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CLARIFICATION OF THE SLOPE MASS RATING PARAMETERS ASSISTED BY SMRTOOL, AN OPEN-SOURCE SOFTWARE

José Luis Pastor*, Adrián J. Riquelme, Roberto Tomás, Miguel Cano

Department of Civil Engineering. University of Alicante, P.O. Box 99, 03080, Alicante, Spain.

* Corresponding author. joseluis.pastor@ua.es Tel.: +34 965903400 Ext 2470; fax: +34 965903678

ABSTRACT

Geomechanics classifications are used to perform a preliminary assessment of rock slopes stability for different purposes in civil and mining engineering. Among all existing rock mass classifications, Slope Mass Rating (SMR) is one of the most commonly used for slopes. Although SMR is a worldwide applied geomechanics classification, often some misapprehensions and inaccuracies are made when professionally and scientifically used. Nearly all these miscalculations involve the influence of slope geometry and the dip and direction of the discontinuities. These problems can be overcome by a systematic assessment of SMR, which allow users to understand and visualize the relative orientation between discontinuities and slope. To fulfil this purpose a complete and detailed definition of the angular relationships between discontinuities and slope are included in this paper, clarifying the assessment of the SMR parameters. Additionally, a Matlab-based open-source software for Slope Mass Rating (SMRTool) calculation is presented, avoiding miscalculations by automating the calculations and showing the graphical representation of slope and discontinuities. Finally, a general explanation of the method for the use of SMR is reviewed, stressing at the common source of errors when applying this classification. The performance, benefits and usefulness of SMRTool are also illustrated in this paper throughout a specific case study.

Keywords: geology; rock mechanics; Matlab; Slope Mass Rating (SMR); geomechanical classification.

1. INTRODUCTION

Geomechanics classifications are used to perform a preliminary assessment of rock slopes stability for different purposes in civil and mining engineering. These classifications, based on an empirical approach, are of paramount importance at the first stages of a project due to its simplicity, enabling a preliminary assessment of the stability of many slopes in a relatively short period of time. Some of the existing geomechanics classifications for slopes

are Rock Mass Rating (RMR) (Bieniawski 1976, 1989), Slope Mass Rating (SMR) (Romana 1993), Rock Mass Strength (RMS) (Romana 1985), Slope Rock Mass Rating (SRMR) (Robertson 1988), Slope Stability Probability Classification (SSPC) (Hack et al. 1998), Modified Stability Probability Classification (SSPC modified) (Lindsay et al. 2001), Natural Slope Methodology (NSM) (Shuk 1994) and Q-slope Method (Barton and Bar 2015; Bar and Barton 2017). Among all, Slope Mass Rating (SMR), calculated on the base of Rock Mass Rating (RMR), is probably one of the most widely used classifications (Romana et al. 2015). Many technical and educational books of rock mechanics or rock slope stability include a specific chapter or section for this classification (e.g. Hudson and Harrison (1997); Singh and Göel (1999)). SMR has also been included in technical regulations of some countries such as Italy, USA, China and India (Romana et al. 2015; Tomás et al. 2016).

The assessment of the basic RMR is made by rating five parameters: 1) rock strength, 2) rock quality, 3) spacing, 4) condition of discontinuities, and 5) groundwater conditions. Once the basic RMR has been calculated, four new factors have to be taken into account to calculate the SMR index. These new factors depend on the method of excavation of the slope and the relative orientation between discontinuities and slope. SMR value varies between 0 and 100, being 0 a completely unstable slope and 100 a completely stable one. It is important to note that other values are mathematically possible, although those values higher than 100 or lower than 0 do not have a physical sense.

Despite the apparent simplicity of this classification, often some mistakes are made when it is used for professional and scientific purposes. Nearly all these mistakes involve the influence of slope geometry and the strike and dip of the discontinuities. As a consequence of these mistakes, the final result of the slope stability assessment can be completely inaccurate. In this sense, Zheng et al. (2016) observed some problems assessing the two adjustment parameter F_1 and F_3, considering that the original SMR system may contain theory defects. But actually, it is a clarification of the SMR parameters what is needed. This clarification is presented in this paper through a comprehensive review of the SMR index (section 2). In section 3, a complete and detailed definition of the angular relationships between discontinuities and slope, and a redefinition of the mathematical equations for all the possible cases are included. Additionally, to avoid potential misunderstandings, a new Matlab-based open-source software has been developed in order to overcome the difficulties in the SMR calculation (section 4). The performance, benefits and usefulness of SMRTool are also

illustrated and discussed in this paper throughout a specific case study in section 5. Finally, the main conclusions are presented in section 6.

2. SLOPE MASS RATING

Rock Mass Rating (RMR) system was originally published by Bieniawski in 1976 (Bieniawski 1976). Since then, the RMR classification system has experienced successively changes in the ratings assigned to different parameters as more case reports were studied (Bieniawski 1989). Five parameters are used to classify a rock mass using the RMR classification: uniaxial compressive strength of rock, Rock Quality Designation (RQD), spacing of discontinuities, condition of discontinuities (further subdivided into persistence, separation, smoothness, infilling and weathering) and groundwater conditions. The value of RMR is equal to the sum of all these five parameters and it ranges from 0 to 100.

SMR index is obtained from basic RMR according to equation (1), taking into account four new parameters (F_1, F_2, F_3 and F_4) that consider the probability of failure of the slope depending on the slope method of excavation and the relative orientation between the discontinuities and the slope. It is worth noting that the parameters F_1, F_2 and F_3 depend on the expected type of failure for the slope under consideration (Fig. 1).

$$SMR = RMR + (F_1 \cdot F_2 \cdot F_3) + F_4 \quad (1)$$

where

F_1 depends on the angle A (Fig. 2 toFig. 4 and Table 1) between the discontinuity dip direction and slope dip direction (i.e. the parallelism between: a) the strikes of the discontinuity and the slope for planar and toppling failures; and b) the azimuth of the line of intersection and the dip direction of the slope for wedge failure).

F_2 depends on the discontinuity dip angle (B) (Fig. 2 to Fig. 4 and Table 1

F_3 depends on (Fig. 2 to Fig. 4 and Table 1): a) the difference (C) between the discontinuity and the slope dip angles for plane failure; b) the sum (C) of the discontinuity and the slope dip angles for toppling; or c) the difference (C) between the plunge of the line of intersection and the slope dip angle for wedge failure.

F_4 depends on the excavation method (Table 1).

