Innovating Tunnel Design by an Improved Experience-based RMR System.

B. Celada and I. Tardáguila
Geocontrol S.A., Madrid, Spain.

P. Varona
Geocontrol Ltda., Santiago, Chile.

A. Rodríguez
CDIAM., Madrid, Spain.

Z.T. Bieniawski
Bieniawski Design Enterprises, Arizona, U.S.A.

ABSTRACT: The Rock Mass Rating (RMR) System was introduced over 40 years ago, and since then has become a worldwide reference, along with the Q system, for design applications involving estimation of rock mass properties and tunnel support. A massive database of experience has been recorded in the process. On the 25th anniversary of the last modification of the RMR System in 1989, known as the RMR89, an update of this index has now been performed to incorporate the innovations introduced in recent decades and to improve its performance. For this purpose a database of 2,298 cases of RMR89's was compiled from tunnel faces. Based on the experience gained in the last decades, a new RMR14 has been developed, which has a new structure comprising five basic parameters and three adjustment factors. Also a clear correlation between RMR89 and RMR14 is provided and shows that the essence of the RMR System has been maintained for practical use.

1 INTRODUCTION

The Rock Mass Rating (RMR) System was introduced over 40 years ago (Bieniawski 1973). Since then it has become a worldwide reference, along with the Q system, for design applications involving estimation of rock mass properties and tunnel support (Barton and Bieniawski 2008, De Oliveira 2007).

The RMR classifies rock masses from 0 to 100 points, rating five parameters, according to the criteria presented in Table 1.

Table 1. Standard ratings to determine RMR after Bieniawski (1989).

Parameter			Range of values						
1	Strengh of intact rock material	Point-load strength index	> 10 MPa	4-10 MPa	2-4 MPa	1-2 MPa	For this low range- uniaxial compressive test is prefered		
		Uniaxial comp. strength	> 250 MPa	100-250 MPa	50-100 MPa	25-50 MPa	5-25 MPa	1-5 MPa	< 1 MPa
	Rating		15	12	7	4	2	1	0
2	Drill core Quality RQD		90%-100%	75%-90%	50%-75%	25%-50%	< 25%		
	Rating		20	17	13	8	3		
3	Spacing of discontinuities		>2 m	0.6-2 m	200-600 mm	60-200 mm	< 60 mm		
	Rating		20	15	10	8	5		
4	Condition of discontinuities (See E)		Very rough surfaces Not continuous No separation Unweathered wall rock	Slightly rough surfaces Separation < 1 mm Slightly weathered walls	Slightly rough surfaces Separation < 1 mm Highly weathered walls	Slickensided surfaces or Couge < 5 mm thick or Separation 1-5 mm Continuous	Soft gouge > 5 mm thick or Separation >5 mm Continuous		
	Rating		30	25	20	10	0		
5	Ground water	Inflow per 10 m tunnel length (l/m)	None	< 10	10-25	25-125	> 125		
		(Joint water press)/(Mayor principal σ)	0	< 0.1	0.1-0.2	0.2-0.5	> 0.5		
		General conditions	Completely dry	Damp	Wet	Dripping	Flowing		
	Rating		15	10	7	4	0		

The criteria shown in Table 1 are used to calculate the basic RMR, that is RMRb, which is an intrinsic property of the rock mass.

To take into account the effect of the orientation of the axis of a tunnel with respect to the most important set of discontinuities in the ground, the RMRb is obtained with the criteria shown in Table 2.

Table 2. RMR_b adjustment with respect to the orientation of the axis of the tunnel versus discontinuities.

STRIKE PERPENDICULAR TO TUNNEL AXIS				Strike parallel to Tunnel Axis		Irrespective of Strike Dip 0º-20º
Drive with dip		Drive against dip				
Dip 45-90	Dip 20-45	Dip 45-90	Dip 20-45	Dip. 45-90	Dip 20-45	
Very favorable	Favorable	Medium	Unfavorable	Very unfavorable	Medium	Medium
0	-2	-5	-10	-12	-5	-5

In 2000, Geocontrol SA introduced a modification to the criteria for calculating the RMR_b, replacing the RQD assessment and the spacing of the discontinuities by the number of joints per meter in the face of the excavation and extending the criteria for assessing the condition of discontinuities, as shown in Table 3 (Geocontrol SA 2012).

Table 3. Criteria for calculating the RMR_b used by Geocontrol since 2000.

