Practical application of HsQI system to quantitative geotechnical zonation of road corridors in mountain areas.

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Abstract

The Hillslope Quality Index (HsQI) is an indicator of slopes stability and their susceptibility to the occurrence of landslides based on a method of geotechnical classification of slopes in linear projects (roadways, railways, channels, ducts, etc.) for mountainous tropical areas, considering the combined use of geomorphological, hydrological and soil mechanics factors.

The HsQI classification system uses the methodology proposed by the Nancy Mining School (France) as a basis for the zoning of soil and rock slopes; with a modification that translates into a hillslope quality index instead of the Safety Factor (SF). The pioneering methodology of the Nancy Mining School, recommended by Chica-Sanchez (1989) due to its practicality and simplicity was adapted in such a way that its application extends beyond the slope, incorporating the complete hillside and offering a better approach to the real problems of mountain roads, where the effect of the cuts is reflected in land beyond the administrative limits of the road corridor or concessions. In this sense, the HsQI methodology offers data close to the real behavior of the slope stability in terms of possible landslides, considering different conditions of geometry and water table for cases of plane and circular failure.

For the validation of the method, two case studies were developed and applied in a road segment in the La Pintada - La Felisa sector in Colombia (Moreno-Ceballos, 2015) and a segment of the Sifón-La Abundancia road project located in the northern area of Costa Rica (Ocampo, 2016). A statistical analysis of the HsQI depending on the variability of the geotechnical properties of the land, a comparison with SF values calculated with the limit equilibrium method for several slopes and a performance analysis with the graphic method Receiver Operating Characteristics (ROC) (Fawcett, 2006) were performed. Additionally, to improve the classification system, the influence of weather conditions was introduced as a trigger factor, considering the average monthly rainfall of the area represented by the soil moisture parameter (Sh) (Mora and Vahrson Method, 1994) which allows the representation of the position of the water table in relation to the height of the hillside.

The application of the model is aimed at the planning, verification and maintenance of linear projects. It allows to perform and provides:

- *Validations and recommendations for hillslope support systems based on the conditions of the linear project (importance, magnitude and use)*
- *Facilitation of the maintenance, administration and investment plan of a project*
- *Sectorization of maintenance plans during operation*
- *Knowledge of the economic risk associated with the functionality of the structures and probability of losses in the event of a landslide.*

This article develops the HsQI methodology in a projected road segment from the city of Medellín to Puerto Berrio (Antioquia), along a mountainous area in the Colombian Central Mountain Range with high rainfall characteristics and complex geological conditions. The document exposes the use of semi-automation tools of the HsQI method using Geographic Information Systems (GIS) and programming language. The results show great applicability for decision-making processes based on quantitative analyses of geotechnical risk.

1 INTRODUCTION

The Hillslope Quality Index (HsQI) is an indicator of slope stability and its susceptibility to the occurrence of landslides, which is based on a methodology of geotechnical classification of road corridors for mountainous tropical areas, considering the combined use of geomorphological, hydrological and mechanical soil factors.

Below, the application of the methodology is presented in a projected road segment from the city of Medellín to Puerto Berrio (Antioquia), along a mountainous area in the Colombian Central Mountain Range with characteristics of high rainfall and complex geological conditions. The development of the case study is based on the use of automation tools through the application of Geographic Information Systems (GIS) and programming language. The results show great applicability for decision-making processes based on quantitative analyzes of geotechnical hazards with high potential to become a first step in the geotechnical risk assessment for transportation corridors.

2 METHODOLOGY

The HsQI classification system uses as a base the methodology proposed by the Nancy School of Mines (France) for slopes in soil and rock according Chica-Sánchez (1989) with a modification that translates into a hillslope quality index instead of the Safety Factor (SF), providing an indication of the susceptibility of the hillslope to landslides related to the intervention associated with the construction of road projects.

