Inspection and rehabilitation of “Cerro Azul” Tunnel (Ecuador).

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ABSTRACT: Cerro Azul Tunnel is part of the Daule-Peripa transfer, which supplies water to Guayaquil in Ecuador. The tunnel has a length of 6,450 m and was designed to carry a flow of 44 m$^3$/s. Its construction was completed in 1996, but in 2005 a collapse occurred in the central part of it and in 2007 an emergency repair was carried out. In 2012 the Water Secretariat of Ecuador (SENAGUA) decided to undertake the definitive repair of the tunnel and for this, an inspection of the state of the tunnel was carried out, which led to come to the conclusion that it was subjected to a squeezing process, since its construction in 1996. To define the process in the collapsed area of the rehabilitated cavern a back-analysis was performed through a geomechanical 3D model that allowed to reproduce the phenomenon of creep and the correct dimensioning of the support to place. The tunnel repair started in October 2012 and ended in November 2013.

1 INTRODUCTION

Cerro Azul Tunnel, built in 1997, is part of the Daule-Peripa water transfer system, belonging to the Hydrographic Demarcation of River Guayas and managed by SENAGUA, which involves the transfer of water resources from the surplus basin of Daule to the arid areas of Santa Elena Peninsula and to the canton of Beaches in the province of Guayas.

The purpose of this transfer is to attend the supply for human water consumption, agricultural production, strengthening industrial production and for developing the urban and touristic sector. Figure 1 shows the situation of Cerro Azul Tunnel.

The tunnel, with a length of 6,450 m and a cross section of 22.5 m$^2$, suffered in 2007 a collapse in its central part causing a cavern of 1300 m$^3$ on the vault of the tunnel.

The cavern created has a cross section of 178m$^2$, and was eight times bigger than the cross section of the tunnel so its creation was only possible through the combination of a stress-strain collapse and the effect of water transport circulating along the tunnel.

In 2007 an emergency repair was carried out, but the cavern was not filled. In 2012 SENAGUA proposed to increase the flow rate from 22 m$^3$/s to 44 m$^3$/s; for this, in addition to the technical constraints to perform the pumping, it was considered absolutely
necessary to repair definitively the Cerro Azul Tunnel.

In order to define the scope of the repair, an inspection of the tunnel had to be carried out, for which the methodology presented in the next section was adopted.

2 INSPECTION METHODOLOGY AND RESULTS OBTAINED

To perform the inspection a lighting system was assembled on a truck, which also allowed the access to the tunnel vault.

The inspection was carried out on foot and acceding to the tunnel vault by a platform assembled on the truck, as shown in Picture 1.

As a result of the inspection works the following mappings were obtained:
- Damages in the tunnel.
- Supports placed.
- Quality of the grounds.
- Faults crossed

2.1 Damages in the tunnel

Cerro Azul Tunnel presents eight types of damages:
- TYPE I: Segments with rusted bolts in a total length of 2,545 m, which represents 39.5% of the total length.
- TYPE II: Sections with bolts covered with shotcrete and irregular profile, with a length of 3,250 m, which represents 50.4% of the total length
- TYPE III: Sections with steel arches only partially covered with shotcrete, in a total of 10 m.
- TYPE IV: Sections with reinforced concrete formwork cracked, in a total of 55 m.
- TYPE V: Intersections with niches, with supports as bolts without shotcrete and a total length of 165 m.
- TYPE VI: Cut and cover tunnel with rusted steel bars in a length of 110 m.
- TYPE VII: Sections with cracked shotcrete in a length of 90 m of the tunnel length.
- TYPE VIII: Collapse which affects 30 m.

Picture 2 shows a section of the tunnel with cracked shotcrete; phenomenon which corresponds to the type II of damage and which is the most common.

For the second most common type of damage, I, Picture 3 shows the view of a rusted bolt.
2.2 Quality the grounds

In many of the tunnel sections where there is no lining it has been possible to determine the quality of the grounds through the RMR obtaining the sections indicated in Table 1.