I.- CLASSIFICATION PARAMETERS							
RMR (1) UNIAXIAL COMPRESSIVE STRENGTH OF INTACT ROCK							
σ_{ci} (kg/cm²)	>2.500	1.000-2.500	500-1.000	250-500	50-250	10-50	<10
RATING	15	12	7	4	2	1	0

RMR (2+3) RQD AND SPACING OF JOINTS																
JOINTS PER METER	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RATING	40	34	31	29	28	27	26	25	24	23	22	21	20	19	16	17
JOINTS PER METER		16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
RATING		17	16	15	14	14	13	13	12	12	11	11	10	10	9	9
JOINTS PER METER		31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
RATING		9	8	8	7	7	7	6	6	6	5	4	3	3	2	2
JOINTS PER METER		46	47	48	49	50										
RATING		1.5	1	1	0.5	0										

RMR(4)	DISCONTINUITIES CONDITION				
PERSISTENCE	<1 m	1-3m	3-10m	10-20m	20m
	6	4	2	1	0
APERTURE	0	<0,1 mm	0,1-1 mm	1-5 mm	> 5 mm
	6	5	4	1	0
ROUGHNESS	Very rough	Rough	Slightly rough	Smooth	Slickenside
	6	5	3	2	0
INFILLING	NONE	HARD FILLING <5mm	HARD FILLING >5mm	SOFT FILLING	NONE
	6	4	2	2	0
WEATHERING	UNWEATHERED	SLIGHTLY	MODERATELY	HIGHLY	DECOMPOSED
	6	5	3	1	0

RMR (5)	GROUNDWATER CONDITIONS				
STATE	DRY	DAMP	WET	DRIPPING	FlOWING
RATING	15	10	7	4	0

These changes eliminated the difficulty to determine the RQD from excavation faces and to obtain a good assessment of the condition of the discontinuities in the ground.

In 2012, Geocontrol started a major R&D Project, partly funded by the Spanish "Centro para el Desarrollo Tecnológico e Industrial (CDTI)" with the aim to improve the accuracy of the RMR System. This project ends in February 2014.

By 2014, 25 years will have passed since the publication of the RMR89 (Bieniawski 1989) and after such a long period of time, it was considered appropriate to update the RMR 89 taking into account the developments over the last decades.

2 CURRENT RMR UPDATE

The RMR update described in this paper features establishing the criteria for rating the parameters for calculating the RMRb aimed at improving its accuracy by using two new factors.

Accordingly, the RMR14 update is represented by the expression:

$$RMR14 = (RMR_b + F_0) \cdot F_e \cdot F_s \qquad (1)$$

where RMR_b = RMR basic of the rock mass, without an effect of excavation,

F_0 = Adjustment factor for the orientation of tunnel axis with regard to the main set of discontinuities in the rock mass (Table 2). F_0 is always negative.

F_e = Adjustment factor to account for an excavation method.

F_s = Adjustment factor taking into account stress-strain behaviour of the rock mass at the tunnel faces.

The following sections present conceptually the rating criteria for the new RMR_b and the adjustment factors proposed.

2.1 *New RMR structure*

The new RMR structure maintains three parameters composing the RMR89: *uniaxial compression strength of intact rock, number of discontinuities per meter and the water effect*.

The ratings for these parameters are the same as those of RMR89¸ i.e. uniaxial compressive strength has a maximum score of *15 points* and its rating is made by employing the graph presented in Figure 1.

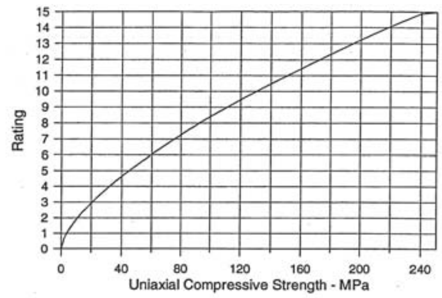


Figure 1. Ratings for strength of intact rock.

The number of discontinuities per meter is evaluated with the graph in Figure 2 and its maximum score is *40 points*; (Lawson and Bieniawski 2013).

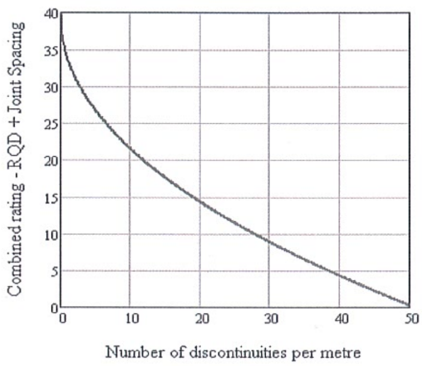


Figure 2. Ratings for the density of discontinuities.

Finally, the effect of water, which has a maximum score of *15 points*, is rated according to the data of Table 4.

Table 4. Rating for the presence of water.

GROUND STATE	Dry	Slightly humid	Humid	Dripping	Water flow
Ratings	15	10	7	4	0

The two new parameters included in the updated RMR are the revised joints condition and the rock alterability due to water (swelling).

The revised discontinuities condition, which has a maximum rating of *20 points*, is rated by the following four aspects:

- Persistence (continuity) of discontinuities.
- Roughness of discontinuities measured through the Joint Roughness Factor (JRC).
- Infilling type in the discontinuities.
- Degree of weathering of the planes in the discontinuities.

The intact rock alterability, which has a maximum rating of *10 points*, is rated according to the results of the Slake Durability Test, as defined in standard ASTM D4644-87.

