A simple model for to introduce the rock deformability at hydraulic tunnels

Un simple modèle pour tenir en compte la déformabilité des roches dans tunnels hydrauliques

Carlos S. Oteo
Prof. on Ground Eng., Spain.

Pedro R. Sola
Ing. C. C. y P, IIT, S.L., Spain

Javier Oteo
Ing. C. C. y P., Spain

ABSTRACT: The design of tunnels excavated in rock requires geotechnical characterization of the rock mass, especially medium deformability. In the case of pressurized hydraulic tunnels, this problem is very important, since the rock has to work under pressure and deformability efforts influences the final tunnel lining.

In this paper a simple model to account for this influence of deformability (with analysis of finite element codes 2D), defining a ring around the tunnel altered by construction effects is presented. The model includes how to estimate the ground deformation moduli most and least altered, from the RMR index Bieniawski, for values inferiors to the rocks of medium to high quality. (RMR ≤ 40). This model is based on the interpretation of actual measurements in tunnels bored in shale and limestone formations.

RÉSUMÉ : La conception des tunnels creusés roches nécessite caractérisation géotechnique du milieu general de la roche, avec la considération particulier de la déformabilité moyenne. Dans le cas des tunnels hydrauliques sous pression, ce problème est très important, car la roche doit travailler sous les efforts de pression et le déformabilité on avait à spécial influence sur de revêtement finale du tunnel.

Dans cette communication on présent un modèle simple à prendre en compte l'influence de la déformabilité (avec analyse des codes d'éléments finis 2D), définissant une couronne autour du tunnel modifié par la influence de la construction est présenté (influence des explosives). Le modèle comprend comment estimer la masse des modules de déformation plus ou moins modifiés, dépendant de l'indice RMR de Bieniawski, pour des valeurs inférieures aux roches de moyenne à haute qualité. (TMR ≤ 40). Ce modèle est basé sur l'interprétation des mesures réelles dans les tunnels creuses en schistes et en granites.

KEYWORDS: Hydraulic tunnels, rock deformability

1 INTRODUCTION

The design of hydraulic tunnels excavated in a rocky medium implies:

- An adequate geomechanical characterisation, in the different stretches of geotechnical behaviour that may be distinguished throughout the tunnel.
- A special definition of the deformational properties, as in this case it is due to hydraulic pressure (that may vary between a few and twenty bars) against the tunnel lining and this against the rock.
- A differentiation in the deformational behaviour according to the distance from the point considered in the rock mass at the edge of the excavation. This differentiation is due, on one hand, to the construction procedure and, on the other to the fractured state of the rock.
- Study the problem of possible hydraulic fracturing, to which attention is not paid in this paper.

The effect of the construction process has a clear influence on the final deformability of the rock. If the tunnel is excavated with explosives, a "crown" or "ring" is usually created around the tunnel, of more deformable material around the tunnel, as the blasting causes a certain opening of the diaclases and a loss of resistance to cutting in these in the area nearest to the tunnel (Figure 1). In that case one might use a bi-dimensional model to define the deformational state of the rock, with a more decompressed and deformable ring around the tunnel (with width B*, that need not be equal at the crown to the sidewalls), the rest of the mass having a more usual deformability to the original.

In the case of excavating with full section tunnel boring machines, the mass is less altered (although some decompression takes place), so the more deformable "crown" then has a thickness B** that is fairly lower than B*, to the point that, in good quality rocks, that might amount to B**≈0. It might even be expressed as follows:

- Good quality rocks (RMR>60): 0-0.2 B*
- Medium quality rocks (45<RMR<60):B**≈(0.3-0.6)B*
- Low quality rocks (RMR<35): B**≈(0.7-0.8)B*

The aim in this notification is:

- To establish a 2D model of the deformability in the rock around a hydraulic tunnel, defining the crown aforementioned.
- To establish the deformation modulus of the "crown" or "ring" zone and the rest of the rock mass, when the quality of the rock is medium to low (RMR<40).
- To use a simple model with elastic hypothesis for to analyse the deformability of the tunnel and rock mass and to estimate the bending moments at the tunnel liner, under the pressure actuating in the tunnel inner.

