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Prediction of Exposure Risk for Buried Pipelines due to Surface Erosion

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ABSTRACT

Pipeline right-of-way maintenance activities face great challenges that have come from different climates, slopes, soils and other environmental conditions. Control of surface drainage and erosion is an important element in the restoration and maintenance of pipeline right-of-ways, since erosion can result in risk of pipe exposure and its consequences. Evaluation of this risk can be a powerful tool to ensure reliability of buried pipelines. The universal soil loss equation is used as a model to estimate the rates of erosion at sections of rights-of-way of a gas pipeline right-of-way near Vitória city in southeast of Brazil. The confrontation of these rates to the actual pipe cover depths is used as a basis to derive a probabilistic procedure for determining the time period over which exposure may occur for a given level of uncertainty. Then, risk can be estimate as a product of the probability (or frequency) of product leakage due to pipeline exposure and the associated consequences of this event. Such risk definition is used to estimate results in an effective guideline to engineers, since it leads to the achievement of optimum and safe erosion control and superficial drainage system projects and results in efficient mitigation planning programs. The results obtained are very promising and show relevant correspondence with the erosion process and cover depth reduction identified on the right-of-way.

Keywords: *Erosion, Risk, EUPS, Pipeline, Right-of-way.*

INTRODUCTION

Minimum cover depths are an important assurance of the security of buried pipelines, since it is designed to dissipate the surface overload that can be transmitted to the buried pipe.

One of the most important activities of the pipeline right-of-way engineering is to treat and prevent erosion process along the rights-of-way. As a linear construction these rights-of-way crosses different kinds of climate, vegetation, soil, topographic characteristics and other environmental conditions that increase the challenges that the engineer faces when those problems need to be solved.

A precise prediction method is an efficient toll to guide the engineer design; however the most common approach only considers the soil loss rates by using the universal soil loss equation without considering the actual soil cover depths (Tansamrit, 2000; Morgan et al., 2003). It is very important to confront values of

cover depths and soil loss equations to estimate precisely the risks of exposure due surface erosion.

This works estimate such risks using a risk matrix based method and also an approach based on the concept of soil loss rate to evaluate the actual condition related to the exposure risks along pipeline rights-of-way. The methods are exemplified using the gas pipeline Cabiúnas – Vitória right-of-way.

METHODOLOGY

Firstly the soil loss equation is briefly discussed, followed by the survey of cover depth along pipeline rights-of-way and then the methods of risk estimation are presented.

Soil loss rates

The soil loss rates can be estimated by means of the universal soil loss equation, expressed by:

$$A = RKLSCP \quad (1)$$

Where:

A = Soil loss rates - $\text{Mg.ha}^{-1}.\text{year}^{-1}$;

R = Rainfall and runoff factor - $\text{MJ.mm.h}^{-1}.\text{ha}^{-1}.\text{year}^{-1}$;

K = Soil erodibility factor - $\text{Mg.h.MJ}^{-1}.\text{mm}^{-1}$;

LS = Topographic factor – dimensionless factor;

C = Cover and management factor – dimensionless factor;

P = Support practice factor – dimensionless factor.

The rainfall and runoff factor consider the climate aspects in the evaluation of erosion rates by the universal soil loss equation. The rainfall and the runoff deriving from it amount of precipitation is considered by this factor, depending on the distribution in the time and in the space of such precipitation. According to Gerra *et al.* (1999) the methodology developed by Wischmeier and Smith (1978) is the most appropriated way to consider the rainfall erosivity. However, the lack of intensity rainfall dates, which is necessary for the R factor by this method, turns impracticable its use in many regions in Brazil. The most common way to overcome this lack of data is to use pluviometric data encountered with more facility. This pluviometric data based methods correlates the R factor to the monthly and annual amount precipitation averages by equations that are only valid at the area where the data for the correlation was picked-up from.

The soil erodibility reveals the capacity of the soil to suffer or to resist the erosion action of rainfall and runoff. The soil erodibility factor is evaluated as a function of the texture of the soil using the relations developed by Roemkes (2003).

The topographic factor, also known by LS factor is dimensionless parameter that considers the slope length and steepness. According to Bertoni and Lombardi Neto (2008) the most suitable equation for soil loss rates evaluation in Brazil is:

$$LS = 0.00984c^{0.63}D^{1.18} \quad (2)$$

where c is the slope length and D is the slope steepness.

The cover and management factor express the ratio between soil loss rates in a cultivated or vegetated area with others with bare soils.

