International Journal of Applied Engineering Research ISSN 0973-4562 Volume 14, Number 15 (2019) pp. 3364-3371
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Strategies for the Restoration of Slopes in Cusiana River's Watershed (Colombia)

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Abstract

This article proposes the evaluation of strategies for the restoration of slopes in the 'Transversal Cusiana' between the departments of Boyacá and Casanare (Colombia), by doing a recollection of information in field of the restoration structures in different critical areas from El Crucero to Pajarito, in which there have been collapses and landslides over the years that have made it necessary for the government to intervene the roadway corridor and to keep the region inhabitants incommunicado. Likewise, a national and international literature and reports review was made related to the techniques used in the area in order to compare some of the restoration strategies that have been used and, finally discuss its implementation in the different areas of study.

Keywords: Strategies, Restoration, Slop, Cusiana, Landslide.

INTRODUCTION

Slop restoration refers to the implementation of geotechnical structures that reduce the landslides. Also, it offers solutions to the erosion problems, overload and humidity, quakes, among others that cause landslides to a road and affect the trafficability for its users. This is why that this type of interventions is important to reduce and relieve the risks, and also to decrease major losses in road infrastructure. In our case, one of the main factors to keep in mind is Cusiana river course and its influence on the adjacent hillsides on the roads.

According to the Economic Commission for Latin America and the Caribbean (known in Spanish as CEPAL or ECLAC in English) [1], the damages caused by the winter season in 2010-2011 are estimated at 3.500 million USD; from these the 61% equivalent to 2.150 million USD affects the acquis of the productive capital and the total of damages sums an equivalent of 5.7% of the yearly gross fixed capital formation in the country. The losses in infrastructure amount to 1320 million USD.

The national government, through INVIAS[1] and ANI[2], has decided to invest during the last years in road infrastructure and maintenance, specifically the roadway corridor that links Boyacá and Casanare, which is called 'Transversal de la Cusiana' in the Corredores de prosperidad project. Over the years, this road has had different problems related to the slopes instability, creating risk for its users and big economic losses besides leaving the inhabitants incommunicado. According to the 2018-2022 National Development Plan: To guarantee the sustainability of the upgrading done, INVIAS will implement a maintenance and rehabilitation program focused on the already intervened sections which are not contracted, in the roadway corridors established by the UPIT[3] and in projects executed by INVIAS taking into account the PMIT[4]. INVIAS and ANI will implement a program of preventive care and retrieval of vulnerable sites in the primary network, which complements its emergency response protocol. Likewise, the Ministry of Transport will reinforce risk management measures in light of phenomena associated to variability and climate change to quantify them and include them in the projects' planning, execution and operation stages [2].

Study area

The El Crucero-Pajarito roadway corridor, in the department of Boyacá, is part of the Sogamoso-Yopal route, connects the cundiboyacense highlands with the lowland piedmont and is 74-km long, with a preferred N-S direction. In the study sections, the route has a mountainous and steep topography, and follows the Cusiana river course [3]. This route is an alternate route to the plain region of the country, due to the collapses from June, 2019 in the Bogotá-Villavicencio main route that caused its closure; that's why it is important to keep it in good condition.

Figure 1. Study area map. From vías equidad 046 consortium

Geology

The El Crucero-Pajarito route is located to the eastern side of the Eastern Mountain Range, conformed by sedimentary rocks from the Lower Cretaceous, gathered in deep marine environments and shallows, mostly conformed by shale (prevailing), with harder rock levels, like sandstone, limestone and siltstone [3]. In Figure 2, the geological map from the zone in which the route, geological faults and fold are shown, is presented. According to Cusiana River's POMCA (Managing and Regulation Planning for the River Course), the area is evaluated as highly geologically unstable. There is also a deforestation and ecosystems transformation process which makes it be seen as an area with high probability of torrential rainfalls and floods, joined to the winter seasons when the river has bigger flows that represent undermining in the unprotected banks of Cusiana River.

