Optimal design of reinforced concrete retaining walls

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This paper aims at developing an understanding of optimal design solutions for three types of reinforced concrete retaining walls, namely, cantilever retaining walls, counterfort retaining walls and retaining walls with relieving platforms. Using genetic algorithms, parametric studies were carried out to establish heuristic rules for proportioning the wall dimensions corresponding to the minimum cost points. Optimal cost-estimates of the retaining walls types were compared to establish the best design alternative for a given height. Also, the advantages of retaining walls with relieving platforms, which are relatively new in India, are discussed.

Keywords: *Reinforced concrete retaining walls; optimal design; relieving platforms; cantilever walls; counterfort walls; genetic algorithms.*

Introduction

The design of retaining wall almost always involves decision making with a choice or set of choices along with their associated uncertainties and outcomes. While designing such structures, a designer may propose a large number of feasible designs; however, professional considerations require that only the most optimal one, with the least cost be chosen for construction. For delivering an acceptable design, today's design practitioners increasingly rely on PC based programs that require parameters, such as toe or heel lengths and stem widths. The process invariably involves a trial and error procedure. Obtaining a satisfactory design per se, does reveal its cost position against the optimal design. The present study therefore aims at developing an optimal design solution for reinforced concrete retaining walls, namely, *cantilever* retaining walls, *counterfort* retaining walls and retaining walls with *relieving platforms*, in terms of minimum cost as per the IS456:2000 code.[1] In this connection, this paper discusses the heuristic rules for the required wall dimensions. Incidentally, it may be noted that one of the wall types studied is the retaining walls with relieving platforms. This wall type provides an innovative design alternative and is common in Europe, but relatively new to India.

The scope of this study was confined to retaining walls ranging from 5 m to 23 m height. Any surcharge was converted to an equivalent height and included in the heuristic rules. The study assumed that proper drainage conditions. However, the effect of earthquake loading was excluded, as the scope was limited to incorporating the effects of gravity loading. The reason for doing so was to insulate the design outcome from the complexities that arise from the seismic zoning of sites, for example, moderate or high seismic zone.

Types of retaining walls

It is well known that retaining walls are structures that hold back soil or rock from a building, structure or area.[2] They prevent down-slope movement or erosion and provide support for vertical or near-vertical grade changes. 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 of the retaining walls. Its 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. Also, the groundwater behind the wall should be dissipated by a suitable drainage system; otherwise, this could lead to an additional horizontal pressure on the wall. Although the effect of surcharge loading was not explicitly considered here, it can be approximated as an equivalent height of retained earth.

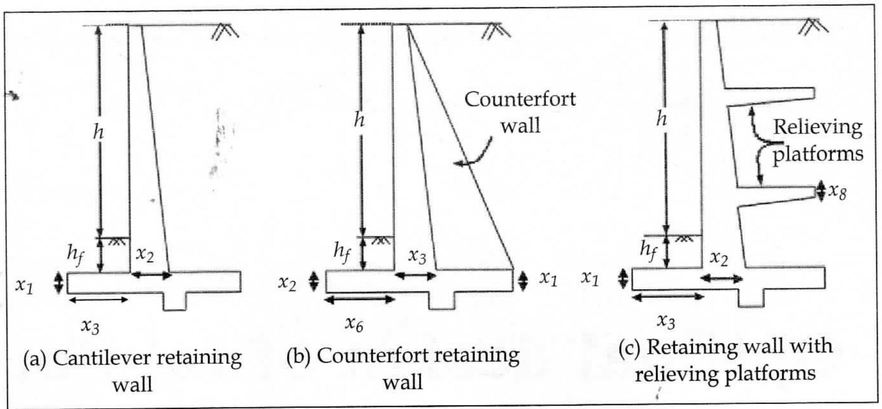

Figure 1. Types of concrete retaining walls

As stated earlier, this study deals with the following types of retaining walls:

- Cantilever retaining wall: Such walls transmit loads from the vertical portion, through the cantilever action, to a large structural footing, converting horizontal pressures from behind the wall to vertical pressures on the ground below. This wall type is believed to be economical up to a height of about 7 m (Figure 1a). 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: Cantilever retaining walls, sometimes, include short wing walls at right angles to the main trend of the wall on their back, to improve their resistance to lateral loads. Introducing transverse supports reduces bending moments, when the heights are large. Such supports, called counterforts, connect the stem with the heel slab. This wall type is believed to be economical for heights greater than 7 m (Figure 1b)[2].
- Retaining wall with relieving platforms: When the depth of soil to be retained is excessive, soil pressures can be reduced by the use of a relieving platform[3]. Retaining wall with relieving platforms is relatively new to Indian construction industry. Such walls are known to provide an economical lightweight design solution for relatively tall walls.[4,5] The retaining wall is shielded from active earth pressure by means of one or more relieving platforms (Figure 1c) which make the pressure diagram discontinuous at the level of the platform. 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. The relieving platforms are designed such that they intersect the plane of rupture from the soil above and behind the platforms preventing any load from the soil to act on the wall. This aspect is the key to designing such walls.