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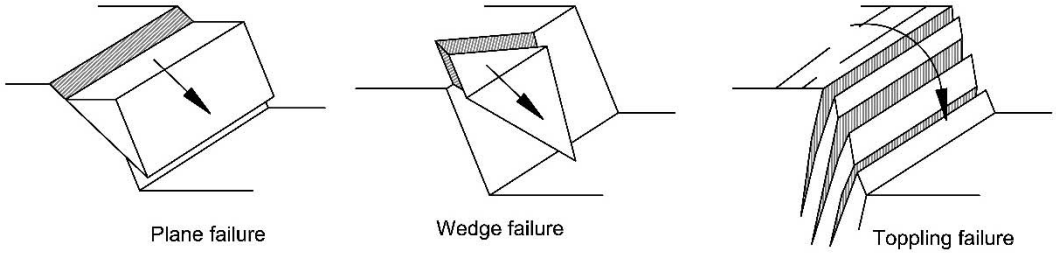

Fig. 1 – Types of possible slope failure to be considered in SMR calculation (Hoek and Bray 1981).

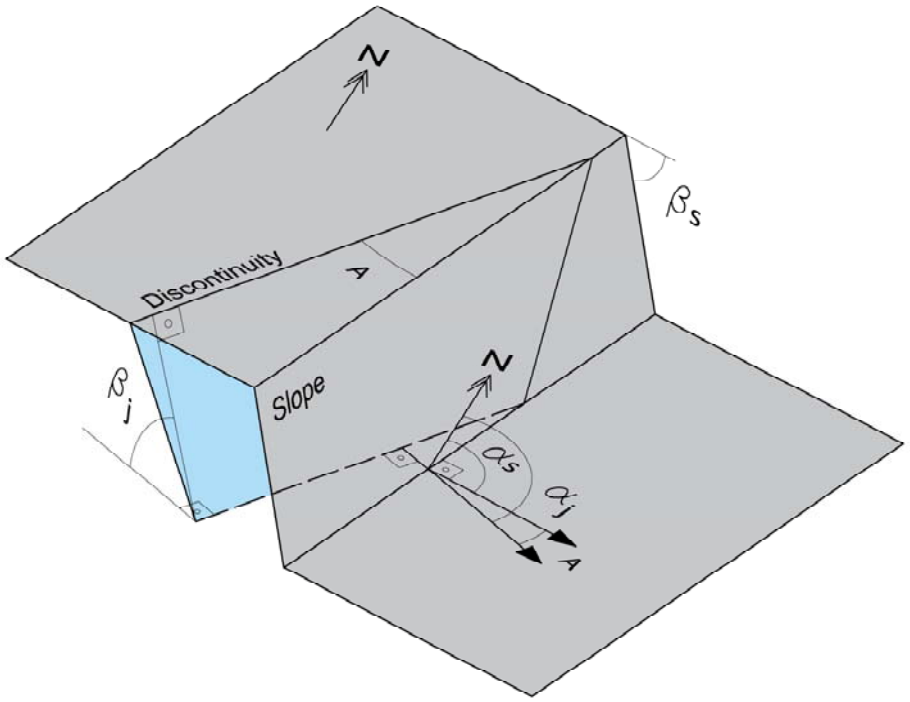

Fig. 2 – Parallelism (A) between discontinuity (α_j) and slope (α_s) strikes for planar failure.

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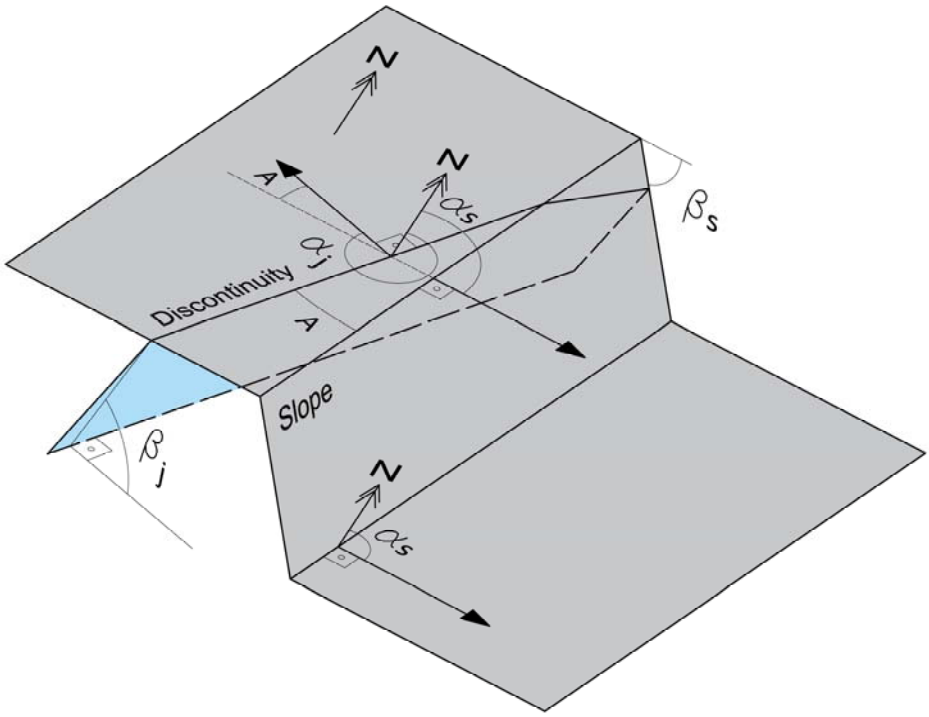

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105 Fig. 3 – Parallelism (A) between discontinuity (α_j) and slope (α_s) strikes for toppling failure.

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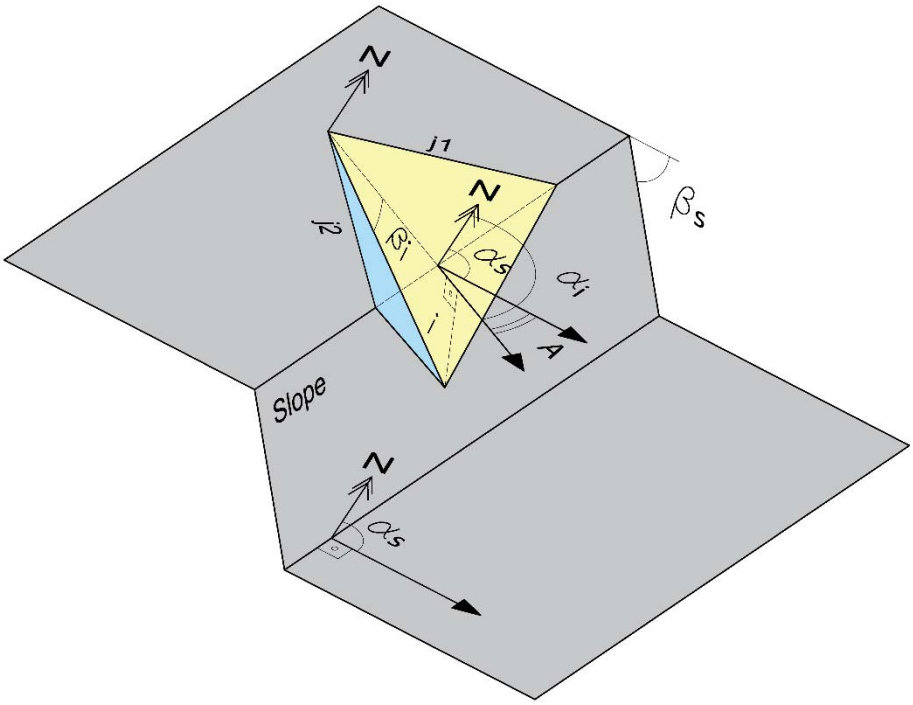

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108 Fig. 4 – Parallelism (A) between the plunge direction of the line of intersection of two
109 discontinuities (α_i) and the slope dip direction (α_s).

