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Stress Measurements: Some Important Case Studies

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ABSTRACT

An understanding of the in-situ state of stress in a rock mass is necessary for the design of structures in rock. Instabilities in jointed rock masses are structurally controlled, driven by unidirectional force (i.e., gravity), at relatively shallow depth. Failure is essentially stress controlled at greater depths where high stresses are existing and the rock mass is more or less isotropic and homogeneous. The in-situ stress field influences the performance of underground structures particularly in the Himalaya having strong influence of topography and geology. It is always advisable to measure the in-situ stresses, in whatever best way possible. Hydraulic fracturing method is one of the popular techniques used for determining magnitude and direction of secondary stresses in rock mass. *In many of the published literature on Himalayan region, the direction of major horizontal in-situ stresses usually trends towards North-East (NE) direction. However, it is not the case always, there are instances, where maximum horizontal stress has been found surprisingly to be in North-West (NW) direction.* In the present paper, three such case studies have been discussed.

Keywords: In-situ stress; Stress measurements; Hydraulic fracturing; Desilting chamber

1. INTRODUCTION

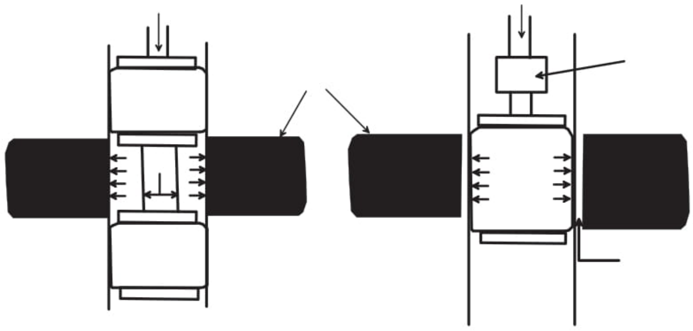
Accurate prediction of the in-situ state of stress in rock and their spatial variation is very difficult and impossible for practical purpose, since, the current state of stress is the end product of long series of post geological events. Rock mass has experienced several phases or cycles of physiochemical, thermal and tectonic processes. Further since, rock masses are rarely homogeneous, isotropic and continuous, stresses cannot be expected to vary linearly. An obvious situation in which stresses are discontinuous is at contacts between rock masses of different lithology and where rocks are intersected by several sets of joints, faults and other structural features (Hudson and Feng, 2010).

The natural stress pattern of Himalaya has not been well established so far and there is strong influence of topography and geology on in-situ stresses (Pankaj et al., 2017). In such a complex situation, any empirical approach for in-situ stress determination may lead to erroneous conclusion (Nripendra et al., 2003). Whereas, direction of major horizontal stress is important for optimising the orientation of underground caverns (Hari Dev et al., 2016), the magnitude of horizontal stress are used to design the rock support measures. Hence, it is important to measure in-situ stresses for better design of underground excavations and critical decision making, as the distribution and magnitude of in-situ stresses affect the geometry, shape, dimensioning, excavation sequence and orientation of underground excavations. In the present paper, results of in-situ stress measurements carried out at desilting chambers of Nathpa Jhakri Hydroelectric Project, Himachal Pradesh, Loharinag Pala Hydroelectric Project, Uttrakhand and Punatsangchhu-II Hydroelectric Project, Bhutan have been discussed.

2. PRINCIPLE OF HYDRAULIC FRACTURING TEST

The hydraulic-fracturing tests were conducted as per the IS: 13946 (Part-I), 1994 suggested test procedure. Basic steps of hydraulic fracturing test are shown in Fig. 1. Fundamental principles underlying the application of hydraulic fracturing is that:

- One of the principle stress components is co-axial with the test hole.
- The long term shut-in pressure is approximated as the magnitude of the minor stress component.
- The crack will generally tend to initiate in a plane normal to minimum stress (i.e., along the maximum stress)



(a) (b)

Fig. 1 - Basic steps involved in hydraulic-fracturing test (Amadei & Stephansson, 1997)

The magnitude of maximum secondary principal stress component for impermeable rocks is determined from the following Eq. 1:

$$\sigma_1' = 3\sigma_3' + S - P_i - P_o \tag{1}$$

where

σ_1' = maximum secondary stress,
σ_3' = minimum secondary stress,
S = fracture strength of the rock,
P_i = fracture initiation pressure, and
P_o = ambient pore pressure.

