ANALYSIS AND DESIGN OF REINFORCED CONCRETE STEPPED CANTILEVER RETAINING WALL

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Abstract

A retaining wall is one of the most important types of retaining structures. It is extensively used in variety of situations such as highway engineering, railway engineering, bridge engineering and irrigation engineering. Reinforced concrete retaining walls have a vertical or inclined stem cast with base slab. These are considered suitable up to a height of 6m.It resists lateral earth pressure by cantilever action of stem, toe slab and heel slab. The tendency of wall to slide forward due to lateral earth pressure should be investigated and a factor of safety of 1.5 shall be provided against sliding. Cantilever retaining walls are found best up to a height of 6m.For greater heights earth pressure due to retained fill will be higher due to lever arm effect, higher moments are produced at base, which leads to higher section for stability design as well as structural design. This proves to be an uneconomical design. As an alternative to this, one may go for counter fort retaining wall, which demands greater base area as well as steel. As a solution to this difficulty, a new approach that is to minimize effect of forces coming from retained fill , short reinforced concrete members in the form of cantilever steps are cast along the stem on the retaining face. Addition of these steps would counterbalance the locally appearing forces and will result into lesser moment and shear forces along the stem. Also it will reduce the bending action that is pressure below the base.

The objectives of the study are
1) To reduce the stresses on the retaining face of the cantilever retaining wall, it is proposed to introduce reinforced concrete steps along the stem.
2) Decide the most economical location of step along length and also along height of wall from number of trials.
3) Decide cross section of the R. C. step as per the stresses due to frictional forces in step.
4) Stability analysis of Cantilever retaining wall with steps for unit width will be done. Check for minimum and maximum stresses will be observed.
5) Cost comparison shall be carried out for these three different alternatives to give most economical retaining wall type.

Keywords: *Mechanism of step, Finalization of Step location, Stabilizing frictional force, Concrete quantity, Steel reinforcement and Cost Comparison of Counter fort and Stepped Cantilever retaining wall.*

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1. INTRODUCTION

A retaining wall is one of the most important types of soil retaining structures. The primary purpose of retaining wall is to retain earth or other material at or near vertical position. It is extensively used in variety of situations such as highway engineering, railway engineering, bridge engineering, dock and harbor engineering, irrigation engineering, land reclamation and coastal engineering etc. Reinforced concrete retaining walls have a vertical or inclined stem cast monolithic with a base slab. These are considered suitable up to a height of 6m. It resists the lateral earth pressure by cantilever action of the stem, toe slab and heel slab. Necessary reinforcements are provided to take care of the flexural stresses. The tendency of the wall to slide forward due to lateral earth pressure should be investigated and if a factor of safety is insufficient, a shear key should be designed to prevent lateral movement of the structure.

1.1 Cantilever Retaining Walls

These walls are made of reinforced cement concrete. It consists of a thin stem and a base slab cast monolithically. This type of wall is found to be economical up to a height 6 to 8m.

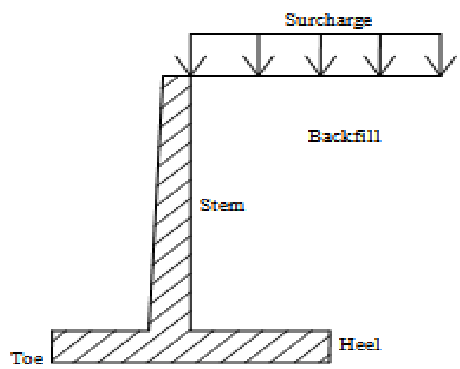


Fig - 1

1.2 Counter fort Retaining Walls

These walls have thin vertical slabs, known as counter forts, spaced across vertical stem at regular intervals. The counter forts tie the vertical stem with the base slab. Thus the vertical stem and the base slab span between the counter forts. The purpose of providing the counter forts is to reduce the shear force and bending moments in the vertical stem and the base slab. The counter fort retaining walls are economical for a height more than 6 to 8m.

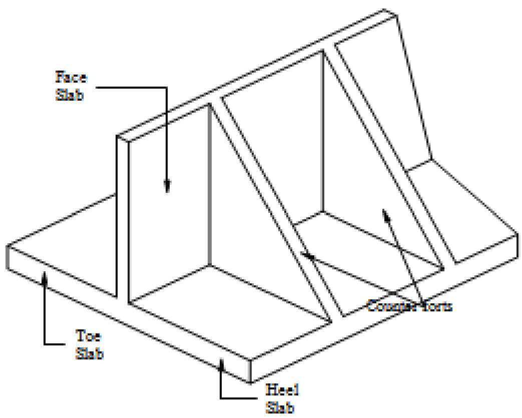


Fig - 2

2. ANALYSIS OF RETAINING WALLS

2.1 Cantilever retaining wall

A) Stability:

Figure 3 shows a cantilever retaining wall subjected to following forces:

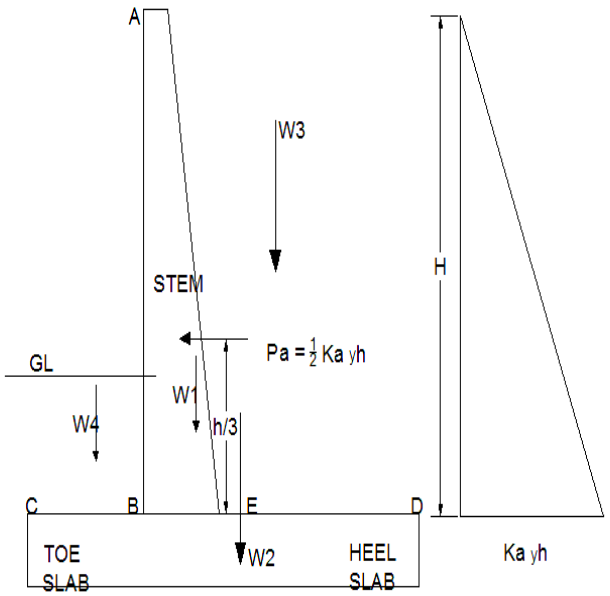


Fig - 3: Mechanism of Cantilever Retaining Wall

- Weight W1 of the stem
- Weight W2 of the base slab
- Weight W3 of the column of soil supported on heel slab
- Weight W4 of the soil supported on toe slab
- Horizontal force Pa equal to active earth pressure acting at H/3 above base slab.

B) Modes of Failure of a Retaining Wall:

- **Overturning about A**
  The most hazardous mode of failure of retaining wall is due to overturning because of unbalanced moments. Here, a minimum factor of safety is used.

- **Sliding:**
  The horizontal force tends to slide the stem and wall away from fill. The tendency to resist this is achieved by the friction at the base. Here, if the wall is found to unsafe against sliding, shear key below the base is provided. Such a key develops passive pressure which resists completely the sliding tendency of wall. A factor of safety of 1.5 is used against sliding.

- **Bending Failure**
  The stem AB will bend as cantilever so that tensile face will be towards the soil face in case if there is no backfill, where as tensile face will be towards the water face in case there is backfill. The critical section will be at E and B, where crack may occur at if it is not properly reinforced. The soil side slab will have net pressure acting downwards, and will bent as a cantilever having tensile face at top for retaining wall, at the same time the heel slab will be subjected to net upward pressure causing tensile face at bottom. The thickness of stem, toe slab, and heel slab must be sufficient to withstand compressive stresses due to bending also; the stem thickness must be check for uncracked section.

2.2 Design Principal of Cantilever Retaining Wall

The various dimensions of wall are so proportioned that the various failure criteria discussed above are taken care of. The design of wall consist of the fixation of base width, design of stem, design of toe slab, design of heel slab.

A) Fixation of Base Width:

The base width of wall is so chosen that the resultant of forces remain within middle third of base slab, the uplift pressure is zero at heel slab side also it should be safe from consideration of sliding.

B) Design of Stem:

The vertical stem is designed as cantilever for triangular loading with Kaγh as base of triangle h as height of it. The main reinforcement is provided at 0.3 % of the area of cross section along the length of wall.

C) Design of Toe Slab:

It is also design as a cantilever beam or slab. The main reinforcement is provided at lower face or bottom side as upward soil pressure load is acting on that face. Thickness is checked for maximum cantilever moment and deflection criterion.

D) Design of Heel Slab:

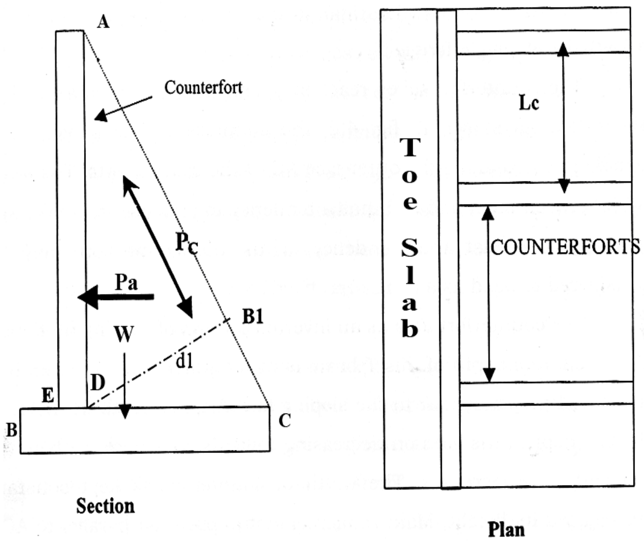
It is also design as a cantilever beam or slab. The main reinforcement is provided at the upper face or top side of heel slab as active load is acting there in form of overburden pressure. The design reinforcement for effective moment due to upward soil pressure should also provide at bottom side of heel slab. The thickness is checked for maximum cantilever moment and deflection criterion for cantilever action.

