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Analysis and Design of Ecological Cantilever Retaining Wall: A Case Study of High-steep Slopes Behind New G.R.A Maiduguri, Borno State, Nigeria

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Abstract:
In recent times, ecological challenges due to increasing global environmental crisis have posed many natural hazards which are growing by the day. The study area in this research is not an exceptional case due to increasing slope gully erosion by the downstream river. This action has over the years encroached the buildings upstream and causing serious destruction to buildings. In this study, RAM Elements software program was used in designing and analyzing the cantilever retaining wall subsequent to geotechnical analysis of the backfill and foundation soils. Soil index properties, shear strength tests, and bearing capacity analysis were conducted to determine the appropriate design parameters for the retaining wall design. Following the analysis of the wall, an economical geometry for the retaining wall (H=5.2m and wall element's thickness T= 450mm) was carefully adopted whose allowable factor of safety against sliding, overturning and bearing capacity using different load combinations are satisfactory. The reinforcement details of the wall were also presented subsequent to design of the elements stem, toe and heel. Based on the detailed analysis and design with the RAM- Elements, the work has proffered a reliable and promising solution in countering the environmental challenge at hand.
KeyWord*:Retainingwall, RAM-Elements, lateral earth pressure, bearing capacity, angle of internal friction*

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I. Introduction

Retaining walls are structures used to retrain soil or any other material from leaving its natural position and make the area above and below it usable. They are introduced in places with steep slopes, landslide-prone areas, or where huge shaping of landscape is required for construction purposes [1,2]. The wall has basically three components; the stem, toe slab and heel slab with toe and heel slabs making the foundation of the wall. Some retaining walls have shear key provided in the footing to prevent it from sliding. The stem may sometimes be provided with weeping holes with slopes for water drainage. The soil behind the stem may be coarse aggregate so that water percolates and exit via drains [3].

Retaining walls could be gravity wall, counterfort or buttress. Gravity wall retain soil by its own weight and it is bigger in size and mainly built with stones or plain concrete. In counterfort, the walls (counterfort) connect the stem and the heel slabs which offers support. The counterforts are concealed in the retained earth and this type of walls are provided where the retaining earth are more than seven meters. The counterfort sub-divided the stem and the heel into rectangular panels which are further supported on three sides and free at one edge.

The buttress wall is similar to counterfort but the support is on the toe side and are not concealed in the earth material. However, counterfort is preferred because it provides usable space in front of the wall and looks clean. In terms of efficiency and economy, buttress wall is preferred. A cantilever retaining wall is the common type of retaining structure usually used for material retention of up to eight meters high. The stem acts as a vertical cantilever under lateral earth pressure, the heel acts as a vertical cantilever under the action of net weight of the retained soil and the toe as a cantilever under the action of net soil pressure. Among many of the engineering solutions for handling landslides and erosion of steep slopes, a retaining wall is a key structure that can provide reliable protection downstream [4].

The magnitude of the lateral earth pressure acting on a wall is usually evaluated by using either of the two lateral earth pressure theories. The analysis of lateral pressure against retaining walls is a precondition for its design and is one of the old fields in engineering [5]. Out of all the theories coined by different researchers, those presented by Coulomb and Rankine are considered more reliable and more often referred to as the classical earth pressure theories [6]. Rankine's lateral earth pressure theory is based on the assumption that the backfill material consists of dry cohesionless soil. However, the theory has been modified by Resal and Bell to contain cohesive soil. Coulomb's theory on the other hand considers a passive case where the wall moves into the soil mass (granular backfill) and has an angle of wall friction at the interface [7]. The general equations for both theories are based on the fundamental assumptions that the retained soil is cohesionless, homogeneous, isotropic (similar stress-strain properties in all directions or in practical terms, not reinforced), semi-infinite (the wall is very long and soil goes back a long distance without bends or other boundary conditions), and well-drained to avoid consideration of pore pressures [8].

The active earth pressure calculations below demand that the wall structure rotates or yields appreciably to engage the entire shear strength of the soils involved to create the active earth pressure state. The magnitude of movement required is largely dependent upon the type of soil retained.

