From Palmström A.: RMi – a rock mass characterization system for rock engineering purposes. PhD thesis, Oslo University, Norway, 1995, 400 p.

APPENDIX 9

A METHOD TO ESTIMATE THE TANGENTIAL STRESSES AROUND UNDERGROUND OPENINGS

"Soil mechanics is the study of the strength of soils while rock mechanics is the study of the weaknesses of rock."
A. M. Muir Wood, 1979

The stresses developed in the ground surrounding an underground opening are mainly a result of the original, in situ (virgin) stresses, the impact from the excavation works, and the dimensions and shape of the opening. Their distribution may, however, be influenced by joints occurring around the opening.

1 Estimating the magnitude of the in situ ground stresses

Several authors have contributed to the understanding and knowledge of ground stresses in the earth's crust from in-situ measurements. Many of the results from these have been summarized and linear regression analyses performed to find the distribution by depth. Fig. A9-1 shows a summary of some results.

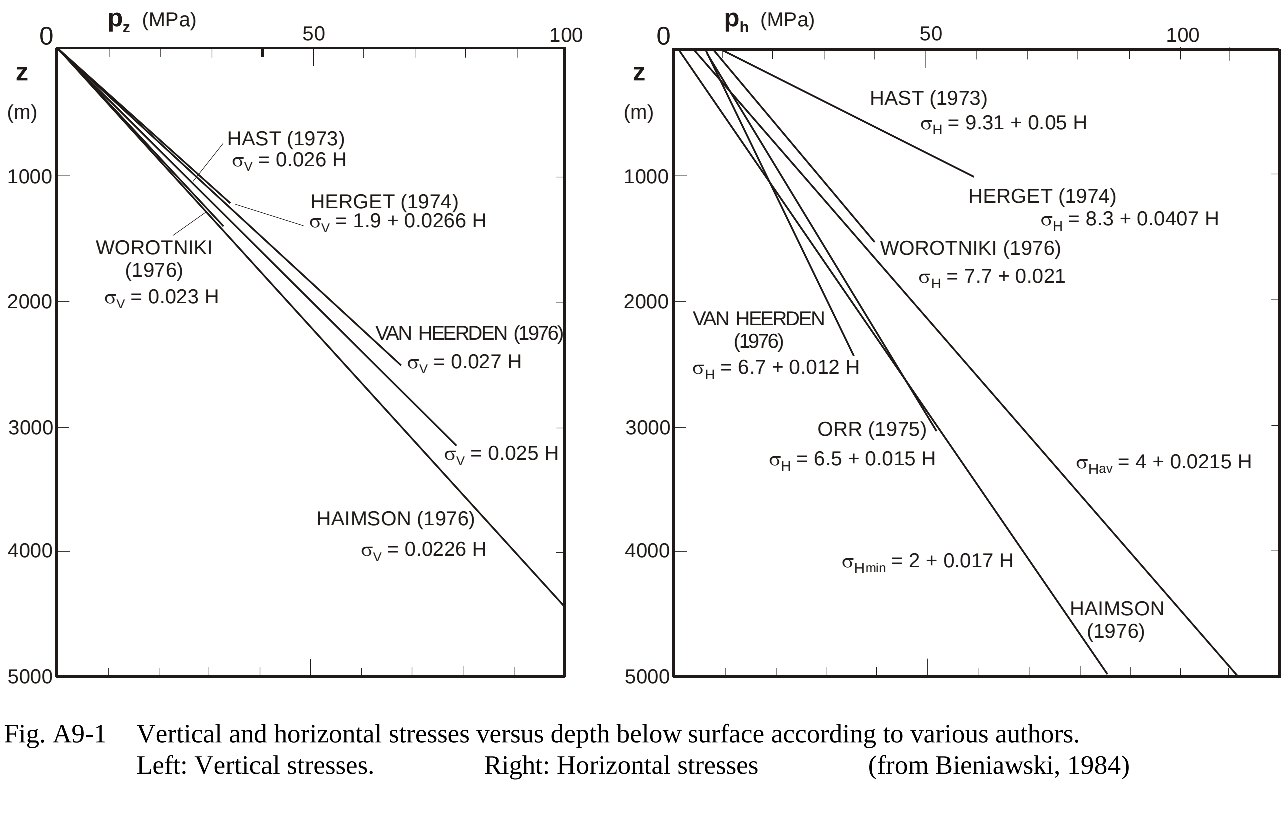


Fig. A9-1 Vertical and horizontal stresses versus depth below surface according to various authors.
Left: Vertical stresses. Right: Horizontal stresses (from Bieniawski, 1984)

Hoek (1981) found that the approximate increase of the vertical stress in excess of 1000 m depth can be reasonably well predicted by:

$$p_z = 0.027\ z \qquad \text{eq. (A9-1)}$$

