Boring with no. 3 EPB TBMs in chaotic Lahar formations under variable cover

R. Grandori(1), A. Barioffi(1), F. Bove(1),
(1)S.E.L.I. S.p.A., Rome, Italy

ABSTRACT: The execution of three long hydropower tunnels in the western region of Panama, close to the border with Costa Rica, in Central America has been awarded. All three tunnels, for a total length of 15 km, develop entirely in “Lahar” formation under covers ranging from 15 to 200 m. This is the first time the tunnel boring machine (TBM) technology has been massively applied in such formation and, due to its critical and variable characteristics, no. 3 earth pressure balance (EPB) TBMs with mix face cutterheads and dual operating mode capability have been selected. The article describes the interaction of the 3 TBMs with the different and changing ground conditions as well the difficulties and special measures adopted to overcome the most critical conditions encountered along these tunnels.

1 Introduction

During the year 2010, the execution of the tunnels of two relevant hydropower schemes in Chiriquí, the western region of Panama close to the border with Costa Rica, has been awarded. The first scheme is composed by two power houses (Pando and Monte Lirio), while the second scheme is composed by one power house (El Alto). Each power house is fed by a conveyance tunnel: all tunnels insist on Chiriquí Viejo river. The main features of the tunnels are:

- Pando: excavation diameter 3778 mm, internal diameter 3000 mm, lined by prefabricated rings 250 mm thick (universal ring composed by 6 pieces, 1200 mm long), length 5170 m
- Monte Lirio: excavation diameter 3928 mm, internal diameter 3200 mm, lined by prefabricated rings 250 mm thick (universal ring composed by 6 pieces, 1200 mm long), length 7878 m
- El Alto: excavation diameter 6790 mm, internal diameter 5800 mm, lined by prefabricated rings 350 mm thick (universal ring composed by 7 pieces, 1400 mm long), length 3348 m

In order to deal with the expected geology, it has been chosen EPB methodology for all tunnels, reconditioning and adapting to the situation at the company own premises in Italy, three machines having mix face cutterheads and dual operating mode capability. At the time being the machines performed respectively 40%, 58% and 84% of the tunnels’ length.

2 The geology

This portion of Chiriquí province is characterized by the presence of the active Volcán Barú, and therefore geology is essentially linked to the pyroclastic deposit of such a volcano (Figure 1). Tunnels are mainly excavated through a volcanic landslide named Lahar, whose consolidation grade hugely and suddenly varies.

A Lahar, originally, is a mixture of water, ice, and sediment that is generated during and sometimes after an eruption. Lahars are gravity-controlled flows that are channeled into valleys as they move downhill. The texture of the Lahar on the exposed surface varies from blocks, large angular fragment, bombs, rounded fragments the size larger than apple, to cinders, which are the size of nuts, ash, the
size of peas, and dust, the finest material. Further is possible to identify a continuum vertical variation of grain size distribution from debris flow, sediment concentration greater or equal to 60% per volume, to hyperconcentrated streamflows, sediment concentration from 20 to 60% per volume.

In the Lahars formation unusually large boulders, some several meters in diameter, are transported by debris flow and tend to sink in the flow due to gravity. Lahar formation can be classified according to the matrix’s characteristics:

- matrix supported Lahar
- clast supported Lahar

In the matrix supported Lahar the cobbles are embedded inside a well graded fine matrix while in the clast supported Lahar, the fines quantity is very low and not well graded. In the Lahar matrix plastic clay seems to be absent, but it is difficult to exclude completely his presence. Sometime andesitic flow can be recognized surrounded by the Lahar. Actually, it is difficult to assume if this andesite has been transported, floating, by the Lahar flow or if it is a witness of an ancient volcanic eruption.

In Lahar formation is very difficult to identify the results of tectonic force such fault. An indication of the fault zone is given by the presence of pulverized material/fault gouge that in this formation can be easily confused as fine Lahar.

