THE CONSTRUCTION OF THE HYDROELECTRICAL PROJECT LA CONFLUENCIA (ANDES, CHILE)

Paul, A.[1], Odekerken, C.[2], Meyer, P.[3], Chavez, E.[4], Galera, J.M.[5], Müller, M.[6]

1 Constructora HOCHTIEF-TECSA S.A. / Project Director / Alfredo Barros Errázuriz 1953. Santiago. Chile. apaul@hochtief.cl
2 Constructora HOCHTIEF-TECSA S.A. / Manager Design / Alfredo Barros Errázuriz 1953. Santiago. Chile. codekerken@chtsa.cl
3 Constructora HOCHTIEF-TECSA S.A. / Construction Manager / Alfredo Barros Errázuriz 1953. Santiago. Chile. pmeyer@chtsa.cl
4 Subterra Ingeniería Ltda. / Geological Engineer / José M. Infante 2802 Ñuñoa, Santiago. Chile. echavez@subterra-ing.com
5 Subterra Ingeniería, S.L. / Managing Director / Vallehermoso, 30 bajo A. 28015 Madrid. Spain. jmgalera@subterra-ing.com
6 HOCHTIEF Solutions AG / Senior Design Manager / Alfredstraße 236. D - 45133 Essen. Germany. mathias.mueller@hochtief.de

ABSTRACT

The hydroelectrical project La Confluencia is located at the Andes, in the VI Region of Chile, close to the Tinguiririca volcano massif.
The owner is Tinguiririca Energy a JV composed by SN Power and Pacific Hydro, and the construction was given to JV headed by Hochtief Solutions AG with Constructora Tecsa S.A.
La Confluencia will provide 166 MW and it is the largest underground excavated hydroelectrical project constructed in Chile as it has a total tunnel length of 22,473 m. The project basically consists of:

- Tunnel Tinguririca, tunnel pressure with a length of 9.5 km and 3 adits. The tunnel excavation width is 6,5 m.
- Tunnel Portillo, free flow tunnel with a total length of 12 km and 3 adits. It has the same geometry.
- High Pressure Tunnel, elbow, manifolds of 636 m length and a construction adit.
- Surge Tank of 16 m internal diameter and 100 m depth and pressure shaft of 264 m depth and 4.10 m internal diameter.

The construction of the tunnels started on August 2008. The whole pressure system was finished one year later on July 2010.
The tunnels have been excavated basically in andesites of good and fair geomechanical quality, with RMR usually higher than 50 points, but also some volcano-sedimentary formations as well as tuffs have been encountered. No major faults have been crossed but in several sections loose materials have been founded.
The main difficulty has been the intersection with a paleo landslide, in which poor rock mass condition and water inflows up to 250 l/s have occur.
The tunnels have been constructed following the NAT method while a 364 m raise boring has been used in the shafts.
The paper describes the characteristics of all the underground excavations as well as the main facts of its construction and the methods used. Finally the equipment and advance ratio reached.

1.- INTRODUCTION

La Confluencia project, is a hydropower project that is under construction by a joint venture between HOCHTIEF Solutions AG and Constructora TECSA S.A. The project is located between the Tinguiririca and Portillo Rivers, about 140 km south from Santiago, at an elevation of 1100m at the powerhouse and 1520m at the highest intake. Figure 1 show the location of the project.