where p_z is the vertical stress (in MPa), and
z is the depth below surface (in m).

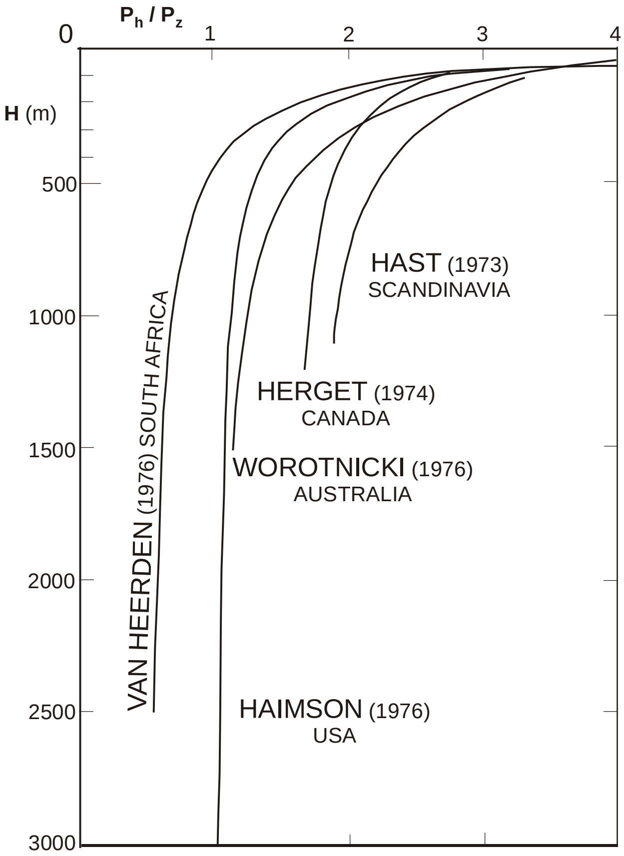


Fig. A9-2 Variation of ratio of average horizontal stresses to vertical stresses versus depth below surface according to various authors (from Bieniawski, 1984).

For the horizontal stresses there is not a similar general increase with depth (Fig. A9-1 right and Fig. A9-2). Especially in the upper 500 meters the horizontal stresses are generally higher the vertical stresses. No simple method exists for estimating the horizontal stresses which often vary in magnitude and direction (Fig. A9-3). The following trends of the horizontal stresses were formulated by Hoek (1981):

- With the exception of deep level South African gold mines, average horizontal stresses are generally higher than vertical stresses for depths of less than 1,000 m below surface.
- At a depth of 500 m below surface, the average horizontal stress is approximately 1.5 times the vertical stress with higher ratios being evident at shallower depths.
- For depths in excess of 1,000 m below surface, the horizontal and vertical stresses tend to equalize, except in South African mines in quartzites where the ratio of average horizontal to vertical stress is 0.75.
- In the Scandinavian Precambrian and Palaeozoic and in the Canadian crystalline rocks the horizontal stresses are significantly higher than the vertical stress down to a few hundred meters.