Typically, a retaining wall design includes[2]:

- Performing stability checks for the retaining wall against sliding and overturning.
- Computing the maximum and minimum bearing pressures present under the toe and heel and comparing them with the allowable soil pressure.
- Designing the reinforcing steel for the toe, heel, stem and other parts considering the corresponding bending and shear forces.

Estimation of earth pressure

Two classical theories are used for estimating the lateral earth-pressures: [5]

- Rankine's theory
- Coulomb's theory

Table 1. Comparison of results obtained from designs following Rankine's and Coulomb's theories

Parameter	Rankine's theory	Coulomb's theory
Cact	0.373	0.240
Cpas	2.502	5.789
Footing length, m	4.4	3.6
Concrete weight, kN/m	154.2	140.1
Reinforcement, m^3/m	0.037	0.046
Cost estimate, Rs/m	53,531	44,480

(For a cantilever retaining wall of height 7 m above ground level with SBC=200 kN/m^2; th=25°; fi=37°; thw=15°; mu=0.5; fck=25MPa; fy = 415MPa; Cact and Cpas are the active and passive coefficients)

While Rankine's theory considers the back of the wall to be perfectly smooth, Coulomb's theory considers the existence of friction between the wall and the backfill.[5,6] A designer may find the Rankine's design approach simpler and the one that gives a more conservative design, but Coulomb's design is seen as more practical one since it involves real life scenario – the friction between the wall and the backfill. The Coulomb's design approach gives a cost-effective design as compared to Rankine's design approach, and the extent of savings could be as high as 20 percent in some instances.[7] Table 1 compares the results obtained from these two design approaches.

In view of the above, this paper follows the Coulomb's design approach for optimising the genetic algorithm.

Formulation for optimal design

Since the purpose of optimization in this study was to minimize the cost, the objective function included in the formulation were the material costs of concrete and steel, the carriage cost of steel, the cost of centering and shuttering and the cost of excavation.

Minimize cost,

$$C_r = 1.1\,(V_cR_c + V_sR_s + V_eR_e + V_sR_{cc} + L_{cs}R_{cs}) \quad ......(1)$$

where

V_c, V_s, V_e= volumes of concrete, steel and excavation respectively

L_{cs}= length of centering and shuttering provided

R_c, R_s, R_e, R_{cc}, R_{cs} = unit costs of concrete, steel, excavation, steel carriage and centering and shuttering respectively

To arrive at the total, a 10 percent addition to the cost was made to account for the various uncertainties in the assumptions. The costs considered were based on the Delhi Schedule of Rates 2007.

Design inputs

1. Site conditions : h, h_f, th_w
2. Soil properties : SBC, *mu*, *fi*, *th*
3. Material properties : f_{ck}, f_y, d_c, d_s

Where h, h_f and th_w are respectively the height of the retained soil on the heel side of the retaining wall, height of the soil on the toe side of the retaining wall and backfill slope; SBC, *mu*, *fi* and *th* are the safe bearing capacity of the soil, coefficient of friction at the base of the wall, angle of friction of the backfill and angle of friction between the wall and backfill respectively; f_{ck} and f_y are the grades of concrete and steel; d_c and d_s the densities of concrete and steel respectively.

Design variables

Figure 1 shows the design variables considered for various types of retaining walls, the same are listed below:

1. Cantilever retaining wall

Footing thickness (x_1); stem thickness at the bottom (x_2); toe slab length (x_3); bar diameters in the toe slab, heel slab and stem respectively (x_4, x_5 and x_6) (Not in Figure 1)

2. Counterfort retaining wall

Heel slab thickness (x_1); toe slab thickness (x_2); stem thickness at the bottom (x_3); counterfort thickness (x_4); counterfort spacing (x_5); toe slab length (x_6); bar diameters of the main reinforcement in the toe slab, heel slab and stem respectively (x_7, x_8, x_9 and x_{10}) (not marked in Figure 1b)

3. Retaining wall with relieving platforms

Footing thickness (x_1); stem thickness at the bottom (x_2); toe slab length (x_3); bar diameters in the toe slab, heel slab, stem and relieving platform respectively (x_4, x_5, x_6 and x_7); relieving platform thickness (x_8).

Design constraints

The following design constraints were imposed on the variables:

1. Factor of safety against overturning > 1.4
2. Factor of safety against sliding > 1.4

Table 2 Cantilever retaining walls – optimal solutions for various heights

h, m	h_f, m	x_1, m	x_2, m	x_3, m	C, mm^2	B, mm^2	A, mm^2	l, m	C_o, Rs.	C_t, Rs.	Savings, %
5	1.25	0.28	0.45	0.52	499	1244	1748	2.32	25316	33182	23.7
6	1.25	0.33	0.53	0.73	928	1293	2215	2.83	32574	42631	23.6
7	1.25	0.38	0.62	0.96	1525	1340	2682	3.3	41140	53531	23.1
8	1.25	0.45	0.71	1.21	2012	1305	3186	3.83	51147	66166	22.7
9	1.25	0.52	0.79	1.48	2623	1311	3821	4.38	62853	82828	24.1
10	1.25	0.6	0.89	1.75	3192	1289	4365	4.92	76295	100791	24.3
11	1.25	0.72	1.00	2.04	3289	1182	4813	5.48	91497	123585	25.9
12	1.25	0.78	1.10	2.35	4397	1224	5471	6.06	108617	147208	26.2
13	1.25	0.91	1.22	2.67	4594	1163	5945	6.64	128518	182064	29.4
14	1.25	1.02	1.33	3.00	5167	1172	6539	7.24	149741	214338	30.1

