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DEVELOPMENT OF NEW EQUATIONS TO DETERMINE IN SITU STRESSES FROM BOREHOLE SLOTTERTEST RESULTS

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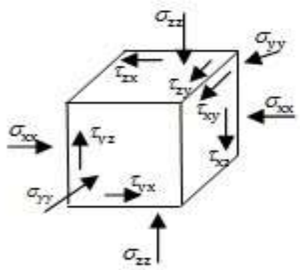
Abstract
To establish a rock structure model, it is essential to estimate in situ stress magnitude and its orientation at site formations. Borehole slotting is one of the newest methods in estimating state of stress. Bakhtiari dam site in Iran consists of seven various zones with different geological properties of materials. Many laboratory tests and site excavations have been performed to determine rock properties. Additionally, the state of stress must be determined in all the zones. But there are problems with cost and time to be consumed in using in situ stress measurements. To overcome these problems, this paper suggests correlations between principles stresses and application of 3D borehole slotter test in Bakhtiari dam. At first stage, through statistical analysis of the experimental results certain equations have been developed between measured principle stresses. Then, for validation of the proposed equations and investigation of depths limitations of borehole slotter test, these equations have been cross checked with hydraulic fracturing equations presented by other investigators. Results of this research show that there are good relationships between components of principle stresses obtained from borehole slotting with vertical stress of the region. It is, also, shown that stresses calculated by these equations carry a good correlation with hydraulic fracturing results up to depths of 44m.

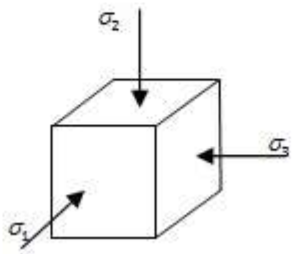
Introduction
Knowledge of in situ state of stress in a rock mass is essential for proper planning and design of any type of rock structures. Most of in situ stress measurement methods involve the observation of a change in deformation or stress resulting from a change in the geometry of an opening in the rock, and the subsequent calculation of the field stresses from those measured changes (Stacey and Wesseloo, 2002).
For the rock stress estimation operation, it is essential to understand the concept of stress. The stress at a point within a rock mass has three normal stress components acting perpendicular to the faces of a small cube, and six shear stress independent components acting along the faces (Fig. 1) (Hudson and Harrison, 1997).



$$\begin{bmatrix}\sigma_{xx} & \tau_{xy} & \tau_{xz}\\ \tau_{yx} & \sigma_{yy} & \tau_{yz}\\ \tau_{zx} & \tau_{zy} & \sigma_{zz}\end{bmatrix}$$

Fig.1.stress components at a point within a rock mass [2].

There is always one cube orientation at which all the shear stress component values are zero. When this occurs, the cube faces represent the principal stress planes. The normal stresses on these planes are the principal stresses (Fig. 2) (Hudson and Harrison, 1997).



$$\begin{bmatrix}\sigma_1 & 0 & 0\\ 0 & \sigma_2 & 0\\ 0 & 0 & \sigma_3\end{bmatrix}$$

Fig.2. principal stress components at a point within a rock mass [2].

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Various methods have been developed to measure the in situ stress regime within the ground. These methods can be generally categorized into hydraulic fracturing, strain relief, borehole breakout, and seismic methods.
Borehole relief methods of deformation-type havebeen used to measure the state of stress for about fivedecades (Saati and Mortazavi, 2011). Borehole slotting is a relatively new stress measuring technique which is designed for quick operation in boreholes and for high density measurements at reasonable cost (Bock, 1993). The borehole slotter is an instrument which is used in boreholes with 96–104 mm diameter, and allows the calculation of 2D and 3D stress tensor. The borehole slotter technique requires cutting of half-moon shaped slots at different orientations parallel to the test borehole axis using a small diamond impregnated blade and monitoring of strains which are relieved normal to the slot direction (Fig.3).
The aim of developing this method was to avoid the high cost associated with other in situ measurement methods and also to increase the accuracy of field measurements (Saati and Mortazavi, 2011). The slotter technique has proven to be reliable in the field and has gained certain commercial successes (Ljunggren et al., 2003).
This paper presents equations for determining the in situ stress state from 3D borehole slotting data. Unfortunately, little works have been done on determining the appropriate relationship between the results of borehole slotter test in different areas. Therefore, the in situ stress measurement equations presented from other methods such as hydraulic fracturing are used in order to investigate the accuracy of the proposed equations. Interesting results have come out from this study, considering the application conditions of the borehole slotting.