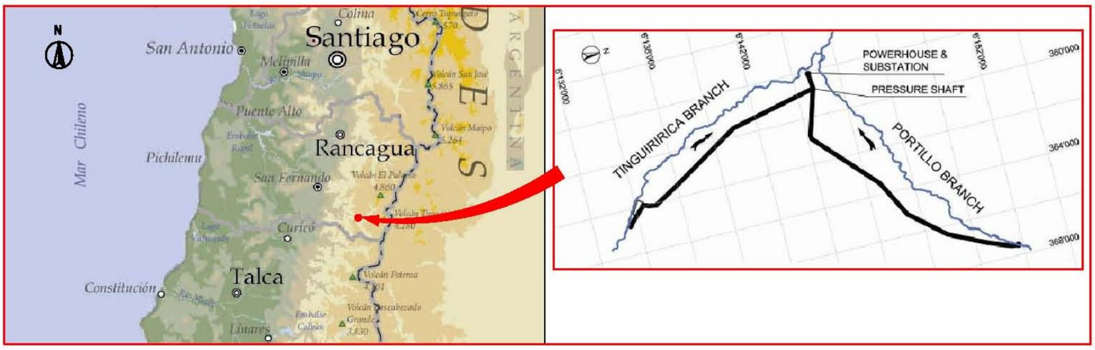

Figure 1.- Location of the project

Stage 1 and 2A of the Project have been already successfully achieved. The Stage 1 comprises the Tinguiririca intake, a low pondage weir and an on-channel reservoir, with a capacity of 1.2 Million m3. Stage 2A adds a 9.5 km pressure tunnel on the Tinguiririca branch to convey water to the junction point with the Portillo tunnel, a Pressure shaft of 364 m depth whose upper part forms a surge tank and a 636 m concrete and steel lined high pressure tunnel to a surface power station. The power station contains two 83 MW turbines and generators which are connected to the La Higuera switchyard through a 16 km long transmission line. The Project Stage 2A has been already handed over to the Owner, Tinguiririca Energía, early2011. Outstanding is the completion of the Project Stage 2B. This stage involves the completion of the second tunnel along the Portillo valley together with the main Portillo intake and three additional secondary intakes on the Azufre, Los Humos and Riquelme rivers. Currently the main intake Portillo and the secondary intake Riquelme have been completed as well as the secondary intakes Azufre and Los Humos. The tunnel excavation was finished last September 10th 2011, under sometimes difficult geological conditions. It is expected to complete Stage 2B works by beginning of 2012 allowing the project to operate at its full capacity with the water resources from both rivers.

2.- HYDROELECTRICAL CONCEPT OF THE PROJECT

La Confluencia hydroelectric power plant makes use of the water of two tributary valleys in the High Andes Mountains, collecting water from the Portillo and Tinguiririca valleys. There is a main intake at each valley with a capacity of 28 m^3/s, 3 secondary intakes in the Portillo valley, namely Azufre (3 m^3/s), Los Humos (3 m^3/s) and Riquelme (1.5 m^3/s), and 2 secondary intakes in the Tinguiririca valley, namely El Ciruelo (1.5 m^3/s) and La Gloria (1.5 m^3/s). The main intakes at Portillo and Tinguiririca contain each a ca. 10 m high dam, a gated weir structure with three spillway bays including radial gates, a gravel sluice, a lateral gated intake structure and an environmental flow gate. Both main intake structures have a total capacity of 28 m^3/s. The secondary intakes Los Humos, Riquelme, El Ciruelo and La Gloria, consist of an ungated Tyrolean type weir and a streambed intake including an environmental flow gate and a flushing gate. Azufre secondary intake is in addition equipped with a regulating radial gate. Any excess water caught by the streambed intake is spilled back to the river by a bypass gate located between the streambed intake and the sand trap gates. The water from the Portillo intake is conveyed first by a ca. 2 km long open and closed channel, and then by a ca. 12 km long unlined Portillo free flow tunnel, whereas the water from the Tinguiririca intake is conveyed to an off-river reservoir of ca. 1.2 Mm^3 storage volume. In the channel between the sand trap of the Tinguiririca intake and the reservoir, an ungated spillway exists, which spills water should the reservoir level rise higher than the operation level. From the reservoir, the water of the Tinguiririca branch is conveyed through a ca. 9.5 km long unlined low pressure Tinguiririca tunnel. The secondary intakes are connected with the tunnels either by drop shafts or inclined free flow tunnels. The Portillo and Tinguiririca tunnels connect to the vertical pressure shaft, which acts in the upper part as a surge shaft. The total height of this concrete lined shaft is ca. 364 m wheras the surge tank inner diameter is 16 m and pressure shaft has 4.1 m internal diameter of the concrete lining. From the pressure shaft, a concrete lined high pressure tunnel with steel lining penstock of approx. 636 m total length leads to the powerhouse, which is equipped with two Francis turbines with an output of 83 MW each. The main branch of the project is the Tinguiririca branch, which represents the pressure system, including the off river reservoir, the Tinguiririca low pressure tunnel, the pressure shaft and the high pressure tunnel. The Portillo branch with its free flow tunnel connects to the pressure shaft on a higher level, so that it is excluded from the pressure system. The capacity of the Tinguiririca pressure tunnel is 52.5 m^3/s, whereas the capacity of the Portillo tunnel is 30 m^3/s. When the power plant is in operation, the inflow brought by the Portillo branch is fully processed by the turbines, while the Tinguiririca reservoir supplies the complement. When the power plant is shut down during the off-peak period, the inflow from the Portillo branch is automatically and fully conveyed to the Tinguiririca compensation reservoir via the Tinguiririca tunnel. At the Tinguiririca and Portillo intakes, the water level up upsteam the weirs is kept constant by the radial gates. The inflow into the intake channels is controlled by fixed wheel gates, which are located right after the trash rack. Any excess water is spilled through the weir. The secondary intakes cannot be regulated; the slide gates can only be in open or closed position. The regulation is done by the main intakes, and with the gates placed upstream of the sand traps, there is great flexibility in operating the system. The environmental flow gates at Portillo, Azufre, Riquelme, Tinguiririca, El Ciruelo, La Gloria intakes provide for the required environmental flow in the river.

