Piedras Blancas Landslide: Mitigation Works

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Abstract *— The Puerto Rico Highway and Transportation Authority has conducted since the 1980s several geotechnical investigations about the Piedras Blancas Landslide in the Municipality of San Sebastian. This landslide has brought damages during various decades, presenting cracks and sinking of the highway PR-111, and settlements of nearby residences and commerce. The failure area has a creek, a natural depression pond, a springs' history, and a sensitive geology, San Sebastian Formation. Also, it is bounded uphill by the Lares Escarpment, a high limestone cliff rich in sinkholes. Through this paper it is possible to appreciate a number of contributing factors that could trigger this landslide and then take care of it through a gabion terraces design. This proposal deals with the topographic and hydrologic impacts to the terrain produced by fill and cut construction works. Soil survey information comes from Puerto Rico Highway and Transportation Authority (PRHTA) reports.*

Key Terms *— back analysis, colluvium, gabions, landslide.*

INTRODUCTION

Landslides are common in the Municipality of San Sebastian located at the northwestern region of Puerto Rico[9]. These failures are more perceptible along the highway PR-111, its principal road, which connects various municipalities such as Utuado, Lares, San Sebastian, Moca, and Aguadilla (Figure 1).

This paper is based on the possible causes that produce the initiation of the Piedras Blancas Landslide, located at PR-111 highway, km 23.9.

Also, it proposes how to decrease the landslide and manage drainage in a better way. This area is only one of the numerous places of the highway PR-111 where ground movement develops. However, it has the particularity that has various geotechnical studies.

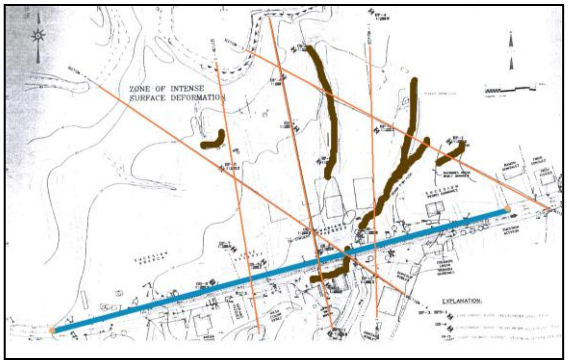

Figure 1
Piedras Blancas Landslide: Survey Map

Geotechnical data for this project was provided by the Soil Engineering Office of the Puerto Rico Highway and Transportation Authority (PRHTA). The slope stability analysis was performed with Slope/W Program from Geostudio where the Spencer Method was used. Since the 1970s, according to official reports, Piedras Blancas Ward has experienced settlements and cracking of its principal road, including the abandonment of nearby residences and commerce (Figure 2). PRHTA faced this situation by performing investigations in the area assisted by external consultants, Geo-Consult and Geocim [3]-[12]. Studies were performed in 1987 and 1999, respectively. The landscape was described by these investigators as a progressive failure with various scarps and fissures oriented from northeast to west, whose prominent head-scarp is in the south side of the highway PR-111, and its toe is found near an unnamed creek in the north side [3]. The site was covered with colluvium and fill soils, underlined by the San Sebastian Formation composed of overconsolidated clayey soils. The colluvium and fill thickness was approximately seven (7) meters and San Sebastian Formation thickness was about five (5) meters. The area has a natural depression pond and has a spring's history confirmed by local residents. The site is bounded uphill by the Lares Escarpment, a high limestone cliff rich in sinkholes whose waters supply the springs in the valley [12].

Figure 2
Piedras Blancas Landslide: Abandon residence

The geotechnical consultants located various springs at northeast and east of the failure zone and near the creek zone. GeoConsult found the presence of two water tables where they concluded that the most important cause of Piedras Blancas failure could be the higher artesian pressures in its soil lower strata [3].

A field visit to Piedras Blancas failure was performed on 2008, in this inspection it was included the creek route. The creek banks were full of vegetation; some of them with their roots exposed by the erosion, and there are no constructions or structures in this zone. Installations of drill shafts were performing with difficulty near the road. Soil was saturated and water was filling the drilled holes.

Aerial photos and several maps as are flooding map, topographic map, rainfall and geological maps were obtained through GIS to evaluate this site (Figures 3 to 6).