2.3 Analysis of Counter-Fort Retaining Wall:

The counter forts support both the vertical stem as well as base slab. Design principles for various component parts are discussed below in brief. The same criterion is adopted for fixing the base width as cantilever retaining wall.

A) Design of stem

Unlike the stem of cantilever retaining wall, the stem of counter fort retaining wall acts as a continuous slab supported on counters forts. Due to varying pressure over the height of stern, the stem slab deflects outwards and hence main reinforcement is provided along the length of the wall as per design conditions.



Pc - Effect of counter fort
Lc - Spacing of counter forts along length of wall

Fig - 4: Mechanism of Counter fort Retaining Wall

The reaction of the stem is taken by the counter forts, to which it is firmly anchored. The maximum bending moment occurs at Base. The uniformly distributed earth pressure load or water pressure load is calculated for unit height.

B) Design of Heel Slab

The action is similar that of stem. The Heel slab is subjected to the downward load due to weight of soil and self weight, upward load due to upward soil pressure below heel slab. The maximum net pressure is found to act on a strip of unit width near outer edge, since the upward soil reaction is minimum there, the total reaction from the heel slab is transferred to the counter forts, and this load helps to provide a balancing moment against its overturning. The heel slab is firmly attached to the counter forts by means of vertical ties.

C) Design of Toe Slab

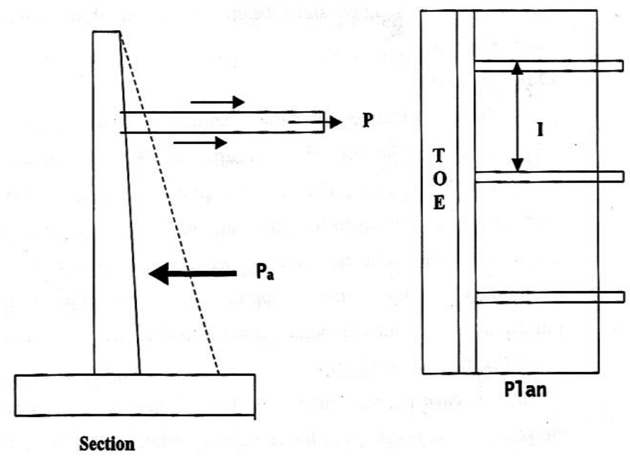
The action of Heel slab is similar to that of cantilever retaining wall.

D) Design of Counter Forts

The counter fort takes reactions, both from the stem as well as Heel slab. As shown in fig. 4.2, the counter forts are subjected to tensile stresses along the outer face AC of the counter forts. The angle ABC between stem and slab has a tendency to increase from 900, and counter forts resist this tendency. Thus the counter fort may be considered to bend as a cantilever, fixed at BC. The counter fort acts as an inverted T beam of varying rib depth. The maximum depth of this T beam is at the junction B. The depth is measured perpendicular to the sloping face AB, i.e. depth dl=BB1. At B, This depth thus goes on decreasing towards Al where the bending moment also decreases. The width of counter fort is kept constant throughout its height; Main reinforcement is provided parallel to AC The faces AB and BC of the counter fort remain in compression. The compressive stresses on face AB are counterbalanced by the vertical upward reaction transferred by the slab. In addition to the main reinforcement, the counter forts are jointed firmly to the stem and base slab by horizontal and vertical ties respectively.

2.4: Stepped Cantilever Retaining Wall (New Approach)

For retaining back fill of heights more than 10-11 meters. The conventional walls like cantilever and counter fort becomes very massive and almost uneconomical hence a suitable modification to these walls so as to economize the retaining wall construction. The proposed modified alternative is ‘Stepped cantilever retaining wall’. The general outline of concept will be clear from figure as shown.



P - Stabilizing frictional force
Pa - Active pressure component
L - Spacing of concrete steps along length of wall

Fig – 5: Mechanism of stepped cantilever retaining wall

The main concept in this type is supporting the high stem at critical points indirectly by means of pulling force developed due to surface Friction of concrete steps with backfill. Here the effect of self weight of these steps in stabilizing wall against active pressure is not considered as it may be negligible. Conventionally in case of sheet pile walls, there was use of anchor rods and the concrete plates or concrete dead man was used to develop frictional force. In case of sheet pile wall with vertical concrete plates the mechanism of pulling force was due to passive resistance of soil mass bounded by height of concrete wall and in that case the role of concrete wall was different from frictional resistance function. In case of sheet pile walls the thickness of stem was very small but it is continuous wall with membrane action than beam/slab action but in this case, these concrete steps are used as supporting mechanism for conventional cantilever wall which gives relatively less dimensions for assumed slab beam mechanism than conventional design approach.

