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IN SITU STRESS MEASUREMENT AND ITS APPLICATION FOR HYDRO-ELECTRIC PROJECTS—AN INDIAN EXPERIENCE IN THE HIMALAYAS

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Abstract: Any attempt to design engineering structures in rock mass requires knowledge of the prevailing in-situ stress field. It is always advisable to measure it, in whatever best way possible. The prior knowledge of the prevailing stress field helps in the alignment and the design of support system for the underground cavern, estimation of grouting pressure in the dam foundation, design of steel liners for Head Race Tunnel, Penstock, etc. There are various methods of determination of in-situ stresses in rock mass. However it has been experienced that the hydrofracturing technique is the most convenient to conduct and interpret the test results. This paper briefly describes the various uses of stress measurements, details of hydraulic fracturing test system, test procedure adopted and the concept of hydrofracturing in arriving at the in-situ stresses of the rock mass. The results for the above applications conducted at four mega hydroelectric projects in India and neighbouring countries of Bhutan and Nepal located in the Himalayas are presented.

Key words: in-situ stress, hydrofracturing, cavern, grouting, steel liner, hydro-electric project.

1. INTRODUCTION

Knowledge of the virgin stress field is very important in many problems dealing with rocks in Civil, Mining and Petroleum engineering as well as in Geology, Geophysics and Seismology.With the development of water resources projects in the hilly region particularly in Himalayan regions the disturbing force has increased. The modern Rock Mechanics engineer has to be well acquainted with the basics of rock stresses and rock stress measurements. The need for understanding in-situ stresses in rocks has been recognized by geologists and engineers for a long time and many methods to measure these stresses have been proposed since early 1930’s.

2. USES OF STRESS MEASUREMENTS IN CIVIL ENGINEERING

In-situ stresses should be understood as rock mass properties like deformability, strength, permeability, etc. Like any of these properties, in-situ stresses may vary from point to point in a rock mass and are volume dependent. Stress measurement can be put into various uses in science and engineering to solve the various day to day engineering and environmental problems. Some of the most common applications in hydroelectric projects are for design of under ground works, pressure tunnel, underground excavations, grouting and permeability, recharge of aquifers. These uses can be broadly grouped under the following two paragraphs.

2.1 Underground excavations

In Civil and Mining engineering, in-situ stresses control the distribution of stresses around underground cavities such as tunnels, mines or caverns. These stresses may be large enough to mobilize the strength of the rock mass and create failure, rock bursts, squeezing and deformation in the form of wall closure and roof or underground surface subsidence. Cases of extremely high horizontal stresses causing stability problems in excavations at shallow depths have been found in Canada. Excavation in highly stressed rock masses is difficult and requires more support. From a practical point of view, when designing underground excavations in rocks, the goal is to minimise stress concentration problems, create a stress field as uniformly distributed as possible in the excavation of underground structures so that the optimum support systems is provided without compromising the safety of the structure. As the crack propagates perpendicular to minimum principal stresses, the large surface excavation can be planned to minimise the cost. Similarly the excavation in mining can be planned to give maximum output with greater safety.

2.2 Design of underground structures

In general, the distribution and magnitude of in-situ stresses affect geometry, shape, dimensioning, excavation sequence and orientation of under ground excavations like caverns, tunnels etc. The performance of hydraulic structures such as pressure tunnels is also strongly dependent on the magnitude and orientation of in-situ stresses since, in this case, hydraulic fracturing of the rock mass can be avoided. The orientation of long dimension of the cavern should be avoided perpendicular to the greater principal stress. The shape of the cavern should be selected to minimise the stress concentration especially in the region of high stresses. The layout of the complex should be planned so as to avoid crack propagation from one cavern to the other. Pressure tunnel, penstock and similar structures can be constructed and operated without lining if the in-situ stresses are greater than the internal water pressure.

In other situations like support design etc. the knowledge of the state of stresses can be integrated with design process along with the geological information.