The magnitude of minimum secondary principal stress is equal to the shut-in pressure (S_i). Therefore,

$$\sigma_3' = S_i \tag{2}$$

The fracture strength, 'S' can be found from Eq. 3

$$S = P_i - P_r \quad (3)$$

where P_r is fracture reopening pressure.

Equation 3 can be rewritten as

$$S - P_i = - P_r \quad (4)$$

Neglecting P_o term, as the ambient pore pressure can normally be assumed to have been dissipated in the close proximity of an underground opening, the Eq. 1 can be rewritten as follows with the help of Eq. 4:

$$\sigma_1' = 3\sigma_3' - P_r \quad (5)$$

P_i, P_r and S_i can be obtained from pressure time record. S_i is calculated by the double tangent method.

The vertical stress is estimated from the depth of overburden rock by:

$$\sigma_v = \gamma h \quad (6)$$

where σ_v is vertical stress, h is depth of overburden, and γ is average density of rock mass.

Direction of the stresses is determined from the impressions of the induced cracks obtained on the impression packer. These directions are obtained with reference to true North.

In the present study, magnitude and direction of minimum (σ_h) and maximum (σ_H) horizontal stresses were determined from the hydro-fracturing tests carried out in vertically downward drillholes. All the case histories described here pertain to desilting chambers for hydropower development.

3. CASE STUDY I: NATHPA JHAKRI HYDROELECTRIC PROJECT, HP

The Project is located in Kinnaur and Shimla districts of Himachal Pradesh (HP) and was commissioned in 2004. The project comprises of a 60.50 m high concrete dam on Sutlej River, an underground desilting chambers of 525m (L) x 16.31m (W) x 27.50m (H) each; a 10.50m dia and 27.30 km long head race tunnel; an underground powerhouse complex having six francis units of 250MW each.

The diversion dam, desilting complex and initial reaches of the head race tunnel are located in the formations which are predominantly gneisses. The gneisses, in general, are found to be hard and tough. Rest of the HRT length, traverses through formations which are either predominantly gneisses with schist bands or schist with gneiss bands. The project is located in Lesser Himalaya and falls in Zone-IV of the seismic zoning map of India.

Eight hydraulic fracture tests were carried out in 190 m deep, 'NX' size vertical borehole in the desilting chamber. The minimum and maximum horizontal stresses vary from 2.16 to

5.40 MPa and 2.52 to 7.92 MPa, respectively. The direction of maximum horizontal stress has been estimated as N10^{0}W. The test details are shown in Table 1 (CSMRS, 1994) and pressure versus time plot and fracture impression record of one of the tests is shown in Fig. 2.

Table 1 - Hydraulic fracturing Test Details, Desilting Chamber, Nathpa Jhakri H.E. Project, HP

Test No.	Depth of Test (m)	Max. Horz. Stress (σ_H) (MPa)	Min. Horz. Stress (σ_h) (MPa)	Orientation of Max. Horz. Stress
1	52.55	-	-	N 16.4^{0}W
2	83.70	5.76	5.04	N 6.7^{0}W
3	87.50	6.48	5.40	-
4	96.70	4.68	2.88	N 1.6^{0}E
5	123.64	3.24	2.16	N 34.5^{0}W
6	132.50	2.37	2.16	-
7	170.60	7.92	4.68	N 9.6^{0}E
8	182.50	2.52	2.16	-
Average		4.71	3.50	N 9.28^{0}W