C, B, A = areas of steel in the toe slab, heel slab and stem respectively in mm^2/m, as shown in Figure 2; l = length of the base slab in m
C_t= traditional cost of construction of the wall per unit length in Rs/m; C_o= optimal cost obtained from GA coding per unit length in Rs/m

Table 3. Counterfort retaining walls – optimal solutions for varies heights

h, m	hf, m	x_1, m	x_2, m	x_3, m	x_4, m	x_5, m	x_6, m	l, m
5	1.25	0.25	0.26	0.33	0.2	2.47	0.46	2.32
6	1.25	0.28	0.33	0.35	0.21	2.52	0.66	2.82
7	1.25	0.29	0.4	0.37	0.24	2.56	0.93	3.38
8	1.25	0.3	0.47	0.39	0.27	2.6	1.12	3.87
9	1.25	0.31	0.56	0.41	0.3	2.63	1.39	4.44
10	1.25	0.32	0.65	0.43	0.34	2.65	1.66	5
11	1.25	0.33	0.74	0.45	0.4	2.68	1.95	5.59
12	1.25	0.34	0.84	0.46	0.48	2.7	2.26	6.19
13	1.25	0.36	0.94	0.47	0.54	2.71	2.58	6.81
14	1.25	0.38	1.04	0.49	0.62	2.73	2.91	7.43

h, m	A, mm^2	B, mm^2	C, mm^2	D, mm^2	E, mm^2	F, mm^2	G, mm^2	H, mm^2	C_o, Rs.	C_t, Rs.	Savings, %
5	450	782	578	300	396	396	396	1237	37006	40422	8.4
6	675	820	580	336	420	420	420	1684	47161	51625	8.6
7	1088	798	567	348	444	444	444	2216	58595	63908	8.3
8	1443	924	616	360	468	468	468	2834	71499	78087	8.4
9	1776	874	598	372	492	492	492	3528	85997	94258	8.7
10	2162	836	597	384	516	516	516	4312	102559	113441	9.6
11	2701	796	572	396	540	540	540	5239	120863	133719	9.6
12	3187	751	569	416	552	552	552	6220	140847	158042	10.9
13	3770	692	526	448	564	564	564	7353	164057	186047	11.8
14	4402	653	504	480	588	588	588	8652	189504	216805	12.6

l = length of base in m; A = area of steel reinforcement in toe slab, as shown in Figure 3(a) in mm^2/m; B, C = top reinforcement near the counterfort and bottom reinforcement at the middle of heel slab 1m from the end, due to continuous beam action; D = top reinforcement in heel slab, due to cantilever action; E, F = rear and front face reinforcements in stem, due to continuous beam action; G = rear face reinforcement in stem, due to cantilever action; H= counterfort reinforcement, as shown in Figure 3(b) in mm^2/m; C_t = traditional cost of construction of the wall per unit length in Rupees/m; C_o= optimal cost obtained from GA coding per unit length in Rupees/m

Table 4. Retaining walls with relieving platform – optimal solutions for varies heights

h, m	hf, m	x_1, m	x_2, m	x_3, m	x_8, m	A, mm^2	B, mm^2	C, mm^2	D, mm^2	*l*, m	C_o, Rs.	C_t, Rs.	Savings, %
5	1.25	0.32	0.39	0.74	0.20	474	1923	673	1812	2.56	25826	28893	10.7
6	1.25	0.40	0.48	0.86	0.22	565	2549	916	2146	2.96	33464	36827	9.2
7	1.25	0.49	0.56	0.98	0.24	658	3340	1203	2620	3.35	42651	46428	8.2
8	1.25	0.58	0.67	1.09	0.29	762	4228	1323	2966	3.72	53601	56436	5.1
9	1.25	0.65	0.80	1.32	0.34	1010	5100	1604	3235	4.21	66208	69326	4.5
10	1.25	0.71	0.96	1.60	0.39	1343	5830	1963	3413	4.75	80898	85825	5.8
11	1.25	0.81	1.08	1.90	0.44	1637	6365	2413	3858	5.31	97591	100095	2.6
12	1.25	0.90	1.25	2.20	0.50	2085	6592	2833	4098	5.87	116161	122096	4.9
13	1.25	0.97	1.38	2.53	0.57	2814	7495	3232	4562	6.45	137185	142397	3.7
14	1.25	1.08	1.51	2.86	0.64	3328	7962	3712	5051	7.04	159210	168705	5.7
15	1.25	1.18	1.67	3.22	0.71	4050	8198	4274	5455	7.65	186107	201869	7.9
16	1.25	1.28	1.81	3.58	0.80	4863	8763	4732	5963	8.27	214234	236542	9.5
17	1.25	1.39	1.96	3.96	0.89	5706	9132	5271	6472	8.91	245396	282854	13.3
18	1.25	1.50	2.13	4.34	1.15	6655	9269	4528	6915	9.53	278953	321143	13.2

Here, C, B, D and A are the areas of steel in the toe slab, heel slab, relieving platform and stem respectively in mm2/m, as shown in Fig.4; l is the length of the base slab in m; Co is the optimal cost obtained from GA coding and Ct is the traditional cost of construction of the wall per unit length in Rupees/m.

