How tunnel boundary irregularities can influence the stresses in a shotcrete lining

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The shape of a tunnel boundary excavated by drill & blast in fractured rock masses is influenced by geological conditions and blasting operations. The overbreaks, apart from influencing the construction times and costs, also have an important influence on the stresses acting in the shotcrete lining, particularly when it is used as the final lining.
These effects have been analyzed, on the basis of a parametric numerical analysis, and the results have shown that if the boundary shape is more irregular there are traction stresses. These tractions are not evident if a regular shape of the boundary is considered in the numerical model

Influenza della forma del profilo di una galleria sugli sforzi agenti in un rivestimento in calcestruzzo proiettato. *La forma e la rugosità del perimetro di una galleria scavata con il metodo convenzionale con uso di esplosivo in un ammasso roccioso fratturato è influenzato dalle condizioni geologiche e dalla qualità delle operazioni di abbattimento. I sovraprofili, oltre ad influenzare i tempi ed i costi di costruzione, hanno però anche un effetto non trascurabile sugli sforzi agenti nei rivestimenti delle gallerie.*
Questo effetto, usualmente trascurato nella progettazione, è però rilevante qualora si voglia utilizzare il rivestimento in calcestruzzo proiettato come rivestimento definitivo della galleria.
Nell'articolo questi effetti sono stati studiati mediante un'analisi parametrica che ha messo in luce come al crescere dell'irregolarità della superficie della roccia crescano sforzi di trazione sul rivestimento in calcestruzzo che non sono calcolati né evidenziati qualora si esegua una modellazione nel quale il rivestimento è considerato di spessore costante.

Influence de la forme du tunnel sur les efforts dans un revetement de beton ejecte. *La forme et la rugosité du périmètre d'un tunnel creusé conventionnellement avec des explosifs dans un amas rocheux fracturé sont influencées par les conditions géologiques et la qualité des opérations d'abattage. Les "surprofils", en plus d'influencer les temps et les coûts de construction, ont aussi un effet non négligeable sur les efforts agissant dans les revêtements des galeries.*
Cet effet, généralement négligé dans la conception du projet, est important si vous voulez utiliser un revêtement en béton éjecté comme revêtement définitif du tunnel.
Dans cet article ces effets ont été étudiés avec une analyse paramétrique qui a montré que à l'accroissement de l'irrégularité de la surface de la roche correspond à la croissance des efforts de traction sur le revêtement en béton qui ne sont pas calculés ou mis en évidence si vous exécutez un modelage dans lequel le revêtement est considéré avec une épaisseur uniforme.

Introduction

Tunnel excavation in rock is frequently carried out by drilling and blasting, therefore the final shape of the tunnel boundary has a relatively irregular surface due to overbreaks that are mainly related to the blasting method, rock stiffness, rock joint orientation, scaling and workmanship ability.

Reduction of the overbreaks is an important task since they can cause a considerable increase in the construction costs as a larger amount of muck has to be removed, heavier scaling operations are required and a larger amount of shotcrete is needed. Furthermore, as Hoek and Brown (1980) and Son and Cording (2007) highlighted, irregularity of a tunnel excavation boundary induces high stress concentrations in the shotcrete liner, that could result in cracking and, sometimes in local collapses. Since the use of shotcrete as the final lining is becoming more frequent in tunnelling, the presence of cracks can affect the durability and impermeability of the structure with consequent relevant problems of refurbishments. Even though the consequences of this irregularly are well known, linings are usually designed under the assumption that the tunnel surface is smooth and the linings heve a constant thickness. It is therefore important for designers to have information available on the influence of these irregularities and this data can only be obtained through a parametrical analysis with different lining geometries.

Reasons for overbreaks

The level of overbreak irregularity depends on (Mancini et al., 1993; Ibarra et al., 1996; Schmitz, 2003): the geological conditions of the rock mass (i.e. strength, joint patter orientation and spacing), the quality of drilling of the blasting hole pattern (particularly along the periphery), the adequacy of the used blasting scheme, the distance between the peripheral charges and round length, distance between the installation position of the lining and the tunnel face, the scaling activity and finally on workmanship ability.