Several investigations have been done in landslides. The Catena engineering case in Brazil and [10] project in USA were the most relevant for this study. Their studies analyzed how the topographic and morphological impact triggers landslides. According to Catena engineers from Brazil, although the slope is considered as the mayor attribute affecting hydrology and slope stability analysis, other morphological attributes as hill slope forms, concave forms (hollow) must be considered. Also, they recommended the integration of news parameters in the computer programs to evaluate the slope stability [5]. For the Piedras Blancas failure a proposed analysis and design is presented in this paper. It has nine (9) terraces retained by gabions walls: two of six (6) feet height, two of nine (9) feet height and five of ten (10) feet height. Terraces are a simple but effective soil conservation measure, used for crop production and control of soil erosion [11]. The proposed terraces resemble the natural topographic contours, lose by fill and cut construction works. For this design, they are aligned from east to west as natural contours were directed. Gabions are used for construction of retaining structures in all environments and climates [8]. They have advantages over more rigid structures because they have flexibility and can conform to ground movement, dissipate energy from flowing water and drain freely. They permit differential settlement. Their strength and effectiveness may increase with time in some cases, as silt and vegetation fill the interstitial voids and reinforce the structure [14]. Their structures merge with the natural environment [8].

AREA OF STUDY

The Piedras Blancas Landslide is a rotational translational slide, located in Piedras Blancas Ward, San Sebastian [3]. The terrain has low angle slopes. It was described as a large landslide with an area of 40,000 m^2. Geotechnical investigations were done since the 1980s by GeoConsult and Geocim. Twenty borings were drilled in the zone with piezometers and inclinometers installed to depths of thirty and fifty feet. Several direct shear and CD triaxial tests were performed. Stability analyses were performed by computer programs as STABL and PC-Slope, and GeoSlope [3]-[12].

These analyses showed that the immediate cause for this slide is the bank erosion of the named creek located at north of the site. In 2000the failure dimensions increased to two hundreds (200) meters in width and length, and stayed near a depth of ten (10) meters. Currently, PRHTA uses the data to remediate the failure; these works consist in the realignment of the road and its reinforcement with a drill shaft wall. The soil was classified as: MH, CH, and CL in the Unified Soil Classification System and as A-7-5 (14) and A-7-6, GI from 18-37 in the AASHTO system. The upper layer of colluvium had natural moisture content from 10 to 72%. The San Sebastian Formation layer had moisture content from 5 to 36% [12]. In 1987, a landslide motion to depths of nine (9) to thirteen (13) meters was observed with the inclinometers [3]. In 1999, Geocim instruments registered motions to depths of seven (7) to eleven (11) meters. Works to re-establish the zone were done during these years then causing the difference of depths. It was mentioned in the Geocim report that this zone has had 0.5 meters of asphalt added periodically to stabilize this road [12].registered motions to depths of seven (7) to eleven (11) meters.

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Landslide Contributing Factors

There are several factors than can contribute to the landslide and they are earthworks, geology, climate and topography. All these factors will be explained for this project and how they will affect the landslide risk.

- **Earthworks**

Fill and cuts, necessary for residence and road construction diminish slope stabilization [2]. Previous studies on Piedras Blancas failure present information about cuts on the south side of the highway PR-111 and fill works in the north side of the road where residences collapsed [3]. Any cut in a colluvium slope as is Piedras Blancas case, needs monitoring and maintenance because this soil is marginally stable [2]. Also, construction of highway PR-111 on early 1900's could impact the geomorphology of the site, bringing destabilization of side cast material, gullying, channel network expansion, stream flow, etc. [10].

In 1994, David Montgomery performed shallow landslides studies in Huelsdonk Ridge, Washington. He found that historical aerial photographs from landslides inventories shows that the rate of landslide initiation increases significantly following road construction and clear cutting [10]. In 2003,Keith Kahklen and Jeffrey Moll measured effects of roads on groundwater leveling, concluding that they reduce hydraulic conductivity of the soil and re-rout groundwater to the surface [9].

