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Engineering Geology 69 (2003) 273–285
ENGINEERING GEOLOGY
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SRC rock mass classification of tunnels under high tectonic stress excavated in weak rocks

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Received 1 August 2002; accepted 11 December 2002

Abstract

This paper describes the application of the SRC rockmass classification system to tunnels under high horizontal tectonic stress excavated in weak rocks. The analysis was performed on 25 tunnels in Spain and Italy, for which it was found that much heavier supports than those estimated by the RMR index were required. SRC and RMR indices and other relevant geomechanical data were obtained during the site investigation and construction stages. Data corresponding to in situ stress measurements, analysis of tectonic structures and instability problems arising during construction were used to asses the state of stress.

The relationship between tunnel section convergence and the SRC and RMR indices was also analysed. Support measurements based on SRC and RMR classification were compared with those actually used during construction. These analyses indicate that for most of the tunnels examined, supports estimated using the SRC were much closer to those actually installed than those predicted by the RMR index.

Based on the case histories presented, the factors mainly contributing to deformability and consequently to assessing support measurements were: high horizontal tectonic stress, low strength of rocks, overburden thickness and structural anisotropy related to tunnel axis orientation. According to these factors, the tunnels investigated were classified as three types. Tunnels classed as type I were those of low overburden thickness under high horizontal tectonic stress excavated in low strength rocks. The supports installed for these tunnels were much heavier than those predicted by the RMR index, being more in line with those indicated by the SRC index. The type II tunnels had thick overburdens and showed similar stress and strength conditions to the former. The supports installed were practically those foreseen by the SRC index, appreciably differing with respect to the RMR index. Finally, tunnels included in the type III class were those under low to moderate tectonics stress, irrespective of overburden thickness. These tunnels gave rise to RMR and SRC indices that provided acceptable results.

Keywords: Rockmass classification; Geomechanical classification; Tectonic stress; In situ stress; Tunnels; Weak rocks

1. Introduction

The use of rock mass classification systems over the past 25 years has provided a vast amount of data and allowed the evaluation of tunnels of different section, dimensions, overburden thickness, etc., affected by very different geological conditions. These years have also been witness to deformational processes in tunnels, both in the short- and long-term, due to reduced rock strength and to the rheological behaviour of the rockmass. Tunnel construction technology has also

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doi:10.1016/S0013-7952(02)00286-7

Table 1
Geomechanics rockmass classification SRC[a]

Rock quality indexes	Range of values						
(1) Intact rock strength							
Point-load test (MPa)	>8	8–4	4–2	2–1	Not applicable		
Uniaxial compressive strength (MPa)	>250	250–100	100–50	50–25	25–5	5–1	<1
Rating	20	15	7	4	2	1	0
(2) Spacing or RQD							
Spacing (m)	>2	2–0.6	0.6–0.2	0.2–0.06	<0.06		
RQD (%)	100–90	90–75	75–50	50–25	<25		
Rating	25	20	15	8	5		
(3) Conditions of discontinuities	Very rough surfaces	Slightly rough surfaces	Slightly rough surfaces	Slickensided surfaces	Slickensided surfaces		
	Not continuos joints	Not continuos joints	Not continuos joints	Continuous joints	Continuous joints		
	No separation	Separation>1 mm	Separation 1 mm	Joints open 1–5 mm	Joints open <5 mm		
	Hard joint wall	Hard joint wall	Soft or weathered joint walls	Gouge materials	Gouge materials millimeter thick		
Rating	30	25	20	10	0		
(4) Groundwater							
Inflow per 10-m tunnel length (l/min)	None	<10	10–25	25–125	>125		
General conditions	Dry	Slightly moist	Occasional seepage	Frequent seepage	Abundant seepage		
Rating	15	10	7	4	0		
(5) State of stresses							
Competence factor[b]	>10	10–5	5–3	<3	–		
Rating	10	5	−5	−10			
Tectonic structures	Zones near thrusts/faults of regional importance	Compression	Tension				
Rating	−5	−2	0				
Stress relief factor[c]	>200	200–80	80–10	<10	Slopes		
					200–80	79–10	<10
Rating	0	−5	−8	−10	−10	−13	−15
Neotectonic activity	None or unknown	Low	High				
Rating	0	−5	−10				
(6) Rock mass classes							
Class number	I	II	III	IV	V		
Rock quality	Very good	Good	Fair	Poor	Very Poor		
Rating	100–81	80–61	60–41	40–21	≤20		

[a] After González de Vallejo (1985).
[b] Uniaxial intact rock strength/vertical stress.
[c] Ratio between the age of the last main orogenic deformation affecting the rock mass (in years $\times 10^{-3}$) and maximum overburden thickness (in meters).

undergone appreciable change over this period, in that excavation and support systems have evolved towards integrative mechanisation capable of boring large sections. All these technological developments have been based on a more complete understanding of factors conditioning the behaviour and stability of rock masses, among which the state of stress of the rock plays a key role.