3.- GEOLOGY

Following the main geological data of the two principal tunnels are provided. Figure 2 show a synthetic geological profile of both tunnels.

a) Geology along the Portillo Tunnel

Between the u/s portal and Riquelme creek, the tunnel crosses basically the quaternary volcanic unit named Tinguiririca – Sordo Lucas (Qb), in which the following sub-units can be distinguished:

- volcanic non consolidated deposits (Qb2)
- tuffs and pyroclastic flows (Qb1)
- columnar andesites and basalts (Qb3) that doesn’t affect to the tunnel
- intrusive hypabyssal rocks (Qbh)

Downstream of Riquelme, the tunnel alignment was changed to avoid the intersection with a slumped mass. Making this change the tunnel crosses the cretaceous rocks of the Coya – Machalí Unit (KCM) in which basically 3 sub-units may be differentiated:

- Shales and intercalated tuffs and thin layers of reddish sandstones and shales (KCM-t)
- Thin layers of continental sediments as reddish and brown sandstones with shales and cineritic tuffs (KCM-s). This unit has been crossed under Cipreses stream with a thickness of about 50 m.
- Andesites, andesitic tuffs and volcanic breccias (KCM-a)

The materials of the Qb unit seem to form a series of subhorizontal, relatively thick individual flows, affected by subvertical columnar jointing in some cases, dipping gently to the West.
The rocks of the Coya-Machali Formation (KCM-a, KCM-t, KCM-s) dip at 45-50° towards SW. The strike of the bedding planes favourably cuts the axis of the tunnel at 60-80° angles.

