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TECHNICAL PAPER

Development of a Soil Erosion Classification System for Cut and Fill Slopes

David Hernando[1] · **Manuel G. Romana**[1]

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Abstract The Universal Soil Loss Equation (USLE) has been widely used to predict the long-term average annual soil loss associated with sheet and rill erosion caused by rainfall and runoff. Initially developed for agricultural purposes, it was later modified and extended for estimating soil loss on cut and fill slopes. In addition to this valuable equation, management of cut and fill slopes also requires a classification system in order to prioritize erosion control measures and maintenance operations based on estimated soil loss. Currently available erosion classifications (focused on soil productivity and sustainable agriculture) may not be relevant to transportation infrastructure slopes, in which soil loss rates are dramatically higher and primarily concern operational service conditions. Therefore, the objective of this study was to develop a classification system based on soil loss rates computed by the USLE model that can be valuable for management of cut and fill slopes. It was assumed that erosion classifications developed for agriculture could be used in cut and fill slopes as long as the ratio between respective soil loss rates was applied. It was found that the topographic factor, which accounts for the length and steepness of the slope, may explain most of the difference in respective soil loss rates. For typical values of the topographic factor, soil loss rates on cut and fill slopes were found to be roughly ten times greater than those on agriculture. Based on this finding, a new classification with six erosion levels was developed. Finally, validation analysis showed that the proposed classification successfully ranked soil loss rates reported in the literature into different categories.

Keywords Soil erosion · Universal Soil Loss Equation · Slope management · Classification system · Cut and fill · Transportation infrastructure

✉ David Hernando
davhernando@gmail.com

Manuel G. Romana
manuel.romana@upm.com

[1] Department of Civil Engineering—Transport, Technical University of Madrid, Profesor Aranguren 3, 28040 Madrid, Spain

Introduction

Soil erosion is a major concern for its long-term effects on soil productivity, sustainable agriculture, and water quality. It is a problem of wider significance occurring additionally on land devoted to forestry, transportation, and recreation [1]. The Universal Soil Loss Equation (USLE) developed by Wischmeier and Smith [2–4] is the most widely used equation for soil erosion analysis all over the world. It is an empirical model that predicts the long-term average annual soil loss associated with sheet and rill erosion caused by rainfall and runoff:

$$A = R \cdot K \cdot LS \cdot C \cdot P \tag{1}$$

where A is the long-term average annual soil loss rate (in units of mass area^{-1} year^{-1}), R is the rainfall erosivity factor, K is the soil erodibility factor, LS is the topographic factor (length and steepness of slope), C is the cover and management factor, and P is the conservation practice factor.

Israelsen et al. [5] modified and extended the USLE model for estimating soil loss potential on cuts and fills of construction sites, resulting in the following equation:

$$A = R \cdot K \cdot LS \cdot VM \tag{2}$$

in which A is the long-term average annual soil loss rate; R, K, and LS are those defined for Eq. 1; and VM is the erosion control factor. Equation 2 was successfully applied to slopes up to 84 % [5], which are in the order of the slopes commonly found on highways, railways, parking lots, and other construction sites. In addition to this valuable prediction model proposed by Israelsen et al. [5], management of cut and fill slopes requires a classification system such that erosion control measures and maintenance operations can be assessed and prioritized according to estimated soil loss rates. Currently available erosion classifications focus on the concept of tolerable soil loss, which is mainly related to the maximum rate that could occur indefinitely without adversely affecting soil productivity [1, 3, 6, 7]. However, classification systems based on soil productivity may not be generally applicable to evaluate soil erosion on transportation infrastructures, in which maintaining fully operational service is of paramount importance. Therefore, the objective of this study was to develop an erosion classification system based on soil loss rates that can be truly valuable for management of cut and fill slopes on highways, railways, and other transportation infrastructures.

