World Stress Map (WSM) as an Initial Research Tool for In Situ Stresses and the Contribution of Data Referring to Brazil

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RESUMO: O Mapa Mundial de Tensões, conhecido como World Stress Map (WSM) compila um banco de dados globais de informações sobre o estado de tensão tectônico da crosta terrestre. O conhecimento do campo de tensões em determinado local é importante para o entendimento de processos geodinâmicos, como por exemplo terremotos, e essencial para projetos de escavações subterrâneas. Desde 1986 o WSM vem compilando dados de tensões nos 40 km superiores da crosta terrestre e apresentando atualizações no banco de dados. Destaca-se que a versão 2008 do WSM continha 21.750 registros de dados de tensões, enquanto que na versão 2016 houve um incremento significativo que apresentou um total de 42.870 registros. A alta densidade de registros de dados de tensões em determinada localidade permite a investigação de variações de campos de tensões regionais, o que produz maior conhecimento das orientações das tensões principais predominantes em determinada região. Neste artigo é discutida a relevância, para a avaliação geotécnica, do estudo e da determinação por meio de testes de campo das tensões in situ atuantes num maciço rochoso. Apresenta-se uma visão geral da origem, qualidade e distribuição espacial dos 42.870 registros de dados disponibilizados no relatório técnico do World Stress Map de 2016, bem como a contribuição dos registros de dados referentes ao Brasil.


ABSTRACT: The World Stress Map (WSM), compiles a global database of information on the tectonic stress state of the earth’s crust. Knowledge of the stress field at a given location is important for understanding geodynamic processes, such as earthquakes and essential for underground excavation projects. Since 1986 the WSM has been gathering stress data in the upper 40 km of the earth’s crust and presenting updates in the database. It is noteworthy that the 2008 version of the WSM contained 21,750 records of stress data, while the 2016 version there was a significant increase that presented a total of 42,870 records. The high density of stress data records, in a given location, allows the investigation of variations in regional stress fields, which produces greater knowledge of the orientations of the principal stress prevailing in a given region. This article discusses the relevance, for the geotechnical evaluation, of the study and determination, by means of field tests, of in situ stresses acting on a rock mass. An overview of the origin, quality, and spatial distribution of the 42,870 data records provided in the 2016 World Stress Map technical report is presented, as well as the contribution of data records for Brazil.

KEYWORDS: World Stress Map, in situ stresses, Rock engineering, geotechnics
1 Introduction

Stress field knowledge in the earth’s crust is fundamental for the understanding of geodynamic processes, seismic hazard assessments, and stability of underground openings, such as: tunnels, mines, and wells (Fuchs and Muller, 2001). This knowledge is never excessive, especially when it comes to Rock Engineering, being of fundamental importance. Similar to the other physical properties of the rock mass, the in situ stresses can present different values when measurements are made in different volumes and spatial locations, so the stress concentrations in a drift or tunnel, for example, can overcome the rock’s strength. With the evolution of more localized data and at low depths, WSM has demonstrated its usefulness as an initial investigation tool of the in situ stress state.

In situ stresses, also known as natural or virgin stresses, are stresses that exist in the rock mass before any human interference there. The in situ stress state is controlled by the current conditions of the rock mass and by the past geological processes associated with it; and over geological time, fluctuations in the in situ stress state of a rock mass may occur, which may be related to several factors, such as physical-chemical processes (e.g., precipitation, recrystallization of minerals) and mechanical processes (e.g., movement of tectonic plates).

The first methods used to determine in situ stresses come from the 1930s and 1940s through methodologies addressing the study of surface stress relief, and over the last few decades, techniques for measuring in situ stresses have been evolving significantly. In 1950, the flat jack method appeared, in the 50s and 60s, the overdrilling methods emerged and, later, in the 70s, hydraulic fracturing method. Due to the emergence of different methodologies, it is currently possible to determine in situ stress values at depths of 3 to 4 km, and in specific cases, stress measurements can reach 9 km in depth using the hydraulic fracturing method (Amadei & Stephansson, 1997).