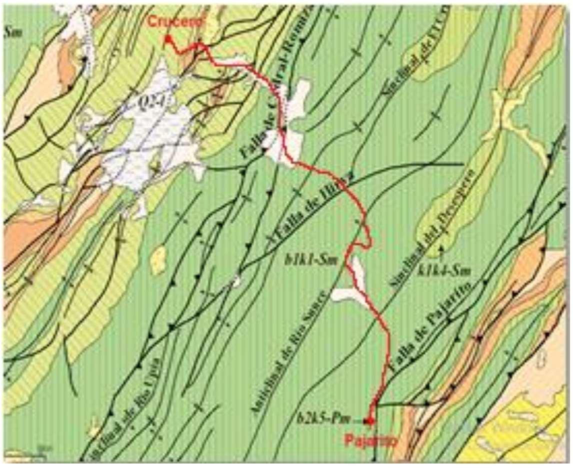

Figure 2. Zone's geological map. From Agustin Codazi Geographic Institute

METHODOLOGY

A fieldtrip was done to the study area, in which the different geotechnical constructions were demonstrated. These have been implemented over the years to mitigate the collapses and landslides caused by heavy rains, the Cusiana River flow growth. According to a piece of news by El Tiempo newspaper, it was possible to identify some critical sites like:

1. Peña de Gallo Sector: PR 52+0070: where some collapses are frequently presented from a big upper slop mass on the roadway.
2. Curisi Sector: PR 77+0900: Stable site with rock fall from the upper slope on the bank.
3. Huerta Vieja Sector: PR 80+0200: Slopes high instability area with bank's collapse, roadway with horizontal reduced radius curve and a hydraulic construction in a poor state.
4. Los Grillos Sector: PR 91+0200: Bank reduced to one track due to continuous avalanches of the gorge, with a failed hydraulic construction.
5. Chorro Blanco Sector: PR 81+0800: Site of instable slopes with bank's collapse.
6. El Verbeno Sector: PR 83+000: Landslides in an accelerated process, with bank's collapse.
7. Barro Negro Sector: PR 85+0600: Bank loss due to slope collapse and landslide and bank´s collapse.
8. La Chigüerera Sector: PR 87+0650: Damage in construction and bank's partial loss due to continuous avalanches.
9. La Orquidea Sector: PR 86+0500: Slopes high instability area with bank's collapse, roadway with horizontal reduced radius curve and a hydraulic construction in a poor state.
10. La Esmeralda Sector: PR87+0650: Hydraulic construction and roadway covered with avalanche material during different winter seasons.
11. El Cogollo Sector: PR 88+0360: Road reduced to one lane with inner slope loss, caused by the onslaught in the Cusiana river flooding.
12. La Cascada Sector: PR 89+0400: Hydraulic constructions and roadway that are blocked by avalanche material during winter seasons.
13. La Cónguta bridge Sector: PR 76+0400: Temporary metallic bridge with damages caused by extradimensional vehicles [4].

It is important to stress that the concession had two contracts to intervene the roadway. The first contract consists of long-term interventions and guarantees a good work. The second one covers trafficability; however this one cannot provide guarantee because the area's geology has too many geological faults and the intervention is a short-term basis, which is not viable due to the high costs of both material and labor. According to the contractor, the strategies used in the restoration of slopes (upper and inner) were suitable to prevent big mass movements and, the majority of the sectors were already intervened. On the other hand, primary information was collected: pictures from the area were taken and information from the construction workers, who have been working there for a long time, was registered. As secondary information, some documents by the Vías equidad 046 consortium were revised, about soil studies and designs of some sections. In Figure 3, the critical points with more instability regarding its proximity to the river and the problems caused by the river course and the heavy rainfalls were selected. Cusiana River course is shown in color blue and, in dark blue is shown the roadway that connects El Crucero and Pajarito.

Figure 3. Study points. From Google Earth.

Hereafter, we number the critical points that we consider the most important ones in the cross and in which different strategies were used.

1. K50+300 y K50+540 Rockfill and retaining wall with piling

Figure 4. From vías equidad 046 consortium

According to the Vías equidad 046 consortium, in the section K50+000 – K50+620, in which the roadway goes through Cusiana river flow, its torrential tendency has affected historically the river banks' stability causing sideway scour problems that affect either the river containment wall stability, or the stability of the deposits on the left sideway, which bring rockfalls that hit the existing walls and rockfills, producing the loss of confinement in the roadway bank. The roadway bank is on the alluvial deposits (Qal), causing serious problems of sideway scour and impacts on the transported block on the existing containing wall and rockfills. All of this while on a high longitudinal slope from the river's flow in the area. The scour problems also influence the river's right sideway.