The importance of in situ stress in the design of underground excavations has been discussed extensively by Hoek and Brown (1980), Herget (1988), Hudson and Harrison (1997), etc. In general, data on in situ stress determinations indicate maximum horizontal stress exceeds vertical stress in most cases at depths under 500 m, while these tend to balance out beyond a depth of 1000 m. These stresses are mainly due to tectonic and gravitational forces, tectonic stresses being of most significance in tunnelling.

Based on data derived from applying SRC and RMR classification systems to 25 tunnels, in which support measurements had been underestimated by the RMR index, these classification systems were evaluated in terms of their suitability for tunnels in weak rocks affected by high horizontal tectonic stress. This was undertaken by comparing supports estimated by SRC and RMR indices with those actually installed. The Q system was occasional applied and only partial results were obtained for this index. This analysis was then used to identify the key factors that need to be considered when assessing deformability and supports based on rock mass classification.

2. SRC classification

The surface rock classification (SRC) system (González de Vallejo, 1983, 1985) was developed from the RMR index to take into account in situ stress, data from outcrops and tunnel construction conditions. The SRC index is calculated from the parameters shown in Table 1, to which the correction factors shown in Table 2 are applied. The scores obtained and the corresponding rock classes geomechanically classify the rock mass in conditions prior to excavation and represent the SRC basic. To account for effects due to construction conditions, the correction factors shown in Table 3 are applied to give the SRC-corrected. To characterise the properties of the rock mass and estimate support measurements, the criteria used in RMR classification are directly applied to the value obtained for the SRC. Thus, the same RMR rockmass classes and their support measurements are used in SRC (Table 4).

Table 2
Adjustment to ratings to account for surface data for the geomechanics rockmass classification SRC[a]

Spacing or RQD
Compression fractures = 1.3
Tension fractures = 0.8
Grade of weathering ≥ IV = 0.8
Grade of weathering III = 0.9
Grade of weathering I or II = 1.0
For depths < 50 m = 1.0
The maximum score is 25 points
Conditions of discontinuities
Compression fractures: + 5
Tension fractures: 0
Not applicable for depths < 50 m
The maximum score is 30 points
Groundwater
Compression fractures: + 5
Tension fractures: 0
Not applicable for depths < 50 m

[a] After González de Vallejo (1985).

3. In situ stress in rock mass classification

In general, the state of stress has hardly been considered in rock mass classification systems. The RMR calculation procedure (Bieniawski, 1973, 1979) does not account for the state of stress, although it is recommended that an adjustment factor of 0.6 for in situ stress be applied to the RMR value for mining applications (Bieniawski, 1989).

The Q system (Barton et al., 1974; Barton and Grismtad, 1994) considers the state of stress in the stress reduction factor (SRF) which is determined from the four factors:

(a) presence of planes of weakness.
(b) σ_c/σ_1 and σ_θ/σ_c ratios in competent rocks under stress.
(c) presence of squeezing rocks or plastic deformation under high pressure.
(d) presence of swelling rocks in the excavation.

Table 3
Adjustment to ratings to account for construction factors for the geomechanics rockmass classification SRC[a]

The total rating from Table 1 must be adjusted for the following factors:	
Excavation methods	
Tunneling boring machines, continuos miner, cutter machines, roadheaders, etc.	+ 5
Controlled blasting, presplitting, soft blasting, etc.	0
Poor-quality blasting[b]	− 10
Support methods[c]	
Class I	0
Class II	
< 10 d	0
>10 − < 20 d	− 5
>20 d	− 10
Class III	
< 2 d	0
>2 − < 5 d	− 5
>5 − < 10 d	− 10
>10 d	− 20
Classes IV and V	
< 8 h	0
>8 − < 24 h	− 10
>24 h	− 20
Distance to adjacent excavation[d]	
AEF < 2.5	− 10
Portals, accesses and areas with small overburden thickness[e]	
PF < 3	− 10
Rock resistance to weathering[f]	
Rock of high durability (low clay content)	0
Rock of low durability (high clay content)	− 5
Rock of very low durability (very high clay content)	− 10

Discontinuity orientations[g]

Strike perpendicular to tunnel axis				Strike parallel to tunnel axis		Dip 0–20° at any direction
Drive with dip		Drive against dip				
Dip 45–90° (very favourable)	Dip 20–45° (favourable)	Dip 45–90° (fair)	Dip 20–45° (unfavourable)	Dip 45–90° (very unfavourable)	Dip 20–45° (fair)	Unfavourable
0	− 2	− 5	− 10	− 12	− 5	− 10

[a] After González de Vallejo (1985).
[b] Conventional blasting: 0.
[c] Based on Bieniawski's (1979) graphic representation of the stand-up time and the unsupported span, the ratings are applied in relation to the maximum stand-up time. d: days, h: hours.
[d] AEF is the adjacent excavation factor, defined as the ratio between the distance to an adjacent excavation (in meters) from the excavation under design and the span of the adjacent excavation (in meters).
[e] PF is the portal factor, defined as the ratio between the thickness of overburden and the span of the excavation, both in meters.
[f] Durability can be assessed by the slake durability test, or indirectly by the clay content.
[g] After Bieniawski (1979).