Where the stresses cannot be measured they may be evaluated from theory and the stress conditions experienced at other nearby locations. There are, however, features that tend to complicate the stress pattern underground. Bieniawski (1984) is of the opinion that in a competent rock the horizontal stress probably varies considerably from its mean value on account of jointing and inhomogeneity. In addition, tectonic features may cause $k = p_h / p_z$ to vary.

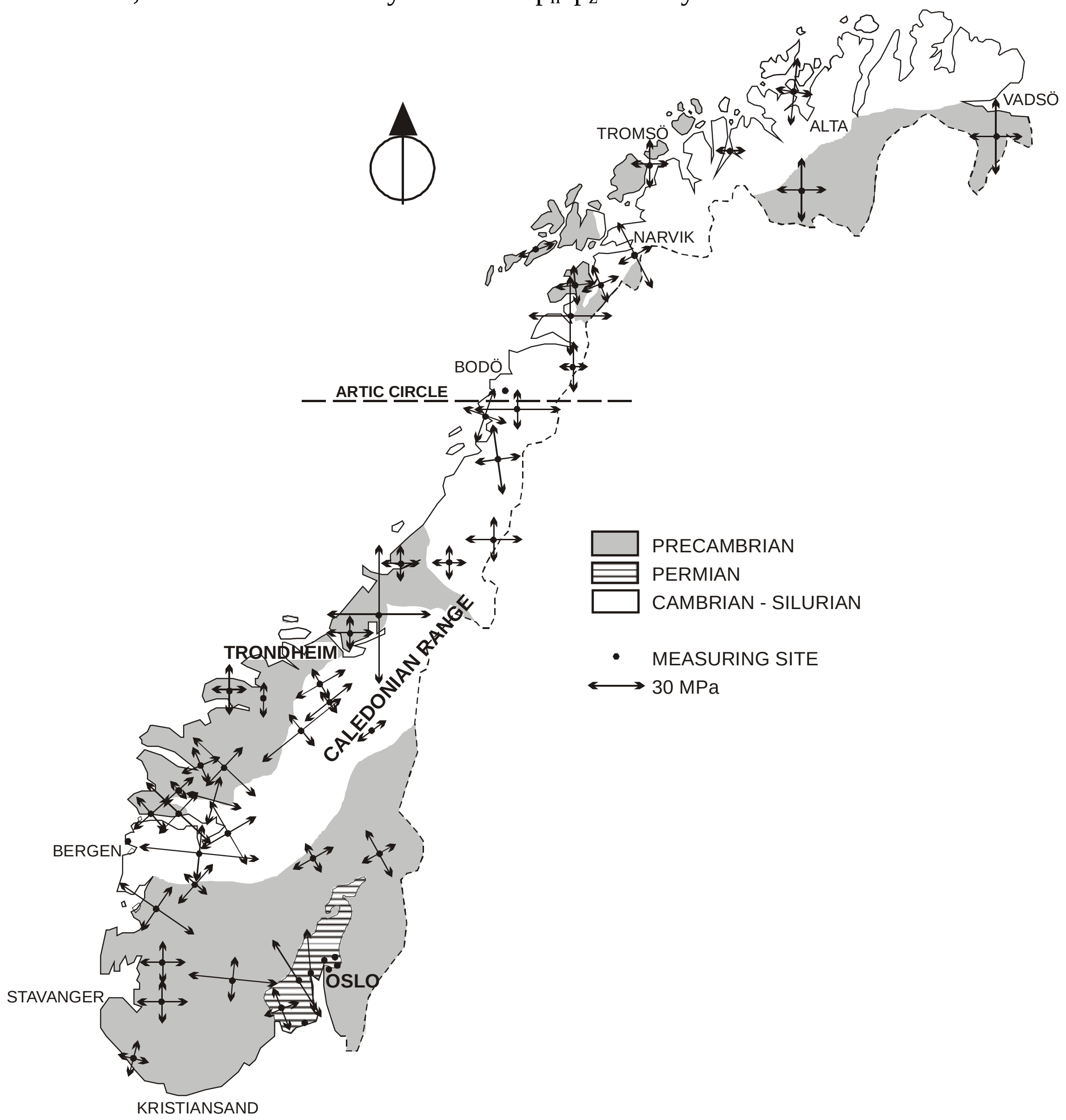


Fig. A9-3 Directions and magnitudes of measured horizontal stresses in Norway (from Nilsen and Thidemann, 1993, based on data from Myrvang)