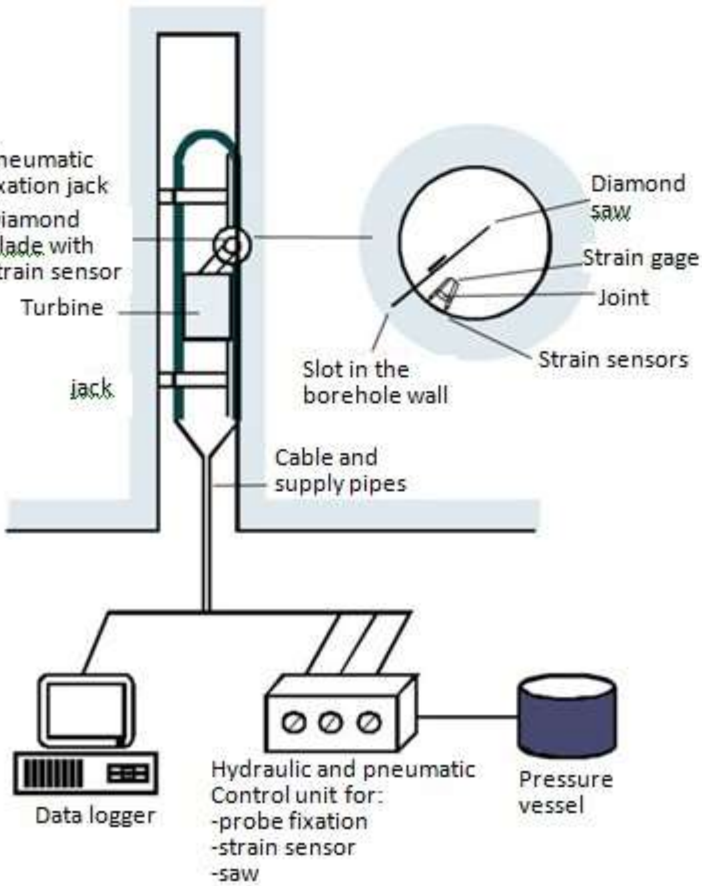

Fig.3. Plan view of the slotter test set up (not to scale).

Project description

Bakhtiari dam site is located in the southwest of Iran, almost 70 km northeast of Andimeshk town (Khuzestan province) and almost 65 km southwest of Dorud town (Lorestan province). The dam axis lays at 290725 E and 3648729 N points. Fig.4. shows the Location of the project area on Iran map.
The project area is covered by sedimentary bedrocks of Sarvak and Garau formations. Sarvak formation is divided into 7 units from Sv1 to Sv7. Properties of these units are presented in Table 1. Garau Formation, which is divided into two units, is younger than Sarvak Formation.

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In the dam site, the main structure is an anticline called Siahkuh. The dam axis is almost on the southwest flank of SiahKuh anticline near its axis. Three faults called F1, F2 and f3 are other important structural phenomena in the area.
To acquire rock mass quality at the dam site 136 boreholes and 6 galleries (GL) have been excavated in the area. To achieve a high core recovery the rotational method with double tube core-barrel has been used. Borehole slotting has been performed in Gl5 and GL6, to measure in situ stress in these galleries (Fig. 5). The depths of boreholes were different from 3 to20 meters.

Fig.4.Location of the project site

The stratigraphy of the units can be described by observations and studying the cores derived from the boreholes (Table1).

Table1. Lithological description of units in Bakhtiari dam.

Units	Lithologicaldescrioption
SV_1	An intercalation of medium to thick-layered marly limestone (of dark gray color if fresh or light gray if weathered) and laminated marls and shale (black-grey if fresh and relatively dark gray if moderately weathered).
SV_2	Marly limestone (grey color if fresh or moderately weathered) with thin intercalations of marl and shale (dark grey if fresh and relatively black grey if moderately weathered)
SV_3	An intercalation of marly limestone of black-grey color if fresh and of gray color if moderately weathered and of siliceous limestone (dark grey color if fresh and reddish light brown if moderately weathered).
SV_4	Medium to thick layered limestone of dark gray color, if fresh, and of gray color if moderately weathered. It has layers of nodules of siliceous limestone including some chert.
SV_5	Thick to very thick bedded, nodular limestone. The limestone is of dark-gray color if fresh and of gray color if moderately weathered.
SV_6	Limestone and marly limestone of thick layers with thin marl intercalations. The color of the limestone and marly limestone layers in fresh sections is dark gray and in moderately weathered surfaces it is gray.
SV_7	Limestone and marly limestone of thin to medium thick layers with thin marl intercalations. The reduced thickness of the singhle layers differentiates this unit from Sv6.

