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Failure Modes in Road Tunnels of Sierra Valle Fertil. San Juan. Argentina

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SUMMARY: The Sierra de Valle Fertil is located in the west of Argentina (San Juan province). It is crossed by the National Road 150, that has 40 km in length including six bidirectional road tunnels with a total length of 2000 meters. The geological formations are various Carbonic-Permian (Paganzo Basin) and Triassic (Ischigualasto-Villa Union Basin) sedimentary rocks, in an area adjacent to the Ischigualasto Natural Park. The Sierra has been formed by the reactivation of the basin during the formation of the Andes (Pliocene-Pleistocene) with a thick-skinned tectonics.
The trace of the route follows a creek that cuts anticlinal folds. The first three tunnels are developed through soft sandstones with siltstones and shales (middle Triassic). The two following slightly cemented sandstones and conglomerates (Lower Triassic) and the last is in rigid greywackes (upper Carbonic). The support provided by the design was estimated by using RMR and Q method. During construction geological surveys were conducted on the front as it was excavated, and expected support was adjusted according to them. Different failure modes observed in rigid and soft rock are analyzed together with the solutions provided during construction. The tunnels excavated in stiff rocks were less demanding than those provided for in the design. Instead, the tunnels in soft rocks required more supports than those stipulated in the design.

KEYWORDS: Valle Fertil, failure mode, road tunnels, sedimentary rocks.

1 INTRODUCTION

The Sierra de Valle Fertil is located in the west of Argentina (San Juan province). It is crossed by the National Road 150. This road is a part of a bi-oceanic corridor that runs from Porto Alegre (Brazil) to La Serena (Chile) (figure 1) (Aceituno et al 2014).

This road sector has 40 km in length including six bidirectional road tunnels with a total length of 2000 meters (figure 2).

All tunnels have the same horseshoe shape cross section.

Figure 1. Location of Valle Fertil tunnels (circle), within bi-oceanic corridor (Porto Alegre-La Serena).