Furthermore, since the final support has a pre-defined thickness and because removing an underbreak is more expensive than filling it, tunnel constructors have a tendency to allow a large safety margin in

the blasting design thus considering larger overbreaks than those actually encountered. The thickness of overbreaks (Wahlstrom, 1973; Muller, 1978; Schmitz, 2003) usually ranges between 6-38% of the tunnel diameter with a value of 10% of the tunnel diameter for an average quality of drilling and blasting and with more than 25% in fractured rock or when the blast is badly carried out. Other global data have been reported by Schmitz (2003) who gave the following overbreak ranges: 0.05-0.10m of overbreak in a compact stable rock mass with few joints or fractured rock mass with small joint spacing, if the support is correctly selected and installed; 0.15-0.30m in fractured, unstable rock masses prone to caving and 0.5m in a compact stable rock mass with large joint spacing.

With reference to the classification proposed by Mancini at al. (1993), which is in good agreement with that of Ibarra et al. (1996), an overbreak can be (Fig. 1):

- *physiologic*, due to the divergence of the peripheral holes linked to the operative offset of the drilling machine. These overbreaks, linked to the length of the round, are unavoidable, even with perfect operational conditions and in a "perfect" geological rock mass;
- *pathologic*, due to badly carried out drilling operations. These problems do not only depend on the workers' skill and the drilling machine quality, but can also be influenced by:
- the heterogeneity of the rock mass (i.e. alternating hard and soft rock): that can deviate the drilling rod
- the charge effect of the explosive: too high an amount of explosive in the profile charges can damage the rock to a greater extent than a correct charge thus causing irregular detachments and overbreaks (Mancini and Pelizza, 1977; Singh and Xavier, 2005);

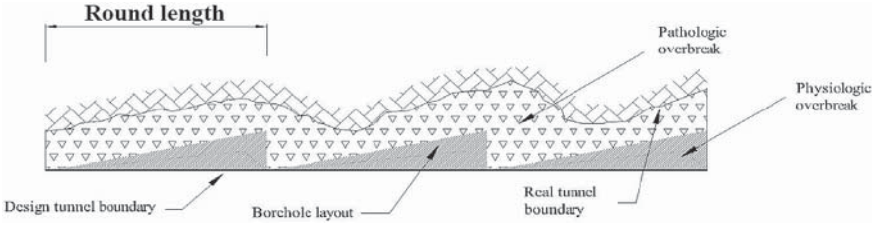

Fig. 1. Schematic representation of physiologic and pathologic overbreaks (redrawn from Mancini et al.; 1994.
Rappresentazione schematica dei sovrascavi patologici e fisiologici (ridisegnato da Mancini et al.; 1994).

- geological conditions of the rock mass: the joint pattern causes local detachments that depend on the length of the blast round but cannot be controlled by the operational procedure. The volume induced by this last cause are normally the highest between the "pathological" overbreaks.

Influence of the geology

The influence of the geological factors on overbreaks is mainly linked to the joint pattern geometry: the key blocks (Goodman and Shi, 1985), after the excavation find a new free surface and they detach towards the new void thus leading to the detachment of new rock elements. This effect is less important when the main joints have an orientation that is almost orthogonal to the tunnel advancement direction, but it is much more important when the joints are parallel to the tunnel advancement direction. The worst condition is when sub-horizontal joints or rock bedding planes and sub-vertical joints are present. Key block design analysis can be used to evaluate the geometry of these detachments, taking into account the local joint patterns and length of the blast round (Fig. 2).