In civil and mining engineering, in situ stresses control the distribution and magnitude of stresses around underground openings, such as: tunnels, mines, wells or caves (Hoek & Brown, 1980). In this way, the distribution and magnitude of in situ stresses directly influence the geometry, shape, dimensioning, orientation, and sequencing of an underground excavation. Thus, the study of the in situ stress state of a rock mass is extremely relevant for the evaluation of problems and aspects related to rock excavation projects (Amadei & Stephansson, 1997).

Knowing the importance of knowledge of the in situ stress state and that, in general, in Brazil, not all projects carry out these studies, the present work is directed towards promoting this investigation of the in situ stress state, addressing the relevance from measuring in situ stresses, presenting the WSM as an initial research tool, as well as highlighting that it is always essential to carry out field tests for final confirmation of in situ stress data to be used in engineering projects.

2 Relevance of in situ stress measurement in Rock Engineering

The study of the in situ stress state, as well as other properties of a rock mass (deformability, strength, and permeability), is necessary to estimate responses to disturbances related to the development of rock excavation projects. Similarly, to the specific physical properties of a rock mass, in situ stresses can vary from point to point and present different values when measurements are made at different volumes and spatial location. As previously mentioned, the stress concentrations in an underground drift, for example, can be large enough to overcome the rock resistance, mobilizing blocks around the drift. In situ stresses are rarely uniform and their distribution depends on the structures of the rock mass (discontinuities, heterogeneities, foldings, faults, dikes, etc.) and the loads applied under the mass throughout its geological history.

Detailed studies of rock mass in situ stresses are being developed in several mines in the world, mainly studies that involve the investigation of places for permanent disposal of radioactive waste in plutonic rocks. Atomic Energy of Canada Limited (AECL), for example, has developed a study program on the state of in situ
stress state through the Underground Research Laboratory (URL). Another example can be seen in regulation 10CFR of the US Nuclear Regulatory Commission (U.S.NRC) which requires the determination of the in situ stress state before and during the construction of a geological repository for disposal of high-level radioactive waste in the United States.

The methods for determining in situ stresses employ the principle of collecting information from the response to a controlled disturbance. In order to determine the in situ stresses, adequate planning must be taken, that considers factors that may influence the results, such as openings from nearby excavations. Detailed information on how to carry out an adequate planning is described by Armelim (2010) who addresses, among other aspects, clear identification of the objectives, geology of the area, technical team trained in measurement methodologies, adequate equipment, etc.

According to Hudson et al. (2003) before the commencement of the tests of determination of in situ stresses, an assessment of the existing information and geological evidence must be carried out previously, such as (i) knowing and understanding the data present in the WSM, (ii) carrying out preliminary geological investigation, observing the specific geological structures of the site under analysis, (iii) carrying out a bibliographic survey, among other procedures.

In open pit mining projects, studies on determining the in situ stress state are generally considered of less importance and influence on the geotechnical assessment of the rock mass. This approach may be suitable for small mines, but it can be questioned for large mines (Hustrulid et al., 2001), where aspects such as concentrations of induced stresses become relevant for the adequate characterization and assessment of the rock mass. This approach of little relevance on the part of some professionals is related to the fact that the levels of uncertainties associated with the determination of the properties of the rock mass and the hydrogeological conditions can interfere in any alteration associated to the variations of the in situ stress state (Read and Stacey, 2010). Additionally, it is assumed that the in situ stresses do not directly influence the stability of the slopes, since the rupture process would be controlled primarily by gravitational forces and by the properties and characteristics of the rock mass (discontinuities, foliation, etc.).

In Brazil, the first tests to determine in situ stresses were carried out in hydroelectric power plant projects, such as the Paulo Afonso HPP, Capivari Cachoeira HPP, and Ilha Solteira HPP. According to Nieble and Kanji (2006), several tunnels built at the Ita HPP showed phenomena of rock plastification or relaxation on the drifts’ roof and, following stress status studies carried out at the site, the rock mass that was classified in the Q System with values of 1.0 for the SRF (Stress Reduction Factor), was reevaluated and reclassified to values between 2.5 and 25. The studies carried out proved that there was a concentration of high residual stresses with magnitudes of the order of 30 MPa (N-S) and 5 MPa (E-W), demonstrating the importance of studying the stresses state for the proper assessment of the rock mass.

