In-situ stress amplification in tunnels from Spain, Iran and Chile estimated by TSI and SAF indices

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ABSTRACT: TSI and SAF methodologies have been applied to 6 tunnels located in Spain, Iran and Chile to estimate the regional tectonic in-situ stress (K) and the increment of the principal horizontal stress over the regional horizontal stress in a particular tunnel section (SAF). For high values of SAF, deformations in the tunnel sections were much higher than those expected in the design. The increment of the principal horizontal stress over the mean regional horizontal stress, due to local geological and geomechanical anisotropies have ranged from 1.1 to 2.9. In-situ stress tunnel zoning in terms of the variation of SAF values is presented potential zones of tunnel instability. These methodologies can be particularly important in regions with complex geological conditions and with high or moderate in situ stress.

1 INTRODUCTION

The importance of the in-situ stress on the stability of underground excavations is widely recognised. When anisotropic or high in-situ stress are present, failure and plastification phenomena such as squeezing or rockburst may occur, so that it is essential to know the magnitude and direction of in-situ stress for any underground project (Hoek and Marinos, 2009). However, this important consideration is often ignored and many tunnels are still designed without in-situ stress measurements. The importance of these anisotropies has often been underestimated and very little research into this subject is available.

This paper focuses on the influence of geological anisotropies on the magnitude of in-situ stress in tunnel projects. Based on practical experience of long-term stability problems in tunnels and underground mines located in the study area of Pajares Mountains (N. Spain), where significant deformations linked to faults and other geological anisotropies has been detected, a study was carried out of the new high speed railway tunnels recently constructed in these mountains, as well as in other tunnels located in Iran and Chile, both under high tectonic stresses.

2 ESTIMATING IN-SITU STRESS BY TSI INDEX AND SAF FACTOR

Empirical relationships have been proposed by González de Vallejo and Hijazo (2008) using the TSI index to account for tectonic stress. This index considers geological parameters and elastic properties of the rocks (Eq. (1)). The relationships between K and the TSI were derived from an extensive worldwide database corresponding to different zones in which several in-situ stress measurements were taken to give a mean K value (Hijazo, 2009). Eqs. (2) and (3) show K–TSI relationships obtained from global data as a function of the age of the main tectonic orogeny affecting the rock mass.

Eqs. (4) and (5) show regional K–TSI relationships for Spain (Fig. 1):

$$TSI = \log [(T/H \cdot E)] \quad (1)$$

where T=age of the first orogenic cycle or main folding period affecting the rock mass (years) (Hercynian = 300 Ma, Alpine = 12 Ma and Caledonian = 600 Ma); E = elastic modulus of the intact rock (GPa); H = maximum overburden thickness throughout its geological history (meters).

$$K_{global} = -1.93 \cdot TSI + 8.38 \text{ for Hercynian rocks} \quad (2)$$

$$K_{global} = -2.09 \cdot TSI + 6.15 \text{ for Alpine rocks} \quad (3)$$

$$K_{regional} = -2.27 \cdot TSI + 9.51 \text{ for Hercynian rocks} \quad (4)$$

$$K_{regional} = -2.45 \cdot TSI + 7.27 \text{ for Alpine rocks} \quad (5)$$

To account for local factors (structural and perturbed in-situ stresses) influencing the in-situ stress in a tunnel excavation, the following methodology has been developed by Hijazo and González de Vallejo (2012) (Fig. 2):

