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A new method of estimating the ratio between in situ rock stresses and tectonics based on empirical and probabilistic analyses

L.I. González de Vallejo *, T. Hijazo

Department of Geodynamics, Geological Engineering, Universidad Complutense de Madrid, 28040 Madrid, Spain

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ABSTRACT

This paper describes a new procedure for assessing the ratio between in situ stresses in rock masses by means of K ($K=\sigma_H/\sigma_v$, being σ_H and σ_v principal stress) and tectonics for purposes of engineering geology and rock mechanics. The method combines the use of the logic decision tree and the empirical relationship between the Tectonic Stress Index, TSI, and a series of K in situ values obtained from an extensive database. The decision tree considers geological and geophysical factors affecting stress magnitudes both on the regional and local scale. The TSI index is defined by geological and geomechanical parameters. The method proposed provides an assessment of the magnitude of horizontal stresses of tectonic origin. Results for several regions of Europe are presented and the possible applications of the procedure are discussed.

1. Introduction

In rock mechanics and engineering geology, certain properties of rock masses are generally estimated through empirical relationships. However, for in situ stresses, the available empirical relationships do not allow to estimate stress magnitudes within an acceptable range. In this paper K is defined as the ratio between the major horizontal stress (σ_H) and the vertical stress (σ_v) (Goodman, 1989), being σ_v the weight of overburden. Fig. 1 shows K–depth relationships using the stress data compiled in this study. Envelope lines obtained from these data and those proposed by Hoek and Brown (1980) are also included in Fig. 1. Large variation in the value of sigma H at the depths commonly dealt with in engineering is observed. Other methods of estimating stresses (Sheorey, 1994) are based on the thermoelastic properties of rocks, but do not consider the main factors affecting the state of stress of the rock. Approaches such as geological (tectonic structure analysis), seismic (focal mechanisms) give an estimate of the orientations of stresses but not their magnitude. Indirect estimation methods include acoustic emission (AE), anelastic strain recovery (ASR) measurements (Villaescusa et al., 2002; Lin et al., 2003) and borehole breakouts and core disking. Available procedures to directly measure stress magnitudes such as hydrofracturing, overcoring, or doorstopper techniques are described by ISRM (2003).

In this paper, a new procedure is described whereby the value of K (σ_H/σ_v) can be estimated for a given rock mass. The method is based on applying the probabilistic decision tree method and the empirical relationship between the TSI (Tectonic Stress Index) and K. The decision tree considers the geodynamic and geophysical factors that determine horizontal stress magnitudes on both a regional and local scale and results are expressed qualitatively as very high, high, intermediate or low magnitudes along with the possibility of local stress amplification effects. The TSI takes into account the geological history of the rock, its elastic modulus and the maximum lithostatic load. Using a large world database of in situ measurements of K, empirical correlations between K and TSI have been established. The results of applying these correlations to a wide range of cases are presented.

2. Factors affecting the state of stress

Any method of evaluating the state of stress for rock mechanics and engineering geology purposes needs to consider the factors affecting natural stresses, including the origins and the mechanisms that generate these stresses, as well as their spatial distribution and magnitude. Table 1 provides a summary of the main models and hypotheses proposed to explain the origins and formation mechanisms of the stresses affecting the Earth's crust or upper elastic lithosphere.

* Corresponding author. Tel.: +34 91 3502007; fax: +34 91 3503876.
E-mail address: vallejo@geo.ucm.es (L.I. González de Vallejo).

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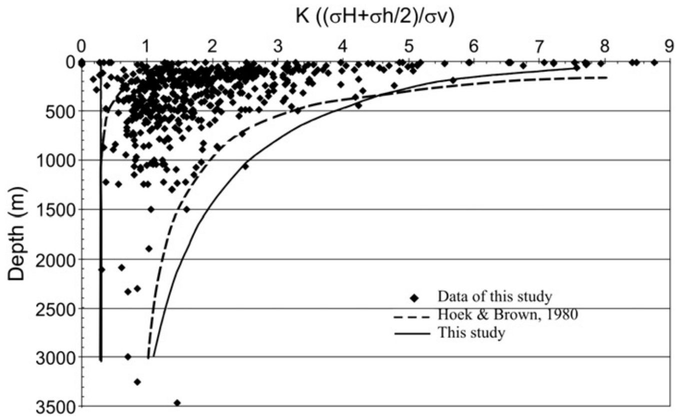

Fig. 1. Variations in K with depth based on world data compiled for this study. —— Present study, – – – Hoek and Brown (1980). For the purpose of comparing the envelopes lines used by Hoek and Brown and the stress database used in this paper. K values have been plotted as defined by Hoek and Brown: $K=(\sigma_H+\sigma_h/2)/\sigma_v$.