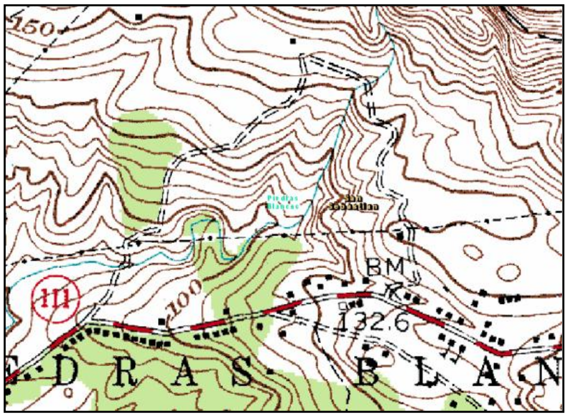

Figure 3
Topographic Map of San Sebastian

- **Geology**

The Municipality of San Sebastian is characterized by landslides because its geology and climate [9].

These failures have occurred during decades and they have been associated are associated to heavy rain season and a sensitive geology San Sebastian Formation. Puerto Rico can be divided into three different physiographic regions according to Watson H. Monroe. San Sebastian is in the Northern Karst and Groundwater Province. The terrain ranges from abrupt slopes and shear cliffs to gently rolling hills. Most drainage is underground, which results in extensive collapse features [4]. Rocks in the Northern Karst province are Oligocene and Miocene in age (Figure 4).Oligocene section consists of products from the igneous rock of the mountainous areas as are clays, sands, and gravels cover by limestone. The Miocene section consists of as much as 1400 m of limestone. Piedras Blancas failure has Tst geology, corresponding to a tan or brown sandstone and siltstone (colored in purple), and is surrounded by Tsr geology, a brown, red or mottled red and green clay (colored in lilac) and by landslides deposits (colored in red) (Figure 5). Differential weathering usually produces hydraulic discontinuities in its weathered layer, obstructing infiltration after intense rainstorms events. Thus it may contribute to soil saturation and to the development of critical pore-water pressures [5]. The soil hydraulic conductivity is an important factor in a landslide event, particularly in areas with thick weathered profiles as are tropical hill-slopes cases.

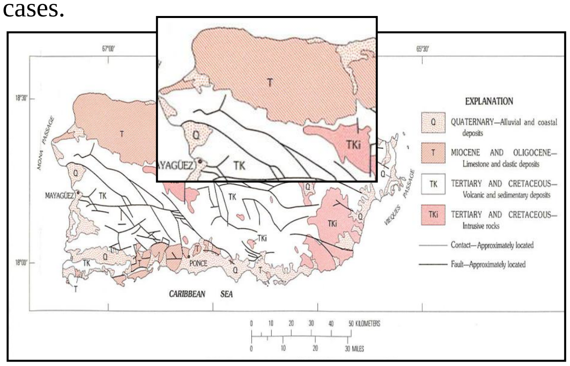

Figure 4
Generalized Geological Map of PR

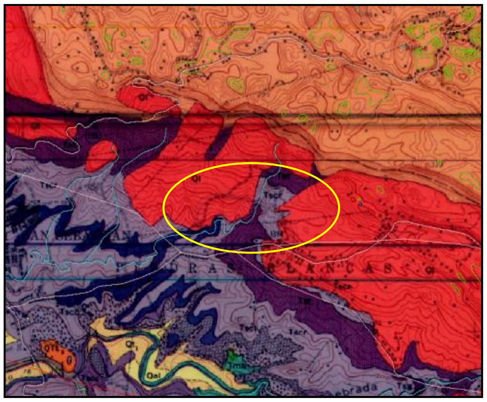

Figure 5
Geological Map of Piedras Blancas

- **Climate**

The climate in Puerto Rico is warm and humid with the temperatures ranging from 20 and 30Celsius degrees, and with a relative humidity about 80 percent during the year. San Sebastian annual rainfall is about 2500 mm (Figure 6).

The combination of warm and moist air with heavy rainfall produces rapid, deep weathering of surficial materials, bringing severe erosion and slope stability problems throughout the island[4]-[9].

