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Optimization of Reinforced Concrete Retaining Walls of Varying Heights using Relieving Platforms

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Abstract— **During development of land, one often comes across with the challenge of creating a difference in terrain elevation over an arbitrary horizontal distance. This can often be done by creating slopes or by constructing retaining walls. Retaining walls are structures that are constructed to retail soil or any such materials which are unable to stand vertically by themselves.**

In this paper the study of the behaviour and optimal design of three types of reinforced concrete walls of varying heights namely cantilever retaining wall, counterfort retaining wall and retaining wall with relieving platforms is done. Cost against each optimal design of wall for particular height is calculated by using the volume of concrete and the amount of steel. Amidst the cost estimates of all the three optimal designs for particular height, a comparative study is carried out and the alternative with the least cost estimate is chosen as the best design solution.

Keywords- Reinforced concrete retaining walls, cantilever retaining wall, counterfort retaining wall, retaining wall with relieving platforms, optimal design

I. INTRODUCTION

A retaining wall is a structure designed to sustain the earth behind it. It retains a steep faced slope of an earth mass against rupture of slopes in cuts and fills and against sliding down. The retained material exerts a push on structure and this tends to overturn and slide it.

Besides the self-weight, the main predominant force for analysis and design of the retaining wall is lateral earth pressure. The lateral earth pressure behind the wall depends on the angle of internal friction and the cohesive strength of the retained material, as well as the direction and magnitude of movement of the stems. It's distribution is typically triangular, least at the top of the wall and increasing towards the bottom. The earth pressure could push the wall forward or overturn it if not properly addressed. Retaining walls are encountered and constructed in various fields of engineering such as roads, harbours, dams, subways, railroads, tunnels, mines, and military fortifications.

This paper deals with following three types of reinforced concrete retaining walls namely

1. Cantilever retaining wall: The wall consists of vertical stem and base slab made up of two distinct regions: heel slab and toe slab. These walls cantilever loads (like a beam) to a large, structural footing, converting horizontal pressures from behind the wall to vertical pressures on the ground below. Since the backfill acts on the base, providing most of the dead weight, the requirement of construction materials for this wall type is much less than a traditional gravity wall.
2. Counterfort retaining wall: To improve the resistance against lateral loads, sometimes cantilever retaining walls are provided with walls perpendicular to the stem. Introducing transverse supports reduces bending moments, when the heights are large thus decreasing the size of concrete components and steel requirements. In this study both back and front counterforts are provided. The counterforts subdivide the vertical slab into rectangular panels and support them on two sides and themselves behave essentially as vertical cantilever beams of T-section and varying depth.
3. Retaining wall with relieving platforms: The concept of providing pressure relief platforms towards the backfill side of retaining wall reduces the earth pressure on the wall which make the pressure diagram discontinuous at the level of the platform which results in reducing the thickness of the wall and ultimately to get an economic design. Also, the relieving platform carries the weight of the soil above it and any surcharge loading, transferring them as a 'relieving' moment to the vertical stem.

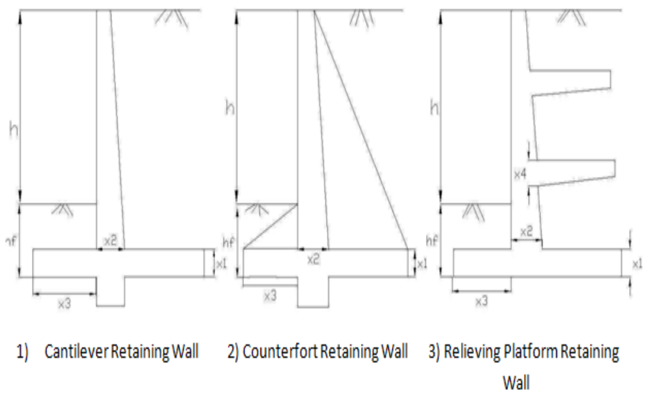

Fig.1 Types of Reinforced Concrete Retaining Walls

II OBJECTIVES

The primary objectives of the study are as under –

1. To study the behaviour of retaining wall through bending moment and shear force in various components.
2. To design the retaining wall for the optimal cost.
3. Cost comparison of all the three types of retaining walls and choosing the best alternative for particular height.
4. Providing approximate design equations for different design variables.