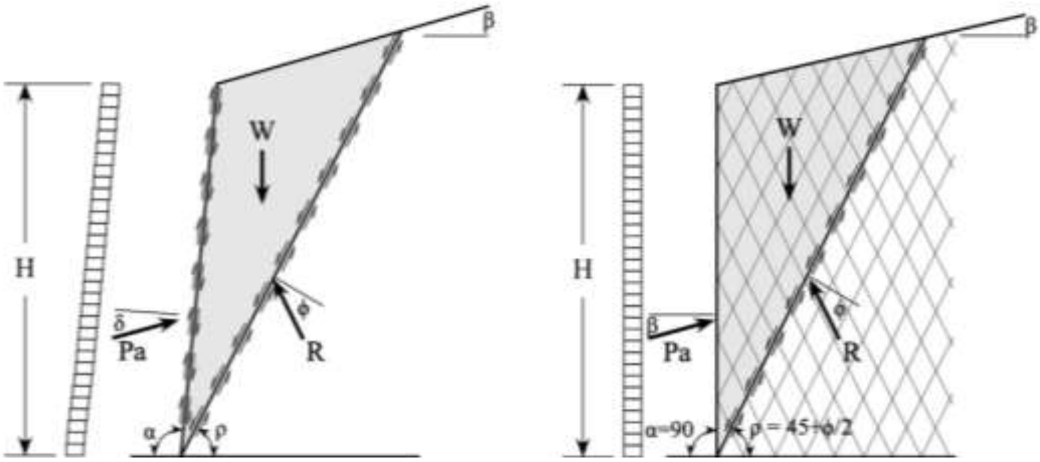

Figure 1 (a & b): Coulomb/Rankine Active Earth Pressure Diagrams (**Source:** Keystone Retaining wall system,2021).

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

$$Ka = \frac{\sin^2(\alpha+\varphi)}{\sin^2(\alpha)\sin(\alpha-\delta)\left[1+\sqrt{\frac{\sin(\varphi+\delta)\sin(\varphi-\delta)}{\sin(\alpha-\delta)\sin(\alpha+\beta)}}\right]^2} \ldots\ldots\ldots\ldots\ldots (2)$$

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

$$Ka = \cos\beta\left[\frac{\cos\beta - \sqrt{\cos^2(\beta) - \cos^2(\varphi)}}{\cos(\beta) + \sqrt{\cos^2(\beta) - \cos^2(\varphi)}}\right] \ldots\ldots\ldots\ldots\ldots(4)$$

Failure Modes of Cantilever

The failure modes in cantilever walls are basically sliding, overturning and bearing pressure failure.

- Overturning: in this failure mode, the toe acts as a center for rotation and the wall deforms in that direction. In the absence of a toe, the footing base below the stem acts as the center for rotation. All the lateral pressures will act as overturning forces while the weight of soil and the wall will act as stabilizing forces. Therefore, the wall must be safe against overturning about the toe. For a factor of safety against overturning;

$$F_O = \frac{\sum M_R}{\sum M_O} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Where, $\sum M_R$= sum of the resisting moment about toe

$\sum M_O$= sum of the overturning moment about toe

The value for the factor of safety against overturning moment should between 1.5 – 2.0

- Sliding: in this, all lateral forces try to slide the wall. The resistance against sliding is mainly provided by base slabs and the soil below it. When the lateral pressure is high and the wall fails by sliding, a shear key can be introduced to increase the sliding resistance. The position of the shear key is decided in such a way that flexural reinforcement from the stem can be extended into the shear key to create maximum counter pressure. The pressure generated by shear key resists the lateral pressure. The factor of safety against sliding is given by:

$F_{S=\frac{\mu R_V}{R_H}}$ ……………………………………………………………(6)

Where, R_V and R_H are vertical and horizontal components of resultant. A minimum factor of safety of 1.5 against sliding is generally adopted.

- Bearing pressure of the foundation soil plays an important role in resisting the pressure coming from the entire wall system. If the soil below the wall is not capable of resisting these loads, the wall fails in bearing pressure.

