MAIN CAUSES OF THE PINHEIROS CAVERN COLLAPSE

Nick Barton

Nick Barton & Associates, Fjordveien 65, 1363 Hovik, Norway

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INTRODUCTION

In January of 2007, seven people in a São Paulo street, four of them in a small bus, were suddenly sucked into falling soil and saprolite, from a street (Rua Capri) located about 20 m above a metro station cavern of 19 m span and 40 m length. This was under construction in Brazil's largest city. Despite the evidence of four surrounding and one central borehole, and six more boreholes around the adjacent station shaft, the assumed mean rock cover of just 3 m above the 20 m deep cavern arch, proved locally to be more than 10 m in error, due to a buried ridge of rock running high above the cavern arch, with one fateful low point exactly where drilled on the cavern centre-line.

SUB-SURFACE RIDGE OF ROCK WENT UNDETECTED

Due to the assumed low rock cover, heavy lattice girders, embedded in 40 cm of S(fr) were used as temporary support. The feet of the lattice girders were founded on broad 'elephant' footings. Due to the unknown loading from an adversely wedge-shaped, clay-bordered, ridge of rock and saprolite, weighing some 15,000 tons, all forms of temporary support would eventually have failed. Post-collapse, painstaking, police-supervised excavation of the entire 20 by 20 by 40 m of collapsed materials, taking some 15 months, finally revealed large remnants of the arch and wall support, crushed and folded beneath the ridge of fallen gneiss and amphibolite, plus saprolite, sand and soil. On the way down through collapsed material, the deformed remnants of the ridge were exposed all along the centre of the excavation. Even after falling 10 m to the floor of the cavern, the ridge of rock was 1 to 4 m above the original cavern arch. This fact seems to have been overlooked by the official investigators, the institute IPT. This is remarkable, but may be due to errors in elevations on their drawings of the collapsed rock. Nevertheless in dip-and-strike recordings, elsewhere in their 46 volumes report for the prosecuting authorities, IPT give the correct elevations of the fallen ridge.

Figure 1. The dramatic cavern collapse in São Paulo, during construction of the Line 4 subway. The feature 'FF' marks the limit of the collapse, in the street Rua Capri., where six people died.

Figure 2. (Left):The anticipated mean depth to rock, giving a mean 3 m of rock cover over the station cavern arch, based on five boreholes surrounding the cavern, with one drilled on the centreline. (Right): The extraordinary reality, greatly simplified. Most of the collapsed rock in the centre of the cavern fell 10 m, to a top elevation of 704-707 m, i.e. remaining 1 to 4m above the (original) cavern arch.

The five boreholes that gave information on the *mean* rock cover of only 3 m, as shown in over-simplified form above, were drilled through sand, soil and saprolite, reaching rock after about 16-18 m. The core boxes below (Figure 3) show on the left the fated borehole drilled on the cavern centre-line, which remarkably failed to detect and sample the 10 m high ridge due to chance geometrical factors illustrated in Figure 4. It must have been drilled at a 'central' low point.

Figure 3 (Left): The appearance of the rock core from borehole 8704 that was drilled near the centre of the (future) station cavern. (Righ)t: Another of the closest boreholes, 8702, drilled right next to the (future) cavern wall, and in the (future) shaft wall.

Figure 4. The undetected ridges of rock (1, 2) missed due to the fated location of borehole 8704.

Figure 5. A view of the heavy primary support in the top heading of the station cavern. Lattice girders were at 0.85 m c/c spacing, embedded in at 35-40 cm thickness of steel fibre-reinforced shotcrete. The pre-injection process at the cavern face (ch.7126 m) seen on the right was for the future intersection with the running tunnel at the eastern end of the cavern, just beyond Rua Capri.