<table>
<thead>
<tr>
<th>From Abscissa</th>
<th>Until Abscissa</th>
<th>RMR</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>0+100</td>
<td>3+100</td>
<td>55-61</td>
<td>Conglomerates, sandstones, siltstones</td>
</tr>
<tr>
<td>3+100</td>
<td>3+400</td>
<td>35-45</td>
<td>siltstones silicified (faults areas)</td>
</tr>
<tr>
<td>3+400</td>
<td>6+450</td>
<td>44-55</td>
<td>siltstones silicified</td>
</tr>
</tbody>
</table>

2.3 Type of support

The quality of the grounds in Cerro Azul Tunnel is, in general, 40 < RMR < 60; and this is the reason why the most common support consists of bolts and shotcrete, as shown in Table 2.

<table>
<thead>
<tr>
<th>Support</th>
<th>Length (m)</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bolts</td>
<td>2,545</td>
<td>39.46</td>
</tr>
<tr>
<td>Bolts and shotcrete</td>
<td>3,250</td>
<td>50.04</td>
</tr>
<tr>
<td>Steel arches and shotcrete</td>
<td>10</td>
<td>0.15</td>
</tr>
<tr>
<td>Moulded concrete</td>
<td>645</td>
<td>1.00</td>
</tr>
</tbody>
</table>

2.4 Faults crossed

Figure 2 shows the longitudinal profile of Cerro Azul Tunnel.

Figure 2. Longitudinal profile of Cerro Azul Tunnel.

Basically, the geological profile of Cerro Azul Tunnel consists of sandstones, siltstones and a small section of marl and limestone.

Sandstones, which constitute half of the tunnel, are separated from siltstone by a large fault and a smaller one, in which is located the cavern which emerged in 2007.

3 CORRECTIVE MEASURES

According to the damages observed during the inspection, the six reinforcement types were defined in Table 3.

<table>
<thead>
<tr>
<th>TYPE</th>
<th>DESCRIPTION</th>
<th>REPAIR WORK</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Rusted rock bolts</td>
<td>Replacement of rock bolts and shotcrete</td>
</tr>
<tr>
<td>II</td>
<td>Cracks in shotcrete</td>
<td>Rock bolts and shotcrete</td>
</tr>
<tr>
<td>III</td>
<td>Steel arches without shotcrete</td>
<td>Shotcrete projection</td>
</tr>
<tr>
<td>IV</td>
<td>Rusted Steel bars</td>
<td>Epoxi mortar</td>
</tr>
<tr>
<td>V</td>
<td>Unfilled junctions</td>
<td>Filling and concrete wall</td>
</tr>
<tr>
<td>VI</td>
<td>Cavern</td>
<td>Reconstruction of the tunnel and filling</td>
</tr>
</tbody>
</table>

The most frequent typologies applied are I and II, in order to cover the type of damages presented in section 2.1

4 DESIGN OF THE RECOVERY OF THE CAVERN FORMED IN 2007

Figure 3 shows the cross section, in the midpoint of the cavern that was formed in 2007, which is located in the centre of the tunnel.

Figure 3. Cross section in the midpoint of the cavern.

This cavern has a height above the invert of the tunnel of 15.5 m and a maximum width of
15m. In Picture 4, taken from the East side wall view, this aspect can be appreciated.

The cross-section of this cavern was $178m^2$; that means eight times bigger than the regular cross section of the tunnel.

The inspection carried out found that the geometry of the cavern was conditioned on the East-West dimension by the presence of two faults, with direction and dip N-130-E and 80° S, which are transverse to the layout of the tunnel and in the direction of the axis of the tunnel, by a fracture with direction and dip, N-200-E 80° S. The roof of the cavern belongs to a stratification plane. Figure 4 shows the geological and geotechnical plan of the cavern.

In the inspection carried out it was also found that the repaired shotcrete which was placed in 2007 was cracked, as shown in Picture 5.