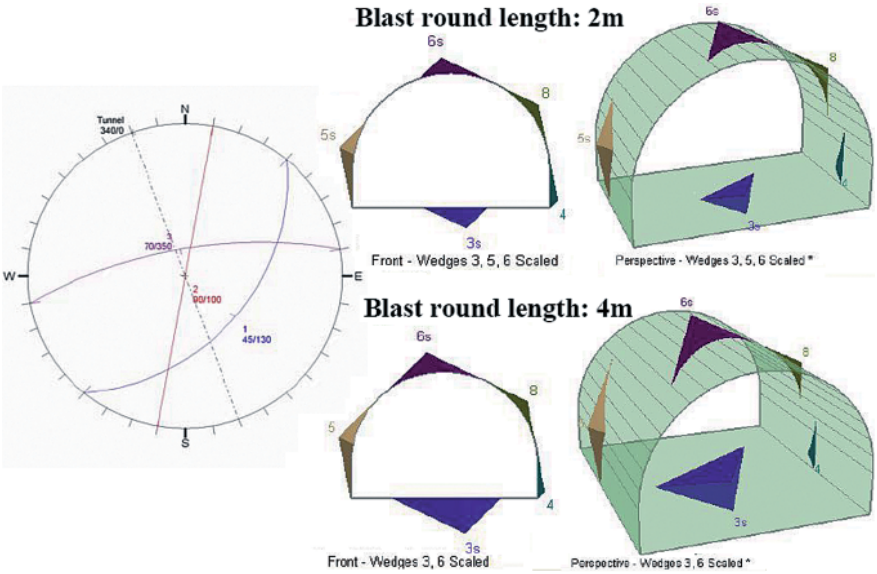

Fig. 2. Example of the evaluation of overbreak size for two different blast rounds for a road tunnel. The example highlights how an increase in the blast round induces the collapse of larger key blocks.
Esempio di valutazione dei sovrascavi per due differenti sfondi per il tunnel stradale. L'esempio evidenzia come una aumento della lunghezza dello sfondo induca il collasso di blocchi di dimensione maggiori.

Influence of blasting

The drilling accuracy, the type and quantity of charge in the holes and the blast round pattern are the key-factors in in the control of the size of overbreaks. The larger the blast round and the specific charge (quantity of explosive/blasted volume) the greater the probability of inducing a detachment and, consequently, pathological overbreaks. In addition, the design of the peripheral charges is of great importance for a reduction of the overbreaks (Wyllie and Mah, 2004; Mancini e Cardu, 2001).

Analysis of the distance between the tunnel face and the lining on the overbreaks

The distance between the tunnel face and the lining (free span), which in the drill and blast procedure corresponds to the blast round length, is unsupported for a certain time. Therefore, it must remain stable to permit the scaling, mucking and support installation to be developed, under safe conditions.

The free span and the corresponding self supporting time are linked to the rock mass properties (Bieniawski, 1988), but they directly influence the number and size of the key blocks that can detach around a tunnel, as shown in Fig. 2. Therefore, reducing this length, it is possible to minimize the number of potentially unstable elements and thus improve the final quality of the tunnel periphery. The round length cannot be reduced below a certain technical value since this reduction causes an increase in the excavation costs due to an increase in the working phases.

Tunnel design is usually based on the assumption that the tunnel shape is perfectly smooth although, as previously discussed, it is technically impossible to reduce the level of irregularity below a pre-define level. It is therefore important to investigate the behaviour of a shotcrete lining when a certain level of irregularity is present to clarify whether if this condition could be critical for the lining design.

In order to evaluate whether this parameter is relevant and to what extent, a numerical parametric study has been performed varying the irregularity (i = 0.2m and 0.4m) of the tunnel boundary for a theoretical horse-shaped tunnel (Figure 3)