For the application of the method it is necessary to know the geological and geomorphological configuration of the study area, the geometry of the road project, the geotechnical parameters and physical properties of the materials that make up the hillslope and the position of the water table. This last parameter can be established by means of the direct determination or by the application of the Mora and Vahrson Method (1994) that allows to represent the position of the water table in relation to the height of the hillslope, involving the monthly average rainfall of the area of study represented by the soil moisture parameter (Sh), thus introducing the influence of climate as a trigger factor.

Next, the methodology for the classification system application is presented once the case study is defined:

2.1 Definition of the analysis sections

Initially, sections of analysis with a transverse length and a longitudinal arrangement are defined, which depend on the geometry of the project and the hillside morphometry, in order to verify the influence of the slopes/cuts. The geometric aspects are schematized in Figure 1 to take into account in the definition of the analysis sections for a particular road project.

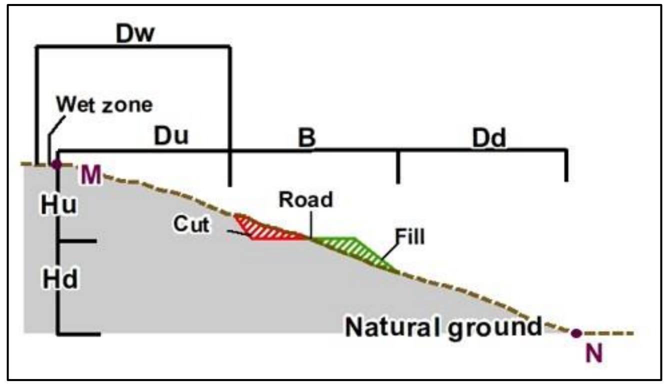

Figure 1. Definition of analysis sections for hillside characterization.

Where:

- B: Project cross length including cuts and fills.
- D_d: Analysis distance downhill to where topographic break is detected. If there is no such break (concave or convex), the value D_d = B must be taken. This distance defines point N.
- D_u: Analysis distance uphill to where a topographic break is detected. If there is no such break (concave or convex), the value D_u = B must be taken. This distance defines point M.
- D_w: Analysis distance uphill to where a flat area is detected or where a wet zone is detected. If the existence of such zones is verified at a distance $D_w < 2B$, the distance D_w must replace the distance D_u in the analysis of the slope stability. The position of point M must be redefined to be compatible with D_w.
- H_u: Upper height of analysis, from the level of grade of the track to point M.
- H_d: Lower height of analysis, considered from the level of grade of the track to point N.

The length of the cross section is limited by the lines M (uphill) and N (downhill) (Figure 2). In order to properly perform the HsQI analysis, geological, geomorphological and hydrological information must be available along the transportation corridor. The scale of the base information must be compatible with the level of detail of the project.

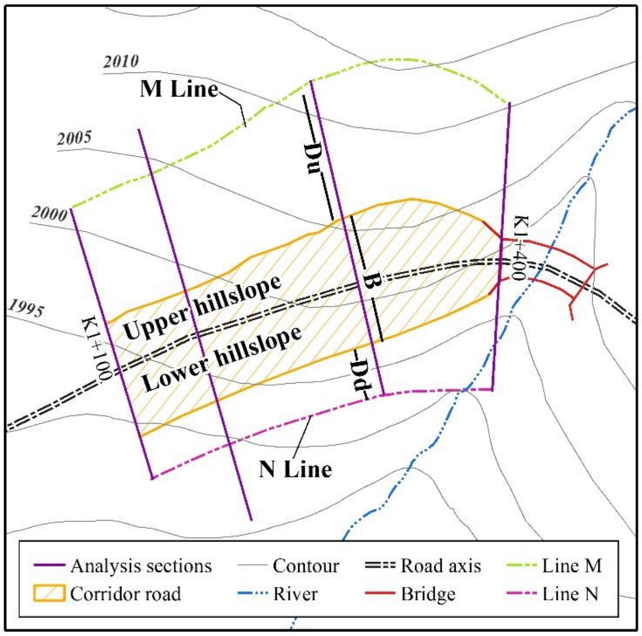

Figure 2. Definition of the hillside analysis area up and down the corridor.