A) Design Principles

Design principles for various component parts are discussed below in brief. The procedure of analysis is same as cantilever retaining wall but their preliminary dimensions given will be based on load distribution assumed for actual analysis. Like any other analysis and design this will be Iterative (trial and error) method, the preliminary dimensions may be approximately given as half of that for purely cantilever wall with some exiting thumb rules.

B) Fixation of Base Width

In this case it is not necessary that the base width of wall is so chosen that the resultant of forces remain within middle third and the minimum (uplift) pressure at toe is zero but these dimensions can be chosen approximately without these checks.

C) Design of Stem

The vertical stem is designed as cantilever for triangular loading but reinforcement will be provided from actual modified Pressure diagram due to restoring force developed by concrete steps. Distribution reinforcement may be provided as per standards.

D) Design of Toe Slab

It is also designed as a cantilever slab/beam. Reinforcement is provided at lower face. There will major reduction in depth and steel reinforcement in toe and heel slab due to reduction in the active pressure and addition in self-weight of wall. This will effectively economize the wall construction. Thickness is checked for the maximum cantilever moment.

E) Design of Heel Slab

It is also designed as a cantilever. Reinforcement is provided at the upper face. Thickness is checked for the maximum cantilever moment.

F) Design of Concrete Steps

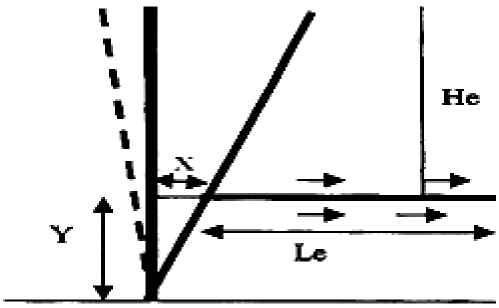
The concrete steps will be placed along length at suitable spacing L. The mechanism of friction generation is fully dependant on overburden load i.e. depth of step from top of wall hence the step provided at more depth will give better results. The one more effective element in friction development is embedment length and width of step. The overlaying or overlapping of steps and embedment in various pressure zones like passive or rest will also be important. These steps will act as free cantilevers spanning from stem or somewhat like plates supported on spring or elastic media depending upon degree of compaction of backfill. These assumptions dominate its design or depth at stem and free end. If steps assumed as slab strips supported on elastic media then their depth and steel reinforcement for moment will be less than its minimum depth as per standards and steel required for tensile forces developed due to frictional resistance.

G) Calculation of Frictional Resistance offered by Plate

The concrete plates are inserted in compacted backfill. They will develop frictional force along contact planes of concrete and soil due to overburden pressure and compaction. This frictional force will act as indirect stabilizing force for overturning retaining wall and will pull wall inside.

Mechanism

The concrete plate separated from stem inserted in soil is as shown in figure 4.



Displaced stem
Active state zone

Fig - 6: Mechanism of step

- The effective frictional pressure=Coefficient of friction x height of backfill on plate x dry density of backfill.

1) Stepped Retaining Wall of Height 6m:

Assumptions

1. Back fill is enough compacted.
2. Step length embedded in backfill - 3.5m
3. Step dimensions - 400 x 300 mm

- Effective length of plate =Length of plate beyond active zone.
- Effective frictional force =Width of plate x effective length of plate x 2 x Effective frictional pressure.

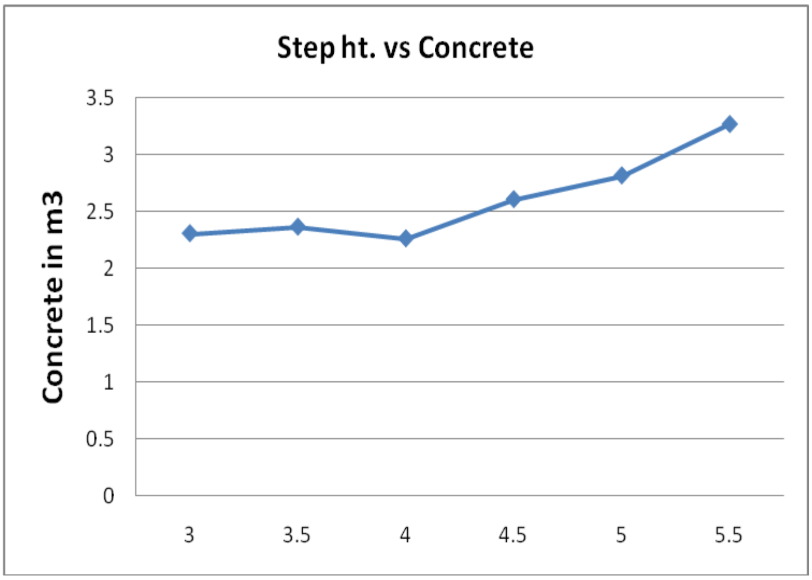
H) Finalization of Step Location

For actual analysis to decide location of step along length and along height of wall is most important task as it may hamper most of assumptions. Hence the length of step immersed in backfill was kept constant and the location of plate along length of wall was fixed from number of trails for stability. For finalizing the location of step along height of wall, the number of trials is taken starting from half of height and with interval of 500 mm. The stability analysis of each wall is done and concrete quantity, steel reinforcement and cost per meter are compared. The most economical wall is selected for final comparison as alternative with other retaining wall types. The following table shows all aspects of stepped cantilever wall for various step heights from top of wall. The comparison is also shown graphically by subsequent graphs for each height.