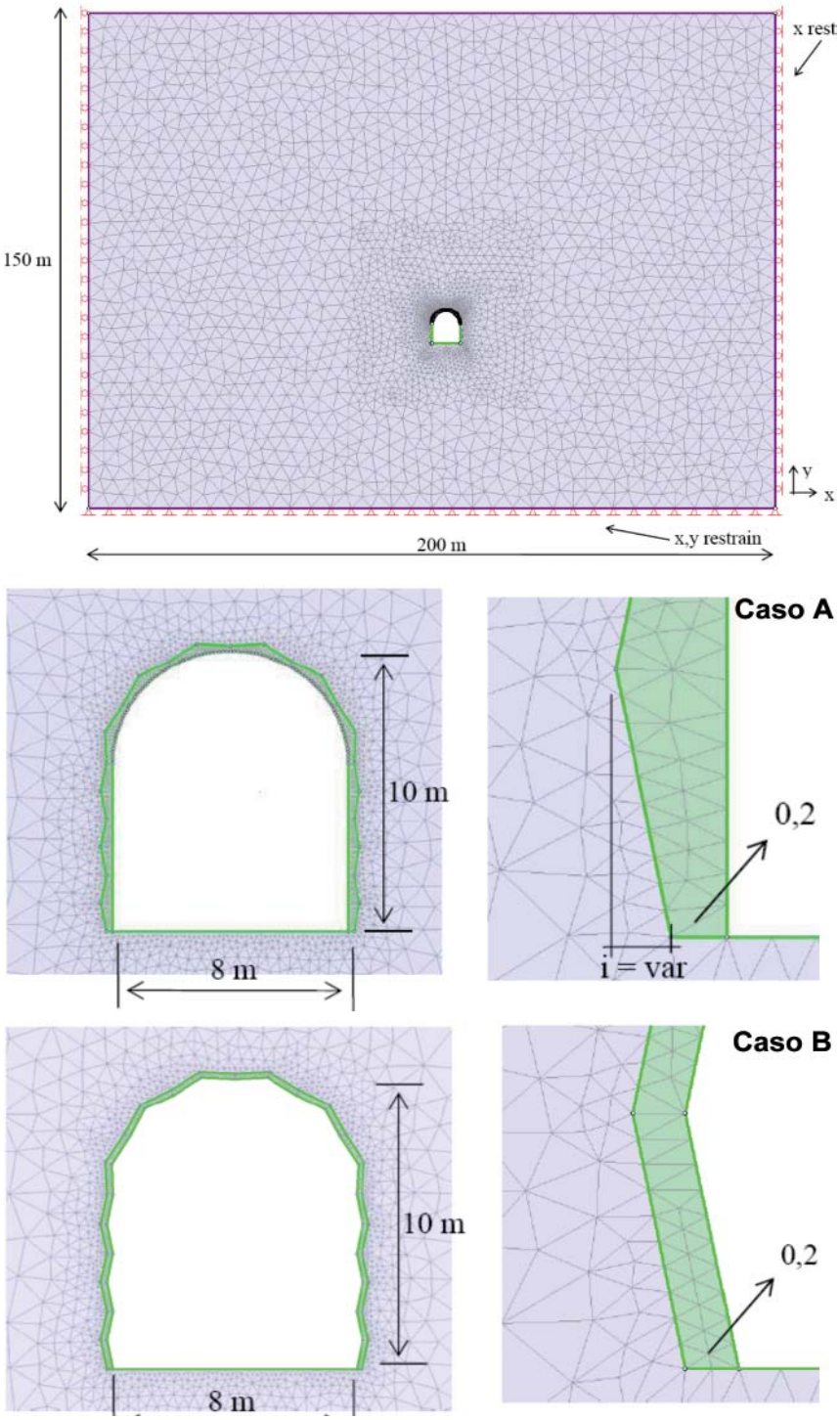

Fig. 3. Geometry of the numerical models.
Geometria del modello numerico.