Problem Statement

Several classifications based on soil loss or soil removal have been reported in the literature for sheet and rill erosion. Zachar [8] proposed six grades of soil removal intensity: insignificant, slight, moderate, severe, very severe, and catastrophic erosion, which ranged from <0.5 m^3 ha^{-1} year^{-1} (insignificant) to >200 m^3 ha^{-1} year^{-1} (catastrophic). Wall et al. [9] defined five classes of potential soil loss ranging from very low or tolerable erosion (<6 t ha^{-1} year^{-1}) to severe erosion (>33 t ha^{-1} year^{-1}).

Morgan et al. [10] developed a classification to appraise soil erosion in the field that ranged from very slight (<6 t ha^{-1} year^{-1}) to catastrophic (>500 t ha^{-1} year^{-1}). One of the most extensively used references in soil erosion classification was proposed by FAO-PNUMA-UNESCO [11]. This classification (Table 1) defined four erosion levels based on soil loss rates computed using the USLE model. Low erosion level was defined for soil loss rates <10 t ha^{-1} year^{-1}, whereas very high erosion was established as that occurring at rates >200 t ha^{-1} year^{-1}.

The aforementioned classifications were primarily developed for agriculture and may not be fully applicable to cut and fill slopes for two major reasons. First, concerns in slope management are not related to soil productivity, but operational service conditions associated with deposition of sediments along the infrastructure right-of-way. Eroded material accumulates on ditches, culverts, and sediment traps and may eventually reach the shoulder, constituting a potential hazard for infrastructure users. In addition, a clogged drainage system may result in overflow, washout, undermining, and collapse of earthworks and structures [12, 13]. Secondly, soil loss rates on cut and fill slopes are reported to be dramatically higher than those on agricultural lands. Navarro [14] stated that soil loss on construction sites typically ranges from 125 to 600 t ha^{-1} year^{-1}. Soil loss rates from 62 to 887 t ha^{-1} year^{-1} were measured on highway cuts in Georgia [15]. Haigh [16] reported values from 373 to 426 t ha^{-1} year^{-1} in Oklahoma. Soil loss rates up to 248 t ha^{-1} year^{-1} were measured on granitic cut slopes in Idaho [17]. In the Qinghai-Tibet highway (China), Xu et al. [18] found soil losses of 24 and 109 t ha^{-1} for periods of 28 and 78 days, respectively, which would be equivalent to average annual rates of 310–510 t ha^{-1} year^{-1}. In Spain, rates from 79 to 962 t ha^{-1} year^{-1} were predicted on slopes of highways and railways, as well as peak values near 1100 t ha^{-1} year^{-1} under severe rainfall events [19, 20].

As shown above, soil erosion on cut and fill slopes of transportation infrastructures clearly exceeds the maximum soil loss rates defined by agricultural classifications. The approach followed in this study consisted of identifying the ratio of typical soil loss rates on cut and fill slopes to those on agricultural lands. It was assumed that erosion classifications developed for agriculture could be used in cut and fill slopes as long as the identified ratio between respective soil loss rates was applied. This ratio was the basis for the development of a new classification system based on soil loss rates estimated according to the USLE model.

Table 1 Level of erosion based on average annual soil loss rate for agriculture [11]

Soil loss rate (t ha^{-1} year^{-1})	Erosion level
<10	Low
10–50	Moderate
50–200	High
>200	Very high

Relationship Between Soil Loss Rates on Cut and Fill Slopes to Those on Agricultural Lands

The factors contained in the USLE model (Eqs. 1–2) were analyzed in this section to estimate the ratio of typical soil loss rates on cut and fill slopes to those on agricultural lands. The following observations were made:

