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The accident at the Pinheiros underground station of line 4 of São Paulo's metropolitan subway: A case of local geological conditions that led to an unforeseen geomechanical behaviour

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ABSTRACT: Authors technical papers have been written discussing the sequence of events and the knowledge acquired during the forensic excavations for the investigation of the causation of the Pinheiros Station collapse on January 2007 (Assis, A. P. 2008 and 2009, Barton, N., 2008 and Sadowski et Alii, 2008), which led to seven deaths. It is the understanding of the authors, all part of the Board of Consultants created by the Construction Consortium to investigate and present a diagnosis for the failure, that local geological conditions detected after the accident led to an unforeseen geomechanical behavior.

1 INTRODUCTION

The Pinheiros underground Station of São Paulo's Metropolitan Subway – line 4 exhibits a 19,5 m span, a 16 m height and a length of 47 m at the side of a shaft of 40 m in diameter, was being excavated by blasting, top heading and two benchs, with the application at the tunnel crown, forepoles, steel arches and 35 cm thick shotcrete reinforced with steel fibers; at the first bench, 15cm-thick shotcrete and wire mesh.

On January 12th 2007, at 14:00 p.m., a violent collapse took place and brusquely propagated itself, reaching the shaft, as seen the illustration below (Fig. 1).

This work presents a diagnosis of the causes of the accident, based on prior studies, and on additional detailed investigations carried out concomitant to the debris removal and the reconstruction activities of the site.

Figure 1. Tunnel collapse reaching the shaft.

2 LOCAL GEOLOGICAL CONDITIONS

Local geological conditions are presented in the paper by Sadowski et Alii 2008. The following plan view (Fig. 2) indicates the boreholes available during basic and detailed design stages of the project.

After the collapse numerous additional investigations were performed, including:

a) geological mapping and detailed geomechanical classification, conducted at each elevation of the excavation for debris removal of the collapse;
b) rotatory boreholes, vertical and inclined, with televiewing of the borehole's walls;
c) 4 rotatory boreholes, horizontal, drilled from the trackway tunnel in direction of the collapsed zone, also with televiewing;

Figure 2. Investigations for basic and executive design.

Figure 3. Open NW joints, altered walls, with filling.

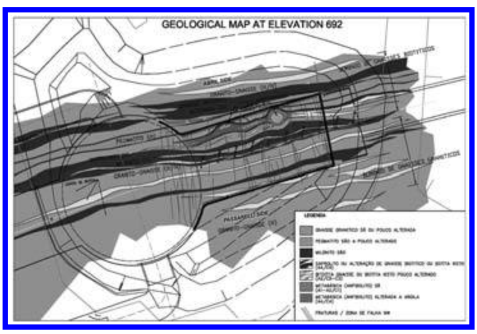

Figure 4. Geological plan view.

d) televiewing on 37 rotatory boreholes;
e) undisturbed sampling of relevant geomaterials encountered in the excavation;
f) special laboratory tests at CESP and the Polytechnic School of USP.

The major geological structures within the site may be summarized as follows:

The foliation, which coincides with the attitude of the Caucaia shearing zone, and consequently with the biotitic zones and the metabasite bands, in N75—85A-attitude slickenside bodies, with subvertical dips towards NW and SE.

At the site of the accident, the rock mass was delineated by these structures, which dipped in opposite directions, forming potential wedges in the station tunnel span.

The NW joints (Fig. 3), which free the blocks laterally for the formation of the wedge, generally exhibit millimetric openings, of a flat and undulated, smooth and coarse surface, with oxidation, alteration, and locally with clay coating. In some of these joints the presence friction slickenside within the argillaceous filling material was observed.

When the excavation reached levels 693 to 692, with the removal of all the collapsed material, the presence of an expressive exposure of metabasic (amphibolitic) rock came outcropped with the format of a thin and lenticulated layer, 30 to 40 m long and 3 to 5 m thick,

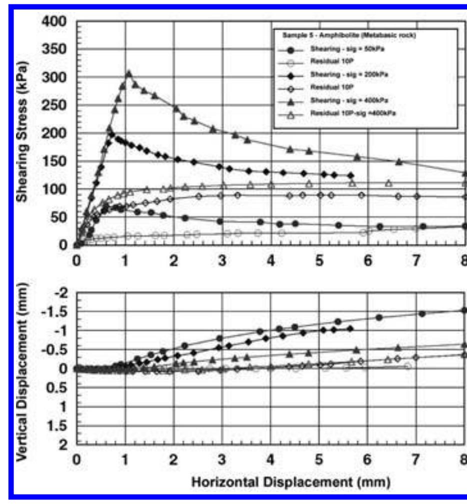

Figure 5. Stress-strain behavior.

accompanying one of the walls sub-parallely. This material is generally found altered to the fragments and clay. Within two points of greater thickness, there is occurrence of two bodies of sound metabasic rock measuring 1×3 m and 4×4 m respectively, according to the figure below (Fig. 4). Occurring, furthermore, is an altered biotitic level, surrounding both bodies.