Factor (a) is an indicator of accumulated tectonic stresses, but these planes also occur in decompressed rock masses and in areas of tectonic extension, whose residual stresses have already been released and, thus, the influence of tectonic stress is uncertain. Factors (b) and (c) are related to the lithostatic load and the

Table 4
Guidelines for excavation and support of 10-m-span rock tunnels according to the RMR System[a]

Rock mass class	Excavation	Rock bolts (20-mm diameter, fully grouted)	Shotcrete	Steel sets
(I) Very good rock, RMR: 81–100	Full face, 3 m advance	Generally no support required except spot bolting.		
(II) Good rock, RMR: 61–80	Full face, 1–1.5 m advance; complete support 20 m from face	Locally, bolts 4 m long, spaced 1.5–2 m in crown	50 mm in crown where required	None
(III) Fair rock, RMR: 41–60	Top heading and bench 1.5–3 m advance in top heading; commence support after each blast; complete support 10 m from face	Systematic bolts 4 m long, spaced 1.5–2 m in crown and walls with wire mesh in crown	50–100 mm in crown and 30 mm in sides	None
(IV) Poor rock, RMR: 21–40	Top heading and bench 1.0–1.5 m advance in top heading; install support concurrently with excavation, 10 m from face	Systematic bolts 4–5 m long, spaced 1–1.5 m in crown and wall with wire mesh	100–150 mm in crown and 100 mm in sides	Light to medium ribs spaced 1.5 m where required
(V) Very poor rock, RMR: < 20	Multiple drifts 0.5–1.5 m advance in top heading; install support concurrently with excavation; shotcrete as soon as possible after blasting	Systematic bolts 5–6 m long, spaced 1–1.5 m in crown and wall with wire mesh; bolt invert	150–200 mm in crown, 150 mm in sides and 50 mm on face	Medium to heavy ribs spaced 0.75 m with steel lagging and forepoling if required; close invert

[a] After Bieniawski (1989).

strength of the rocks, whereas factor (d) depends on the chemical composition of the rocks and the presence of water.

In SRC classification, the following parameters are used to asses the state of stress:

(a) competence factor: σ_c/σ_1.
(b) tectonic accidents of regional magnitude present or near the site and their tectonic regime.
(c) stress relief factor, expressed as the ratio between the age of the last main orogenic deformation affecting the rock mass (in years $\times 10^{-3}$) and maximum overburden thickness (in metres). Main orogenic deformations are considered as Hercinian and Alpine in Spain and Italy. The age of these folds is of the order of 300 million years for the Hercinian and 10–12 million for the Alpine. Maximum overburden thickness refers to the existing overburden plus that supported by the rock mass throughout its geological history, which could be absent because of erosion processes.
(d) seismic activity in the zone.

No specific analyses are required to calculate these parameters, but rather an approximation based on geological data, in some cases taken from the literature. An example of how state of stress parameters are estimated is presented below.

Tunnel excavated in Palaeozoic shales and sandstones for which the following data were obtained:

– mean density: 2.1 t/m^3
– mean uniaxial compressive strength: 1,500 t/m^2 (15 MPa)
– present overburden thickness: 300 m
– age of folding: Hercinian, approximately 300 million years
– maximum overburden thickness: 500 m (actual overburden thickness 300 m plus 200 m of eroded materials according to regional geological data).
– competence factor: $1500/300 \times 2.1 = 2.3$ (-10 points).

(a) tectonic accidents: faults of regional significance in the tunnel area (-5 points).
(b) stress relief factor: $\{300{,}000{,}000 \text{ years} \times 10^{-3}/500 \text{ m}\} = 600$ (0 points)

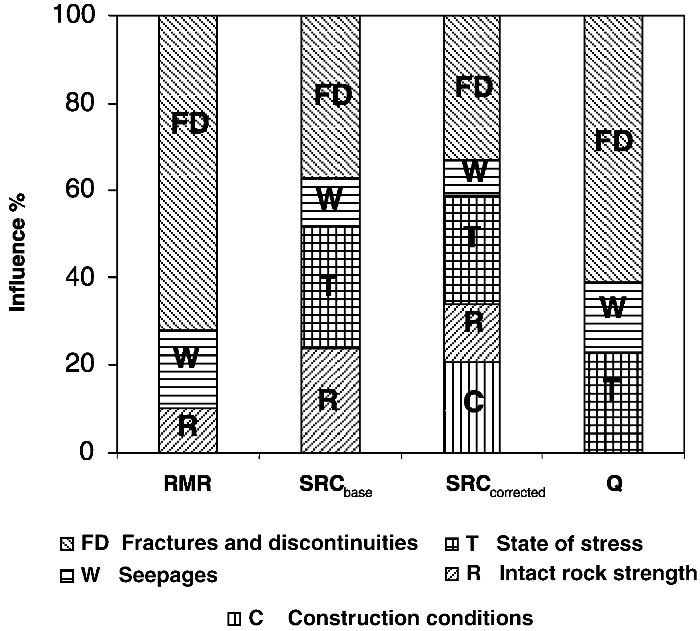

Fig. 1. Relative influence of the geomechanical parameters in RMR, Q and SRC rockmass classification.

