터널과 지하공간, 한국암반역학회
Vol. 1, 1991, pp. 91～101

深度에 따른 岩盤內 初期應力의 變化와 그 傾向性

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The Trends and Variations of Natural Stresses in Rock Masses with Depth

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要 約

空洞 設計를 爲한 基礎 資料를 얻기 위하여 地表로 부터 깊이가 142m에서 802m에 이르는 8個 地域 12個所에서 3方向의 孔徑 變形計(3-diametral borehole deformation gage)를 使用하여 初期應力을 計測하였다.

三浪津 및 茂朱의 揚水發電所, 울산의 LPG 備蓄基地 그리고 上東, 第一蓮花 및 第二蓮花 등 金屬鑛山과 江原炭鑛 및 石公 咸白炭鑛 等에서 筆者들이 지난 10餘年 동안 實測하여 部分的으로 發表하였던 內容을 綜合하여 우리나라에서의 岩盤內 應力이 深度에 따라 變化하는 傾向性을 推定한 結果는 다음과 같다.

深度(Z, m)에 따른 鉛直應力(σ_z)의 크기

$$\sigma_z = 1.36 + 0.0233Z(\text{MPa})$$

深度에 따른 平均水平應力(σ_{hav})의 크기)

$$\sigma_{hav} = 2.78 + 0.0183Z(\text{MPa})$$

1. Introduction

In addition to the development of mines, large excavations in rock masses such as underground powerhouses, LPG and crude oil storages, subway stations in urban area have recently been constructed in Korea. Determination of the stress field is considered one of the most important in the design of the underground structures. The magnitudes and the directions of the principal stresses as well as average stress components at any test sites have been evaluated utilizing field measurement.

Empirical relationships between the measured

* 1991年 5月 接受.
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in-situ stress and the depth have been presented by Hast(1969), Worotnicki and Denham(1976), Haimson(1978), Brown and Hoek(1978), etc[1]. However the state of natural stresses in Korea has not yet been reported.

The regional state of stresses is known to be controlled by geological processes such as tectonic and recent erosive processes. The strike, dip, and thickness of geologic formations in Korea vary sometimes severely over small area. Moreover, structural geologic features have also been considered extremely complica-ted due to successive crustal movements. Beca-use of different geologic environments, it is im-possible to predict the state of stresses in Korea from empirical formulas developed in other countries.

Considerable efforts have been made for the stress measurements in Korea during the past ten years. The authors have carried out a series of rock stress measurements in different geologic formations at different depths ranging from 142m to 802m.

This paper presents current informations on stress measurements in Korea.

2. Measurement and Procedure

The stress measurements in Korea were carried out first at the Sangdong tungsten mine in 1979 and continued later at the Samrangjin underground powerhouse, the Yeonhwa and 2nd Yeonhwa lead-zinc mine, the Kangweon and Hambaek collieries, the Ulsan L.P.G. storage cavern and Muju underground power-house[3,4,5].

Most of the test sites are located in the south-eastern part of Korea as shown in Fig. 1.

Measurements of rock stresses were made utilizing the three-directional borehole deformation gage designed by the U.S.B.M. Measurements were made in a plane normal to the axis of the hole, and the complete stress tensor was determined by measurements in three non-parallel holes.

1. Samrangjin
2. Ulsan
3. Mugu
4. Songdong
5. Hambaek
6. lst Yeonhwa
7. Kangweon
8. 2nd Yeonhwa

Fig. 1 Locations of Measurements.

The overcoring procedure for the determination of in-situ stress is relatively well known and not explained here.

Strain-relief measurements are affected by many factors such as the moduli of elasticity of rock and the distance from the tunnel wall. To calculate the natural stress from the strain reli-

Table 1 Initial Stresses and Related Data.

Site	Depth (m)	Rock	σ_{hav}(Mpa) σ_v(Mpa)	$\sigma_1, \sigma_2, \sigma_3$ (Mpa)	Direction of σ_1 (dir/inc, degree)
Samrangjin	150	rhyolite	− 4.89 − 5.2	− 6.9 − 5.08 − 3.0	110/97
Ulsan	142	siltstone	− 2.8 − 3.8	− 4.2 − 3.1 − 2.1	55/152
	195	siltstone	− 3.44 − 4.9	− 5.2 − 3.86 − 2.72	34/165
Sangdong	285	limestone	− 6.53 − 7.20	− 10.7 − 5.86 − 3.7	313/105
	594	slate	− 13.77 − 15.3	− 22.4 − 14.8 − 5.68	132/107
Yeonhwa	315	limestone	− 7.4 − 8.5	− 12.6 − 7.0 − 3.7	224/128
2nd Yeonhwa	200	limestone	− 7.52 − 5.6	− 12.2 − 5.2 − 3.24	71/107
	440	limestone	− 25.1 − 20.5	− 39.1 − 18.1 − 13.5	134/103
Kangweon	802	sandstone	− 36.96 − 25.9	− 51.8 − 30.7 − 17.32	182/92
Muju	267	gneiss	− 6.32 − 5.89	− 9.43 − 5.21 − 3.89	144/117
Hambaek	198	sandstone	− 7.08 − 4.97	− 9.2 − 6.2 − 3.73	187/102

