Design of Cantilever and Gabion Retaining Walls for Slope Failure Caused by Hurricane Maria in Lares, PR

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Abstract *— Due to the rain caused by Hurricane Maria there were various slope failures around Puerto Rico (PR). This project evaluates a failure in Lares, PR, road PR-124. The evaluation consists in mitigate that failure with two designs for retaining walls (Cantilever and Gabions).*

Key Terms *— Cantilever Retaining Wall, Gabion Retaining Wall, Hurricane Maria, Slope Failure.*

INTRODUCTION

It is our 3rd anniversary of Hurricane Maria's passing thru the island of Puerto Rico (PR), and even though time has passed, the struggle at the island persists. This project is going to focus on the designs of cantilever and gabion retaining walls for slope failure due to Hurricane Maria, in Lares, PR (PR-124). To design these types of walls, an engineer must know the parameters of both the soil that is going to be retained behind the wall and the soil under the base slab, which are: the unit weight (γ), the angle of friction (Φ), and the cohesion (c). Both cantilever and gabion walls are under the category of Gravity Walls, which depend on their own weight to achieve stability (resist failure from overturning, sliding, and bearing capacity); they can be made of concrete, bricks, or stone.

PROBLEM STATEMENT

Hurricane Maria caused various slope failures around the island, which means that those areas were affected and need a design to prevent slope failure.

OBJECTIVE

- On this project we will create a design for both cantilever and gabion walls for the soil at Lares, PR.
- Provide a design that is easy to apply to other types of soil in the island.

CONTRIBUTIONS

Some contributions made with this project are:

- Minimizing slope failures in PR by using this design for retaining walls.
- Preventing the high costs that involve the repair of such failures.

LITERATURE REVIEW

The unexpected happened in the island of Puerto Rico. It was on September 20, 2017, when Hurricane Maria, a category 5 hurricane, unequal to any other storm, hurricane that has passed the island, made landfall in Puerto Rico. This event caused mass destruction on the entire island, it caused rivers to overflow, destruction of houses, it ruined everything at its passage, with all the rain that fell during this event, it caused slope failures around the island. In this project we will focus on Lares, PR, shown on Figure 1, on PR-124, Figure 2. The data that we are using for this work was produced by a private laboratory, due to a previous boring log test in the area. The following information was given: Cohesion (c), Unit Weight (γ), and Angle of Friction (Φ).

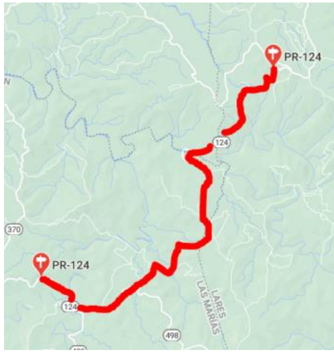

Figure 1
Shows PR-124

As discussed before, for this project we will design a type of Gravity Walls—gabion and cantilever—which depend entirely on their weight to create stability, which means to not fail due to overturning, sliding, or bearing, Figure 3. A Gabion Wall consists of baskets made with steel or plastic mesh in rectangular/cylindrical shape filled with stone. An advantage of this style is that it provides free drainage to the wall.

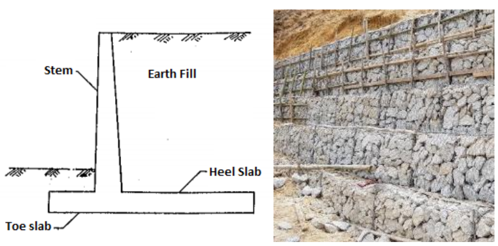

Figure 2
Illustrates Cantilever and Gabion Wall

METHODOLOGY

The soil properties for both retaining wall designs are:

- Cohesion (c) = 0
- Unit Weight (γ) = 130 pcf
- Angle of Friction (Φ) = 32°
- The report gave various heights along the road, in this case we took the worst-case scenario which are the following:
    - Cantilever Wall – H = 20 ft
    - Gabion Wall – H = 21 ft