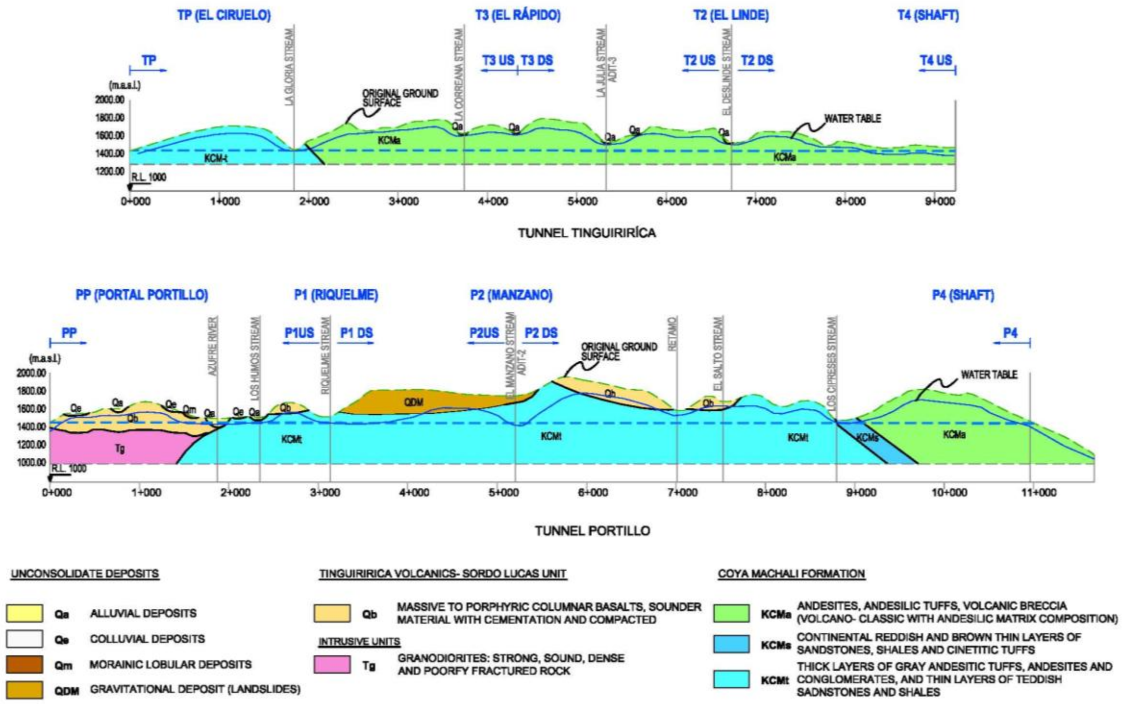

Figure 2.- Geological synthetic profile of the tunnels. Location of the adits.

b) Geology along the Tinguiririca Tunnel

The entire Tinguiririca Tunnel is located in the Coya-Machali Formation. Between the Gloria stream and the surge shaft, the tunnel is located in the KCM-a unit already described which consists of alternating, medium to thick bedded andesites, andesitic tuffs and volcanic breccias. The bedding planes, dipping at 35-45°, are oriented more or less parallel to the slope. The strike of the bedding planes are intersected at low angle (15-35°).

The geological conditions along the Tinguiririca Tunnel upstream of La Gloria are of lower geotechnical quality as the KCM-t was encountered.

Some minor faults have been crossed at both tunnels.

Concerning seismicity, there is no specific earthquake code for power plants in Chile. The closest code available is NCh 2369-2002. According to this code, PGA for La Confluencia would be 0.2g (Zone 1):

4.- DESCRIPTION OF THE UNDERGROUND WORKS

The underground works in La Confluencia project consist of about 24.25 km of tunnels and shafts distributed in the following elements:

- Portillo Tunnel, unlined, ca. 11’500 m long
- Tinguiririca Tunnel, unlined, ca. 9’200 m long
- Surge Shaft, concrete lined, ca. 100 m deep
- Pressure Shaft, concrete lined, ca. 264 m deep
- High Pressure Tunnel including two manifolds, concrete/steel lined, ca. 636 m long
- Adits for the HPT (H4), ca. 95 m
- Adits for the Portillo Tunnel (P4, Manzano P2, Riquelme P1), ca. 1545 m.
- Adits for the Tinguiririca Tunnel (T4, T2 El Linde, T3 El Rápido), ca. 930 m.

The tunnels have been excavated by conventional drill & blast methods. The shafts sections have been excavated by raise boring method (5 m diameter) in all its depth (364 m) and enlarged to 17 m by drill & blast, down from the top.