3 The World Stress Map Project – WSM

The main objective of the WSM project (Figure 1) is to provide a global compilation of in situ stress records in the earth’s crust originating from various measurement methods and classified into five categories of data qualities (A, B, C, D, and E), with category A indicating the most reliable data and category E the least one.
Figure 1. World Stress Map 2016. Data records for categories A, B and C (Heidbach et al., 2016). The lines show the orientation of the maximum horizontal stress ($S_{Hmax}$) and the symbols indicate the measurement methods. The colors indicate the stress regimes: red = normal faulting (NF), green = strike-slip faulting (SS), blue = thrust faulting (TF) and black = unknown (U). Adapted from WSM Technical Report 16-01 and available at: http://doi.org/10.5880/WSM.2016.001.

The WSM project started in 1986 under the auspices of the International Lithosphere Program - ILP, led by Mary-lou Zoback, as a global cooperative effort by universities, the industrial sector and various government organizations, with the aim of understanding the origins and stress states in the earth's crust (Heidbach and Hohne, 2008). From 1995 to 2008, there was a project of the Heidelberg Academy of Science and Humanities of the Institute of Geophysics of the University of Karlsruhe (Germany), under the coordination of Karl Fuchs and Friedemann Wenzel, and since 2009 it has been maintained by the German Research Center for Geosciences in Potsdam in Germany. The first version of the WSM contained 3,574 data (Zoback et al., 1989), the second with approximately 7,300 data (Zoback, 1992) and the most recent version was published in 2016 with 42,870 data (Heidbach et al., 2016).

At the beginning of the WSM project, the work was oriented towards the investigation of stresses on a large scale, specifically in the field of tectonic plates. With the significant increase in data over the years, the project's philosophy has changed to a compilation of oriented data, leading researchers to conclude, for example, that (i) in large interior regions of many tectonic plates, the horizontal stress fields are uniform and consistently oriented, as in eastern North America and Western Europe, and (ii) most intraplate regions are dominated by compressive stress fields in which one or both horizontal stresses are greater than the vertical stress (Zang et al., 2012).

WSM data come from different measurement techniques and are available in a standardized format to be comparable around the world (Heidbach et al., 2007; Sperner et al., 2003; Zoback et al., 1989; Zoback, 1992; Zoback and Zoback, 1991).
3.1 Types of data

WSM’s data is grouped into four main groups: 1) earthquake focal mechanisms; 2) Well bore breakouts and Drilling-Induced Fractures (DIF); 3) in situ stress measurements (overcoring, hydraulic fracturing, etc.); and 4) analysis of young geologic data (from fault-slip analysis and volcanic vent alignment). It is noted that the information on stresses comes from different techniques that involve a variation of 10^3 to 10^9 m^3 of rock volume (Ljunggren et al., 2003).

3.2 Data Quality Classification

In situ stress data records receive a quality rating between categories A and E. Data associated with category A means that the \( S_{\text{Hmax}} \) orientation is accurate within ± 15° range, category B data within ± 20°, category C within ± 25°, category D within ± 40°. For most stress measurement methods, these categories are defined using \( S_{\text{Hmax}} \)’s standard deviation. Data classified in category E do not provide enough information or have a standard deviation greater than 40°. In general, data categorized between A and C are considered reliable for use in analysis of regional stresses and interpretations of geodynamic processes (Heidbach and Hohne, 2008).

3.3 Database Access

All information in WSM’s database is standardized and available, for free, on the internet (https://doi.org/10.5880/WSM.2016.002). Each stress data record contains, at least, the following information: \( S_{\text{Hmax}} \) orientation, quality classification, measurement method, geographic location, average depth of measurements, stress regime and reference data publication.