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The rating of these four parameters for the SMR calculation is shown in Table 1, in which it can be seen that orientation-dependent factors are zero or negative, while the excavation method factor can be positive or negative.

Table 1. Adjusting factors for discontinuities (F_1, F_2, and F_3) and excavation method (F_4). Modified from Romana (1985) by Tomás et al. (2007).

Auxiliary angle Adjusting factor	**Very favourable**	**Favourable**	**Fair**	**Unfavourable**	**Very unfavourable**
A	> 30º	30º - 20º	20º - 10º	10º - 5º	< 5º
F_1	**0.15**	**0.40**	**0.70**	**0.85**	**1.00**
B	< 20º	20º - 30º	30º - 35º	35º - 45º	> 45º
F_2	**0.15**	**0.40**	**0.70**	**0.85**	**1.00**
	1.00				
C	> 10º	10º - 0º	0º	0º - (-10º)	< (-10º)
	< 110º	110 - 120º	> 120º	-	-
F_3	**0**	**-6**	**-25**	**-50**	**-60**
Excavation method	Natural slope	Presplitting	Smooth blasting	Blasting or mechanical	Deficient blasting
F_4	**+15**	**+10**	**+8**	**0**	**-8**

In order to make computation simpler, Romana (1993) proposed the following continuous function for F_1 and F_2 as alternative values to that shown in Table 1:

$$F_1 = (1 - \text{sen } |A|)^2 \quad (2)$$

$$F_2 = \tan^2 B \quad (3)$$

In order to reduce subjective interpretations in the assignation of the values near the borders of the intervals, Tomás et al. (2007) proposed asymptotical continuous functions for F_1, F_2 and F_3 correction factors (Table 2) that show maximum absolute differences with discrete functions lower than 7 points. These functions can be also easily implemented into software routines for SMR assessment.

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Table 2. Asymptotical continuous functions for F_1, F_2 and F_3 calculation, (Tomás et al. 2007).

Parameter	Planar failure	Toppling failure
F_1	$F_1 = \frac{16}{25} - \frac{3}{500} atan\left(\frac{1}{10}(\lvert A\rvert - 17)\right)$	
F_2	$F_2 = \frac{9}{16} + \frac{1}{195} atan\left(\frac{17}{100}B - 5\right)$	$F_2 = 1$
F_3	$F_3 = -30 + \frac{1}{3} atan\ C$	$F_3 = -13 - \frac{1}{7} atan(C - 120)$

A is equal to the parallelism between discontinuities and slope strikes for planar and toppling failures and the angle formed between the intersection of the two discontinuities (the plunge direction) and the slope dip direction for wedge failure.
B = βj or βi
C = βj - βs for plane failure, C = βi - βs for wedge failure and C = βj + βs for toppling failure.
β_j = joint dip angle; β_i = line of joint intersection dip angle; β_s = slope dip angle.
Note that atan has to be expressed in degrees.

Once the SMR of a slope has been calculated, the slope can be classified within one of the five different stability classes shown in Table 3. Each one of these classes is associated empirically with a different failure mode. Table 3 also provides recommendations of remedial measurements of a slope based on SMR depending on the stability class.

Table 3. Description of SMR classes (Romana 1985).

Class nº	V	IV	III	II	I
SMR	**0 - 20**	**21 - 40**	**41 - 60**	**61 - 80**	**81 - 100**
Description	Very bad	Bad	Fair	Good	Very good
Stability	Completely unstable	Unstable	Partially stable	Stable	Completely unstable
Failures	Big planar or soil-like	Planar or big wedges	Some joints or many wedges	Some blocks	None
Support	Reexcavation	Important / corrective	Systematic	Occasional	none

3. DETAILED DESCRIPTION OF SMR CORRECTION FACTORS

The correct and accurate determination of parameters F_1, F_2 and F_3 is crucial for a reliable calculation of the SMR index. SMR is especially sensitive to F_1 and F_2 parameters (Tomás et al. 2012b), since their product ($\Psi=F_1 \times F_2$) can be considered as the percentage of factor F_3 mobilized (Tomás et al. 2012a). Therefore, a special attention has to be paid in the calculation of the auxiliary angular relationships. A wrong determination of some of the

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correction parameters can lead to a sub-estimation or an overestimation of the geomechanic quality of the slope and, thus, of the evaluation of its stability.

The first step for a systematic definition of the parameters is the description of the involved variables. To this aim, hereinafter, it is adopted that α_j and α_s are the discontinuity and slope dip directions and β_j and β_s the discontinuity and slope dip angles, respectively. Three auxiliary angles are used to define F_1, F_2 and F_3 adjustment factors: A, B and C, as defined by Tomás et al. (2007).

A refers to the parallelism between discontinuities and slope strike for planar and toppling failures (Fig. 2 and Fig. 3) and the angle formed between the intersection of the two discontinuities (the plunge direction) and the slope dip direction for wedge failure (Fig. 4). Originally, Romana (1985) stated in a general way that the parallelism (i.e. A angle) could be calculated as:

$$A = \begin{Bmatrix} |\alpha_j - \alpha_s| & for\ planar\ failure \\ |\alpha_j - \alpha_s - 180^o| & for\ toppling\ failure \end{Bmatrix} \quad (4)$$

However, these formulas are not valid for the calculus of the parallelism between the slope and the discontinuity (A) in all possible relative orientations, leading to errors in its calculation and therefore in the estimation of SMR. According to (4), angles higher than 90º are possible, although the parallelism between the discontinuity and slope strikes has to be always equal or less than 90º. This is the main source of error when calculating SMR and thus, a detailed description of this parameter is required as follows. When $|\alpha_j - \alpha_s|$ is less than 90º planar failure is expected and A is directly equal $|\alpha_j - \alpha_s|$. Nevertheless, a mathematical correction is needed in all other cases. When $|\alpha_j - \alpha_s|$ is higher than 270º planar failure is also expected but A is equal to $360^o - |\alpha_j - \alpha_s|$. Toppling failure is expected when $|\alpha_j - \alpha_s|$ is between 90º and 270º, so in this case, instead of the equation $|\alpha_j - \alpha_s - 180^o|$ which is only valid when $\alpha_j \geq \alpha_s$, the most general equation $||\alpha_j - \alpha_s| - 180^o|$ should be used to the assessment of A. For wedge failure, the two joints intersection line dip direction (α_i) is taken into account to study the parallelism between this line and the slope dip direction. When $|\alpha_i - \alpha_s|$ is less than 90º or higher than 270º a wedge failure can happen. Nevertheless, when $|\alpha_i - \alpha_s|$ is between 90º and 270º the wedge failure is kinematically not feasible (i.e. the wedge dips towards the slope), Fig. 5.