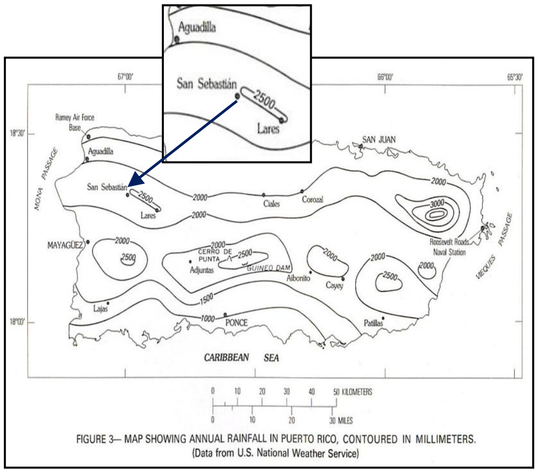

Figure 6
Map of Annual Rainfall in Puerto Rico

- **Topography**

Water converges to Piedras Bancas failure zone. This zone is near a hollow area (Figures 3). This type of topography is susceptible to the initiation of landslide, [10]. They act not only as sources of landslides but also as conduits for debris flow of previous events. This must be an alert to project planners and designers. He suggests hollow mapping and identification in landslide hazard map [13].

DISCUSSION

Analysis of failure site has been done with field inspection and examining previous geotechnical studies. Also, evaluating maps and modeling the failure with Slope/W computer program.

Methodology 1: Field Mapping

Evaluation of the land survey map prepared by previous investigators (Figure 1), together with the data on Figure 7 of this project, and visits to the site has permitted the following observations:

- Higher groundwater level occurred near the creek or the highway proximity.
- Irregularities of the surface are seen clearly because fill, cut and re-grading works.

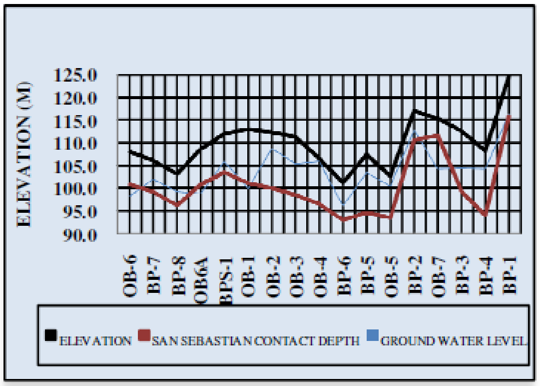

Figure 7
Elevations vs. Borings Layout at San Sebastian Formation

Figure 7 presents groundwater leveling, surface leveling, and San Sebastian Formation leveling vs. borings' layout. Chart intends to show the influence of these levels with the deformed areas. Figure 1 corresponds to Piedras Blancas failure's survey map prepared by Geocim and PRHTA [12].

Figure 7 and survey map data present similarities in borings OB-7, OB-1, OB-6 and OB6-A. These borings are located near the highwayPR-111 and have their groundwater levels below the San Sebastian Formation contact zone. On the other hand, the survey map shows borings OB-7and OB-1 near large scarps and fissures but boringsOB-6 and OB6-A without any noticeable deformation. It was observed that there no construction of residences at OB-6 and OB6-A zones.

Also, it showed in the survey map that exist large scarps and fissures near borings BP-1, BP-3, BP-5, OB-5, BP-7 and BP-8. However, the inclinometers did not indicate any deformation at the borings BP-1 or BP-3, whose boring logs show limestone layers of 12 meters and 6 meters, respectively. The limestone stratum facilitates groundwater flow through large openings formed along bedding planes, fractures, joints, and faults [14]. Boring BP-5 exists in an area with fill, where waters converge to it. The boring log show that the water content was of 64% in its upper layers. Boring BP-7 is in a fill area with a soil water content of 50-63 % in its upper layers. Boring OB-5 had soil water content of 60-65% in its upper layers, and boring BP-8 is located near reported spring's zone. It was observed in the Geocim boring logs that most of the deformed areas have higher water content in their upper layers [12].

Boring logs of BPS-1 and BP-6 show the existence of sand layers to a depth of 15 feet. In these layers occurred deformation. Boring BPS-1 is located in the south side of highway PR-111 and has 14.5 meters of sand. Boring BP-6 is in the north side near the failure toe and has 6 meters of sand [12]. Borings as BPS-1 and BP-6 contain sand layers useful for vertical draining. It is suggested to explore and find more sand zones like these to drain these areas vertically and then horizontally through trench drains in the upper layers [2]. It not recommended deep trench drains because Piedras Blancas has failed to a depth of 15meters, it would be very expensive.