The support practice factor is a dimensionless factor that considers how support and agricultural practices reduces the soil loss at cultivated areas.

Pipe cover depth

Soil cover depths are designed to dissipate the overloads that can be transmitted to the buried pipe. According to Standard PETROBRAS N-464 Rev. H (2007) the procedure of buried pipelines construction should obey the following minimum soil cover depths, shown by Table 1.

Table 1 – Minimum soil cover depths according to N-464.

Location	Cover (m)
Industrial, commercial, and residential areas	1.5
Rock excavation	0.6
Any other area	1.0

Exposure risks evaluation

When soil loss rate at a determined point is considered together its actual soil cover depth one can evaluate the risks of the pipeline becomes exposed at this same point due surface erosion process. This kind of analysis can be done in two different ways: the first is to use risk matrices. The risk matrix used in the study is an adaptation of the Risk Assessment Matrix from military standard MIL-STD-882B developed by Department of Defense of USA. The original matrix provides a systematic method for assigning a hazard level to a failure event based on the severity and frequency of the event. Associating frequency and consequence categories, a hazard level is determined, represented by a risk category. Risk categories assist risk-management team members in differentiating credible high-hazard threats that may result in loss of life and property from less probable risks, therefore aiding management in risk versus cost decisions. A risk matrix is used in the risk assessment process; it allows the severity of the risk of an event occurring to be determined.

Although risk matrices experience problems like poor resolution and errors due to subjective interpretation, they can be used as an additional tool for managing pipeline right-of-way maintenance and integrity. Instead of hazards and probabilities this study uses the soil loss rates and the soil cover depths to categorize the exposure risks of a buried pipeline due surface erosion.

Another different approach to consider the exposure risks at buried pipelines is to use the concept of soil loss rate. Regarding the units of the parameter A in eq. 1 one can write:

$$A = \frac{M}{Ta} \quad (3)$$

where M is the mass of an amount of soil lost in a determined period of time T , over an area of surface equals to a .

If the soil type and soil loss rate is considered constant over the entire area a , and the mass of lost soil M is equal to:

$$M = \rho Ha \quad (4)$$

where ρ is the specific mass of the soil and H is the soil cover depth, the soil loss rate can be rewrite as:

$$A = \frac{\rho H}{T} \quad (5)$$

Equation (5) can be re-arranged and the time until exposure of the buried pipeline can be estimated as:

$$T = \frac{\rho H}{A} \quad (6)$$

If the soil loss rate in equation (6) is assumed to be equal to the tolerance value and the depth of cover is assumed to be equal the minimum cover depth value, one can define a standard or allowed time until exposure:

$$T_{al} = \frac{\rho H_{\min}}{A_{tol}} \quad (7)$$

By dividing equation (6) by equation (7) it is possible to settle a time dimensionless parameter τ , expressed by:

$$\tau = \frac{T}{T_{al}} = \left(\frac{H}{H_{\min}} \right) \left(\frac{A_{tol}}{A} \right) \quad (8)$$

The time parameter defined by eq. (8) allows a joint analysis between soil loss rates and cover depths in the process of buried pipeline exposure due surface erosion. If τ is greater or equal to 1 one can expect that risks of exposure at this point is considered very low.

The derivation of this methodology considers that the soil loss is evenly distributed across an area. Even though at pipeline rights-of-way the soil conditions are different due to the presence of the pipeline trench, the assumption of an average soil loss across the area is acceptable, because the company approach to construction affects all the width of the right-of-way at the superficial soil layers. And the deeper layers at pipe trench tend to become similar to the natural soil of the right-of-way, some differences will occur when the erosion process is faster than the soil before prior construction characteristics are recovered.

EXAMPLE OF APPLICATION

The gas pipeline Cabiúnas-Vitória (GASCAV) right-of-way is used as case of study to show how the proposed methods are used to determine the risks of pipe exposure due surface erosion. This pipeline right-of-way was choose as example

because it was recently constructed, this fact allows a good correlation between the predict soil loss rates and the significant erosion problems identified at the final inspection of the right-of-way implementation (Gavassoni and Zambom, 2009).

Figure 1 – GASCAV right-of-way.

Study site description

The considered stretch of the GASCAV right-of way on this study ranges from the border between the Rio de Janeiro and Espírito Santo States at the southeast part of Brazil to the north zone of the city of Vitória the Espírito Santo capital. This stretch of 162 km has a constant length of 20 m resulting in an area of 3.24km^2 (324 ha). The map of the GASCAV right-of-way is shown by Figure 1. The right-of-way crosses an area inhabitant by 1.4 million of people (IBGE, 2008).