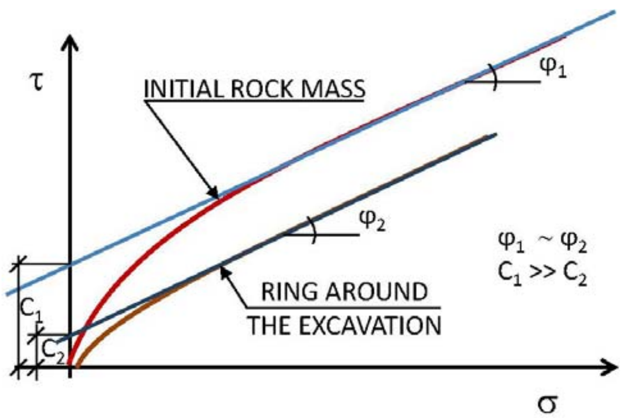

Figure 1. Possible variation of the shear strength of fractures near a tunnel bored by blasting.

2 ESTIMATION OF DEFORMABILITY OF A ROCK MASS

A series of graphs have been used for more than thirty years to estimate the apparent deformation modulus of the rock mass, E*, or field modulus. Figure 2 reproduces the well known Deere graph, that links modulus E* to that obtained from test pieces tested under simple compression in the laboratory, E_{lab}, through Deere index RQD. This parameter is usually various times larger (due to it concerning a more healthy material and with hardly any diaclase) than E*. For low RQD values (<50-60), the ratio proposed by Deere is: $E^*/E_{lab} \approx 0.15\text{-}0.20$. This correction, at that time, was very important (and this continues to be the case), as it informed the technicians of the scarce value of the determinations in the non-confined compression tests.

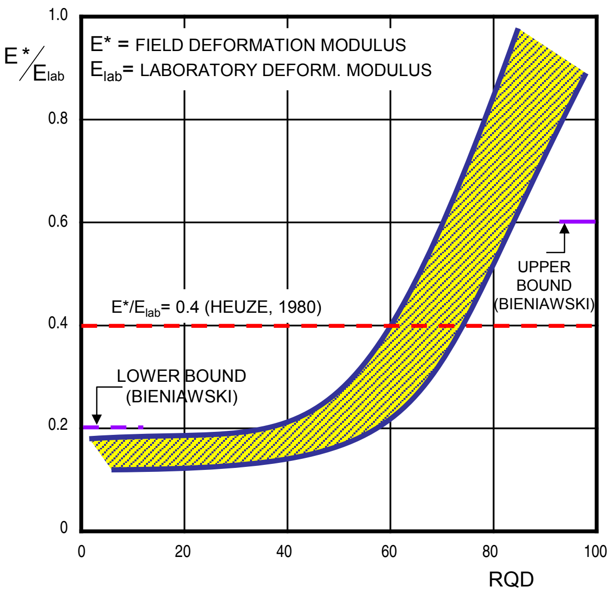

Figure 2.

Later on the Bieniawski rock quality index (1979) or RMR was taken. In Figure 3 various proposals have been grouped together to determine the apparent deformation module of the rock mass, E*, according to index RMR: a) That of Bieniawski, in 1978, with the formula proposed by him. b) That of L. Serafim and Pereira (1983), with an empirical formula also proposed by those authors. c) That subsequently proposed by Hoek and Brown, in 1997, according to resistance to simple compression.

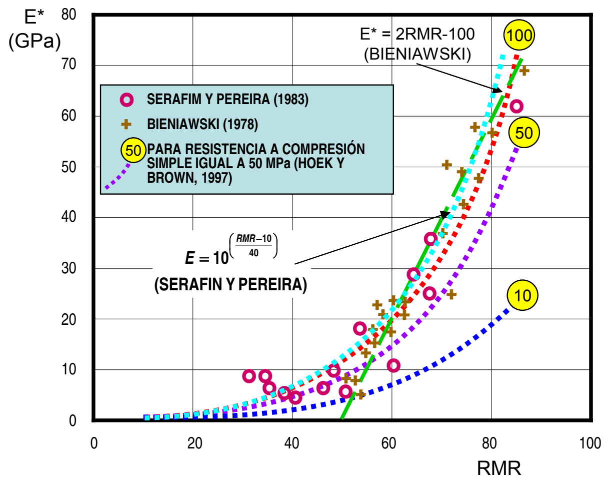

Figure 3. Correlationship between the RMR index and the bulk deformation modulus

That graph and formulations are based on a series of average vus measured in the field by Bieniawski (1978) and by Serafim & Pereira (1983), so it appears that the adjustment between theories and real measurements is fairly good. However, one must point out that:

- It is not very clear that the real values are comparable, as they correspond to different types of rocks (granites, schist, etc.).
- Practically all the field values are for medium to very quality high rocks, with an RMR index above 40.
- The few real values of RMR<40 clearly go beyond the theoretical lines.
- The field values generally correspond, in the case of foundations of gravity dams, to zones to be worked under compression, thus their high quality, with high RMR values.