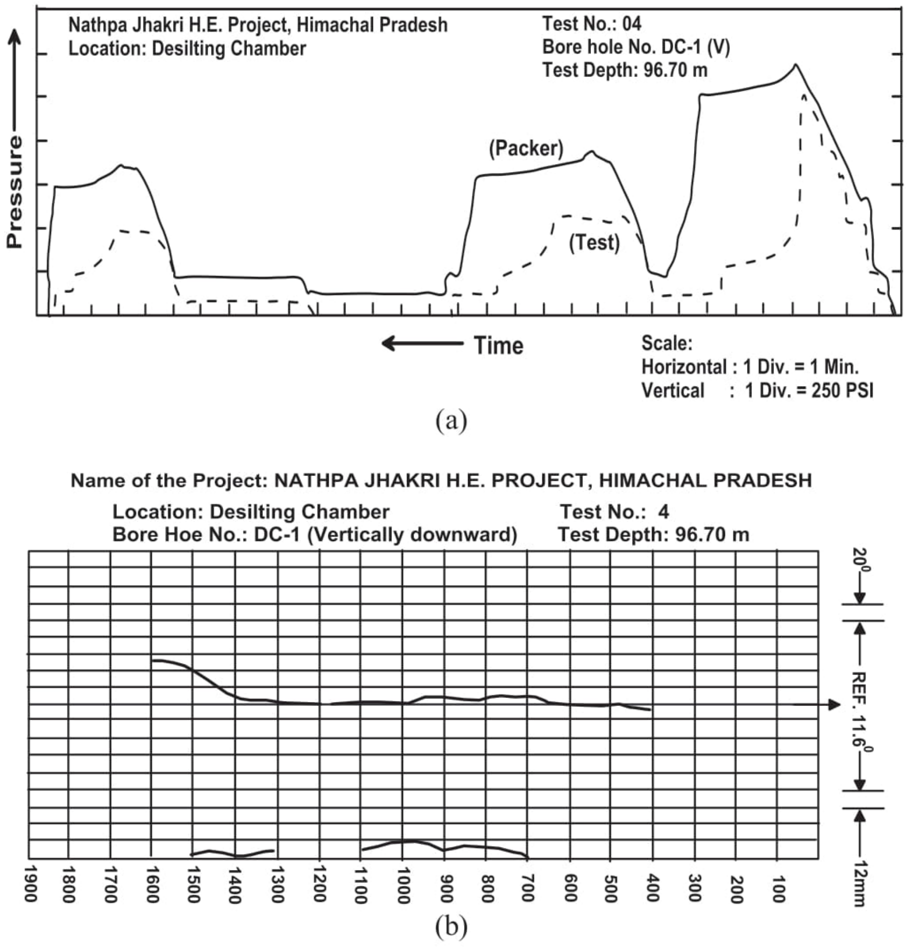


Fig. 2 - (a) Pressure Vs time plot and (b) Fracture impression record

4. CASE STUDY II: LOHARINAG PALA H.E. PROJECT, UTTRAKHAND

The project is a run-off-the-river scheme on river Bhagirathi (tributary of Ganga; NNW-SSE trend in project area) in Uttarkashi district of Uttrakhand and consists of a barrage; desilting chambers of 250m x 15.5m x 20m size; horse shoe type head race tunnel; underground power house to produce 600 MW of power.

The exploration of drillholes around the barrage axis indicated overburden upto a depth of 50.5m (EL 2079.906m) with a thick sandy horizon from 28.5m to 50.05m depth, below which bed rock consisting of grey fine grained gneiss are encountered. Overburden consists of boulders of granite gneisses, quartzite, augen gneisses, tourmaline granites in a sandy matrix. Similarly the drillhole at the exit end of the desilting basin has proved overburden consisting of boulders in a sandy matrix upto 20m depth and below this sandy horizon has been met upto the drill depth of 38.45m.

Eight hydraulic fracture tests in two 'EX' size vertical drillholes in the desilting chamber were conducted. The minimum and maximum horizontal stresses obtained from the tests were found to be 4.66 MPa and 6.69 MPa respectively. Orientation of maximum horizontal stress was measured as N52.2^{0}W. All the test results are given in Table 2 (CSMRS, 2007). Pressure vs time plot, is a real time plot obtained from plotter during the test is shown in Fig. 3.