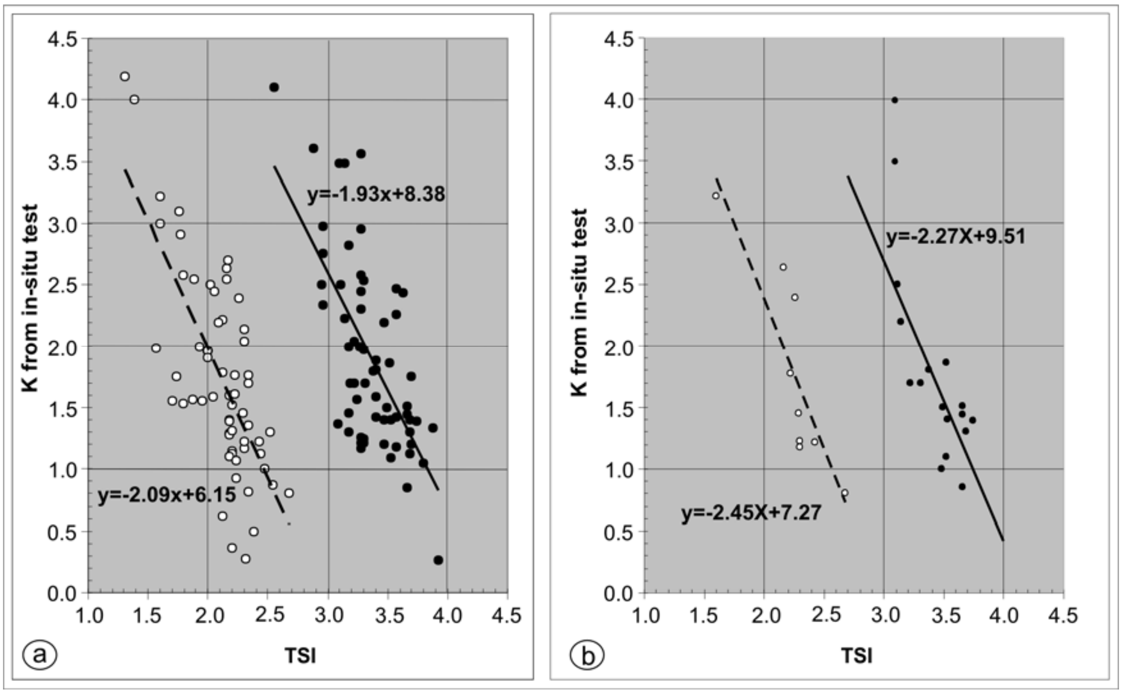

Figure 1. a: K-TSI relationships from global data, after González de Vallejo e Hijazo (2008). ● Hercynian rocks; ○ Alpine rocks; ▬▬ Global K-TSI relationship for Hercynian rocks; ▬ ▬ Global relationship for Alpine rocks. b: Regional K-TSI relationships for Spanish data. ● Hercynian rocks; ○ Alpine rocks; ▬▬ Regional K-TSI relationship for Spanish Hercynian rocks; ▬ ▬ Regional K-TSI relationship for Spanish Alpine rocks.

- From the hydrofracture test and TSI index (K–TSI relationships) a representative value of $K_{regional}$ is assigned for an undisturbed rock mass not affected by perturbed in-situ and structural stress (Fig. 2: 1a, 1b and 1c).

- σ_H can be obtained from $K_{regional}$ assuming this is the maximum horizontal stress due to tectonic stress and corresponds to $\sigma_{Hregional}$ (Fig. 2: 1d).

- Before tunnel excavation the support is designed and the support pressure (P_o) is calculated for different tunnel sections. A mean in-situ stress value equivalent to $K_{regional}$ is usually adopted for support calculations (Fig. 2: 2a).

- If some tunnel zones deform more than expected during excavation, the support has to be modified by increasing the support pressure (P_f) as required to stabilise the rock mass deformations (Fig. 2: 2b).

- Geological and geomechanical surveys can identify geological structures and rock mass anisotropies associated with the tunnel zones affected by significant deformations. In these cases the increment of the support pressure (P_f–P_o) can be attributed to the structural and perturbed in-situ stresses, where this increment is $\Delta\sigma_{Hlocal}=P_f-P_o$ (Fig. 2: 2c).

- In the tunnel zones with significant deformations the maximum horizontal stress is assumed to be equivalent to: $\sigma_{Hlocal}=\sigma_{Hregional}+\Delta\sigma_{Hlocal}$. The sign in this equation is positive because only the tunnel zones where σ_{Hlocal} is higher than the $\sigma_{Hregional}$ are considered (Fig. 2: 2d).

- In these tunnel zones the in-situ stresses are affected by structural and perturbed in-situ stresses and the new K values (K_{local}) can be obtained for each zones, where $K_{local}=\sigma_{Hlocal}/\sigma_v$ (Fig. 2: 2e).

- $K_{local}/K_{regional}$ ratios are calculated to obtain the Stress Amplification Factor (SAF). This factor is related to the increment of the in-situ stress due to structural and perturbed in-situ stresses (Fig. 2: 3).