However, in works in hydraulic and railway tunnels, etc., it is more normal to find rocky foundations with a lower RMR index. For example, in various tunnels (Bolaños, El Espiño, etc.) on the Zamora-Orense High Speed Railway Line (Spain) excavation has been performed in shale materials in Galicia (Spain) with RMR values from 30 to 40, magnitudes that dropped to 16-25 in the case of laminated shale with ampelite. In this case the fracturing was of a very high degree and the “rock mass” even behaved practically like a soil with scarce cohesion. In some cases of excavation with a tunnel boring machine in such materials, there has been over-excavation of up to 300% and, in others, using conventional excavation (NATM, with explosives) there have been convergences of up to 300-400 mm over ten to fifteen months, to the point that, in order to avoid so much deformation, on reaching 80 mm of horizontal convergence, the section was reinforced using buttresses with self-drilling bolts at a slope (from sidewalls and cut face).

In other problem materials, such as karstified limestone, it is easy to find relatively healthy areas (RMR≥50-60) altered by others that are more fractured, or affected by karstic phenomena (caves, galleries, etc.), with an RMR of about 25 to 40. Tunnels have been executed in such materials in Spain and Central America.

With these materials, using graphs such as those in Figure 3, in order to estimate the value of the apparent or field deformation modulus, E*, it is highly difficult and subject to a very strong variation, as such graphics are not considered for low and medium RMR. In fact, the recommendation by Bieniawski is a linear relation between E* and RMR (Figure 3), that begins its validity at RMR=50. And the field reference measurement points all correspond to RMR values above

30-35. It is difficult to estimate E* using these recommendations under RMR=35.

In Figure 4 we have represented a series of values of E*, for shale and karstified limestone materials, obtained from the interpretation (back-analysis) of the convergence measurements in diverse tunnels excavated in Galicia and Andalucia (Spain) and in Guatemala (OTEO, 2015), as well as some "laws" apparently defined by the points (E*-RMR) thus obtained. The karstified limestone are of the massive kind with caves of Ø 2-4 m. The mass rock is continous in the zone of the RMR determination.

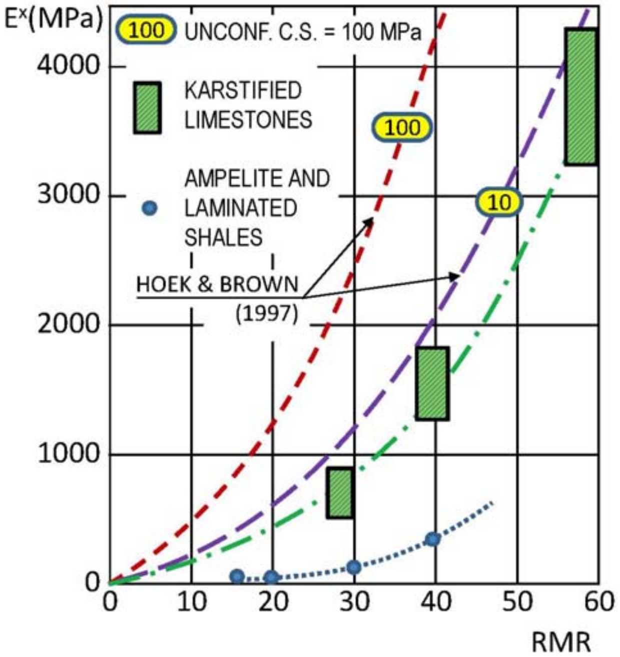

Figure 4. Variation of E* in limestones and laminated shales, compared with Hoek & Brown recommendations

As may be seen in that Figure 4, the variation laws are of the exponential type, such as those of Bieniawski and other authors in Figure 3. However, if they are compared with those recommended by Hoek & Brown (1997), better defined for medium and low RMR values, the laws are clearly lie below those recommendations. Both in the case of laminated shales and karstified limestone, this is much below the recommendation by Hoek & Brown for simple compression resistances of 10 MPa.