σ_{hav} : average horizontal stress.
σ_v : vertical stress.
σ_1, σ_2, σ_3 : maximum, intermediate and minimum principal stress.
Direction : bearing from the north.
Inclinations are referred to vertical downward as being 0°, horizontal as 90° and upward as 180°.

ef measurements, elastic constants and Poisson's ratio of the rock were determined by uniaxi-al and biaxial compression tests. The components of stresses were calculated assuming plane strain condition[7]

Site selection was carefully considered based on the geologic and mining conditions having the stress field in an undisturbed state. To avoid stress concentration effects induced by the excavation of the tunnel, strain-relief deformations were taken at depths 6.5m to 14.7m from the tunnel wall. This distance is larger than tunnel diameter. In mines and collieries all testing sites were chosen to be more than 400m from mining areas and could be considered to be free of stress concentration due to excavations.

3. Results and Discussions

More than 150 measurements for determining the natural stresses in the undisturbed rocks have been made at twelve testing sites in eight different localities.

Table 1 provides the natural stresses and related data, i.e. three principal stresses, the vertical and average horizontal stresses, and the direction and inclination of the maximum principal stress.

Many factors complicate the interpretation of in-situ stress determinations and are discussed here. Topographic irregularities(2), structural features(9), tectonic conditions, erosional process (10) and inhomogeneity of the rock mass can alter the regional state of stress.

3.1 Influence of topography on vertical stress

The natural stress field consists of current gravitational and tectonic(current, residual) stresses. The surface topography overlying the testing sites is mountainous. Gravitational

Table 2 Magnitude of Vertical Stress(σ_v) and Topographic Effect on Stress.

Site / items	Samrang-jin	Ulsan	Sangdong site 1	Sangdong site 2	Yeonhwa	2nd Yeonhwa	Kangweon	Hambaek
Depth (m)	150	142	285	594	315	200	802	198
(a) Measured stress (MPa)	5.2	3.8	7.2	15.3	8.5	5.6	25.9	4.97
(b) Calculated stress (MPa) (b=c+d)	4.42	3.94	8.33	17.6	9.2	6.0	23.0	5.75
(c): $\sigma_z=\gamma h$	3.78	3.69	7.51	15.7	8.4	5.4	21.2	5.2
(d): stress due to topographic effect	0.64	0.25	0.82	1.9	0.80	0.6	1.8	0.55
(a)/(b) (%)	117.6	96.4	86.4	86.9	92.4	93.4	112.6	86.4
(d)/(a) (%)	12.3	6.6	11.4	12.4	9.4	10.7	7.0	11.1
Height of peak mountain in the vicinity of test sites (above sea level, m)	631	132	1,150	1,150	950	800	1,040	1,171

stress in influenced by mountain peaks as well as overburden depth. The influence of topography on stress can be calculated by finite element method, or distributed load[2].

In this paper the effects of topography is approximated by considering the mountain as a distributed load acting on the boundary of a semi-infinite plate[7]. The results for each site are given in Table 2.

The influence of the local topography on the change of overburden vertical stress is found to be 6.6−12.4% of the measured stress but the effect decreases with increasing depth.

At the Samrangjin and the Kangweon, the measured vertical stresses are greater than the calculated ones by 17.6% and 12.6% respectively, while at the Sangdong and the 2nd Yeonhwa they are smaller by 13.6% and 6.6% respectively.

3.2 Changes of Stress with Depth

The measured vertical stresses are approximately equal to the estimated vertical stress by gravity(Table2) but the measured horizontal stresses are much larger than the estimated stresses. The average horizontal stress are presented in Table 3. Table 2 and Table 3 where the average rock stress components in the vertical(σ_v), east(σ_x) and north(σ_y) coordinate systems are also shown.

The data is also shown graphically in Figure 2 and Figure 3 in which vertical and average horizontal stresses are plotted with respect to the depth Z(m).