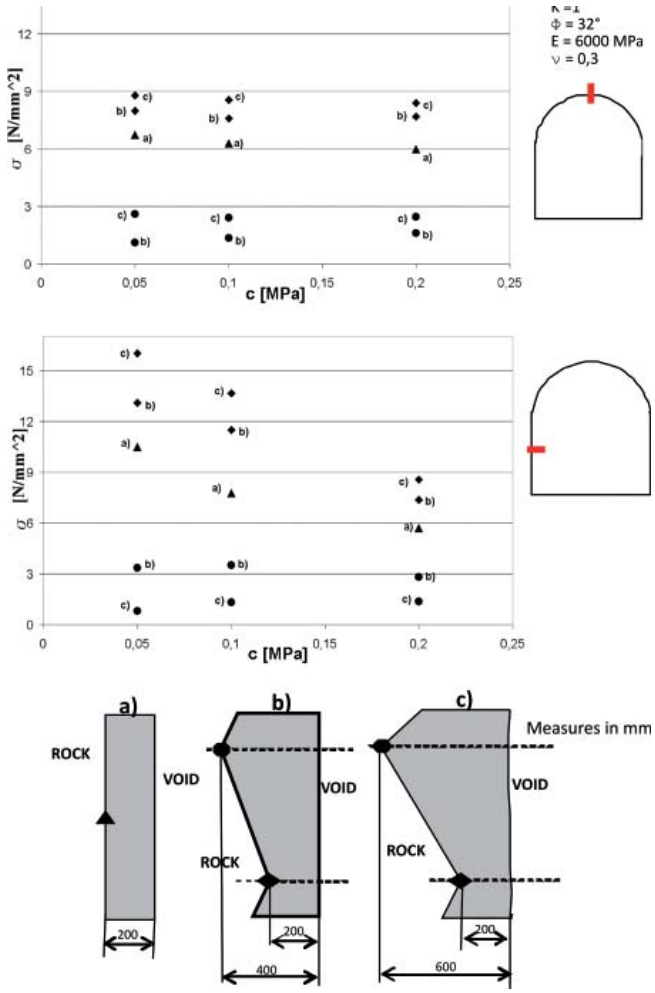

Fig. 4. Stresses computed at the estradox of the tunnel for K=1 vs cohesion of the rock mass – Case A.
Tensioni calcolate all'estradosso del tunnel per K=1 al variare della coesione della roccia – Caso A.

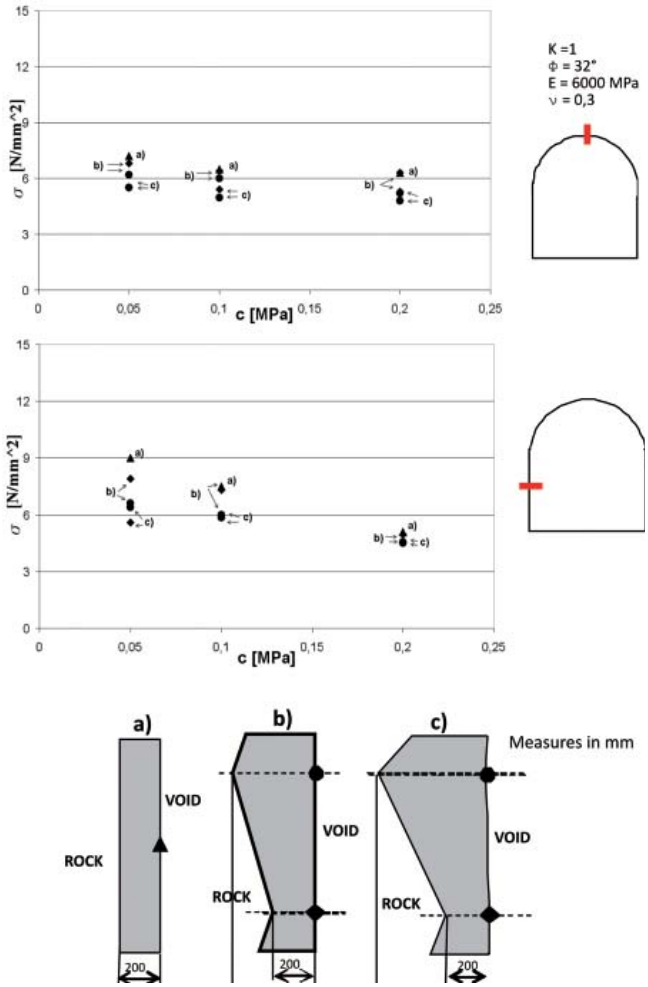

Fig. 5. Stresses computed at the intradox of the tunnel for K=1 vs cohesion of the rock mass- Case A.
Tensioni calcolate all'intradosso del tunnel per K=1 al variare della coesione della roccia – Caso A.

supported by a shotcrete lining with a 0.20m predefined thickness both with a inner shape regular (case A) and with an inner shape that follows the shape of the tunnel boundary (case B). The considered rock mass has a deformability modulus of 6000MPa, a Poisson modulus of 0.3 and a friction angle of 34°, while the cohesion has been varied in the range: 0.05-0.20MPa, that is to say a rock mass of poor or average quality.

The numerical calculation was performed with the 2D FEM Phase^{2D} code (ver. 5.0 – Rocscience, 2005) to evaluate the effect of the boundary irregularity on the lining stresses which are modelled with an elastic behaviour with E = 8000 MPa and v = 0.15 (Melbye et al., 2001; Oggeri & Peila, 1996, Alun, 2009). The tunnel face advancement was modelled by reducing the rock mass elastic modulus inside the tunnel till a value of 60% of the initial modulus was reached, then the lining was installed and the tunnel excavated.