2. K50+800 Rockfall

Figure 5. Taken by the authors.

There is a flow of big-sized debris in a non-consolidated deposit because of the concentration of water and the saturation of soil. Besides, there is a sideways scour in the right river bank. The license advices the installation of piling tangent to the road to protect the bank, and protecting rockfill in the right river bank in order to decrease the damages caused by the bank erosion in this section.

3. K52+850 Peña de Gallo bridge

Figure 6. From vías equidad 046 consortium

This point is one of the most critical ones in the area since there are frequent landslides caused by the heavy rainfalls and these blocked the freight car's pass. To solve this issue, INVIAS decided to change the alignment of the roadway with the construction of a viaduct in order to solve the reduced mobility and protect the freight cars. In the viaduct's construction, they drained the water flow to avoid it impounds.
This construction costed 7,3 million USD, and it is a kind of a cantilever bridge subsequent and weighted. It has a 360-meters-long constant curve y a 11-meters-long section. This structure facilitates the communication between the municipalities of Aquitania, Sogamoso, Pajarito, Aguazul, Yopal and Arauca.

4. K56+000 Geomanto y biolodo

Figure 7. From vías equidad 046 consortium

There was a great magnitude landslide in the slope because of the saturation of the soil due to the heavy rainfalls. It was decided to stabilize by the terraces mining method, 7 meters width each, every 10 height meters, and protect the slope with geomat, which is a high-strength mesh-made synthetic fabric that allows the growth of grass seeded with bioslurry. Wherever grading is done, grass must be seeded according to the area.

5. K76+300 Rockfill

Figure 8. From vías equidad 046 consortium

While roadway maintaining work was being made, Cusiana River had an increase of flow that affected part of the inner slope. It was immediately decided to implement an approximately 100-meter-linear-long rockfill to protect the slope; besides, there was an improvement in the roadway and reinforced concrete ditches.

6. Gabion wall and draining constructions K80+000

Figure 9. Taken by the authors.

There was a great magnitude landslide in the slope because of the saturation of the soil and runoff water, it was decide to implement a gabion wall to protect the roadway because the sideway hill was low. Some filter trenches were constructed to drain water to the closest gorge.

7. La Orquídea Bridge K86+510

Figure 10. From vías equidad 046 consortium

There was a mass removal process in the sideway, and it brought a movement in the northern stay of the bridge to the lower part of the sideway causing a 20 cm uplift and a breaking approximately in the center of the light. This incident compromised the closing pour and the next to this one. Afterwards, the bridge was closed for security purposes and a pan was constructed over the gorge. The construction of a 60-meter-long FEEILY bridge is proposed which is supported on three in piling in each stay with a diameter of 1,50 meters and a depth of 35 meters. The bridge would cost 2 million USD approximately.

DISCUSSION

As shown, there are different instability zones in the study area due to the characteristic geology and the geomorphology in some of the movements produced. As in K86+150, where some problems associated with runoff water infiltration were found and, according to Suarez [5], when identifying such problems it is important to implement draining works and power dissipation in the upper part of the sideway to reduce the instability linked to material saturation and water erosion in the sideways. In some cases, the instability problems have caused deterioration in the river systems, increasing the fluvial erosion and scour in the structures; the change in the use of soil because of the rice cultivation and the high deforestation in the area have contributed to the before-mentioned problems in the river course. In addition to this, in most of the cases, the triggering factor is the heavy rainfalls in the zone; this is why the rain rate in Cusiana River was consulted in the IDEAM (Spanish acronym for the Institute of Hydrology, Meteorology and Environmental Studies); this date is presented in Chart 1, in which is also presented the information from three rain gauge stations in different points of the Cusiana river basin: Toquila for the upper basin and Corinto and Pajarito for the middle basin. Regarding this information, it is possible to infer that the highest rainfall happens in the middle basin of Cusiana river, which is from Vado Hondo Sector to Pajarito, the areas with most instability are within the middle basin, where the highest yearly values registered were 3621 mm for 2015. This allows us to conclude that these are high rainfall values because they go over the yearly 2000 mm according to the IDEAM. On the other hand, it is possible to say that the highest rainfall is in Cusiana River's middle basin, from Vado Hondo to Pajarito, between June and July (noted in red); the areas with most instability are within the middle basin, where the highest yearly values are 3261 mm for 2015.