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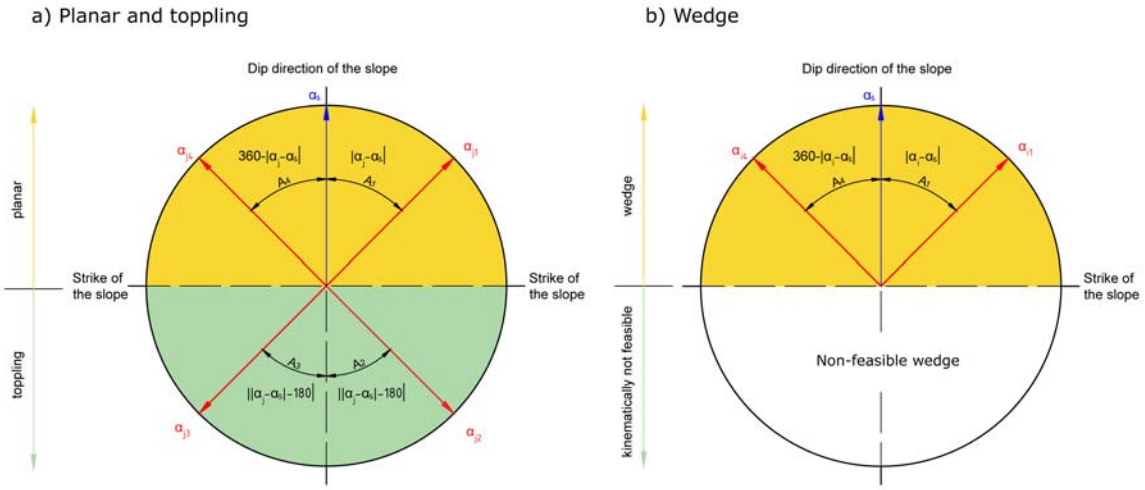

Fig. 5 – Calculation of the auxiliary angle A for a) planar and toppling failure and b) Wedge failure. The figure can be turned to make α_s perpendicular to the strike of the slope under consideration.

B angle is less problematic when calculated. The auxiliary angle B is the dip angle of the discontinuity or wedge, and no conversion is needed. The only caution to keep in mind when calculating the F_2 parameter is that it is always 1 for toppling failure.

Finally, the auxiliary angle C is the relation between discontinuity dip angle and slope dip angle. Its calculation is also quite simple and is shown in Fig. 6 . For planar and wedge failures C is equal to $\beta_j - \beta_s$ and $\beta_t - \beta_s$, respectively, and can adopt positive (Fig. 6 - b) or negative (Fig. 6 - a) values. For toppling, C is calculated as $\beta_j + \beta_s$ (Fig. 6 - c). Therefore, the identification of the failure mode compatible with each discontinuity is required before the calculation of this parameter.

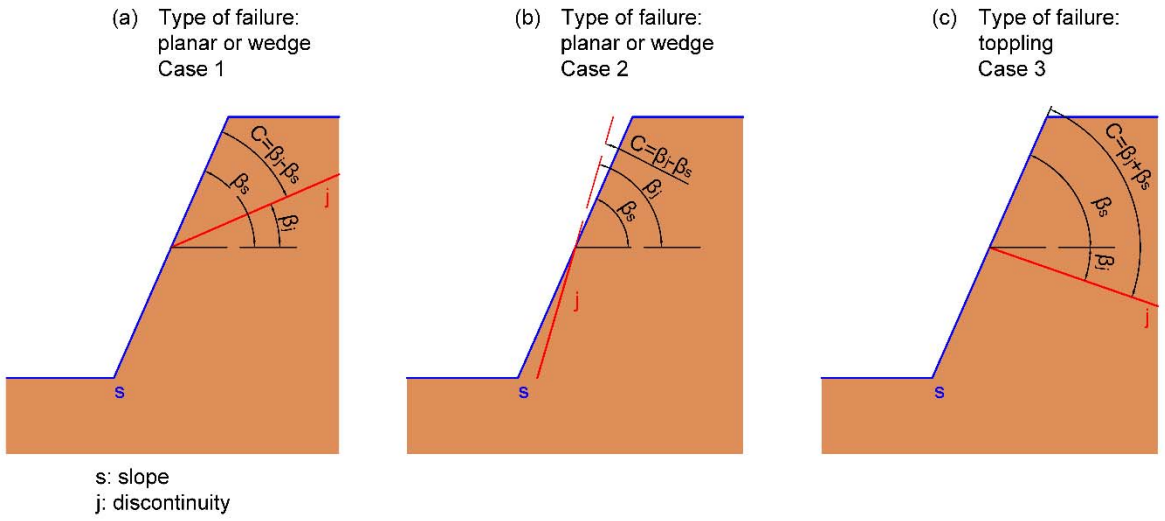

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Fig. 6 – Calculation of the auxiliary angle C. (a) and (b) show two possible cases of planar failure; (c) shows a toppling.

Table 4 summarizes the formulas used for the calculation of A, B and C angular relationships for the determination of F_1, F_2 and F_3 parameters, respectively, using the dip and dip direction of the slope and the discontinuities affecting the slope.

Table 4. Summary of the formulas used for the calculation of A, B and C angular relationships.

Failure mode	Angular relationship	Calculation of A	Calculation of B	Calculation of C
Planar	$\lvert\alpha_j - \alpha_s\rvert < 90^o$	$A = \lvert\alpha_j - \alpha_s\rvert$	$B = \beta_j$	$C = \beta_j - \beta_s$
	$\lvert\alpha_j - \alpha_s\rvert > 90^o$	$A = 360^o - \lvert\alpha_j - \alpha_s\rvert$	$B = \beta_j$	$C = \beta_j - \beta_s$
Wedge	$\lvert\alpha_i - \alpha_s\rvert < 90^o$	$A = \lvert\alpha_i - \alpha_s\rvert$	$B = \beta_i$	$C = \beta_i - \beta_s$
	$\lvert\alpha_i - \alpha_s\rvert > 90^o$	$A = 360^o - \lvert\alpha_i - \alpha_s\rvert$	$B = \beta_i$	$C = \beta_i - \beta_s$
Toppling	$90^o < \lvert\alpha_j - \alpha_s\rvert < 270^o$	$A = \lvert \lvert\alpha_j - \alpha_s\rvert - 180^o \rvert$	Not necessary	$C = \beta_j + \beta_s$

4. OPEN-SOURCE SOFTWARE DESCRIPTION

An open source software has been developed for an automatic and accurate calculation of the angular relationships and parameters involved in the calculation of SMR (https://personal.ua.es/en/ariquelme/smrtool.html). This software will help engineers and geologists with a graphical representation of the geometry data used as input for the SMR calculation and guiding them in the whole process. The process followed by the software for the SMR assessment can be seen in Fig. 7.