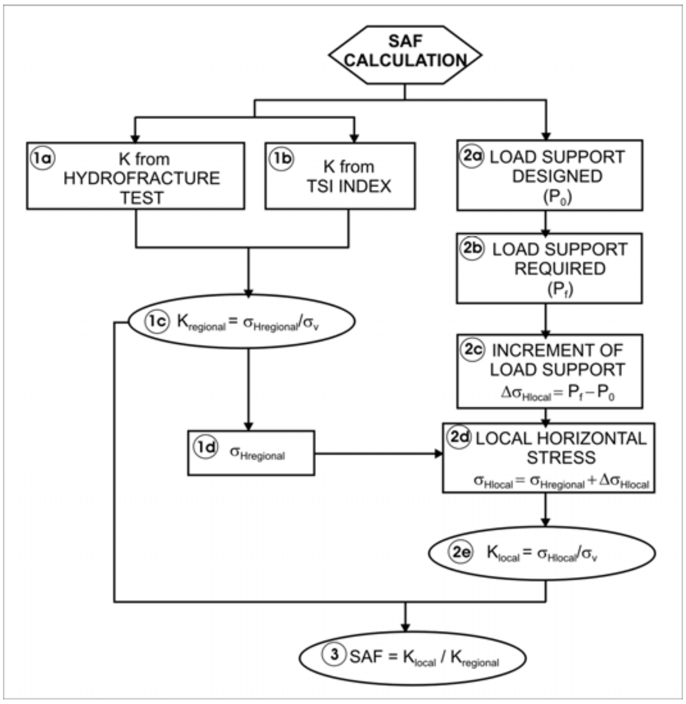

Figure 2. Estimating the Stress Amplification Factor (SAF) in the Pajares tunnels (Hijazo and González de Vallejo, 2012).

3 CASE STUDIES

Six tunnels located in Spain, Iran and Chile where large deformations were observed during the excavation have been analysed. These tunnels represent a wide variety of lithologies, tectonic conditions and different geological settings. All have been excavated by drill and blasting and according with the NATM methods and they have been designed for railway or roads.

3.1. *Pajares Tunnels*

The previously described methodology was applied to four tunnels, *Buen Suceso I*, *Peredilla*, *Nocedo* and *Alba,* located in the Cantabrian Mountains between León and Asturias, N. Spain (Fig. 3), as a part of a new high speed railway line. The tunnel sections and lengths range from 75 to 90 m^2 and 391-684 m respectively, with a total length of 2177 m and a maximum overburden thickness from 70 to 116 m.

Rocks mass consist on Devonian and Carboniferous rocks, predominantly limestones, dolomites, shales, sandstones, conglomerates and quartzites.

The geomechanical properties are summarised in Table 1. The geological cross section of the *Buen Suceso I* tunnel is shown in Figure 4 as an example. Hydrofracture tests and geotechnical instrumentation were installed during the tunnel excavation.

The tunnels are located in a complex geological structure formed by folds and thrust faults with heterogeneous materials. Important deformations were observed in tunnels and mines located in this region, affecting the same type of materials and geological structures as in the tunnels analysed.

Hydrofracture tests provide a mean value of K=1.5 in nearby mines (Hullera Vasco-Leonesa, 1988). Hydrofracture tests carried out on these tunnels have shown K values between 1.39 and 1.80 (U.T.E. Geoconsult-Ineco-CGS, 2003). TSI index was calculated obtaining a range value of K from 1.27 to 1.52 (Table 2).

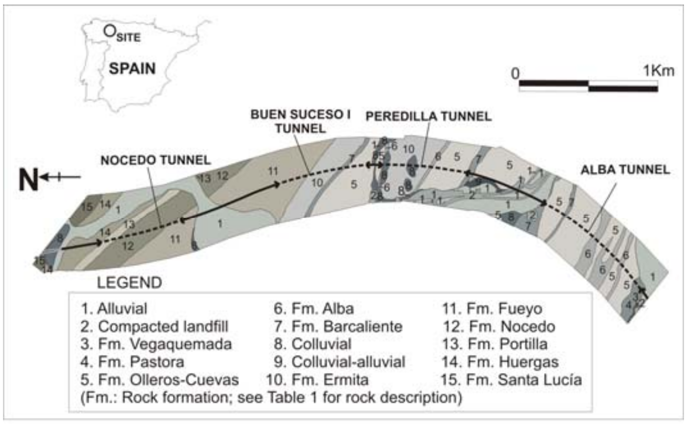

Figure 3. Site locations of Pajares tunnels and geological sketch

During tunnels construction significant deformations were measured in forty tunnel sections. An investigation on tunnel deformations and geological anisotropies was carried out. Geological and geomechanical surveys identified thrust faults, folds and contacts between rocks with significantly contrasting strength and deformability properties in those tunnel sections where large deformations were observed (Fig. 4).