- Rainfall erosivity and soil erodibility are prefixed by nature and cannot be altered by human activities [5]. Thus, R and K factors are preset and do not necessarily differ between agricultural lands and cut and fill slopes.
- The effect of land use and management on soil loss is taken into account by the term C·P in Eq. 1 and by VM factor in Eq. 2, respectively. For agricultural fields, C·P includes crop type, tillage system, and support practices (e.g., contouring, contour stripcropping, terracing). For cut and fill slopes, Israelsen et al. [5] condensed all erosion control measures that can be implemented on any cut and fill slope in a single factor (VM). Reported values for C·P and VM suggest that land use and management may not explain the substantial difference in soil loss rates between agricultural lands and cut and fill slopes [4, 5].
- Conversely, the topographic factor definitely presents distinct values because of the different nature in length and steepness. Relatively flat slopes and long lengths are frequent on agriculture, whereas steep slopes and short lengths are commonly used on cuts and fills.

The above discussion led to the assumption that the dramatic difference in soil loss rate may be primarily explained by the different values in topographic factor. The following equation was given by Wischmeier and Smith [4] to determine the topographic factor (LS):

$$LS = \left(\frac{\lambda}{22.13}\right)^m \cdot \left(65.41 \cdot \sin^2\theta + 4.56 \cdot \sin\theta + 0.065\right) \quad (3)$$

in which λ represents the distance from the point of origin of overland flow to the point where either deposition begins or the runoff water exits the slope, θ is the angle of the slope (°), and m is an exponent dependent upon slope steepness (m=0.2 for s<1 %, m=0.3 for s=1–3 %, m=0.4 for s=3.5–4.5 %, and m=0.5 for s>5 %). Although some studies have indicated that Eq. 3 might overpredict the topographic factor on natural steep slopes [21–24], Israelsen et al. [5] proved its validity for cut and fill slopes with steepness up to 84 %. Thus, Eq. 3 was selected in this study to evaluate the topographic factor for a wide range of slope height and steepness. For cut and fill slopes, steepness ranged from 25 to 100 % according to common values used in highways, railways, and other infrastructures [25], while a maximum steepness of 12 % was considered for agricultural lands [1, 26]. Figure 1 shows the average values of the topographic factor (LS) for cut and fill slopes and for agricultural lands as well as the ratio between them (LS ratio, Eq. 4):

$$LS\ ratio = \frac{LS\ on\ cut\ and\ fill\ slopes}{LS\ on\ agricultural\ lands} \quad (4)$$

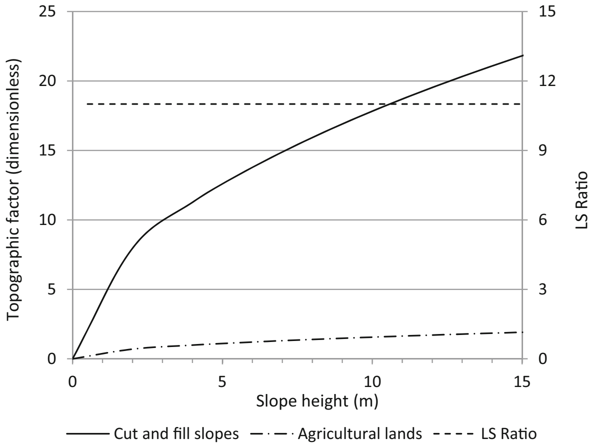

Fig. 1 Determination of the LS ratio based on typical values of the topographic factor for cut and fill slopes and agricultural lands

As can be seen in Fig. 1, LS for agricultural lands rarely exceeds 5, whereas values >10 are obtained for cut and fill slopes just 3 m high. The LS ratio was found to be roughly 10 for any given height. Assuming that the topographic factor accounts for most of the difference in soil loss rate, it can be stated that soil loss rates on cut and fill slopes are expected to be ten times greater than those on agriculture.

Soil Loss Classification System for Cut and Fill Slopes

Proposal of Erosion Levels

The identified ratio of ten was used to convert the maximum soil loss rate of 200 t ha^{-1} year^{-1} defined by FAO-PNUMA-UNESCO for agriculture to a maximum soil loss rate of 2000 t ha^{-1} year^{-1} for cut and fill slopes. Six levels of erosion were established following the qualitative classification defined by Zachar [8]: insignificant, slight, moderate, severe, very severe, and catastrophic erosion. The proposed classification is given in Table 2. As can be seen, erosion causing an average annual soil loss below 50 t ha^{-1} year^{-1} was considered as insignificant (i.e., tolerable) for cut and fill slopes.