2.2 Obtaining the HsQI

The method considers different conditions of geometry and water table as well as two mechanisms of failure: circular and planar failure. For its application the definition of the geometric and geotechnical parameters of the slope is required, which must be entered in the functions X and Y. The following are the parameters that must be defined (SI Units are recommended):

- ϕ: Effective friction angle of the material
- c: Effective cohesion
- γ: Unit weight
- H_u: Top analysis height
- H_d: Lower analysis height
- H_w: Water table height
- i: slope angle of the hillside
- Z_o: Tension crack depth
- β: Apparent dive angle of the main family of discontinuities in the analysis section

The X and Y functions are defined for the two failure mechanisms: structurally uncontrolled rupture (circular) and structurally controlled rupture (planar) and must be applied according to the conditions of the water table (drained slope, slope with normal water table or slope with a horizontal water table) and according to the presence of morphodynamic processes (slope without crack, slope with crack with drained tension and slope with crack with saturated tension).

The function X depends on the slope of the hillside, the angle of friction of the material and the height of the water table on the slope. The Y function depends on the cohesion and the specific weight of the material, and the height of the slope, as presented next:

A. Mechanisms of rupture not structurally controlled

1. Case 1: Drained hillside

$$X = i\text{-}1.2\phi \tag{1}$$

2. Case 2: Drained hillside without tension crack

$$Y = \frac{\gamma H}{c} \tag{2}$$

3. Case 3: Hillside with normal water table

$$X = i\text{-}\phi\left(1.2\text{-}0.3\frac{Hw}{H}\right) \tag{3}$$

4. Case 4: Hillside with drained tension crack

$$Y = \left[1 + \left(\frac{1\text{-}25}{100} * \frac{Zo}{H}\right)\right]\frac{\gamma H}{c} \tag{4}$$

5. Case 5: Hillside with horizontal water table

$$X = i\text{-}\phi\left(1.2\text{-}0.5\frac{Hw}{H}\right) \tag{5}$$

6. Case 6: Hillside with tension crack saturated

$$Y = \left[1 + \left(\frac{1\text{-}10}{100} * \frac{Zo}{H}\right)\right]\frac{\gamma H}{c} \tag{6}$$

B. Structurally controlled rupture mechanisms

1. Case 1: Drained hillside

$$X = 2\sqrt{(i\text{-}\beta)(\beta\text{-}\phi)} \tag{7}$$

2. Case 2: Drained hillside without tension crack

$$Y = \frac{\gamma H}{c} \tag{8}$$

3. Case 3: Hillside with normal water table

$$X = 2\sqrt{(i\text{-}\beta)\left[\beta\text{-}\phi\left(1\text{-}0.1\left(\frac{Hw}{H}\right)^2\right)\right]} \tag{9}$$

4. Case 4: Hillside with drained tension crack

$$Y = \left[1\text{-}\frac{Zo}{H}\right]\frac{\gamma H}{c} \tag{10}$$

5. Case 5: Hillside with horizontal water table

$$X = 2\sqrt{(i - \beta)\left[\beta - \phi\left(1 - 0.5\left(\frac{Hw}{H}\right)^2\right)\right]} \quad (11)$$

6. Case 6: Hillside with tension crack saturated

$$Y = \left[1 - \frac{3Zo}{H}\right]\frac{\gamma H}{c} \quad (12)$$

To determine the depth of the tension crack, the abacus proposed by Hoek and Bray (1974) were incorporated into the model.

In type A mechanism (rupture not structurally controlled), the conditions indicated by cases 1, 3 and 5 are used to determine the function X, and those of cases 2, 4 and 6 to determine the function Y; similarly, for the type B mechanism (structurally controlled rupture).