The maximum pressure is given by:

$P_{max} = \frac{R_V}{b}\left[1 + \frac{6e}{b}\right]$………………………………………………...... (7)

The minimum pressure is given by:

$P_{min} = \frac{R_V}{b}\left[1 - \frac{6e}{b}\right]$ …………………………………………………….. (8)

The factor of safety against bearing, $F_{b=\frac{q_{na}}{P_{max}}}$ …………………………(9)

Where q_{na} represent the allowable bearing capacity. A minimum factor of safety of 2 is adopted for cohesionless soils while a minimum of 3 is adopted for cohesive soils.

In recent years environmental degradation as a result of natural, human and industrial activities has become a cause for common concern. The case of New G.R.A Maiduguri, Borno State is not an exception where some part of the area has experienced increasing slope gully erosion as a result of water from Alau Dam passing through the route (river channel) downstream. The downstream slope is easily eroded because of the loose nature of the soil. This phenomenon has made residents in that area to continue to shift their existing fences whenever their land is been encroached on as a result of the erosion. This has led to the loss of land and existing property in the area. Conventional Geotechnical Engineering has suggested the use of retaining walls will help to curtail the effect of such environmental problems poised due to such as slope gully erosion by the downstream. This study is therefore aimed at providing a solution to this ecological problem by introducing a retaining wall to permanently reclaim the area taking into consideration the nature of the soil and existing site dimensions

II. Material And Methods

The materials used for the collection of samples include measuring tape, mold,digital weighing balancesterilized digger and shovel, mobile phone with a google map application and polythene bags. The soil samples (disturbed) were collected across the study area along a span of 60m manually. Samples from both backfill material and foundation soil were collected. The sample for foundation soil was collected at a depth of 1.5m while that of backfill was collected by dipping a mold into the loose material. Three (3) samples each for backfill material and foundation soil were collected and packaged in polythene bags to avoid moisture loss. The study location is on latitude11^o 48$'$ 45$''$ N and 13^o 10$'$ 03$''$ E longitude at an elevation of 317m above mean sea level. Figures 2a and 2b showed the google earth image and photo of the area with the river at the downside of the steep slope.

Plate 2a: Google earth map of the study area **Plate 2b:** Photo of the area showing the slope

Methods

Soil index properties

The index properties tests were conducted on both the backfill material and foundation soil samples in accordance with specifications outlined in British Standard [9].

Laboratory direct shear test

The direct shear test was conducted to determine the effective shear strength parameters of the soil, c and ϕ, the values are used in this study to calculate the bearing capacity of soil. The whole test was carried out using the procedure outlined in British Standard [9]. The square prism of soil was laterally restrained andsheared along a mechanically induced horizontal plane while subjected toa pressure applied normal to that plane. The shearing resistance offered bythe soil as one portion was made to slide on the other was recorded at regularintervals of displacement.Failure occurs when the shearing resistancereachesthemaximumvaluethatthesoilcansustain.

Foundation Soil Bearing Capacity and Modulus of Subgrade Reaction

The bearing capacity of foundation soil was calculated using Terzaghi's general formulae for ultimate bearing capacity which states that:

$q_{u=}CN_c + qNq \;\; + 0.5B\gamma N\gamma$ …………………………………. (10)

Where $q_{u\,=}$ ultimate bearing capacity of the soil which is usually divided by a suitable factor of safety to get the allowable bearing capacity.

C= cohesion, q = surcharge, B = foundation width, γ = unit weight of soil and N_c, Nq and$N\gamma$ are dimensionless coefficients that depend on the angle of internal friction of soil.

The modulus of subgrade reaction on the other hand was calculated using the relation:

$K = 40(SF)q_a$ ………………………………………………… (11)

Where K= modulus of subgrade reaction of the foundation soil

q_a= allowable bearing capacity

SF= safety factor

RAM Elements software procedures

RAM element is a computer software for structure and foundation design and analysis. It has easy interface, offering finite element analysis and collecting different codes. The software has design modules that include trusses, concrete, masonry, tilt-up walls with or without openings, spread and combined footings, continuous beams, concrete columns with interaction diagrams, and retaining walls. In this study, RAM Elements Connect V16, 2020, was used for the analysis and design of the retaining wall. The general design procedure after opening RAM Elements environment is as follows:

- Click 'module' on the toolbar, select standalone and choose retaining wall
- Select unit system and design code
- Choose wall type/material and input geometry data
- Input backfill material and foundation soil data
- Choose loads and create load combinations
- Input design data/ optimization parameters
- Analyze the model and generate design report

As for the geometry of the cantilever retaining wall, dimensions were presumed using the followings ranges: Base width L= 0.5H to 2/3H, the thickness of base D = 0.10H, stem thickness at the bottom C= 0.10H, the width of the toe = 0.25L to 0.33L and stem thickness at the top T= 250mm (minimum). However, this approximate proportion of the wall was suggested and optimized in the software.