Similarly, Selmer-Olsen (1964 and 1988) and Muir Wood (1979) mention that in the vicinity of steep cliffs or valley sides a strongly anisotropic stress distribution is often found (Fig. A9-4). Thus, the regional stresses may be influenced by local perturbations arising from topographic relief, or from geological structures such as faults or folds, or adjacent excavations. Where the ground stresses may strongly influence the stability of a planned underground excavation, stress measurements should be carried out. Haimson (1993) suggests accurate information on the local stress regime within the volume of rock containing the underground structure that is to be designed and excavated (typically a block of 10 - 1000 m on each side). Also Bieniawski (1984) recommends, in critical cases or in cases where the rock mass has been subjected to recent tectonic activity, in-situ measurements of rock stress be carried out as early in the project as possible.

For the method of estimating rock support in *discontinuous* (jointed) rock masses, described in Section 4.1 in Chapter 6, only a rough estimate of the stress level is required. For *continuous* rock masses, however, the effect of rock stresses developed around the opening may turn out to be far more important if they result in incompetent ground.

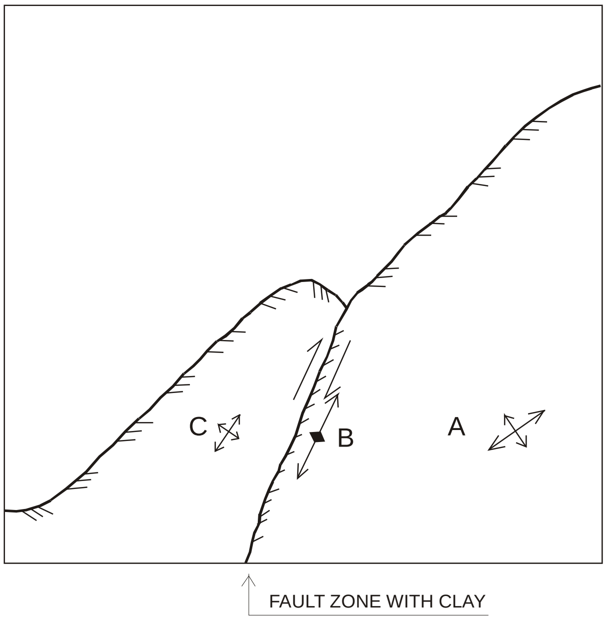


Fig. A9-4 A fault or weakness zone in a valley side may cause large local variations in the ground stress distribution. The length of the arrows indicate the relative magnitude of the stress. At 'A' there is a general stress situation, at 'B' highly anisotropic and at 'C' a destressed situation (from Selmer-Olsen, 1988).

2 The tangential stresses developed around an underground opening

During and after an underground opening is excavated in a rock mass, the in-situ (virgin) stresses which acted upon the rock volume that is removed, are redistributed in the remaining rock mass. This results in local stress concentrations in the immediate vicinity of the opening. This phenomenon has been described by many authors. The calculations made are generally based on idealized conditions: isotropic, homogeneous materials. The theoretical considerations show, however, that the stress concentrations fall off quickly as shown in Fig. A9-5.

The stresses induced around the opening will change by time. Short time effect occurs during and shortly after excavation and a secondary, long term effect takes place when deformations and cracks develop in the surrounding rock mass. Sauer (1988) has made investigations of the stress redistribution pattern in the vicinity of a tunnel in weak ground during excavation. He found that stresses increase relatively rapidly at about 1 - 1.5 tunnel diameter in front of the working face to a first (initial) maximum 0.5 diameter in front of the face. From this point there is a small decrease to a stress minimum approximately 0.5 diameter behind the face. A second maximum occurs about 1.5 - 2 diameter behind the face, provided use of adequate support. Relaxation of the second maximum takes several months, depending on the rheological properties of the rock. This is shown in Fig. A9-6.