Once these conditions and the values of the functions X and Y are defined for each analysis section, the results are introduced in the abacus established for the rupture case being analyzed: structurally uncontrolled rupture (Figures 3) and structurally controlled rupture (Figures 4), thus obtaining the value of the HsQI represented in the plotted curves. Abacuses were systematized to allow the interpolation of intermediate values. In the abacuses, the stability conditions of the slope can also be verified; high HsQI values indicate stable slopes with low susceptibility to the occurrence of mass movements derived from the construction of contemplated cuts in the design of the road.

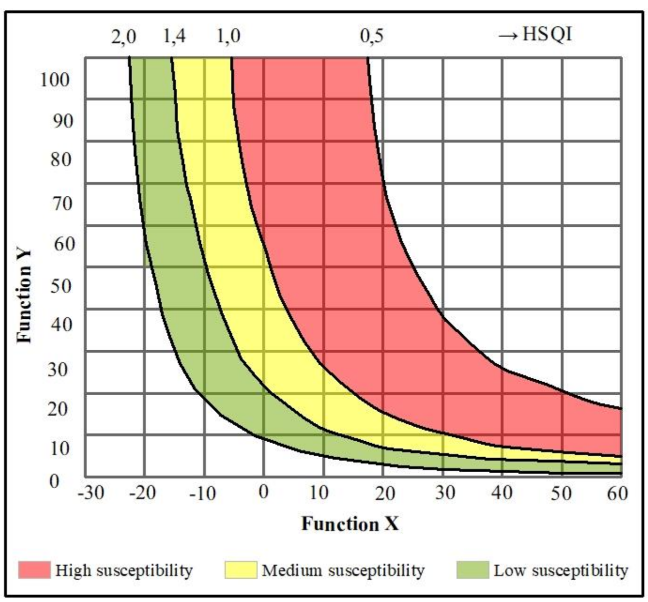

Figure 3. HsQI for landslides with rupture mechanisms not structurally controlled (circular failure).

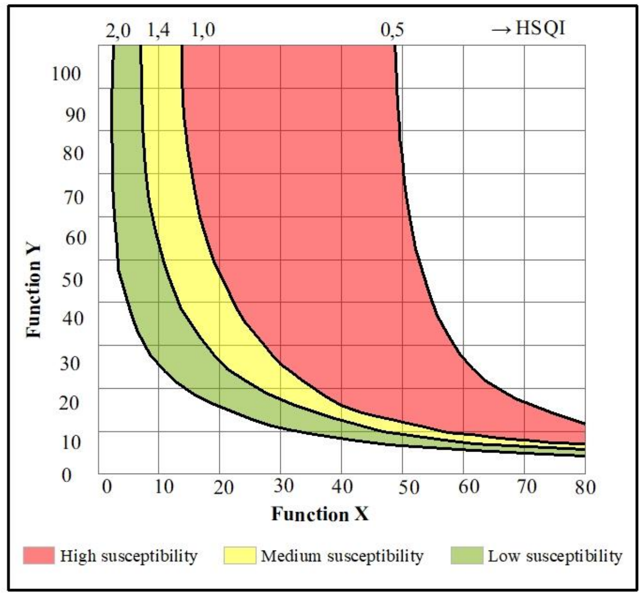

Figure 4. HsQI for landslides with structurally controlled rupture mechanisms (planar failure).

The analysis is carried out for the slopes on both sides of the sections defined as explained in section 2.1. The heights H_u and H_d are used to calculate the HsQI and then the lowest value is selected as the representative value of the hillslope in the analyzed cross section.

2.3 Zoning of the corridor

Table 1 shows the HsQI values to classify the susceptibility of the slope to landslides. These values should be attributed to each defined analysis section.

Table 1. HsQI values for corridor zonation.