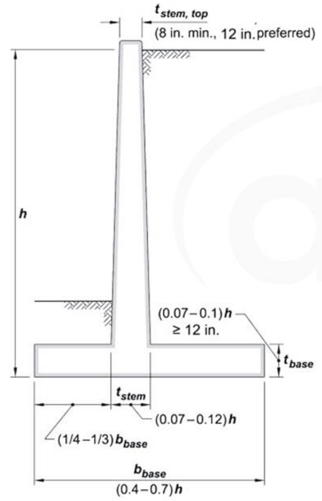

Figure 3
Shows the model based on the design [1]

PROCEDURE

GeoSlope [2] is used to evaluate the slope failure in Figure 4. Although the failure did happen, the program will recreate the slope to see how it failed. The failure of this project is illustrated in Figure 5, which contains the piezometer line, and Figure 6 evaluates the failure without water content to compare them both. As expected, due to the heavy rain caused by the hurricane, the Safety Factor in the slope with water pressure is smaller than the one with no water pressure, which makes it the most critical in both cases. The Safety Factors were the following:

- $SF_{Saturated}$= 0.667
- SF_{Dry} = 1.490

Figure 4
Shows the slope failure in PR-124

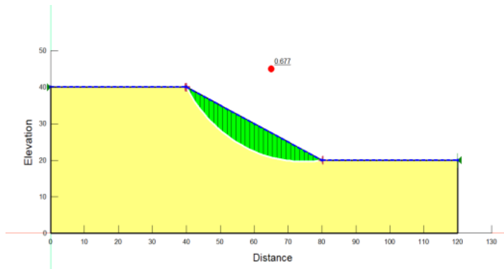

Figure 5
Illustrates GeoSlope using the Piezometric Line

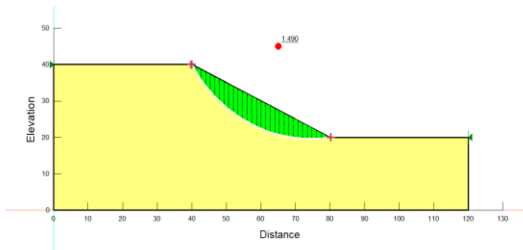

Figure 6
Illustrates GeoSlope without the Piezometric Line

Cantilever Wall Design

1. Get the information of the soil: Unit Weight (γ), Cohesion (c), and Angle of Friction (Φ).
2. Design the wall with certain dimensions, that might change eventually (trial and error), start with Figure 3.
3. First, calculate K_a (Active Earth Pressure Coefficient) and K_p (Passive Earth Pressure Coefficient).

$$Ka = tan^2(45 - \frac{\phi}{2}) \quad (1)$$

$$Ka = tan^2\left(45 - \frac{32}{2}\right) = 0.31$$

$$Kp = tan^2(45 + \frac{\phi}{2}) \quad (2)$$

$$Kp = tan^2\left(45 + \frac{32}{2}\right) = 3.25$$

After various trials and errors, the final dimensions are shown in Figure 7:

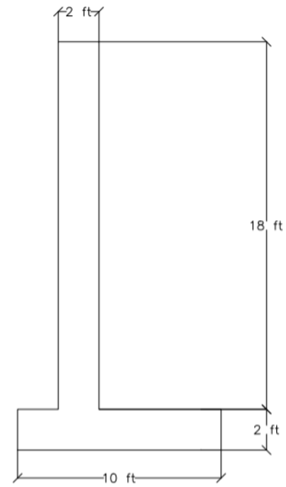

Figure 7
Final Dimensions

4. Calculate Pa and Pp.

$$Pa = \frac{1}{2} Ka\gamma H^2 \quad (3)$$

$$Pa = \frac{1}{2}(0.31)(130)(20)^2 = 8060\ lb/ft$$

$$Pp = \frac{1}{2} Kp\gamma H^2 \quad (4)$$

$$Pp = \frac{1}{2}(3.25)(130)(20)^2 = 7605\ lb/ft$$

5. Calculate the Overturning Moment (OTM).

$$M_{OTM} = P_a * \frac{H}{3} \quad (5)$$

$$M_{OTM} = 8060 * \frac{20}{3} = 53733.3\ {}^{lb-ft}/_{ft}$$

6. Calculate the Vertical Loads (Gravity Loads).

$$\text{Vertical Loads} = \text{Area} * \gamma \quad (6)$$

Vertical Loads (Gravity Loads)		
Wc_1 =	5400	lb/ft
W_{C2} =	3000	lb/ft
W_{S1} =	14014	lb/ft
W_q =	1440	lb/ft
Σ =	23854	lb/ft

7. Calculate the Resisting Moment (RM), by multiplying the Vertical Loads with the centroid of each load (ẋ).

	RM	
W_{C1} =	16200	lb*ft/ft
W_{C2} =	15000	lb*ft/ft
W_{S1} =	105105	lb*ft/ft
W_q =	10800	lb*ft/ft
Σ =	147105	lb*ft/ft

8. Calculate Safety Factor for Overturning (SF_O), it must be higher than 2.

$$SF_O = \frac{RM}{OTM} > 2 \quad (7)$$

$$SF_O = \frac{147105}{53733.3} = 2.7 > 2$$

9. Calculate Safety Factor against Sliding (SF_S), it must be higher than 1.5.

$$\text{SF} = \frac{\mu \Sigma Fv \tan(k_1\phi_2) + Bk_2c' + Pp}{Fh} > 1.5 \quad (8)$$

$$\text{SF} = \frac{(0.55)(23854)\tan\left(\frac{2}{3}(32)\right) + 7605}{8060} = 1.6 > 1.5$$

10. Calculate Safety Factor for Bearing Capacity (SF_B), it must be higher than 3.

$$e = \frac{B}{2} - \frac{M_R - M_{OTM}}{\Sigma V} \quad (9)$$

$$e = \frac{10}{2} - \frac{147105 - 53733.3}{23854} = 1.08 < \frac{B}{6}$$

$$q_{max}/q_{min} = \frac{R}{B}\left(1 \pm \frac{6e}{B}\right) \quad (10)$$

$$q_{max}/q_{min} = \frac{23854}{10}\left(1 \pm \frac{6(1.08)}{10}\right) = 3931\ psf/839\ psf$$

$$B' = B - 2e \quad (11)$$

$$B' = 10 - 2(1.08) = 7.84ft$$

$$\lambda_{qd} = 1 + 2tan\phi'_2(1 - sin\phi'_2)^2\left(\frac{D}{B'}\right) \quad (12)$$

$$\lambda_{qd} = 1 + 2\tan(32)\,(1 - \sin(32))^2\left(\frac{6}{7.84}\right) = 1.74$$

$$\lambda_{cd} = \lambda_{qd} - \frac{1 - \lambda_{qd}}{N_c tan\phi'_2} \quad (13)$$

$$\lambda_{cd} = 1.74 - \frac{1 - 1.74}{35.49\tan(32)} = 1.77$$

$$\lambda_{\gamma d} = \lambda_{\gamma i} = \lambda_{qi} = \lambda_{ci} = 1$$

$$q = \gamma D \quad (14)$$

$$q = 130 * 6 = 780psf$$

Bearing-Capacity Factors N_c, N_q, and N_γ

ϕ' (deg)	N_c	N_q	N_γ	ϕ' (deg)	N_c	N_q	N_γ
0	5.14	1.00	0.00	26	22.25	11.85	12.54
1	5.38	1.09	0.07	27	23.94	13.20	14.47
2	5.63	1.20	0.15	28	25.80	14.72	16.72
3	5.90	1.31	0.24	29	27.86	16.44	19.34
4	6.19	1.43	0.34	30	30.14	18.40	22.40
5	6.49	1.57	0.45	31	32.67	20.63	25.99
6	6.81	1.72	0.57	32	35.49	23.18	30.22
7	7.16	1.88	0.71	33	38.64	26.09	35.19
8	7.53	2.06	0.86	34	42.16	29.44	41.06

