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Technical Note

Trends in Relationships between Measured *In-Situ* Stresses and Depth

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Knowledge of the pre-excavation state of stress at a given location in the Earth's crust is a prerequisite for the rational design of large underground excavations in rock. Measuring the complete *in situ* state of stress can be a difficult, expensive and often frustrating task. It is hardly surprising, therefore, that there has been long-standing interest in the development of theories or empirical relationships that may be used for the prediction of *in-situ* stresses. The most familiar of these theories calculates the vertical stress at a point as the stress due to the weight of the overburden, and the horizontal stress as that stress required to completely restrain lateral deformation of an elastic body acted upon by this vertical stress. This theory predicts that the horizontal stress will be some fraction of the vertical or overburden stress dependent upon the value of Poisson's ratio for the rock.

When, in 1958, Hast [1] reported having measured horizontal stresses of several times the vertical stress at a number of sites in Scandinavia, the results were treated with extreme scepticism. However, during the past 20 years such a pattern has been recorded at shallow depths by so many investigators in so many different locations and geological environments that it may now be considered to be the rule rather than the exception. It is not the purpose of this Note to discuss the origins of these high horizontal stresses, but it should be noted that they have been ascribed to such diverse causes as movements of crustal plates, plastic yield and subsequent elastic deformation on unloading during partial denudation [2], creep under sustained loads on a geological time scale, topography [3], tectonic forces of sometimes ill-defined origin, and a general contraction of the Earth's crust [4].

As might be expected, no mathematical theory is available to account for the wide range of *in situ* stress patterns that have been recorded. However, a number of investigators have been able to establish empirical relationships that hold on a regional or sub-continental basis. Hast [4], for example, showed that 40 measurements of horizontal stresses in the Fennoscandian block fitted the relationship

$$\sigma_1 + \sigma_2 = (18.73 \pm 0.10) + Z(0.097 \pm 0.003) \quad (1)$$

where σ_1 and σ_2 are the horizontal principal stresses in MPa and Z is the depth of the measuring point in metres. Hast found that data from a number of other parts of the world fell on a line having the same slope as that given by equation (1) but with a different intercept at $Z = 0$. Kropotkin [5] found that equation (1) fitted data from a number of localities in the U.S.S.R. and other countries, but suggested that such a relationship does not hold in sedimentary cover and fissured rocks. Hast [6] claimed that relationships of the form of equation (1) had been found to apply for all competent rock. He also suggested that equation (1) could be re-written as

$$\sigma_1 + \sigma_2 = 18.63 + Z\,(\mathrm{MPa}). \quad (2)$$

Herget [7] found that a number of sets of data from disparate localities in which horizontal stresses were greater than the vertical stresses could be represented by the equations

$$\sigma_{h\,\mathrm{av}} = (8.16 \pm 0.54) + Z(0.042 \pm 0.002) \quad (3)$$

and

$$\sigma_v = (1.88 \pm 1.23) + Z(0.026 \pm 0.003), \quad (4)$$

where $\sigma_{h\,\mathrm{av}}$ and σ_v are the average horizontal and vertical stresses in MPa and Z is the depth in metres. It should be noted that Herget also found other sets of data for which $\sigma_{h\,\mathrm{av}} < \sigma_v$ and $\sigma_{h\,\mathrm{av}} \simeq \sigma_v$.

More recently, Haimson [8] found that a number of *in-situ* stress determinations made in the U.S.A. using the hydrofracturing technique, could be fitted by the relationships

$$\sigma_{h\,\mathrm{av}} = 4.90 + 0.020\,Z \quad (5)$$

and

$$\sigma_v = 0.025\,Z. \quad (6)$$

Worotnicki and Denham [9] found that the horizontal stresses at a number of sites in Australia were lower than those reported by Hast [4, 6], Kropotkin [5] and Herget [7], being represented by

$$\sigma_{h\,\mathrm{av}} = 7.26 + Z(0.0215 \pm 0.0028). \quad (7)$$

Like Herget, Worotnicki and Denham also found that there were a number of Australian sites at which the horizontal stresses were less than or equal to the vertical stresses.