Hillslope Quality Index	Landslide susceptibility	Colour
HsQI < 1,0	High	
1,0 ≤ HsQI ≤ 1,4	Medium	
HsQI > 1,4	Low	

2.4 Slope Height Correction Factor

A factor was introduced to correct the height of the slope depending on the importance of the project that is planned to be built, in order to obtain criteria for the optimization of treatment systems according to the susceptibility obtained with the HsQI.

The Correction Factor (CF) was established according the philosophy to the criteria of Barton et al. (1974) that suggests Excavation Support Ratio (ESR) values relating the intended use of the excavation with the degree of solicitation required of the support system to ensure stability.

Table 2 shows the recommended CF values for the particular case of road analysis according to their importance.

Table 2. Slope height Correction Factor.

Type	Importance of the road	CF
I	Temporary	1,5
II	Permanent with low vehicle flow forecast	1,3
III	Permanent with medium vehicle flow forecast	1,0
IV	Permanent with high vehicle flow forecast	0,8
V	Fundamental with high vehicular flow forecast	0,6

Once the CF is defined, the corrected height (H_c) is calculated according to Eq. (13) by entering the height (H) considered in each analysis section (H_u or H_d):

$$Hc = \frac{H}{CF} \tag{13}$$

2.5 Performance graph

In accordance with the HsQI values obtained and the established CF, stabilization and drainage recommendations are presented according to the performance graph shown in Figure 5. These recommendations allow the project owner to make cost estimates, validate designs and establish maintenance plans among others.

Each area of the graph presents recommendations ranging from erosion control and drainage installation (low landslide susceptibility), shotcrete, geosynthetics, and concrete walls (medium landslide susceptibility), to berms, anchored curtains and fall protection systems (high landslides susceptibility). Reader is encouraged to consult original performance graph with full description of geotechnical recommendations in Ocampo-Araya (2016) and Moreno-Ceballos (2015).

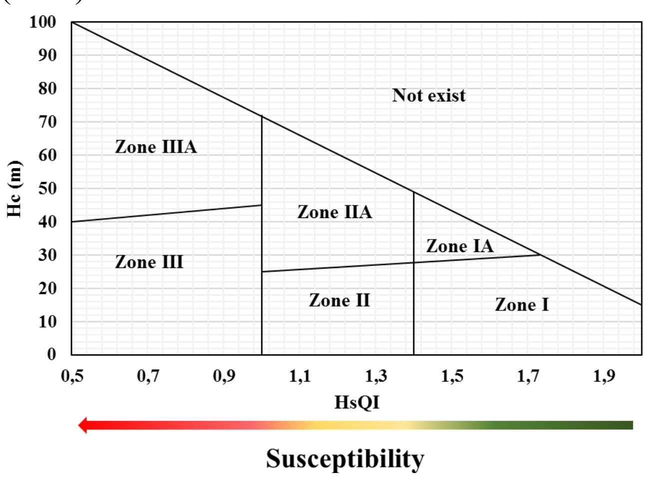

Figure 5. Performance graph for HsQI methodology.

3 APPLICATION OF THE METHODOLOGY

For the case study, a segment of the projected road was selected from the city of Medellín to the municipality of Puerto Berrio, located at the Northeast Antioquia Region (Figure 6). For the paper purposes a 2 km length portion was selected, taking care of being representative in terms of variety of geographical and geological conditions. The track selected presents a number of cuts, fills and creeks that provide a wide sample of different analysis cases. The analysis is focused on the effects of the cuts on the hillside geotechnical stability in terms of the potential effect of the road construction on the landslide susceptibility.