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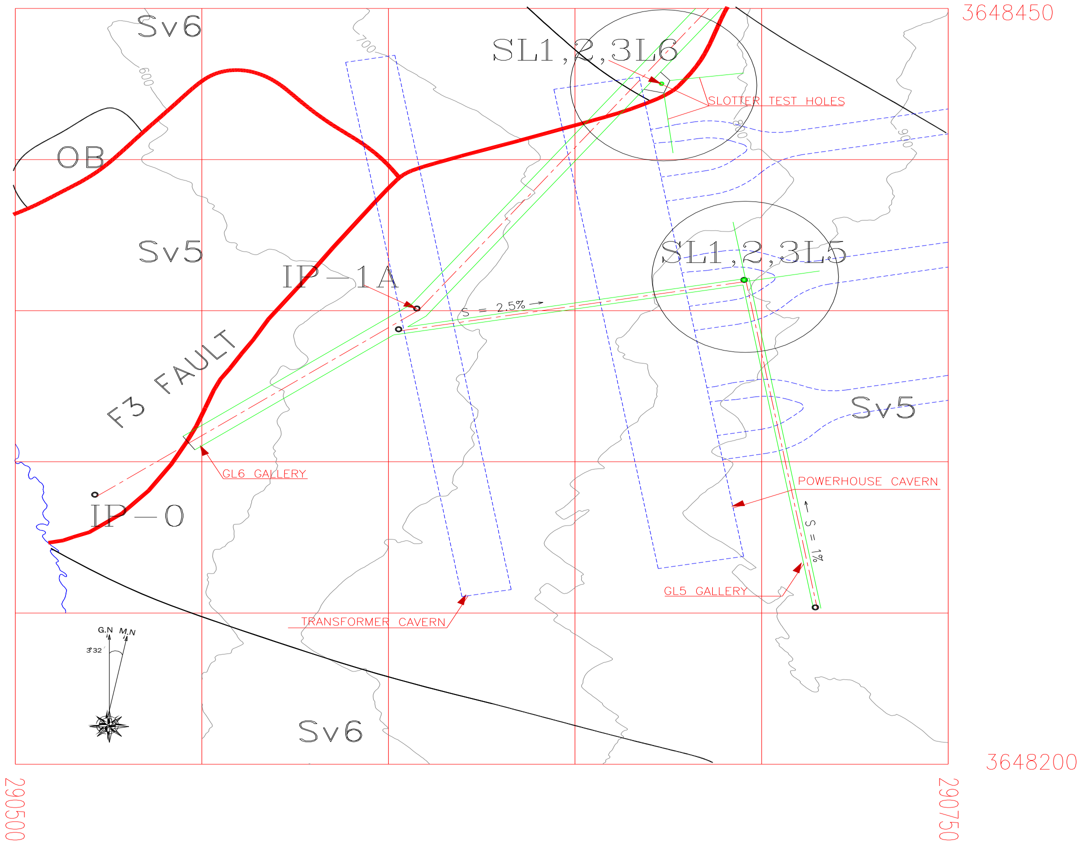

Fig.5. Locations of some boreholes slotter tests in GL5 and GL6.

A large numbers of rock samples have been taken from the cores and many laboratory tests have been carried out on them. The modulus of elasticity and the Poisson's ratio of the rock have been determined by laboratory tests at each borehole slotting point. Table 2 presents summarized results of the laboratory tests.