The weathered metabasic bodies have a limited vertical presence, taking the form of bands or films right above the bench.

3 GEOMECHANICAL CONDITIONS

The geomechanical tests carried out at the laboratories of CESP and, s at the Polytechnic School of the University of São Paulo, show the following:

a) the tested materials exhibit a typically elastic-fragile behavior, in other words, they lose great amount of resistance at minor displacements, once stress peaks are surpassed;
b) the shear strength of the greenish soil (amphibolite) without flooding, exhibits a 0.05 MPa cohesion and a 33° friction angle, for "in natura" tests;
c) the residual strengths reach friction-angle values of 20° and cohesion zero, for the biotitic material; whereas for the greenish soil (amphibolite), these values are on the order of 18°, for cohesion zero.
d) the uniaxial compressive strength values of the weathered amphibolites, in the condition of saprolite, vary significantly between 600 kPa and 3000 kPa, and also exhibit low magnitude of displacements, practically elastic prior to the collapse (Fig. 6).
e) the amphibolites exhibit highly swelling characteristics, reaching pressures on the order of 1100 kPa, in tests conducted on non-deformed samples; the tests conducted on samples with various contents of humidity exhibit significant swelling pressures even in samples with a high degree of initial humidity (Fig. 7).

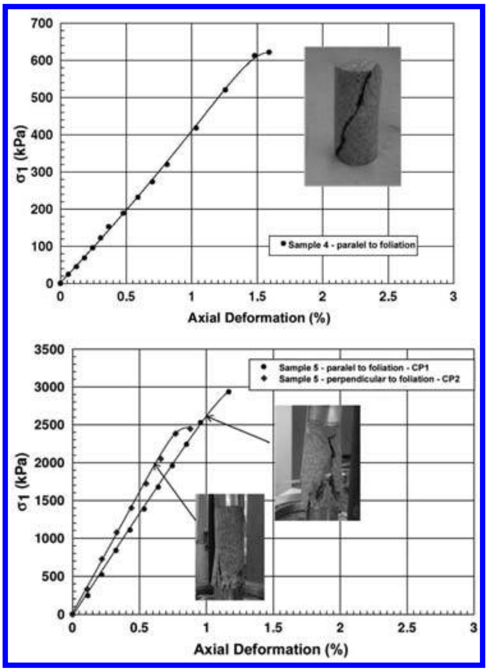

Figure 6. Uniaxial compressive strength values of the weathered amphibolites.

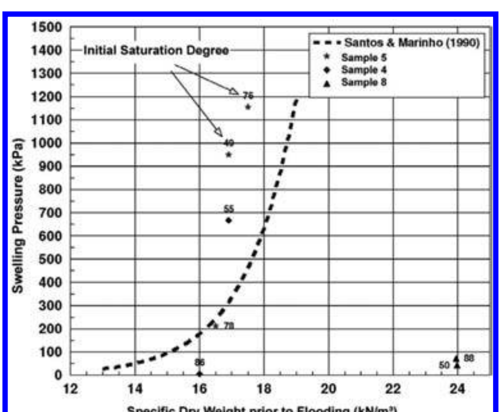

Figure 7. Swelling pressure tests.

4 GEOMECHANICAL BEHAVIOR, MONITORING AND SEQUENCE OF THE COLLAPSE

The sections monitored externally with tassometers and, internally, with convergence and topographic control measuring, are presented below (Figs. 8–9).

The situation of the tunnel as indicated by the monitoring immediately prior to the accident was as follows.

The graph above exhibits the convergence measurements prior to the accident, evincing that a rotation took place, showing increased settlements in the direction where metabasic rocks are present.

Furthermore, the illustrations above show that the maximum displacements and convergences ascertained were on the order of 35 mm (less than 0.02%) and intensified themselves with the resumption of the excavations subsequent to the recess, albeit still displaying constant gradients on the order of 1 to 2 mm/day, without acceleration.

In other words, one passed from a stage of practically constant gradients and total displacements that could be considered small vis-à-vis those measured in other tunnels, to a stage of outright and brusque

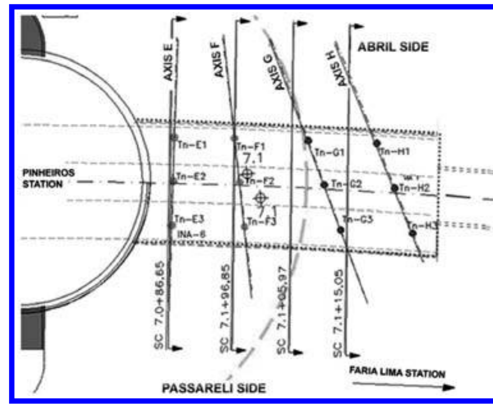

Figure 8. Plan showing monitored sections.