Stress fields alter the permeability of rock mass since compressive stresses tend to close natural fractures whereas tensile stresses tend to open them. On other hand, rock mass structures such as joints and foliation planes affect the distribution of in-situ stresses

3. GEOTECHNICAL IMPLICATIONS

Thus it can be realised that the insitu stress affects the design, construction and excavation of rock structures in number of ways. To summarise geotechnical implications of in-situ stresses, Hudson’s compilation, Hudson (1992), for rock engineering system is worth mentioning. The in-situ stresses affect the rock properties in about twenty ways. Some of which are stated below:

- A stronger rock can sustain a higher in-situ stress.
- Stress concentrations decreases with displacements.
- In-situ stresses normal to discontinuities with large apertures will be low.
- Effective stress is reduced by increasing pore water pressure
- In-situ stress affects the stability of caverns.
- Hydrostatic in-situ stresses tend to close discontinuities.
- Stress field alters permeability of rock mass
- Stresses causes rock fracturing normal to minimum principal stress direction.
- High stress causes rock mass to fracture and its quality to deteriorate.
- Rock bursts in highly stressed rock masses affects excavation methods.
- Depth of caverns is limited due to higher in-situ stresses at depth.
- Caverns in highly stressed rock mass need more support.
- Ideal cavern shape is controlled by in-situ stress field.
- Tectonic stresses, erosion, topography and other factors affect stress field.
- In-situ stress varies with depth.
- Discontinuities control magnitudes and directions of in-situ stress field.
- A highly variable in-situ stress field exists in a fractured rock mass.

4. HYDROFRACTURING TESTS

For measuring in-situ stresses many methods are available. Each method has distinct advantages and disadvantages. The different methods for stress measurements used in civil engineering applications are 1) Hydraulic Fracturing 2) Overcoring 3) Bore hole Slotting 4) Flat Jack. Most common methods include hydraulic and relief methods.

Out of all the methods hydrofracturing method is the easiest, quick and simple in measuring in-situ stresses. Hydrofracturing technique has been widely used in solving many Civil and Mining engineering problems. This can be put into variety of uses in river valley projects. This method is used to find out the magnitude and direction of Maximum and Minimum Horizontal stress in deep drill holes or in shallow drill holes which is normally not possible with other methods. The complete stress tensor can be obtained by conducting stress measurements in three mutually orthogonal drill holes.

Hydraulic fracturing involves applying hydraulic pressure to a drill hole to determine the fracture pressure and hence the stress.

In a vertical drill hole, the magnitude of maximum and minimum secondary horizontal stress component for impermeable rocks is determined from the expression, Haimson & Fairhurst (1967 & 1970).

$$\sigma_H = 3\,\sigma_h + S_i - P_i - P_o \qquad (1)$$

where σ_H is maximum secondary horizontal stress, σ_h is minimum secondary horizontal stress, S_i is fracture strength of the rock = P_i - P_r, P_i is fracture initiation pressure, P_r is fracture reopening pressure and P_o is ambient pore pressure. The magnitude of minimum secondary horizontal stress is equal to the shut-in pressure Si.

The vertical stress can be estimated from the overburden by

$$\sigma_V = \gamma h \qquad (2)$$

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

A typical pressure time curve is given in Figure 1 from where P_i, P_r and S_i are obtained.

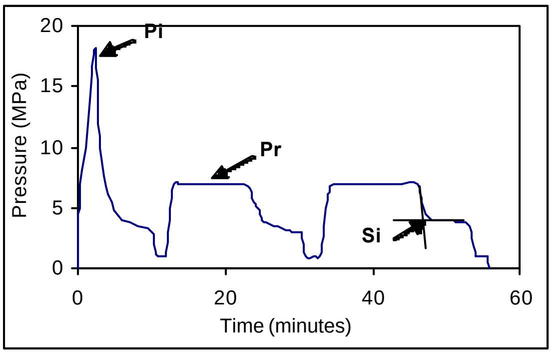


Figure 1. Typical pressure vs. time curve for hydrofracturing test.

5. DISCUSSIONS

The test results of four projects have been discussed, which were conducted to find the in-situ stresses in rock mass in three projects and the grouting pressure for one project in the Himalayas which also indicates the variation of the stresses in various regions.

5.1 Tehri Dam project (Uttaranchal, India)

The Tehri Hydro-electric Project, located in Garhwal District of Uttar Pradesh, envisages the harnessing of hydropower potential of the river Bhagirathi in the Himalayas with a total capacity of 2000 MW. The main rock type encountered in the project is different grades of Phyllites, which is relatively weak rock.

Conventionally, to decide the grouting pressure for curtain grouting, permeability tests are conducted. These tests are a function of porosity of rock mass as well as the quality of joints in it.