Figure 8

Shows the Bearing Capacity Factors

$$q_u = c_2N_c\lambda_{cd}\lambda_{ci} + qN_q\lambda_{qd}\lambda_{qi} + \frac{1}{2}\lambda_2B'N_\gamma\lambda_{\gamma d}\lambda_{\gamma i} \quad (15)$$

$$q_u = 46860\ psf$$

$$\text{SF}_B = \frac{q_u}{q_{max}} > 3 \quad (16)$$

$$\text{SF}_B = \frac{46860}{3931} = 11.9 > 3$$

Cantilever Wall Stem Design:

1. Calculate the Lateral Loads (Factorized), the sum of the loads is the Ultimate Shear, Vu.

Lateral Loads (Factorized)		
Pa=	12896	lb/ft
Rq =	6912	lb/ft
Σ =	19808	lb/ft

2. Calculate ultimate moment, Mu, it is the sum of the multiplication of the factorized lateral loads with the distance in y.

	Mu	
Pa=	86016.3	lb*ft/ft
Rq =	69120	lb*ft/ft
Σ =	155136	lb*ft/ft

3. Calculate ΦVc.

$$\Phi Vc = \Phi * 2 * \sqrt{f'c} * b * d \quad (17)$$

$$\Phi Vc = 21Kips$$

4. Calculate ρ, ρ_{min} = 0.0018

$$\rho = \frac{0.85 * f'c}{fy}(1 - \sqrt{1 - 2.353\frac{Mu}{\Phi * b * d^2 * f'c}} \quad (18)$$

$$\rho = 0.0075$$

5. Compare ρ with ρ_{min}, you choose the largest.

6. Calculate As_{req}.

$$As_{req} = \rho * d * b \quad (19)$$

$$As_{req} = 1.84\, in^2/ft$$

For both faces of the wall, the As_{req} will be 1.84/2 = 0.92 in^2/ft.

7. Calculate Spacing for the reinforcement.

$$Spacing = \frac{As}{As_{req}} * 12 \quad (20)$$

$$Spacing = \frac{0.79}{0.92} * 12 = 10"$$

On both sides there will be #8@10".

8. Calculate the minimum reinforcement for horizontal, using Eq. 18.

$$As_{req} = 0.44\, in^2/ft$$

For both faces of the wall, the As_{req} will be 0.44/2 = 0.22 in^2/ft.

9. Calculate Spacing for the reinforcement.

$$Spacing = \frac{0.20}{0.22} * 12 = 10"$$

On both sides there will be #4@10".

Cantilever Wall Toe Design:

1. Calculate Vu.

$$Vu = V * 1.6 \quad (21)$$

$$Vu = 23854 * 1.6 = 38166.4\, lb/ft$$

2. Calculate Mu.

$$Mu = RM * 1.6 \quad (22)$$

RM = step #7 of the Cantilever Design

$$Mu = 235368\, lb - ft/ft$$

3. Calculate OTMu.

$$OTMu = OTM * 1.6 \quad (23)$$

$$OTMu = 85973.28\, lb - ft/ft$$

4. Calculate the location of the resultant

$$x = \frac{Mu - OTMu}{Vu} \quad (24)$$

$$x = 3.91\, ft$$

5. Calculate q_{max}/q_{min}

$$eB = \frac{B}{2} - x \quad (25)$$

$$eB = 1.09\, ft$$

$$q_{max}/q_{min} = \frac{R}{B}\left(1 \pm \frac{6e}{B}\right) \quad (26)$$

$$q_{max}/q_{min} = 6312.7\, psf/1320.6\, psf$$

6. Calculate q_{UT}.

$$q_{UT} = qmax - \left(\frac{qmax - qmin}{B}\right) * X \quad (27)$$

$$q_{UT} = 5314.3\, psf$$

X = the length of the Toe

7. Using static equations, calculate Vu and Mu in the Toe.

Vu =	11.6	K/ft
Mu =	11.93	K-ft/ft

8. Compare Vu with ΦVc (17).

Vu< ΦVc OK

9. Calculate ρ (18).

$$\rho = 0.00053$$

Since ρ is less then ρ_{min}, we will use 0.0018.