This development with the short-time increase and long-time reduction of the tangential stresses surrounding a tunnel is utilized in the NATM, as mentioned in Chapter 8.

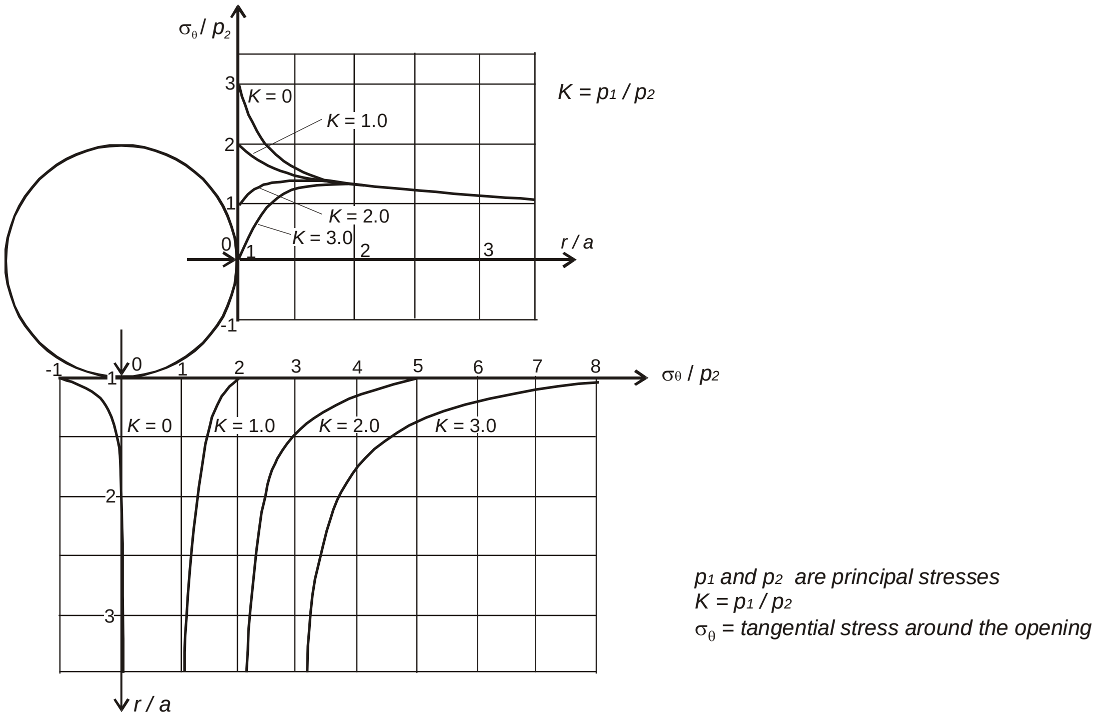


Fig. A9-5 Stresses around a circular hole in an isotropic, linearly elastic, homogeneous continuum (from Goodman, 1989).