Table 2 - Hydraulic fracturing Test Details, Desilting Chamber, Loharinag Pala H.E. Project, Uttrakhand

Test No.	Test Depth	Crack Initiation Pressure	Crack Reopening Pressure	Shut-in Pressure	Max. Horz. Stress (σ_H)	Min. Horz. Stress (σ_h)	Max. Horz. Stress Orientation
	(m)	(MPa)	(MPa)	(MPa)	(MPa)	(MPa)	
1	14.45-14.90	12.42	8.97	5.52	7.59	5.52	-
2	12.00-12.45	13.11	6.90	4.83	7.59	4.83	N48^{0}W
3	11.00-11.45	16.56	5.18	4.14	7.24	4.14	N63^{0}W
4	7.45-7.90	10.35	4.48	2.76	3.80	2.76	-
5	6.25-6.70	12.42	6.21	3.45	4.14	3.45	N52^{0}W
6	21.95-22.40	9.66	7.93	5.18	7.61	5.18	N47^{0}W
7	10.45-10.90	17.25	10.35	6.22	8.31	6.22	N50^{0}W
8	4.45-4.90	15.87	8.28	5.18	7.26	5.18	N53^{0}W
Average					6.69	4.66	N52.2^{0}W

5. CASE STUDY III: PUNATSANGCHHU-II HYDROELECTRIC PROJECT, BHUTAN

This is a run-off-the-river project on Punatsangchhu River (WNW-ESE trend in project area) in Wangdue Phodrang district of Bhutan and envisages construction of a 42.5 m high (from river bed) concrete dam; a 12.40 km long head race tunnel (HRT); an underground power house complex (1020 MW); four numbers of underground desilting chambers of 420 m (L) x 19 m (W) x 24.7 m (H) size.

The rock mass exposed in the area is mainly quartzitic gneisses, biotite gneisses, belonging to sure formation of Thimpu group, occasionally intruded by pegmatite. The foliation is widely varying and the general strike of foliation is N60^{0}E to N80^{0}W-S60^{0}E to S80^{0}W with 10^0-30^0 dipping towards SE. In the excavated portion of adit to desilting chamber the rock type encountered is quartzo-feldspathic, biotite gneisses with intrusion of pegmatite veins. At some places dripping was observed. Fair rock mass condition is seen in the excavated portion of adit to desilting chamber, the Q value ranges from 1.2 to 6.8.