10. Calculate As_{req} (19).

$$As_{req} = 0.44\, in^2/ft$$

11. Calculate Spacing (20).

$$Spacing = \frac{0.44}{0.44} * 12 = 12"$$

Use #6@12" Bottom

Cantilever Wall Heel Design:

1. Calculate the Weight of the heel.

$$W_h = b * h * \gamma \quad (28)$$

$$W_h = 6 * 2 * 150 = 1800\ lb/ft$$

2. Calculate Vu.

$$Vu = \Sigma Vertical\ loads * 1.6 \quad (29)$$

$$Vu = 20704.8\ \text{lb/ft}$$

Σ Vertical loads = include W_h from previous step.

3. Calculate Wu.

$$Wu = \frac{Vu}{b} \quad (30)$$

$$Wu = \frac{20.7}{6} = 3.45\ K/ft$$

b = length of the heel

4. Compare Vu with ΦVc (Eq.17).

Vu< ΦVc OK

5. Calculate Mu.

$$Mu = Wu * \frac{b^2}{2} \quad (31)$$

$$Mu = 3.45 * \frac{6^2}{2} = 62.1\ K - ft/ft$$

6. Calculate ρ (Eq. 18).

$$\rho = 0.0028$$

7. Calculate As_{req} (Eq. 19).

$$As_{req} = 0.69\ in^2/ft$$

8. Calculate Spacing (Eq. 20).

$$Spacing = \frac{0.60}{0.69} * 12 = 10"$$

Use #7@10" Bottom

9. Calculate As_{min} for dowels.

$$As_{min}\ dowel = 0.005 * Ag \quad (32)$$

$$As_{min}\ dowel = 0.005 * 24 * 12 = 1.44\ in^2/ft$$

Ag = width of the stem (in) * 12in

There will be two dowels, the As_{req} will be 1.44/2 = 0.72 in^2/ft.

10. Calculate Spacing (Eq. 20).

$$Spacing = \frac{0.79}{0.72} * 12 = 13"$$

Use 2 dowel #8@13"

Gabion Wall Design [3]

1. First, you need to collect the information for the soil.

2. Design the wall with certain dimensions, that might change eventually (trial and error).

3. Calculate the Active Earth Pressure Coefficient, K_a.

$$K_a = \frac{\cos^2(\phi - \beta)}{\cos^2\beta\cos(\delta + \beta)\left[1 + \sqrt{\frac{\sin(\phi + \delta)\sin(\phi - \alpha)}{\cos(\delta + \beta)\cos(\alpha - \beta)}}\right]^2} \quad (33)$$

$$K_a = 0.27$$

β = Back Face Slope Angle = -6°

δ = Angle of Wall Friction

ϕ = Angle of Internal Friction of Soil

4. Calculate Lateral Earth Pressure, P_a.

$$P_a = K_a w_s \frac{H^2}{2} \quad (34)$$

$$P_a = 0.27 * 130 * \frac{21^2}{2} = 7739.5\ lb/ft$$

w_s = Soil Density

5. Calculate the Horizontal Component, P_h.

$$P_h = P_a \cos\beta \quad (35)$$

$$P_h = 7697.1\ lb/ft$$

6. Calculate the distance, d_a, for P_a.

$$d_a = \frac{H(H + \frac{3q}{ws})}{3(H + \frac{2q}{ws})} + B\sin\beta \quad (36)$$