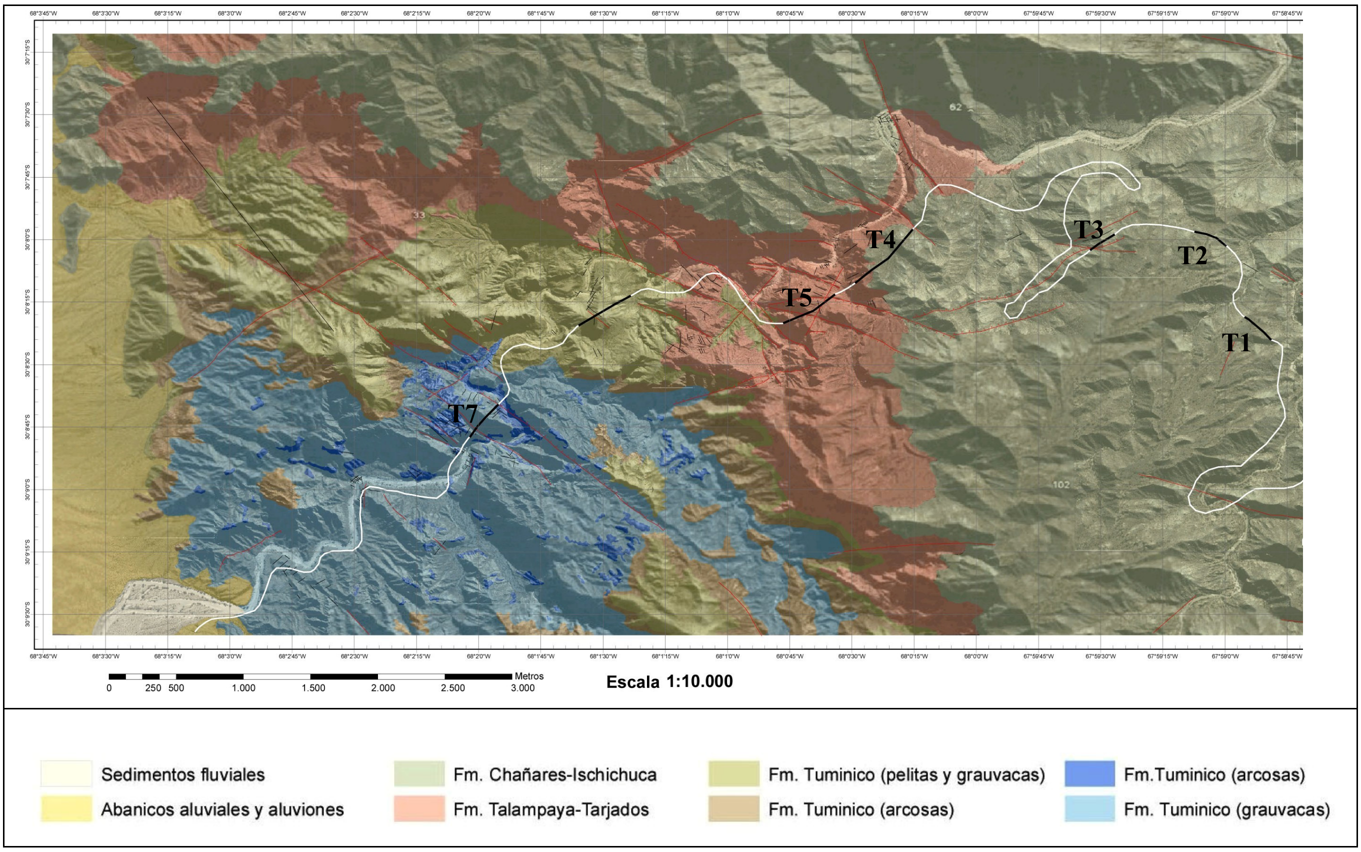

Figure 2. Location of the tunnel within the geological environment.

They were designed following criteria given by Highway Tunnels of PIARC "Cross Section Design for Bi -Directional Road Tunnels" of 2004 (Figure 3).

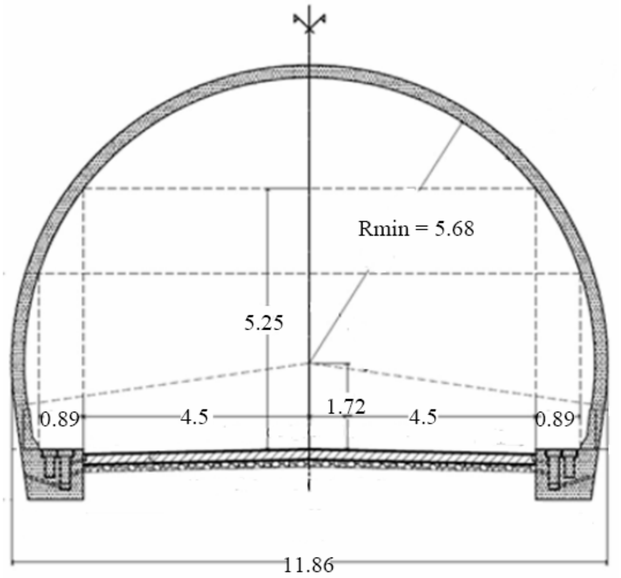

Figure 3. Cross section of all tunnels (expressed in m.).

The circular portion has an inner radius of 5.68 m. with a tolerance of 0.10 m. The area itself is about 70 m^2, which includes the area between the roadway, sidewalks side gables and the inner perimeter.

The minimum free structure gauge, vertically, is 5.25 m., a value that complies with current regulations and provides a rematch to accommodate any resurfacing.

It was considered desirable to reduce the longitudinal slope gradient as much as was possible. They vary between 1.7% (Tunnel 7) to a maximum of 2.9% (Tunnel 1).

2 GEOLOGICAL SETTING

2.1 Regional Geology

The geological formations are various Carbonic-Permian (Paganzo Basin) and Triassic (Ischigualasto-Villa Union Basin) sedimentary rocks, close to a National Reserve (Azcuy and Morelli, 1979, Bossi, 1971, Curri et al, 2009, Gioia et al, 2006, Miall, 1977, Roger et al, 1993, Rosello et al, 1996, Romer and Jensen, 1966, Sill, 1969, Stipanicic, 2002). The Sierra has been formed by the reactivation of the basin during the formation of the Andes (10by bp) with a thick-skinned tectonics. (Figure 2). GPS measurements show that Valle Fertil fault, that is the west limit of the range, is a feature that separates two tectonic regions, with high seismogenetic potential. The trace of the route follows a creek carved by Agua de la Peña River that cuts anticlinal folds.