3. 0 <Eccentricity of the resultant reaction force at the footing< footing length /6

4. Maximum reaction pressure on the footing < SBC

5. Minimum reaction pressure on the footing > 0

6. Restrictions on maximum and minimum reinforcement percentage and reinforcement spacing as per IS 456:2000 code[1]

7. Restrictions on maximum shear stress in the footing, stem and other parts based on concrete grade as per IS 456:2000 code[1]

Optimization using genetic algorithms

This study used Genetic algorithms (GA) for carrying out searches within the design space. GA is a heuristic search method, which uses the process of natural selection for finding the global optimum[8]. These algorithms search a given population of potential solutions to find the best solution. They first apply the principle of survival of the fittest to find better and better approximations. At each generation of values for design variables, a new set of approximations is created by the process of selecting individual potential solutions (individuals) according to their level of fitness in the problem domain and breeding them together using GA operators. GA does not use the gradient but uses the values of objective functions and hence it can be used where the search space is discontinuous. Programs were developed incorporating the formulations described earlier using MATLAB. A faster convergence was achieved when the population size, number of generations, mutation rate and crossover rate were at 250, 50, 0.075 and 0.8 respectively.

Results of optimization

Typical optimal solutions

The programs developed were applied to generate optimal solutions for the three different types of walls of various heights. The heights ranged from 5 m to 14 m in the case of cantilever and counterfort walls, however for the walls with relieving platforms, the range was 5 m to 18 m. In all the cases h_f = 1.25 m and a linear tapering in the stem wall thickness assumed (0.2 m – 0.3 m at the top). Also, the soil properties assumed were :SBC = 200 kN/m^2, th = 25°, fi = 37°, th_b =15° and mu = 0.5. It may be noted that when the height considered was greater than 14 m, no feasible solutions were possible for the cantilever and counterfort retaining walls cases, as the computed maximum bearing pressure on the footing exceeded the Safe Bearing Capacity of the soil, i.e., bearing check failed.

This was also the case with the wall with relieving platforms when its height exceeded 18 m. Feasible solutions are possible only when the SBC is higher than the computed maximum bearing pressure on the footing. This is explored further in the paper.

Tables 2, 3 and 4 list the optimal solutions generated for the three wall types, considering M25 grade of concrete and Fe415 grade bars for the main reinforcement steel. Fe250 grade bars were used for temperature and shrinkage reinforcement. Nominal reinforcement was provided wherever necessary. Figures 2, 3 and 4 show the typical reinforcement detailing in the three walls. In the case of the counterfort wall, only the main bars are shown in Figure 3; curtailments of reinforcement at 2/3rd and 1/3rd heights of the stem (calculated using basic principles) are not shown. Also, the additional horizontal and vertical ties provided in the counterfort are not shown. In the case of walls with the relieving platforms, two relieving platforms at 1/3rd and 2/3rd locations of the wall height, were assumed for all wall heights to maintain consistency in results.

Figures 5, 6 and 7 show the variations in the optimal geometric dimensions (wall / slab thickness) for the three types of walls. These comprise: footing thickness (x_1), stem base thickness (x_2) and toe slab length(x_3) in the case of the cantilever wall (Figure 5); heel slab thickness (x_1), toe slab thickness (x_2), stem base thickness (x_3), counterfort thickness (x_4), counterfort spacing (x_5) and toe slab length (x_6)in the case of the counterfort wall (Figure 6); and footing thickness (x_1), stem base thickness (x_2), toe slab length (x_3) and relieving platform thickness

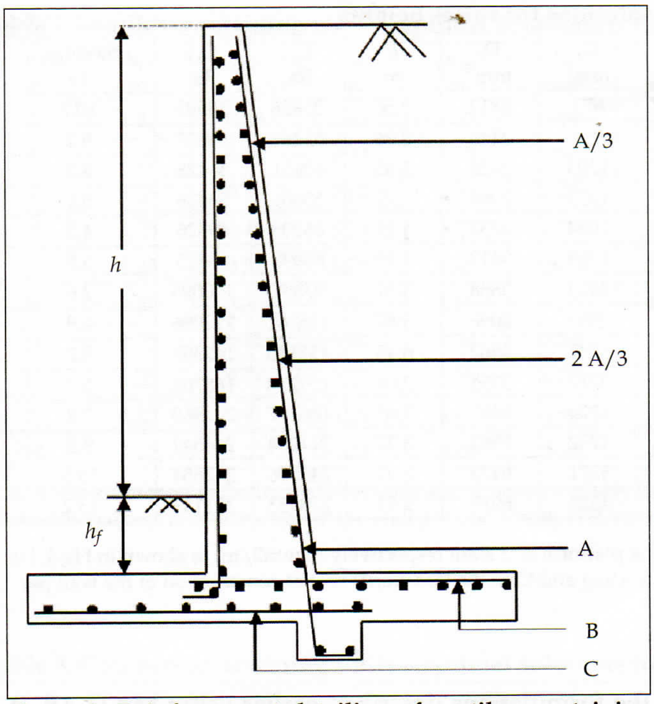

Figure 2. Reinforcement detailing of cantilever retaining wall. (A, B, and C are area of reinforcement in mm^2/m; *h* and h_f are in m)