The ratings to assess the two new parameters are listed in Table 5 and explained in paragraph 2.3.2.

Table 5. Ratings for new parameters of $RMR14_b$.

Discontinuities Condition				
Continuity	< 1 m	1-3m	3-10m	> 10m
	5	4	2	0
Roughness	Very rough	Rough	Smooth	Slickensided
	5	3	1	0
Gouge infilling	Hard		Soft	
	< 5mm	> 5mm	< 5mm	> 5mm
	5	2	2	0
Weathering	Unweathered	Moderately weathered	Highly	Decomposed
	5	3	1	0

Intact Rock Alterability			
Alterability I_{d2} (%)			
> 85	60-85	30-60	< 30
10	8	4	0

2.2 *Adjustment factors*

It is proposed that the RMR_b is adjusted by the following three factors.

2.2.1 *Tunnel axis orientation*

To take into account the effect of the tunnel axis orientation with respect to the major set of discontinuities present on the rock mass, it is proposed to continue using the criterion currently employed, in accordance with Table 2. This adjustment factor is called F_0.

2.2.2 *Excavation method*

The excavation method, whether mechanical or blasting, modifies the stress-strain behavior of the ground in different ways with respect to the RMR as determined at the faces excavated by conventional methods.

The utilization of mechanical means (TBM's, road headers or hydraulic hammers) is less damaging to the remaining rock than blasting, which implies an improvement in the behavior of the excavated faces.

Regarding the use of blasting in tunnels, we must remember that for RMR < 35 this is practically not used and that for good quality grounds, RMR > 80, the effect of blasting on the remaining rock is not very significant, as long as that the blasting is well planned and executed.

The research carried out by Geocontrol on this project (2012-2014), has revealed that explosives used in tunnels excavated in ground with 35<RMR<80 only affect about 10-20 cm of the surrounding rock.

Therefore, in the design of tunnels this effect can be considered insignificant, especially as that after each blast the excavation perimeter is cleaned up to remove the affected rock fragments.

The positive effect of mechanical excavation was investigated by Alber (1993) and updated by Bieniawski (2011) as shown in Figure 3.

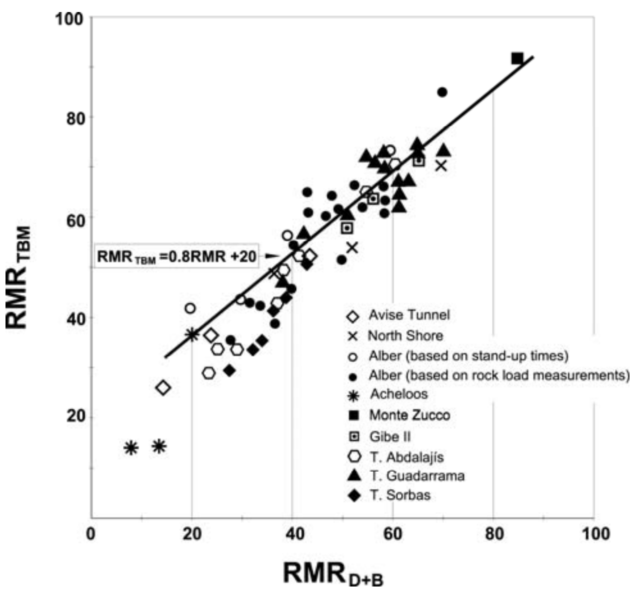


Figure 3. Correlation between RMR_{D+B} and RMR_{TBM}.

According to the data from Figure 3, the correlation proposed by Alber is very good for RMR_{D+B} > 40, but below this value it is too optimistic. Therefore a new correlation curve is proposed for RMR_{D+B} < 40, which is marked with a broken line in Figure 3.

When comparing the values of RMR_{D+B} with the corresponding ones of RMR_{TBM} a new correlation for RMR_{D+B} < 40, based on the results obtained and indicated in the Table 6, is proposed.

Table 6. Improvement of RMR_{D+B} when using TBM.

RMR_{D+B}	20	40	60	80
RMR_{TBM}	21	53	70	85
$\frac{RMR_{TBM}}{RMR_{D+B}}$	1.05	1.32	1.16	1.06

According to the above, an expression was developed for the adjustment factor related to the excavation method (F_e), which is:

$$for\ RMR < 40: \quad F_e = 1 + 2 \cdot \left(\frac{RMR}{100}\right)^2 \qquad (2)$$

$$for\ RMR > 40: \quad F_e = 1.32 - \frac{\sqrt{(RMR-40)}}{25} \qquad (3)$$

Figure 4 shows the F_e as a function of RMR.