With the background of these previous studies of the problem and their own knowledge of many of the sites

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TABLE 1. *IN-SITU* STRESS MEASUREMENT DATA

Point	Location	Rock type	Depth (m)	σ_v (MPa)	$\sigma_{h\,\mathrm{av}}/\sigma_v$	Ref.
	Australia					
1	CSA mine, Cobar, N.S.W.	Siltstone, chloritic slate	360	16.6	1.46	9
2	CSA mine, Cobar, N.S.W.	Siltstone, chloritic slate	360	8.0	1.30	9
3	CSA mine, Cobar, N.S.W.	Siltstone, chloritic slate	540	15.2	1.70	9
4	CSA mine, Cobar, N.S.W.	Siltstone, chloritic slate	330	10.0	1.40	9
5	CSA mine, Cobar, N.S.W.	Siltstone, chloritic slate	455	11.0	1.90	9
6	CSA mine, Cobar, N.S.W.	Siltstone, chloritic slate	245	8.4	2.10	9
7	CSA mine, Cobar, N.S.W.	Siltstone, chloritic slate	633	13.7	2.00	9
8	NBHC mine, Broken Hill, N.S.W.	Sillimanite gneiss	1022	6.2	1.66	9
9	NBHC mine, Broken Hill, N.S.W.	Garnet quartzite	668	13.8	1.17	9
10	NBHC mine, Broken Hill, N.S.W.	Garnet quartzite	668	4.8	2.73	9
11	NBHC mine, Broken Hill, N.S.W.	Garnet quartzite	570	15.9	1.32	9
12	ZC mine, Broken Hill, N.S.W.	Sillimanite gneiss	818	20.0	1.07	9
13	ZC mine, Broken Hill, N.S.W.	Sillimanite gneiss	818	26.9	1.17	9
14	NBHC mine, Broken Hill, N.S.W.	Sillimanite gneiss	915	13.1	1.29	9
15	NBHC mine, Broken Hill, N.S.W.	Sillimanite gneiss	915	21.4	0.97	9
16	NBHC mine, Broken Hill, N.S.W.	Sillimanite gneiss	766	9.7	1.85	9
17	NBHC mine, Broken Hill, N.S.W.	Garnet quartzite	570	14.7	1.43	9
18	NBHC mine, Broken Hill, N.S.W.	Garnet quartzite	570	12.7	2.09	9
19	NBHC mine, Broken Hill, N.S.W.	Garnet quartzite	818	20.3	1.72	9
20	NBHC mine, Broken Hill, N.S.W.	Gneiss and quartzite	670	13.0	2.40	9
21	NBHC mine, Broken Hill, N.S.W.	Gneiss and quartzite	1277	19.2	1.60	9
22	NBHC mine, Broken Hill, N.S.W.	Gneiss and quartzite	1140	6.9	2.40	9
23	NBHC mine, Broken Hill, N.S.W.	Gneiss and quartzite	1094	25.5	0.82	9
24	NBHC mine, Broken Hill, N.S.W.	Rhodonite	1094	15.9	1.81	9
25	NBHC mine, Broken Hill, N.S.W.	Gneiss and quartzite	1094	18.6	1.62	9
26	NBHC mine, Broken Hill, N.S.W.	Gneiss and quartzite	1094	26.9	1.34	9
27	NBHC mine, Broken Hill, N.S.W.	Gneiss and quartzite	1140	29.7	1.43	9
28	NBHC mine, Broken Hill, N.S.W.	Gneiss and quartzite	1423	24.2	1.51	9
29	Mount Isa Mine, Qld.	Silica dolomite	664	19.0	0.83	9
