Geotechnical Stability Analysis of San Francisco Tunnel

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SUMMARY

In underground excavations the geotechnical evaluation of stability is fundamental. The tunnel to be built will help to solve the transport problem in Lima city due to the population growth, which was the reason for the stability analysis of two alternative proposals A and B in the portals and tunnels, using software Rocplane, Swedge and Unwedge, recommending the corresponding supports. The rock's RMR is type II and III, in both alternatives there is at least one family of fractures parallel to the excavation direction, which would cause some instability.

INTRODUCTION

The research project comprises the geological - geotechnical study of the tunnel that would link La Molina and Santiago de Surco districts, two alternatives are presented: A, approximately 340 m in length and B, approximately 220 m in length, it will have two lanes and the dimensions would be 11 m wide and 8 m height, similar to the Santa Rosa tunnel (currently in operation) linking San Juan de Lurigancho and Rímac districts, according to the Metropolitan Lima's Master Plan of Road Development, elaborated in the 70's. It is important to analyze it because it will reduce the time that is used in the transport.

The rocky massif geomechanical classification (RMR and Q), wedge analysis with Unwedge software was carried out, determining the corresponding support with the design chart of the Q system (Grimstad and Barton, 1993).

PROBLEM PRESENTATION

The Metropolitan Lima's Master Plan for Road Development, developed in the 1970s to plan and organize urban transport, decided to carry out a series of projects to minimize the distances traveling, so it is necessary to cross some rocky hills, opting to build tunnels such as the Santa Rosa and San Martin tunnels (currently in operation) linking San Juan de Lurigancho and Rímac districts, Puruchuco tunnel linking Av. Javier Prado and Ate Vitarte district (currently in operation) and San Francisco tunnel (in project) that would unite La Molina and Santiago de Surco districts.

The project is located in the central part of the Peruvian coast in Lima Region, between La Molina and Surco districts, at an altitude between 245 and 355 meters above sea level between the geographic coordinates NORTH: 8660700 - 8661200 and EAST: 287400 - 288000 corresponding to the hills (witnessing hills in the middle of Lima's alluvial cone) bordering the Cordillera Occidental foothills.

The rocky massif is formed by Batolito de la Costa intrusive igneous rocks formed by granites, granodiorites and diorites with undifferentiated contacts, of phaneritic texture, holocrystalline, medium-to-fine-grained, hipidiomorphic; and volcanic rocks (Andesite) of aphanitic and porphyritic texture, these rocks are covered mainly by residual soil of little thickness, the slopes foot is covered by colluvial deposits, the ravines are covered by blocks and fragments angular fallen from the high parts with few fines.

Figure 1. Location of the San Francisco tunnel.

OBJECTIVES

- Evaluate tunnel stability with Unwedge software application and determine the appropriate support to stabilize it.

SPECIFIC OBJECTIVES

- Rock massif classification RMR (Bieniawski, 1979) and Q (Barton et al., 1974).
- Tunnel portals stability analysis with Rocplane and Swedge software.
- Tunnel stability analysis with Unwedge software and determination of the safety factor.

METODOLOGY

For this project, two possible tunnel traces (alternatives A and B) have been analyzed, comprising three stages.

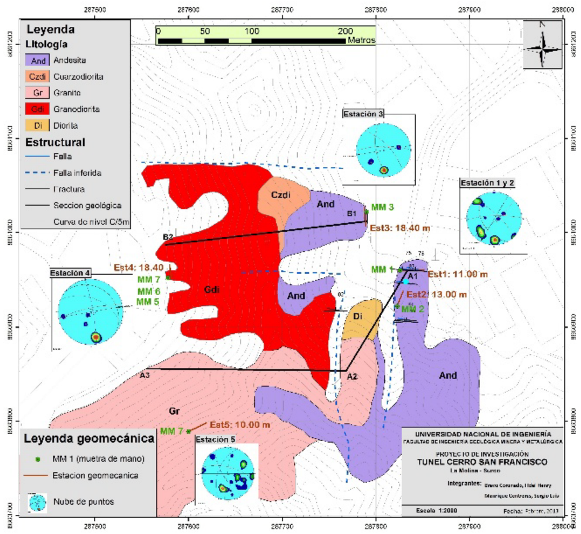

Figure 2. Geological map with two possible stroke alternatives.