Table 1. Geomechanical properties of the Pajares tunnels.

Lithologies*		Unit weight	Uniaxial compressive strength (σ_c)	Elasticity Modulus
		kN/m^3	MPa	GPa
Conglomerates	1	27.9	12.0	13.0
	2	26.5	10.4	16.6
Shales	3	26.8	12.3	12.3
	4	28.0	19.3	7.5
	5	26.8	17.1	32.0
Sandstones	6	26.8	53.0	17.1
	7	27.4	53.4	37.7
	8	25.5	15.5	17.2
	9	27.2	34.5	31.8
	10	27.4	37.5	35.4
Limestones	11	27.0	53.7	52.9
	12	27.0	30.0	40.6
	13	27.0	38.5	50.4

* 1: Fm. Pastora, 2: Fm. Candanedo, 3: Fm. Huergas, 4: Fm. Fueyo, 5: Fm. Olleros, 6: Fm. Huergas, 7: Fm. Nocedo, 8: Fm. Fueyo, 9: Fm. Ermita, 10: Fm. Olleros, 11: Fm. Portilla, 12: Fm. Alba, 13: Fm. Barcaliente. Fm: rock formation. The data refer to mean values.

Table 2. $K_{regional}$ estimated by TSI index as $K_{regionalSpain} = -2.27 \cdot TSI + 9.51$ for Pajares tunnels.

Tunnel	T	H	E	TSI	$K_{regional}$
	Ma	m	GPa		
Buen Suceso I	300	2000	34.8	3.63	1.27
Peredilla	300	2000	34.9	3.63	1.27
Nocedo	300	2000	45.3	3.52	1.52
Alba	300	2000	39.6	3.58	1.38

To stabilise the excavations the support initially designed in the project had to be reinforced by a heavier one. Based on a back analysis of the rock mass deformations and the support pressure needed to stabilise the tunnel sections, SAF values were estimated in the forty tunnel sections (Table 3) following the methodological procedure described in Section 2.

3.2. *Qazvin-Rasht Tunnel*

This is the nº 7 of the 14 railway tunnels located in the Qazvin province, North of Iran (Fig. 5). Tunnel section is 104 m^2, length 595 m and the mean overburden thickness is 150 m. Rock mass consists on andesites and some tuffs affected by large faults and sheared zones being both the main source of inestabilities.

Geomechanical properties are shown in Table 4. The tunnel is located in the Alborz region characterised by a complex geology within an active plate border. In situ stress measurements were not available, but high to moderate in situ stress can be expected. $K_{regional}$ have been estimated by $K_{regional}$-TSI relationship (Eq. (3)) as previously described. A mean value of K=1.41 was obtained. During excavation large deformations were observed in 18 tunnel sections. The geological anisotropies related with these tunnel sections are listed in Table 5, as well as the estimated SAF and K_{local} values.

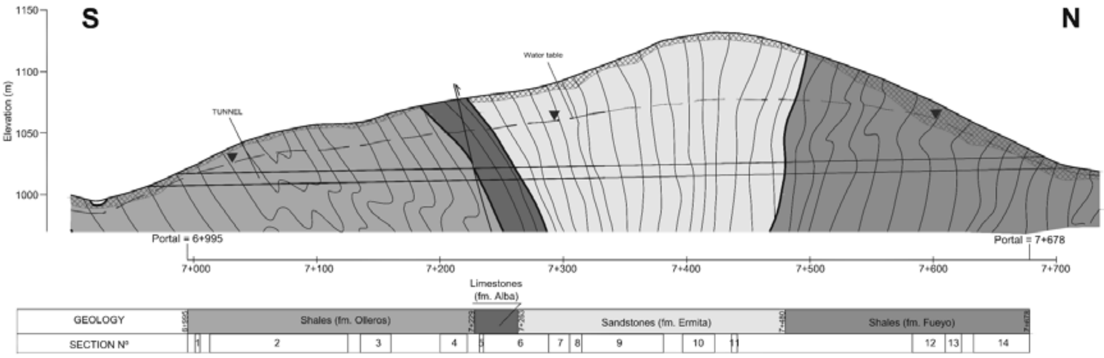

Figure 4. Geological cross section of Buen Suceso I tunnel and tunnel sections where large deformations were observed.