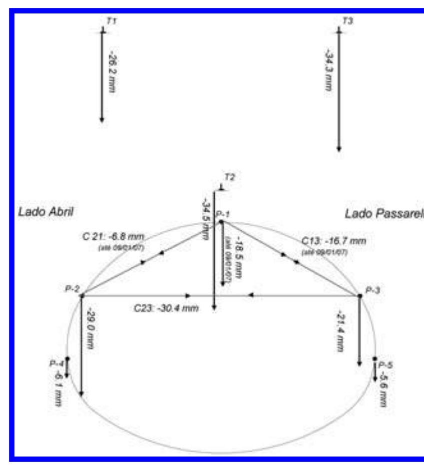

Figure 9. Tassometers and convergence measurements.

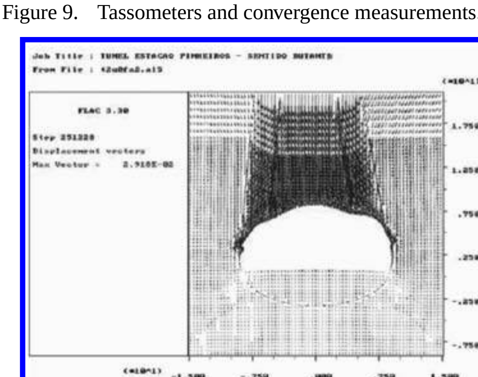

Figure 10. Flac numerical analyzes.

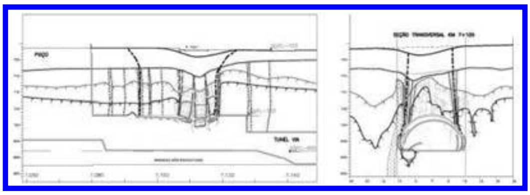

Figure 11. Initial phase of collapse.

collapse, with immediate propagation along the tunnel, characterizing an elastic-brittle behavior.

A great rock wedge, limited by the NW subvertical structures, between piles 7090 and 7120, in the longitudinal direction, and by the less resistant layers of biotite or amphibolite in the transversal direction, which dipped in opposite directions within the laterals of the tunnel, precipitated the beginning of the outright collapse, giving rise to a subsidence at rua Capri. This collapse quickly propagated itself through the tunnel of the Station.

Numerical analyzes developed with help of the Flac (Fig. 10) program tried to simulate the collapse, arriving at displacements on the order of 30 mm.

As can be seen on figure 11, the rock mass loses strength – The rock mass at the foot of the steel arch/bench exceeds peak strength and drops to the residual within a site of poorer amphibiolitic/metabasic geomechanical qualities, and, with an air blast, the collapse has a violent onset.

The phenomenon progresses in an abrupt manner within the tunnel.

5 CONCLUSIONS

In short, non-anticipated conditions due to the presence of weathered, subvertical biotite and amphibolite bands, parallel to weathered gneissic rock, conferred an essentially heterogeneous, anisotropic, discontinuous and elastic-fragile behavior to the massif.

The opposite dipping in the layers/bands of the highly tip bands of biotite taking place simultaneously in the sections transversal to the tunnel, made possible the formation and gradual unfastening of big rock wedges, limited transversally by the NW transversal structures, unfavorable to stability in the top of the station's tunnel.

The layers of weathered metabasic rock, of long extent, weakened the rock mass in several places, at the rock pillar presented hereinafter, as regards their deformability, compressive strength in the subvertical direction, parallel to the same, tensile strength in the perpendicular (subhorizontal) direction and shearing strength.

They also gave rise to the development of swelling pressures in the lining.

Many authors, including Selmer Olsen, Kovari & Anagnostou, Barla, Witke-Gattermann, among others submitted cases on swelling materials and analyzes related to the phenomenon.

It is very difficult to evaluate the effects of the amphibolite's swelling pressure at the rock pillar in

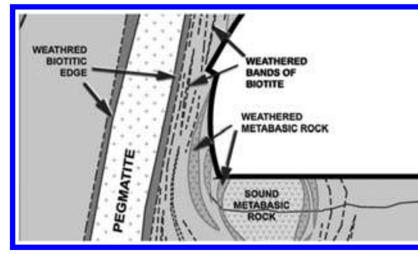

Figure 12. Geological cross section where failure started.

the bench, right below the top heading, given that this pillar is limited by the biotite tape next to the pegmatite and by the excavation surface (Fig. 12).

The following aspects increased the effect of metabasic swelling pressures:

a) The excavation of the bench had been interrupted precisely next to pile 7090, on the site wherein the weathered metabasic rock showed itself below the base of the steel arch, with the resumption of the excavations altering the condition of local stresses;
b) The displacements verified in the mass allowed an increased access of water to the amphibolite, by means of the above layers of biotite; the immediate application of shotcrete on the wall of the bench led to increase in the amphibolite's degree of saturation.

Thus, significant horizontal swelling pressures may have developed.

Therefore, one may conclude that the cause of the accident may be attributed to a geomechanical behavior of the rock mass, heterogeneous, anisotropic, and of a rheological almost "elastic-brittle" type, within particularly adverse local geological conditions.

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