The terrain conditions crossed by the GASCAV right-of-way consists mostly of plain lands mainly in the south part of Espírito Santo State and at some points the pipeline crosses the foothills the Castelo mountain range which occupies 40% of the area of the Espírito Santo State. Such foothills areas are responsible by the critical topographic factor values encountered in the soil loss predicted rates.

The climate in the study site is classified as a tropical wet and dry. This means that the average amount of precipitation is about 1000 mm and that there is a definite dry season, which in this region is from April to August. The rain gauges installed at points in the Castelo mountain range the amount of precipitation is higher, like 1500 mm.

The soil uses activities consist of agriculture and animal husbandry.

Soil loss results

The parameters of soil loss equation and soil loss rates estimated for the GASCAV right-of-way are shown in this section.

According to the map proposed by Silva (2004) the appropriated equation for the annual rain erosivity at the GASCAV area is that one proposed by Leprun:

$$R = \sum_{i=1}^{12} 0,13(p_i)^{1,24} \quad (9)$$

where p_i is the monthly average of amount of precipitation of each pluviometric station.

The historical series of pluviometric data for a fifty years period was taken from the HidroWeb, the digital collection of pluviometric data of the Brazilian Federal Water Agency (ANA, 2009). Seven pluviometric stations were used in this study. The area of influence of each pluviometric station was determined by the use of the Thyssen polygons method.

The soil erodibility was evaluated via the soil texture results. These results were obtained by sieve analysis on the samples collected at the penetration tests performed at every kilometer of the right-of-way in the pipe construction phase.

Topographic factor values for the entire GASCAV right-of-way were evaluated by means of eq. 2, where the c and D values were taken from the "As Built" projects of the right-of-way.

Soil loss rates are then estimated by eq. 1 and shown at Table 2. The soil loss rates are classified according to the intervals proposed by Silva *et. al.* (2007). The result of the combination of the USLE factors revealed that there is a predominance of the class that indicates "low" soil loss expectation (that means a soil loss expectation lesser than 10 Mg.ha⁻¹.year⁻¹). This class occurs in 44.84% of the area. The class "medium to high" (50.1 - 120 Mg.ha⁻¹ year⁻¹) is the second predominant class and occurs in 23.77%, followed by class "medium" (15.1 - 50 Mg.ha⁻¹.year⁻¹) with 14.64%, "high" (120.01 - 200 Mg.ha⁻¹ year⁻¹) with 10.43%, "moderate" (10.01 - 15 Mg.ha⁻¹ year⁻¹) with 3.68% and "very high" (> 200 Mg.ha⁻¹.year⁻¹) with 2.68%.

Table 2 – GASCAV soil loss rates

Soil Loss (Mg/ha/year)	Class	Extension (km)	% of area
0.0 - 10.0	Low	72.60	44.84
10.1 - 15.0	Moderate	5.95	3.68
15.1 - 50.0	Medium	23.71	14.64
50.1 - 120.0	Medium to High	38.50	23.77
120.01 - 200.0	High	16.89	10.43
> 200.0	Very High	4.34	2.68

Pipe cover depth results

Soil cover depths were surveyed at the phase of construction of the pipeline. This survey was performed with the use of topographic devices at least every 12 m of

the pipeline, where are located the pipe joints. The entire GASCAV right-of-way is located at rural locations, where the minimum soil cover depth required by N-464 is equal to 1.0 m. The results of the cover depth survey were divided into six different classes according to chosen ranges and are shown in Table 3. Rock excavation, crossings of inland bodies of water, public paved roads and railroads points are not considered here because there is no bare soil to suffer surface erosion process. The ranges of table 3 are product of a technical group of the company and they are based on the company risks management.

Results from Table 3 show that the class I is the predominant with 33.14% of the points, followed by class II with 28.66%, class III with 27.07%, class IV with 9.91%, class V with 0.96% and class VI with 0.26%.

The 11,160 points surveyed along the GASCAV right-of-way show that 98.78 % of these points are higher than those required by Standard N-464. However, depending on the soil loss rates at these points, one may expects a accelerated decreasing of soil cover depth by erosion processes, this fact is more important in the case of the points whose cover depth is slightly higher than those minimum values required by N-464. This fact suggests that the soil loss rates and cover depths should be analyzed together, not as distinct matters when risks of exposure or covers depths bellow minimum values.