The first three tunnels are developed through soft sandstones with siltstones and shales (middle Triassic). The two following slightly cemented sandstones and conglomerates (Lower Triassic) and the last is in rigid greywackes (upper Carbonic).

2.2 Eastern tunnels

Tunnels T1, T2 and T3 have similar structural geology features, but as the tunnel alignments changed, their influences were different (figure 4).

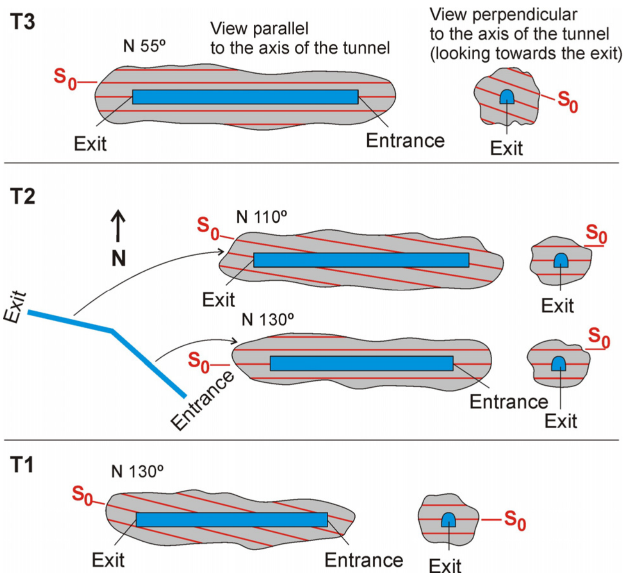

Figure 4. Influence of geological features on T1, T2 and T3.

T1, T2 and T3 were excavated in a sequence of fine silty and tuffaceous sandstones with interbedded siltstones and triassic dark shales. In T3 predominates sandy layers, while the T1 and T2 are excavated in shaly facies (figure 7).

2.3 Western tunnels

Tunnels T4 and T5 share the same geology and structural features (figure 5).

In this case, they are formed by red cross-stratified sandstone, with red clay levels and layers and lenses of coarse matrix. The thickness of the layers varies between a metric to decimeter size.

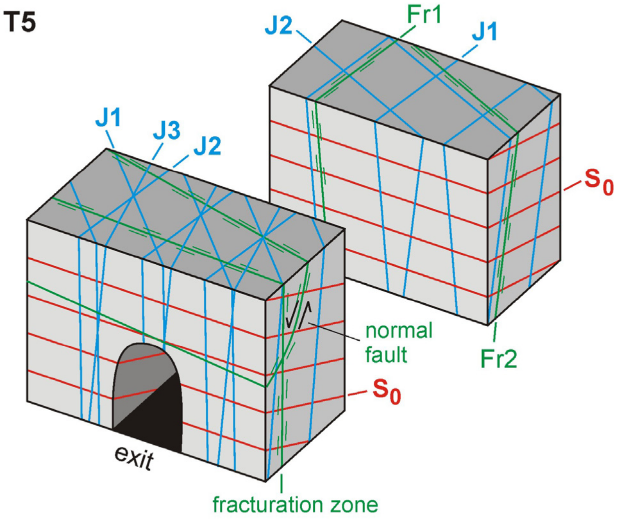

Figure 5. Structural features of T4 and T5

Tunnel T7 shows reddish-brown sandstone formed by greywacke with gray fresh cut formed in Carboniferous age. They have well stratified planar layers of variable thickness (from 0.5 to 0.10 m to 1 m). There are thin layers of white sandstone lens shaped, of centimeter thickness, interspersed in the gray greywacke (figure 6).