Table 3 Magnitudes of Horizontal Stresses.

Site	Depth (m)	Hor. Stresses (measured, Mpa)			Ave. hor. Stress (Mpa)		Difference (a)−(b)	Excess hor. stress (difference/100m depth)
		σ_x	σ_y	Ia	(a) measured	(b) calculated		
Samrangjin	150	6.37	3.41	1.86	4.89	1.21	3.68	2.45
Ulsan	142	3.3	2.3	1.43	2.8	0.96	1.84	1.30
	195	3.67	3.22	1.14	3.44	1.55	1.89	0.97
Sangdong	285	5.82	7.25	1.24	6.53	3.52	3.01	1.06
	594	14.83	12.7	1.17	13.77	5.90	7.87	1.32
Yeonhwa	315	8.73	6.1	1.43	7.4	4.01	3.39	1.08
2nd Yeonhwa	200	10.24	4.80	2.13	7.52	1.80	5.72	2.86
Kangweon	802	23.0	50.92	2.21	36.96	5.76	31.20	3.89
Muju	267	5.50	7.13	1.30	6.32	1.79	4.53	1.70
Hambaek	198	6.77	7.38	1.09	7.08	1.24	5.84	2.95

1) Ave.horizontal stress (measured) $\sigma_{hav}=1/2(\sigma_x+\sigma_y)$.

2) Estimated horizontal stress $\sigma_x=\sigma_y=K\sigma_v=(\upsilon/1-\upsilon)\sigma_v$.

3) Ia (horizontal stress anisotrophy) $=\sigma_x/\sigma_y$ or $\sigma_y/\sigma_x(\sigma_{h\ max}/\sigma_{h\ min})$.

The regression equations for the vertical and average horizontal stress, utilizing data in Table 1 and Table 3, are as follows :

σ_v(Mpa) = 1.36+0.0233Z :(1)

correlation coefficient r=0.97

σ_{hav}(Mpa) = 2.78+0.0183Z :(2)

r=0.86

Z in meter

The vertical and the average horizontal stress gradients are 0.0233 and 0.0183 respectively. The measured stresses in Korea follow a straight line with a non-zero intercept.

Herget, Brown, Worotnicki and Danham, Hast, Haimson and others have studied the state of stress at different locations in the world [1] and analysed it statistically to establish the most common trend in the change of stress with depth(Fig. 2, Fig.3.).

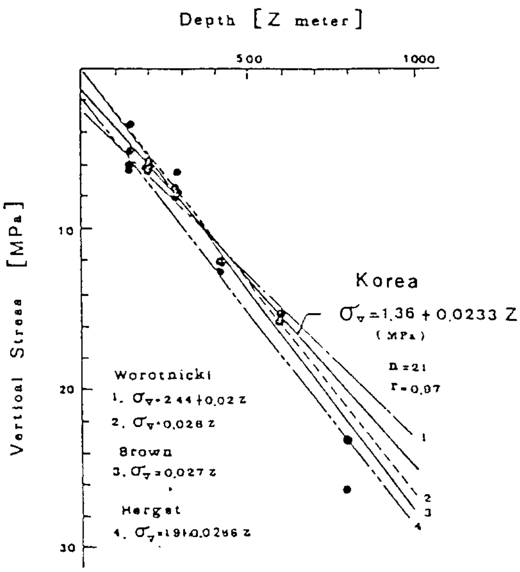


Fig.2 Variation of Vertical Stresses with Depth.

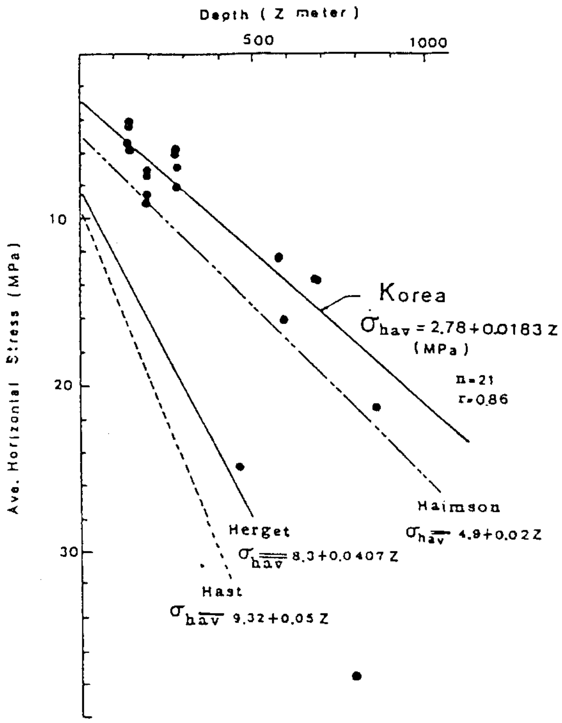


Fig. 3 Change of Ave. Horizontal Stresses with Depth.