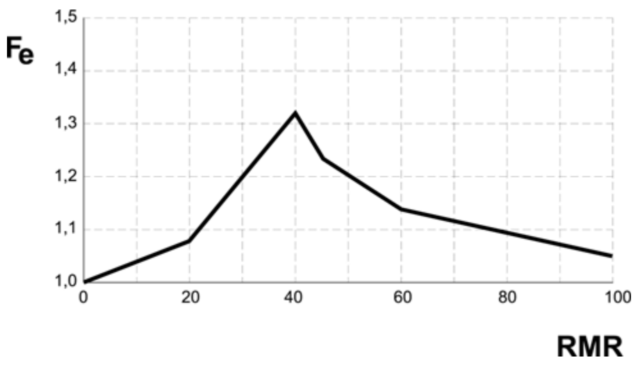


Figure 4. Representation of F_e as function of RMR.

Note that F_e = 1 is used when the excavation is performed by blasting.

2.2.3 *Stress-Strain behaviour*

The RMR should be determined in the design phase of a tunnel using data from boreholes, and during the construction of the tunnel by geological mapping of the excavation surfaces.

Ideally, the RMR values estimated in the project planning phase and those determined during construction should be similar.

However, the reality is that, in addition to operational errors, the effects of yielding of the excavation face and walls causes an RMR at the face to be significantly lower than expected during the design phase.

This circumstance makes it necessary to introduce a new factor (F_s) which allows for the diminishing effect of yielding at the face.

To define F_s it is helpful to employ the "*Índice de Comportamiento Elástico*" (ICE) proposed by Bieniawski and Celada (2011), which is defined by the equations:

$$for\ K_0 \leq 1: ICE = \frac{3704\sigma_{ci} \cdot e^{\frac{RMR-100}{24}}}{(3-K_0) \cdot H} \cdot F \qquad (4)$$

$$for\ K_0 \geq 1: ICE = \frac{3704\sigma_{ci} \cdot e^{\frac{RMR-100}{24}}}{(3K_0-1) \cdot H} \cdot F \qquad (5)$$

Where:

σ_{ci} = uniaxial compressive strength of intact rock (MPa).

K_0 = ratio of the horizontal to vertical virgin stress.

H = tunnel depth (m).

F = shape coefficient, see Table 7.

Table 7. F values for calculating ICE.

Underground excavation	F
Circular tunnel, ϕ = 6 m	1.3
Circular tunnel, ϕ = 10 m	1.0
Conventional tunnel, 14 m wide	0.75
Caverns 25 m wide x 60 m high	0.55

ICE makes it possible to predict the stress-strain behavior of the faces of the tunnels classifying them into five categories as show in Table 8.

Table 8. Designation of stress-deformation behavior of a tunnel section as a function of the "*Índice de Comportamiento Elástico*" (ICE).

ICE	Stress-deformation behaviour
> 130	Completely elastic
70-130	Elastic with incipient yielding

40-69	Moderate yielding
15-39	Intensive yielding
< 15	Mostly yielding

According to the above, only the excavation faces in which ICE < 70 will present substantial deformation for significant variations in the determination of RMR.

When the expressions were applied to the RMR ratings over the last decades, particularly when analyzing the RMR's obtained from boreholes in the Chuquicamata Mine (Chile), it was found that the factor F_s ranges between 0 and 1.3, according to Figure 5.

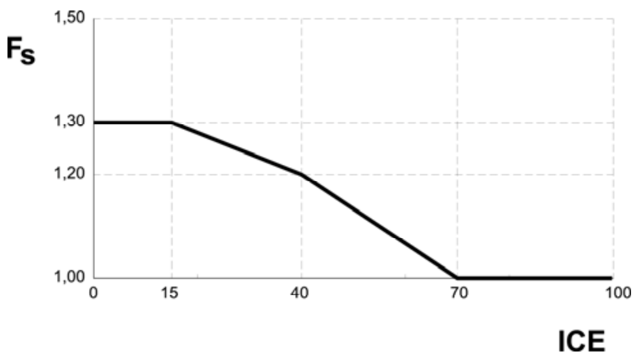


Figure 5. F_s values depending on the ICE.

The graphic of Figure 5, can be adjusted with the following expressions

ICE < 15 $\qquad F_s=1,3$

15<ICE<70 $$F_s = \frac{2.3\cdot\sqrt{100-ICE}}{7.1+\sqrt{100-ICE}} \qquad (6)$$

ICE > 70 $\qquad F_s=1$

2.3 *Criteria for assessing the new parameters of the RMR*

It has already been indicated that the RMR update has retained two parameters of the RMR89: uniaxial compressive strength and the effect of water; the RQD and the discontinuities spacing have been combined and are expressed as the number of discontinuities per meter.

All of these factors are rated employing the same criteria in the RMR89; therefore, one needs only to establish the criteria for assessing the discontinuities condition and the alterability of the intact rock.

The discontinuities condition is rated in accordance with the criteria contained in Table 9, which are derived from the "Guidelines for Classification of Discontinuity Conditions", Bieniawski (1989), which means that the maximum score for this parameter is *20 points*.

Table 9. Ratings for Discontinuities Condition.