(c) seismic activity: none (0 points).
(d) total state of stress score: $-10-5+0+0=-15$ points.

Fig. 1 shows the relative influence of the different factors contributing to SRC, RMR and *Q* indices. Whereas the state of stress does not contribute to the RMR index, the strength of the intact rock is not included in *Q*.

4. Tunnels under high tectonic stress

The expansion of rapid transport systems, mainly railways and roads, has meant that many tunnels have been constructed in Spain and Italy in the last decade. Twenty-five tunnels from these countries were analysed, since it was observed that the support measurements estimated according to RMR classification were much lower than those required to stabilise deformations occurring during construction. These tunnels have been described in detail by Encinas (1992), Alfani (1993), Alfani et al. (1994) Bellini (1998) and González de Vallejo (1998). Table 5 includes some relevant data on these tunnels. Despite showing highly variable conditions both in geological and construction terms, these tunnels share the following features:

– located in Spain and Northern Italy, mostly for high-speed railways,
– sections up to120 m^2,
– predominance of low strength rocks (shales, schists, argillites, etc.),
– significant folding and deformation structures (folds, faults, thrusts, etc.),
– overburden thicknesses up to 700 m.

In 22 of the 25 cases, the main type of rock was of low strength, with typical strength values of 10–15 MPa. These weak rocks were composed of shales, schists and argillites which show highly anisotropic behaviour.

The state of stress was evaluated by considering the following data:

– tectonic history of the region, presence of deformation structures and current tectonic regime,
– in situ stress measurements,

Table 5
Tunnels analysed and mean RMR, SRC and Q values

No.	Ref.[a]	Location[b]	H^c (m)	Lithology	σ_c^d (MPa)	In situ stress[e]	Type	RMR*[f]	SRC	RMR	RMR*/SRC	RMR*/RMR	Q	Q*[g]
1	1	AVE M–S	< 150	Shales	5–15	High	I	17	25	46	0.68	0.37	NA	NA
2	1	AVE M–S		Shales		High	I	18	57	60	0.32	0.30		
3	1	AVE M–S		Shales		High	I	19	27	52	0.70	0.37		
4	1	AVE M–S		Shales		High	I	18	24	45	0.75	0.40		
5	1	AVE M–S		Shales		High	I	16	26	48	0.62	0.33		
6	1	AVE M–S		Shales		High	I	27	30	58	0.90	0.47		
7	1	AVE M–S		Shales		High	I	32	30	50	1.07	0.64		
8	1	AVE M–S		Shales		High	I	30	30	54	1.00	0.56		
9	1	AVE M–S		Shales		High	I	34	34	64	1.00	0.53		
10	1	AVE M–S		Shales		High	I	34	60	68	0.57	0.50		
11	2	TAV G–M (Val Lemme)	100 –250	Argillites and Shales	< 10	High–very high	I	16	22	38	0.73	0.42		
12	3	CF S–V (Savona)	250	Gneiss	10–20	High–very high	II	26	31	56	0.84	0.46		
13	3	CF S–V (Savona)		Gneiss		High–very high	II	26	40	55	0.65	0.47		
14	3	LF V–G (Genoa)		Meta-Basalts	30–60	High–very high	II	35	37	66	0.95	0.53		
15	3	LF V–G (Genoa)		Schists	< 15	High–very high	II	35	35	47	1.00	0.74		
16	4	Peñarroya (Córdoba)	400–600	Shales	10–20	High	II	33	41	41	0.80	0.80	1.3	0.4
17	4	Peñarroya (Córdoba)		Shales		High	II	28	33	47	0.85	0.60		
18	4	Andorra (Teruel)		Shales	5–10	Moderate	II	24	31	34	0.77	0.71	0.4	0.2
19	4	Peñarroya (Córdoba)		Shales	10–20	High	II	15	17	54	0.88	0.28	1.3	0.4
20	2	TAV G–M (Castagnola)	200–600	Argillites and schists	10–15	High–very high	II	25	28	45	0.89	0.56	NA	NA
21	4	S–H (Granada)	100–300	Schists	10–40	Low–moderate	III	36	36	35	1.00	1.03	0.2–0.4	0.3–0.7
22	4	S–H (Granada)		Schists		Low–moderate	III	27	29	30	0.93	0.90		
23	4	S–H (Granada)		Schists		Low–moderate	III	29	37	33	0.78	0.88		
24	4	S–H (Granada)		Schists		Low–moderate	III	40	41	49	0.98	0.82		
25	4	S–H (Granada)		Schists		Low–moderate	III	40	37	43	1.08	0.93		

NA: not available.