III. RESULTS

The results for geotechnical properties of the soil which include bulk density, dry density, unit weight, angle of internal friction and cohesion is presented in Table 1. Detailed analysis for resisting and destabilizing forces on the cantilever retaining wall as well as global stability calculations is shown in Table 2,3 and 4 respectively. Table 5, 6 and 7 presents the bending and shear calculations for the wall elements while figures 3, 4 and gives the geometry, body diagram and reinforcement detailing of the cantilever wall.

Table 1: Geotechnical properties of backfill and foundation soils

	Index properties				Shear strength parameters	
Sample	ρ_b (KN.m^{-3})	ρ_d (KN.m^{-3})	γ (KN.m^{-3})	ω (%)	C(kPa)	ϕ (deg)
PB1	1.60	1.49	15.69	7.4	1	28
PB 2	1.62	1.50	15.89	7.9	0	30
PB 3	1.58	1.49	15.49	6.3	1	29

FS 1	1.59	1.42	15.59	12.1	0	30
FS 2	1.63	1.5	15.99	11.7	0	30
FS 3	1.50	1.39	14.72	10.9	0	30

Table 2: Detailed Calculations of Resisting Forces on the Wall

Description		Force [KN]	Distance [m]	Moment [KN*m]
Weight of soil over heel (W1)		86.24	2.10	181.10
Weight of sloped soil over heel (W2)		2.66	2.33	6.21
Surcharge over heel (W3)		5.60	2.10	11.76
Weight of soil over toe (W5)		10.97	0.47	5.21
Stem weight (W7)		56.16	1.17	65.99
Base weight (W9)		30.24	1.40	42.34
Key weight (W10)		3.29	1.18	3.87
Total	195.17		316.48	
Vertical component of active pressure (Pav)		11.45	2.80	32.06
Toe horizontal soil pressure against sliding (Pp)		52.31	0.20	10.29
Toe horizontal soil pressure against overturning (Pp)		33.26	0.40	13.31

Table 3: Calculation of Destabilizing Forces on the Wall

Description	Force [KN]	Distance [m]	Moment [KN*m]
Heel horizontal soil pressure (Pah)	64.94	1.64	106.73
Wind force (Pw)	0.04	5.05	0.18

Table 4: Detailed Calculation for Global Stability

Load case [mm]	qu qnmax [N/m2]	Bear. Cap. [N/m2]	RM SF	OTM [KN*m]	Overt. [KN*m]	Res F SF	Slid F [KN]	Slid. Defl [KN]	SF
S1	234201.21	90622.44	2.38	318.02	106.73	2.98	114.86	64.94	1.77
	15.41								
S2	239855.08	89622.44	2.47	329.78	106.73	3.09	116.71	64.94	1.80
S3	233991.44	90761.57	2.37	318.02	106.91	2.97	114.86	64.97	1.77
S4	239646.80	89761.57	2.46	329.78	106.91	3.08	116.71	64.97	1.80
	16.25								