Table 3. Geological anisotropies, stress amplification factors (SAF) and K_{local} values obtained for Buen Suceso I, Peredilla, Nocedo and Alba tunnels.

Tunnel	Tunnel Section	Geological anisotropies	SAF	K_{local}
Buen Suceso I	1	Not identified	1.54-2.09	1.95-2.65
	2	Synclinal fold	1.10-1.26	1.39-1.60
	3	Folds+lithological anisotropies	1.08-1.09	1.37-1.38
	4	Fault	1.07-1.08	1.36-1.37
	5	Fault	1.07	1.36
	6	Fault	1.42-1.44	1.80-1.83
	7	Lithological anisotropies	1.42-1.45	1.80-1.84
	8	Not identified	1.33-1.35	1.69-1.71
	9	Not identified	1.24-1.32	1.57-1.68
	10	Not identified	1.23-1.24	1.56-1.57
	11	Not identified	1.26	1.60
	12	Important lithological anisotropies	1.55-1.69	1.97-2.15
	13	Important lithological anisotropies	1.64-1.83	2.08-2.32
	14	Low overburden thickness	1.15-2.04	1.46-2.59
Peredilla	1	Fault and highly fractured rocks	1.57-1.62	1.99-2.06
	2	Fault and highly fractured rocks	1.62-1.68	2.06-2.13
	3	Fault and highly fractured rocks	1.49-1.51	1.89-1.92
	4	Not identified	1.33-1.39	1.69-1.77
	5	Not identified	1.51-1.54	1.92-1.96
	6	Not identified	1.45-1.46	1.84-1.85
	7	Low overburden thickness	5.07-11.86	6.44-15.06
Nocedo	1	Not identified	1.34-1.44	2.04-2.19
	2	Fault	1.28-1.29	1.95-1.96
	3	Fault and lithological anisotropies	1.23	1.87
	4	Fault and lithological anisotropies	1.24	1.88
	5	Not identified	1.32-1.35	2.01-2.05
	6	Fault	1.86	2.83
	7	Fault	2.00	3.04
	8	Important lithological anisotropies	2.22-2.90	3.37-4.41
	9	Low overburden thickness and fault	2.90-3.21	4.41-4.88
Alba	1	Low overburden thickness	1.37-1.38	1.89-1.90
	2	Low overburden thickness	1.36	1.88
	3	Low overburden thickness	1.33-1.34	1.84-1.85
	4	Low overburden thickness and highly fractured rocks	1.26-1.33	1.74-1.84
	5	Low overburden thickness and highly fractured rocks	1.24-1.26	1.71-1.74
	6	Low overburden thickness and highly fractured rocks	1.16-1.23	1.60-1.70
	7	Low overburden thickness and highly fractured rocks	1.15-1.16	1.59-1.60
	8	Intense folding and fault	1.09-1.10	1.50-1.52
	9	Intense folding and fault	1.55-1.56	2.14-2.15
	10	Intense folding and fault	1.40-1.44	1.93-1.99

3.3. *San Cristóbal Tunnel*

This road tunnel is located in Santiago de Chile city, underneath the Cerro de San Cristóbal. Tunnel section is 80 m^2, length 1777 m and the mean overburden thickness is 153 m. The rock mass is formed by andesites affected by large faults (Fig. 6). Table 6 shows the geomechanical properties of the materials.

During excavation important instabilities were observed in relation with faults and landslides affecting the south portal (Contreras et al., 2008).

Seven tunnel sections needed to be stabilised during excavation and a heavier support have been implemented. Convergence measurements, extensometer and pressure cells in 74 tunnel sections were installed. K has been estimated by the following relationship: $K_{regional}$=-2.09·TSI+6.15, obtaining a mean $K_{regional}$ value as 2.05. This result is in accordance with the tectonics location of the tunnel near a plate tectonic border with high seismicity. In-situ stress measurements were not available. Large deformations have been identified in 7 tunnel sections associated with faults and geomechanical anisotropies that could induce local amplifications of in-situ stress. SAF and K_{local} values have been calculated for each of the 7 tunnel sections following the previously described methodology (Table 7).

Table 4. Geomechanical properties of the Qazvin-Rasht tunnel.