Validation

The classification proposed in Table 2 was validated using soil loss rates from cut and fill slopes available in the literature. Figure 2 shows the range of soil loss rates reported by different authors [14–20], along with the proposed erosion levels. While most reported soil loss rates would simply fall under the category of very high erosion according to the limits proposed by FAO-PNUMA-UNESCO (>200 t ha^{-1} year^{-1}), this new classification ranked soil loss

Table 2 Soil erosion classification proposed for cut and fill slopes

Soil erosion level	Soil loss rate (t ha^{-1} year^{-1})
Insignificant	<50
Slight	50–200
Moderate	200–500
Severe	500–1000
Very severe	1000–2000
Catastrophic	>2000

rates into more representative categories. This finding supports that the proposed classification is indicative of the typical soil loss rates obtained on cut and fill slopes.

Additional Parameters for Soil Erosion Evaluation on Transportation Infrastructures

Soil loss rates are typically reported in units of mass per unit area, although the use of volume or thickness removed per unit area is also common. For transportation infrastructures, such as highways and railways, soil loss rates per unit area may not be so convenient because of the dominance of the longitudinal dimension. It should be noted that soil eroded from slopes tends to deposit along the right-of-way, so erosion rates expressed in terms of mass, volume, or thickness removed per linear meter may result in more adequate management of transportation infrastructures. Thus, the classification proposed in this study was extended by defining three additional parameters: effective soil loss rate, volumetric soil loss rate, and thickness loss rate.

The effective soil loss rate (A′, Eq. 5) represents the average annual weight of material eroded per linear meter along the infrastructure, and it is expressed

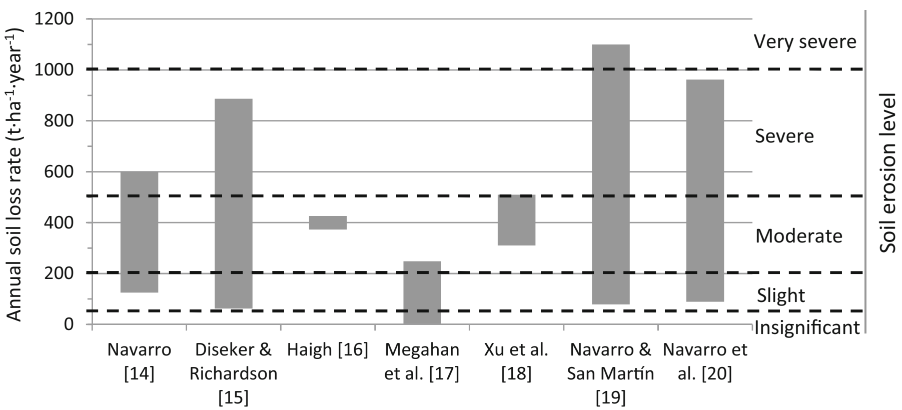

Fig. 2 Validation of soil erosion classification based on annual soil loss rates reported in the literature

in kg m^{-1} $year^{-1}$ (kg was selected as reference weight unit to avoid the use of decimals). It is obtained as the product of the average annual soil loss rate (A) in t ha^{-1} $year^{-1}$ and the slope length (l) in meters:

$$A' = 0.1 \cdot A \cdot l \tag{5}$$

The volumetric soil loss rate (A_v, Eq. 6) is the average annual volume of material removed per linear meter of infrastructure, in units of m^3 m^{-1} $year^{-1}$. It is the result of dividing the effective soil loss rate (A′) by the bulk density of the material (ρ) in kg m^{-3}:

$$A_v = \frac{A'}{\rho} = 0.1 \cdot \frac{A \cdot l}{\rho} \tag{6}$$

The thickness loss rate (e, Eq. 7) is calculated as the volumetric soil loss rate (A_v) over the slope length (l) in meters, expressed in mm m^{-1} $year^{-1}$. It is equivalent to the soil loss rate (A) over the bulk density of the material (ρ), with the corresponding adjustment in units:

$$e = 1000 \cdot \frac{A_v}{l} = 1000 \cdot \frac{A'}{\rho \cdot l} = 100 \cdot \frac{A}{\rho} \tag{7}$$

In order to establish erosion levels for A', A_v, and e, an average slope length of 13 m was adopted based on the analysis of a range of height and steepness on cut and fill slopes and values reported from field studies [25–27]. As for soil bulk density, 1700 kg m^{-3} was selected according to a broad review on typical materials for slopes of transportation infrastructures [28, 29]. Based on Table 2 and Eqs. 5–7, these values resulted in the erosion classification given in Table 3. As can be seen, insignificant erosion on transportation infrastructures was defined by a maximum soil loss rate of 65 kg m^{-1} $year^{-1}$, 0.1 $m^3 \cdot m^{-1}$ $year^{-1}$, or 3 mm m^{-1} $year^{-1}$. On the upper limit, catastrophic erosion would occur for soil loss rates greater than 2600 kg m^{-1} $year^{-1}$, 1.5 m^3 m^{-1} $year^{-1}$, or 120 mm m^{-1} $year^{-1}$.

Effect of Surface Conditions on Soil Erosion Level

The equation proposed by Israelsen et al. for estimating soil loss potential on cut and fill slopes (Eq. 2) includes an erosion control factor (VM) that allows for consideration of

Table 3 Soil erosion classification for slopes on transportation infrastructures

Soil erosion level	Effective soil loss rate (kg m^{-1} $year^{-1}$)	Volumetric soil loss rate (m^3 m^{-1} $year^{-1}$)	Thickness loss rate (mm m^{-1} $year^{-1}$)
Insignificant	<65	<0.1	<3
Slight	65–260	0.1–0.2	3–12
Moderate	260–650	0.2–0.4	12–30
Severe	650–1300	0.4–0.8	30–60
Very severe	1300–2600	0.8–1.5	60–120
Catastrophic	>2600	>1.5	>120

different surface conditions throughout the life of a slope. Furthermore, VM accounts for all erosion control measures that can be implemented on any cut or fill slope for the purpose of reducing soil loss, such as vegetation and mechanical and chemical treatments, as well as different soil state (e.g., loose, compacted, scarified).

In order to evaluate the effect of surface conditions on the erosion level defined by the classification system proposed in this study, five different scenarios were considered: (1) freshly compacted/scarified slope, which corresponds to the loosest state during construction, thus, higher susceptibility to erosion; (2) bare soil (no seeding); (3) 6 months after seeding and fertilizing; (4) surface with appreciable scrub or bushes (40–60 % cover); and (5) surface with appreciable herbaceous plants (60–80 % cover). The corresponding VM values for the five conditions are presented in Table 4. It should be pointed out that the purpose of this section is to evaluate the erosion level for a limited number of surface conditions so that the proposed classification system can be verified. An extensive list of VM values for additional surface conditions can be found elsewhere [1, 5, 30].

The selected surface conditions were evaluated on three slopes with varying geometry (Fig. 3). Case A represents a high and steep slope; case B simulates a slope with intermediate height and steepness; and case C corresponds to a short slope with relative low steepness. For the sake of comparison, the rainfall erosivity factor and the soil erodibility factor were fixed for the three cases (R=100 MJ cm ha^{-1} h^{-1} year^{-1} and K= 0.35 t h MJ^{-1} cm^{-1}, respectively). The topographic factor (LS) was calculated for each slope geometry according to the methodology described by Israelsen et al. (Eq. 3).