$$d_a = 5.46\ ft$$

q = the surcharge = 240 psf

7. Calculate the Overturning Moment, M_o.

$$M_o = d_a P_a \quad (37)$$

$$M_o = 42257.7\ lb - ft/ft$$

8. Calculate the Weight of Gabions, W_g.

$$W_g = Htw_g \tag{38}$$

$$W_g = 21 * 3 * 100 = 6300\ lb/ft$$

H = the height of the wall
t = thickness of the wall
w_g = gabion fill density

9. Calculate the Horizontal Distance, d_g, to W_g.

$$d_g = \frac{t}{2} + \left(\frac{H}{2}\right) tan\beta \tag{39}$$

$$d_g = 2.60\ ft$$

10. Calculate the b.

$$b = B - t - Htan\beta \tag{40}$$

$$b = 9.18\ ft$$

11. Calculate the Weight of Soil Wedge, W_s.

$$W_s = \left(Htan\frac{\beta}{2} + b\right) Hw_s \tag{41}$$

$$W_s = 32565.9\ lb/ft$$

12. Calculate the Horizontal Distance, d_s, to W_s.

$$d_s = [(H^2 tan\beta)\left(Htan\frac{\beta}{3} + t\right) + (Hb)\left(\frac{b}{2} + Htan\beta + t\right)]\frac{w_s}{W_s} \tag{42}$$

$$d_s = 8.23\ ft$$

13. Calculate the Weight of Surcharge, W_q.

$$W_q = qb \tag{43}$$

$$W_q = 2203.2\ lb/ft$$

14. Calculate the Horizontal Distance, d_q, to W_q.

$$d_q = \frac{b}{2} + Htan\beta + t \tag{44}$$

$$d_q = 9.8\ ft$$

15. Calculate the Resisting Moment, M_r.

$$M_r = W_s d_s + W_g d_g + W_q d_q \tag{45}$$

$$M_r = 305989\ lb - ft/ft$$

16. Calculate the Safety Factor against Overturning, SF_o, it must be higher than 2.

$$SF_o = \frac{M_r}{M_o} \tag{46}$$

$$SF_o = 7.24 > 2$$

17. Calculate Total Vertical Weight, W_v.

$$W_v = W_s + W_g + W_q \tag{47}$$

$$W_v = 41069.1\ lb/ft$$

18. Calculate the Safety Factor against Sliding, SF_s, it must be higher than 1.5.

$$SF_s = \frac{\mu W_v}{P_h} \tag{48}$$

$$SF_s = 3.33 > 1.5$$

$\mu = tan\phi$

19. Evaluate the eccentricity, e.

$$e = \frac{B}{2} - \frac{M_r - M_o}{W_v} \tag{49}$$

$$e = 0.928\ ft$$

20. Verify if it is within limits of eccentricity

$$\frac{-B}{6} \leq e \leq \frac{B}{6} \tag{50}$$

$$-2.45 \leq e \leq 2.45 \quad OK$$

21. Calculate Maximum Pressure under the base, P.

$$P = \left(\frac{W_v}{B}\right)\left(1 + \frac{6e}{B}\right) \tag{51}$$

$$P = 3852.46\ psf$$

22. Compare with the Allowable Soil Bearing Pressure, P_b.

$$P \leq P_b \quad (52)$$

$$P \leq 4000\ psf$$

23. Calculate the pressure at every distance z (ft), f_v.

$$F_v = w_s z + q \quad (53)$$

$$F_v = 130z + 240$$

24. Calculate Tensile Stress, T, on every layer of reinforcement in vertical segment of soil thickness, S_v (ft).

$$T = S_v K_a f_v \quad (54)$$

z (ft)	S_v (ft)	F_V (psf)	T (lb/ft)
3	3	630	510.3
6	3	1020	826.2
9	3	1410	1142.1
12	3	1800	1458
15	3	2190	1773.9
16.5	1.5	2385	965.925
18	1.5	2580	1044.9
19.5	1.5	2775	1123.88
21	1.5	2970	1202.85