Due to the assumed low rock cover, the previously planned rock bolts were not used as temporary support for the cavern, as the rock was strongly weathered, and it was assumed that bolt holes would have been difficult to grout. Instead, heavy lattice girders and an average 40 cm of fibre-reinforced shotcrete was used. Early installation of these measures, and the completed top-heading are shown in Figure 5,

ROCK QUALITY LOGGING

During construction of the eastern station cavern, geologists registered an increasing volume of medium quality class III (RMR = 44-48) in the centre of the cavern in the direction of Rua Capri. This 'core' (B) of improved rock is indicated by these simplified cavern face maps, two of which are shown in relation to cavern progress in Figure 6. Clay was logged on two of the joint sets.

Figure 6. The RMR rock class values of the 'core' (B) and the surrounding rock (A) are listed.

Pre-injection screens were suspended after the third one (Figure 6), due to improving rock quality of the cavern under Rua Capri. The volume of better quality rock increased due to the greater volume of class III. The Class III 'core' mapped along almost the whole length of the cavern centre was surrounded by poorer quality Class IV rock (RMR= 34-36) on either side (i.e. classes A/B/A). That this better quality rock 'core' could be a threat to cavern stability was not of course imagined, since a core-logged *mean* 3 m thickness of rock cover had been 'confirmed' by all five nearest boreholes.

DIFFERENTIAL WEATHERING MAY BE THE KEY CAUSE OF COLLAPSE

With the benefit of hind-sight following the collapse, the possibility of differential weathering was considered, since a high ridge of rock was soon indicated, in contradiction to the earlier borehole evidence. A high ridge of rock means that upper parts reaching nearer to the surface would have been strongly weathered, but surrounded by lower quality rock that had became saprolite. This concept, and possible development over a 'geomorphological time scale', is illustrated in Figure 7.

Figure 7. Conceptual 'seismic tower' models that were developed as possible explanations of the gradual development of differential weathering, eventually leaving a threatening ridge (and wedge) of rock that threatened stability as it prevented efficient arching above the cavern. Even more adverse wedge-shaped structures were required for failure to develop. (See later UDEC modelling).

Seismic refraction was used with limited success by the Brazilian government institute IPT, working at that time for the São Paulo Metrô (in 1997), due presumably to a combination of 24 hour traffic noise, deep weathering, and inevitable access limitations in this major metropolis of 17 million people and 5 million cars. The apparent consistency of all borehole data did not suggest the need of further attempts to perform seismic in 2004. Following the collapse, IPT who were now leading the investigations for the public prosecutor, again failed to get viable results with seismic refraction. Clearly there are fundamental difficulties, perhaps due to predominantly vertical structure.

Figure 8. Lattice girders were at 0.85 m c/c, and embedded in more than 35cm of S(fr). Note the 'elephant-feet' recesses for the lattice girder footings. The exceptional load caused by the unknown ridge-of-rock that failed these footings along part of the cavern, is modeled by fracture mechanics code FRACOD later in this paper.

POST-COLLAPSE EXCAVATION REVEALS LIKELY COLLAPSE MECHANISMS

During most of 2007 and the first 3 months of 2008, the fallen rock (and soil and saprolite) sketched in Figure 4 was carefully excavated, under the supervision of the investigating institute IPT. This excavation occurred from the base of an increasingly deep open excavation, supported eventually by hundreds of tie-backs. (Figure 9). Excavation through the fallen material was done with reasonable care and was almost comparable to an 'archeological' excavation, with 1 to 2 m high cuttings along longitudinal-sections, and similar cuttings along cross-sections, with careful recordings of each stage performed by the 24-hours field-team of institute IPT, who were reporting to the public prosecutor and police. The final open excavation of about 30 m depth will later be completed as a cut-and-cover station platform construction.

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Figure 9.(Left): Initial appearance of the open excavation.(Right): Excavation near the end of 2007.

Figure 10. Two examples of the central ridge-of-rock that had a loosened appearance due to its fall of about 10 m. (Left):The sides exhibited a curved, smoothed surface due to deep weathering. This is assumed to be 'remnant' Class III. (Right):The remnant ridge-of-rock has top elevation 707 m, even after its 10 m fall.