The right behavior of a slope on soil works depending on different variables like: geometric factors (pending and height) and conditions of the ground like geological and geotechnical (mineralogical composition, grading, specific weight, strength parameters, etc.), even though there are other variables to take into account like triggering agents (content variations and water circulation, modification of the gradient of the slope, erosion processes, etc.) [6], they must come with a modeling to estimate the security factors by methods like limit equilibrium analysis, among others.

Chart 1. Rain Rate in Cusiana River's Basin.

Rain Gauge Station		35197080	35195050	35190050
Location		**Toquilla**	**Corinto**	**Pajarito**
Monthly average rainfall (mm)	**Jan**	16,6	45,8	25,7
	Feb	29,5	61,6	47,8
	Mar	63,6	140,5	129,9
	Apr	119,7	268,0	317,1
	May	153,0	406,0	417,2
	Jun	206,9	423,5	479,9
	Jul	198,5	395,4	481,5
	Aug	170,8	395,4	439,3
	Sep	130,9	335,0	362,8
	Oct	119,6	340,0	302,2
	Nov	71,1	274,7	188,5
	Dec	33,4	97,6	69,1
Yearly (mm)		1313,6	3183,5	3261,0

In K50+800, it can be used the technique of flexible systems of high strength anchored to the ground given that, in Fernandez's [7] thesis, he explains how this methodology can prevent rock or soil slides. It consists of a flexible membrane formed by a network of cables or a wire mesh, which is attached to the ground through anchoring, generally anchor bars (bolts) and allows to incorporate horizontal or vertical reinforcement cables that come together in the bolts creating square patterns. This strategy allows us to avoid that soil slides or rock falling reach the drive way, which is what has been found in the study area; this is why we consider it is appropriate since, as shown in Figure 2, the slope is close to the driveway and an incident like this would cause the complete closure given the debris flow that would fall on the road. In the winter seasons (May to August), there is an increase in the river flow when there are heavy rainfalls, causing a progressive erosion rise in the sideways of the road, the consortium in charge proposed a rockfill over the inner slope. Chávez, Blanco and Watson state that the changes in the river course and the construction of development works over one of its banks have resulted in an instable slope, prone to slides and mudslides that cause damages in the constructions [8]. They also say some stabilization techniques (concrete walls, gabion walls, among others) have not been successful because in the end they are completely destroyed by the water. They presents a solution to this problem, in which they test an alternative to the injection method, mixed with the piling ramming method. They designed and built along the slope some retaining walls consistent in injected perforations with cement grout, reinforced with steel bars. When the slope confinement is improved, the shear strength of the existent materials in the sideway or slope is increased, which brings improvements in the stability development. This restoration strategy is, according to our criteria, good given the increase of the characteristics of resistance in the materials that form the slopes, increasing its resistance to erosion processes. Additionally, it favored the slope's inner structure with a greater confinement, which increased its stability.

As shown in Figure 7, the final appearance of the structure is natural, it contains a geomant that helps its waterproofing and it also allows the flora's growth in the external surface, it is draining in the frontal parameter. Cesar Augusto Urteaga Posadas researched another stabilization strategy using the Erdox system, shown in Figure 11. This system consists of a retaining wall that has a mono-anchor, which is made with a pyramid-shaped metal structure. The author states that some of the advantages of this structure are quick installation, lightweight, immediate stability and also, it can be previously assembled in a nearby place [9].

Figure 11. Erdox system structure [9].