Lithologies	Unit weight	Uniaxial compressive strength (σ_c)	Elasticity Modulus
	kN/m^3	MPa	GPa
Andesites	26.0	80-110	40.0
Altered Andesites	23.5	70-110	-
Andesite lava and Tuffs	19-23	40-70	-

Table 5. Geological anisotropies, SAF and K_{local} values of tunnel nº 7 (Qazvin-Rasht).

Tunnel sections	Geological anisotropies	SAF	K_{local}
1	Low overburden thickness	2.34	3.30
2	Low overburden thickness	1.48	2.08
3	Not identified	1.18	1.66
4	Fault + Important lithological anisotropies	1.20	1.69
5	Fault	1.63	2.30
6	Fault	1.52	2.14
7	Fault	1.59	2.24
8	Inverse fault	1.24	1.74
9	Inverse fault	1.19	1.67
10	Inverse fault	1.42	2.01
11	Fault	1.38	1.95
12	Fault	1.33	1.87
13	Normal fault	1.11	1.57
14	Normal fault	1.06	1.49
15	Not identified	1.09	1.54
16	Not identified	1.07	1.51
17	Not identified	1.06	1.50
18	Normal fault	1.06	1.49

Table 6. Geomechanical properties of San Cristóbal Tunnel.

Lithologies	Unit weight	Uniaxial compressive strength (σ_c)	Elasticity Modulus
	kN/m^3	MPa	GPa
Andesites (A1)	25.7	162.4	36.7
Porphyric andesites (A2)	26.2	62.4	24.4
Andesitic tuffs (A3)	24.9	67.3	9.47
Intrusive rock (Tp) (porphyric andesites)	26.9	117.2	36.9
Intrusive rock (Tp) (altered porphyric andesites)	26.8	80.56	41.5

Table 7. Geological anisotropies, SAF and K_{local} values of San Cristóbal tunnel.

Tunnel sections	Geological anisotropies	SAF	K_{local}
1	Fault	1.18	2.42
2	Fault	1.24	2.54
3	Fault	1.23	2.52
4	Fault	1.26	2.58
5	Geomechanical anisotropies	1.33	2.73
6	Geomechanical anisotropies	1.19	2.44
7	Geomechanical anisotropies	1.79	3.67

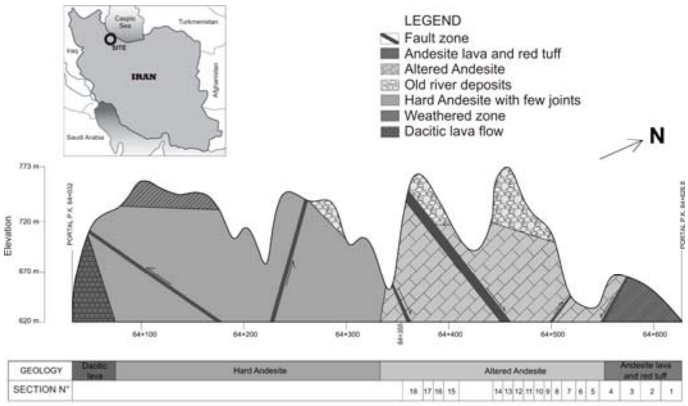

Figure 5. Site location and geological cross section of tunnel nº 7, Qazvin-Rasht (Entezari et al., 2011).

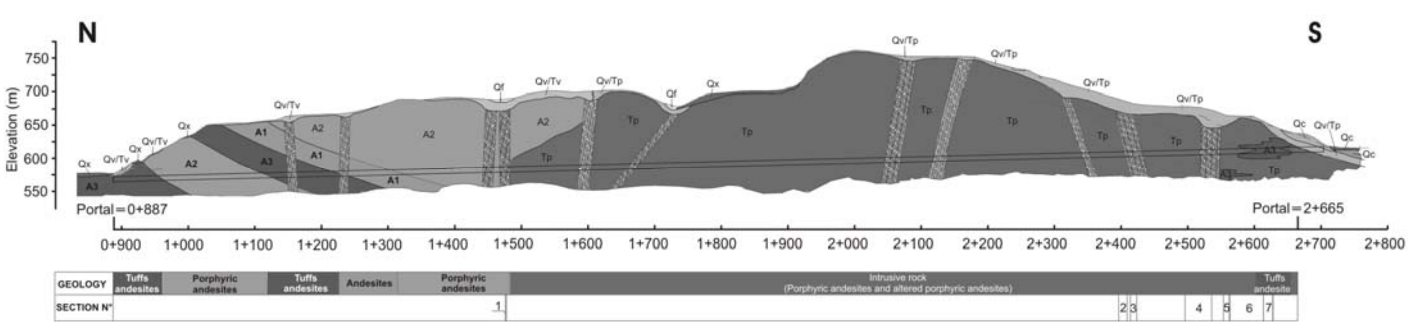

Figure 6. Geological cross section of San Cristóbal tunnel (Chile).