Table2. Summary of laboratory test results in Bakhtiari dam site

Type of Test	Sv1	Sv2	Sv3	Sv4	Sv5	Sv6	Sv7
Density (gr/cm^3)	2.74	2.74	2.74	2.74	2.74	2.74	2.74
Porosity (%)	0.22	0.22	0.22	0.22	0.22	0.22	0.22
Water Absorption (%)	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Compress Strength (MPa)	85	85	85	85	85	85	85
Elastic Modulus (GPa)	73	73	73	73	73	73	73
Passion Ratio(-)	0.25	0.25	0.25	0.25	0.25	0.25	0.25

Overview of hydraulicfracturingtest

Hydraulic fracturing, as a method of in situ stress measurement, is now well established. It appears that Scheidegger and Fairhurst were the first to suggest the method for in situ stress measurement and early research in the field was carried out by Haimson and Von Schoenfeldt (Scheidegger, 1962; Fairhurst,1964; Haimson, 1968; Schoenfeldt, 1970). It is a stress measurement method that gives a direct output of stress. Conventional hydraulic fracturing involves pressurizing of a short length in a borehole, isolated using hydraulic packers on either side of it, until the hydraulic pressure causes the rock to fracture.
According to studying for depths below 2000m, principle stresses are as follows (Hoek and Brown, 1980):

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$\sigma_h<2.7+0.5\sigma_v$ (1)

$\sigma_H<40+0.5\sigma v$ (2)

Where σh is minor horizontal principle stress, σH is major horizontal principle stress and σv is vertical principle stress.

$\sigma_h=2.8+1.48\sigma_v$(3)

$\sigma_H=2.2+0.89\sigma_v$(4)

According to Sengupta[10], in Himalayan region (depths below 400m) principle stresses are as follows:

$\sigma_h=1.5+1.2\sigma_v$ (5)

$\sigma_H=1+0.5\sigma_v$ (6)

Stephansson and Sengupta proposed the equation 7 to calculate vertical stress in equations 1-6 (Stephansson, 1993; Sengupta, 1998):

$$\sigma v=\sum_{i=0}^{n}\gamma_i\,.\,Z_i(7)$$

Where Z represents the depth and γ indicates the specific weight of the different layers of rock mass (Hoek and Brown 1980; Stephanson, 1993; Sengupta, 1998).

Borehole slotter tests in bakhtiyari dam

The Borehole Slotter Test (SLT) creates strain relief by cutting a slot in the wall of a borehole and measuring the strain relief adjacent to this slot. The diameter and thickness of cutting saw are 90 and 1 mm respectively. In this test, a pneumatically driven diamond saw is used to create slots of up to 25 mm deep into the wall of a borehole of 95–103 mm diameter (Saati and Mortazavi, 2011). Before, during, and after slotting the circumferential strain is measured at the borehole wall in the vicinity of the slot. The tangential strain is measured by a specially developed recoverable strain sensor. Strain gauge is mounted at 15□ from the slot location according to the test procedure recommendation (Foruria, 1987).

To determine the 3D stress state in rock the procedure must be conducted in three boreholes with different azimuth and dip angles. The dip directions and inclinations of the boreholes which should be as near as possible are to be exactly measured, as these values enter into the calculation of the stress tensor.

The method is attractive from a practical point of view since many slots can be cut during a mining shift, and many slots can be cut in a single borehole.

In this research, eleven series of 3D SLT have been performed in underground powerhouse space (UGPH). Nine series of SLT have been performed in three boreholes, perpendicular to each other, drilled at a test station in Gallery 5 (GL5), located at the middle upstream end of UGPH. Eight series were performed at a station in gallery 6 (GL6), located in the upstream part of UGPH. Table 3 summarizes results of four test series obtained at Bakhtiari dam. The measurement points of these experiments are shown by circles in Fig. 5. The IFSL23 programs designed by Inerfels Company are used for processing and evaluating the data of borehole slotter measurements.

Table.3. Summary results of 3D Borehole SlotterTests at Bakhtiari dam

TEST No	Parameter	Borehole Code	Depth (m)	Value (MPa)	Azimuth (degree)	Dip (degree)
1	σ_1	SLT1L5	4.00	5.9	78	37
	σ_2	SLT2L5	3.00	4.0	291	47
	σ_3	SLT3L5	4.50	2.8	182	17
2	σ_1	SLT1L5	14.00	5.8	306	7
	σ_2	SLT2L5	13.00	4.6	216	2
	σ_3	SLT3L5	12.00	3.9	110	83
3	σ_1	SLT3L6	2.60	4.6	179	53
	σ_2	SLT2L6	4.00	1.8	70	13
	σ_3	SLT1L6	3.50	1.1	331	34
4	σ_1	SLT3L6	11.00	3.5	234	25
	σ_2	SLT2L6	18.00	2.3	95	58
	σ_3	SLT1L6	7.50	1.9	333	18