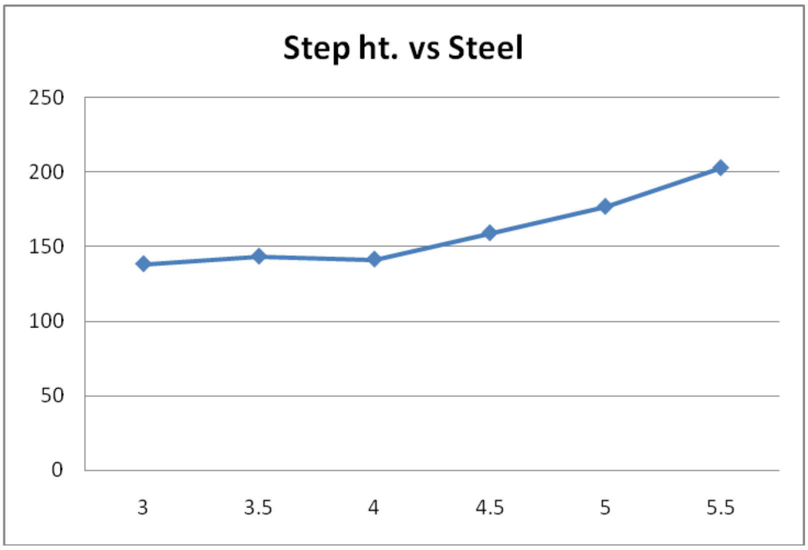
Table 1: Stability analysis and cost comparison

Step from top m.	Width of toe slab	Width of heel slab	Depth of base slab	Total base slab	Stem thick m	
					At top	Bottom
3	0.85	2.5	0.4	3.7	0.2	0.35
3.5	0.65	2.5	0.4	3.5	0.2	0.35
4	**0.65**	**1.9**	**0.4**	**2.9**	**0.2**	**0.35**
4.5	0.65	2.42	0.4	3.42	0.2	0.35
5	0.65	2.6	0.4	3.6	0.2	0.35
5.5	0.65	2.9	0.45	3.9	0.2	0.35

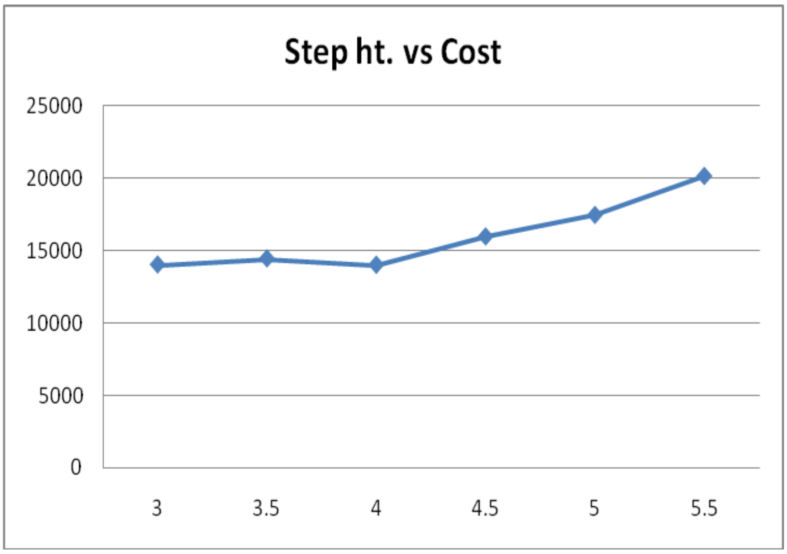
Upward soil pressure in KN/m2		Effective frictional force	Concrete m3	Steel quantity Kg/m	Cost Rs/m
Pmax.	Pmin.				
101.7	295.2	38.21	2.305	138.26	14012.68
103.6	292	51.85	2.3625	143.3	14430.65
88	**296.5**	**67.56**	**2.26**	**141.38**	**13989.34**
94.7	299.1	85.36	2.6055	158.99	15955.82
101.7	296.1	105.23	2.815	176.65	17448.45
106.9	305.4	127.18	3.2675	202.55	20145.9



Graph 1: Step location Vs concrete m3 for wall Ht. 6.0 m



Graph 2: Step location Vs steel kg for wall Ht. 6m



Graph 3: Step location Vs cost per meter for wall Ht. 6.0 m

2) Stepped Retaining Wall of Height 8m:

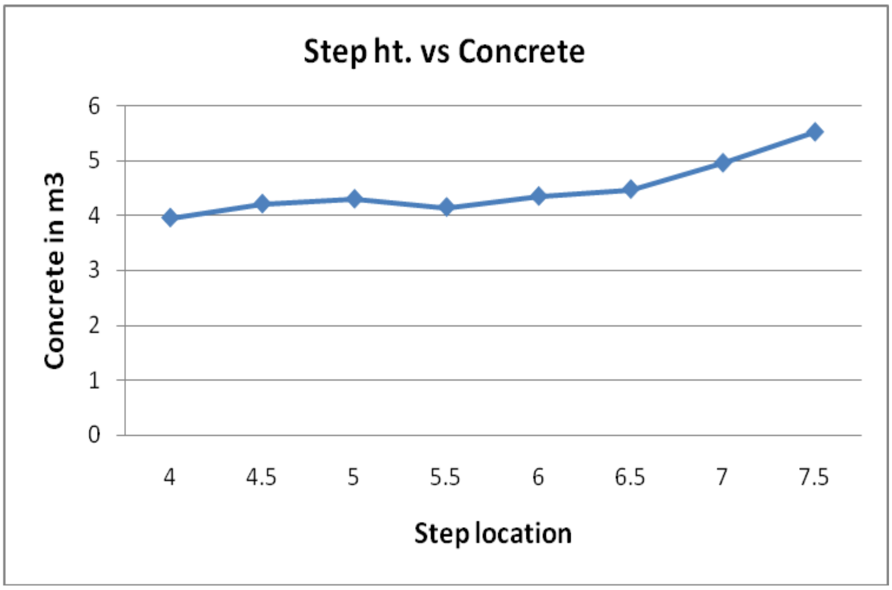
Assumptions

1. Back fill is enough compacted.
2. Step length embedded in backfill - 4.5m
3. Step dimensions - 500 x 300 mm

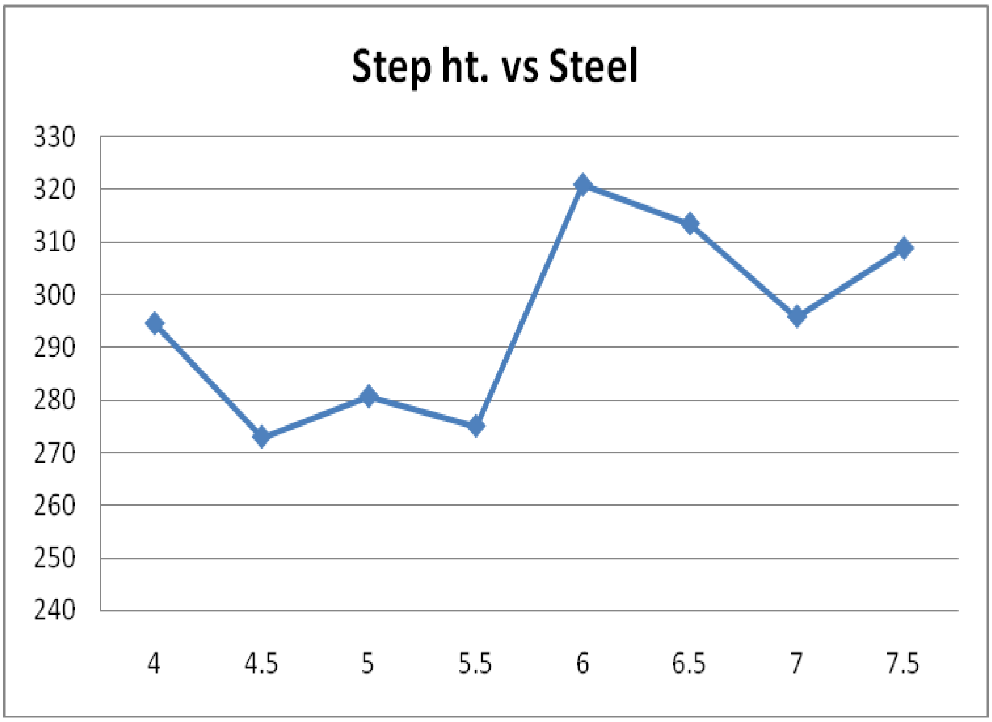
Table2: Stability analysis and cost comparison for wall ht.8m

Step from top	Width of toe slab	Width of heel slab	Depth of base slab	Total base slab	Stem thickness in m	
					at top	Bottom
4	1.3	3.95	0.47	5.65	0.25	0.4
4.5	1.2	3.9	0.5	5.5	0.25	0.4
5	1.1	3.85	0.5	5.35	0.25	0.4
5.5	**0.95**	**3.9**	**0.45**	**5.25**	**0.25**	**0.4**
6	1.15	3.4	0.45	5	0.25	0.45
6.5	1.25	3.2	0.45	4.9	0.25	0.45
7	1.35	3.12	0.45	4.995	0.25	0.525
7.5	1.45	3.15	0.45	5.2	0.25	0.6