![Figure 1. Lahar conformation in the area](image)

### 3 Investigations and geotechnical characterization

Seismic and electrical investigations were performed by the Client prior to the contract awarding that can be summarized into two categories that are randomly distributed all along the tunnels’ length, as follows:

- Unconsolidated Lahar: clasts of different dimensions are embedded in a loosened and not cemented matrix. Medium permeability.
- Consolidated Lahar: clasts are merged into a cemented matrix. Low permeability.

Mechanical samplings were executed just to calibrate geophysical investigations.

The average uniaxial compressive strength (UCS) of rock samples varies within a range starting form 50 MPa and up to 170 MPa. The water table should be everywhere close to the surface and the permeability of the ground between 2 and 6x10⁻⁶ m/sec, except in marginal zones defined as “electrical anomalies”.

Both according to literature and investigations, the expected average dimension of boulders was no more than 40 cm.

Overburden ranges from 15 to 200 m and can suddenly vary within a short area, as typical in volcanic landscapes.
4 The machines

Having considered the challenging geology proposed by the tunnels, it has been chosen EPB technology, being the more flexible in such variable situation; moreover machines were chosen with a high torque factor if compared with usual EPBs (Figure 2).

![Figure 2. Torque factor's evaluation](image)

Furthermore, TBMs have been previously modified in order to better cope with the expected Lahar, i.e. machines can work efficiently both in open and closed mode.

![Figure 3. General layout of Pando and Monte Lirio's TBMs: longitudinal section](image)

![Figure 4. General layout of El Alto TBM: longitudinal section](image)
In Figure 3 is reported the longitudinal section of the two smaller machines, where it has to be noted the screw conveyor position (nearly horizontal) due to the limited excavation diameter and related motorization. The screw conveyor helix (diam. 560mm) allows the passage of debris sized no more than 180 mm.

On the other hand, in Figure 4 is reported the longitudinal section of the bigger machine (El Alto tunnel), where a more comfortable TBM diameter allows a classical screw conveyor design. The screw conveyor helix is dimensioned for debris smaller than 290 mm.

Based on the available information, the initial “boring” idea was to design the cutterhead in order to deal with homogenous and competent material, similar to a soft rock, with the possibility to improve towards a hard rock (portions of andesite flow) or to worsen towards a loose soil (EPB technology). The cutterhead configurations are shown on Figures 5 and 6 and the typical cutterhead tools’ configuration can be summarized as follows:

- Pando: 23 cutters and 30 cutter bits,
- Monte Lirio: 24 cutters and 32 cutter bits,
- El Alto: 39 cutters and 92 cutter bits

### Table 1. Main features of the three machines

<table>
<thead>
<tr>
<th>Tunnel</th>
<th>Pando</th>
<th>Monte Lirio</th>
<th>El Alto</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>TBM.EPB.3728</td>
<td>TBM.EPB.3928</td>
<td>TBM.EPB S-387</td>
</tr>
<tr>
<td>Excavation diameter</td>
<td>3778 mm</td>
<td>3928 mm</td>
<td>6790 mm</td>
</tr>
<tr>
<td>Cutterhead</td>
<td>Two directions, variable speed</td>
<td>Three rows of rollers and pressurized lubrication</td>
<td>A two flanged sleeves and pressurized lubrication</td>
</tr>
<tr>
<td>Main Bearing</td>
<td>12 cylinders, 13538 kN</td>
<td>19x2 cylinders, 50000 kN</td>
<td></td>
</tr>
<tr>
<td>Thrust system</td>
<td>13538 kN @ 340 bar</td>
<td>50000 kN @ 350 bar</td>
<td></td>
</tr>
<tr>
<td>Nominal Thrust</td>
<td>2227 kNm @ 1.8 rpm</td>
<td>5400 kNm @ 3.02 rpm</td>
<td></td>
</tr>
<tr>
<td>Unblocking torque</td>
<td>2776 kNm</td>
<td>9928 kNm</td>
<td></td>
</tr>
<tr>
<td>Cutter diameter</td>
<td>15.5&quot;</td>
<td>17&quot;</td>
<td></td>
</tr>
</tbody>
</table>

Furthermore the conditioning system was upgraded from the manufacturer configuration increasing the quantity of foam, bentonite and polymer’s nozzles.
5 The experience

Therefore, besides the very initial strokes, the excavation started in open mode at all three job sites, and having considered the required “learning curve” and the temporary site yard configuration (installation of the continuous conveyor belt at El Alto site), production was confirming such an intuition. For the small TBMs, in fair expected geological conditions, a monthly advance rate of 600 m was recorded.