Figure 4 depicts the erosion level obtained for each case under the selected conditions. Case A (high and steep slope) yielded the highest erosion rates, reaching a very severe level when no vegetation was implemented (conditions 1 and 2). For conditions 3, 4, and 5, the erosion grade was reduced to severe, moderate, and slight, respectively. Although case B can potentially reach a severe level during the construction stage (condition 1), erosion rates ranged between moderate and slight, depending on vegetation type and cover. Finally, case C shows that short slopes with relatively low steepness typically result in fairly low erosion rates.

Results from Fig. 4 show the positive effect of long-standing vegetation on reducing potential soil loss. Even for medium to high slope height and steepness, soil erosion can potentially be maintained beneath a severe level by means of proper surface management. Furthermore, these results support the idea that the classification system proposed in this study is sensitive to erosion levels associated with different surface conditions throughout the life of a slope.

Table 4 Erosion control factor (dimensionless) for different surface conditions of a slope (adapted from [1, 5, 30])

Surface condition	Erosion control factor (VM)
1. Freshly compacted/scarified	1.30
2. Bare soil (no seeding)	1.00
3. Seeded and fertilized, after 6 months	0.54
4. Scrub or bushes (40–60 % cover)	0.34
5. Herbaceous plants (60–80 % cover)	0.12

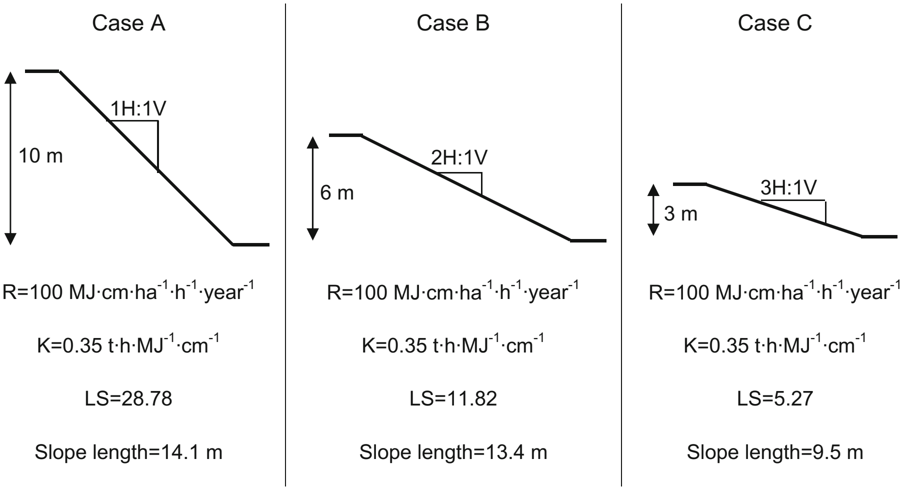

Fig. 3 Parameters of the three study cases under evaluation

It is noteworthy to mention that, although short slopes with low steepness are desirable from the standpoint of soil erosion, geometric constrains often hinder this option. Furthermore, vegetation growth may be difficult in arid environments or steep slopes. In these circumstances, other control measures or surface treatments can be implemented in order to reduce soil loss, for example, geotextiles, mats, cellular blocks, shotcrete, etc.