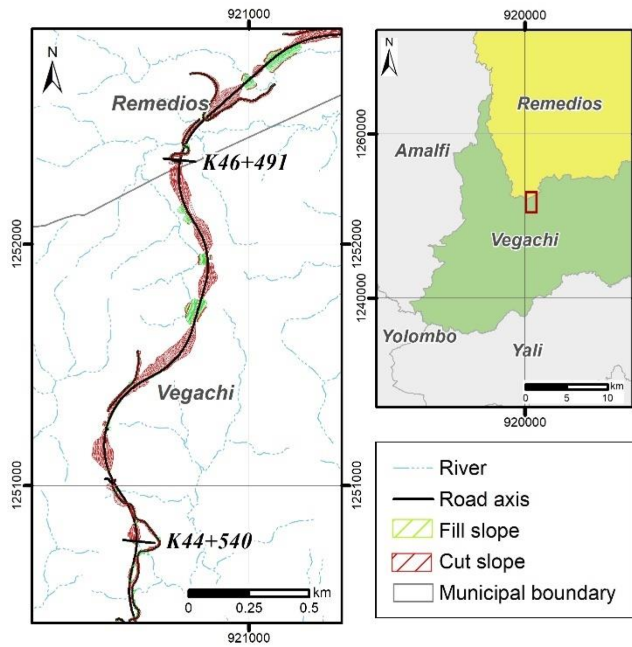

Figure 6. Location of the study area.

The cutting slopes are projected with heights up to 45 m high with a mean value of 25 m, on residual soils and saprolites of the gneisses of the so-called Cajamarca Complex (Gonzalez, 2001; Restrepo et al., 2011) and deposits of alluvial and colluvial origin. The morphology patterns are variable from flat areas to very steep hillsides.

To define the subsurface flow condition of the study area according to the method of Mora and Vahrson (1994) calibrated by Ocampo- Araya (2016), the monthly multi-annual average rainfall (Figure 7) of the *El Nus* weather station was taken. Its values show a bimodal type regime with rainy seasons in the months of April to May and from September to October. With this record, a S_h factor of 0.5 was determined, which implies a 50% relationship between the height of the slope and the water table (H / H_w).

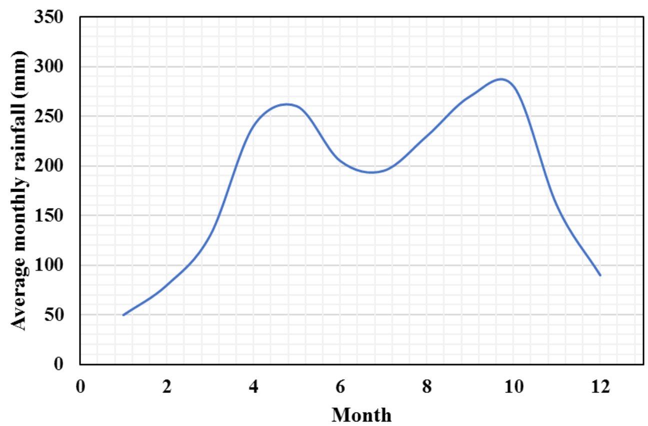

Figure 7. Average multiannual monthly rainfall in the study area (1956 to 2015).

The geotechnical parameters and the physical properties of the materials were established in accordance with direct and indirect exploration campaigns, laboratory tests and geomechanical characterizations carried out within the framework of the project (Table 3).

Table 3. Geotechnical parameters and physical properties of materials.

Lithology	Horizon (BS-5930)	γ (kN/m^3)	C (kPa)	ϕ (°)
	VI	18	20 ± 8	25 ± 2
Gneiss	V	18	29 ± 9	28 ± 3
	IV	20	25 ± 10	32 ± 3
Colluvial deposits	Qcol	17	8 ± 4	28 ± 3
Alluvial Deposits	Qal	19	10±5	30 ± 3

4 RESULTS AND CONCLUSIONS

The analysis sections were established in accordance with section 2.1. A total of 69 sections were analyzed. During the construction of the analysis sections and the determination of functions X and Y, some aspects were identified that made the application of the methodology wasteful, so improvements and modifications were necessary in order to enhance the method.