This system is very convenient when it is necessary to intervene immediately the slopes stability, because it has good versatility and dynamism. This solution is recommended given that the environmental impact it causes is low because it is possible to sow on the structure once it is built, which helps preserving the landscape. Besides, the mechanical development of this type of structure is very stable, brings safety and prevents other failure mechanisms like overturning. According to the author, compared to the Terramesh System, it has advantages in labor, machinery, and mainly in costs and execution time. Depending on the characteristics of the project, Cesar Urteaga affirms that it is possible to reach efficiency and costs three times better when using Erdox. According to Perez, Martin, Abad and Perez, given the ground conditions and the trigger factor of landslide because of the heavy rainfall, the most optimal immediate solution was lowering the piezometric level by means of a deep draining system, which had been also used in Andalucía (Spain) with really good results. In addition to this, another solution was presented, it consists of a structural retaining wall with piling and, according to them, most of the times it was successful [10]. Moreover, some methodologies had been implemented without success. These changed the gradient, which allows us to conclude that the instable area's geology, morphology, and other characteristics influence the choice of the methodology to use. However, for K56+000 there is a similarity in the methodology used, it is possible to use a waterproofing geocomposite in order to collect rainwater in the transversal crown trenches leading them to the inner part of the slope decreasing erosion in the slope's structure and avoiding the rainwater infiltration, all of this accompanied by re-vegetation systems that reduce the probability of instability.

In our x-axis K56+000 there is no direct inflow with Cusiana River but there is a heavy rainfall in the area, a high gradient, in which a terracing was made and there are ditches in the upper part. The strategies implemented in this section are also presented in [6], where different stabilization measures are shown and their effect over the years; the usage of gabion walls and draining buttress has been successful, in most of the cases implemented with gradient variation. They also conclude that the less effective measure is the artificial re-vegetation in some slopes when it is not accompanied by other deep surface drainage techniques, as it hasn't been able to prevent a severe surface erosion even after one decade. In this regard and confirming what was done in the sixth point, K80+000, the gabion walls or breakwaters with draining trenches are commonly used in sideways with a low gradient and with runoff water problems since they allow the flow of water or, with the help of filter trenches, they conduct the water to the roadway or river ditches. According to Suarez [11], in tropical countries with high mountain, usually gabion is the most cost effective material for containment structures followed by the soil structures reinforced with geosynthetics. These structures are more cost effective than the simple or reinforced concrete walls.

Gonzalez [12] affirms that many of the problems presented in the rivers are because of the borders' erosion due to the lack of protecting vegetation, the presence of obstructions to the water flow (naturals or human-made), or to the excessive growth of macrophites (for the excessive eutrophication of the water and high temperatures). All of the techniques and methodologies that are implemented in a restoration project must favor the natural river's dynamics. The aesthetic or economic excuses are pointless, in this sense, to explain the choosing of techniques which implementation in the river is impossible, either for the materials used, for the conditions of operation, or simply as an excuse to promote an increase in the regulation and constriction of the river. The author proposes specific techniques that are commonly used in the rivers and riversides restoration, as shown in Figure 12:

a) Bolus introduction
b) Slopes re-grading
c-d) Usage of bioengineering techniques

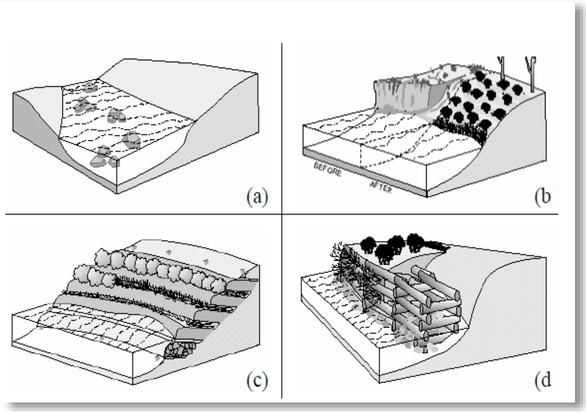

Figure 12. Rivers and riversides restoration. [12]

In Castellanos's bachelor thesis, it is shown the characterization, calculus and measures of control to face the problems of scour in the Buque spout (Colombia). Also, the more convenient mitigation works are presented depending on the area characteristics. There is a summary of the information presented in Chart 2:

Chart 2. Mitigation Works summary. [13]