III. DESIGN OF RETAINING WALL

Technically while designing, all the necessary parameters and requirements (if any) are considered and all the possible solutions are generated. Then a thorough analysis and calculations are carried out considering all the parameters especially cost involved and the risk and the uncertainties involved. Then the solution with the optimal cost is chosen as the best solution. Thus, it is overall a rigorous decision making process.

The design of retaining wall includes the following steps:
1. Fixation of the base width and other wall dimensions
2. Performing stability checks and computation of maximum and minimum bearing pressures.
3. Design of various parts like stem, toe slab, heel slab, relieving platforms, back counterfort and front counterfort.

TABLE I RETAINING WALL DESIGN INPUT PARAMETERS

Coefficient of active earth pressure, Ca	0.333
Coefficient of passive earth pressure, Cp	3
Depth of foundation, hf	1.2 m
Equivalent height of surcharge, h_1	1.2 m
Safe bearing capacity	150 kN/m^2
Angle of friction of backfill, ϕ	30 °
Coefficient of friction at base of the wall, μ	0.5
Grade of concrete, fck	M25
Grade of steel, fy	Fe500
Unit weight of soil, γ_s	18 kN/m^3
Unit weight of concrete, γ_c	25 kN/m^3

In design of retaining wall, Rankine's theory is used for calculation of coefficient of lateral earth pressure. In design of cantilever and counterfort retaining wall, a shear key is provided at the base except for three 3 m height of retaining wall. In case of retaining wall with relieving platform, two relieving platforms are taken up to height of 7 m and above 7 m three relieving platforms are taken in the design to achieve economical design. The relieving platforms are provided at H/3 height.

Where H = Height of retaining wall + depth of foundation + height of surcharge

Curtailment of bars is done at h/3 and 2h/3 height of retaining wall.

Where h = Height of retaining wall + depth of foundation

For the analysis purpose three reinforced concrete retaining walls namely cantilever retaining wall, counterfort retaining wall and retaining wall with relieving platforms with height ranging from 3 m to 15 m with interval of 2 m are considered except cantilever retaining wall with 15m as safe bearing capacity used in the design is 150 kN/m^2 which is less. Length of relieving platform is kept equal to length heel slab for analysis purpose.

IV. DESIGN DIMENSION VARIABLES

Figure1 shows the design dimension variables of three types of reinforced concrete retaining walls with varying heights.

1. Cantilever Retaining Wall

Thickness of base slab (x1); thickness of stem at the bottom (x2); length of toe slab (x3)

2. Counterfort Retaining Wall

Thickness of base slab (x1); thickness of stem at the bottom (x2); length of toe slab (x3); thickness of counterfort (x4); Spacing between counterforts (x5)

3. Retaining Wall with Relieving Platforms

Thickness of base slab (x1); thickness of stem at the bottom (x2); length of toe slab (x3); thickness of relieving platform (x4)

V. STABILITY CHECKS

The following stability checks are used in the design of retaining wall:

1. Eccentricity of the resultant reaction force should lie between 0 and base width/6.
2. Factor of safety against sliding is taken greater than 1.5.
3. Factor of safety against overturning is also taken greater than 1.5.
4. The maximum and minimum bearing pressure is taken greater than 0 and less than safe bearing capacity.
5. Maximum and minimum reinforcement percentage and reinforcement spacing is taken as per IS 456:2000 Code.
6. Restrictions on maximum shear stress in different parts are based on concrete grade as per IS 456:2000 code.

VI. FORMULA FOR OPTIMAL COST DESIGN

As mentioned in the objective, the design with the optimal cost is chosen as the best solution, the formula involved in calculation of the optimal cost is given below:

Optimal Cost = (Volume of concrete * Cost of concrete per m^3) + (Amount of steel in kg *cost of steel per kg)

VII. RESULTS AND DISCUSSIONS

In the present study, the behaviour of retaining walls is studied and cost comparison is done for three types of retaining wall of varying heights. The results are compared in tabular form and graphically for the analysis of the retaining wall

A. *Variation of Bending moment with height*

From table 2 and figure 2, it is evident that in case of cantilever retaining wall bending moment increases with increase in the height of the retaining wall because with increase in height lateral earth pressure increases resulting in increase in bending moment. The percentage increase in the bending moment in stem, toe and heel varies from 64.2% - 172.5%, 62.1% - 504.5% and 39.6% - 170.8%.