Figure 3 show the sections of the main underground structures. It can be observed that an enlarged section was adopted for the adits, as they had the aim to ensure the excavation rates at two faces, upstream and downstream.

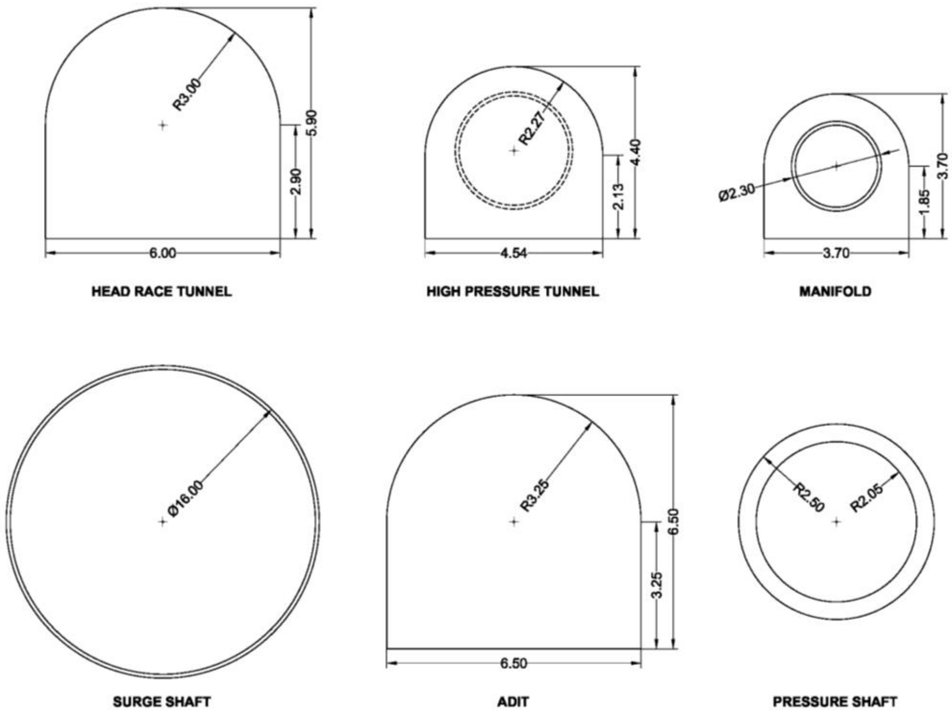

Figure 3.- Sections of the main underground structures

5.- SUPPORT DESIGN

NATM was chosen to construct all the tunnels while for the shaft a raise-boring 5 m diameter, was selected and afterwards enlarged up to 17 m.

The excavation was mainly made using drill and blast, while in few sections basically along faces PP and P2, some mechanical excavation was done in side the landslide materials and in some soft tuffs of the Sordo Lucas formation.

Table 1 show the seven support classes used in adits and tunnels as well as the round lengths adopted and the ranges of rock mass quality of application for each class

An additional support class Vc was considered including additional reinforcements for very poor quality rock masses. All the supports were validated using stress-strain calculation solved with FLAC 2D code and rock wedge calculation using UNWEDGE code.

Table 1.- Support classes

Q	EXCAVATION CLASS	RMR	EXCAVATION METHOD	UNSUPPORTED SPAN (m)	WIRE MESH	FIBER REINFORCED SHOTCRTE (cm)	ROCK BOLT L=2.0 M ∅ 22	STEEL RIBS
> 30	I	> 75	D+B	5	Yes	-	-	-
10-30	II	65-75	D+B	4	Yes	-	Occasional	-
3-10	III	55-65	D+B	4	No	5	2.0x2.5	-
3-1	IV	45-55	D+B	2	No	3+5	1.5x2.0	-
3-1	Va	35-45	D+B	1.5	No	3+9	1.5x1.5	-
1-0.3	Vb	28-35	mechanical	1	No	3+15	-	Laticce girders @ 1m
0.3	IVb	55-65	D+B	1.5	No	3+9	1.5x1.5 L= 4 m	-

6.- TUNNEL CONSTRUCTION

6.1.- Main data

The excavation of the tunnels started in August 2008 at two adit faces, H4 and T4, while Tunnel Tinguiririca was started in December 2008 and completed in April 2010 (17 months), allowing for start of the power generation in March 2011 and the construction of Tunnel Portillo started in November 2008 and was ended last September 2011 (34 months). As it has been said this means the completion of 24.25 km of tunnel.