Comparing both vertical and average horizontal stresses with depth in Korea with measured stresses in other part of the world, the stress level appears to be lower in Korea.

The ratio of maximum to minimum horizontal stress, presented in Table 3, varies widely from 1.09 to 2.21 depending on different localities. The horizontal stress shows anisotropy in most cases.

3.3 The Ratio of Horizontal to Vertical Stress

The ratio(K) of measured average horizontal to vertical stress is one of the most important factors in the design of underground openings. The results are given in Table 4, but the value is not uniform.

Table 4. The Relation between K and Depth.

Site	Depth (m)	Ave. hor. stress (Mpa)	Vertical stress (Mpa)	K (σ_{hav}/σ_v)
Samran-gjin	150	4.89	5.2	0.94
Ulsan	142	2.8	3.8	0.74
	195	3.44	4.9	0.71
Sangdong	285	6.53	7.2	0.91
	594	13.77	15.3	0.90
Yeonhwa	315	7.4	8.5	0.87
2nd Yeonhwa	200	7.52	5.6	1.34
Kangweon	802	36.96	25.9	1.43
Muju	267	6.32	5.89	1.07
Hambaek	198	7.08	4.97	1.42

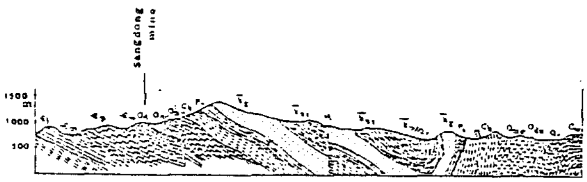
In South Africa and U.S.A., this ratio reported to be less than one at depths of greater than one kilometer, while in Canada it trends to be greater than one[8].

3.4 Presence of Excess Horizontal Stress

The excess horizontal stress, which is produced tectonically, could be calculated from the difference between the measured and the theoretical horizontal stresses. In order to analyze the excess horizontal stress, it is proposed to adopt the principle of denudation[10].

Neglecting the thermic effect of the rocks, unloading due to erosion can alter the state of stress. An attempt is made to find a correlation between the assumed flat surface and the measured current horizontal stress.

The depth of denudation of flatly layered formations has been estimated by using equation 3, while the estimated thickness in Table 5 has been measured from the geologic map.



Symbol	Subdivisions of geologic system
Qr	recent river deposit
kn	Nogam series
kg	Gobangsan
Ps	Sadong
Ch	Hongjeom
Omg	Maggol limestone
Odu	Dumugol formation
Od	Dongjeom
Ew	Hwajeol
(Es)	Sesong
Ep	Pungchon
Em	Myobong
Ej	Jangsan quartzite
pEt	Taebaegsan series

Fig.4 N−S Cross section through Sangdong mine area.

Figure 4 shows an example of the estimated thickness due to erosion at Sangdon mine areas.

At all sites except the Kangweon colliery, the excess horizontal compressive stresses can be expected to have been affected by erosional

$$\sigma_{he} = \sigma_{hm} - \sigma_{hc} = \sigma_{hm} - (\nu/(1-\nu)), \sigma_v = \sigma_{hm} - (\nu/(1-\nu)) \rho gh \; : \; (3.a)$$

$$h' = ((1-\nu)/\nu) \frac{1}{\rho g} \times \sigma_{he} = ((1-\nu)/\nu) \frac{1}{r} \sigma_{he} \; ; \; (3.b)$$

where σ_{hm}, σ_{hc}, σ_{he} : measured, calculated and excess horizontal stress respectively.

σ_v ; calculated vertical stress.

ρ ; density of overburden rock.

h ; current overburden depth.

h' : depth of denudation.

r : specific weight or unit weight.

ν : Poisson's ratio.

Table 5 Estimated Depth of Denudation based on Excess Horizontal Stress

Site	Depth (m)	Excess horizontal stress (Mpa)	Depth of denudation (m)	
			calculated	estimated thickness from geologic map
Samrangjin	150	3.68		tuff breccia area
Ulsan	142	1.84	273	depositional aera
Sangdong	594	7.87	884	approx. 1000m (from Maggol to Gobangsan formation)
Yeonhwa	315	3.39	420	approx. 660m (from Pungchon to Dumungol formation)
2nd Yeonhwa	200	5.72	706	approx. 950m (from Dumugol to Hongjeom series)
Kangweon	802	31.20	4,682	approx. 1,310m (from Dosagog to Donggo formation)
Hamvaek	198	5.84	884	approx. 900m (from Jangseung to Gohan formation)

process. However at Kangweon it may be caused by erosion and tectonic process such as the Cheolam fault, the Cheolam syncline and the Baiksan thrust.

