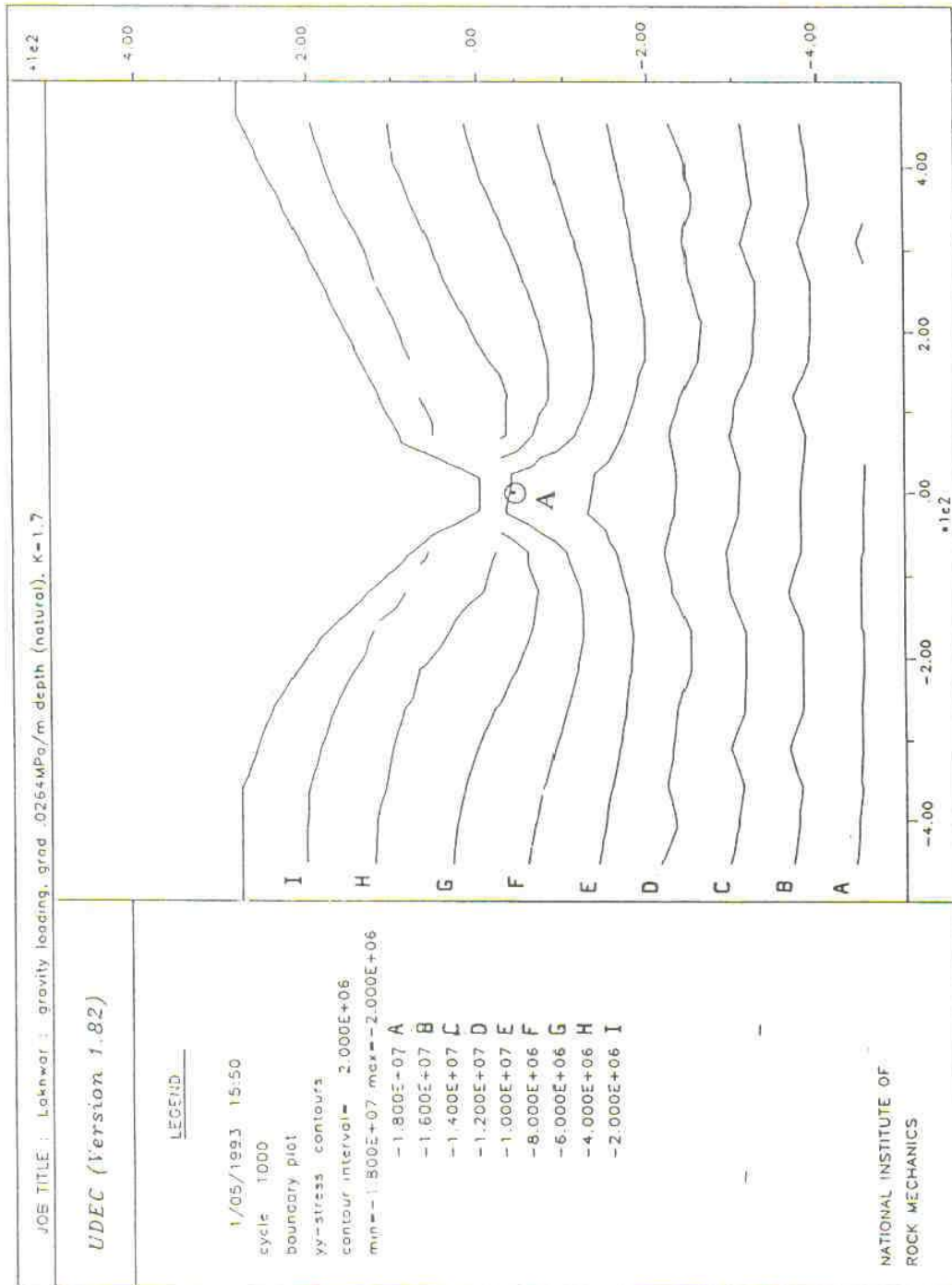


Figure 8. Vertical stress contour near the valley for load case 1.7.