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In situ stresses equations

Twenty borehole slotter measurements have been performed in GL5 and GL6. Principal stress values were determined for each series of experiments. Fig. 6 depicts the graphs of minor and major measured horizontal stresses versus vertical principle stress. Fig.6 also shows the graph of average measured horizontal stresses versus vertical stress.
Regression based data analysis results in Equations (8), (9) and (10) for minor, major and average horizontal stresses respectively. Coefficients of determination (R2) for these equations are 0.62, 0.63 and 0.63 respectively.

$\sigma_h = 0.89\sigma_v + 1.83$ (8)
$\sigma_H = 0.85\sigma_v + 3.31$ (9)
$\sigma_{have.} = 0.83\sigma_v + 2.71$ (10)

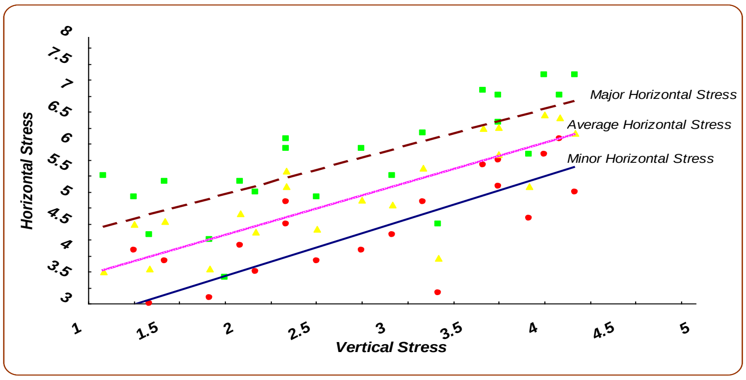

Fig.6. Minor and major horizontal stresses versus vertical stress.

In the above equations σh, σH ,σhave. are minor, major and average measured horizontal stresses respectively and σv is the vertical stress.
Borehole slotter test is one of the economical, quick and most recent methods. The previously popular methods such as hydraulic fracturing have been utilized in many places. Based on the data obtained from this method, there are many relations between in situ stresses components in hydraulic fracturing. Therefore, to verify the validity of the equations derived from borehole slotting, they can be compared with the results of hydraulic fracturing equations proposed by other researchers. If appropriate results obtained from these comparisons, then, the slotting equations can be used for other parts of the site.
The values of minor horizontal stress obtained from Bakhtiari dam borehole slotting have been depicted against the relations developed by Sengupta and Stephansson, for hydraulic fracturing results, in Figure 7. The level of agreement between these equations with Equation 8, developed in this study, for borehole slotting, is visible from Fig. 7. The values of minor horizontal stress calculated from each of the equations are shown in Table 4. As seen from Table 4 and Fig. 7, the inclinations of the line representing values calculated by Stephansson equation against the values obtained from equation 8 is about 45 degrees.

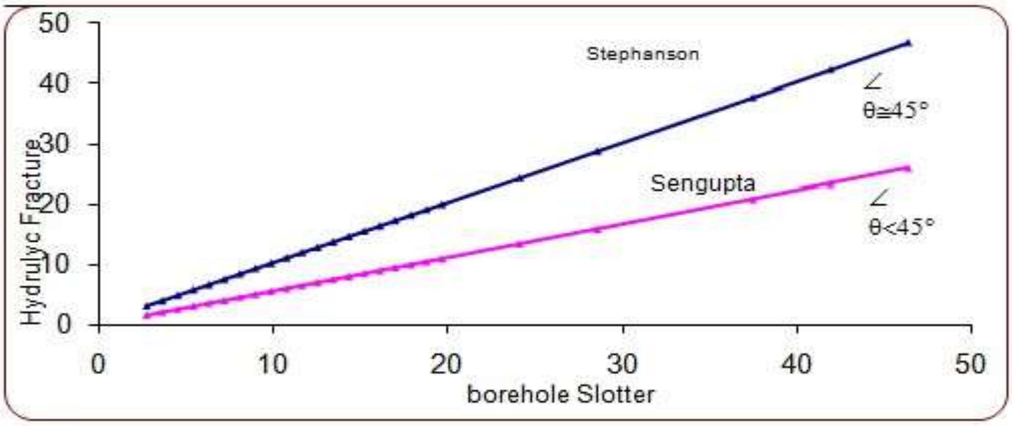

Fig.7. Comparing minor horizontal equations in borehole slotting and hydraulic fracturing.