Based on these results and the recomendations by the authors already stated, we have prepared Figure 5 that represents a possible variation of E* with an RMR index, for different types of rocks: massive rock with high strength, massive rock with medium strength and very fracturated rock. These graphs may be complemented with the information from Figure 2, for practical purposes in the named materials.

3 THE CASE OF HYDRAULIC TUNNELS

Although when designing any subterranean work, it is highly convenient to estimate the deformability of the ground around the excavation (this is essential to analyse finite differences and finite elements using numerical codes), in the case of hydraulic tunnels with water pressure, it is essential. Indeed, it not only suffices to build the tunnel, that may have a horseshoe section, and to design its support using the Bieniawski recommendations (for example). In the case of pressure galleries, one must design a lining with the most circular intrados possible and take the deformability of the ground into account.

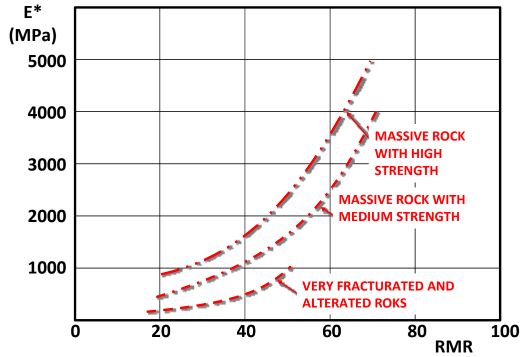

Figure 5. Possible variation of E* as a function of RMR index (OTEO, 2015)

To these ends, in tunnels excavated using conventional methods and use of explosives - such as those we have already stated – the existence of a more decompressed "crown" or "ring" is usually introduced, with more open fractures; thus that is more deformable.

That is to say, one may consider a simplified 2D model such as that in Figure 6, in which the existence of a decompressed ring with an apparent deformation module E** has been distinguished. That ring or crown has meant that it has a constant thickness, B*, to simplify, although it might be considered variable throughout the tunnel (1.5B* at the crown, B* on sidewalls and 0.7B* on the invert).

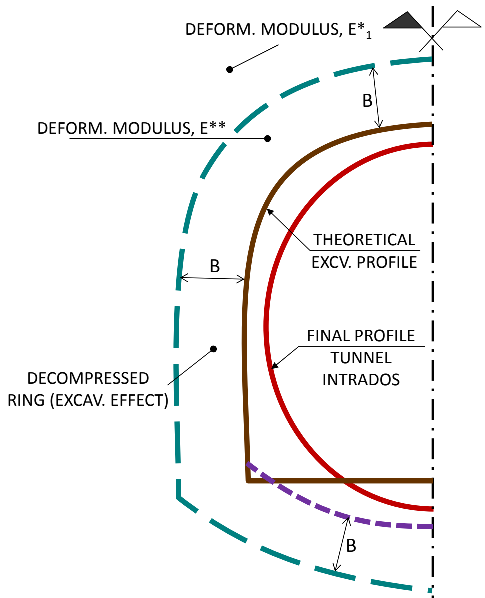

Figure 6. 2D Schematic model of rock deformation around hydraulic tunnels

In order to determine the value of B*, the geometric conditions of Figure 6 have been supposed, with the supposition that the reinforced concrete lining has a minimum thickness of 30 cm (and reaching 50 cm at the points under the and above the sidewalls), with an excavation height between 3 and 4 m. Based on these conditions, the thickness of the plastified "rock" (Mohr-Coulomb criteria) around the tunnel has been calculated, obtaining the result included in Figure 7. The initial deformation modulus of the ground are those obtained using the results in Figure 5 for the case of massive rocks with high strength, supposing a Mohr-Coulomb model, with cohesion and friction obtained on the basis of RMR and the recommendations by Oteo (2005).