Continuity	< 1 m	1-3m	3-10m	> 10m
	5	4	2	0
Roughness	Very rough	Rough	Smooth	Slickensided
	5	3	1	0
Gouge infilling	Hard		Soft	
	< 5mm	> 5mm	< 5mm	> 5mm
	5	2	2	0
Weathering	Unweathered	Moderately weathered	Highly	Decomposed
	5	3	1	0

To define the intact rock alterability ratings, a comparative study of this RMR update and the RMR89 was performed by compiling a large database established by Geocontrol.

2.3.1 *Database employed*

Geocontrol has a database composed of 2,298 cases of tunnel sections, constructed by the NATM, where the RMR89 has been determined.

The average value of the basic RMR in this database, without adjusting for the orientation of the tunnel, is 51 points and its frequency histogram is shown in Figure 6.

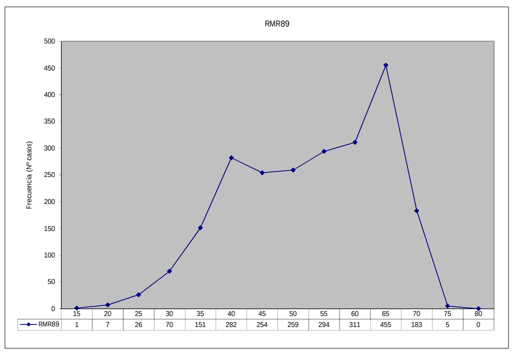


Figure 6. Database RMR89 frequency histogram.

The highest value of RMR89, in the database, is 73 points and the lowest one is 15 so the range has 58 points.

In this database, 68.5% of the cases are between 65 and 40 points, which matches well with the range of RMR in Spanish rock masses, when the RMR is not adjusted for discontinuities.

Figure 6 also shows that there are only five cases with RMR>70; which also matches with the usual practice that indicates that the RMR89 tends to concentrate the values in the central third of its range.

2.3.2 *Tested ratings for intact rock alterability*

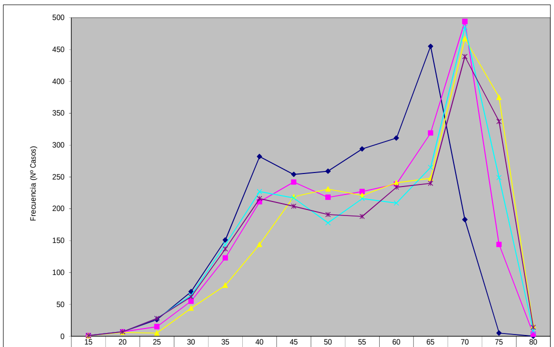
As indicated, the alterability of intact rock is determined using the Slake Durability Test, as defined in ASTM D 4644-87, which allows one to obtain the index I_{d2}.

In order to select the ratings for the alterability, four hypotheses were considered, which are presented in Table 10.

Table 10. Ratings tested for alterability.

Hypothesis	VALUES OF I_{d2} (%)					
	>98	95-98	85-95	60-85	30-60	<30
RMR14-I	10	8	6	4	2	0
RMR14-II	10	10	10	8	4	0
RMR14-III	10	9	8	2	1	0
RMR14-IV	10	10	9	3	1	0

Figure 7 shows the frequency histograms of the four hypotheses to rate the alterability along with the histogram of RMR89.



	15	20	25	30	35	40	45	50	55	60	65	70	75	80
RMR89	1	7	26	70	151	282	254	259	294	311	455	183	5	0
RMR14-I	1	7	15	55	123	211	242	218	227	239	319	494	144	3
RMR14-II	1	6	5	44	80	144	219	231	221	241	248	467	375	16
RMR14-III	1	7	28	64	144	227	217	178	216	209	265	485	249	8
RMR14-IV	1	7	28	62	137	216	204	191	188	234	240	439	337	14

Figure 7. RMR89 and the four hypothesis for the rock alterability.

This figure clearly shows that the ratings from hypothesis RMR14-II produce the desired effect of distributing the sample from the central third of the range to the upper third; thereby solving the RMR89 defect, mentioned above.

If a correlation factor R = 1 is assigned to the RMR89 it results in the correlation factor of RMR14-II being R = 0.982; whereby it is proved that, despite the RMR14-II sample shifts towards the highest RMR values, this correlation is not significantly worse.

According to the above, the ratings to take into account the alterability in the RMR14 are shown in Table 11.

Table 11. Ratings for intact rock alterability.

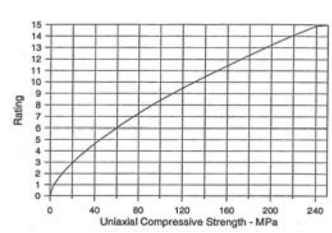
Alterability I_{d2} (%)			
> 85	60-85	30-60	< 30
10	8	4	0

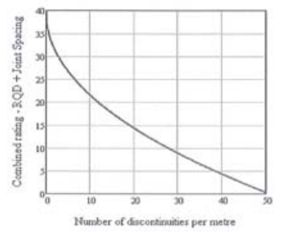
2.4 *RMR14 calculation*

Table 12 summarizes all the ratings for evaluation of the five parameters which comprise the RMR14, without adjusting for the tunnel axis orientation with respect to the most important set of discontinuities.