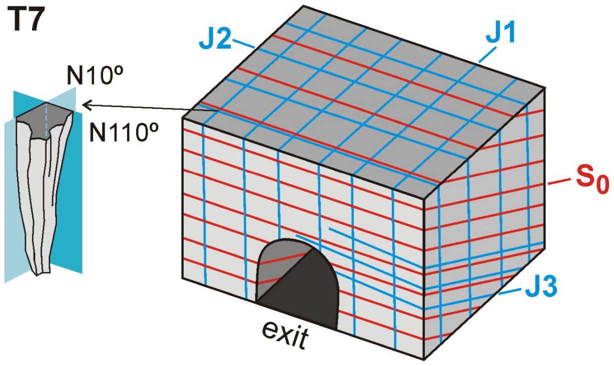

Figure 6. Structural features of T7

3 GEOTECHNICAL FEATURES

3.1 Tunnel Classification

Rock mass characterization was done following the Hoek-Brown model. Tables 1 and 2 summarize the results of compression tests and diametrical uniaxial compression (Brazilian test) samples of sandstone and mudstone.

It is observed that intact rocks samples present are of medium to high resistance. The support provided by the design was estimated by using RMR (Bieniawski, 1989) and Q (Barton el al, 1974) method. During construction geological surveys were conducted on the front as it was excavated, and expected support was adjusted according to them.

Table 1. Uniaxial Compressive Strength

ID	**Location**	**Lithology**	**UCS (Mpa)**
CP1	PS T2	Yellow sandst.	108
CP2	PS T5	Red sandstone	81
CP3	PS T5	Red sandstone	75
CP4	PE T7	Black Sandst.	220
CP5	PE T7	Black Sandst.	182
CP6	PS T5	Mudstone	128
177-06	PORTAL	Mudstone	87

Table 2. Indirect Tensile Strength (Brazilian Test)

ID	**Location**	**Lithology**	**Brasilean test (Mpa)**
CP1	PS T2	Yellow sandst.	4.3
CP2	PS T5	Red sandstone	3.0
CP3	PS T5	Red sandstone	4.3
CP4	PE T7	Black Sandst.	10.6
CP5	PE T7	Black Sandst.	2.4
CP6	Ps T5	Mudstone	9.9

3.2 Support types

The solutions were raised in five kinds of support, modifying the provisions of the RMR method.

Support Type S1 (Q> l0 - RMR> 55) was not found in the excavation front and was not used.

Support Type S2 (5 <Q <l0 - 48 <RMR <55) considered sealed with H25 shotcrete with 4 cm minimum thickness. Also, 25 mm diameter dowels and 4.0 m long in the crown, spaced 1.5 m x 1.5 m, and a 1st layer of H25 fiber shotcrete support with 7 cm minimum thickness. Final lining consists of Projected H25, with 7cm minimum thickness.

Support Type S3 (l <Q <5 - 35 <RMR <48) considered sealed with 5 cm minimum thickness of H25 fiber shotcrete. Also, 25 mm diameter dowels and 4.0 m in length, in walls and crown, spaced 1.5 m x 1.5 m, and a first layer of H25 fiber shotcrete with a minimum 10 cm thick. Final lining consists of 10 cm. of H25 shotcrete.

Support Type S4 (0.05 <Q <l - 10 <RMR <35) considered a sealed with 5 cm of H25 fiber shotcrete, and 25mm diameter dowels and 4.0 m in length, in walls and crown, spaced 1,25 m x 1,25 m. Also, a 1st layer of shotcrete support with H25 fiber shotcrete with 7cm minimum thickness profile and HEA or HEB steel sets spaced 1.25 m between them and a 2nd layer of H25 fiber shotcrete with a minimum thickness of 13cm. Final lining was 10cm thick of H25.

Support Type S5 (Q <0.05 - RMR <10) was not used in the tunnels.

In all cases fiber shotcrete has 40 kg/m^3 of steel fibers. In some places, it was replaced with wire mesh l00 mm x 100 mm x 6 mm in diameter.

Additionally, in faulty sectors, swellex bolt and spiling were applied.

A summary of the support types found in tunnels is shown in Table 3.