[a] (1) Encinas (1992), (2) Bellini (1998), (3) Alfani et al. (1994), (4) González de Vallejo (1998).

[b] AVE M–S: High-Speed Railway Madrid–Seville. TAV G–M: High-Speed Railway Genoa–Milán. LF VG: Railway Voltri–Genoa. CF SV: Railway Link Savona–Vado. SH = hydraulic scheme.

[c] H: overburden thickness (m).

[d] σ_c: uniaxial compressive strength.

[e] Low: $\sigma H/\sigma V \leq 0.5$, moderate: $\sigma H/\sigma V \leq 1.0$, high $\sigma H/\sigma V \geq 1.0$, very high $\sigma H/\sigma V \geq 2.0$.

[f] RMR*: RMR value corresponding to the support actually installed.

[g] Q*: Q value corresponding to the support actually installed.

– instability problems arising during excavation and their relation to tectonic structures.

In situ stress measurements carried out in the regions where the tunnels were excavated have shown high values of K ($K = \sigma_H/\sigma_V$) ranging from 1.3 to 2.0 in central and southern Spain. The case histories cited in Table 5 as numbers 1–10, 16,17 and 19 refer to tunnels located in these areas (González de Vallejo et al., 1988). High K values in the range 1.5–3.0 have also been reported for northern Italy (Martinetti and Ribacci, 1980; Crivelli et al., 1994) and correspond to the areas of case histories numbers 11–15 and 20.

Based on the above-mentioned data, the state of stress was assessed as follows:

- High tectonic stress was considered for tunnels under compressive tectonic regimes, mainly situated in zones of Alpine folding expected to show high horizontal stresses.
- Moderate tectonic stress was assumed for tunnels mostly located in Palaeozoic massifs folded in the Hercinian that were frequently affected by later tectonics of the extension type and also for those located in zones undergoing erosion processes.

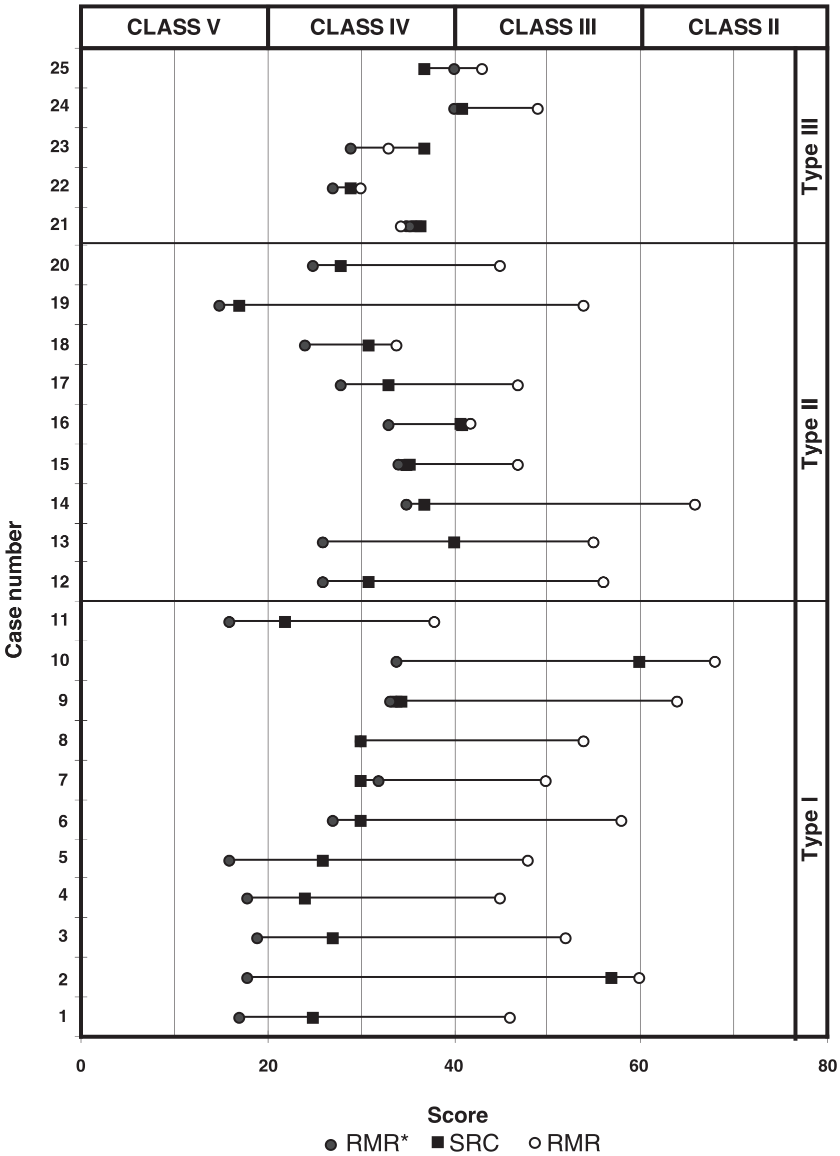

Fig. 2. Variation intervals of RMR and SRC indices with respect to RMR* in the study cases.