Table 12. Rating for calculating $RMR14_b$.

1. Strength of Intact Rock 2. Number of discontinuities





3. Discontinuities Condition

Continuity	< 1 m	1-3m	3-10m	> 10m
	5	4	2	0
Roughness	Very rough	Rough	Smooth	Slickensided
	5	3	1	0
Gouge infilling	Hard		Soft	
	< 5mm	> 5mm	< 5mm	> 5mm
	5	2	2	0
Weathering	Unweathered	Moderately weathered	Highly	Decomposed
	5	3	1	0

4. Presence of water

Ground state	Dry	Slightly wet	wet	Dripping	Water flow
Assessment	15	10	7	4	0

5. Alterability

Alterability I_{d2} (%)			
> 85	60-85	30-60	< 30
10	8	4	0

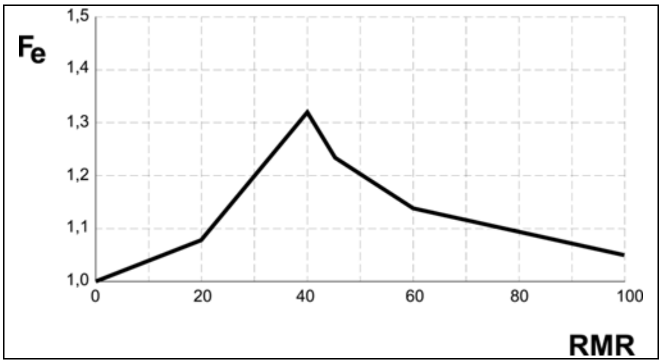
The three adjustment factors are calculated according to the information contained in Table 13.

Table 13. Adjustment Factors for RMR14.

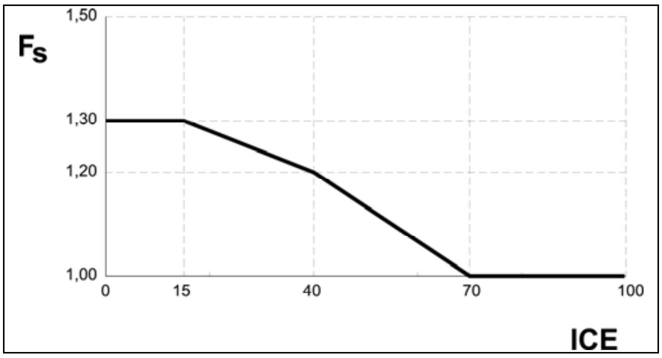
I. Tunnel orientation versus that of discontinuities (F_0)

STRIKE PERPENDICULAR TO TUNNEL AXIS				Strike parallel to Tunnel Axis		Irrespective of Strike Dip 0º-20º
Drive with dip		Drive against dip				
Dip 45-90	Dip 20-45	Dip 45-90	Dip 20-45	Dip. 45-90	Dip 20-45	
Very favorable	Favorable	Medium	Unfavorable	Very unfavorable	Medium	Medium
0	-2	-5	-10	-12	-5	-5

II. Mechanical excavation



III. Stress - Strain behavior



3 CORRELATION BETWEEN RMR89 AND RMR14

Figure 8 shows an excellent correlation between RMR89 and RMR14, calculated with 2,298 cases of the database, corresponding to the equation:

$$RMR14 = 1.1 \cdot RMR89 + 2 \qquad (7)$$

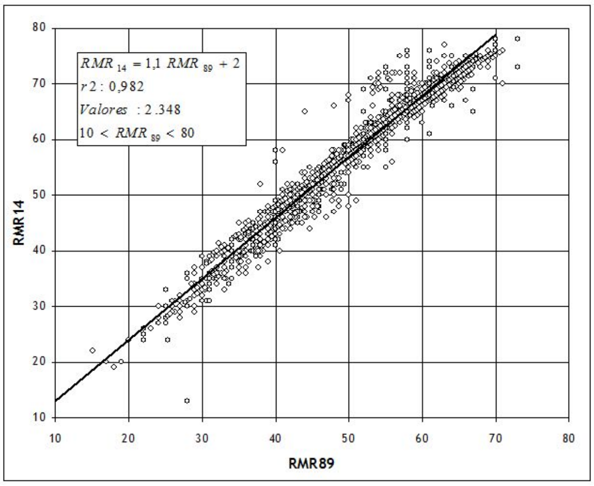


Figure 8. Correlation between RMR14 and RMR89.

4 WORKS IN PROGRESS

This R & D project of Geocontrol, partly funded by the CDTI, ends in February 2014 and by then it is expected to perform the following two tasks:

Software to calculate the RMR14: A software that allows determination of the RMR14 and the parameters for stress-strain calculations.

Empirical selection of supports: A chart that provides an empirical guide for the support and reinforcement of underground works, with respect to their dimensions and the "stress-strain-behavior of the rock mass".

