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TUNNELS AND STATIONS THAT SHOULD BE DEEPER

Dr N Barton (Nick Barton & Associates, Oslo) and **M Abrieu** (CVA Consortium, São Paulo) expose the false economies and dangers of shallow tunnelling for metros in urban areas, arguing that deeper tunnels and longer escalators are well worth the extra cost

Recently completed metro Line 4 (Yellow Line) of São Paulo metro was the first major underground construction project in the southeast corner of the 17 million-population Brazilian city. Following the usual, but unfortunate, wish of many owner-operators for shallow stations and short escalators, the contractor struggled to build 4.5km of shallow tunnels and five shallow stations which would be a much-needed addition to the city metro.

Problems encountered inevitably included mixed-face rock-saprolite conditions, deep differential weathering when in biotite gneiss, deeply weathered core-stone conditions when in granite, and generally more difficult saprolite and soil conditions than anticipated by the experienced contractor, who supplemented the owner's extensive vertical site exploration with around 30 deviated boreholes.

A single breakthrough to street level was also experienced, on this occasion caused by a very long, several hundred-ton slab of gneiss which penetrated through the bolt and shotcrete reinforcement. The failure was caused by the smooth-planar and deeply-weathered vertical boundary jointing which was aided by a saprolite cover of some 20m thickness that had been fully-saturated by preceding heavy rainfall. As usual, several adverse factors all occurred at the same time and place, forming a typical scenario for failure – fortunately without fatalities.

Right, figure 1: A price has to be paid for tunnelling too close to the 'dotted line', illustrated from the particular case of weathered granite from Dartmoor, England, after Linton (1955) and Fookes et al. (1971). In general, Q-parameters are not easily determined in the Grade V (brown) saprolite

Above, figure 2 a and b: Laboratory investigations of fresh and weathered (Grade I to IV) Hong Kong granites, that were recovered in routine site investigations. Lumb, 1983. By implication, Grade V saprolite with its increased porosity, incurs further strength and stiffness reductions

FLAWED OPTIMISM

Although shallow tunnelling in tropical climates is known to frequently cause difficult tunnelling conditions, there seems to be a built-in optimism on the part of owners, contractors and consultants which assumes a new project will not suffer the fate of other projects. The possibility of breakthrough to surface due to too shallow siting seems to be the fate of many well-prepared projects, as fairly recent events in Porto, Portugal (Babendererde et al. 2006) and Singapore (Zhao et al. 2006) have shown. With such projects in mind, the contractor-consortium CVA in São Paulo managed to persuade the owner São Paulo Metrô, to accept NATM-style tunnelling in place of an originally planned hybrid EPB TBM.

In retrospect, and with regard to the frequent mixed-face conditions, this switch of method was probably extremely fortuitous, despite the more numerous access shafts that were constructed to increase the number of faces for drill-and-blast construction.

NEAR-SURFACE CONSEQUENCES

The classic core-stone differential weathering resulting from previous tropical weathering, *(Figure 1)*, brings with it the risk of low or zero RQD, low uniaxial compressive strength *(Figure 2a)*, and low deformation modulus *(Figure 2b)*.

In combination, these reductions, and the implicit increase of porosity give, by a process of 'back analysis', a significantly low 'equivalent Q-value'. The dilemma of Q-classification for saprolite is emphasised by simultaneous reference to the 'brown' areas of Figure 1, and to the contrast in material strengths.

NEAR-SURFACE CONDITIONS, SÃO PAULO

Much of the experience from the close-to-surface tunnelling of the Line 4 São Paulo metro can be deduced by the graphic photographs of conditions that were recorded in numerous locations along Line 4 tunnels, where best months of 60m progress were frequently interspersed with only 10m-20m/month, due to a range of construction difficulties.

The soil, saprolite, mixed-face and weathered rock conditions required a wide variety of techniques, including horizontal jet piling, piperoof, top-heading with temporary curved invert, systematic lattice girder and shotcrete construction, drainage, pre-injection, spiling, and of course rock bolting. Full-face construction was regrettably rare.

The 'rock-section' of the station cavern (at Butantá) illustrated in Figures 3 and 4 contrasts greatly from the conditions revealed by excavation in the opposite direction. The station cavern excavated from the opposite side of the 60m-diameter station shaft encountered wet running ground with soil over saprolite, and took five months of laborious pre-treatment, excavation and support for its completion.

Far left, figure 3: A station cavern with only 6m of rock cover due to overlying 'core-stone' weathering. Overbreak approaches 3m to 5m due to the unfavourable Jn/Jr (9/1) and Jr/Ja (1/4) ratios, which could have only been prevented by pre-bolting

Left, figure 4: The scale of overbreak caused by three sets of planar, weathered rock joints. Much shotcrete has already been applied

Left, figure 5: Longitudinal section showing the low cover, mixed-face, and saprolite conditions

Far left, figure 6: Butantá Station arch. Dry saprolitic conditions were soon followed by wet, unstable soil, even worse than shown here

Left, figure 7: Full-face tunnelling on 'rock-cover-side' of Butantá Stn. It is assumed here that the extreme proximity of wet saprolite assisted in the failure of this major wedge, where an adverse, deeply-weathered shear zone and 'sufficient jointing' was also present

Far left, figure 8: Breakthrough to street level, fortunately without fatalities, was initiated by the fall of a large slab of rock with unfavourable Jn/Jr and Jr/Ja ratios

Left, figure 9: Grade VI, V and IV in the first core box, with the latter (deeply weathered rock) reached at 29m-30m depth, should suggest tunnelling at 40m depth, despite longer escalators

Above, figure 10: Dr Barton's interpretations of the possible causes of the collapse and of other major overbreak. Preventative measures could have included high-pressure pre-grouting, but with the limitation here of the proximity of saprolite just above the weathered rock

In general, it was the soil–saprolite sections of the project that were the most time consuming, and where pre-treatment of the ground turned out to be the most delaying factor.