3.5 Relations between Direction of the Maximum Principal Stress and the Local Orientation of Fractures

Table 1 shows the mean bearing and

Table 6 The Relation between the Direction of the Maximum Principal Stresses and Predominant Orientation of Fracture.

Location	Depth (m)	Direction of Max. Principal Stress	Local Orientation of Fracutrues	Remarks
Samrangjin	150	N 110°	N 50° E	approximatelv parallel to the slope of mountatin(N80° E)
Ulsan	142	N 55° E N 34° E	N 50° E B 60−70° E	approximately parallel
Sangdong (site 1)	285	N 313° (N 47° W)	N 50−80° W	approx. parallel to orientation and slope of mountain(N 69° W)
(site 2)	594	N 132° (N 48° W)	N 30−50° W	parallel
Yeonhwa	315	N 224° (N 44° E)	NS−N 30° E	approximately parallel
2nd Yeonhwa (site 1)	200	N 71°	N 50° E	parallel to orientations of local joints and slope of moutain(N 78° E)
(site 2)	440	N 134° (N 46° W)	N 10−60° W N 60−80° E	approximately perpendicular to fault (N 60° E)
Kangweon	802	N 182° (N 46° W)	N 10−60° W N 60−80° E	Oarallel
Muju	267	N 182°	nearly N−S	approximately parallel at site 1
Hambaek	198	N 187°	N 10−30° E	approximately parallel to the Dangog fault and the Dangog anticline

inclination of maximum principal stress at the test sites. It shows that the inclination of maximum principal stress is subhorizontal both shallow and at great depths except for Ulsan.

Table 6 also presents the relation between the direction of the maximum principal stresses and the predominant orientation of fractures existing in each test area.

For example at the Samrangjin, the Sangdong, site 1 of the 2nd Yeonhwa and the Kangweon etc, there is a predominant joint orientation that persists through the test area. At site 2 of the 2nd Yeonhwa, however, a predominant joint group strikes between N 10° W and N 60° W, a second group strikes between N 60° E and N 80° E, while the fault strikes N 60° E. At all test sites except the Samrangjin, and site 2 of the 2nd yeonhwa, the directions of the maximum principal stresses are nearly parallel to the predominent orientation of local fractures but at the Samrangjin, the direction of the maximum principal stress is parallel to the slope of mountain under which powerhouse station is located.

The latter may be due to the topographic effect.

4. Conclusion

In−situ stress measurements performed in the south−eastern part of Korean peninsula show a current regional state of stress in rock masses. Although the number of measurements may not be sufficient, some general observations can be made as follows;

1. Vertical stresses are in agreement with the calculated values considering the overburden depth and the influence of local topography. The ratios of measured to calculated stresses are varied from 86.4−117.6%. The regression equation obtained for the vertical stress components (σ_v,MPa) as a function of depth (Z. meter) is $\sigma_v = 1.36 = 0.0233Z$.

The influence of surface topography on the magnitude of stress has been analyzed by using a distributed load. The increase of the stress due to topography appears to be 6.6−12.4% of the measured stress, but the effect decreases with increasing depth.

2. The regression equation for the average horizontal stress (σ_{hav}, MPa) is $\sigma_{hav} = 2.78 + 0.0183Z$.

The two horizontal stresses σ_x, σ_y also show a considerable differences, and the ratio ranges from 1.09 to 2.21, indicating anisotrophy.

3. The ratios of horizontal to vertical stress at the test sites varies 0.71−1.43. The average horizontal stresses at all sites except tht 2nd Yeonhwa, the Kangweon, the Hambaek and the Muju are less than vertical stresses, but higher horizontal stresses are measured at the 2nd Yeonhwa, the Kangweon and the Hambaek.

4. The state of stress in the Kangweon, and 2nd Yeonhwa area is considered to be affected by geologic tectonic structures such as the Cheolam fault, the Cheolam syncline, and the Baiksan thrust, while the state of stress in the Hambaek is influenced by the Hambaek syncline and Dangog fault, etc.

The in−situ state of stresses in the south−eatern part of Korea can be characterized by a considerably high horizontal stress.

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