25. Calculate the distance, X, to the wedge failure plane.

$$X = H\tan\left(45 - \frac{\phi}{2}\right) - H\tan\beta \quad (55)$$

$$X = 9.43\ ft$$

Γ = scale correction factor, is assumed 0.65

26. Calculate minimum embedment length, L_{em}.

$$L_{em} = \frac{1.5T}{2\Gamma f_v \tan\phi} \quad (56)$$

27. Calculate the Length of embedment past the wedge, L_e.

$$L_e = B - t - \frac{X(H-z)}{H} \quad (57)$$

28. Compare L_e with L_{em}.

$$L_e > L_{em} \quad (58)$$

z (ft)	S_v (ft)	F_V (psf)	T (lb/ft)	L_e (ft)	L_{em} (ft)
3	3	630	510.3	3.62	1.34
6	3	1020	826.2	4.96	1.34
9	3	1410	1142.1	6.31	1.34
12	3	1800	1458	7.66	1.34
15	3	2190	1773.9	9.01	1.34
16.5	1.5	2385	965.925	9.68	0.67
18	1.5	2580	1044.9	10.35	0.67
19.5	1.5	2775	1123.88	11.03	0.67
21	1.5	2970	1202.85	11.70	0.67

RESULTS

Cantilever Wall Design

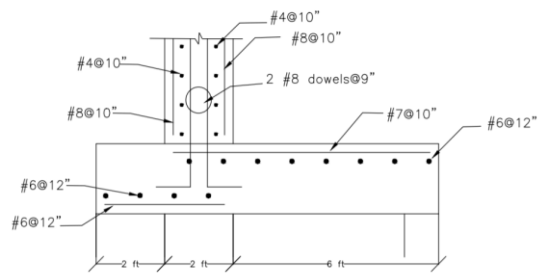

Figure 9
Reinforcement Detail of the Cantilever Wall

Gabion Wall Design

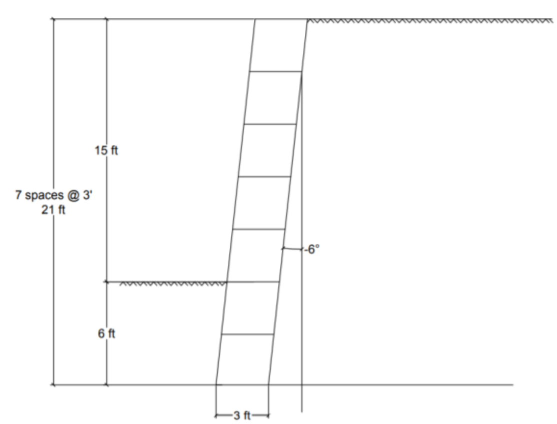

Figure 10
Cross Section of Gabion Wall Design

CONCLUSION

Although Hurricane Maria caused devastation on the island, it gave people an impulse to innovate new ideas. While simulating the slope in GeoSlope with both conditions, saturated and dry, as expected, the most critical safety factor was the saturated, 0.677. The designs presented in this project came to be because of that devastation. Although this project takes place in Lares, PR, both designs can be used around the island.

RECOMMENDATIONS

For future work it is recommended to:

- Evaluate and design the drainage for these walls, Figure 11, to avoid the premature failure caused by the increase in water pressure.
- Create other types of retaining walls and evaluate the costs.
- Use these designs at other cities of PR that had slope failures, and compare the soil types, type of failure, and how is most effective to mitigate the failure.

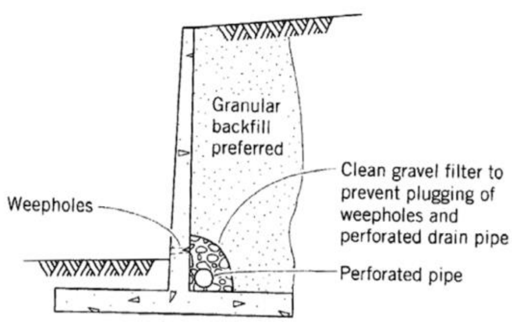

Figure 11
Example of a drainage design

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