30	Mount Isa Mine, Qld.	Silica dolomite	1089	16.5	1.28	9
31	Mount Isa Mine, Qld.	Dolomite and recrystallised shale	1025	28.5	0.87	9,12
32	Mount Isa Mine, Qld.	Shale	970	25.4	0.85	9
33	Warrego mine, Tennant Creek, NT	Magnetite	245	7.0	2.40	9
34	Warrego mine, Tennant Creek, NT	Chloritic slate, quartz	245	6.8	1.80	9
35	Warrego mine, Tennant Creek, NT	Magnetite	322	11.5	1.30	9
36	Kanmantoo, SA	Black garnet mica schist	58	2.5	3.30	9
37	Mount Charlotte mine, WA	Dolerite	92	11.2	1.45	9
38	Mount Charlotte mine, WA	Greenstone	152	10.4	1.42	9
39	Mount Charlotte mine, WA	Greenstone	152	7.9	1.43	9
40	Durkin mine, Kambalda, WA	Serpentine	87	7.4	2.20	9
41	Dolphin Mine, Kings Is., Tas.	Marble and skarn	75	1.8	1.80	9
42	Poatina, Tas.	Mudstone	160	8.5	1.70	9,13
43	Cethana, Tas.	Quartzite conglomerate	90	14.0	1.35	9
44	Gordon River, Tas.	Quartzite	200	11.0	2.10	9
45	Mount Lyell, Tas.	Quartzite schist	105	11.3	2.95	9
46	Windy Creek, Snowy Mts., N.S.W.	Diorite	300	12.4	1.07	9
47	Tumut 1 Power Station, Snowy Mts, N.S.W.	Granite and gneiss	335	11.0	1.20	9
48	Tumut 2 Power Station, Snowy Mts, N.S.W.	Granite and gniess	215	18.4	1.20	9
49	Eucumbene Tunnel, Snowy Mts, N.S.W.	Granite	365	9.5	2.60	9
	Canada					
50	G.W. MacLeod Mine, Wawa, Ontario	Siderite	370	16.1	1.29	7
51	G.W. MacLeod Mine, Wawa, Ontario	Tuff	370	15.1	2.54	7
52	G.W. MacLeod Mine, Wawa, Ontario	Tuff	575	21.5	1.23	7
53	G.W. MacLeod Mine, Wawa, Ontario	Tuff	575	14.6	1.25	7
54	G.W. MacLeod Mine, Wawa, Ontario	Meta-diorite	480	18.7	1.54	7
55	G.W. MacLeod Mine, Wawa, Ontario	Chert	575	26.6	1.52	7
56	Wawa, Ontario	Granite	345	20.0	2.50	14
57	Elliot Lake Ontario	Sandstone	310	(11.0)^a	2.56	15
58	Elliot Lake, Ontario	Quartzite	705	(17.2)	1.70	15
59	Elliot Lake, Ontario	Diabase dyke	400	17.2	1.90	16
60	Churchill Falls, Labrador	Diorite gneiss	300	7.8	1.70	17
61	Portage Mountain, B.C.	Sandstone and shale	137	6.8	1.42	18
62	Mica Dam, B.S.	Gneiss and quartzite	220	6.9	1.50	19
	United States					
63	Rangeley, Colorado	Sandstone	1910	(43.5)	1.04	20
64	Nevada Test Site	Tuff	380	(7.0)	0.90	21
65	Fresno, California	Granodiorite	300	(8.2)	0.91	22
66	Bad Creek, South Carolina	Gneiss	230	(6.2)	3.12	22
67	Montello, Wisconsin	Granite	136	(3.5)	3.29	8
68	Alma, New York	Sandstone	500	(7.9)	1.61	23
69	Falls Township, Ohio	Sandstone	810	(14.1)	1.25	23