Element: Toe

Table 5: Bending and Shear Calculation for Toe

Nr.	**Station** Dist	**d** [mm]neg	**M**[KN*m] pos	neg	**Mr**[KN*m] pos	ext	**Asreq**[mm2] int	ext	**Asprov**[mm2] int	ext	**sb** int
1	0%	367.80-14.12	62.78	-128.79	83.72	101.38	449.18	919.83	585.80	133.05	177.80
	0.75										
2	10%	367.80-11.44	51.36	-115.38	74.86	82.12	367.49	819.83	522.11	133.05	177.80
	0.69										
3	20%	367.80-9.04	40.98	-101.82	65.94	64.88	293.24	719.82	458.42	133.05	177.80
	0.62										
4	30%	367.80-6.92	31.69	-88.12	56.96	49.68	226.72	619.82	394.74	133.05	177.80
	0.56										
5	40%	367.80-5.08	23.51	-74.27	47.92	36.50	168.19	519.81	331.05	133.05	177.80
	0.49										
6	50%	367.80-3.53	16.48	-60.28	38.82	25.34	117.92	419.81	267.36	133.05	177.80
	0.42										
7	60%	367.80-2.26	10.65	-46.15	29.67	16.22	76.19	319.80	203.67	133.05	177.80
	0.36										
8	70%	367.80-1.27	6.05	-31.88	24.52	9.12	43.26	219.80	139.98	133.05	177.80
	0.25										
9	80%	367.80-0.56	2.71	-24.52	24.52	0.00	0.00	119.80	76.29	133.05	177.80
	0.11										
10	90%	367.80-0.14	0.68	-24.52	24.52	0.00	0.00	19.79	12.60	133.05	177.80
	0.03										
11	100%	367.800.00	0.00	-24.52	24.52	0.00	0.00	0.00	0.00	--	--

C	0% 0.75	367.80-14.12	62.78	-128.79	83.72	101.38	449.18	919.83	585.80	133.05	177.80

Maximum allowed spacing between bars: 300.00 [mm]

Base transverse reinforcement:

Top reinforcement: 635.55 [mm^2]

Bottom reinforcement: 635.55 [mm^2]

Minimum shrinkage and temperature reinforcement: 585.00 [mm^2]

Element: Heel

Table 6: Bending and Shear Calculation for Heel

	Station	**d**	**M**[KN*m]		**Mr**[KN*m]		**Asreq**[mm2]		**Asprov**[mm2]		**sb**
Nr.	Dist	[mm]neg	pos	neg	pos	ext	int	ext	int	ext	int
1	0% 0.62	367.80-102.81	2.91	-165.07	90.61	738.17	20.85	1195.78	635.55	133.05	177.80
2	10% 0.53	367.80-83.42	0.64	-158.55	90.61	598.93	4.56	1145.57	635.55	133.05	177.80
3	20% 0.45	367.80-66.02	0.00	-147.08	90.61	474.02	0.00	1057.92	635.55	133.05	177.80
4	30% 0.38	67.80-50.63	0.00	-133.00	86.51	363.54	0.00	951.41	605.91	133.05	177.80
5	40% 0.33	367.80-37.26	0.00	-113.25	73.46	267.54	0.00	804.04	512.06	133.05	177.80
6	50% 0.28	367.80-25.92	0.00	-93.18	60.27	186.10	0.00	656.66	418.20	133.05	177.80
7	60% 0.23	367.80-16.62	0.00	-72.81	46.96	119.31	0.00	509.29	324.34	133.05	177.80
8	70% 0.18	367.80-9.36	0.00	-52.12	33.53	67.22	0.00	361.91	230.49	133.05	177.80
9	80% 0.13	367.80-4.17	0.00	-31.12	24.52	29.93	0.00	214.54	136.63	133.05	177.80
10	90% 0.04	367.80-1.04	0.00	-24.52	24.52	0.00	0.00	67.16	42.77	133.05	177.80
11	100%	367.800.00	0.00	-24.52	24.52	0.00	0.00	0.00	0.00	--	--
C	0% 0.62	367.80-102.81	2.91	-165.07	90.61	738.17	20.85	1195.78	635.55	133.05	177.80

Maximum allowed spacing between bars: 300.00 [mm]

Element: Stem (Block 1)