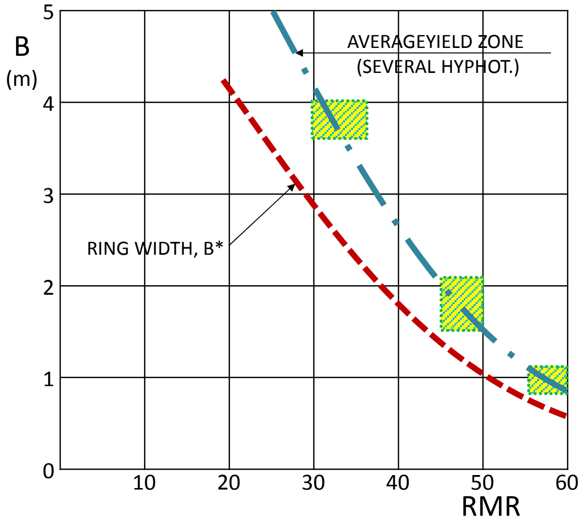

Figure 7. Width of the decompressed ring

Given the dispersion (not large) of the results, we have aimed to simplify the result, with an average valuation of B*, taking into account that the decompression will be greater the nearer the land is to the contour of the tunnel excavated, so a similar curve has been defined to the theoretical one obtained by deduction. This curve, that provides the values of B* is also recommendable for inclusion in Figure 7.

Figure 8 completes this simplified model, as it represents the variation of E* adopted for this analysis (that of Figure 5, for massive rocks with high strength) and the value of E** or average deformation moduli of the decompressed ring zone, deduced from the elasto-plastic analysis mentioned.

That is: E** ≈0.58 E*, so we consider this result may be extrapolated to other less resistant types of rocks.

That is, one may estimate the deformability of the rocky medium using the data from Figure 5, for average-low RMR values, determine the thickness of the decompressed ring with Figure 7 and deduct E** with the above expression.

4 CONCLUSIONS

The following conclusions may be extracted from the foregoing:

- In the case of low values of the Bieniawski RMR index, it is difficult to estimate the apparent deformability of rock, E*.
- The representation shows the results obtained from interpretation of the convergence measures in tunnels in laminated shale and karstified limestone. This allows one to obtain the ratio E*-RMR for low RMR values.
- A simplified model has been represented for the case of hydraulic tunnels, with a more decompressed ring of ground around the tunnel, with width B* and deformation modulus E**.
- An elasto-plastic numerical analysis has been carried out to evaluate B* and E**, in simplified form.
- These conclusions are not totally generals. These are referred only to the named materials (laminated shales and karstified limestone) and can be used as a empirical propose.

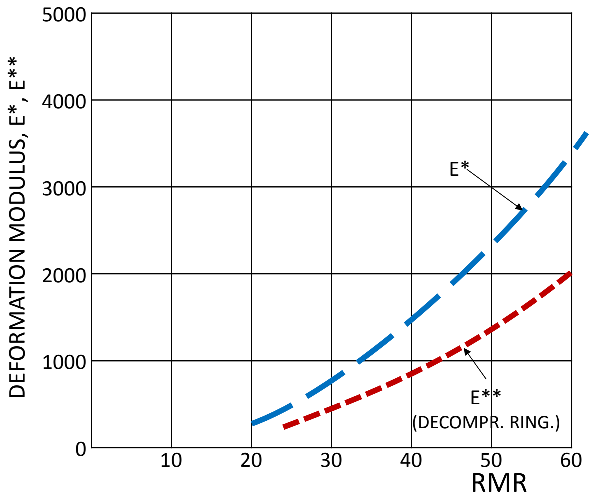

Figure 8. Recommended deformation moduli

5 ACKNOWLEDGEMENTS

The authors wish to thank diverse organizations for their permission to use some data included here (ADIF, COBRA, Directorate General of Highways of Spain), as well as the Engineer Rafael Salado of EIS-GUÍA, for his collaboration in performing diverse numerical analyses.

6 REFERENCES

Bieniawski, Z. T. (1979). “The geomechanics classification in rock eng. Applications”. 4 Int. Congress on Rock. Mech.. Montreux. Vol. 2, pp. 41-48

Oteo, C. (2005). “Geotecnia, auscultación y modelos geomecánicos en los túneles ferroviarios de Guadarrama”. Chap. Of the Book *"Túneles de Guadarrama"* (pp. 189-220). Madrid: Ed. Entorno Gráfico.

Oteo, C. (2015). *“Quince lecciones y un epílogo sobre Geotecnia de Obras Subterráneas”.* Madrid: Asociación Técnica de Carreteras.

Serafim, J. L., & Pereira, J. P. (1983). “Considerations of the geomechamical classification of Bieniawski”. Proc. Int. Symp. On Eng. Geol. And Underground Construction. Lisboa.

Hoek, E., & Brown, E. T. (1997). *“Practical estimates of rock mass strength”.* International Journal of Rock Mechanics and Mining Sciences, 34(8), 1165-1186.