The obtained results for the case A (Borio & Peila, 2009), summarized in figures 4 and 5, show that the stress in the thinnest portion of the lining grows at the lining extrados

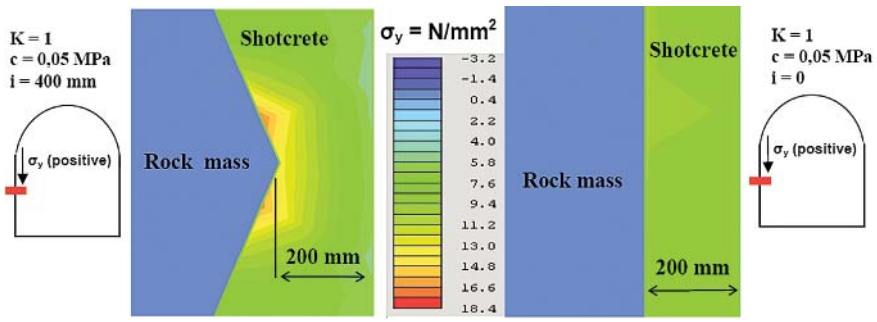

Fig. 6. Different stress concentrations for different boundary geometries (Case A).
Diverse distribuzioni di tensione per differenti geometrie al contorno (Caso A).

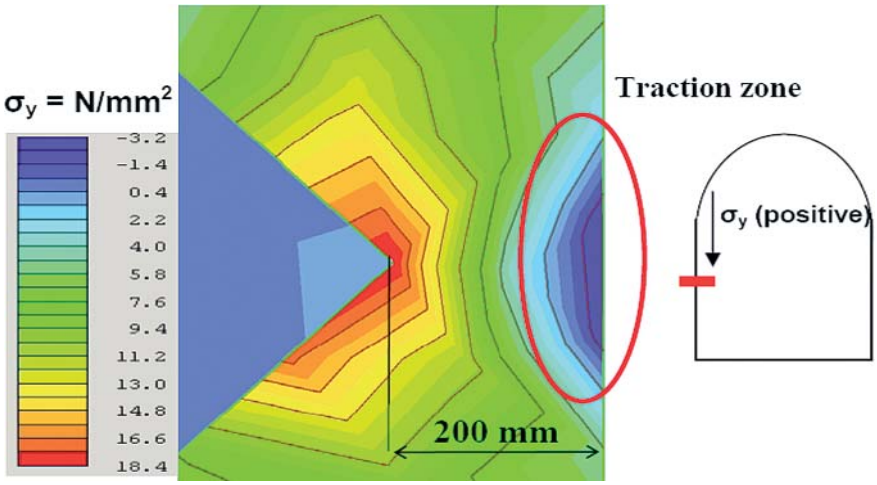

Fig. 7. Example of the principal maximum stress condition at the intradox of the lining with an irregularity of i = 1 m.The induced traction in the shotcrete is evident (Case A).
Esempio delle condizioni delle tensioni principali all'intradosso del rivestimento con una irregolarità di 1m. La trazione indotta nel calcestruzzo è evidente (Caso A).

with the increase in the irregularity and that the difference is larger when the cohesion is lower and K is higher. For example, when c=0.05MPa, K=1 and i=0,4m there are differences of 36% at the tunnel crown and for i = 0.2m of 23% and of 66% and of 36%, respectively, at the tunnel wall. The influence on the intrados is less important even though a smaller increment can also be observed. Figure 6, that is the detail of the lining at the tunnel wall when c=0.05 MPa, i = 0.4 m and K=1 shows the area when the vertical stress, induced by the rock mass irregularity, was arisen. If the irregularity rises to 0.8 m at the lining intradox, traction stresses develop that can be critical for the local stability and maintenance of the shotcrete lining (Figure 7).