Table 3. Summary of support types for tunnels

	SUPPORT (m)						
	S1	S2	S3	S3M	S4	S4M	S5
1	-	-	155	-	30	-	-
2	-	-	170	20	40	-	-
3	-	-	-	-	142	51	-
4	-	120	394	-	12	-	-
5	-	50	354	-	34	-	-
7	-	-	271	-	50	-	-

3.3 Failure Modes

3.3.1. Tunnels in soft rocks

Tunnel 1 was excavated in rock mass classified as S3 (84%) and S4 (16%) and in dry conditions. Only one minor fault was found and there were five joint families, including stratification.

Tunnel 2 excavation was done in S3 type (74%), S3M (9%) and S4 (17%) and also in dry conditions. Minor faults were mapped between within 30 m. and four joint families were identified discontinuities.

Tunnel 1 and 2, were excavated in a pelitic rock mass with horizontal layers and the failure were due weakening of slabs in the tunnel key and falling rock (Figure 7). To a lesser extent it was observed small falls of block with size range from centimeter to decimeter.

Figure 7. Excavation front within horizontal layers of shale and sandstone in T1.

Tunnel 3 were excavated in S4 type (74%), S3M (9%) and S4M (26%) and also in dry conditions. It was possible to use mechanical excavation procedures.

Rock mass was part of an old slide and showed a high degree of extensional fracturing, stepped and rotated blocks (Figure 8 and 9). Open joints up to 10 cm width, filled with pieces of rock were found in outcropts (figure 8b) and inside the tunnel excavation.

Figure 8a. Stepped and rotated block due to the slide process near portal of T3.

Figure 8b. Close up of figure 8a. Open joints are filled with pieces of rocks.

The main fault areas have been mapped in outside outcrops, with strike sub-parallel to the valley and T3 axis, and perpendicular to the direction of movement of the slide. This morphology was generated by the relaxation of the valley sides during the formation of the hill and the erosion of the antecedent river that carved it.

Figure 9. Stepped and rotated blocks in T3.

These successive fault zones caused stability problems in the crown of the tunnel. (figure 10). Most of the tunnel trace follows a loose zone filled with more than 2 m thick cataclastic soil matrix vertical layer, and up to 10 cm thick voids that could be part of the slide. Several incidents involved cave in flows of broken pieces of rock and soil, up to 5 meter above the crown. The excavation cycle was very slow due to the need for installing steel sets.

3.3.1. Tunnels in hard rocks

Tunnel 4 and 5 were fully excavated in hard rock, red sandstone (Fm. Talampaya) and T7 in grey greywakes, using conventional drill and blasting methods.

Figure 10. Cataclastic fill between rock blocks inT3.

Tunnel 4 excavation was done in type S2 (23%), S3 (75%) and S4 (2%) and in dry conditions. One important failure zone was observed during 14m. along the axis. Three families of discontinuities were identified.

Tunnel 5 was excavated in S2 type support (11%), S3 (81%) and S4 (8%). It went through some minor subvertical faults and perpendicular to the axis of the tunnel and 4 families of discontinuities were surveying.

The main problem encountered during excavation was the falling wedge blocks of rock formed by the combination of discontinuities. These falls caused some overbreaks mainly in the crown and shoulder (figure 11).

Figure 11. Typical rock wedges formed in T5

The effectiveness of the support was verified with convergence measurements at stations located at specific positions of the tunnels. The measurements were performed with tape extensometer.

4 CONCLUSIONS

The excavation of the tunnels crossing the Sierra del Valle Fertil was controlled by sedimentary rock formations. In hard rocks, drill and blasting methods were used and in soft rock, it was possible to use mechanical excavation procedures.

Failure incidents were related with the rock mass characteristics. Soft rock, shale and sandstone presented in T1 and T2, produced horizontal slabs that tend to fall. In T3, the valley generated by the river induced stress relaxation and direct faulting. One of this was observed along the tunnel axis.

In hard rock, mainly sandstone and conglomerate, crossed by T4, T5 and T7, the stability of rock wedges were the main problem.

Convergence was monitored by measurements with extensometer tape sections. Its measurement showed stabilization within a few weeks after the excavation.

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