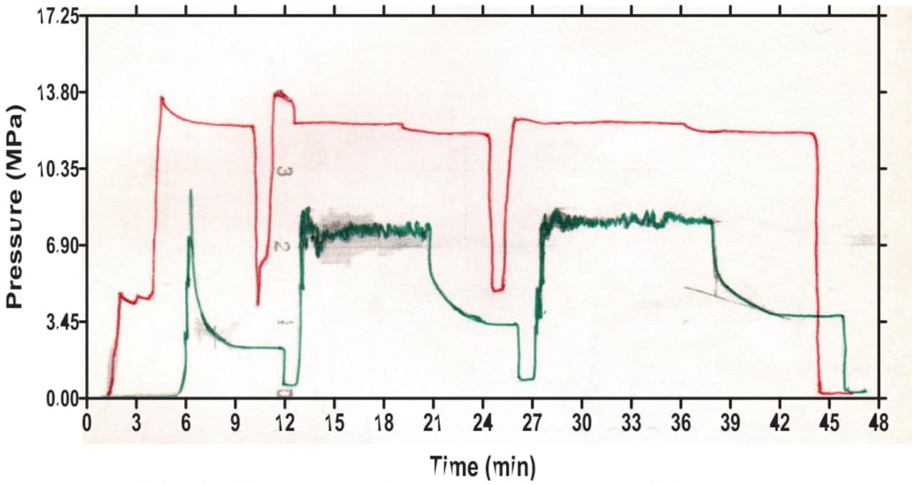


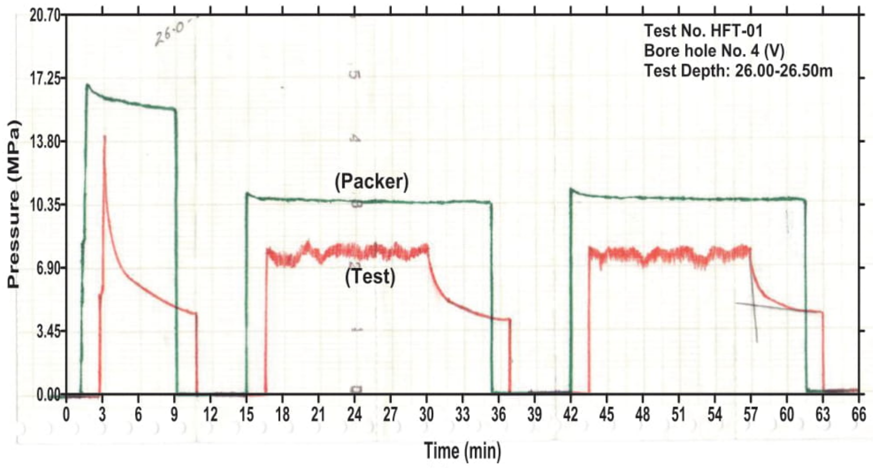
Fig. 3 - Pressure vs time record from one of the tests

Seven hydraulic-fracture tests were conducted in two 'EX' size vertically downward drillholes in the desilting chamber and the results are shown in Table 3 (CSMRS, 2012). The pressure versus time plot, is a real time plot obtained from plotter during the test and fracture impression record of one of the tests is shown in Fig. 4.

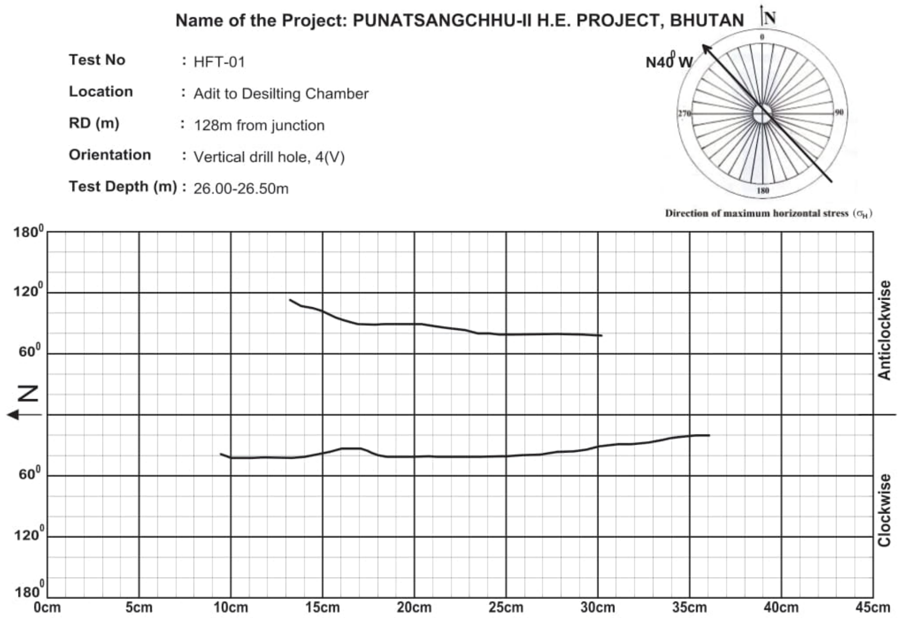
Table 3 - Hydraulic Fracturing Test Details, Desilting Chamber, Punatsangchhu-II HEP, Bhutan

Sl. No.	Test No.	Test Depth (m)	Crack Initiation Pressure (MPa)	Crack Reopening Pressure (MPa)	Shut-in Pressure (MPa)	Max. Horz. Stress (σ_H) (MPa)	Min. Horz. Stress (σ_h) (MPa)	Orientation of Max. Horz. Stress
RD-128m from junction, Bore hole - 4 (V), Vertically downward								
1	HFT-01	26.00-26.50	14	8.0	5.1	7.3	5.1	N40^{0}W
2	HFT-02	19.90-20.40	12	9.0	5.4	7.2	5.4	N40^{0}W
3	HFT-04	9.00-9.50	13	7.8	4.1	4.5	4.1	N65^{0}W
4	HFT-05	4.50-5.00	22	12.1	6.2	6.5	6.2	N50^{0}W
RD-128m from junction, Bore hole - 1 (V), Vertically downward								
5	HFT-06	26.00-26.50	12	7.2	4.5	6.3	4.5	N50^{0}W
6	HFT-07	11.50-12.00	14	7.1	4.8	7.3	4.8	N50^{0}W
7	HFT-08	6.20-6.70	13	6.0	3.8	5.4	3.8	-
Average						6.09	4.71	N49.16^{0}W