These results are in good agreement with those obtained by Son and Cording (2007) who found that the increase in the moment was closely dependent on the irregularity height, natural earth pressure coefficient (K) and flexibility ratio between the rock mass and the lin-

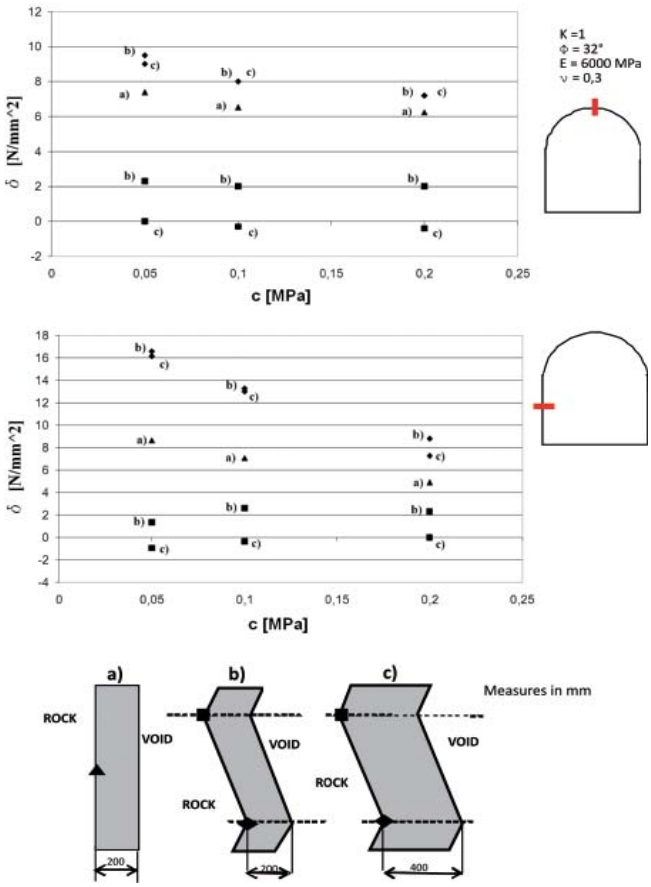

Fig. 8. Stresses computed at the estradox of the tunnel for K=1 vs cohesion of the rock mass – Case B.
Tensioni calcolate all'estradosso del tunnel per K=1 al variare della coesione della roccia – CasoB.

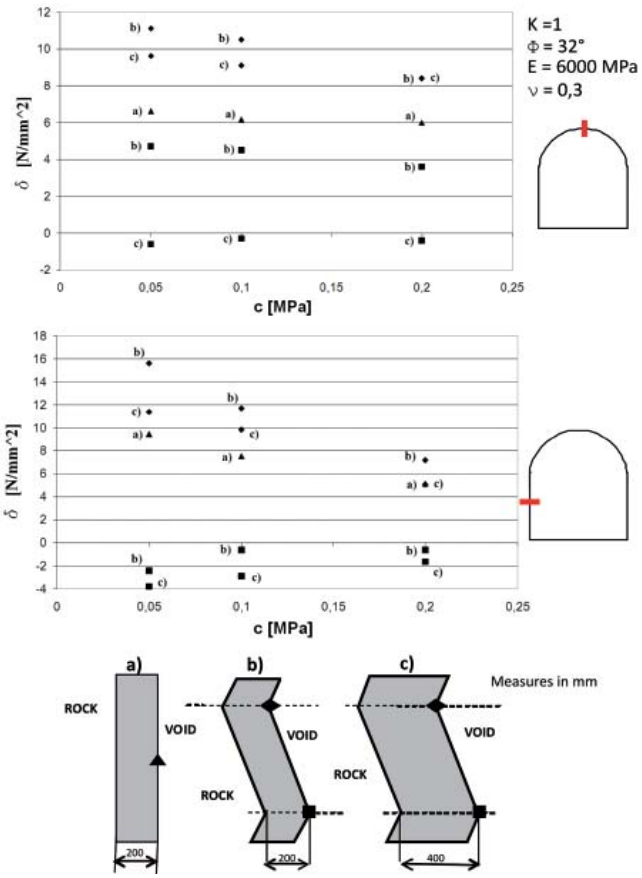

Fig. 9. Stresses computed at the intradox of the tunnel for K=1 vs cohesion of the rock mass – Case B.
Tensioni calcolate all'intradosso del tunnel per K=1 al variare della coesione della roccia – Caso B.

ing deformability and they showed that if a lining of only shotcrete is designed with a regular shape and large irregularities are expected, due to the rock mass geological properties, it is also necessary to take into account this factor.