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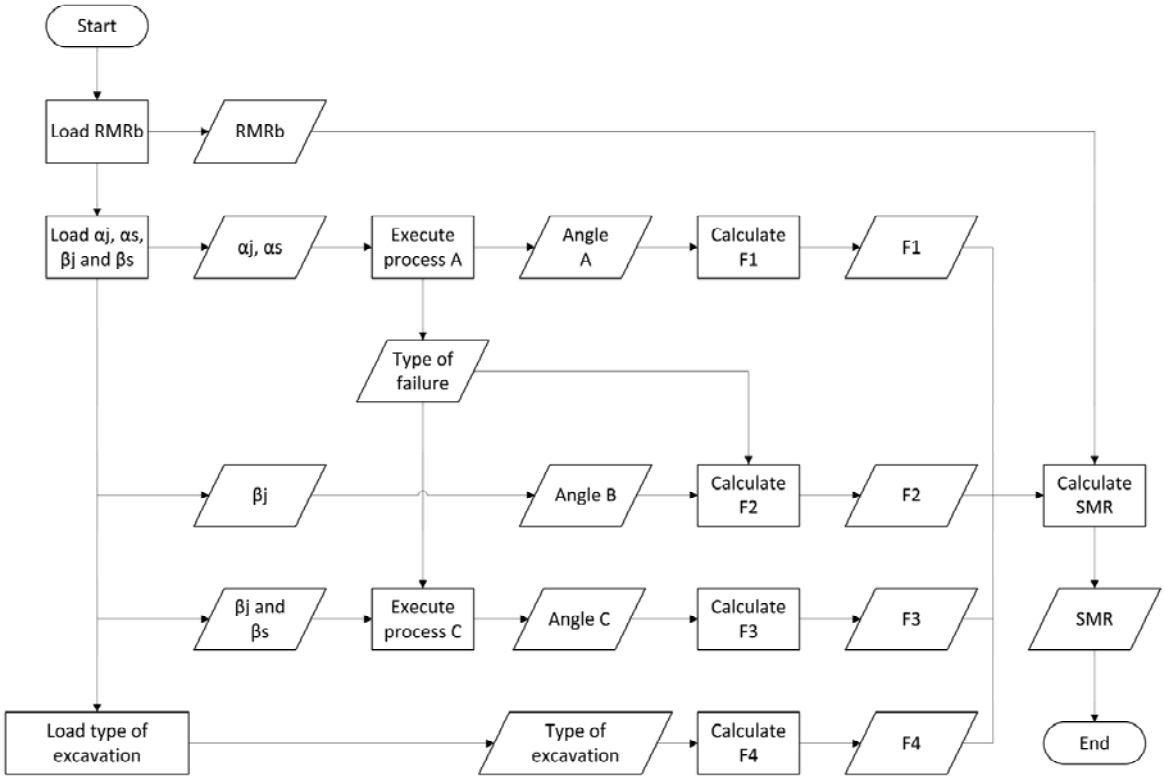

Fig. 7 – Flowchart for the SMR calculation.

The pseudocodes of the processes A, F_1, F_2, C and F_3 (Fig. 7) are described in the Algorithms 1 to 5 (Fig. 8 to 12). It is worth noting that when a wedge instability is being calculated, the software equals $\alpha_i = \alpha_j$, and $\beta_i = \beta_j$ using the same algorithm as for planar failure.

```
procedure A
    Input: α_s, α_j
    Output: A, type-of-failure
    A ← |α_s − α_j|
    type-of-failure ← planar-wedge
    if A > 90° and A < 270° then
        type-of-failure ← toppling
        if A > 180° then
            A ← A − 180°
        else
            A ← 180° − A
    if A ≥ 270° and A ≤ 360° then
        A ← 360° − A
```

Fig. 8 – Algorithm 1. Pseudocode for the process A.

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```
procedure F_1
    Input: α_s, α_j, A
    Output: F_1
    if A > 30° then
        F_1 ← 0.15
    if A ≥ 20° and A < 30° then
        F_1 ← 0.4
    if A ≥ 5° and A < 10° then
        F_1 ← 0.85
    if A < 5° then
        F_1 ← 1
```

Fig. 9 - Algorithm 2 Pseudocode for the process F_1.

```
procedure F_2
    Input: type-of-failure, β_j
    Output: F_2
    if type-of-failure = toppling then
        F_2 ← 1
    else
        if β_j ≤ 20° then
            F_2 ← 0.15
        if β_j > 20° and β_j ≤ 30° then
            F_2 ← 0.4
        if β_j > 30° and β_j ≤ 35° then
            F_2 ← 0.7
        if β_j > 35° and β_j ≤ 45° then
            F_2 ← 0.85
        if β_j > 45° then
            F_2 ← 1
```

Fig. 10 - Algorithm 3 Pseudocode for the process F_2.

```
procedure C
    Input: β_j, β_s, type-of-failure
    Output: C
    if type-of-failure = toppling then
        C ← β_s + β_j
    else
        C ← β_j − β_s
```

Fig. 11 - Algorithm 4 Pseudocode for the process C.

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```
procedure F3
    Input: C, type-of-failure
    Output: F3
    if type-of-failure = toppling then
        if C < 110° then
            F3 ← 0
        if C ≥ 110° and C < 120° then
            F3 ← −6
        if C ≥ 120° then
            F3 ← −25
    else
        if C > 10° then
            F3 ← 0
        if C > 0° and C ≤ 10° then
            F3 ← −6
        if C = 0° then
            F3 ← −25
        if C ≥ −10° and C < 0° then
            F3 ← −50
        if C ≤ −10° then
            F3 ← −60
```

Fig. 12 - Algorithm 5 Pseudocode for the process F_3.