Methodology 2: Modeling

For this analysis the failure event was modeled through the computer program, GeoStudio (Slope/W). In this project five cross sections were analyzed. Cross sections #1, #2, #3, were directed from south to north and cross sections #4 and #5were directed from south–east to north-west. The strength parameters were determined by back analysis method; assuming a safety factor equal to one, this value would indicate a failure event. The back analysis has been reported successfully for reactivated slides when is assumed c' = 0 (Chandler, 1977) [7].

Several running were done. The resulting friction angles that corresponded to a slope and toe failure are presented in Tables 1 to 3. Due the soil characteristics modeling was done and the safety factor was determined varying their $\phi_{f/c}$. It was assumed only two layers with the followings conditions:

- Fill/colluvium:

γ = 19.6 kN/m^3 = 125 pcf , c = 0 kPa, =0 psf , varying $\phi_{f/c}$, friction angles for fill/ colluvium.

- San Sebastian Formation layer:

γ = 19.6 kN/m^3 = 125 pcf, c = 19.2

kPa, = 400 psf, ϕ = 25 °

Legend is as follows:

GW1- Groundwater level observed at field from previous studies.GW2 is ground water leveling in saturated conditions. GW3 is related with lowering GW1, level 3 meters

Table 1

Failure: Safety Factors varying GW1

c= 0 kPa	$\varphi_{f/c}$	SF **GW1**	SF **GW2**	SF **GW3**
Cross Section #1	13	0.99	0.55	1.2
Cross Section #2	8	1.00	0.64	1.00
Cross Section #3	Higher SF			
Cross Section #4	7	1.09	0.55	1.11
Cross Section #5	33	1.09	0.38	1.09

Table 2

Failure: Friction Angles varying GW

Safety Factor =1, c=0 Kpa	$\varphi_{f/c}$ (GW1)	$\varphi_{f/c}$ (GW2)
Cross Section #1	13	15
Cross Section #2	8	13
Cross Section #3	SF ≠ 1, higher SF	
Cross Section #4	7	13
Cross Section #5	33	No significant changes

Table 3

Failure: Safety Factors varying Cohesion

Saturated (GW2)	$\varphi_{f/c}$	C, varying (kPa)	SF
Cross Section #1	13	13	1.5
Cross Section #2	8	4	1.5
Cross Section #3	n/a	higher SF	
Cross Section #4	7	4	1.47
Cross Section #5	33	33	1.5

The cross sections, #1, #2 had toe failures in all the cases assumed. Slopes failures did not occurred. The cross sections, #3 did not fai1. The cross sections, #4, #5 had slope failures. The cross sections, #1, #2, and #4 showed safety factors of one when their friction angles, $\phi_{f/c}$ were 13, 8 and 7degrees, respectively (Table 1). The cross section#3 showed safety factors higher than 3, However, it reached a safety factor of 1.23 not 1.0 with $\phi_{f/c}$ equal to 4 degree. The cross section #5 showed safety factor of one when $\phi_{f/c}$ was 33 degrees. First three results were associated to residual strength conditions. Cross section #4 was the most critical case (Table 1). Testing soil behavior in a saturated condition and keeping soil cohesion equal to zero, brought the following results (Table 1): In cross section #1, safety factor diminished from 0.99 to 0.55. In cross section #2, the safety factor diminished from 1.0 to 0.64. In cross section #4, the safety factor diminished from 1.02 to 0.55, and in cross section #5, the safety factor lowered from1.09 to 0.38. Saturation diminished approximately 50% the former slopes stabilities (Table 1). It was observed also that the failure events occurred with higher $\phi_{f/c}$ (Table 2). There are studies related to colluvium soil stability. During 1974 and 1984, colluvium investigators, Rodine and Johnson [13], proposed an approximated soil Mobility Index, MI. This parameter is the ratio of saturated water content (in place soil) and water content required for the soil to flow. This value must be approximately ≤ than 1.0 to avoid colluvium flow.