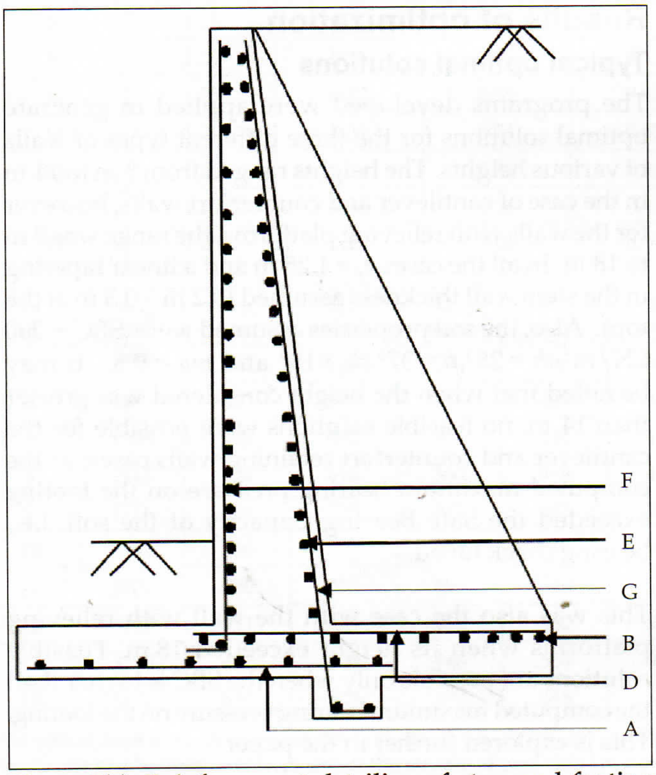

Figure 3(a). Reinforcement detailing of stem and footing slab for counterfort retaining wall. (A, B, D, E, F and G are area of reinforcement in mm^2/m)

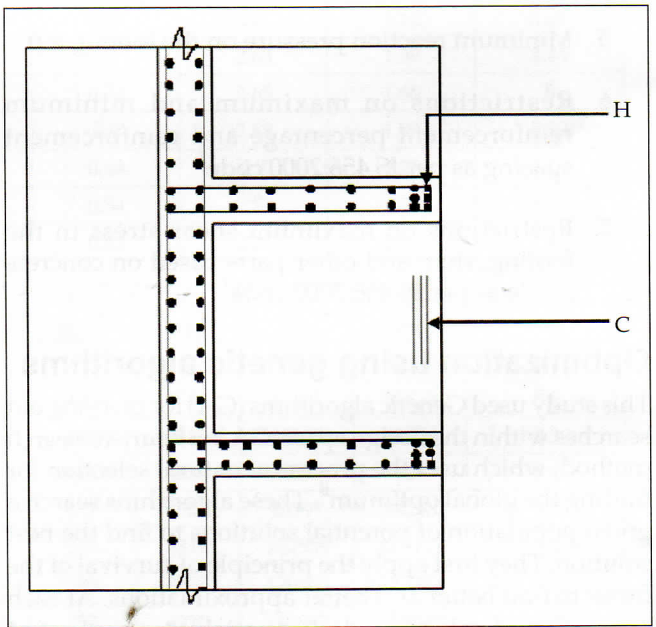

Figure 3(b). Top view of counterfort retaining wall – reinforcement detailing. (C and H are area of reinforcement in mm^2/m)

(x_8) in the case of the wall with relieving platforms (Figure 7). From the figures, it appears that the slab thickness increases somewhat linearly with the increase in the wall height. Using the trends in Figures 5-7 and Tables 2-4, it is possible to arrive at heuristic rules for optimal proportioning of the various elements.