A compact graphical user interface has been designed, allowing the user to check the inputs and outputs in the same window. This graphical user interface is shown in Fig. 13 . The *Input data* panel can be seen on the top left and the top centre of this figure. As input data, the user must introduce the slope geometry (dip direction and dip), the slope excavation method, which is chosen from a list, the discontinuity geometry (dip direction and dip) and the Rock Mass Rating of the set of discontinuities for which the SMR wants to be calculated. In this case, in which the analysis is being done for an individual set of discontinuities, the user must choose the type of element analyzed between plane or wedge. If the user wants to run the analysis not for one individual set of discontinuities but for all sets of discontinuities within the rock mass, *Planes and Wedges* panel should be used. This panel is in the centre of the upper half of the graphical user interface. Geometry and RMR for each discontinuity or set of discontinuities to be considered have to be introduced here. In this case, it is not necessary to select the type of element being analyzed, as after clicking the button “Calculate wedges”, the software will calculate all the possible wedges from the intersecting plane discontinuities and analyze if the failure is kinetically possible. When the wedge is kinetically non-possible a value of 0 is shown in the possibility section of the *Planes and Wedges* panel, and the SMR for this wedge is shown as equal to 100, meaning that there are no stability problems for this wedge.

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Based on the dip and dip direction of the slope and discontinuities (Clar's notation), the possible slope failure type is calculated by the software. As said in the previous section, the formulae to be used to assess the parameters F_1, F_2 and F_3 depends on the type of failure considered (i.e. plane, wedge or toppling) and considers all possible geometrical situations illustrated in Fig. 5 andFig. 6 . Therefore, the automatic assessment by the software avoids mistakes in this step.

All the intermediate calculations are shown on the SMR Calculations panel. The upper half of this panel shows the SMR auxiliary angles A, B, and C previously described. The parameters F_1, F_2, F_3 and F_4 calculated according to Romana (1985) and Tomás et al. (2007) are presented on the lower half panel, allowing users to compare the results obtained between these two methods.

The SMR result is shown on the SMR Geomechanics Classification panel, which is in the centre of the lower half of the graphical user interface. In addition to the SMR numerical result, the stability classification of the slope, the description, the stability, the expected type of failure and the remedial measurement recommended according to Romana (1993) are also shown on this panel. Therefore, this is the results main panel, showing all the necessary data to analyze the slope stability.

Finally, two graphical representations of the relative orientation between slope and discontinuities are depicted at the right side of the interface, helping users to understand the expected type of failure. The figure on the upper right-hand side shows a top view of the angle between the slope and the discontinuity dip directions. Plane or wedge failure, but no toppling, will be expected when the angle between these two vectors is less than 90º (acute angle). On the contrary, only toppling can be expected when the angle is obtuse. The figure on the lower right-hand side shows a cross section of the slope in which the discontinuity has been depicted. This figure clarifies the type of failure expected (plane, wedge or toppling) according to the slope and discontinuity geometry. These two figures have clarifying purpose as they make clear the importance of related properties of the slope geometry and the direction and dip of the discontinuities within the stability calculations, avoiding mistakes involving the relative orientation between discontinuities and slope. It is worth noting that this kind of miscalculation is the most common when applying SMR.

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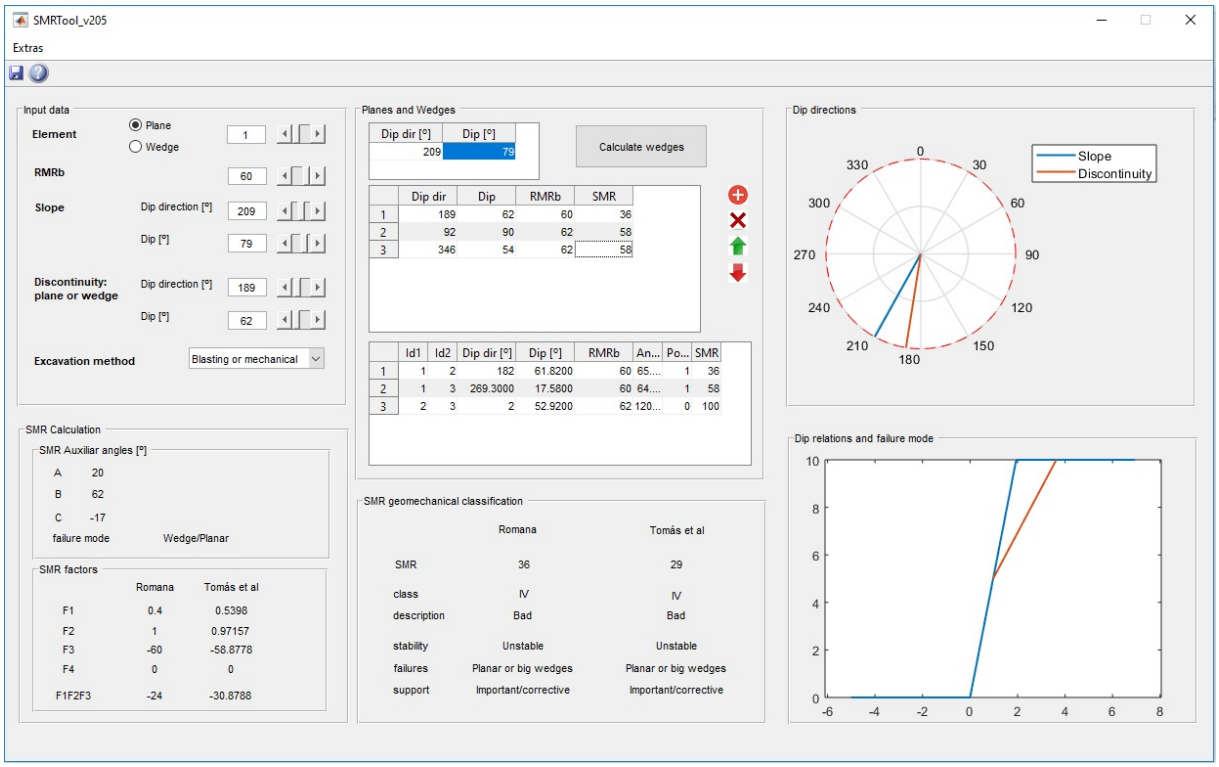


Fig. 13 – Graphical user interface of the SMRTool software.

5. CASE STUDY

A case study of an 18 m high slope composed of Jurassic slightly weathered limestone (Martín and Campos 1974) with a strong structural control is presented in this section in order to illustrate the applicability of the developed software and the calculation of the angular relationships and correction parameters. A general view of the slope of the example is shown in Fig. 14 . All the necessary geomechanical data obtained during the field works and in the previous calculations for SMR assessment of the slope are summarized in Table 5. In this case, three sets of discontinuities were recognized in the slope: DS1 to DS3.