Table 3 – GASCAV soil cover depths

Class	Cover Depth - H (m)	Number of Points	%
I	$H > 1.75$	3698	33.14
II	$1.50 < H \leq 1.75$	3199	28.66
III	$1.20 < H \leq 1.50$	3021	27.07
IV	$1.00 < H \leq 1.20$	1106	9.91
V	$0.75 < H \leq 1.00$	107	0.96
VI	$H \leq 0.75$	29	0.26
Total		11160	-

Exposure risks results

The exposure risk matrix developed has as rows the soil cover depths classes and as columns the soil loss rates classes. The resulted matrix with the risk categorization is shown in Table 4. Even though Tables 2 and 3 consists of six classes of soil loss taxes and cover depth respectively the results on the risk matrix are divided on three groups to obtain a simple analysis of the results when the procedure is applied to real pipelines.

The points are now categorized according to the risk matrix shown by Table 4 and the results are shown in Table 5. According to the categorization presented by Table 5, the classification of exposure risk for the GASCAV right-of-way is shown in Table 6. Most of the GASCAV right-of-way is characterized by low risks of exposure due surface erosion with 52.69% followed by medium risks with 26.59% and high risks with 20.78% of the 11,160 where the cover depth was surveyed.

Using now the dimensionless parameter τ , for time until exposure, the risks classification is evaluated using the tolerance for soil loss rate equals to 10 Mg/ha/year and for the minimum cover depth the value required by the Standard N-464 of 1.0 m. The values of τ are divided into three categories, high, medium and low risks. The results are shown in Table 7 and are very similar to the results obtained via the matrix of risks. The substantial amount of points classified by high and medium risks of exposure due surface erosion both by the method using the matrix of risks and the method using the τ parameter indicates that conservative and preventive practices must be taken to decrease the amount of problems in caused by surface erosion at the GASCAV right-of-way.

Table 4 - Exposure risk categorization (L = low risk, M=medium risk, H=high risk)

Cover Depth	Soil Loss rates					
	Low	Moderate	Medium	Medium to High	High	Very High
Class I	L	L	M	M	H	H
Class II	L	L	M	M	H	H
Class III	L	L	M	H	H	H
Class IV	L	L	M	H	H	H
Class V	L	M	M	H	H	H
Class VI	M	M	H	H	H	H

Table 5 - Exposure risk categorization results for the GASCAV right-of-way.

Cover Depth	Soil Loss rates					
	Low	Moderate	Medium	Medium to High	High	Very High
Class I	1601	224	511	871	368	123
Class II	1582	168	447	622	251	129
Class III	1632	58	446	620	342	145
Class IV	520	13	53	140	96	62
Class V	76	0	6	15	1	9
Class VI	11	0	5	7	1	5

Low
Medium
High

Table 6 - Exposure risks classification via Risk Matrix

Risks Level	Number of Points	%
Low	5874	52.63
Medium	2967	26.59
High	2319	20.78
Total	11160	-

Table 7 - Exposure risks classification via τ parameter

τ	Class	N de Pontos	%
$\tau > 0.75$	Low	6002	53.78
$0.75 \geq \tau > 0.15$	Medium	2985	26.75
$0.15 \geq \tau$	High	2173	19.47
-	Total	11160	-

CONCLUSIONS

Buried pipeline may be exposed by action of surface erosion processes. These processes can be mitigated and prevented if a correct evaluation of risks is carried on the pipeline rights-of-way. A precise exposure risk analysis must evolve the joint influence of the actual cover depth and the potential soil loss rate at every point. The methodologies used in this study use the universal soil loss equation with the surveyed values of cover depth at determined points along the pipeline right-of-way. Two approaches are followed on this study, the first make use of a matrix of risks and the second uses the concept of soil loss rate to create a dimensionless parameter related to the time until exposure of the pipe.

Both approaches are demonstrated in the risks analysis of the GASCAV right-of-way. The results show that conservational and preventive practices must be used to reduce the levels of medium and high risks that in both methods are approximately equal to 47% of the 11,160 of surveyed depth cover along the GASCAV right-of-way.

Further work will include this evaluation of other rights-of-way pipelines and the risks analysis of cover depth loss until a value below to those required by technical standards. Test investigation on soil loss tolerances and soil loss equation parameters also are necessary to determine more appropriate values related to surface erosion in pipeline rights-of-way.

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