TABLE 1—*continued*

Point	Location	Rock type	Depth (m)	σ_v (MPa)	$\sigma_{h\,av}/\sigma_v$	Ref.
70	Winnfield, Louisiana	Salt	270	5.5	0.95	24
71	Barbeton, Ohio	Limestone	830	24.0	1.94	24
72	Silver Summit Mine, Osburn, Idaho	Argillaceous quartzite	1670	56.7	1.26	25
73	Star Mine, Burke, Idaho	Quartzite; orebody	1720	37.9	0.60	26
74	Crescent Mine, Idaho	Quartzite	1620	40.3	1.17	27
75	Red Mountain, Colorado	Granite	625	18.1	0.56	28
76	Henderson Mine, Colorado	Granite	790	24.2	1.23	28
77	Henderson Mine, Colorado	Orebody	1130	29.6	0.98	28
78	Piceance Basin, Colorado	Oil Shale	400	(9.8)	0.80	29
79	Gratiot County, Michigan	Dolomite	2806	(63.1)	0.78	8
	Scandinavia					
80	Bleikvassli Mine, N. Norway	Gneiss and mica schist	200	6.0	1.92	30
81	Bleikvassli Mine, N. Norway	Gneiss and mica schist	250	7.0	2.00	30
82	Bidjovagge Mine, N. Norway	Pre-Cambrian rocks	70	2.8	4.64	31
83	Bjornevann, N. Norway	Gneiss	100	(2.7)	5.56	30
84	Sulitjelma, N. Norway	Phyllite	850	10.0	0.99	31
85	Sulitjelma, N. Norway	Phyllite	900	11.0	0.55	31
86	Ställberg, Sweden	Pre-Cambrian rocks	915	(24.7)	1.56	1,30
87	Vingesbacke, Sweden	Granite and amphibolite	400	(10.8)	4.99	32
88	Laisvall, Sweden	Granite	220	(5.9)	3.72	32
89	Malmberget, Sweden	Granite	500	(13.4)	2.41	30
90	Grängesberg, Sweden	Pre-Cambrian rocks	400	(10.8)	2.31	31
91	Kiruna, Sweden	Pre-Cambrian rocks	680	(18.4)	1.90	31
92	Stalldalen, Sweden	Pre-Cambrian rocks	690	(18.6)	2.58	32
93	Stalldalen, Sweden	Pre-Cambrian rocks	900	(24.3)	2.02	32
94	Hofors, Sweden	Pre-Cambrian rocks	470	(12.7)	2.74	32
95	Hofors, Sweden	Pre-Cambrian rocks	650	(17.6)	2.25	32
	Southern Africa					
96	Shabani Mine, Rhodesia	Dunite, serpentine	350	10.7	1.46	33
97	Kafue Gorge, Zambia	Gneiss, amphibolite schist	160	7.5	1.57	10
98	Kafue Gorge, Zambia	Gneiss, amphibolite schist	400	12.5	1.60	10
99	Ruacana, SW Africa	Granite gneiss	215	4.0	1.95	11
100	Drakensberg, S.A.	Mudstone and Sandstone	110	3.0	2.5	11,41
101	Bracken Mine, Evander, S.A.	Quartzite	508	13.9	0.99	10
102	Winkelhaak Mine, Evander, S.A.	Quartzite	1226	38.4	0.82	10
103	Kinross Mine, Evander, S.A.	Quartzite	1577	49.5	0.64	10
104	Doornfontein Mine, Carletonville, SA	Quartzite	1320	39.0	0.48	10
105	Harmony Mine, Virginia, S.A.	Quartzite	1500	33.1	0.49	10
106	Durban Roodeport Deep Mine, S.A.	Quartzite	2300	68.5	0.67	10
107	Durban Roodeport Deep Mine, S.A.	Quartzite	2500	59.0	1.02	10
108	East Rand Mine, S.A.	Quartzite and shale	2400	37.4	0.72	10
109	Prieska copper mine, Copperton, S.A.	Quartz amphibolite schist	279	8.8	1.41	34
110	Prieska copper mine, Copperton, S.A.	Quartz amphibolite schist	410	9.6	1.01	34
111	Western Deep Levels Mine, Carletonville, S.A.	Quartzite	1770	45.6	0.63	35
112	Doornfontein Mine, Carletonville, S.A.	Quartzite	2320	58.5	0.54	10
	Other regions					
113	Dinorwic, N. Wales, U.K.	Slate	250	9.0	1.28	36
114	Mont Blanc, France	Gneiss-granite	1800	48.6	1.00	37
115	Idikki, Southern India	Granite gneiss	360	8.3	1.96	38
116	Woh, Cameron Highlands, Malaysia	Granite	296	10.6	1.03	39
117	Reykjavik, Iceland	Basalt breccia	203	(5.4)	0.96	8,40
118	Reykjavik, Iceland	Basalt breccia	285	(7.6)	0.75	8,40
119	Reykjavik, Iceland	Basalt breccia	350	(9.3)	0.75	8,40
120	Reykjavik, Iceland	Basalt breccia	375	(10.0)	0.64	8,40