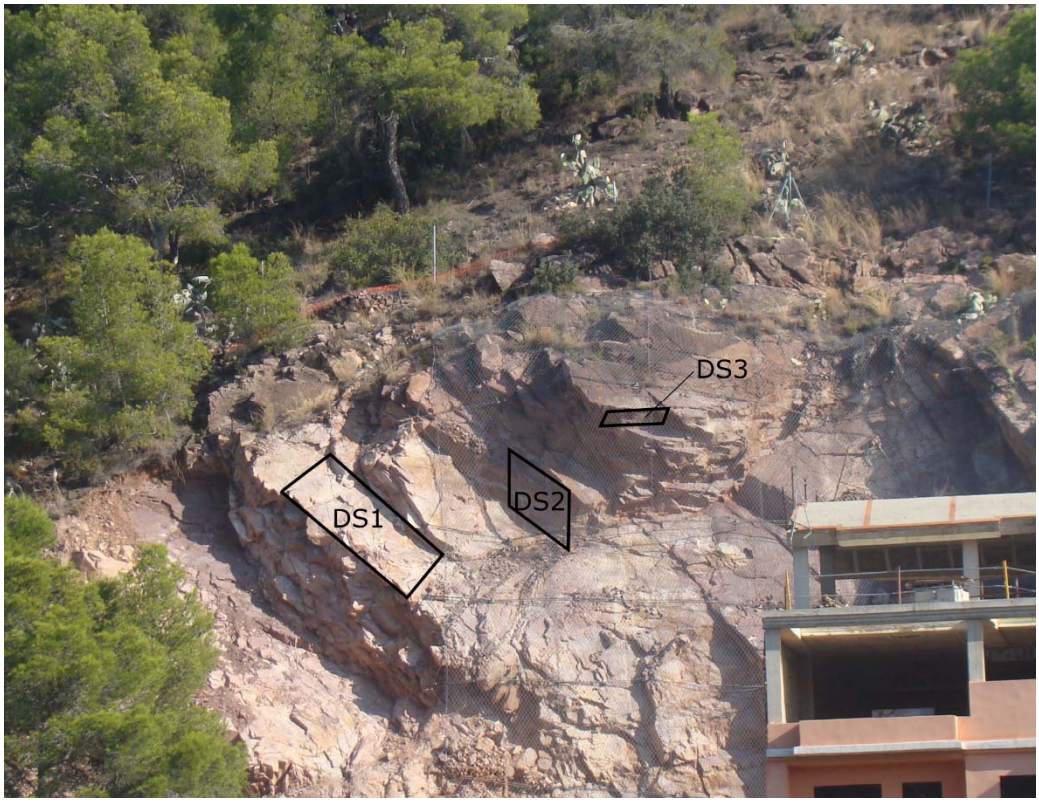
Table 5. Data obtained in the field and previous calculations for SMR assessment.

Discontinuity set	Dip Direction (º)	Dip (º)	RMR_b
Slope Mechanical excavation	209	79	--
DS1	189	62	60
DS2	92	90	62
DS3	346	54	62

This is a preprint version of the article published by Springer in the Bulletin of Engineering Geology and the Environment, 2019. https://doi.org/10.1007/s10064-019-01528-9

297

298 Fig. 13 shows the SMRTool graphical user interface using the input data of Table 5.
299 These input parameters can be seen in the top centre panel in which dip direction and dip of
300 the slope are first shown. The dip direction and dip of the three sets of discontinuities are
301 included below. The mechanical excavation method is introduced in the top left panel, where
302 the data of plane 1 (discontinuity set 1) can also be seen. Once all the data have been
303 introduced, the SMR values for each discontinuity set is shown in the last column of the top
304 centre panel. SMR values of 36, 58 and 58 are obtained for DS1, DS2 and DS3, respectively.
305 The software runs the wedges analysis by clicking the *Calculate wedges* button in the top
306 centre panel. After doing this, the SMR values for the possible wedges are shown in the centre
307 of the graphical user interface.
308



309

310 Fig. 14 – View of the slope of the example where three discontinuity sets can be
311 distinguished.
312

313 In order to better understand the calculation process, the value of the auxiliary angles
314 A, B and C are shown in the SMR panel, where the likely failure mode is outlined. A, B and
315 C angles of 20º, 62º and -17º are obtained for plane 1 (DS1), being wedge or planar the
316 possible failure mode. The SMR factors are shown on the lower half of the SMR panel, where

it can be seen the difference between these factors calculated according to the discrete values proposed by Romana (1993) and according to the continuous functions proposed by Tomás et al. (2007). The first factor, for example, equals 0.4 when calculated by Romana (1993) and 0.5398 when calculated by Tomás et al. (2007). This example illustrates the benefit of using the continuous functions for the factor assessment, especially when the parameters, are near the borderline between two different ratings. In this case, the absolute value of the difference between joint dip direction and slope dip direction for factor 1 equals 20º. Therefore F_1 can be rated as 0.4 or 0.7 according to Table 1 (Romana 1993), whilst the continuous functions do not exhibit this issue.

The SMR numerical result for plane 1 (DS1) is shown in the SMR Geomechanics Classification panel, being equal to 36 when the factors are calculated according to the original discrete functions (Romana 1993) and equal to 29 when are calculated using the continuous functions (Tomás et al. 2007). Despite the difference of the SMR value obtained by these two methods for this example, for both cases, the stability classification is IV. Being the description "bad" and unstable, with planar or big wedges failures expected, and important corrective measures needed. Finally, the dip direction graphical representation shows the alignment between slope and discontinuity dip direction, needed for factor 1 assessment. The dip directions and failure mode representation let the user understand why a planar failure mode is expected for plane 1 (DS1) (see the failure modes presented in Fig. 1).

We can change the data shown on the graphical user interface by clicking on the number of the plane shown on the top left panel (i.e. the input data panel). If we set the plane number 2 (DS2), all the data, results and plots shown will correspond to this plane, Fig. 15 . In this case, toppling failure is expected, being all the calculations done (auxiliary angles, etc.) according to this type of failure. Looking at the dip directions (upper right plot) and failure mode representation (lower right plot) it can be seen that the slope and the discontinuity set are dipping in opposite directions. Therefore, it is easy to understand why toppling is the expected type of failure. The calculated SMR value for DS2 is equal to 58 and 57 calculated by Romana (1993) and Tomás et al. (2007), respectively. Dip direction representation, where no alignment between discontinuity and slope direction are seen, explains these SMR values higher than those calculated for plane 1. For both SMR values (i.e. discrete and continuous), the stability classification is III, described as "normal", being partially stable with some joints or many wedges expected, needing systematic corrective measures. It is noteworthy that the results of the auxiliary angle A for DS2 are different when calculated according to the general

equation $||\alpha_j - \alpha_s| - 180^o|$, included in the detailed description of angular relationships of Table 4, and using the original equation $|\alpha_j - \alpha_s - 180^o|$ from Romana (1993). In this particular case, the parallelism (A) is equal to 63º when it is calculated according to the proposed equation, and this is the value shown by the SMRTool software, Fig. 15 and Table 6. However, a value of 297º is obtained by the use of the original general equation published by Romana (1993). By coincidence, the value of F_1 is the same for both angles (0.15). Nevertheless, if the slope dip direction were 60º smaller, F_1 would be equal to 1 calculated with the proposed equation and 0.15 calculated with the equation from Romana (1993). This miscalculation would lead to a very different stability assessment. In fact, the calculation made using the relationships listed in Table 5 would be on the safe of security in comparison with those made using the general expression proposed by Romana (1993).