TABLE II BENDING MOMENT IN VARIOUS COMPONENTS OF CANTILEVER RETAINING WALL

Height of Retaining wall (m)	Bending moment in stem (kN-m)	Bending moment in toe (kN-m)	Bending moment in heel (kN-m)
3	170.942	36.8	91.23
5	467.464	222.577	247.058
7	960.881	550.491	474.699
9	1758.96	1036.705	951.207
11	2830.19	1680.057	1683.307
15	4358.744	2811.87	2349.926

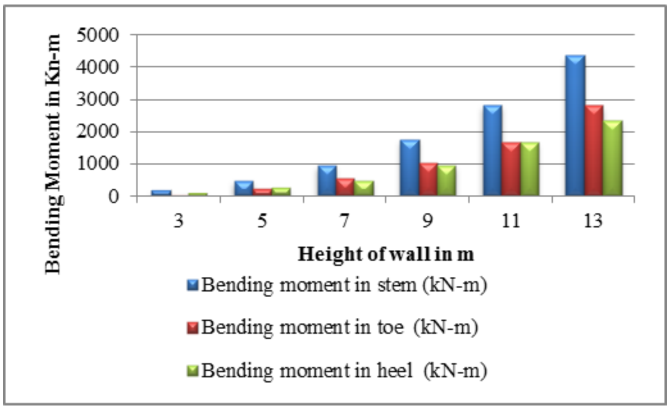

Fig.2 Bending moment in various components of Cantilever Retaining Wall

From table 3 and figure 3, it is evident that in counterfort retaining wall bending moment increases with increase in the height of the retaining wall in case of back counterfort and front counterfort whereas bending moment decreases in case of toe slab and heel slab. In stem bending moment increases up to a height of 9m then decreases because as the height increases thickness of counterfort increases and spacing between counterforts decreases.

TABLE III BENDING MOMENT IN VARIOUS COMPONENTS OF COUNTERFORT RETAINING WALL

Height of Retaining wall (m)	Bending Moment (kN-m)				
	Stem	Toe slab	Heel slab	Back counter -fort	Front counter -fort
3	20.76	96.166	58.929	221.638	78.07
5	28.094	93.824	65.364	795.799	443.754
7	32.361	84.369	53.061	1906.89	988.555
9	37.446	80.24	46.843	3670.486	1899.488
11	36.843	66.323	46.646	6141.615	3542.535
13	23.989	37.258	45.954	8660.018	6468.78
15	21.526	29.431	41.625	12856	9852.375

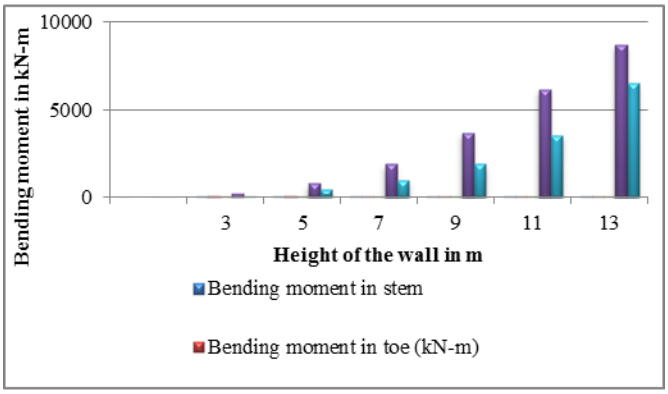

Fig.3 Bending moment in various components of Counterfort Retaining Wall

From table 4 and figure 4, it is evident that in case of retaining wall with relieving platforms bending moment in each component increases with increase in the height of the retaining wall except in stem and relieving platform in the case of retaining wall of 9 m height because in 9 m number of relieving platforms are increased from 2 to 3. The percentage increase in the bending moment in stem, toe, heel and relieving platform varies from 61.2% - 324.75%, 56.4% - 319.1%, 4.4% - 203.1% and 18.4% - 114.2%

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TABLE IV BENDING MOMENT IN VARIOUS COMPONENTS OF RETAINING WALL WITH RELIEVING PLATFORMS

Height of Retaining wall (m)	Bending Moment (kN-m)			
	Stem	Toe slab	Heel slab	Relieving platforms
3	22.845	20.269	9.57	26.436
5	97.035	84.93	17.05	56.274
7	224.88	207.24	51.677	120.54
9	216.6	310.549	146.568	118.023
11	582.9	611.586	155.412	152.139
13	1054.73	1036.15	166.028	188.155
15	1699.5	1619.98	173.2	222.731