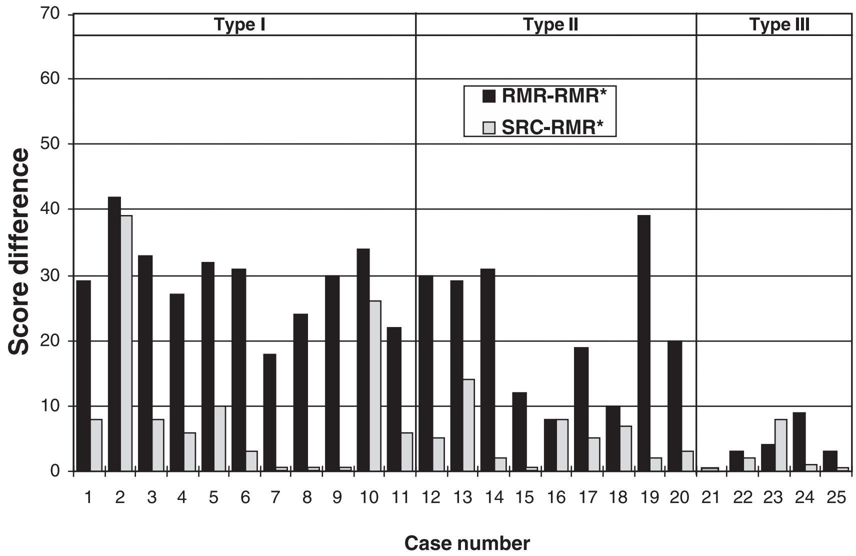

Fig. 3. Score differences between RMR and SRC indices with respect to RMR* for the study cases.

The following information was also analysed for each tunnel:

– Project stage: geological and geomechanical data, RMR and SRC indices, and recommended supports according to these classifications.
– Construction stage: geological and geomechanical data from the excavation fronts, RMR and SRC indices, section convergence, problems related to instability and supports installed.

Measurements of the supports installed in the tunnels were assigned to one of the five classes described in Table 4. Though a simplification, this classification was nevertheless useful for establishing comparative criteria for the different types of support installed in the tunnels.

The RMR and SRC indices measured at the excavation fronts were compared with those estimated in the project. When the supports installed were significantly different from those predicted by the classification score, the RMR corresponding to the support installed was calculated, yielding an empirical RMR value denoted RMR*. The RMR* was determined either from direct measurements at the excavation front or by back analysing the support installed. Mean RMR* values are shown in Table 5, and the differences between RMR* and RMR or SRC are represented in Figs. 2 and 3. In some cases, Q and Q^* values were also obtained (Table 5).

5. Results

The tunnels examined were classified into three types:

– Type I: tunnels located in zones subjected to high horizontal tectonic stresses with low overburden thicknesses (generally less than 150 m).
– Type II: tunnels located in zones subjected to high horizontal tectonic stresses with high overburden thicknesses (higher than 150 m, but generally more than 250 m).
– Type III: tunnels located in zones of low to moderate tectonic stresses, irrespective of overburden thickness.

To evaluate differences between the rock mass classifications results and rock mass behaviour after excavation, the ratios RMR*/SRC and RMR*/RMR and the differences in rock class between RMR* and RMR, and between RMR* and SRC were calculated for each type of tunnel. The results shown in Table 6

Table 6
Mean relations between RMR* and SRC and RMR for each type of tunnel

Type	RMR*/SRC (mean)	RMR*/RMR (mean)	Difference in rock class with respect to RMR* (%)					
			Same class		One class		Two classes	
			SRC	RMR	SRC	RMR	SRC	RMR
I	0.75	0.44	36	0	55	36	9	64
II	0.84	0.56	78	11	22	67	0	22
III	0.95	0.91	100	100	0	0	0	0

indicate that most differences between the RMR* and RMR or SRC were shown by type I tunnels under high tectonic stress with low overburden thicknesses. Mean RMR*/SRC and RMR*/RMR ratios were 0.75 and 0.44, respectively. Type II tunnels showed the same tendency but yielded somewhat higher values for these ratios; 0.84 for RMR*/SRC and 0.56 for RMR*/RMR. The ratio with respect to RMR* was close to 1.0 in both cases for type III tunnels; 0.95 for RMR*/SRC and 0.91 for RMR*/RMR.