The existence of these cracks makes clear that the cavern has had movements since its repair in 2007 until nowadays. These movements can be explained by the phenomenon of squeezing, which occurs when the ground supports a pressure higher than 60% of its compressive strength.

Therefore, the information contained in the "as built" had been reviewed in detail. It was found that some convergence stations, placed in 1994, had a clear phenomenon of squeezing, as shown in Figure 5.

According to this, it was decided to perform a simulation of the creep process of the cavern zone using the FLAC 3D software, with the option of "ubiquitous joint". The rock mass
properties used in the calculations are shown in Tables 4, 5 and 6.

### Table 4. Resistance characteristics of the grounds.

<table>
<thead>
<tr>
<th>Ground</th>
<th>RMR</th>
<th>$\sigma_{ci}$ (MPa)</th>
<th>$m_i$</th>
<th>$d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Siltstones</td>
<td>40</td>
<td>40</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>Sandstones</td>
<td>60</td>
<td>50</td>
<td>10</td>
<td>0</td>
</tr>
</tbody>
</table>

### Table 5. Elastoplastic properties of the rock mass.

<table>
<thead>
<tr>
<th>Ground</th>
<th>$E$ (MPa)</th>
<th>$\nu$</th>
<th>$c$ (MPa)</th>
<th>$\phi$ ($^\circ$)</th>
<th>$\gamma$ (t/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Siltstones</td>
<td>2400</td>
<td>0.2</td>
<td>0.5</td>
<td>34</td>
<td>2.6</td>
</tr>
<tr>
<td>Sandstones</td>
<td>9200</td>
<td>0.2</td>
<td>1.1</td>
<td>43</td>
<td>2.6</td>
</tr>
</tbody>
</table>

### Table 6. Characteristics of the joints.

<table>
<thead>
<tr>
<th>Joint type</th>
<th>Dip</th>
<th>$c$ (t/m$^3$)</th>
<th>$\phi$ ($^\circ$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ubiquitous joints</td>
<td>25$^\circ$</td>
<td>5</td>
<td>28$^\circ$</td>
</tr>
<tr>
<td>Fault</td>
<td>90$^\circ$</td>
<td>2</td>
<td>30$^\circ$</td>
</tr>
</tbody>
</table>

Once the creep simulation was performed, evolution of convergence curves were obtained, which are shown in Figure 6.

![Calculated convergences curves in creep mode.](image)

Comparing the curves in Figure 6 with the ones actually measured, which are represented in Figure 5, it is found that the part corresponding to the creep phenomenon in the curves have similar slopes in both cases.

This confirms that the modelled phenomenon of squeezing represents the behaviour of the tunnel section were the cavern was formed.

To stabilize the cavern and recover the form of the tunnel it was decided to rebuild the collapsed section of the tunnel by building an artificial tunnel and filling the whole of the cavern remaining over it.

The projected construction sequence was as follows:

1. Strengthening the current support in two tunnel sections, one before the cavern between the abscissas 3 +505 and 3 +510 and the another one between the abscissas 3 +530 and 3 +535.

2. Cleaning up the sections of tunnel adjacent to the cavern by removing the unstable wedge between 3 +510 and 3 +514.

3. Cleaning up the walls of the sunk section in order to place frames with the shape of the tunnel and shotcrete the surface area of the cleaned up ground.

4. Placing in the collapsed section steel arches, HEB-160, with a wheelbase of 1 m, lining the viewed wing with metal plates, Bernold type and backfill frames against the ground with shotcrete.

5. Building a concrete arch, H-280, over steel arches, with a minimum thickness of 1 m.

6. Filling the remain volume of the cavern located with mortar which has a minimum strength of 50 kp/cm$^2$ over the crown with 1 m thick concrete.

7. Grout injection at a pressure of less than 3 kgf/cm$^2$ to fulfil the possible gaps between the cement mortar and the ground.