In 1987 Ellen and Fleming [13] proposed a soil Mobility Index called AMI. This parameter is the ratio of saturated water content (in place soil) and liquid limit [2]. Evaluating Piedras Blancas boring logs, in search of colluvium's liquid limit sand water contents it was found that only two boring have both colluviums parameters; OB-4 with w = 66% , LL = 118, ratio = 0.56< 1and BP-2 with w = 37, LL = 69.3, ratio = 0.53 and the did not deformed. The colluvium investigators correlated saturation with soil movement as happened in this project modeling. Evaluating soil behavior in saturated condition but varying $c_{f/c}$, cohesion in the fill/colluviums layer, produced the following results (Table 3): In cross section #1, the safety factor increased from 0.55 to 1.5 when $c_{f/c}$ was increased from 0 to 13. In cross section # 2, the safety factor increased from 0.64 to 1.50 when $c_{f/c}$ was increased from 0 to 4. In cross section # 4, the safety factor increased from 0.55 to 1.47 when $c_{f/c}$ was increased from 0 to 7. In cross section # 5, the safety factor increased from 0.38 to 1.5 when $c_{f/c}$ was increased from 0 to 33.I

Investigating soil behavior but lowering water level three (3) meters from GW1, produced the following results: In cross section #1, the safety actor increased from 0.99 to 1.2. In cross sections#2, #4 and #5 values did not increased considerably. Finally, water levels were lowered until 12 meters in cross sections #1, # 2, #4 and #5 but without significant changes (Table 1). Water levels lowered near the San Sebastian Formation contact zone. San Sebastian Formation lower layers are more complex strata than those assuming in the modeling. It is needed more understanding of the groundwater route through the site especially under the road.

The back analysis utilized in modeling is valuable but it operate based on fundamental assumptions as soil homogeneity, slope, and slip surface geometry and pore pressures conditions along the failure surface.

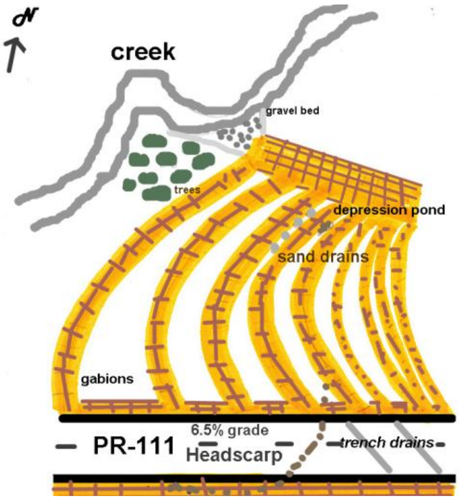

Figure 8
Piedras Blancas Terraces Alignment

Terraces Use

The design proposes nine terraces reinforced by gabion walls (Figure 8). The gabion walls have three different heights of 6, 9 and 10 feet (Figures 9 to 11). Stability calculations were done with a friction angle of 15 degrees. It is a conservative value chosen considering that cross sections # 4 and#5 had values of 7 and 33 degrees, respectively. (Table 1). These sections are aligned toward northwest more similar to terraces that are directed toward the west. Terraces elevations are close to the natural contours elevations presented in the topographic map (Figure 3). It is a way to return balance to the site. Terrace number six has the San Sebastian Formation soil. It needs special consideration for drainage (Tables 6 & 7). It could affect terraces five and seven.

Calculations

Data -

γ_{soil} =125 pcf =19.6 kN/m^3

γ_{gabion} =150 pcf , 3 0 % porosity [8]

ϕ =15 ^{0}, c' $_2$ = 400 psf = 19.2 Kpa

D = 3ft

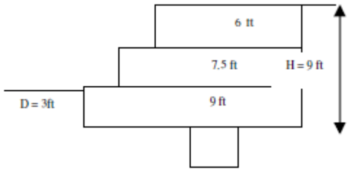

Figure 9
Gabion Wall Type 2

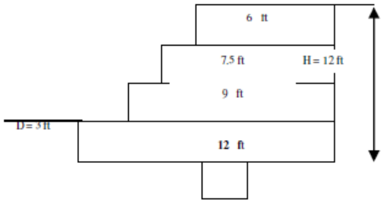

Figure 10
Gabion Wall Type 2

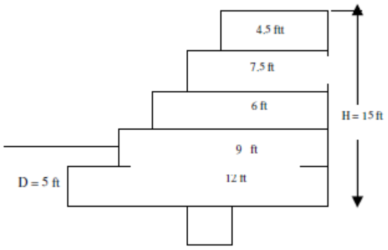

Figure 11
Gabion Wall

Terraces are distributed in a distance of 318.75meters (Table 6 & 7). Distance begins from east to west. Calculations for gabion walls stability were done. Results are presented in Tables 4 and 5. Calculations are as follow (English system is used):

