LESSONS FROM BRAZILIAN UNDERGROUND STRUCTURES EXCAVATED IN ROCK BY CONVENTIONAL TUNNELLING

André P. ASSIS, *UnB / EPFL / ITA, Brasília, Brazil, aassis@unb.br*

This paper presents lessons from some Brazilian underground structures, excavated in rock by conventional tunnelling, in the last 10 years. These underground structures are part of hydroelectric and mining projects, which are two of the most important economic activities in Brazil. In order to illustrate the enormous demand of these activities in the near future in Brazil, it is worth to mention that the energy needs grow 4 to 5% per year, which means 4000 to 5000 MW of new energy source every year. Most of this energy in Brazil comes from hydroelectric sources, considering the tradition, availability of river and land, and most important, the competitive price of this source compared to the other ones. Also the mining sector grows, even more, 8% per year, and it is responsible for 10% of the gross national product of Brazil. Both activities are heavily dependent on underground structures excavated in rock for optimising their exploitation, with high benefit-cost ratios, and minimising environmental impacts. However it should be also mentioned that Brazil has a limited tradition and experience in rock mechanics applied to underground structures, and for this reason, some lessons learnt during the last decade are presented in this paper using case-histories from hydroelectric and mining projects.

Regarding the hydroelectric case-histories, firstly, it has to be pointed out that during the last decade there has been a shift in the traditional layout of Brazilian dams. In the 60s till 80s, the tradition layout was dominated by the geology of wide valleys, where the hydraulic circuit of the dam, built in concrete structures, was based on rock foundation nearby the river bed. More recently during the last decade, a layout more appropriate to narrow valleys has been adopted, where the hydraulic circuit is excavated underground in one of the abutments of the valley. The valley itself is close by a high and short geotechnical dam, usually made of rock fill with earth core or upstream concrete slab, as impervious barrier. This later layout usually generates smaller reservoir and the underground structures maximise the use of the potential energy, which leads to very low environmental impact index. For these reasons, it is forecasted that during the next two or three decades, numerous hydroelectric projects will be built in Brazil and a substantial part of them using underground hydraulic circuits.

Three case-histories illustrating this layout conception are presented and briefly described. The Itá Hydroelectric Power Plant (HPP) has a potential energy production of 1450 MW (operation in 2002) and its dam has 880 m of length, 125 m of height and 9.6 million m3 of volume, with a hydraulic circuit of 650,000 m3 of underground structures. The Queimado HPP has a potential energy of 105 MW (operation in 2004) and its dam has 1060 m of length, 62 m of height and 2.2 million m3 of volume, with a hydraulic circuit of 230,000 m3 of underground structures. And the Serra da Mesa HPP has a potential energy of 1275 MW (operation of 1998) and its dam has 1520 m of length, 154 m of height and 14 million m3 of volume, with a hydraulic circuit of 550,000 m3 of underground structures. In all cases, the underground structures are located between 100 and 200 m of depth.

Despite being separated from each other by hundreds or even thousands of kilometres and settled in distinct geological and geotechnical conditions, these three hydroelectric projects presented a common feature: very high in-situ stresses. In-situ stresses are one of the most important design inputs, but unfortunately the most poorly-evaluated one. The reasons for that are probably based on the fact that there is no a universal test type for determining it (type of test depends of the type and degree of fracturing of the rock mass), and all types of tests are considered expensive at the first impression. However, the lack of measuring or simply miscalculating in-situ stresses by simplified formulation can cause considerably more negative financial consequences to the project.

The Serra da Mesa case-history is presented in more details including how the in-situ stresses were evaluated at different stages of the project (design and construction), using different techniques (hydraulic fracturing - HFT, small flat jacks - SFJ and stress tensor tube - STT tests). The results indicated that the in-situ horizontal stresses were the major ones, giving ko in the range of 2 to 6. Not only the magnitudes of the in-situ stress tensor were considered in the design, but also their directions, leading to a re-orientation of the main underground structures, minimising support needs and avoiding eventual failures (Melo Franco et al., 1997). The other two sites also presented very high in-situ horizontal stresses, Queimado in the range of 2 to 3 and Itá in the range of 6 to 9. More details about their determination can be found in Hidalgo et al. (2004) and Mafra (2001), respectively.

Another lesson from these case histories and other shafts for mining activities is the effects of the dependence between rock deformability and stress state. Despite being a well-known issue and commonly considered in petroleum engineering, the state-of-the-practice in civil and mining applications is still to consider a constant modulus around the opening. However in cases of deeper and deeper underground opening and not strong rock masses, at least the dependence of rock deformability parameters and confining stresses is much expected. It is presented a case study where in a distance of 2 to 3 diameters from the opening, the modulus of the rock differs by a factor of 10 from that found in the vicinities of the opening wall (unsupported during construction). The results highlight the effects of such dependence: first, the modulus distribution around the opening depends on the in-situ stress state; second, as stress distribution is dependent on the material stiffness, the induced stresses by the opening are highly affected by the modulus distribution and quite differ from those when a constant modulus is adopted; finally, all consequences of the stress field are affected such as the displacement field and existence or not, and size of failure zones. More details can be found in Lionco & Assis (2000).

The last lesson presented is related to the characterisation and modelling of rock masses and was demanded from some very deep mining open pits, which are presently studying the feasibility to shift to underground exploitation. The characterisation and modelling of rock masses can be done by direct or indirect approach. The first one attempts to measure directly the properties of the intact rock and discontinuities of the rock mass, and finally simulates the rock media considering the spatial orientation and characteristics of the discontinuities. The indirect approach is based on empirical methods that attempt to consider the experience of previously excavations in rock. It treats the rock mass as an equivalent media, also considering the discontinuity characteristics. As point out both approaches are heavily dependent on the mapping of the discontinuities. However, it has to be recognised that this mapping is limited to sampling windows and moreover the discontinuity parameters are not constant, presenting a natural variability. These main difficulties, how to deal with statistical variables and how to extrapolate sampling-window variables to the whole rock mass, have led to a probabilistic approach for modelling three-dimensionally the rock mass, as proposed by Lauro & Assis (2002).

The main steps of this methodology are: first, measurements of rock mass characterisation, such as discontinuity orientation, spacing, length, roughness, aperture, filling etc., from sampling windows; second, correct these measures to avoid bias from the sampling window; third, transform each measured variable to the best-fit statistical distribution; finally, using all statistical distributions, one for each rock mass variable, generate the probable rock mass, out of the sampling window, using a probabilistic method, which deals with those statistical distribution. The main result of this approach is to obtain a probable view of the rock mass in its depth or in other location, and not only a mirror forecast as it was found (seen) in the sampling window.

One mine in Brazil that presents a very deep open pit (500 m) was used to test and calibrate this methodology. Two levels of calibration were made: mapping up to 200 m of depth and then forecasting to the level of 400 to 500 m of depth; and also forecasting the rock mass around three galleries excavated in the same level (200 m of depth), but 70 m inside the rock mass. The results demonstrated the enormous potential of this technique, not in terms to determine the absolute location of a certain rock mass quality, but to determine the amount of sessions with a certain rock mass quality. Also, it was found that the model can be calibrated step-by-step according to the evolution of the excavation, improving more and more its forecast performance along the works.

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