Thus, through the use of Geographic Information Systems (GIS) and programming language, automatic tools were developed for the geometric construction of sections and functions for automatic abacus reading. These developments become important to the extent that they allow the use of the methodology in the application of consulting engineering, by reducing the use of valuable resources in tasks of little added value.

The 69 sections were analyzed according to the geometric characteristics of the project and the geomorphological characteristics of the hillside for each particular section. The value of functions X and Y was calculated, and the graph for non-structurally controlled landslides (circular failure) was applied, obtaining HsQI values from 0.5 to 2.0.

Figure 8 shows the zoning of susceptibility due to landslides in the analyzed road segment.

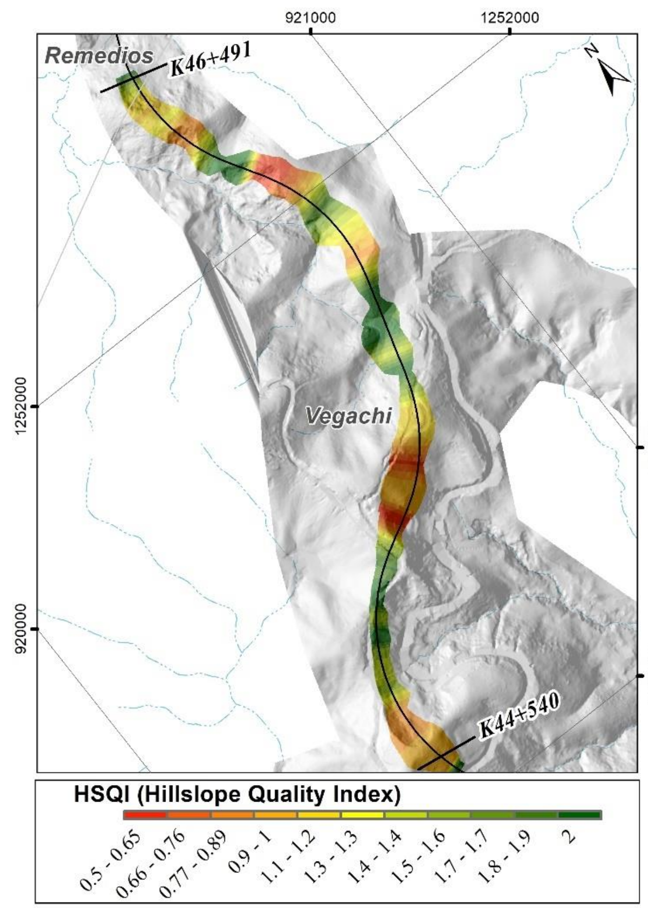

Figure 8. Zoning of susceptibility to landslides of the road corridor.

In order to establish the recommendations to the support systems for each analysis section, a CF of 0.8 was established for a type IV road with a permanent importance and high vehicle flow forecast. Figure 9 shows the performance graph for the case study and Figure 10 shows the particular cases of support recommendation for three sections with high, medium and low susceptibility respectively.

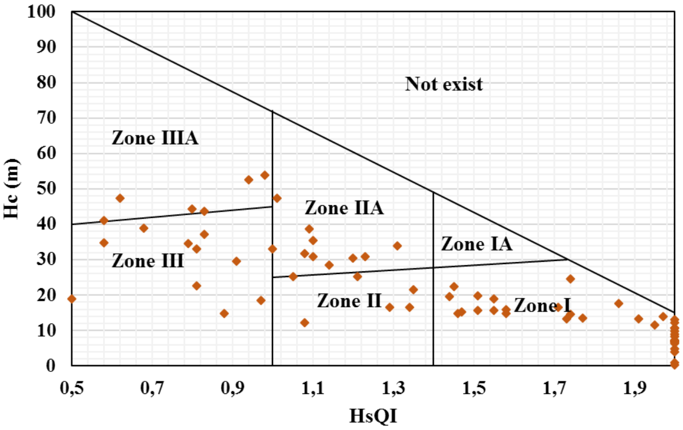

Figure 9. Performance graph for the road corridor studied.