During these 37 months the number of active tunnel faces has ranged between a minimum of 2 faces and a maximum of 12 faces.
Figure 4 show the relation between the number of faces and the advance reached for each month. As it can be observed there is an excellent correlation with an average value of 100.2 m/month of advance.

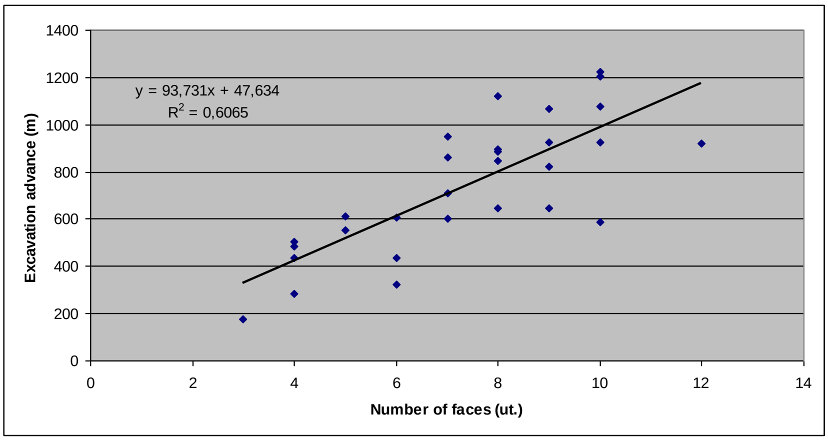

Figure 4.- Relation between the tunnel excavation advance and the number of tunnel faces

Most part of the tunnel construction, about 72.5 % of the total tunnel length, was done between October 2010 and April 2010. For this period the average number of tunnel faces has ranged between 7 and 12, with a mean value of 8.3 and a statistical rate of advance of 846.25 m/month for each tunnel face. These logistic have permitted to reach peak rates of advance of 1223 m in October 2010 with an average of 122 m/month at each tunnel face.
For the tunnel adits highest rate was reached at P1 with a value of 132.5 m/month while the lowest one, corresponds to P2 in which only 39.8 m/month were achieved. This last value has a clear explanation as most of the adit's length was excavated crossing the Manzano landslide to reach the Portillo tunnel in a safe position under the basal slide detachment plane. Table 2 shows the rate of advance for the three main tunnels and adits.
It can be clearly observed that Tunnel Tinguiririca has been excavated in a better quality rock mass than Tunnel Portillo.
Photos 1 to 10 show different aspects of the construction of the main tunnel structures.

Table 2.- Rate of advance of all the tunnel faces

TUNNEL	FACE	LENGTH (m)	EXCAVATION RATE m/month
Tinguirica (7 faces)	TP	1829.05	107.6
	T2	480.33	96.1
	T2Ds	958.47	119.8
	T3Us	1690.30	105.6
	T3Ds	1483.90	114.1
	T4Us	2167.38	142.5
	T4Ds	318.32	63.7
Portillo (7 faces)	PP	1815.22	83.2
	P1US	838.53	90.1
	P1DS	1849.37	113.4
	P2US	1330.27	100.0
	P2DS	1047.92	89.4
	P4US	4266.01	121.9
	P4DS	156.40	48.60
High Pressure (1 face)	HPT	712,35	125.71

6.2.- Main incidents
The main incidents during the tunnel construction have been convergences (squeezing), face collapses, wedges failures, spalling, water, and swelling. Following these main incidents are described.