Tectonic stresses are the main causes of stress in the lithosphere and are generated through two basic mechanisms (Fig. 2):

Plate boundary forces generated by the movement of tectonic plates give rise to compressive or extension stresses. These stresses can reach magnitudes of 50 MPa at collision borders and 20 MPa at expansion margins (Park, 1988).

Forces produced by isostatically isostatically-compensated loads due to large topographical elevations (mountain ranges) whose weight is compensated by zones of less lithospheric density or by an increase or reduction in crust thickness. This mechanism of isostatic compensation leads to a combined effect of vertical loads and a rising push (buoyancy forces), generating horizontal stresses in adjacent zones. Their magnitudes can be of the order of 50 MPa (Park, 1988).

Both types of stress are permanent and continuous over geological time and constitute the so-called renewable stresses. Coexisting with these stresses are those denoted non-renewable. These are not tectonically significant since they are not long-standing, being gradually released over time. However, they do give rise to brittle fractures and creep processes. The main non-renewable stresses are (Bott and Kusznir, 1984):

Flexural stresses, due to non-isostatically-compensated loads.
Membrane stresses, due to changes in the Earth's curvature.
Thermal stresses, due to differential heat gradients.

Loading stresses, due to sedimentary processes, piling volcanic rocks, glacial ice deposition or unloading stresses due to erosion and ice retreat.

The regional distribution of stresses depends on the prevailing tectonic regime. Two large types of setting can be distinguished:

Intraplate regions in which compressive stresses predominate, which are largely uniform both in terms of their orientation and geographical extension. In these intraplate zones, the orientation of the compressive stress field depends of on the following factors: compressive plate margin forces, ridge push and continental collision stresses as well as the geometry of the plate margins on which they act. Discrepancies both in magnitudes and orientations can be attributed to buoyancy forces (Zoback et al., 1989).

Continental regions with large mountain systems. Here, the predominance of extensive stresses affects the different tectonic settings (continental collision, intraplate rift, back-arc regions). In some cases, changes in the direction of extension stresses are related to lateral changes in the thickness of the lithosphere and heat flow differences.

The distributions and orientations of stresses on continental and regional scales can be found in the World Stress Map (WSM) (Zoback et al., 1989; Reinecker et al., 2004).

The factors that most affect stress magnitudes are:

Rheological behaviour. On the lithospheric scale, this behaviour controls the relationship between stress magnitude and depth, and depends on the heat gradient and on crust composition and thickness.

Heat flow affects stress magnitudes, such that the greater the heat flow, the greater is the amplifying effect of stresses in the most superficial zone of the lithosphere, in which brittle behaviour predominates. Conversely, in the lower part in which the predominating behaviour is ductile, stresses decrease with depth (Kusznir, 1991). The concept of amplifying effect of stresses due to build-up of stresses in the upper most elastic part of the lithosphere. This effect is the consequence of the more ductile behaviour of the lower lithosphere compared to the upper lithosphere, which leads to transfer of stresses from the lower to upper area (Kusznir and Bott, 1977). The effect is most intense in plate margin zones.

Crust thickness. Since the upper crust layer is mainly comprised of quartz and feldspar and the lower layer of olivine, the uppermost portion of the crust is weaker. Thus for high crust thicknesses, the proportions of quartz and feldspar will exceed that of olivine and stress magnitudes will be lower.

Rock composition and its geomechanical behaviour. These two factors are linked: depending on the nature of the rock, its geomechanical behaviour will be more brittle or ductile, thus affecting strength and state of stress.

The area affected by plate margin forces depends on the thickness of the elastic crust enduring these forces. Thus, the greater the thickness the higher the wavelength or surface affected by the applied forces.

Time of stress. As the time of stress increases, so does the amplification effect along with the thickness of the elastic crust. However, due to this increased thickness, stress magnitudes are lower in intraplate and low heat flow regions (cratons), than in more tectonically active regions with high heat flows and a thinner crust (Kusznir and Bott, 1977). In regions in which moderate or low stresses are exposed to a prolonged period of tectonic forces, the effect may be comparable to that experienced by regions of high or

Table 1
Stress models

Bott and Kusznir (1984)	
Renewable stresses (subjected to amplification)	Plate margin forces Forces due to isostatically-compensated loads
Non-renewable stresses (not subjected to amplification effects)	Flexural stresses Membrane stresses Thermal stresses
Zoback et al. (1989)	
First category stresses	Plate margin forces Forces generated by geodynamic processes Thermoelastic forces Shear forces at the base of the lithosphere Forces arising from plate geometry
Second category stresses	Flexural stresses Buoyancy forces