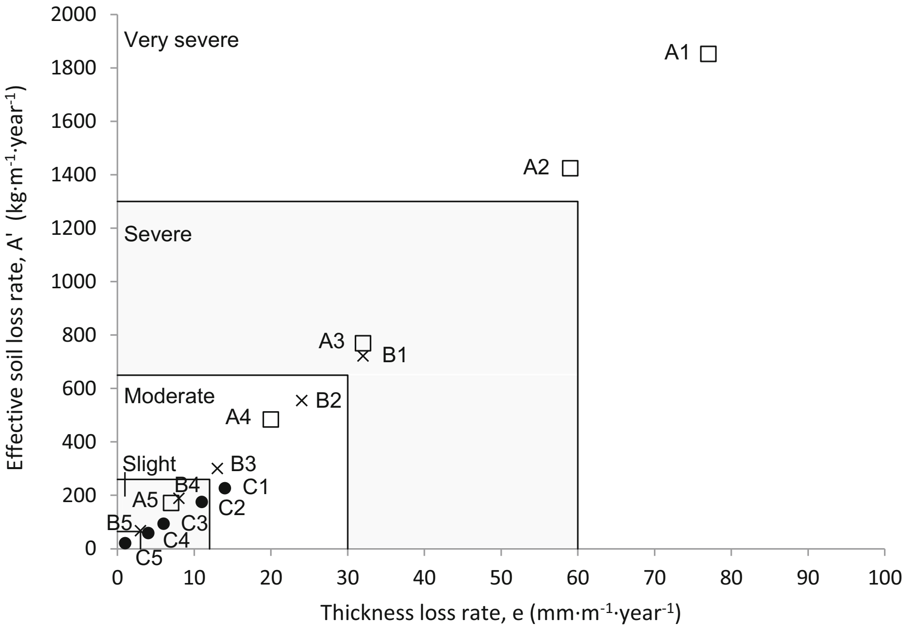

Fig. 4 Evaluation of soil erosion level for different slopes (**a**, **b**, and **c**) under different conditions (*1* freshly compacted/scarified; *2* bare soil; *3* seeded and fertilized, after 6 months; *4* scrub or bushes with 40–60 % cover; *5* herbaceous plants with 60–80 % cover)

Summary and Conclusions

Available soil erosion classifications, which were primarily developed for agricultural purposes, may not be directly applicable for the study of cut and fill slopes. Maximum soil loss rates proposed by these classifications were established to guarantee adequate soil productivity over time, and therefore, their values are not significant in the context of infrastructures. Proper management of transportation infrastructures is primarily concerned with operational service conditions rather than soil productivity, and as such, a valuable erosion classification should take into consideration the relative difference in soil loss rates.

With that goal in mind, an analysis of the different factors contained in the USLE model was conducted in this study to estimate the ratio of typical soil loss rates on cut and fill slopes to those on agriculture. It was found that the topographic factor, which accounts for slope length and steepness, may explain most of the relative difference in soil loss rate. A broad study of typical values of the topographic factor showed that average values on cut and fill slopes were roughly ten times those on agricultural lands for any slope height. This finding led to the conclusion that soil loss rates on cut and fill slopes were expected to be ten times greater than those on agriculture. The identified ratio of ten was used to convert the maximum soil loss rate of 200 t ha^{-1} $year^{-1}$ established by FAO-PNUMA-UNESCO for agriculture to a maximum soil loss rate of 2000 t ha^{-1} $year^{-1}$ for cut and fill slopes. Then, six levels of erosion were proposed following the qualitative classification defined by Zachar [8]: insignificant, slight, moderate, severe, very severe, and catastrophic. The developed classification was validated using soil loss rates from cuts and fills reported in the literature. It was observed that reported soil loss rates fell into a broad spectrum of categories, which confirms that the classification developed in this study is relevant for the typical soil loss rates that can be found on cut and fill slopes. Furthermore, three additional parameters were defined to simplify the application of the proposed classification on transportation infrastructures, which are characterized by the dominance of the longitudinal dimension. These parameters were successfully employed to show the effect of surface conditions (e.g., soil state, long-standing vegetation, and other surface treatments) on soil erosion level for three different slope geometries.

This study constitutes a first attempt to develop a valuable classification for soil erosion analysis on cut and fill slopes of infrastructures. Limited verification of the erosion levels was obtained on the basis of soil loss rates reported in the literature. Therefore, it is highly recommended that further verification efforts be continued on additional slopes with different erosion control measures, in which both a quantitative and a qualitative evaluation of soil erosion can be obtained.

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