Table 6 also shows the differences in rock classes between RMR* and RMR, and between RMR* and SRC. RMR* was always lower or equal to the RMR or SRC indices, which meant that supports heavier than predicted were installed. 100% of cases showed differences in classes between RMR* and RMR, compared to 64% between RMR* and SRC. Greatest differences were recorded for type I tunnels, which showed a difference of two classes between RMR* and RMR in 64% of the cases analysed, versus 9% between RMR* and SRC. In type II tunnels, where

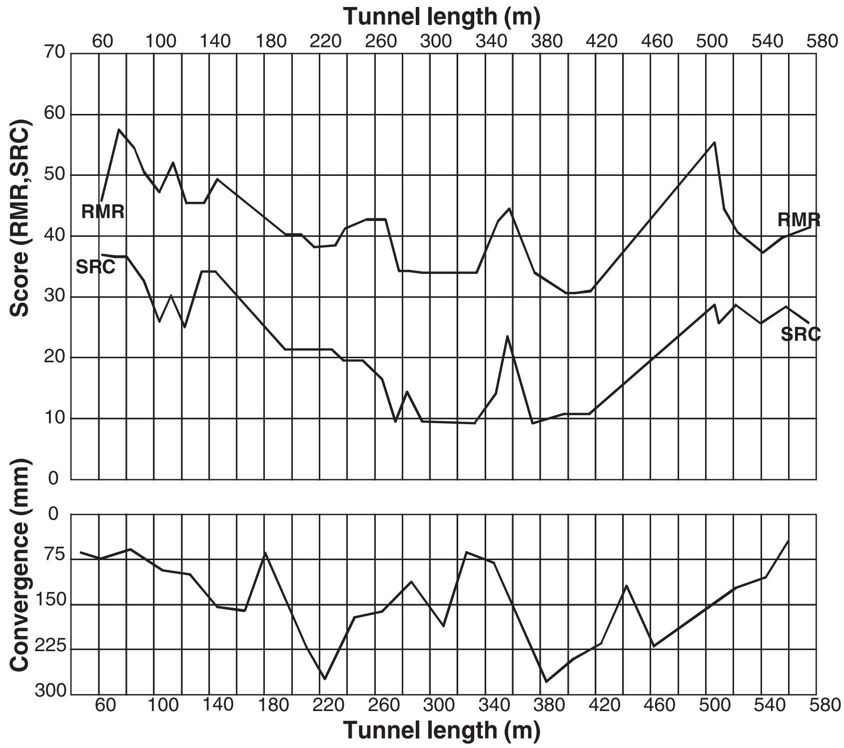

Fig. 4. RMR and SRC indices and convergence values for the Val Lemme Tunnel, a tunnel with a thin overburden and schistosity parallel to the tunnel axis (Bellini, 1998).

89% of all cases showed class differences between RMR* and RMR, and 22% between RMR* and SRC, the greatest percentage corresponded to a difference of one class of rock in 67% of cases between RMR* and RMR; no significant class differences between RMR* and SRC being noted in 78% of cases. For the type III tunnels, both RMR and SRC presented the same class of rock as RMR*. For types I and II, the means of these ratios were: RMR*/RMR ≈ 0.5 and RMR*/SRC ≈ 0.8.

The *Q* index was only determined in some cases, thus, the same comparative criteria as for RMR and SRC could not be established. The results for type II tunnels, corresponding to cases 16, 17 and 19 (Table 5), indicate a difference in one class of support from Class D (Poor) to Class E (Very Poor); Class D corresponds to the estimated support, and Class E to the support actually installed. For case 18, the predicted type of support was the same as those actually installed. For type III tunnels, cases 21–25, installed supports were as predicted. No *Q* values were available for type I tunnels. These results suggest that the *Q* index provides a better estimate of support requirements than the RMR for type II tunnels. However, more data would be needed for comparisons with the SRC index and for type I tunnels.

Highly variable relationships were observed between the deformations or convergences determined in tunnel sections and RMR and SRC indices. In general, neither index could adequately predict convergence nor establish acceptable correlation between rock classification and deformation. This lack of correlation could be explained by the influence of the following key geomechanical parameters, besides construction factors not accounted for in these classification systems such as the shape and size of the