Mitigation Works	**Description**
Rock dams with concrete binding	They are implemented in permanent course and with some conditions of foundation soil resistance and a good consolidation, normally they don't go over three meters height
Gabion dams	They are implemented in courses of high amount of sediments, to correct polluted courses, they usually have rectangular section and are coated in concrete to increase their useful life.
Reinforced concrete dams	They are implemented in the areas where there is an increased push by the flows and their location must be cautious, they most have additional works designed in order to guarantee their stability against scour. They are commonly used in course correction.
Wood dams	They are of temporary nature and are used for the control of small or intermittent river-beds for the purpose of allowing the development of covering vegetation.
Dry Stone dams	Generally, they are implemented in grounds that have a soil with low foundation and of low resistance. They are frequently used in drain lines and secondary courses with low flows and high sediment release.
Bank protection works	Used to protect the sideway slopes that form the permanent course banks against scour. In straight sections, the protection is necessary in both Banks, in the curves only in the external bank.
River-bed control works	It serves the purpose of setting the bed at a predetermined level and prevent the deepening of the bottom of permanent water flows.

Chart 3. Comparative chart.

In the context of our region, which is located in a tropical zone, it is common to find torrential courses in the winter seasons due to the topography, geology and geomorphology and heavy rainfalls that increase the runoff water, influenced by the high rate of deforestation. All of these determining factors help the water from the gauges that disgorge in Cusiana River increase its flow, thus its scour power and sediment transporting that in the end hit the constructions that confine the roadway. This is why it is of major significance that the bank protection works prevent the bank loss, as it is presented in K50+300 and K76+300.

In chart 3 there is a comparison chart between the used and suggested methodologies by the respective author (s).

Author	**Country**	**Thrilling Factor**	**Geology**	**Sideway gradient**	**Type of intervention**
[6]	Spain	Gully processes due to the Surface runoff and material loss.	The alternance of arsenics and quartzite prevail, as well as strong black slate sequences.	1H/1V(45°) 2H/3V(56.3°) 1H/2V(63.4°) 1H/3V(72°)	Sanitation techniques: -Slope re-vegetation -Transversal Crown trenches construction -Reduction of slope's original gradient Containment techniques: -Buttress drain. -Gabion walls
[7]	Spain	Breaking in a soil slope or a section's landslide in a rock slope	Any kind of soil and rock. Like the sedimentary, metamorphic and igneous rocks.	Convex, dished and plains.	Flexible high resistance systems anchored to the ground.
[8]	Ecuador	Changes in the river course and the construction of urbanization Works on one of the banks.	Shale, tophaceous limonite, limestone lutites, clay mix, limey-sandy, gravel	It is not specified, but can be implemented in any kind of gradient.	Injection method with cement grout strengthened with Steel bars.
[9]	Peru	Slopes instability due to heavy rainfalls and the presence of geological faults, which caused landslides.	For a clay soil where clay prevails, but also has sand and silt.	It is not specified, but can be implemented in any kind of gradient.	ERDOX System
[10]	Spain	Heavy rainfalls	Marls and loamish clay	4H:1V	Anchored piling retaining walls and deep draining
[13]	Colombia	Scour	Colluvial quaternary, which consists of gravel with boulder and boulder y sub-angular blocks	Variating gradients along the river.	Gabion wall

CONCLUSIONS

- It becomes apparent that the main cause of the mass movements in the study area is triggered by the rainfalls, as shown in Chart 3, the most common constructions are the gabion walls, piling retaining walls and flexible systems anchored to the ground. These constructions must be accompanied by surface draining structures in the crown of the slope to spawn a better performance of the containing structure.
- The dynamic processes associated with the course increase in Cusiana River banks are reason to the instability in some sections. This is why it is important to understand the erosion and scour causes on account of the river course. It is emphasized the importance of the water and bank erosion to prevent infiltration and soil loss, which could provoke mass movements in the area. It is important to explore the use of bioengineering in the banks given the change of land use.

- According to POMCA, it is important to control the different land uses in the area since it is observed that the deforestation has increased, causing erosion problems and unsettling some sideways in the study area. Some public policies should be considered in order to restrict the changes of land use the community makes.

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