Hydrofracturing tests were conducted for finding out in-situ stresses vis-à-vis reopening pressure of the existing joints. This reopening pressure was utilised to decide the maximum pressure at which grouting is to be done.

However, because of the highly jointed rock mass, as was evident from core recovery, these values were found to be very low. The average values of reopening pressure and the minimum in-situ stress determined below the core portion of the Dam site were 2.38MPa and 0.57MPa respectively. The recommended maximum consolidation grouting pressure was of the order of 0.2 to 0.4MPa and the recommended maximum grouting pressure for curtain grouting was of the order of 1.0 to 1.2MPa. This recommended maximum grouting pressure was safer as the average reopening pressure from test results was 2.38MPa and the minimum reopening pressure was 1.725MPa.

The results of the various tests conducted for the determination of grouting pressure /reopening pressure are shown in Table 1.

Table 1. Results of Reopening pressure by Minifrac test at three locations.

Test No	Location/Rock Type	Test Depth (m)	Reopening Pressure (MPa)
1	D/s of Dam axis Chainage 1.6m RL 808.275m, PQT*	9.70	1.73
2		10.70	2.07
3		11.20	2.07
4		12.20	1.72
5	Drift GR3 RL 640m RD 5.0m,PQM*	10.30	2.41
6		12.20	1.72
7	Drift AGL3 RL 638.7m RD 517.0m, PQM*	5.25	2.76
8		7.25	4.14
9		9.25	3.45
10		14.25	1.72

*PQT- Phyllitic Quartzite Thinly bedded
*PQM-Phyllitic Quartzite Massive

5.2 Tala H.E. Project (Bhutan)

The Tala Hydroelectric Project, located in Western Bhutan, consists of 91m high concrete gravity diversion dam, a 356m long diversion tunnel of diameter 6.8m at the right bank, three desilting chambers, each of size 250m x 13.9m x 18.5m , a 22.40 km long, 6.8m diameter modified horse-shoe shaped concrete lined head-race tunnel, a 180m high & 15m diameter underground restricted orifice type surge shaft; two inclined pressure shafts each 992m long and 4m diameter, an underground powerhouse cavern 18m wide to house six Pelton turbines each of 170MW. A 7.5m diameter tail-race tunnel of 2.2km length will be used to discharge water back into the river. Power will be generated under the design head of 819m.

The rock type encountered in the pressure shaft at three elevations where the tests were conducted were mainly moderately jointed, fresh & hard phyllitic quartzite & quartzite., moderately jointed, highly folded phyllite with thin bands of amphibolite belonging to Shumar formation, moderately jointed, highly folded, fresh, variants of gneiss, muscovite / biotite schist, amphibolite and quartzite of Thimphu formation.

In this investigation, information on the in-situ state of stress obtained was utilized to design the Pressure Shaft for underground Powerhouse. The average values of in-situ stresses determined in the Pressure Shaft are given in Table 2& 3.

Table 2. Insitu stress in vertical holes.

Elevation (m)	Average		σ_V (MPa)
	σ_H(MPa)	σ_h(MPa)	
501	21.65	12.59	14.77
770	16.22	10.01	10.66
1010	9.66	5.52	9.49

Table 3 Insitu stress in horizontal hole.

Elevation (m)	Average		σ_V (MPa)
	σ_H(MPa)	σ_h(MPa)	
770	10.07	6.77	10.66

The orientation of maximum horizontal stress determined is N 62^0 E at an elevation of 501 m.

5.3 Nathpa Jhakri H.E. Project (H.P., India)

The Nathpa Jhakri H.E. Project located in Kinnaur and Shimla district of Himachal Pradesh envisages harnessing the hydropower potential of 1500MW across river Sutlej. The main features of the project are a 60.5 m high concrete dam, an underground desilting complex, a 10.15m diameter and 27.30 km long head race tunnel and underground powerhouse along with other structures. Due to the presence of lot of underground structures some of which rank amongst the biggest underground cavities in the world, there was a strong need to measure the rock stress field present at various locations of underground excavations/structures.

The Head Race Tunnel (HRT) crosses through a terrain which has Quartz-Mica- Schist as the main rock. Biotite rich Schist and Schistic Quartzite are also encountered. At some places the rock cover at HRT is only 8-9 m; hence steel liners were proposed in low rock cover zone with reduced diameter of tunnel. To determine the length of steel liner, hydrofracturing tests were conducted at the start and at the end of proposed steel liner in HRT.