For case B, whose results are summarized in figures 8 and 9, it is possible to see values of the acting stresses which have the same trend as case A, but with a much larger difference between the regular shape and the irregular one.

In particular it is possible to see that there are important traction values on the corner of the lining, as shown in figure 10, which reports the results for c = 0,05 MPa, K=1 and s = 400 mm

Conclusions

Overbreaks are unavoidable when the drill and blast tunnelling method is adopted and they are linked to both operational and geological factors. In the present paper the influence of the irregularity of a tunnel boundary on the stresses acting in the shotcrete lining is studied. A parametric numerical analysis of different reference cases has shown that when the irregularity of the rock boundary increases there is an increase in the acting compression stress at the lining estradox while tractions appear at the lining intradox. This traction can be critical since it can induce cracks in the lining.

Therefore the irregularity of the tunnel boundary after the excavation cannot be disregarded in the design phase when a shotcrete lining is used and particularly when it is used as final lining.

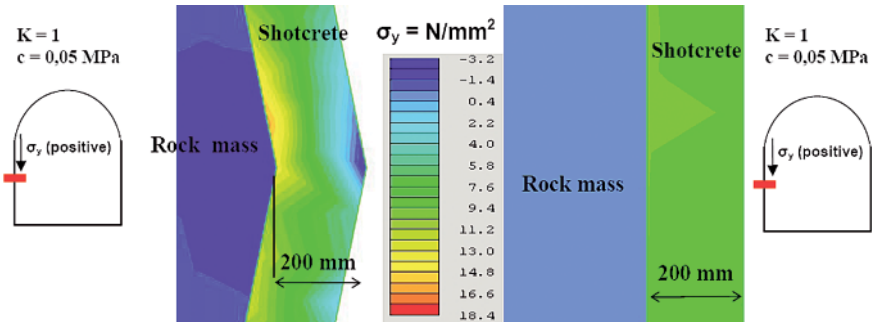

Fig. 10. Different stress concentrations for different boundary geometries (Caso B).
Diverse distribuzioni di tensione per differenti geometrie al contorno (Caso B).

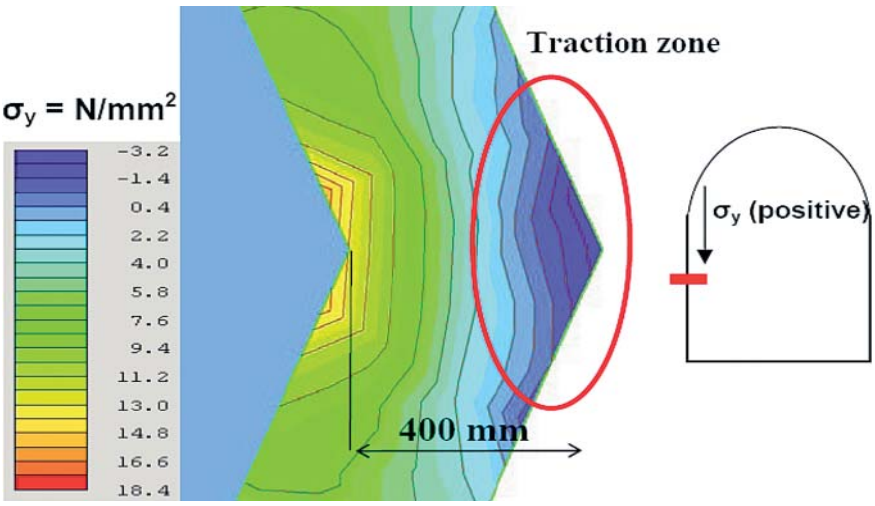

Fig. 11. Example of the principal maximum stress condition at the intradox of the lining for the case B. The induced traction in the shotcrete is evident.
Esempio delle condizioni delle tensioni principali all'intradosso del rivestimento per il Caso B. La trazione indotta nel calcestruzzo è evidente.

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