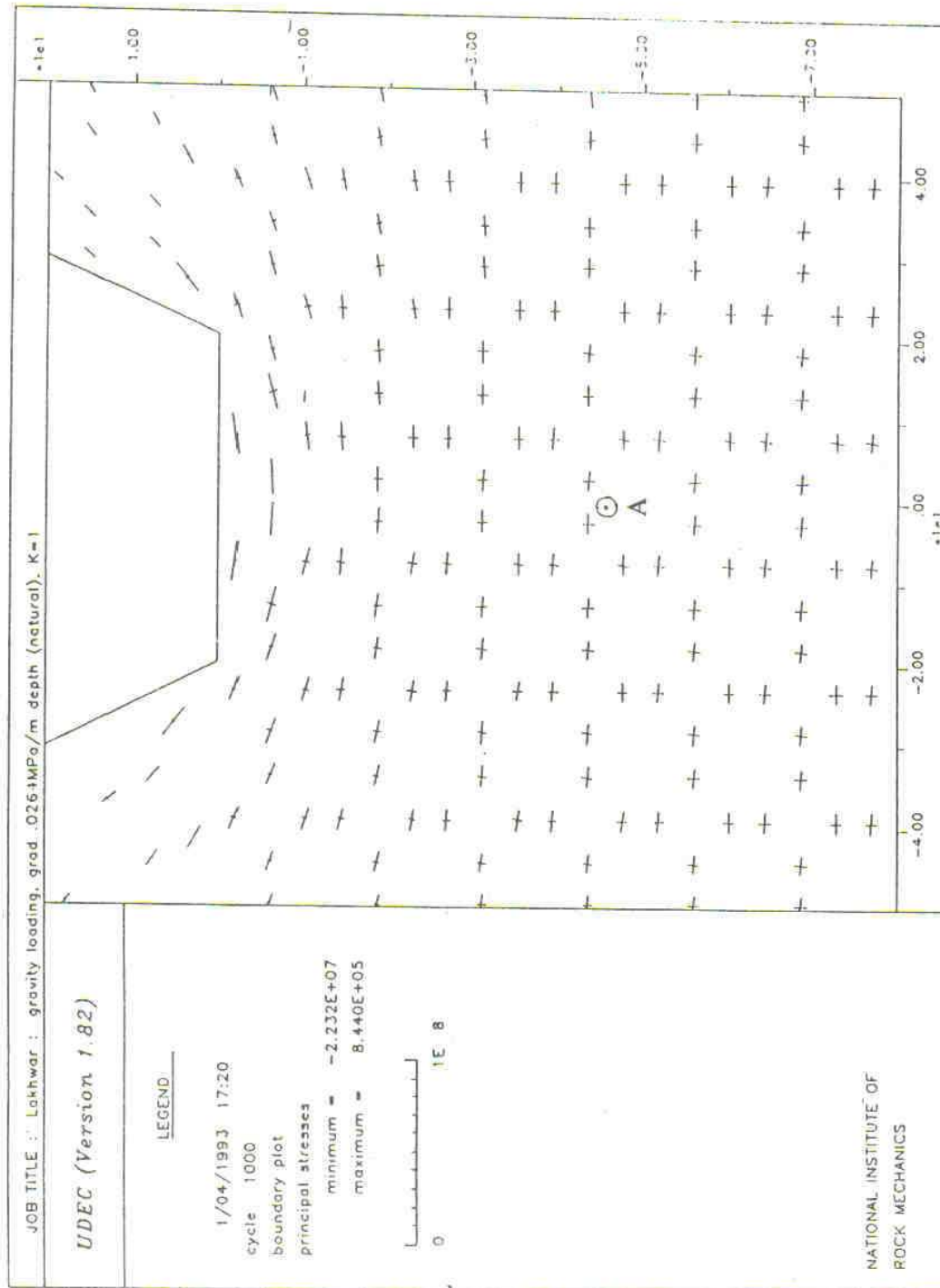


Figure 9. Principal stress plots below the valley at the measuring site.