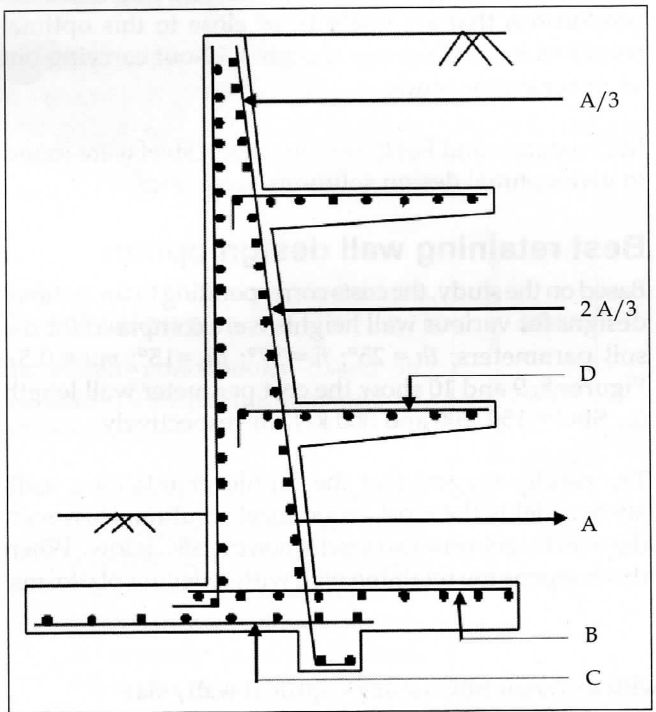

Figure 4. Reinforcement detailing of retaining wall with relieving platforms. (A, B, C and D are area of reinforcement in mm²/m)

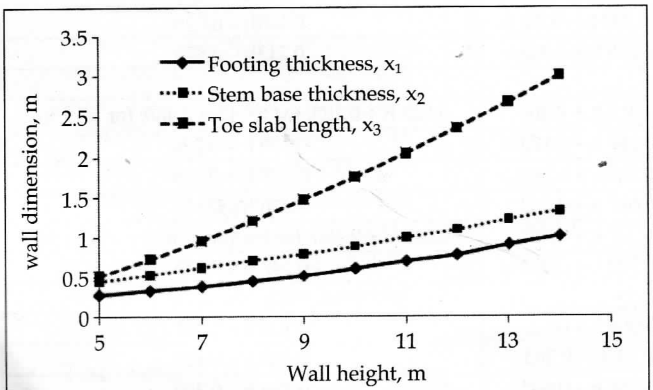

Figure 5. Variation of cantilever wall dimensions with wall height

Cost comparison between optimal design and conventional design

The literature suggests that Genetic algorithms always give a better optimal solution than the conventional design methods practised in the industry[7]. The following inferences may be drawn from Tables 2-4, which include the conventional design costs.

- For 5 m and 14 m high cantilever walls on a soil of SBC 200 kN/m^2 s, for the given parameters, the savings provided by the optimal design, compared to the conventional design, were between 23.7 to 30.1 percent. The savings increase with the increase in the wall height.
- Similarly, for the optimal counterfort walls, the savings was 8.4 percent to 12.6 percent for the height increase from 5 to 14 m respectively.

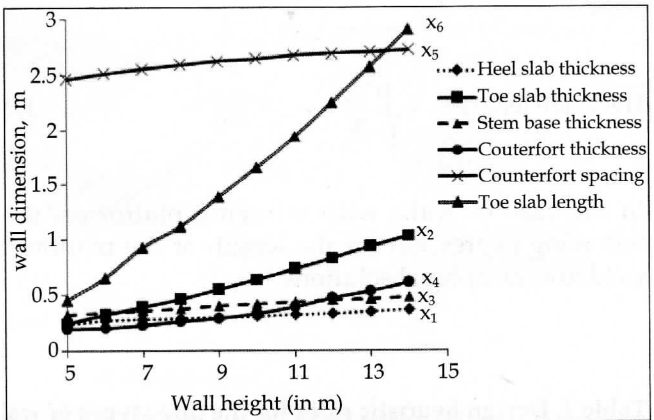

Figure 6. Variation of counterfort wall dimensions with wall height

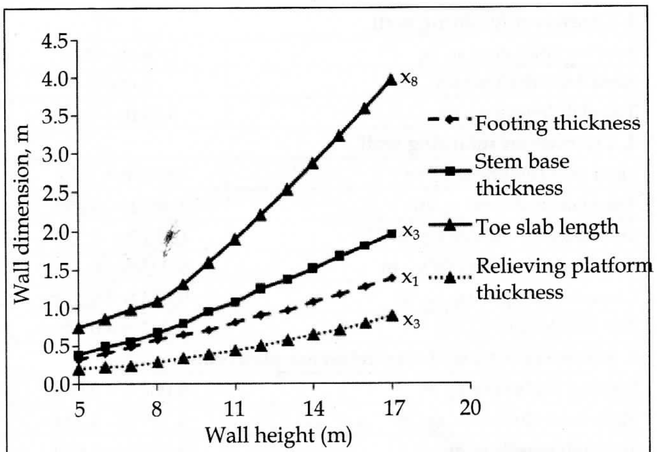

Figure 7. Variation of retaining wall with relieving platform dimensions with wall height

- In the case of walls with relieving platforms, the optimisation of cost savings increased from 2.6 percent (for wall height of 11 m) to 13.2 percent (for wall height of 18 m) by 10.6 percent. In the case of heights less than 11 m, no definite trend in the saving was observed.

Effect of change in soil bearing capacity

The optimization study was extended to include the soil bearing capacities in the range 150 kN/m^2 to 300 kN/m^2. The results suggest that the linear trends observed earlier for SBC = 200 kN/m^2 also hold good for the extended range.[6] However, the optimal solutions for various wall / slab thicknesses were dependent on the SBC. These were included in the heuristic rules.