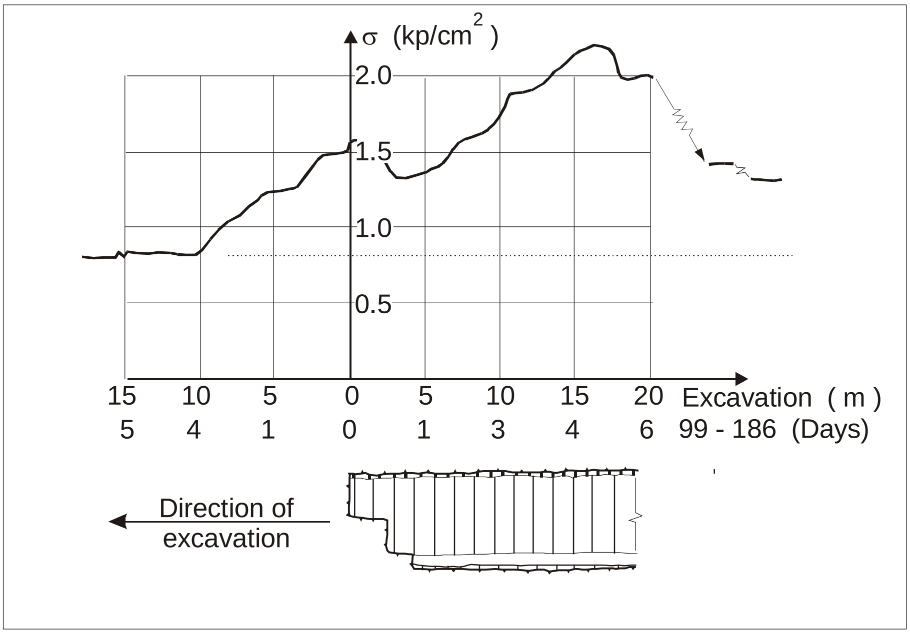


Fig. A9-6 The variation of stress level before, during and after excavation (from Sauer, 1988).

3 A practical method to estimate the magnitude of the tangential stresses

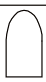
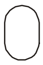
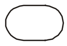
A practical method to estimate the magnitude of the tangential stresses around various types of underground openings has been developed by Hoek and Brown (1980). From a large number of detailed stress analyses by means of the boundary element technique, they have presented the following correlations:

- The tangential stress in roof $\sigma_{\theta r} = (A \times k - 1)p_z$ eq. (A9-2)
- The tangential stress in wall $\sigma_{\theta w} = (B - k)p_z$ eq. (A9-3)

where A and B are roof and wall factors for various excavation shapes in Table 6-13
k is the ratio horizontal/vertical stress
p_z is the vertical virgin stress

Eqs. (A9-2) and (A9-3) are shown graphically in Fig. A9-7.

TABLE A9-1 VALUES OF THE FACTORS 'A' AND 'B' FOR VARIOUS SHAPES OF UNDERGROUND OPENINGS (from Hoek and Brown, 1980).

VALUES OF CONSTANTS A & B									
									
A	5.0	4.0	3.9	3.2	3.1	3.0	2.0	1.9	1.8
B	2.0	1.5	1.8	2.3	2.7	3.0	5.0	1.9	3.9

Applying eq. (A9-2) and (A9-3) approximate estimates of the stresses acting in the rock masses surrounding a tunnel can be found where the magnitudes of the vertical stresses and the ratio $k = p_h / p_v$ is known. As an example the tangential stresses in the ground around a horseshoe shaped tunnel are considered. From eq. (A9-2) and Table A9-1 the tangential *roof* stress is

$$\sigma_{\theta r} = p_z \ (3.2\ k - 1)$$

For many situations where the vertical stress can be expressed by eq. (A9-1) the above expression can be written as

$$\sigma_{\theta r} = 0.027\ z\ (3.2\ k - 1)$$

In Scandinavia, the value of (k) is often in the range 2 - 3. In such cases the tangential roof stresses varies between

$$\sigma_{\theta r} = 5.5\ p_z \ \text{ to } \ 8.6\ p_z$$

or if expressed by the depth below surface

$$\sigma_{\theta r} = 0.14\ z \ \text{ to } \ 0.224\ z$$

Similarly, the tangential *wall* stress can be expressed as

$$\sigma_{\theta w} = p_z\ (2.3 - k)$$

In the same ground conditions as listed above

$$\sigma_{\theta w} = 0.008\ z \ \text{ to } \ -0.018\ z$$

which indicates that tension stresses will occur where high values of (k) occur.