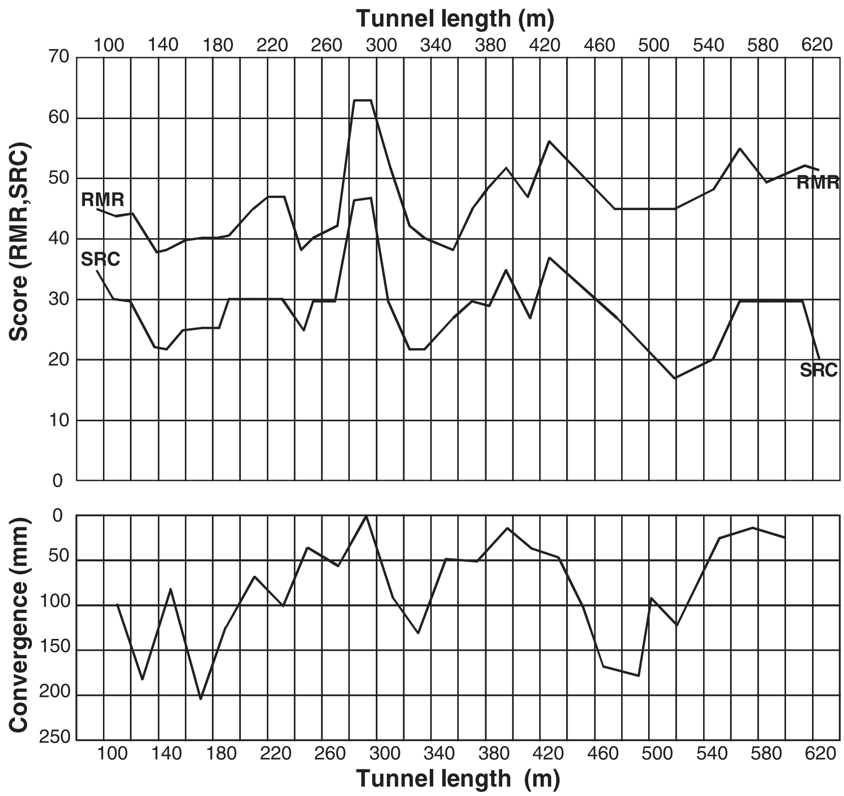

Fig. 5. RMR and SRC indices and convergence values for the Castagnola Tunnel, a tunnel with a thick overburden and schistosity perpendicular to the tunnel axis (Bellini, 1998).

tunnel section, the excavation system and the type of support:

- high horizontal stress
- low rock strength
- thin overburden
- unfavourable structural anisotropy with respect to tunnel axis orientation

In the tunnels examined, structural anisotropy due to bedding planes and schistosity, and confinement degree played a major role in deformation. In tunnels with thin overburdens, the effect of structural anisotropy was marked, while this effect was much reduced in tunnels with thick overburdens. These features are shown in Figs. 4 and 5. In Fig. 4, correlation between deformations and RMR and SRC indices is low for a tunnel of thin overburden with schistosity parallel to the tunnel axis, while Fig. 5, in which correlation is much improved, corresponds to a tunnel of thick overburden with schistosity perpendicular to the tunnel axis (Bellini, 1998).

6. Conclusions

The results presented in this investigation, allowed us to compare supports determined according to SRC and RMR indices with those actually installed. In the majority of the tunnels investigated, heavier supports were used than those predicted by RMR. Systematic analysis during excavation of geomechanical data, SRC and RMR indices, in situ stress and tunnel section deformability served to identify the main geomechanical factors contributing to underestimation of supports as:

- high horizontal tectonics stress
- low rock strength
- thin overburden
- highly anisotropic rock behaviour.

The results of applying SRC and RMR indices to the 25 tunnels analysed can be summarised by the following types of behaviour:

- Type I. Shallow tunnels under high horizontal tectonic stress excavated in weak rocks. In these tunnels, highly anisotropic rockmass behaviour depends on structural anisotropy and its orientation with respect to the tunnel axis. The supports installed in all cases were much heavier than those estimated by the RMR index: 64% of cases showed a difference of two classes and 36% showed a difference of one class, thus, accounting for all the tunnels of this type. However, corresponding results for the SRC index were 9% showing a two-class difference, 55% a difference of one class and 36% showing the same class. Correlations between SRC or RMR indices and convergence measurements in tunnel sections were low for these tunnels.
- Type II. Tunnels with high overburden thickness, high horizontal tectonic stress and low strength rocks. Rock mass behaviour is less anisotropic than for type I tunnels, and RMR or SRC indices correlated well with tunnel convergence. Supports installed in 78% of cases were the same as those estimated by the SRC index, while the RMR underestimated supports in 89% of these tunnels.
- Type III. Tunnels under low to moderate horizontal tectonic stress regardless of overburden thickness excavated in weak rocks. The supports installed were consistent with those predicted by both the RMR and SRC indices.

In general, these findings indicate that the SRC index provides a reasonable estimate of tunnel support in tunnels under high horizontal tectonic stress excavated in weak rocks. In contrast, under the conditions of the present analysis, the RMR can underestimate support requirements by one or two classes of rock.

Acknowledgements

The author thanks Dr. Marino Trimboli and Dr. Sergio Pedemonte for their valuable contributions to this study. The authors of theses on rock mass classification undertaken at the Universidad Complutense de Madrid (Valeria Bellini, Ignacio Encinas and Luis Muñoz) and at the Universita di Genova (Marco Alfani) are also gratefully acknowledged. Thanks are also due to Dr. M. Ferrer and Sr. J.M. Insua for their help during preparation of the paper.

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