First stage:

- Recognition of the work area.
- Geological and geotechnical mapping.
- Selection of structural domains and location of discontinuity measurement stations.
- Field data collection: rock matrix for petrographic and petrologic studies, rock mechanics (resistance) and annotation of discontinuities characteristics (spacing, persistence, continuity, roughness, resistance of walls, opening, filling and water leaks).

Second stage:

Office I6 235 and Geology Laboratory No 8:

- Elaboration of geological-geotechnical plane.
- Macroscopic description and microscopic study of rock matrix for identification, resistance determination in the Rock Mechanics laboratory-FIGMM.

Third Stage:

Classification of the rock mass RMR, Q, stability analysis of the portals, stability analysis of wedges and calculation of support.

Determination of RMR (Bieniawski, 1979)

Developed by Z. T. Bieniawski during the years 1972-73, and has been modified in 1976 and 1979, based on more than 300 real cases of tunnels, caverns, embankments and foundations.

To determine the RMR index of rock quality, use is made of the six parameters of the terrain, which are listed below:

- Material resistance to simple compression
- RQD (Rock Quality Designation)
- Discontinuities spacing
- Discontinuities state
- Water presence
- Discontinuities orientation

The RMR is obtained as a sum of scores that correspond to the values of each of the six parameters listed (Table 1).

1	RESISTENCIA A LA ROCA SANA (MPa)	Ensayo carga puntual	> 10	4-10	2-4	1-2	-
		Compr. simple	> 250	100-250	50-100	25-50	5-25 / 1-5 / < 1
	VALORACIÓN		15	12	7	4	2 / 1 / 0
2	RQD%		90-100	75-90	50-75	25-50	< 25
	VALORACIÓN		20	17	13	8	3
3	SEPARACIÓN DISCONTINUIDADES		> 2m	0.6-2	0.2-0.6m	0.06-0.2m	< 0.06m
	VALORACIÓN		20	15	10	8	5
4	ESTADO DIACLASAS		Muy rugosas Discontinuas Borde sano y duro	Ligeramente rugosas e < 1mm Borde duro	Ligeramente rugosas e < 1mm Bordes blandos	Rellenos e < 5mm Abiertas Continuas	Rellenos blandos e < 5mm Continuas
	VALORACIÓN		30	25	20	10	0
5	PRESENCIA DE AGUA	Caudal en 10m túnel	Nulo	< 10 l/min	10-25 l/min	25-125 l/min	> 125 l/min
		σ_w/σ_3	0	0-0.1	0.1-0.2	0.2-0.5	> 0.5
		Estado	Seco	Ligeram. húmedo	Húmedo	Goteando	Fluyendo
	VALORACIÓN		15	10	7	4	0

Table 1. Bieniawski's Geomechanical Classification (1979).

RMR value ranges from 0 to 100, and the better the rock quality. Bieniawski distinguishes five rocks types or classes according to the RMR value (Table 2).

Calidad de macizos rocosos en relación al índice RMR

Clase	Calidad	Valoración RMR	Cohesión	Ángulo de rozamiento
I	Muy Buena	100-81	> 4 kg/cm²	> 45°
II	Buena	80-61	3-4 kg/cm²	35°-45°
III	Media	60-41	2-3 kg/cm²	25°-35°
IV	Mala	40-21	1-2 kg/cm²	15°-25°
V	Muy mala	< 20	< 1 kg/cm²	< 15°

Table 2. Rocky massifs quality (Bieniawski, 1979).

Orientación de las discontinuidades en el túnel

Dirección perpendicular al eje del túnel				Dirección paralela al eje del túnel		Buzamiento 0°-20°. Cualquier dirección
Excavación con buzamiento		Excavación contra buzamiento				
Buz. 45-90	Buz. 20-45	Buz. 45-90	Buz. 20-45	Buz. 45-90	Buz. 20-45	
Muy favorable	Favorable	Media	Desfavorable	Muy desfavorable	Media	Desfavorable

Corrección por la orientación de las discontinuidades

Dirección y buzamiento		Muy favorables	Favorables	Medias	Desfavorables	Muy desfavorables
Puntuación	Túneles	0	−2	−5	−10	−12
	Cimentaciones	0	−2	−7	−15	−25
	Taludes	0	−5	−25	−50	−60

Table 3: Correction by orientation of discontinuities.