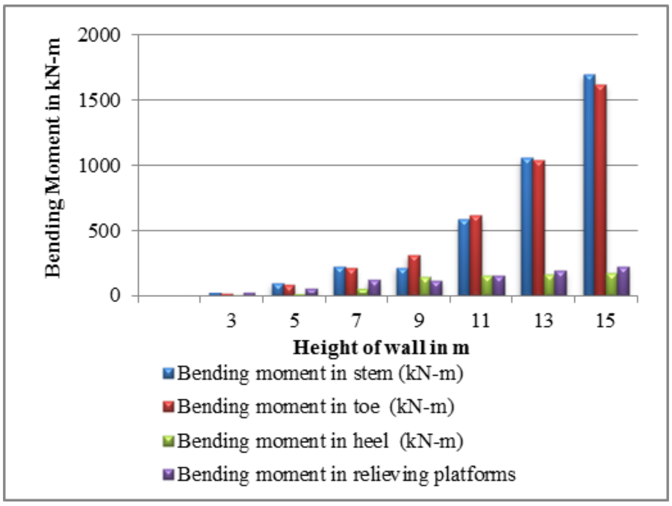

Fig.4 Bending moment in various components of Retaining Wall with Relieving Platforms

B. Variation of Shear force with height

From table 5 and figure 5, it is evident that in case of cantilever retaining wall shear force increases with increase in the height of the retaining wall because with increase in height lateral earth pressure increases resulting in increase in shear force. The percentage increase in the shear force in stem, toe and heel varies from 33.3% - 91.75%, 30.9% - 128.9% and 26.6% - 93.5%.

TABLE V SHEAR FORCE IN VARIOUS COMPONENTS OF CANTILEVER RETAINING WALL

Height of Retaining wall (m)	Shear force (kN)		
	Shear force in stem (kN-m)	Shear force in toe (kN-m)	Shear force in heel (kN-m)
3	110.684	114.009	127.486
5	212.236	260.892	246.694
7	338.1067	412.142	368.037
9	500.072	571.768	497.686
11	695.949	779.437	685.543
13	927.655	1019.738	867.493

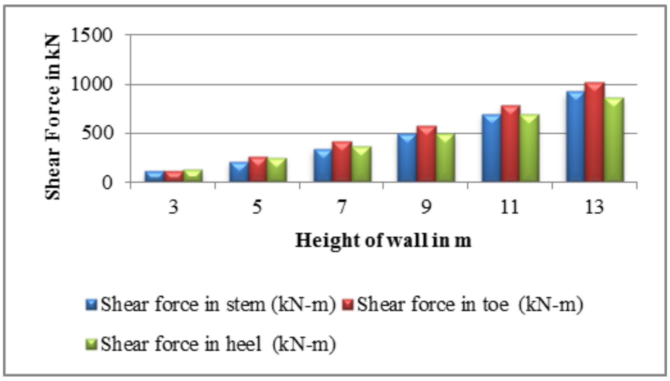

Fig.5 Shear force in various components of Cantilever Retaining Wall

From table 6 and figure 6, it is proved that in counterfort retaining wall shear force increases with increase in the height of the retaining wall in heel slab, back counterfort and front counterfort. In case of stem shear force increases up to a height of 11m and then decreases because as the height increases thickness of counterfort increases and spacing between counterforts decreases. Similarly, in case of toe slab shear force increases up to a height of 9m and then decreases.

TABLE VI SHEAR FORCE IN VARIOUS COMPONENTS OF COUNTERFORT RETAINING WALL

Height of Retaining wall (m)	Shear force in kN				
	Stem	Toe slab	Heel slab	Back counter-fort	Front counterfort
3	53.805	249.113	65.523	181.34	81.663
5	73.608	245.826	111.956	410.844	165.62
7	89.271	232.74	112.313	724.72	315.369
9	105.979	227.121	120.11	1106.972	509.483
11	113.945	205.121	142.296	1537.32	731.817
13	98.583	153.116	274.143	1854	765.497
15	93.351	135.835	282.732	2405.31	1008.46