Heuristic guidelines for optimal design

Based on the optimal solutions obtained for these wall types and heights, several heuristic guidelines can be arrived at[7]. The following expression can be used to arrive at a near-optimal value of the length of the heel slab:

$$\text{Heel slab length} = h\sqrt{\frac{C_{act}}{3}} \quad \text{......(1)}$$

In the case of walls with relieving platforms, the following expression for the length of the platform, yielded near-optimal solutions:[3]

$$\text{Relieving platform length} = 0.33\,h\tan\left(\frac{\Pi}{4}-\frac{fi}{2}\right) \quad \text{......(2)}$$

A linear model was proposed for the variation of wall/slab thickness with wall height, for the sake of simplicity in calculation and application. Based on the above observations, heuristic design rules proposed for a retaining wall built on soil with th = 25°, fi = 37°, th_b = 15° and mu = 0.5 and different SBC values (150, 200 and 300 kN/m^2), are tabulated in Table 5. Using these guidelines, a designer can select wall and slab thickness proportions that are likely to be close to this optimal solutions for preliminary design, without carrying out an optimization study.

M25 concrete and Fe415 reinforcement steel were found to give optimal design solutions in all cases.

Best retaining wall design option

Based on the study, the costs corresponding to the optimal designs for various wall heights were compared for the soil parameters; th = 25°; fi = 37°; th_b =15°; mu = 0.5). Figures 8, 9 and 10 show the cost per meter wall length for SBC = 150, 200 and 300 kN/m^2 respectively.

The results suggest that the cantilever retaining wall, always yields the most economical solution. However, the wall height gets restricted when the SBC is low. When this happens the retaining wall with relieving platforms,

Table 5. Design heuristic rules for the three types of walls with different SBC values - optimal wall / slab thickness values (in m)

Wall / slab thickness	SBC, kN/m^2		
	150	200	300
1. Cantilever retaining wall			
Footing thickness x_1, m	0.064h- 0.04	0.082 h – 0.13	0.091h – 0.173
Stem base thickness x_2, m	0.090 h	0.097 h – 0.04	0.109h – 0.096
Toe slab length x_3, m	0.284h – 0.66	0.275 h – 0.858	0.213h – 0.576
2. Counterfort retaining wall			
Heel slab thickness x_1, m	0.017h + 0.15	0.012 h + 0.204	0.025 h + 0.193; for h< 13m 0.480; for h> 13m
Toe slab thickness x_2, m	0.067h – 0.058	0.087 h – 0.172	0.109 h – 0.296
Stem base thickness x_3, m	0.020h + 0.228	0.019h + 0.242	0.013 h + 0.289
Counterfort thickness x_4, m	0.022 h + 0.117	0.047 h – 0.032	0.076 h – 0.161
Counterfort spacing x_5, m	0.053 h + 2.234	0.027 h + 2.387	0.018 h + 2.390; for h< 15m 2.650; for h> 15m
Toe slab length x_6, m	0.282 h – 0.719	0.272 h – 0.901	0.242 h – 0.812
3. Retaining wall with two relieving platforms			
Footing thickness x_1, m	0.082 h – 0.088	0.089 h – 0.125	0.109 h – 0.227
Stem base thickness x_2 , m	0.129 h – 0.264	0.131h – 0.263	0.165 h – 0.434
Toe slab length x_3, m	0.330 h – 0.899	0.268 h – 0.602	0.226 h – 0.390
Relieving platform thickness x_8 , m	0.054 h – 0.072	0.057 h – 0.087	0.072 h – 0.157

h – Height of wall above the ground level which is a relatively new concept in India, provides the most economical solution. The traditional assumption that walls with counterforts are likely to be more cost-effective than cantilever walls for heights exceeding about 8 m, was not found to be true.[2] The optimally designed counterfort retaining wall was found to be a more costly solution compared to the optimally designed cantilever wall and wall with relieving platforms for nearly all wall heights.

It may be noted that the cost shown in Figures 8-10 were based on Delhi Schedule of rates 2007. The authors believe that even if they change with time, the relative costs of steel and concrete are likely to remain the same.

Conclusions

The salient conclusions, based on the study, can be summarized as follows:

- Coulomb's theory, which accounts for wall friction, gives a better cost-effective design alternative for a retaining wall than Rankine's theory, which is currently used in practice, for convenience.
- The traditional belief that walls with counterforts are likely to be more cost-effective than cantilever walls for heights exceeding about 8 m, was not found to be true, when an optimal design was carried out. The optimally designed cantilever retaining wall was found to be invariably the most cost-effective solution for wall heights, where feasible solutions were possible (depending on safe bearing capacity).
- The retaining wall with relieving platforms, which is a relatively new concept in