The in-situ stresses measurements were conducted in Surge Shaft, De-silting Chamber and Power house area for the orientation and the design of above underground structures at various locations. The values obtained helped in deciding the thickness and length of the steel liner .These results have been utilised for the design of various structures of the project.

The values of in-situ stresses determined at different locations are given in Table 4, Kumar et al. (1995).

Table 4. Results of Insitu stress Nathpa Jhakri project.

Location	σ_H (MPa)	σ_h (MPa)	σ_V (MPa)	Maximum Stress Direction
Surge Shaft	8.10	4.14	3.55	N 5 ^{0} W
Desilting Chamber	2.50-6.48	2.10-5.40	2.10-4.30	N10^{0}W
Power House	7.14 Average Value	5.89	3.93	N 30^{0}E
Power House	13.15 Principal Stress	8.00	4.36	N 7 ^{0}E Overcoring
Manglad Adit	3.12 - 15.87	2.76 - 8.97	0.22	--

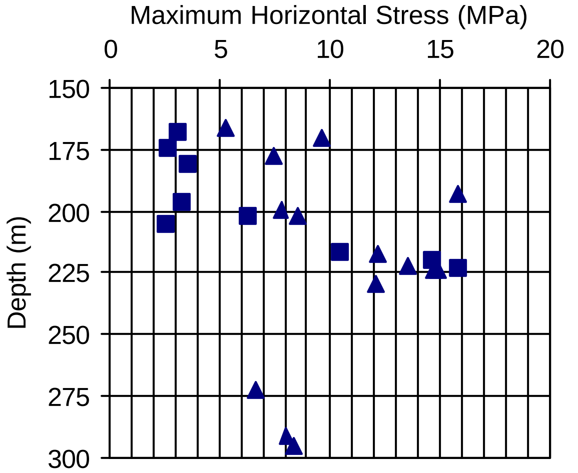
5.4 Pancheswar Multi-Purpose Project (Nepal/India)

The Pancheshwar Multipurpose Project is located in bordering state of Uttaranchal in India and Nepal on river Mahakali. The project envisages the construction of 288m high earth and rock fill dam having impervious clay core, two underground power houses on each bank with generation capacity of 3000MW. The proposed Purnagiri and Rupaligarh re-regulating structures are situated downstream of main Pancheshwar Multipurpose Project. The project envisages harnessing the water resources of river Mahakali near Tanakpur and Tamli border towns within India and Nepal respectively.

The project area falls within Almora Crystalline/ Kalikot Formation (Dadeldhura Group) forming a part of the lesser Himalayan belt. Rocks of the area have been classified into six litho logical units and the overburden into three units on the basis of geological mapping of site. The overburden consists of Talus/Slide Debris, Debris fan, River borne material and the bed rock mainly consists of Interbedded Quartz-Mica Schist and Augen-Gneiss, Granitised-Quartzite, Quartz-Biotite Gneisses and Quartz-Mica Schist.

To determine the values of in-situ stress for the orientation and design of the power houses one each in India and Nepal side, stress measurement tests were conducted in four boreholes.

The variation of the values of 13 tests in three bore holes (SDH-6, DDH-1 & DDH-2) from left bank and 9 tests in one bore hole (DDH-3) from right bank at various depths have been plotted in Figure 2 and is shown in Table 5.



Legend: - ■ Right Bank ▲ Left Bank

Figure 2. Plot of Variation of Maximum Horizontal Stress with Depth, Pancheswar HE Project Nepal

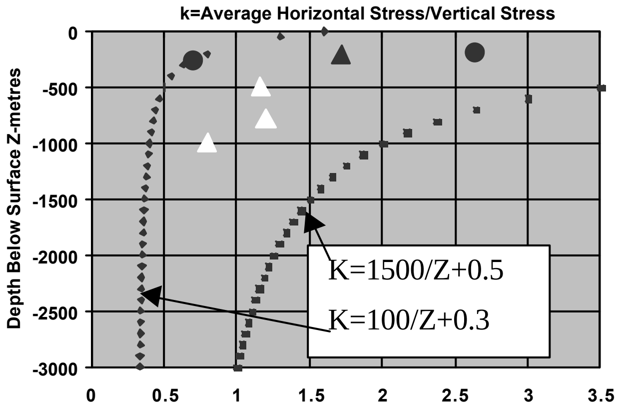
Table 5. Results of In-situ stress tests of various bore holes