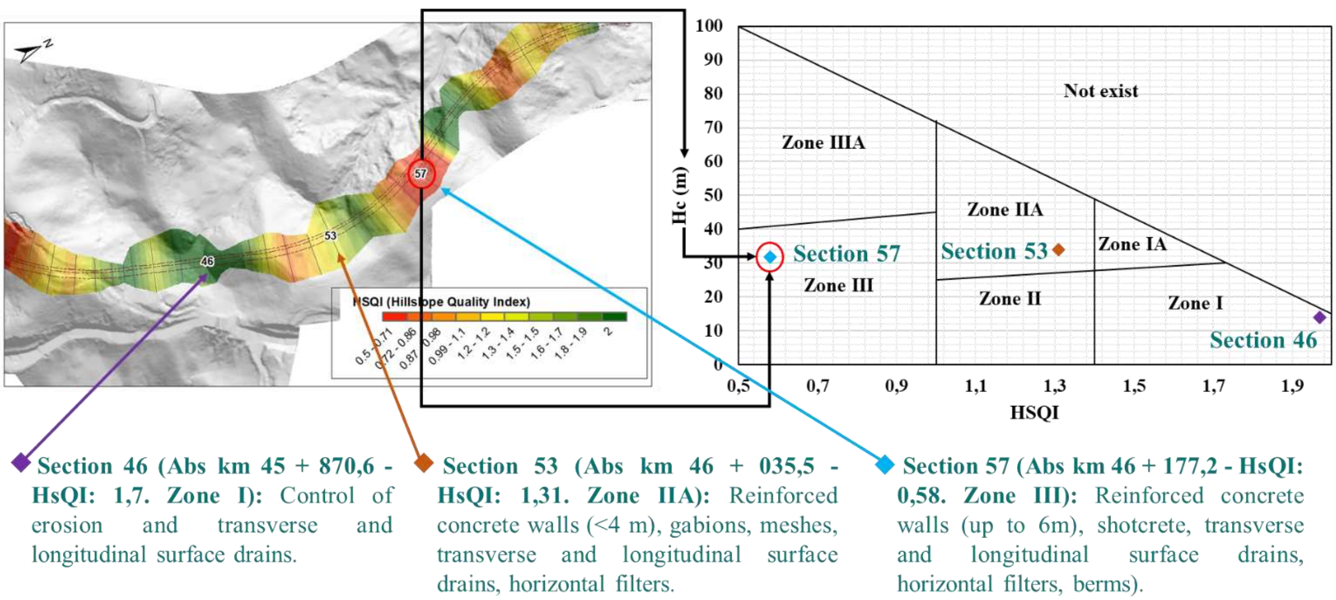

Figure 10. Zoning and performance graph for three particular analysis sections.

These results provide technical arguments that can be addressed to:

- Validations and recommendations for hillside support systems depending on the conditions of the road project: importance, magnitude and use.
- Facilitation of the maintenance, administration and investment plan for the project.
- Improvement of maintenance plans during operation, because sections of high susceptibility to land sliding are perfectly identified.
- The knowledge of the economic risk associated with the functionality of the structures and probability of losses in the event of a slip event, is a straightforward process.

The model application can take into account different rain and earthquake scenarios, by means of proper modifications that are already available in the SIG tools specifically developed for this purpose. Although this methodology is not intended as a substitution of traditional detailed geotechnical procedures, its correct use and interpretation will certainly be an excellent complement for the detailed geotechnical analysis, and of valuable help for decision makers in feasibility stages of road projects. Its potential applications may be extended to existing roads in which there is a need of implement rational maintenance plans and in the topics of risk management for areas prone to landslides. Authors do not encourage its use out of the zonation premises already presented here.

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