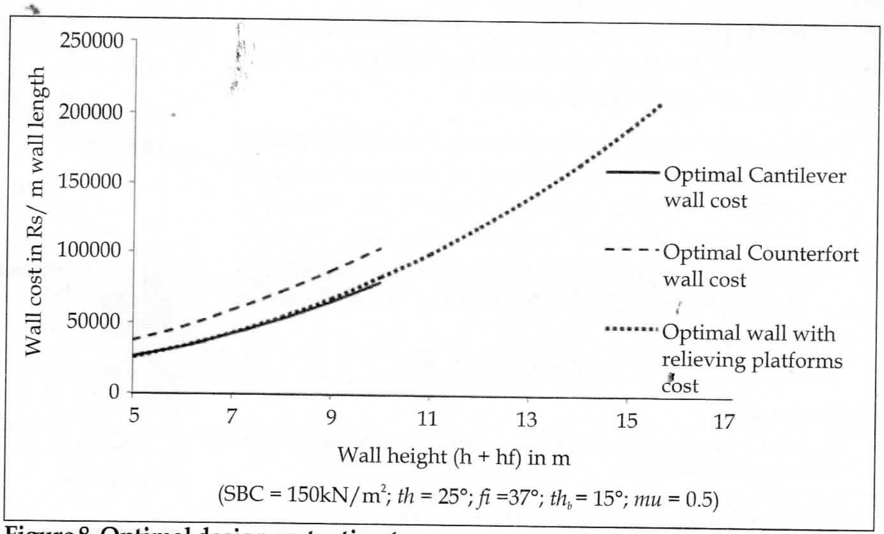

Figure 8. Optimal design cost estimates

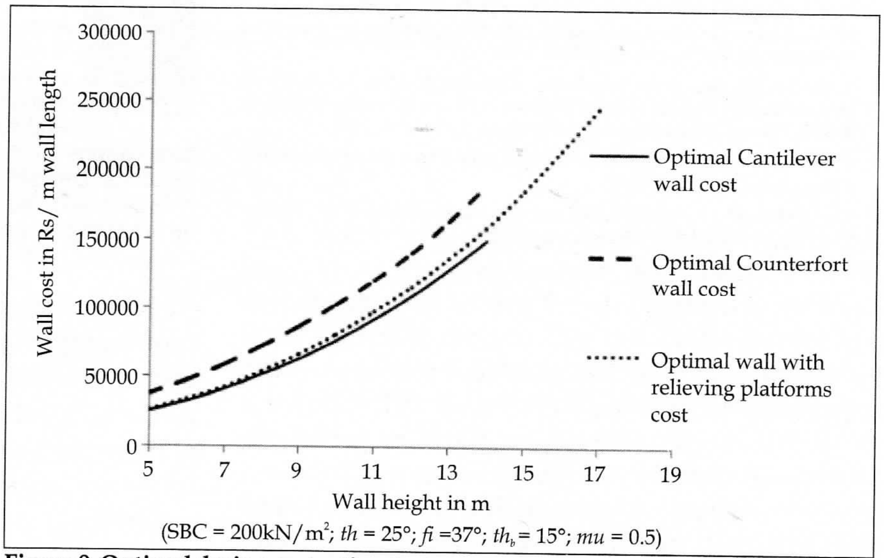

Figure 9. Optimal design cost estimates

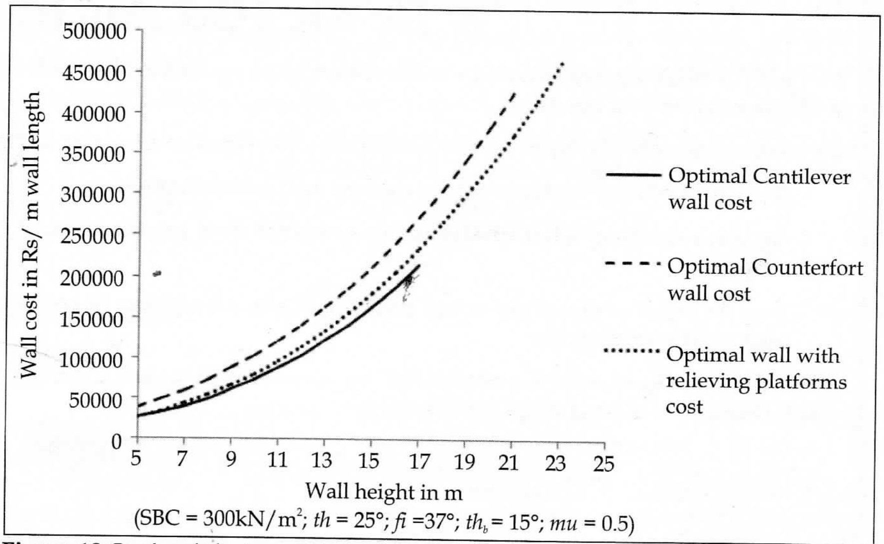

Figure 10 Optimal design cost estimates

India, provides the most economical solution for tall wall heights, where the cantilever retaining wall is not a feasible option.

- Heuristic design rules are proposed in this paper to enable the proportioning of various wall and slab elements for different types of RC retaining walls and different heights. The use of these thumb-rules is likely to result in a near-optimal design, without the need to carry out an explicit optimization.

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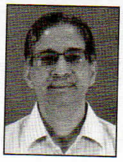

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