Most of all, the current update to the RMR System is being conducted within the framework of an innovative tunnel design methodology termed "Interactive Structural Design" (*Diseño Estructural Activo*, Celada 2011), as depicted in Figure 9 a, b and c.

5 CONCLUSIONS

Since its introduction in 1989, the RMR89 has remained as an accepted worldwide tool to characterize the behavior of rock masses.

Over the past decades there have been many innovations to improve the RMR that have been incorporated in this work, as the result of a research project at Geocontrol, partially funded by the CDTI.

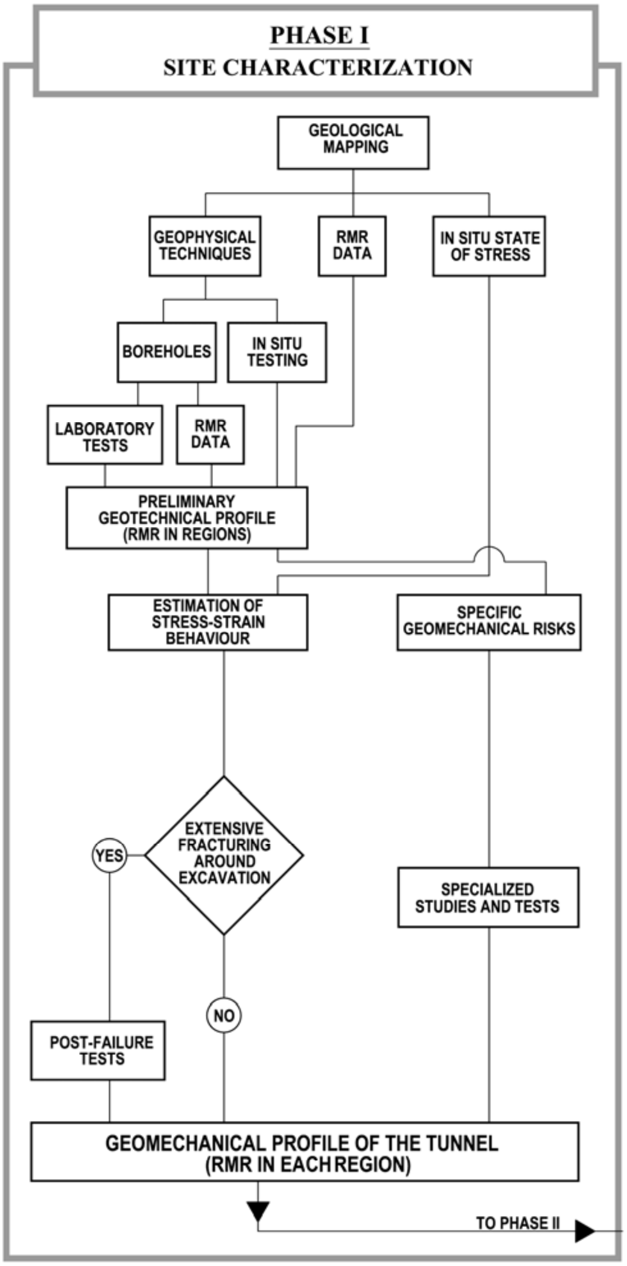


Figure 9 a. The methodology of the"Interactive Structural Design" (Diseño Estructural Activo, Celada 2011) PHASE I. Site characterization.