Location	Depth (m)	σ_H (MPa)	σ_h (MPa)	σ_V (MPa)
SDH-6 L / B	169 - 230	2.8 – 15.8	2.4 – 9.3	4.2 – 5.6
DDH-1 L / B	166 - 231	5.3 – 14.7	4.5 – 8.4	4.1 – 5.7
DDH-2 L / B	265 - 295	3.2 – 8.4	2.8 – 6.7	6.5 – 7.2
DDH-3 R / B	168 - 223	2.5 - 15.8	2.1 - 8.3	4.1 – 5.5

The direction of maximum horizontal stress lies between N 26^0 E and N85^0W. Considering the average of the above values the direction of the maximum horizontal stress was recommended as N 67^0E for left bank and N65^0E. for right bank.

5.5 Variation of Average Horizontal Stress with depth

The average horizontal stress determined at these projects has been plotted in the Hoek and Brown plot 1978. The data of the three mega projects viz. Tala HE Project, Nathpa HE Project and Pancheswar HE Project quite nicely fit into this plot. (Figure 3). It is worth mentioning here that the values of the horizontal stress varies quite a lot especially upto the depth of 500 m., which is the maximum range of the most of the Civil engineering projects. The in-situ stress obtained from three elevations of Tala HE Project has been plotted in Figure 4. It may be seen that in this project a linear relation existed between stresses and depth. But the same is not always true as the stress is highly influenced by the local and regional geology and topography. Moreover it can be seen from the figure 3 that the ratio of average horizontal stress to vertical stress tends to show a decreasing trend at deeper depths.



Legend:

Δ Tala HE Project Bhutan

▲ Nathpa Jhakri HE project India

● Pancheswar HE Project Nepal/India

Figure 3. Plot of Variation of Average Horizontal Stress with depth below Surface (After Hoek and Brown 1978)

5.6 Variation of Direction of Maximum Horizontal Stress

The direction of maximum horizontal stress like magnitude also varies a lot which can be seen from the results of above projects. Hence in arriving at the direction of the stresses the influence of the geology along with the test results should be taken by the designer & the structural-geologist. However considering the results of the above projects the average direction of maximum horizontal stress in Himalayas always come in the North Eastern quadrant.

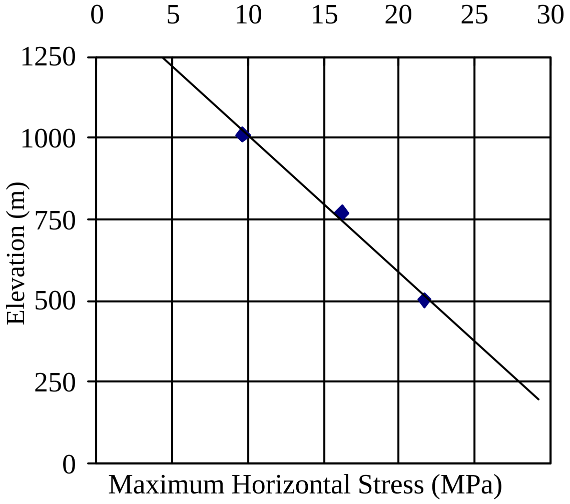


Figure 4. Variation of Maximum Horizontal Stress with Elevation, Tala HE Project Bhutan.

6. CONCLUSIONS

Many areas of Civil and Mining engineering are governed by the Rock Mechanics principles. In-situ stress has strong geotechnical implications which affect the rock mass properties in about twenty ways, Hudson (1992). In-situ stresses in rock have a greater role in the design and construction of underground excavation. From the literature and the analysis of results and the experience gained at various projects it can be concluded that:

- Like strength and deformability characteristics of rock mass, in-situ stresses should be considered as basic rock mass parameter/ attribute
- There is strong influence of geology on in-situ stresses hence, there can be wide variations in the magnitude and the direction of in-situ stresses which should be considered properly in the design, Kumar et al. (2003).
- In-situ stresses must be determined in whatever possible methods available to the investigator.
- The regional stress map will be of great help to the designer and the Engineer to have the first estimate of the in-situ stresses.
- It is not always possible to have a definite mathematical relationship between stresses and depth which is often desired by the designer.

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