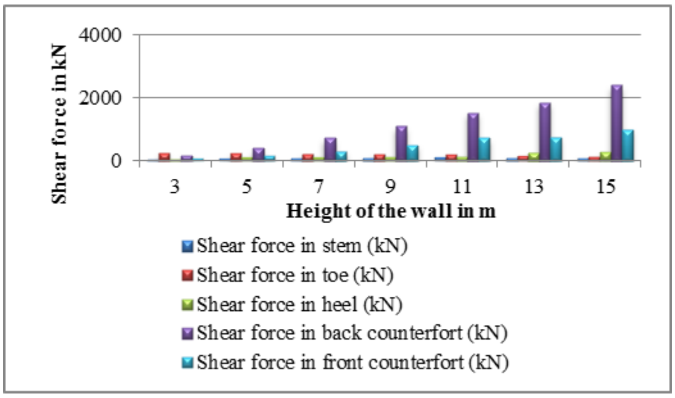

Fig.6 Shear force in various components of Counterfort Retaining Wall

From table 6 and figure 6, it is evident that in case of retaining wall with relieving platforms shear force in each component increases with increase in the height of the retaining wall except in relieving platform in the case of retaining wall of 9 m height because in 9 m number of relieving platforms are increased from 2 to 3. The percentage increase in the bending moment in stem, toe, heel and relieving platform varies from 8.9% - 100.7%, 25.8% - 116.6%, 0.5% - 75.3% and 15.3% - 72.1%.

TABLE VII SHEAR FORCE IN VARIOUS COMPONENTS OF RETAINING WALL WITH RELIEVING PLATFORMS

Height of Retaining wall (m)	Shear force in kN			
	Stem	Toe slab	Heel slab	Relieving platform
3	34.715	77.621	32.665	53.405
5	69.675	168.124	42.185	91.875
7	117.05	274.792	78.417	152.101
9	127.482	345.503	180.337	141.345
11	177.675	482.107	180.632	173.873
13	238.473	633.104	183.868	206.763
15	307.005	797.849	185.278	238.215

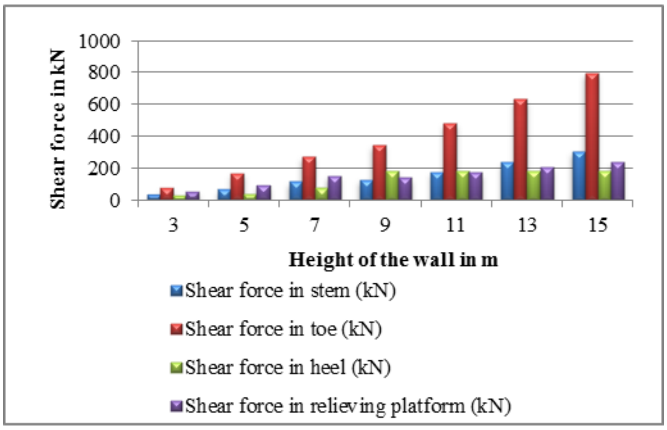

Fig.7 Shear force in various components of Retaining wall with relieving platforms

C. *Comparison of Optimal Cost*

It is very evident from Tables 8, 9 and 10 and figures 8, 9 and 10 that the optimal cost increases with increase in height for all the three types of retaining walls, but the increase in optimal cost may vary from wall to wall. Among all the cases the optimal cost required is least in case of retaining wall with relieving platform because presence of relief platforms towards the backfill side of retaining wall reduces the earth pressure on the wall which make the pressure diagram discontinuous at the level of the platform which results in reducing the thickness of the wall and ultimately to get an economic design.

The percentage reduction in retaining walls with relieving platform from counterfort retaining wall varies from 2% to 48% for all heights. While the reduction in retaining walls with relieving platform from cantilever retaining wall varies from 31% to 52% for all heights respectively.

TABLE VIII COMPARISON OF OPTIMAL COST

Height of Retaining wall (m)	Optimal cost in Rs		
	Cantilever retaining wall	Counterfort retaining wall	Retaining wall with relieving platforms
3	13410	11999	9160
5	29666	23817	19026
7	53964	36842	35859
9	96167	58929	53735
11	142574	90560	73794
13	199583	166280	101573
15		250626	135896