The single collapse to street level that was experienced in early December 2005 *(Figure 8)* was a 'hybrid' type of multiple failure. Sub-vertical joints with unfavourable orientation sub-parallel to the tunnel, were also deeply weathered, and had adverse Jr/Ja ratios, meaning excessive planarity and clay coatings, giving non-dilatant, low resistance to shear.

It is probable that the massive, several-hundred-ton 'vertical slab' that fell through the tunnel arch was assisted in its breakthrough of the support measures by high groundwater pressures resulting from 20m of overlying saprolite, saturated by several days of heavy afternoon rain storms.

Nevertheless this relatively limited tunnel penetration meant that the resulting crater caused by flowing saprolite and soil, caused a 'slower than normal' ground subsidence, with occupants of the damaged house 'tipped out of bed' during the night, due to the 30° rotation of the house into the crater. Floors of neighbouring houses were stretched and cracked out to some 50m radius. Large volumes of foamed concrete were subsequently pumped from the surface, to reimpose crater and tunnel stability.

Interestingly, site offices situated between the subsidence crater and an access shaft were not damaged, perhaps because this building was 'protected' by the added tangential stress in the ground, caused by the vertical shaft excavation.

DISCUSSION

"The cost of deeper access to stations, via longer escalators, would be a small price to pay for much reduced tunnelling and station costs," (Barton, 2006).

This quotation is given in order to introduce an important topic of discussion. Let us suppose that extensive borehole investigations, and intermittent refraction seismic profiles (where access was possible), had revealed a subsurface topography that showed deep penetration of weathering. Would it then be logical for a city metro to remain as 'ideal' shallow excavations? Would the extra cost and time involved in tunnelling 'along the dotted line' *(in Figure 1)* be justified, to achieve the ideal of short escalators?

There are numerous cities with extensive metro systems, that do not have a favourable geology in immediate proximity to the surface. Three examples would be Moscow, Prague and London, where escalators of 200m, 100m and at least 75m length are regularly found. Does a 100m-long escalator create a negative impression on users, when added advertising space may actually make the 20 second-longer journey pass almost too quickly?

When some of the boreholes show conditions that resemble the first core-box details of Figure 9, it is time to ask if a shallow tunnel and station alignment is the correct approach. With soil and saprolite already 'too deep' at 20m–30m, it is inevitable that shallow tunnels and stations will be located in the physically most demanding elevation, with for instance, the tunnel arch in saprolite, and the tunnel lower walls and invert in rock that requires blasting.

CONCLUSIONS

1. Shallow tunnels and stations that have their arch in saprolite and their lower walls and invert in weathered rock for extended lengths of a project, suggest that the focus on shallow stations with short escalators has been detrimental to project completion.
2. The risk that such a tunnel elevation will cause breakthrough to the surface is increased, adding to the uncertainty concerning the completion dates and actual costs involved. ■

REFERENCES

- Babendererde, S., Hoek, E, Marinos, P. & A. Silva Cardoso, 2006. Geological risk in the use of TBM's in heterogeneous rock masses – The case of "Metro do Porto". *Geotechnical Risks in Rock Tunnels*, Campos e Matos, Ribeiro e Sousa, Kleberger & Lopes Pinto (eds), Taylor & Francis, 41-51.
- Barton, N. 2006. Fault zones and TBM. *Geotechnical Risks in Rock Tunnels*, Campos e Matos, Ribeiro e Sousa, Kleberger & Lopes Pinto (eds), Taylor & Francis, 75-117.
- Barton, N. 2006. *Rock Quality, Seismic Velocity, Attenuation and Anisotropy*. 729p, Taylor & Francis, UK & Netherlands.
- Fookes, P.G., Dearman, W.R. and J.A. Franklin 1971. Some engineering aspects of rock weathering with field examples from Dartmoor and elsewhere. *Q. Jl. Engng. Geol.* Vol. 4, 1971, 139-185.
- Irfan T.Y. and G.E. Powell, 1985. Engineering geological investigations for pile foundations on a deeply weathered granitic rock in Hong Kong. *Bulletin of IAEG*, No. 32, Paris, pp.67-80.
- Linton, D.L. 1955. The problem of tors. Geo. Jl. Vol.121, 470-487.
- Lumb, P. 1983. Engineering properties of fresh and decomposed igneous rocks from Hong Kong. *Engineering Geology*, Vol. 19, 81-94.
- Zhao, J. and Q.M. Gong, 2006. Rock mechanics and excavation by tunnel boring machine – issues and challenges. *Rock Mechanics in Underground Construction, 4th Asian Rock Mechanics Symp*. Eds. C.F.Leung & Y.X.Zhou, 83-96. *(see Case C: Mixed Face Ground)*.