Barton's Q classification (1974)
It determines the quality of the massif and is applied in the definition of support requirements in underground excavations.
On a logarithmic scale, from 0.001 to 1000.
Defined from 6 parameters

$$Q = \frac{RQD}{Jn} \times \frac{Jr}{Ja} \times \frac{Jw}{SRF} \qquad \text{(Equation 1)}$$

where:

RQD = Index based on Deere's valuation.
Jn = Index according to the number of fracture systems
Jr = Index according to the roughness of the fractures surface.
Ja = Index according to the alteration in the fractures surface or their filling.
Jw = Reducing coefficient due to water presence.
SRF = (Stress reduction factor) coefficient dependent on the rock mass tensional state.

- Dips software application, to determine discontinuities families.
- Tunnel stability analysis with Unwedge software to determine the wedges.
- Slope stability analysis in portals.

RESULTS

The tunnel will traverse intrusive and extrusive igneous rocks (Figure 3 and 4).

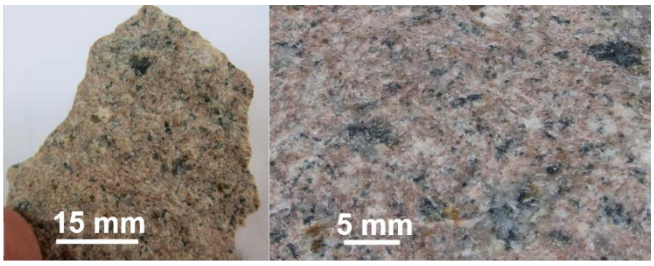

Figure 3. Horblendic granite with rosette shade, 1mm fine-grained crystals, slightly altered.

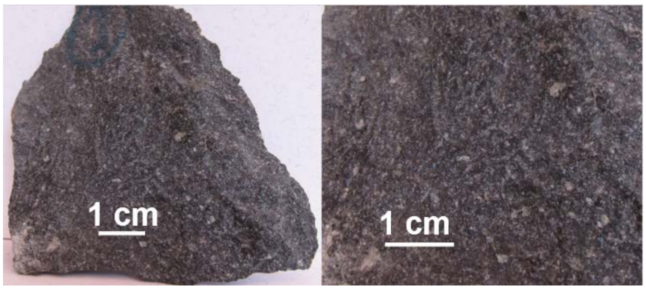

Figure 4. Horblendic porphyritic andesite, blackish gray color.

The rock samples were tested for compressive strength in Rock Mechanics laboratory FIGMM-UNI, obtaining the following results:

Sample	Litology	σ_c (Mpa)
M-1	Andesite	203.37
M-2	Andesite	183.23
M-3	Andesite	190.15
M-4	Granodiorite	121.04
M-5	Granodiorite	90.45
M-6	Granodiorite	214.92
M-7	Granite	218.29
M-8	Granite	234.96

Table 4. Compressive strength test results for eight samples.

Rocky massif RMR classification with harvested field data

CARACTERIZACION DEL MACIZO ROCOSO. RMR

RMR			VALORACIÓN	PUNTUACIÓN
RMR 1	RESISTENCIA A COMP. SIMPLE			12
RMR 2+3	JUNTAS POR METRO	6 10		13 5, 10
		Media		
RMR 4	ESTADO DE LAS JUNTAS	Continuidad		6, 2
		Apertura		1, 5
		Rugosidad		3
		Relleno		2
		Meteorización		3
		Suma		15, 11
RMR 5	PRESENCIA DE	SECO		15
			SUMA	65, 56

POLOS	D.BUZ.	BUZ.
J1	358	78
J2	137	80
J3	044	70
J4	241	42

RESISTENCIA	
R1=Muy debil	
R2=Debil	
R3=Median.	
R4=Resistente	
R5=Muy resist.	X
R6=Extrem. res:	

METEORIZ.	
Grado	
Grado	X
Grado	
Grado IV	
Grado	
Grado VI	

ESTRUCT.	
MASIVA	
EN	
COLUMNAR	
TABULAR	X
IRREGULAR	X
DESMENUZ.	