[a] Vertical stresses in parenthesis calculated from depth below surface.

and stress measuring techniques reported in the literature, the authors have tabulated a wide range of stress measurement data (Table 1) and plotted them in Figs. 1 and 2. In preparing this table, measurements taken in extremely unusual geological environments and measurements not supported by reasonably detailed information on the measuring techniques used and the methods used to process field data have been omitted. Generally, only those sets of data that include both vertical stresses and an average horizontal stress or horizontal stresses measured in two orthogonal directions have been accepted. Exceptions to this rule are provided by the large number of horizontal stress measurements made by Hast and others in Scandinavia, and measurements made using the hydrofracturing technique in which vertical stresses must be calculated from the weight of overburden.

Following Gay [10], the selected data have been plotted in a different way from that used in most other compilations. In Fig. 1, the vertical stress, σ_v, is plotted

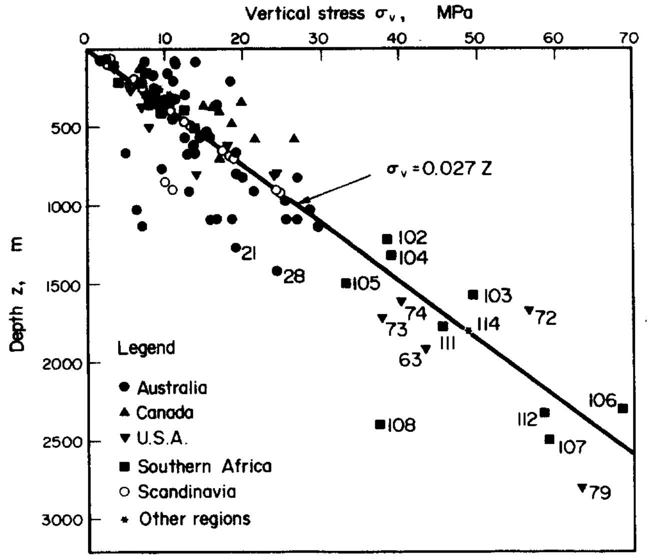

Fig. 1.

against depth Z, while Fig. 2 shows a plot of $k = \sigma_{h\,\mathrm{av}}/\sigma_v$ against depth. This approach has been used because in underground excavation design it is common practice to carry out preliminary two-dimensional stress analyses using a vertical field stress of σ_v and a lateral stress of $k\ \sigma_v$, as shown in Fig. 3. This involves the often unjustifiable assumption that the vertical and horizontal stresses are, in fact, principal stresses. Because the horizontal stresses in different directions at a site can be quite different, the use of the *average* horizontal stress will not always be appropriate.

Figure 1 shows that measured vertical stresses generally follow the trend given by the simple relationship

$$\sigma_v = 0.027\,Z. \tag{8}$$

At shallow depths, there is considerable scatter in the observed values. This may be associated with the fact that these stress values are often close to the limit of the measuring accuracy of the measuring techniques used. On the other hand, the possibility that high vertical stresses may exist cannot be discounted, particularly where some unusual geological or topographic feature may have influenced the entire stress field. It is interesting to note that van Heerden [11] recently proposed that equation (8) be used to calculate *in-situ* vertical stresses in Southern Africa.