This clearly means that equation 8, developed in this study for borehole slotting, is in perfect agreement with Stephansson equation introduced for hydraulic fracturing. As Table 4 indicates when the stress value increases the rate of minor horizontal stresses obtained from Stephansson equation and equation 8 remains constant relatively.

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Table4. Minor horizontal stresses calculated from various equations.

σ_v	$\sigma_{hSLOTTER}$	$\sigma_{hSTEFANSON}$	$\sigma_{hSENGUPTA}$	$\frac{\sigma h_{SLOTTE}}{\sigma h_{STEFANS}}$	$\frac{\sigma h_{SLOTTEF}}{\sigma h_{SENGUPT}}$
1	2.72	3.09	1.5	0.88	1.81
2	3.61	3.98	2	0.91	1.81
3	4.5	4.87	2.5	0.92	1.80
4	5.39	5.76	3	0.94	1.80
5	6.28	6.65	3.5	0.94	1.79
6	7.17	7.54	4	0.95	1.79
7	8.06	8.43	4.5	0.96	1.79
8	8.95	9.32	5	0.96	1.79
9	9.84	10.21	5.5	0.96	1.79
10	10.73	11.1	6	0.97	1.79
11	11.62	11.99	6.5	0.97	1.79
12	12.51	12.88	7	0.97	1.79
13	13.4	13.77	7.5	0.97	1.79
14	14.29	14.66	8	0.97	1.79
15	15.18	15.55	8.5	0.98	1.79
16	16.07	16.44	9	0.98	1.79
17	16.96	17.33	9.5	0.98	1.79
18	17.85	18.22	10	0.98	1.79
19	18.74	19.11	10.5	0.98	1.78
20	19.63	20	11	0.98	1.78
25	24.08	24.45	13.5	0.98	1.78
30	28.53	28.9	16	0.99	1.78
40	37.43	37.8	21	0.99	1.78
45	41.88	42.25	23.5	0.99	1.78
50	46.33	46.7	26	0.99	1.78

As far as the values of major horizontal stresses are concerned, the inclination of both Stephansson and Sengupta equations with equation 9, proposed in this study, are about 45 degrees, as shown in Fig. 8. More details of agreement between the equations in various level of vertical stress can be driven from Table 5. As this table shows for σv of 5MPa and lower borehole slotting is in agreement with Stephansson equation. For 5 to 20 MPa, there are a common trend between equation 9 and Sengupta's equation. When σv exceeds 20 MPa there is no agreement between slotting with any of the two other equations.

One of the limitations set for borehole slotting application is the maximum depth of 30 meter while such limitation dose not exists in hydraulic fracturing method. Figs. 7 and 8 indicate that depth limitation can be overcome by using Equations 8 and 9, suggested in this study. As there is a good agreement between Equation 9 and Sengupta's equation up to 20 MPa of σv, thus horizontal stresses can be calculated by equations 7 and 9 up to depth of 400 meters.

From this investigation it can be concluded that it is possible to use Equations 8 and 9 for other areas of Bakhtiari dam as well as other projects anywhere with similar lithological conditions to that of this site.

Fig.8. Comparing major horizontal equations in borehole slotting and hydraulic fracturing.

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Conclusions

The following conclusions are derived from the results of 3D borehole slotting tests at Bakhtiari dam.

1. New equations have been developed to describe relationships between minor, major and average horizontal principle stresses with vertical principle stresses.
2. The coefficients of determination for regression based models in the three proposed equations are 0.62, 0.63 and 0.63 respectively.
3. The equation developed in this study for minor horizontal stresses of borehole slotting is in perfect agreement with Stephenson equation introduced for hydraulic fracturing.
4. When major horizontal principal stresses are concerned there is quite a good agreement between equations proposed in this study with equations of hydraulic fracturing proposed by Stephenson and Sengupta for amounts of lower than 20MPa.
5. Depth limitation of 30 meters in borehole slotting can be overcome by using equations suggested in this study. Horizontal stresses can be calculated by these equations up to depth of 400 meters.
6. From this investigation it can be concluded that the proposed equations could be used for other areas of Bakhtiari dam as well as other projects anywhere with similar lithological conditions.