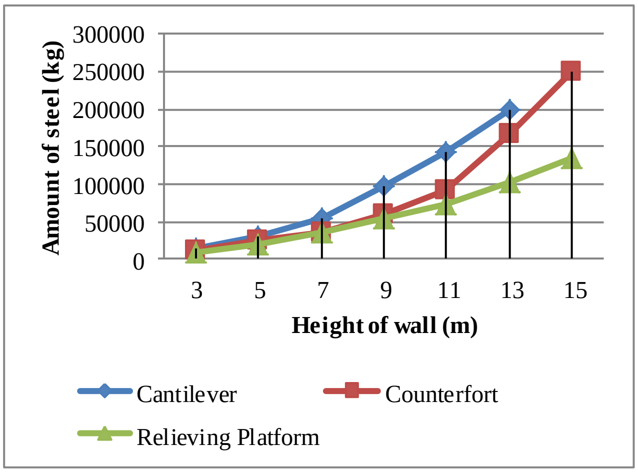

Fig. 8 Comparison of Optimal cost

Fig.8 Shear force in various components of Retaining wall with relieving platforms

D. *Approximate Design Equations*

Based on optimal solution obtained from all types of the wall, several approximate design equations are made for design dimension variables given in tables 9, 10, 11 and 12 and figures 9, 10 and 11.

TABLE IX DIMENSIONS FOR OPTIMAL SOLUTION FOR CANTILEVER RETAINING WALL

Height of Retaining wall (m)	x1	x2	x3	l
3	0.3	0.32	0.62	2.7
5	0.43	0.545	1.63	4
7	0.625	0.715	2.49	5.51
9	0.725	0.965	3.53	7.7
11	0.93	1.115	4.26	9.4
13	1.03	1.395	5.55	11.13

Where x1, x2, x3 and l are base slab thickness, thickness of stem at the bottom, toe slab length and length of retaining wall.

TABLE X DIMENSIONS FOR OPTIMAL SOLUTION FOR COUNTERFORT RETAINING WALL

Height of Retaining wall (m)	x1	x2	x3	x4	x5	l
3	0.22	0.18	0.56	0.175	2.49	2.7
5	0.255	0.22	1.36	0.18	2.47	4
7	0.27	0.23	2	0.275	2.45	5.77
9	028	0.295	2.75	0.28	2.4	7.65
11	0.335	0.32	3.81	0.38	2.32	9.1
13	0.38	0.36	5.64	0.6	2.06	9.93
15	0.4	0.4	6.92	0.74	2	11.57

Where x1, x2, x3, x4, x5 and l are base slab thickness, thickness of stem at the bottom, toe slab length, counterfort thickness, counterfort spacing and length of retaining wall.

TABLE XI DIMENSIONS FOR OPTIMAL SOLUTION FOR RETAINING WALL WITH RELIEVING PLATFORMS

Height of Retaining wall (m)	x1	x2	x3	x4	l
3	0.165	0.2	0.5	0.185	1.66
5	0.28	0.315	0.96	0.25	2.5
7	0.33	0.465	1.45	0.36	3.5
9	052	0.63	1.77	0.26	4.07
11	0.65	0.635	2.505	0.325	4.89
13	0.685	0.7	3.25	0.365	5.77
15	0.75	078	4.06	0.38	6.71

Where x1, x2, x3 and l are base slab thickness, thickness of stem at the bottom, toe slab length, relieving platform and length of retaining wall.