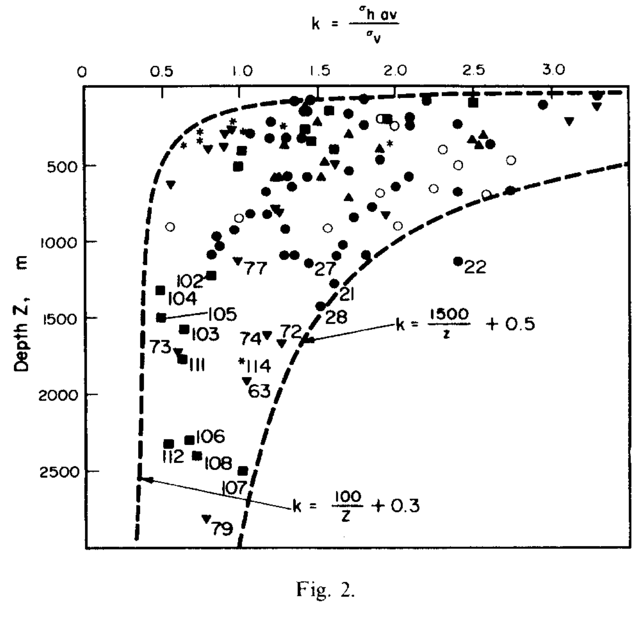

Fig. 2.

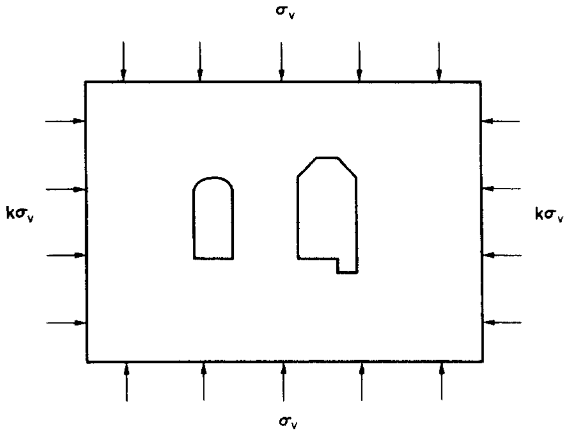

Fig. 3.

Figure 2 shows that the ratio of average horizontal to vertical stress, k, generally lies within limits defined by

$$100/Z + 0.30 \leqslant k \leqslant 1500/Z + 0.50. \tag{9}$$

Substitution of $k = \sigma_{h\,\mathrm{av}}/\sigma_v = \sigma_{h\,\mathrm{av}}/0.027\,Z$ into equation (9) yields the limits for $\sigma_{h\,\mathrm{av}}$

$$2.7 + 0.008\,Z \leqslant \sigma_{h\,\mathrm{av}} \leqslant 40.5 + 0.014\,Z. \tag{10}$$

The essential feature shown by Fig. 2 is the very wide range of values that may be taken by k at a given depth, particularly if that depth is shallow. For example, at $Z = 500$ m, k may range from 0.5 to 3.5; even at $Z = 2000$ m, k may take values in the range 0.35–1.25. Obviously, this range may be reduced somewhat by considering together only results obtained from the same region or geological environment. The results for South Africa analysed by Gay [10] for example, are reasonably well described by equation (8) and

$$k = 248/Z + 0.45. \tag{11}$$

Haimson's results for the U.S.A. [8] given by equations (5) and (6) can be expressed in the form

$$k = 200/K + 0.80 \tag{12}$$

while Worotnicki and Denham's data for Australian sites [9] given by equation (7) can be described by

$$k = 269/Z + 0.80 \tag{13}$$

assuming

$$\sigma_v = 0.027\,Z. \tag{8}$$

Clearly, such relationships will be useful in feasibility or preliminary design studies of underground structures located in regions for which appropriate relationships between Z, k and σ_v have been established. Where the regional relationships are not known or are highly variable, some form of sensitivity analysis using limits such as those given by equation (9) may be required in the preliminary stages of design. Although the trends illustrated in Figs. 1 and 2 and described by equations (8)–(13) are instructive and form a suitable basis for preliminary design studies, the wide variations in the data even for sites in similar geological environments, emphasises the uncertainty inherent in attempts to predict *in-situ* horizontal stresses on the basis of simple theoretical concepts or empirical laws. The authors therefore regard it as essential that careful *in-situ* stress measurements be made as part of the site investigation programme for any important underground excavation project.

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