σ_v	$\sigma_{HSLOTTER}$	$\sigma_{HSTEFANSON}$	$\sigma_{HSENGUPTA}$	$\frac{\sigma H_{SLOTTER}}{\sigma H_{STEFANSON}}$	$\frac{\sigma H_{SLOTTER}}{\sigma H_{SENGUPTA}}$
1	4.16	4.28	2.7	0.97	1.54
2	5.01	5.76	3.9	0.87	1.28
3	5.86	7.24	5.1	0.81	1.15
4	6.71	8.72	6.3	0.77	1.07
5	7.56	10.2	7.5	0.74	1.01
6	8.41	11.68	8.7	0.72	0.97
7	9.26	13.16	9.9	0.70	0.94
8	10.11	14.64	11.1	0.69	0.91
9	10.96	16.12	12.3	0.68	0.89
10	11.81	17.6	13.5	0.67	0.87
11	12.66	19.08	14.7	0.66	0.86
12	13.51	20.56	15.9	0.66	0.85
13	14.36	22.04	17.1	0.65	0.84
14	15.21	23.52	18.3	0.65	0.83
15	16.06	25	19.5	0.64	0.82
16	16.91	26.48	20.7	0.64	0.82
17	17.76	27.96	21.9	0.64	0.81
18	18.61	29.44	23.1	0.63	0.81
19	19.46	30.92	24.3	0.63	0.80
20	20.31	32.4	25.5	0.63	0.80
25	24.56	39.8	31.5	0.62	0.78
30	28.81	47.2	37.5	0.61	0.77
40	37.31	62	49.5	0.60	0.75
45	41.56	69.4	55.5	0.60	0.75
50	45.81	76.8	61.5	0.60	0.74

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Reference

1. Bock, H.F., 1993. Measuring In-Situ Rock Stress by Borehole Slotting, Cambridge.Bock, H.F., Foruria, V., 1984. A Recoverable Borehole Slotting Instrument for In-Situ Stress Measurements in Rock not requiring Overcoring, Zurich.
2. Fairhurst, C., 1964. Measurement of in Situ Rock Stresses with Particular Reference to Hydraulic Fracturing, Geological Survey (U.S.).
3. Foruria, V., 1987. A Borehole Slotting Instrument for Stress Measurement in Rock.MSC.Thesis, James Cook.

INTERNATIONAL JOURNAL OF RESEARCH SCIENCE & MANAGEMENT

4. [Haimson, B.C., 1968. Hydraulic Fracturing in Porous and Nonporous Rock and its Potential for Determining In-Situ Stress at Great Depth, Minnesota.
5. Hoek, E., Brown, E. T., 1980. Underground Excavation in Rock, Institution of Mining and Metallurgy, London.
6. Hudson, J.A., Harrison, J.P., 1997. Engineering Rock Mechanics an Introduction to the Principles, London.
7. Ljunggren, C., Yanting, C., Janson, T., Christiansson, R., 2003. An Overview of Rock Stress Measurement Methods. J. Rock. Mech. Min. Sci. 40(4), 975–989.
8. Saati, V., Mortazavi, A., 2011. Numerical Modeling of In-Situ Stress Calculation Using Borehole Slotter Test. J. Tust. 26(2), 172-178.
9. Scheidegger, A.E., 1962. Stress in Earth's Crust as Determined from Hydraulic Fracturing Data. London.
10. Schoenfeldt, V. H., 1970. An Experimental Study of Open-Hole Hydraulic Fracturing as a Stress Measurement Method with Particular Emphasis on Field Tests, Minnesota.
11. Sengupta , S., 1998. Influence of Geological Structures on In-Situ Stresses, Ph.D. Thesis, Department of Civil Engineering, New Delhi.
12. Stacey, T.R., Wesseloo, J., 2002. Application of Indirect Stress Measurement Techniques (Non Strain Gauge Based Technology) to Quantify Stress Environments in Mines, Witwatersrand.
13. Stepansson, O., 1993. Rock Stress in the Fennoscandian Shield Comprehensive Rock engineering Program, London.