Figures 7, 8 and 9 show respectively Monte Lirio, Pando and El Alto starting weeks.

The first problem encountered was at chainage 720 m of Monte Lirio, where a sudden collapse of the front face got stuck the machine. A mix of large cobbles (up to 2 m) of hard rock and no cohesive fine conveyed by water flow at high pressure (6-8 bar) was surrounding the TBM, entering into the screw conveyor and flooding in within the shields.
After many attempts to resume excavation, by consolidating the front face, it was evident the necessity to open a top heading tunnel to free the machine and to upgrade its configuration. In Figures 10 and 11 the rescue tunnel is shown, while in Figure 12 the modifications applied to the cutterhead to reduce the possibility for big blocks entering into the working chamber, thus blocking the screw conveyor, are detailed.

From the resuming of the excavation in Monte Lirio (late in October 2011), the TBM is advancing at the daily rate of 13.5 m, having excluded further production stops (46 days to consolidate the front face, 22 days to refurbish the screw conveyor, 14 days to assembly the Californian switch).

Similar event was occurring in Pando, starting early on December 2011. TBM was blocked by loose ground composed by boulders and silty matrix with no cohesion that was overcome by intensive injection of polyurethanic foam to strengthen the front face geotechnical characteristics. After some 150 m excavated during January 2012, rock mass collapsed again being accompanied by high water pressure up to 8 bars; after some attempts to resume excavation using the same intensive injection, it was once again evident the necessity to open a top heading tunnel to reach the cutterhead section, to free the machine and to consolidate the surrounding “rock” mass. So far the machine is advancing in
parallel with the top heading and this procedure will continue until the geotechnical situation is not improved.

![Image](image1.png)

**Figure 11. Top heading tunnel: rescue of the cutterhead**

Even on this machine cutterhead design was upgraded to avoid the entrance of boulders into the working chamber and into the screw conveyor.

Finally, the third machine of El Alto has not encountered such challenging situations, with the exception of a three weeks stop due to the crossing of a Lahar fault, where two facies were easily distinguished: sound rock in contact with swelling and sticky material that was blocking the shields. A rapid opening of two lateral passages was resolving the situation with success.

Nevertheless, even this machine was too often suffering the entrance into the working chamber of loose cobbles and blocks, reducing the screw conveyor efficiency enough to assess for a revision of the cutterhead as per Figure 13.

As a further improvement, the sealing lubrication system for the three machines was upgraded pumping grease in order to balance the extremely high water pressure and to prevent the entrance of the suspended solids into the main bearing.

It has finally to be highlighted how in several cases of adverse geological conditions, in order to prevent and to reduce high water pressure and consequent inflow of fine material, the situation has been overcome throughout an “ad hoc” drainage system (longitudinal self-drilling “open” pipes starting from the last rings and draining some meters ahead of the cutterhead).
6 A learned lesson

The excavation through the Lahar formation is resulting very challenging even though an EPB methodology is applied.

The first considerations and experiences to be recorded are:

- The small diameter of the Pando and Monte Lirio machines and the consequent reduced space availability, in case of bad geology, does not help when additional equipment (drilling rigs, pumping stations etc….) are required.
- The bigger diameter of the El Alto machine is helping in all upgrading operations (machine and soil).
- Diameter less than 6m has to be not recommended.
- The use of drainage holes is a simple and efficient technique to overcome several zones where high water pressure values are detected.
- Availability of chemical products as polyurethane resins or polymer, together with conventional drilling rigs, is of paramount importance when it is mandatory the front face consolidation.
- Experienced Personnel is a key issue when so challenging geology has to be faced.
- Segments lining is highly performing also when it is subjected to asymmetric soil pressures and elevate water pressure.
- When geology results as largely expected, EPB TBM demonstrates to be an adequate and economic technique to deal with pyroclastic deposits.

7 References