8. Projection of a layer of shotcrete, 20 cm thick, on the steel arches and Bernold plates to reconstruct the perimeter of the tunnel.

Having defined the solution it was proceeded to its validation by solving a three-dimensional geomechanical model, as shown in Figure 7.

![Modelling of the cavern volume.](image)

Figure 8 shows the section of the model in the central part of the cavern, which matches very well with Figure 3.
Figure 8. Cross section of the model in P.K.3 +527.

Figure 9 shows the simulated support elements in the model which are constituted by:

- Concrete crown H-280, of at least 1 m thick, behind the upper surface of the vault of the frames.
- Steel arches HEB-160.
- Filling the rest of the cavern with mortar with a minimum resistance 40 Kp/cm².

Figure 9. Modelled support elements.

The results of the simulation with the support reinforcement have allowed to obtain the convergence curve of the tunnel in the area of the cavern, since its construction in 1995 until 2030; including the collapse of 2007 and definitive repair in 2013, as show in Figure 10.

Figure 10. Convergence in the section of the cavern between 1995-2030.

It is found that, after the collapse generated in 2007 the convergences increases instantaneously and afterwards the convergence rate comes in a secondary creep with a constant rate which in 2012 of about 3 microns/day.

This figure also shows the effect of the repair, which stopped immediately the convergences.

5 RECUPERATION WORKS

SENAGUA awarded to the Chinese company GEZHOBIA GROUP COMPAY the contract to repair the Cerro Azul Tunnel and this company subcontracted these works to Fopeca.

The supervision of the works was assigned to the Ecuadorian company CEVACONSULT Ltda, which included the collaboration of Geocontrol SA.

The rehabilitation work began in October 2012 and was completed in November 2013.

To start the works inside the tunnel it was necessary to carry out a preparatory work on the access ramp to the portal, as shown in Photo 6.
The lack of space inside the tunnel made necessary to have a detailed planning of the activities to be performed, which were arranged in this way:

1º. Cleaning of the tunnel walls with pressured water.

2º. Evacuation of sludge created because of the cleaning of the tunnel walls.

3º. Reinforcement with rock bolts.

4º. Shotcrete projection.

The rock bolts were installed using pneumatic drilling hammers assembled on a work platform situated on a truck; as illustrated in Picture 7.

The placement of shotcrete was performed with two projecting robots, working in wet mix, as shown in Picture 8.

To work in the cavern area a lift platform was used because of the important height of the cross section. Picture 9 illustrates these works done with the lift platform.

The works have been supervised by a team of engineers which has been permanently present at the works. Also, in order to solve specific problems that occurred during the works, this team was completed with the participation of an engineer specialized in monitoring tunnel construction.

As the works in Cerro Azul Tunnel implied to stop the water transportation from the Daule-Peripa water transfer system it was mandatory to establish a very detailed planning of this work.

Nevertheless, it is noteworthy that during the year in which the works have been developed it has been necessary to stop three times the rehabilitation works in order to allow water to pass through the tunnel, for reasons of shortage.

Overall, the rehabilitation works have been stopped for five months, which represents 41% of the time that has lasted the rehabilitation.
6 CONCLUSION

The available data on the construction of the Cerro Azul Tunnel, completed in 1996, indicated that this tunnel has been subjected to a squeezing phenomenon since its construction, which is considered the cause of the collapse that occurred in 2005.

From the detailed inspection of the tunnel status in 2012, damages have appeared in the support of the tunnel in 50.4% of its length and strong corrosion problems in the rocks-bolts placed in 39.5% of its length.

To recover the area of the cavern a procedure was designed to reconstruct the structure of the tunnel in the collapsed section and filling the existing gap of this structure with concrete and mortar.

The solution has been tested with a 3D model, developed to adjust the phenomenon of squeezing, being totally effective to stop the movements of the cavern.

The repair of the tunnel, which began in October 2012, has successfully been completed in the month of November 2013.

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