Table 5. RMR clasification.

The RMR varies from 56 to 65 but it must be corrected because a family is parallel to the excavation direction, we subtract 12 and the RMR would be 44 to 53: a middle class III rock.

Rocky massif Q index with harvested field data

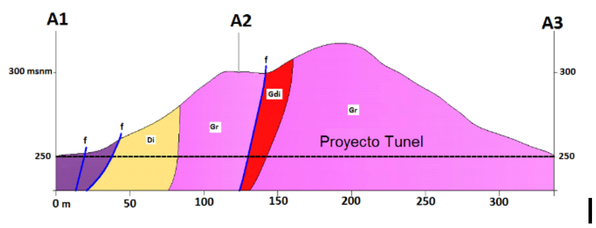

Figure 5. Section A1-A3.

TUNEL ALTERNATIVA A				
Progresivas	0+000 –0+020	0+020 – 0+035	0+035–+080	0+080 –
Tramos (m)	20	15	55	45
Litología	Andesita	Andesita	Diorita	Granito
Estructura	1 Falla	4 Fallas	Falla	Falla
RQD	65	65	75.6	75.6
Jn	18	15	12	12
Jr	1.0 - 1.5	1.0 - 1.5	1.5	1.5
Ja	4	4	3	3
Jw	1	1	1	1
SRF	5	5	2.5	2.5
Indice Q	0.18-0.27	0.21-0.32	1.32	1.32
Sobrecarga	15	30	50	50
Soporte	Sfr(12-15cm) + B(1.3 m)	Sfr(12-15cm) + B(1.3 m)	Sfr(5-9cm) + B(2 m)	Sfr(5-9cm) + B(2 m)

TUNEL ALTERNATIVA A				
Progresivas	0+125 – 0+140	0+140 – 0+0230	0+230 – +0320	0+320 – 0+340
Tramos (m)	20	180		20
Litología	Granodiorita	Granito	Granito	Granito
Estructura	1 Falla			
RQD	75.6	75.6	75.6	75.6
Jn	12	9	9	18
Jr	1.5	1.5	1.5	1.5
Ja	3	2	2	4
Jw	1	1	1	1
SRF	2.5	2.5	5	5
Indice Q	1.26	2.52	2.52	0.315
Sobrecarga (m)	50	60	30	50
Soporte	Sfr(5-9cm) + B(2 m)	Sfr(5-9cm) + B(2 m)	Sfr(5-9cm) + B(2 m)	Sfr(12-15cm) + B(1.3 m)

Table 6. Q clasification.

Q values vary from 0.18 to 0.32 for andesites, the support is shotcrete with 12-15 cm thickness fiber and pins spaced every 1.3 m.

Q values vary from 1.26 to 2.52 for intrusive rocks (Granites, granodiorites and diorites) and support is shotcrete with 5-9 cm thick fiber and bolts spaced every 2 m; and shotcrete with 12-15 cm thick fiber and bolts spaced every 1.3 m for the portal.

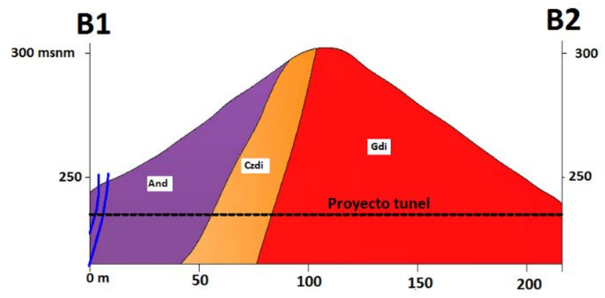

Figure 6. Section B1-B2.