$$P\ active = 0.5*(\gamma)*(H)\ 2*(Ka) \tag{1}$$

$$Ka = (1-\sin\phi) / (1+ \sin\phi) \tag{2}$$

$$Ka = 0.588Kp =1/ Ka = 1.70 \tag{3}$$

$$M\ overturning = (H/3)*Pa \tag{4}$$

Table 4
Results of Resisting Moments and Vertical Forces

Gabion Wall Type	H (FT)	D *(FT)*	M_γ *(KIP-FT/FT)*	Σ^V *KIP/FT*
1	9	3	40,753.12	8032.5
2	12	3	86,113.13	11812.5
3	15	5	99,933.75	13230

$$SF_{overturning} = M_r/M_o \tag{5}$$

$$SF_{sliding} = (\Sigma V) * \tan\left({}^{2}/_{3} * \varphi_2\right) + B * \left({}^{2}/_{3}\right) * c'_2 + Pp)/P_a \tag{6}$$

$$P_p = {}^{1}/_{2} * \gamma * D^{2*} K_p + 2 * c_2 * D * \sqrt{K_p} \tag{7}$$

$$e = {}^{B}/_{2} - (\Sigma M_r - \Sigma M_o)/\Sigma^V \tag{8}$$

$$q_{toe} = \left(\Sigma^{V/B}\right)(1 + 6 * e/B) \tag{9}$$

$$q_{heel} = \Sigma^{V/B}(1 - 6 * e/B) \tag{10}$$

Type 1, q toe = 1212.75 lbs/ft^2, q heel = 572.25 lbs/ft^2 (Figure 10)

Type 2, q toe = 1231.45 lbs/ft^2, q heel = 737.3 lbs/ft^2 (Figure 11)

Type 3, q toe = 1968.75 lbs/ft^2, q heel = 236.25 lbs/ft^2 (Figure 12)

$$q_{ult.} = c'_2 * N_{c*} F_{cd*} F_{ci} + q * N_{q*} F_{qd*} F_{qi} + ½ * \gamma_2 * B' + N\gamma * F_{yd} * F_{yi} \tag{11}$$

N_c=10.98, N_q=3.94, N_γ= 2.65 [1]

$$SF_{bearing\ capacity} = q_{ult.}/q_{toe} \tag{12}$$

Table 5
Results of Equations

<table>
<tr><td colspan="7">γ soil = 125 pcf c = 400 psf γ gabion = 150 pcf</td></tr>
<tr><td>Terraces Type</td><td>D ft</td><td>H ft</td><td>H’ ft</td><td>Safety Factor Over-turnig (5)</td><td>Safety Factor Sliding (6)</td><td>Safety Factor Bearing Capacity (12)</td></tr>
<tr><td>1</td><td>3</td><td>9</td><td>6</td><td>4.56</td><td>2.65</td><td>3.40</td></tr>
<tr><td>2</td><td>3</td><td>12</td><td>9</td><td>4.07</td><td>1.77</td><td>4.94</td></tr>
<tr><td>3</td><td>5</td><td>15</td><td>10</td><td>2.42</td><td>1.62</td><td>3.14</td></tr>
</table>

Safety Factors against overturning must be more than 2.0, against sliding must be more than 1.5 and for bearing capacity must be more than 3[1]. Terrace design is adequate.

Table 6
Layout of Borings in the Terraces

Terrace Numbering	**Borings**	**Boring Elevation (m)**	**Boring Elevation – San Sebastian**
2	BP-1	124.6	4.98 m = 16.33 ft
5	BP-3	112.6	14.27 m = 46.82 ft
6	OB-3	111.3	12.02 m = 39.4 ft
	BP-5	107.4	15.92 = m 52.23 ft
	OB-4	106.5	14.02 m = 45.99 ft
	OB-7	115.3	-1.8 m = 5.90 ft
	OB-2	112.3	10.52 m = 34.25 ft
7	OB-6	108	6.68 m = 21.91 ft
	OB-6A	108.6	6.68 m =21.91 ft
	BP-7	106.1	8.28 m = 27.17 ft
	BP-8	103.1	11.28 m = 37 ft

Table 7
Terraces Elevations

Terrace Numbering	Type	Distance (m)	Elevation
1	1	318.75	122.71
2	1	312.5	120.88
3	2	298.75	119.05
4	2	280	116.31
5	3	255	113.57
6	3	223.75	110.52
7	3	160	107.47
8	3	95	104.42
9	3	0	101.38

CONCLUSION

In this paper has been integrated knowledge of different branches that study the soil behavior with the interest of understand the Piedras Blancas landslide.