4 World Stress Map 2016

The most up to date WSM publication is from September 2016. Altogether there are 42,870 stress data records from various regions of the world (Australia, Canada, China, USA, Italy, among others), with 76% of the data belonging to categories A, B and C (n = 32,465), and 86% of the data in these three categories being determined through earthquake records. About 11% of data from categories A - C do not present information about the active tectonic regime (Figure 2).

Figure 2. Statistics of the WSM 2016 database. a) Percentage distribution of the 42,870-recorded stress data. Of these, 76% are classified in categories A - C (n = 32,465), with the \( S_{\text{Hmax}} \)’s orientation varying within ± 25° range. b) Distribution of data from categories A - C by methodology used: earthquakes (focal mechanisms), BB / DIF (Borehole Breakouts and Drilling Induced Fracture), HF / OC (Hydraulic Fracturing and Overcoring) and GF / VA (Geological Faults and Volcanic Alignment). c) Distribution of data from categories A - C by tectonic regime.

From the results shown in figure 2b) one can verify that a dominant portion (86%) of data comes from the analysis of records collected from earthquakes, which in turn has a depth distribution of up
to about 40 km (Figure 3a). At depths of up to 5 km, methodologies involving drilling-induced fractures (DIF), borehole breakouts (BB), in situ stress measurements (hydraulic fracturing (HF), overcoring (OC)) and geological fault analysis (GF) and volcanic alignment (VA) are prevalent (Figure 3b). Depths greater than 6 km, data records are predominantly from earthquakes, except for very rare oil industry projects.

Figure 3. Statistics of data from categories A - C (n = 32,465). a) with data (n = 27,896) and b) without data from earthquake analysis (n = 4,569) at different depths.

According to the WSM 2016 data, of the 32,465 records classified in categories A - C, 62% (n = 20125) are records from the oceanic crust. Figure 4 shows that the data coming from the continental crust (n = 12,340) originate mainly from the countries of Oceania, North America and Europe, with emphasis on China (n = 1,624; 13.2%), USA (n = 1,588; 12.9%) and Italy (n = 772; 6.3%).

Figure 4. Category A - C data records by countries, except for data from the oceanic crust.

Brazil contributes with 101 records of categories A - C, which represents 0.8% of the 12,340 data from countries, 66% of which were recorded through small earthquakes. In category A, there are only 7 recorded data, all obtained through the Borehole Breakouts (BB) methodology, 16 category B data and 78 in category C (Figure 5), these being obtained mainly through earthquake records. It is noted that the contribution of data from Brazil to the WSM is still incipient, considering that the country has a strong mineral and oil industry. In comparison, Figure 5 shows the quality data A - C from Germany, which has 282 records, 55 (19%) of category A, 70 (25%) of category B and 157 (56%) of category C.
5 Final Considerations

In the initial stage of a project to determine the in situ stress state for a given area, consulting the WSM database is appropriate, as well as carrying out a preliminary geological investigation, bibliographic survey, among other procedures. The detailed map of the stresses recorded in the study area can be generated from an online tool called CASMO (Create A Stress Map Online) on the WSM project website.

As seen, the contribution of data from Brazil to the WSM is still incipient, considering the various research papers already published on studies of orientations and magnitudes of the principal in situ stresses, such as, for example, the studies carried out in the Potiguar Basin (Reis et al., 2013; Assumpção et al., 1985; Ferreira et al., 1998; Lima Neto et al., 2010).

Studies using the WSM database have shown that the high density of stress records in a given area allows for better investigation of regional stress variations, producing greater knowledge of the principal stress orientations (Rajabi, et al., 2017).

It is widely known that the variability in the orientation of the maximum horizontal stress ($S_{Hmax}$) is significantly high (Zang, et al., 2012) at depths of up to 6 km, and that in situ stresses in a given area may vary due to topography and presence of geological structures, such as: joints, stratification, dikes, shafts, etc. Therefore, the estimation of the in situ stress state must consider these local aspects; and it is essential to carry out field tests for the final confirmation of the stress data that will be used in Rock Engineering projects.

REFERÊNCIAS BIBLIOGRÁFICAS