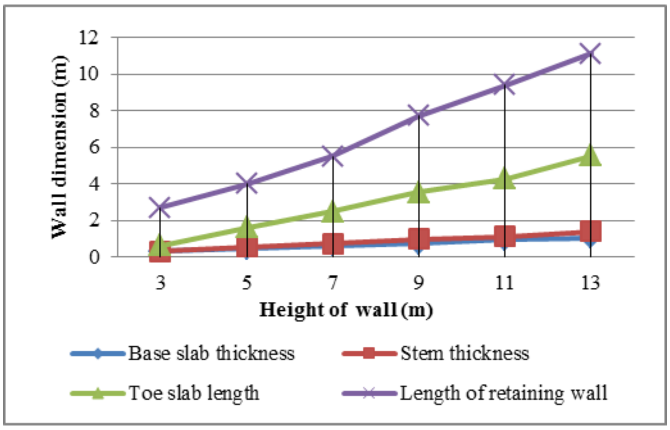

Fig.9 Dimensions for optimal solution for cantilever retaining wall

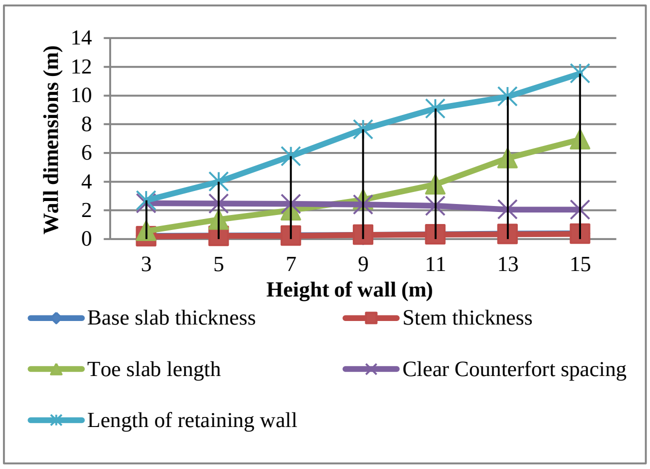

Fig.10 Dimensions for optimal solution for counterfort retaining wall

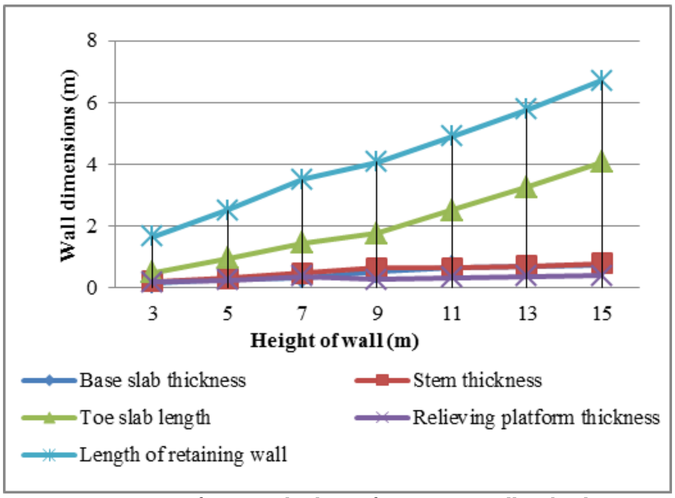

Fig.11 Dimensions for optimal solution for retaining wall with relieving platforms

TABLE XII APPROXIMATE DESIGN EQUATIONS FOR DESIGN DIMENSION VARIABLE

Wall/Slab thickness	**Approximate design equations**
1. Cantilever retaining wall	
Base slab thickness x1, m	0.15 h + 0.1483
Stem base thickness x2, m	0.2096 h + 0.109
Toe slab length x3, m	0.962 h - 0.3587
Length of retaining wall (l), m	1.405 h + 1.26, for h < 8 m 1.715 h + 5.98, for h >8 m
2. Counterfort retaining wall	
Base slab thickness x1, m	0.017 h + 0.215, for h < 9 m 0.0405 h + 0.2475, for h > 9 m
Stem base thickness x2, m	0.04 h + 0.14, for h< 6m 0.0215 h + 0.275, for h> 6 m
Toe slab thickness x3, m	0.721 h - 0.135, for h < 9 m 1.565 h + 2.3333 , for h > 9 m
Counterfort thickness x4, m	0.005 h + 0.27, for h= 3 m – 5 m and 7 m – 9 m 0.095 h + 0.085, for h= 5 m -7 m 0.16 h + 0.1, for h > 9 m
Counterfort spacing x5, m	-0.0811 h + 2.6443
Length of retaining wall l, m	1.4896 h + 1.2829
3. Retaining wall with relieving platform	
Base slab thickness x1, m	0.103 h + 0.0707
Stem base thickness x2, m	0.1325 h + 0.0617, for h< 8m 0.0515 h + 0.5575, for h> 8 m
Toe slab thickness x3, m	0.475 h + 0.02, for h < 8 m 0.7615 h + 0.9925, for h > 8 m
Relieving platform x4, m	0.0875 h + 0.09, for h < 8 m 0.04 h + 0.2325, for h > 8 m
Length of retaining wall l, m	0.8243 h + 0.86

VIII. CONCLUSIONS

The following conclusions are made from the present study:

1. The retaining wall with relieving platform is proved to be most cost effective and advantageous over the cantilever and counterfort retaining wall.
2. Due to discontinuous lateral earth pressure diagram in case of retaining wall with relieving platform, there is better stability in the retaining wall.
3. Reduction in cross-sectional in retaining wall with relieving platforms area reduces the requirement of the construction material like volume of concrete and amount of steel thus reducing overall cost.

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