Table 7: Bending and Shear Calculation for Stem

	Station	**d**	**M**[KN*m]**Mr**[KN*m]		**Asreq**[mm2]		**Asprov**[mm2]		**sb** [mm]		**M**
Nr.	Dist	[mm]neg	pos	neg	pos	ext	int	ext	int	ext	int
1	0% 0.97	365.800.00	108.27	-24.52	111.30	0.00	778.90	0.00	791.34	--	254.00
2	10% 0.66	365.800.00	73.10	-24.52	111.30	0.00	525.86	0.00	791.34	--	254.00
3	20%	365.80	0.00	46.48	-24.52	111.30	0.00	334.39	0.00	791.34	--
4	30% 0.24	365.800.00	27.24	-24.52	111.30	0.00	195.95	0.00	791.34	--	254.00
5	40% 0.13	365.800.00	14.18	-24.52	111.30	0.00	101.99	0.00	791.34	--	254.00
6	50% 0.05	365.800.00	6.11	-24.52	111.30	0.00	43.99	0.00	791.34	--	254.00
7	60% 0.02	365.800.00	1.88	-24.52	111.30	0.00	13.52	0.00	791.34	--	254.00
8	70% 0.00	365.800.00	0.25	-24.52	111.30	0.00	1.80	0.00	791.34	--	254.00
9	80% 0.00	365.800.00	0.02	-24.52	85.67	0.00	0.12	0.00	603.40	--	254.00
10	90% 0.00	365.800.00	0.00	-24.52	40.10	0.00	0.03	0.00	277.84	--	254.00
11	100% 0.00	365.800.00	0.00	-24.52	24.52	0.00	0.00	0.00	0.00	--	254.00
C	0%	365.80	0.00	108.27	-24.52	111.30	0.00	778.90	0.00	791.34	--

Maximum allowed spacing between bars: 300.00 [mm]

Stem transverse reinforcement:
Exterior reinforcement: 0.00 [mm^2]
Interior reinforcement: 635.55 [mm^2]
Minimum shrinkage and temperature reinforcement: 585.00 [mm^2]