TUNEL ALTERNATIVA B					
Progresivas	0+000 – 0+020	0+020 – 0+055	0+55–0+080	0+080 – 0+200	0+200 – 0+220
Tramos (m)	20	35	25	120	20
Litología	Andesita	Andesita	Cuarzodior	Granodiorita	Granodiorita
Estructura	Fallas				
RQD	65	65	75.6	75.6	75.6
Jn	18	12	9	9	18
Jr	1.0 - 1.5	1.0 - 1.5	1.5	1.5	1.5
Ja	4	2	2	2	4
Jw	1	1	1	1	1
SRF	2.5	5	5	5	5
Indice Q	0.216-0.36	0.541-0.81	1.26	1.26	0.312
Sobrecarga (m)	15	30	50	40	20
Soporte	Sfr(12-15cm) + B(1.3 m)	Sfr(9-12cm) + B(1.5 m)	Sfr(5-9cm) + B(2 m)	Sfr(5-9cm) + B(2 m)	Sfr(12-15cm) + B(1.3 m)

Table 7. Q index.

For B alternative the Q values vary from 0.21 to 0.81 for andesites and support is shotcrete with 12-15 cm thick fiber and bolts spaced every 1.3 m.

Q values vary from 1.26 to 0.312 for intrusive rocks (Granites, granodiorites and quartzodiorites) and support is shotcrete with 5-9 cm thick fiber and spaced bolts every 2 m; and shotcrete with 12-15 cm thick fiber and bolts spaced every 1.3 m for the portal.

Tunnel trace geomechanical characteristics

Alternative A

This alternative has proposed a tunnel of 340.00 m in length, which is built in two sections: first section 130 m, direction S30 ° W; second section of 210 m, direction W.
Portal A1 would be located in La Molina district at the end of De los Cóndores ave. and portal A2 in Surco district that would link with Los Constructores ave.

Figure 7. Entrance portal A1, La Molina, geomechanical station 1.

- **A1 portal and progressive tunnel 0 + 000 to 0 + 050 excavation direction S30°W**

Three major fracture systems and an occasional system were determined, which are detailed

- F1: N88°E/77°N
- F2: N45°W/69°NE
- F3: N47°E/81°SE
- F4: N30°W/42°SW

In the stability analysis, the slope orientation E-W / 70°N is stable.
With Unwedege software, the analysis of wedges occurring in the tunnel was carried out, it is possible to form sporadic wedges with a weight of 89 tons.

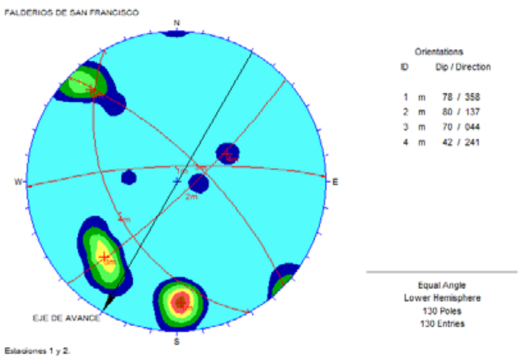

Figure 8. A1 portal and tunnel progresive 0+000 to 0+050.

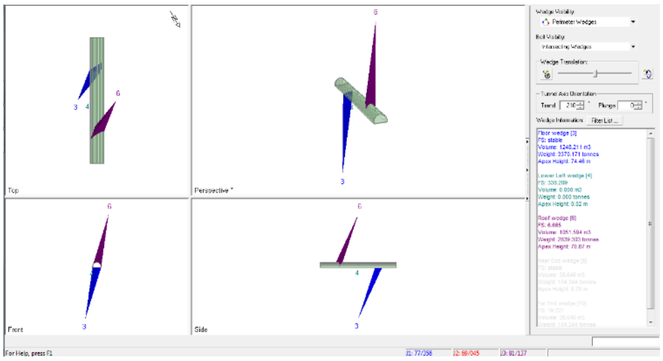

Figure 9. Four wedges with high safety factor.

o A2 portal and progressive tunnel 0+050 to 0+130 and 0+130 to 0+340

Three main and one sporadic fracture systems were determined, with following orientations:

- F1: N 76°W/62°NE
- F2: N30°W/69°SW
- F3: N21°E/48°NW
- F4: N7°E/87°NW

According to the slope stability analysis of this orientation portal N55°E / 45°NW, 2 wedges are presented.