4 RESULTS AND CONCLUSIONS

TSI and SAF methodologies have been applied to 6 tunnels located in Spain, Iran and Chile to estimate the regional tectonic in-situ stress (K) and the increment of the principal horizontal stress over the regional horizontal stress in a particular tunnel section (SAF). These tunnels were excavated in different geological environments with a wide variety of rocks and tectonic structures. Common features of the tunnels include 65 tunnel sections that have shown large deformations mainly attributed to thrust faults, geomechanical anisotropies and folds with steeply dipping flanks.

The results have shown that for high values of SAF, deformations in the tunnel sections were much higher than those expected in the design. The increment of the principal horizontal stress over the mean regional horizontal stress, due to local geological and geomechanical anisotropies have ranged from 1.1 to 2.9, Table 8 and Figure 7.

In- situ stress tunnel zoning in terms of the variation of K values is presented in Figure 8. Potential zones of tunnel instability can be identified. This methodology can be particularly important in regions with complex geological conditions and with high or moderate in situ stress.

Table 8. SAF results for the 6 tunnels analysed.

Tunnels	Geological anisotropies*					
	1	2	3	4	5	6
Buen Suceso I	1.1-1.4	1.1-1.3	1.4-1.8	-	-	1.1
Peredilla	1.5-1.7	-	-	-	-	-
Nocedo	1.3-2.0	-	2.2-2.9	-	1.2	-
Alba	-	-	-	1.1-1.6	-	-
Qazvin	1.1-1.6	-	-	-	1.2	-
San Cristóbal	1.2-1.3	-	1.2-1.8	-	-	-
Range	1.1-2.0	1.1-1.3	1.2-2.9	1.1-1.6	1.2	1.1

*1: fault; 2: folds; 3: geomechanical anisotropies; 4: faults and folds; 5: faults and geomechanical anisotropies; 6: folds and geomechanical anisotropies.

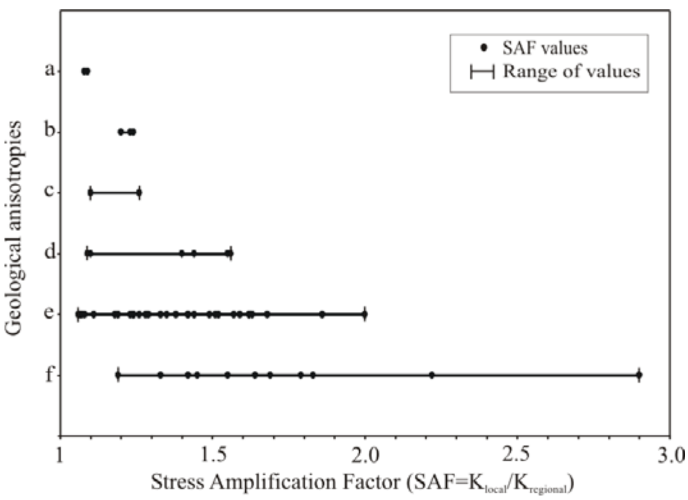

Figure 7. Range of SAF values. a: folds and geomechanical anisotropies; b: faults and geomechanical anisotropies; c: folds; d: faults and folds; e: faults; f: geomechanical anisotropies.

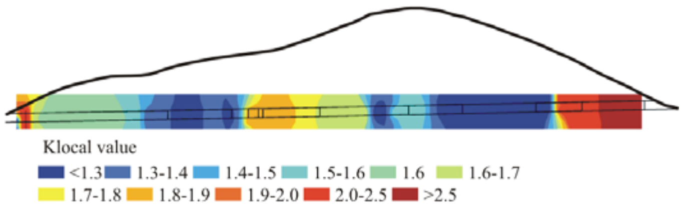

Figure 8. Tunnel zoning in terms of K values of Buen Suceso I tunnel. See Figure 4 for geological details.

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