Tests in two vertical drillholes indicated variation in maximum horizontal stress from 4.2 to 7.3 MPa, and the minimum horizontal stress varied from 3.8 to 6.2 MPa. The average values of minimum and maximum horizontal stresses were determined as 4.84 and 6.36 MPa, respectively (Table 3). The direction of maximum horizontal stress obtained from the impression records of induced cracks was found to be N49.16^{0}W.



(a)



(b)

Fig. 4 - (a) Pressure vs time plot and (b) Fracture impression record

6. DISCUSSIONS

The factors like topography, erosion, isostasy, inclusions, fracture sets, boundary conditions/free surface, plate tectonics etc. influence the state of stresses in rock mass, in terms of both magnitude and direction/ orientation. Hence, the process of estimating in-situ stresses in rocks requires a large amount of judgment and is very much site specific. The relative importance of various phenomena when estimating the in-situ stress field at a given site can be assessed by carrying out parametric studies using analytical or numerical models.

Predictions can also be improved by combining the results of previous or current in-situ stress measurement.

Gowd et al. (1992), prepared stress map for Indian subcontinent using data from borehole breakouts, hydraulic fracturing and earthquake fault plane mechanisms. The study indicated direction of maximum horizontal stress to be in NNE quadrant. In later years, based upon the field measurements, Subrahmanyam (2014) further supported the findings of Gowd et al. (1992) by suggesting the direction of maximum horizontal stresses to be N20^0-30^0E. Similarly, Central Soil and Materials Research Station (CSMRS) has carried out hydraulic fracturing tests at more than 30 hydroelectric projects in India and neighbouring countries in Himalayan belt and reported the orientation of maximum stress direction in North-Eastern (NE) quadrant. In-situ stresses obtained at three projects discussed in the paper are summarized in Table 4.

Table 4 - Summary of the present case studies

Name of Project	Max. Horz. Stress (σ_H) (MPa)	Min. Horz. Stress (σ_h) (MPa)	Orientation of Max. Horz. Stress
Nathpa Jakri H.E. Project, Himachal Pradesh	4.71	3.50	N10^0W
Loharinag Pala H.E. Project, Uttrakhand	6.69	4.66	N52.2^0W
Punatsangchhu-II H.E. Project, Bhutan	6.36	4.84	N49.16^0W

In all these projects the orientation of maximum horizontal stresses falls in North-Western (NW) quadrant and incidentally, all the case histories pertain to gneissic rock formations. These are the exceptions and are not within the range suggested by Gowd et.al. (1992) and Subrahmanyam (2014) and is quite different from the generalized trend. The reason may be attributed to rock inhomogeneity, rock anisotropy, rock discontinuities, surface topography and free surface features (Hudson & Feng, 2010). In the present study, it is also found that the direction of maximum horizontal stresses at Loharinag Pala H.E. Project (N52.2^0W) and Punatsangchhu H.E Project (N49.16^0W) are nearly parallel to the free surface features formed by Bhagirathi river (NNW-SSE) and Punatsangchhu river (WNW-ESE) respectively. Therefore, it will be unfair to generalize the direction of maximum horizontal stress to lay in NE quadrant only. Further research is required to study the variability of in-situ stress state in Himalayan region.

7. CONCLUSIONS

The direction of maximum horizontal stresses at Loharinag Pala H.E. Project (N52.2^0W) and Punatsangchhu H.E Project (N49.16^0W) are nearly parallel to the free surface features formed by Bhagirathi River (NNW-SSE) and Punatsangchhu River (WNW-ESE) respectively.

The study advocates the need for evaluation of stresses using the available techniques rather than estimating or deriving from the literature. In contrast to the generalized trend, exceptional behaviour of the orientation of the maximum horizontal stress in NW direction is reported in the gneissic rock mass.

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