Photo 1. Tunnel Portillo

Photo 2. Portillo portal at the Surge Tank

Photo 3. Surge Tank. Raise Boring

Photo 4. Surge Tank. Concrete Lining

Photo 5. Junction H4-High Pressure Tunnel

Photo 6. High Pressure Tunnel and Manifolds. Steel lining

Photo 7. Power-house. Manifolds portals

Photo 8. Junction of Tinguiririca Tunnel and Surge Tank/Pressure Shaft

Photo 9. Rock Trap at Tinguiririca Tunnel

Photo 10. Junction T3-Tinguiririca Tunnel

a) Convergences

The highest values of convergence were measured in Portillo Tunnel. In this tunnel some values of tunnel convergence ranging above 0.2 % (of the tunnel diameter) were recorded in Sordo Lucas tuffs and especially in tuffs and reddish lutites of KCMt unit between P1 and P2 and also at P4 Upstream.

In Tinguiririca tunnel this values above 0.2 % of convergence was only observed in red lutites at TP face.

Figure 6 show the relation observed between the convergence measured and the rock mass quality expressed by its RMR. In this figure only the sections installed closer than 3 diameters have been considered. The tendency show an asymptote making negible the deformations for RMR values higher than 70. Nevertheless a huge scatter is observed as there are other very important parameters (eg. Overburden) that have not been considered in this analysis. Figure 7 shows the convergence versus the support class. From this figure it can be clearly established that the higher values of convergence are in relation with support classes IV and V.

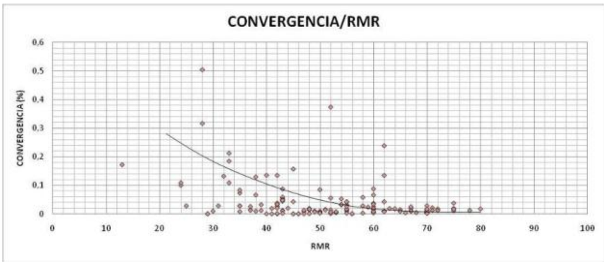

Figure 6.- Convergence measures vs RMR.

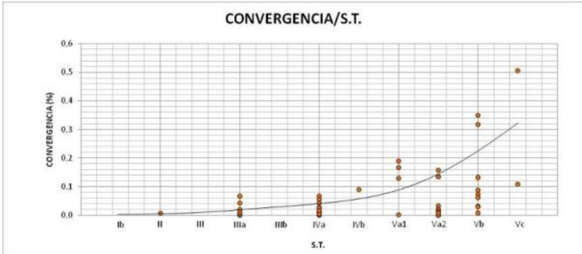

Figure 7.- Convergence vs support class.

b) Face collapses

Few collapses at the faces were reported. Basically the first one took place in P2 in relation with loose material inside the major landslide of Manzano and water rush of 250 l/s and the second one in PP related with loose ashes of Qb unit also with some 100 l/s water inflow.

c) Wedges failures

In sound andesites of KCM unit in T3 and T4 faces as well as in the pressure shaft some wedge failures took place.

d) Spalling

Few rock spalling was reported in the tunnel walls in faces T3 Upstream and P4 Upstream both in relation with the highest existing overburden (about 450 and 600 m respectively).

e) Water

The highest water flow encountered was in Adit P2 inside the landslide. Apart from this incident the major water inflows were registered at La Gloria (40 l/min.m) and T3 (12.5 l/min.m) in Tinguiririca; and Azufre (100 l/s), P1 downstream and P2 upstream (35 l/min.m).

f) Swelling

In some of the reddish lutites and tuffs of KCMt unit, some expansive clay has been encountered. For this reason an inner reinforcement lining was designed to resist a swelling load of 0.4 and 1 MPa for Tinguiririca and Portillo tunnels respectively. The length of the swelling reinforcement has been 401 and 266 m respectively.

8.- CONCLUSIONS

The construction method and the equipment used have provided excellent advance rates and optimum safety condition in the excavation and support of a large underground project.

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