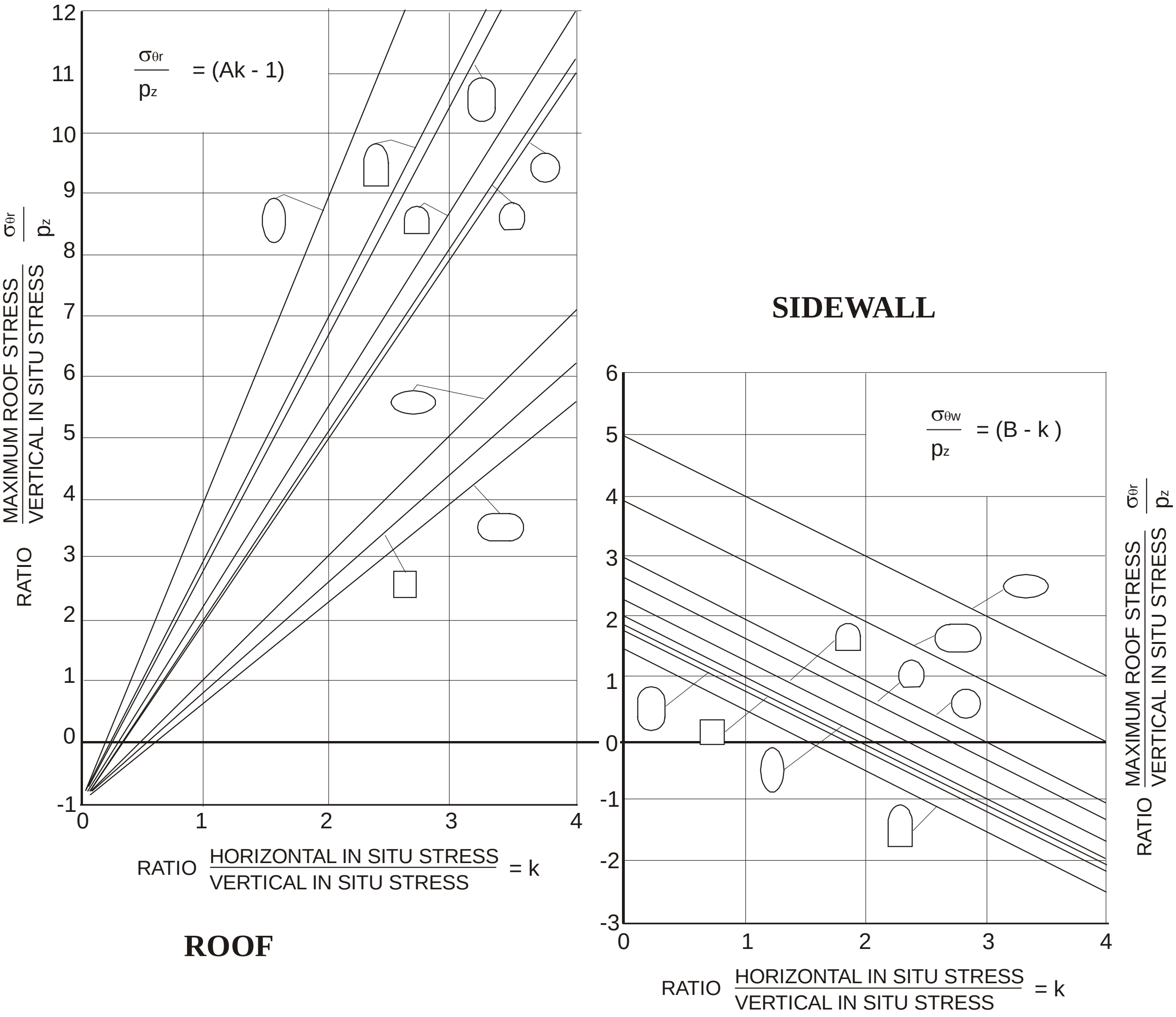


Fig. A9-7 Influence of excavation shape and ratio horizontal/vertical stresses on mobilized tangential stresses around underground openings (from Hoek and Brown, 1980).