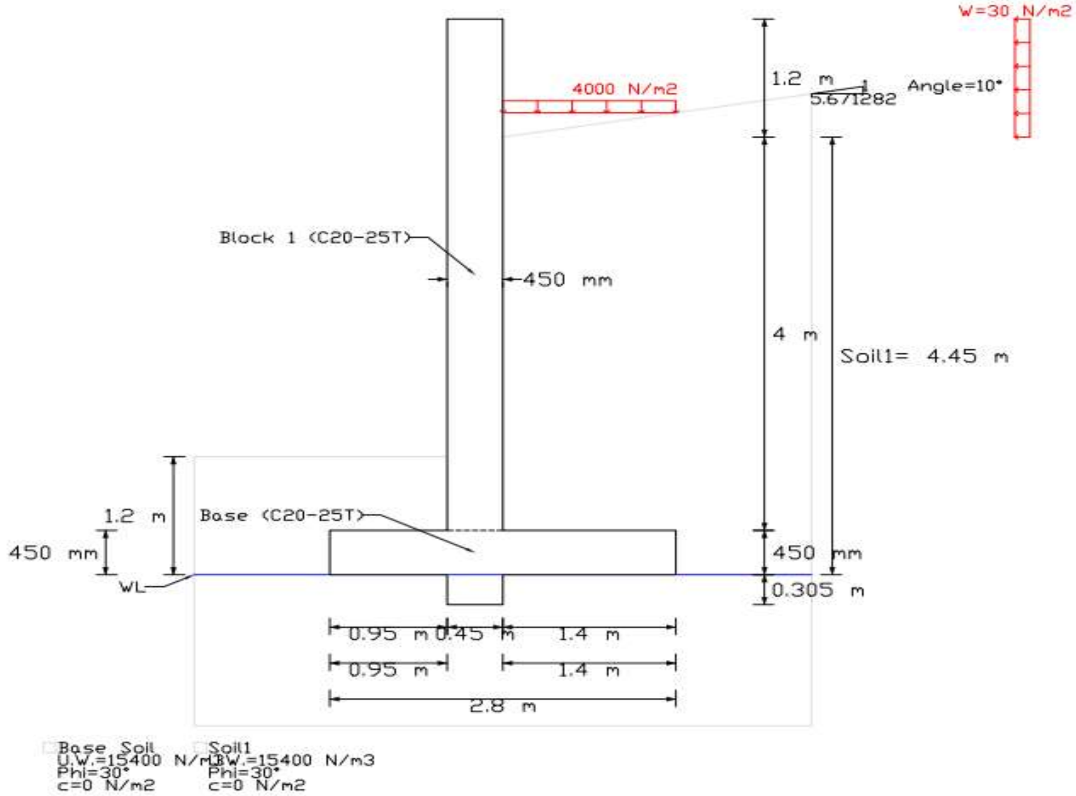

Figure 3: Geometry of the Cantilever Wall

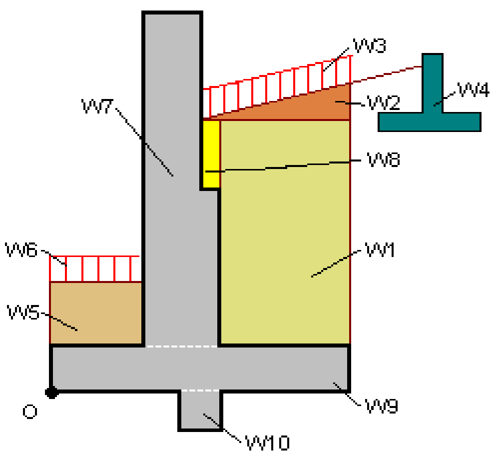

Figure 4: Resisting Forces on the Cantilever Retaining Wall

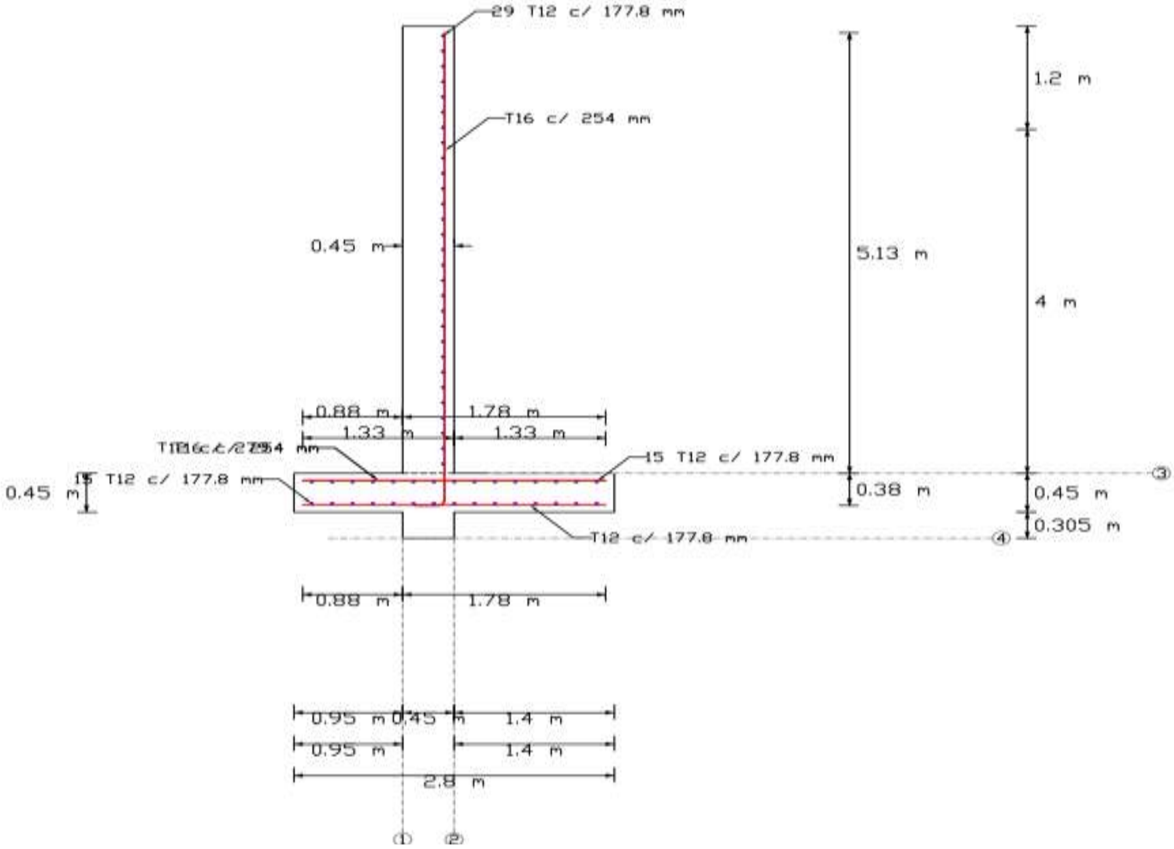

Figure 5: Detailed of Cantilever Retaining Wall

IV. DISCUSSION

The geotechnical properties of backfill and foundation soil materials are presented in Table 1. The results revealed that both the backfill materials and foundation soils have a very low value of internal friction angle and virtually no cohesion. The average value for internal friction angle is 30o while that of unit weight is 15.40 kN.m-3.