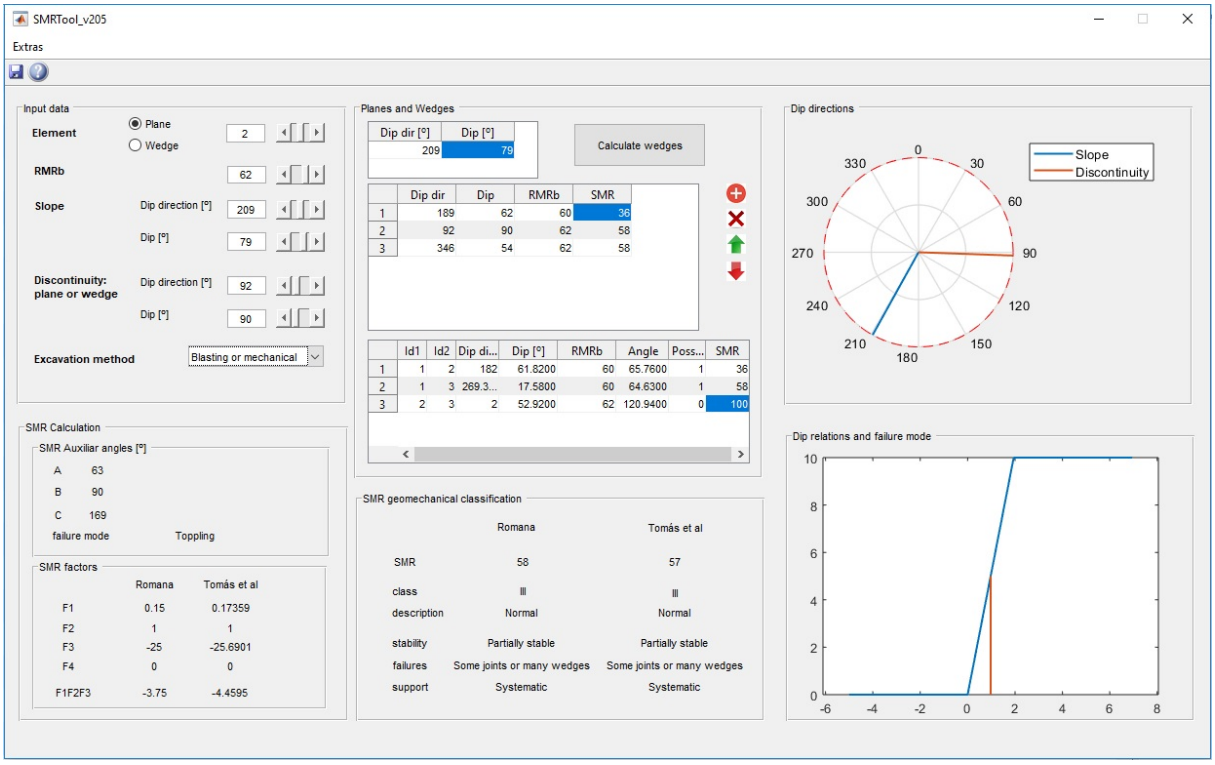


Fig. 15 – Graphical User Interface for plane 2.

The complete results of this case study are shown in Table 6. All the instabilities possible combinations between slope and the three discontinuity sets are shown in this table. One planar failure, two toppling and five wedges were analyzed by the software. The use of the SMRTool allows the user to obtain all this data automatically, making more efficient and quicker the calculation, and avoiding mistakes involving the relative orientation between

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discontinuities and slope. For this case study, the discontinuity set 1 has the worst influence on the stability of the slope. An SMR value of 36 has been obtained using the discrete functions (Romana 1993) and of 29 using the continuous functions (Tomás et al. 2007). The last wedge in Table 6 is not kinematically feasible, as the dip of the wedge is towards the slope, therefore the software shows a value of 0 in the possibility button of the *Planes and Wedges* panel, and the SMR for this wedge is shown as equal to 100. It means that there are no stability problems for the considered wedge.

Table 6. Results obtained using SMRTool for the case study for discrete functions when calculated by Romana (Romana 1993) and for continuous functions when calculated by Tomás et al. (Tomás et al. 2007).

Type of failure	Discontinuity set involved	Auxiliary angles (°)			SMR factors								SMR value	
					Discrete functions				Continuous functions				Discrete functions	Continuous functions
		A	B	C	F1	F2	F3	F4	F1	F2	F3	F4		
Planar	DS 1	20	62	-17	0.4	1	-60	0	0.5398	0.97157	-58.8778	0	**36**	**29**
Toppling	DS 2	63	90	169	0.15	1	-25	0	0.17359	1	-25.6901	0	58	57
Toppling	DS 3	43	54	133	0.15	1	-25	0	0.22623	1	-25.2288	0	58	56
Wedge	DS 1 – DS2	27	61.82	-17.18	0.4	1	-60	0	0.37	0.97128	-58.8896	0	36	38
Wedge	DS 1 – DS3	60.3	17.58	-61.42	0.15	0.15	-60	0	0.17803	0.23653	-59.6891	0	58	57
Wedge	DS 2 – DS3	27	52.92	131.9	Non-feasible wedge								100	100

6. CONCLUSIONS

Slope Mass Rating (SMR) is worldwide used to perform a preliminary assessment of rock slopes stability for different purposes such as civil or mining engineering. Nevertheless, often some miscalculations are made when professionally and scientifically used. Nearly all these mistakes involve the relative orientation between the slope and the discontinuities. Therefore, a detailed description of the geometrical parameters A, B and C involved in the calculation of SMR as never before done has been included in this paper. Furthermore, a Matlab-based open-source software to avoid the above-mentioned mistakes as well as to make more efficient and quicker the calculation of SMR has been programmed. The code of this Matlab-based software is freely downloadable online for analysis of rock slope stability and the algorithms are presented in this paper.

7. ACKNOWLEDGEMENTS

This work has been supported by the University of Alicante under the projects GRE14-04 and GRE17-11, and the Spanish Ministry of Economy and Competitiveness (MINECO), the State Agency of Research (AEI) and the European Funds for Regional Development (FEDER) under projects TEC2017-85244-C2-1-P and TIN2014-55413-C2-2-P, and the Spanish Ministry of Education, Culture and Sport under project PRX17/00439 and CAS17/00392.

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