With Unwedge software, wedges with a high safety factor were determined so that it is stable between the progressive 0 + 050 to 0 + 130 and in the direction of excavation S30°W

Between the progressive 0 + 130 to 0 + 240 two wedges with high safety factors are presented, reason why it is considered that it is stable.

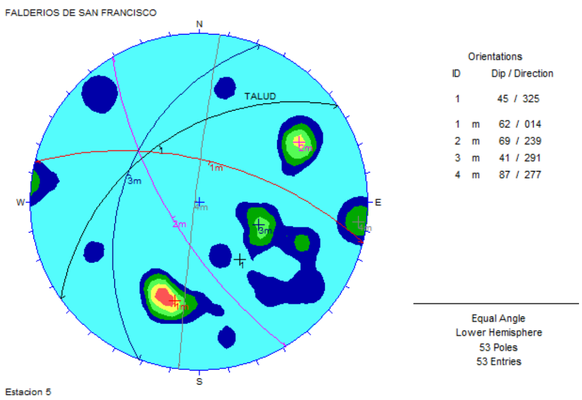

Figure 10. Slope portal A2 of N55°E/45°NW direction.

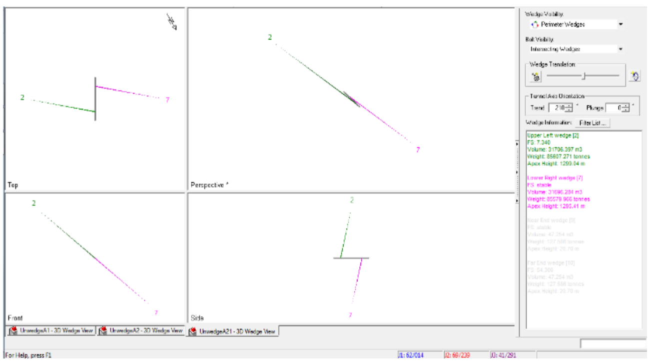

Figure 11. Two wedges of high safety factor are presented.

Alternative B

In this alternative has been proposed a tunnel of length 220.00 m, which would be built in two sections: first section 90 m, direction S80°W; second section of 130 m, direction N80°E.

Portal B1 would be located in La Molina district at the end of Los Cóndores ave. at 70 m in the direction of N40°W of portal A1; portal B2 would be located in Surco district at 150 m in the approximate direction S10°W which would link with Los Constructores ave.

Figure 12. B2 portal: intrusive rocks, faults parallel to the excavation.

o B1 portal and tunnel progresive 0+000 to 0+090 excavation direction S80°W

Three major fracture systems were identified, the orientations of which are as follows:

- F1: E-W/72°N
- F2: N43°W/65°NE
- F3: N12°W/59°SW

According to the slope stability analysis performed in the N-S / 73ºE orientationl, is stable.

With Unwedege software, the analysis of the wedges occurrence in the tunnel was performed, two wedges with high safety factors are presented, making it stable.

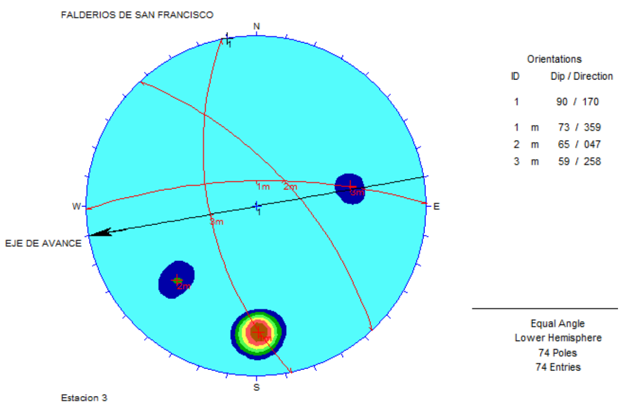

Figure 13. B1 portal and tunnel progresive 0+000 to 0+090.