Based on the average angle of internal friction value of the foundation soil and the unit weight, the ultimate and allowable bearing capacities are 431.4 kN/m^2 and 172.6 kN/m^2 respectively. This value implies a good bearing capacity of the foundation soil.

q_u = 0*30.65 + 15.40*1*18.76 + 0.5*1*15.40*18.51 = **431.4 KN/m^2**

q_a = 431.4/2.5 = **172.6 KN/m^2**

The modulus of subgrade reaction *K* = 40*(2.5) *172.6 = **17260 KN/m^3**

The detailed analysis and design of the cantilever retaining wall of 4.0m height using the RAM Elements software is presented in Figure 3. The design is based on BS 8110-1:1997 (Amendments 2005) design code with C20 concrete grade and steel strength of 460 N/mm^2. The foundation depth was calculated using the relation:

$$D_f = \frac{q_a}{\gamma}\left(\frac{1-\sin\varphi}{1+\sin\varphi}\right)^2 = \frac{172.6}{15.40}\left(\frac{1-\sin 30}{1+\sin 30}\right)^2 = 11.2*0.11 = 1.2\text{m}$$

Overall height, H = 4.0 + 1.2 = 5.2m

Figure 3 shows the general geometry of the retaining wall including load conditions included in the design. The load combinations used in the design are: **Service Load Combinations:** S1 = DL+H, S2 = DL+LL+H, S3 = DL+W+H, S4 = DL+LL+W+H and **Strength Design Load Combinations:** R1 = 1.4DL, R2 = 1.2DL+1.6LL, R3 = 1.2DL+0.5W, R4 = 1.2DL+W, R5 = 1.2DL+W+LL, R6 = 0.9DL+W, R7 = 0.9DL+W+1.6H, R8 = 0.9DL+W+0.9H.

Figure 4 shows the body diagram of the cantilever retaining wall with various resisting forces on it. These include the self-weights of the wall components and total pressures from the soil materials.

The magnitude of various resisting forces on the wall is presented in Table 2 with a total force and moment of 195.17kN and 316.48 kNm respectively. The magnitude of vertical active pressure and toe horizontal pressures against sliding and overturning were also presented. The destabilizing or disturbing forces acting on the wall are the lateral or horizontal earth pressure and wind force. The magnitude of computed forces and moments are given in Table 3.

The global stability of the wall is defined by the allowable factor of safety against sliding, overturning and bearing capacity. The general computation based on service load combinations is shown in Table 4. The allowable factor of safety against overturning for the service load combinations S1, S2, S3 and S4 are 2.98, 3.09, 2.97 and 3.08 respectively. These values are above the allowable value of 1.5 and hence the stability against overturning is considered safe.

The factor of safety against sliding for S1, S2, S3 and S4 are 1.77, 1.80, 1.77 and 1.80 respectively. The values are also above the allowable factor of safety of 1.5 and hence the stability against sliding is safe. The same trend was also observed in the case of bearing capacity where the values are 2.38, 2.47, 2.37 and 2.46 which are above the range of 1.5 to 2 allowable safety factor for bearing capacity.

V. CONCLUSION

The use of a cantilever retaining wall as a solution for the continuous ecological problem in the study area has proven positive. Based on field measurement and laboratory data, the most economical and stable geometry of the wall was selected after different trials for section dimensions using the RAM-Elements software. The stability analysis and design based on different destabilizing and resisting forces acting on the wall have proven satisfactory. In conclusion, this investigation has provided a reliable solution for arresting further erosion and encroachment of land and buildings above the steep slope by water and other environmental agents.

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