Differential weathering along the sides of the 10 to 13 m high ridge of rock was identified during this post-collapse excavation. At some distance above the cavern arch, this unidentified wedge-shaped ridge had developed into a threat to stability, due to its adversely sloping soil and clay-filled boundaries, which must have had insufficient shear strength. These adverse boundaries presumably hindered arching, and instead stood ready to supply a huge load onto the lattice girder and steel-fibre reinforced shotcrete support. Figure 10 shows the condition of the ridge-sides near the worker dressed in green seen in Figure 9 (right).

Figure 11 shows a probable geomorphological 'explanation' from SW England, first the geologist Linton's sketch of the sub-surface effects of variable joint spacing on the depth of saprolite or complete weathering (black area). In this and many other cases from SW England, periglacial effects have subsequently removed the saprolite. Hence 'tors' were formed. In the case of São Paulo, the 'tor' had remained, and tragically collapsed 10 m, when tunnelled under. It is the writer's opinion that this collapse would have occurred with any type of standard cavern support, due to the complete lack of arching caused by an inverted rock-wedge with deformable, weathered sides. The remainder of this paper is devoted to self-explanatory photographs and figures explaining the investigations of collapsed material, including the failed support, and modelling of these processes.

Figure 11. (Left): The sketch of variously jointed granite is from Linton (1955). ('The problem of tors'). Despite the much less massive nature of gneiss (as compared to granites) as was involved in the Pinheiros cavern collapse, the remnants of more jointed, and differentially weathered structures were clearly evident throughout the stage-by-stage excavation. (Right): The arrow shows the conceptual borehole 8704 location, between two towers (in this case remnant 'tors' of granite from Dartmoor in SW England).

Figure 12. (Left): Evidence of 'plastic-hinge' development in the lattice girders. Note the remnants of pre-grouting tubes just above the collapsed shotcrete and lattice girder support in an early part of the left wall. (Right): A deformed excavator which was extensively crushed by the falling ridge-of-rock.

Figure 13. The investigating institute IPT made numerous drawings of the collapsed cavern support. In places there was arch/wall/arch support in the same 1.5 m thick collapsed layer of support.(IPT, 2008).

Figure 14. In two locations there was evidence of rock failure beneath the 'elephant' footings for the lattice girders. Twelve fracture-mechanics models with varied rock strength, loading and deformation moduli, confirmed the presumed mechanism. (FRACOD code modelling by Dr. Shen).

Figure 15.(Left): UDEC model of shearing displacements, prior to 'plastic hinge' softening. Note that the ridge of rock is surrounded by extremely weak saprolite at upper elevations. (Right): After softening of over-stressed structural elements, general failure commences, with surface subsidence. This UDEC modeling was performed for the NB&A study, by Dr. Stavros Bandis of Greece.

In practice, the final gravitational collapse of the undiscovered ridge of rock with its adversely oriented sides was extremely rapid, causing an air-blast down in the adjacent running tunnels, and possible suction beneath the (Rua Capri) road surface, since victims and the small bus were very deeply buried when recovered by teams of firemen and CVA machine operators, after 12 days.

Figure 16. The final factor that may have triggered the collapse some three weeks after very heavy rains, was a storm water/sewage drain pipe of 1000 mm diameter, that reduced to 700 mm diameter (halving the cross-section, maybe raising pressure and causing softening. This crossed the rear discontinuity plane above the cavern. The 700 mm remnant of the cracked pipe was flowing immediately following the collapse.

CONCLUSIONS

The 2007 accident at Pinheiros demonstrated to engineers and planners the high risks involved with shallow sub-urban tunnelling. Elimination of risk, though obviously the desired goal, is probably impossible in the case of too shallow metro construction, because infrastructure and buildings may prevent 'complete' investigation. The planned shallow constructions were of course warned against by several consultants prior to construction. Longer escalators would have been needed, that is all.

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