Contributing factors triggering this failure have been: earthworks; as cut and fill produced by residences and road construction in PR-111, geology; San Sebastian Formation is in a karst and groundwater region with underground drainage, the climate; heavy rains affect soil that are marginally stable as colluvium case, and the topography; failure site is near a hollow zone identified as vulnerable area to landslides.

Several studies about the most recent techniques in landslide remediation were evaluated but surface and groundwater management is one of the most important strategies to improve the slope stability. Studying the influence of groundwater leveling with deformation of the Piedras Blancas site demonstrated that this leveling was higher near the road and creek zone. Landslides investigators predicted that in several cases, roads re-route ground water to the surface. Then it is important to consider an adequate water control in road design.

The analysis of Piedras Blancas boring logs demonstrated that borings showed deformation when they have higher water content in their upper layers or where sand layers appear in the lower layers. These sites were identified as zones where water converged, where springs exist, or where high pressures develop.

Slope/W modeling demonstrated that saturation of the soil is an important parameter in soil stability analysis. The results showed that saturation of the colluvium decreased drastically the stability of the slopes and toes in the cases under study. Slopes andtoes in saturated conditions acquired stability only increasing its cohesion from zero until 4 to 33 kPa. The safety factor increased rising colluviums cohesion. It was the parameter that improves stability after saturation of the soil. Colluvium investigators proposed soil mobility indexes, MI and AMI to predict colluvium ground movement. These parameters correlated saturation with soil movement. If these values are approximately less of one, the failure must not occur. In Piedras Blancas project, borings BP-2and OB-4 had indexes of 0.56 and 0.53 less than one, and they did not deformed as predicted by them. In this project was investigated the effectiveness of the back analysis method. This analysis is valuable but it works based on fundamental assumptions as soil homogeneity, slope, and slip surface geometry and pore pressures conditions along the failure surface.

As Piedras Blancas landslide is a progressive failure, it could present different strengths for each point in the slip surface. However, it was the only tool available to analyze the site. In this project it was useful for the evaluation of the colluvium soil behavior present in the upper layers. Complex strata need other considerations. The topography in this project acts as an important element and the mitigation proposal considers this feature. In this paper has been presented a gabion terraces design that returns the topographic and hydrologic balance to the site and improves drainage in the upper layers. The terraces walls will be reinforced by gabions bringing more stability to the soil. Gabions are flexible and can conform to the ground. They drain freely and can tolerate differential settlements and merge with the environment.

RECOMMENDATIONS

Modeling results in strength parameters wereassociated to residual strength conditions.

Same experience happened to the former investigators. Landslide literature recommended for this case, preventing the difference, collecting soil sample in the discrete shear zone of the ancient landslide not in the general overburden soils. Also, they suggested the use of ring shear apparatus over the direct shear box in the Direct Shear Test.

It recommended study and monitoring the groundwater route under highway PR-11. It suggested a better water control in this road design. It is recommended design roads with broad based dips and no inside itches and with a fully graveling road beds that drains into stream channels.

Vegetation could have favorable influence on the slope stability of Piedras Blancas. It could increase cohesion and intervene in the interception of rainfall and transpiration of groundwater, and reducing humidity and peak groundwater pressures.

It is suggested the underground drainage with vertical sand drains, prefabricated vertical drain sand trench drains. It is necessary to explore and find more deep sand zones as were found in borings BPS-1 and BP-6; then drain these points vertically.

The natural depression pond of the site must be cleaned and protected with coarse grain filter. Clearing and grubbing of the failure zone must be done. The accumulation of damaged structures and debris observed in the zone do not permit a complete evaluation of the site. Finally, land use for sensitive area must be modified; planning and regulating with more comprehensive judgment.

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