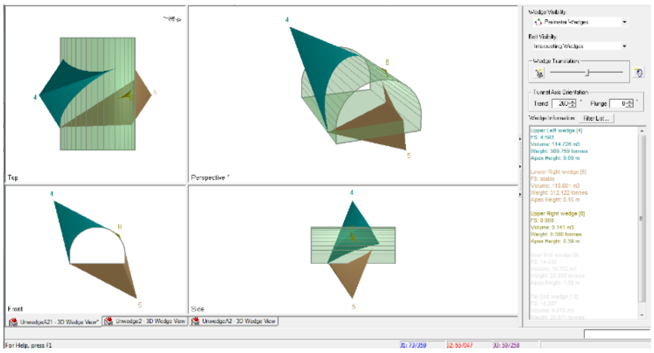

Figure 14. It has three wedges with a high safety factor.

o **B2 portal and tunnel progresive 0+090 to 0+220 excavation direction N 80°E**

Four main and one sporadic fracture systems were determined, the orientations being as follows:

- F1: N 78°E/76°NW
- F2: N50°W/15°NE
- F3: N68°W/44°NE
- F4: N10°W/81°NE

According to the stability analysis, this portal with orientation of N20°W / 30°SW is stable.

With these fracture systems and their respective parameters and with Unwedge software use, 4 wedges with a high safety factor were determined so it is stable.

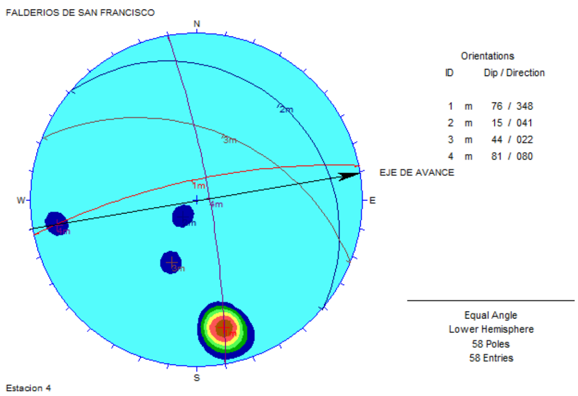

Figure 15. B2 portal and tunnel progresive 0+090 to 0+220.

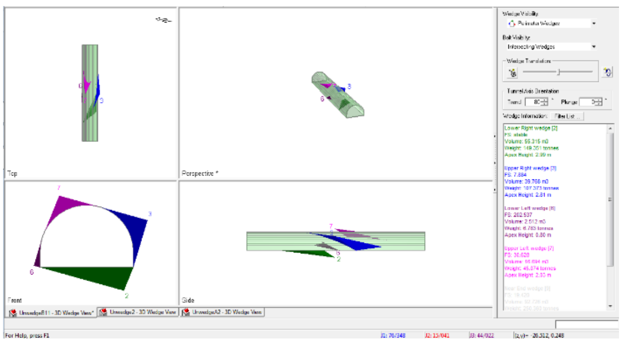

Figure 16. Presence of four wedges.

CONCLUSIONS

- The tunnel that will connect La Molina and Surco districts, would cross volcanic rocks (andesites) of regular quality, type III rock according to the RMR classification in the portals located in La Molina district and by intrusive rocks horblendic Granite, horblendic Granodiorita and good quality rock type II horblendic Cuarzodiorita and in some stretches regular rock types III, according to the RMR classification located in Surco district.

- In alternative A, portal A1, in first 50 m the tunnel will be excavated in andesitic rocks and will cross five perpendicular faults.

- In alternative B, portal B2, tunnel will pass through three faults parallel to the excavation.

- In both alternatives A and B wedges with high values of safety factors are presented, which does not represent risk due to falling blocks, only in portal A1 and along the 50 m of the tunnel can occur sporadic wedges fall.

- In both alternatives there is at least one family of fractures parallel to the excavation direction, which would cause some instability.

- In portal A1, four wedges have a high safety factor. For the A2 portal, two wedges have a high safety factor (both in the 210° and 90° feed).

- For portal B1, it has three wedges with a high safety factor; and four wedges in the 80° direction.

- Portal slope A1 of steering E-W / 70°N, stable. Slope portal A2 of direction N55°E / 45°NW presents 2 wedges.

- Portal slope B1 of direction N-S / 73°E, stable. And finally, B2 slope portal address N20°W / 30°SW, stable.

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