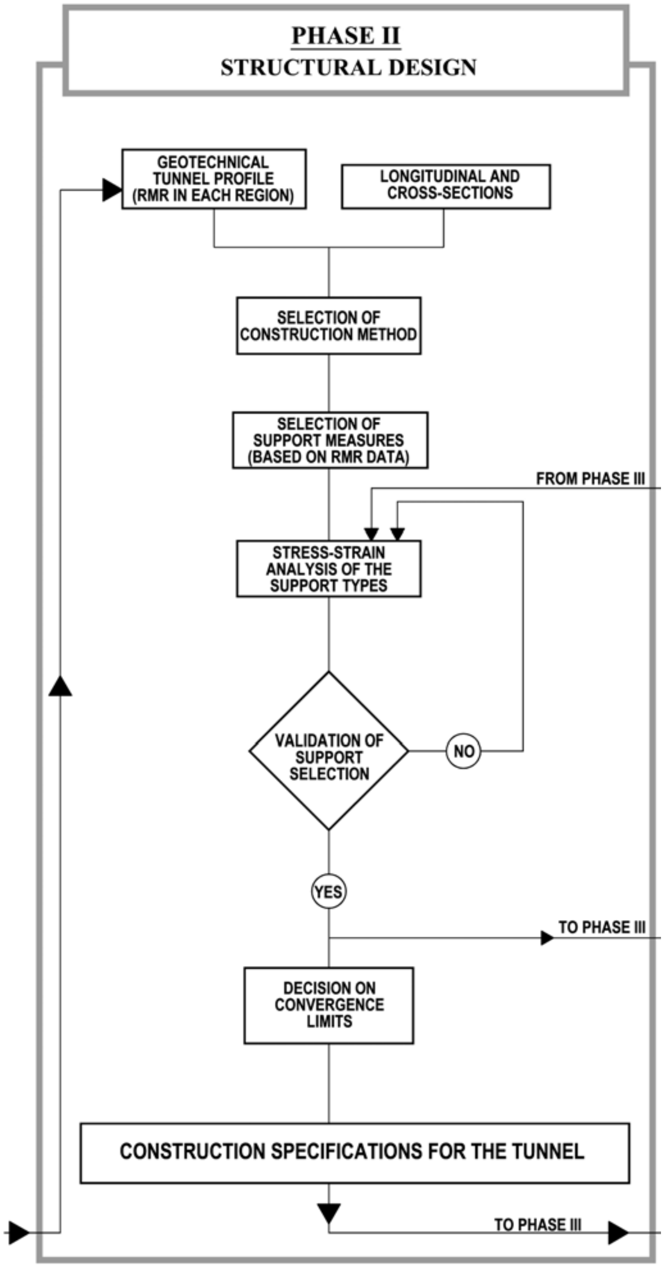


Figure 9 b. PHASE II. Structural Design.

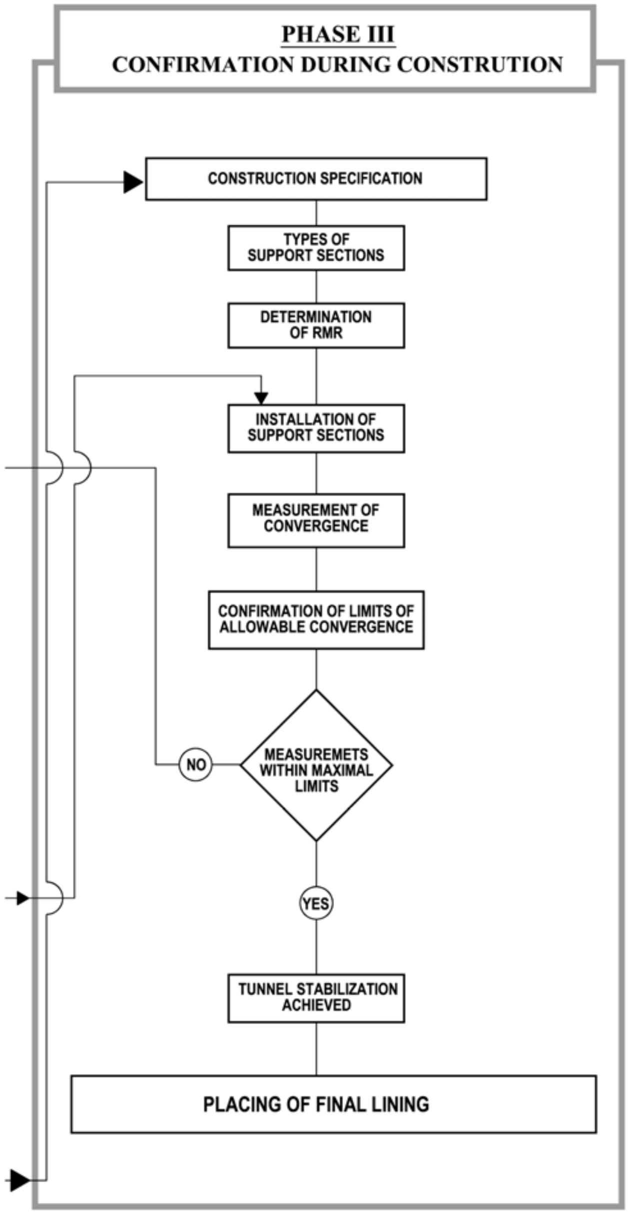


Figure 9 c. PHASE III. Confirmation during construction.

In addition, in recent years, renewed attention was paid to the RMR System because of its applications to the assessment of rock mass excavability (RME) and, especially, its direct correlation with the Specific Energy of Excavation (EEE) for TBMs has shown that it can be used effectively to detect changes in tunneling ground conditions, in real time, when recording TBM performance and serving as a warning of adverse conditions as construction proceeds (Bieniawski and Celada, 2006).

The RMR update presented in this paper, and called RMR14, has a new structure, which consists of three parameters from the RMR89, to which the modified discontinuities condition and the effect of the alterability of the intact rock have been added.

Furthermore, besides the adjustment factor for the orientation of the tunnel already present in the RMR89, the RMR14 includes two new adjustment factors, one for the case in which the excavation is carried out by mechanical means and another one for the stress-strain behavior of tunnel faces.

The new RMR14 correlates well with the RMR89, based on a database containing 2,298 cases, and thus maintains the essence of the RMR System used for over 40 years.

During the WTC in Brazil in May 2014, it is expected to present software for calculating the RMR14 and a comprehensive chart for empirical determination of the support to be installed in tunnels.

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