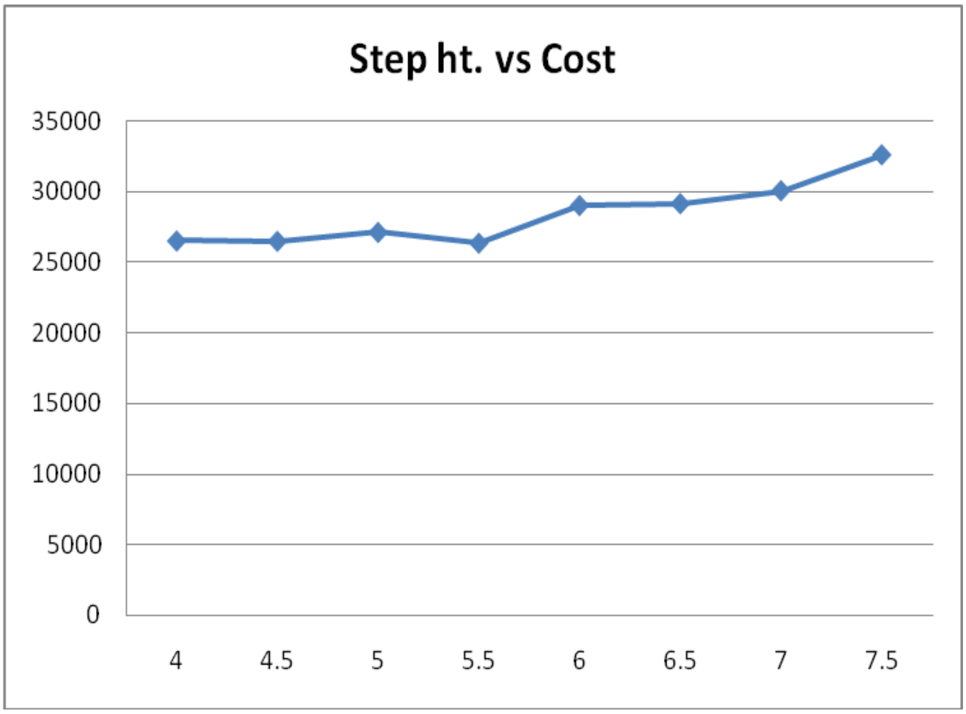
Upward soil pressure KN/m2		Effective frictional force KN	Concrete m3	Steel quantity Kg/m	Cost Rs/m
Pmax.	Pmin.				
220.63	281.53	78.91	3.9555	294.49	26507.32
213.15	299.95	100.46	4.2125	272.96	26481.03
217.81	295.3	124.61	4.3	280.63	27117.09
206.31	294.54	151.35	4.15	275.03	26351.29
197.56	295.12	180.68	4.35	320.84	29021.12
183.01	295.3	212.62	4.48	313.44	29157.92
177.32	289.68	247.15	4.96025	295.81	30080.705
172.75	286.56	284.28	5.5275	308.79	32624.22



Graph 3: Step location Vs concrete cum/m for wall Ht. 8.0 m



Graph 4: Step location Vs steel kg/m for wall Ht. 8m



Graph 5: Step location Vs cost per meter for wall Ht. 8.0 m

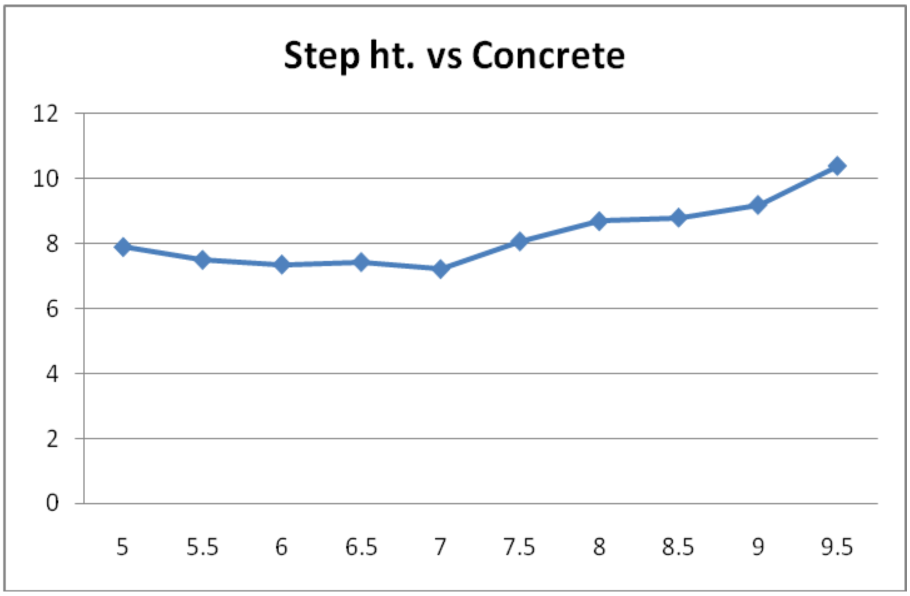
3) Stepped Retaining Wall of Height 10m:

Assumptions

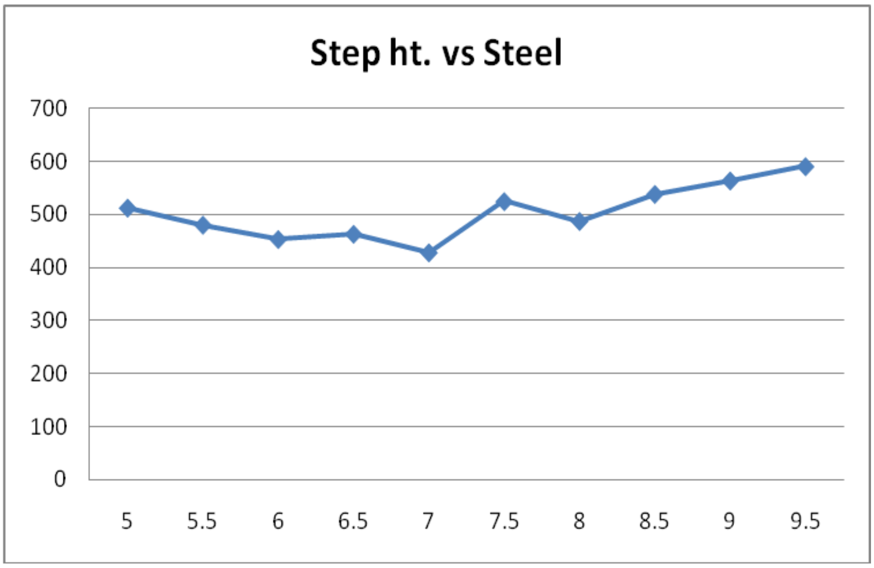
1. Back fill is enough compacted.
2. Step length embedded in backfill - 5.5m
3. Step dimensions - 600 x 300 mm

Table 3: Stability analysis and cost comparison for wall hieght10m .

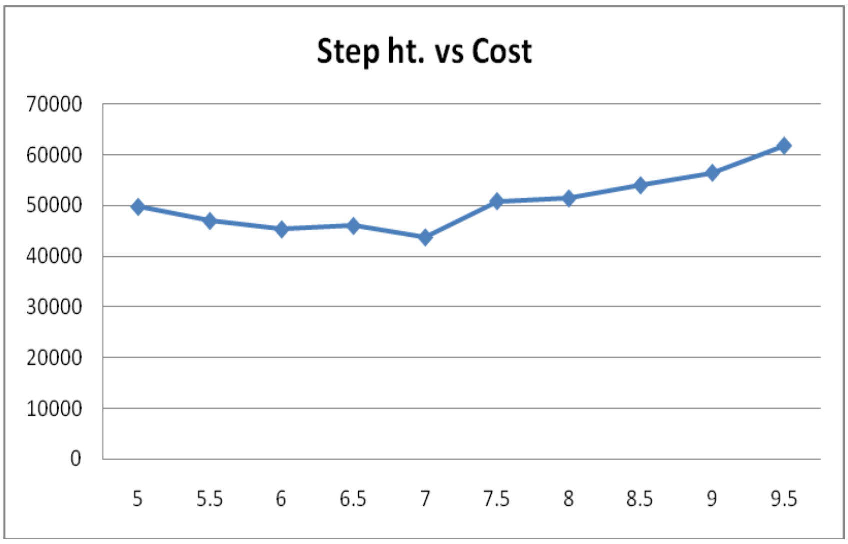
Step from top m.	Width of toe slab m	Width of heel slab m	Depth of base slab m	Total base slab m
5	1.5	8.5	0.55	10.5
5.5	1.45	7.15	0.55	9.15
6	1.4	6.85	0.55	8.75
6.5	1.35	6.65	0.55	8.5
7	**1.5**	**6.5**	**0.5**	**8.5**
7.5	1.45	6.15	0.55	8.2
8	1.5	5.55	0.55	7.8
8.5	1.5	5.25	0.55	7.5
9	1.6	4.925	0.6	7.25
9.5	1.75	5.425	0.6	8



Graph 6: Step location Vs concrete cum/m for wall Ht. 8.0 m.



Graph 7: Step location Vs steel kg/m for wall Ht. 10.0 m



Graph 8: Step location Vs cost per meter for wall Ht. 10.0 m

4) Stepped Retaining Wall of Height 12m:

Assumptions

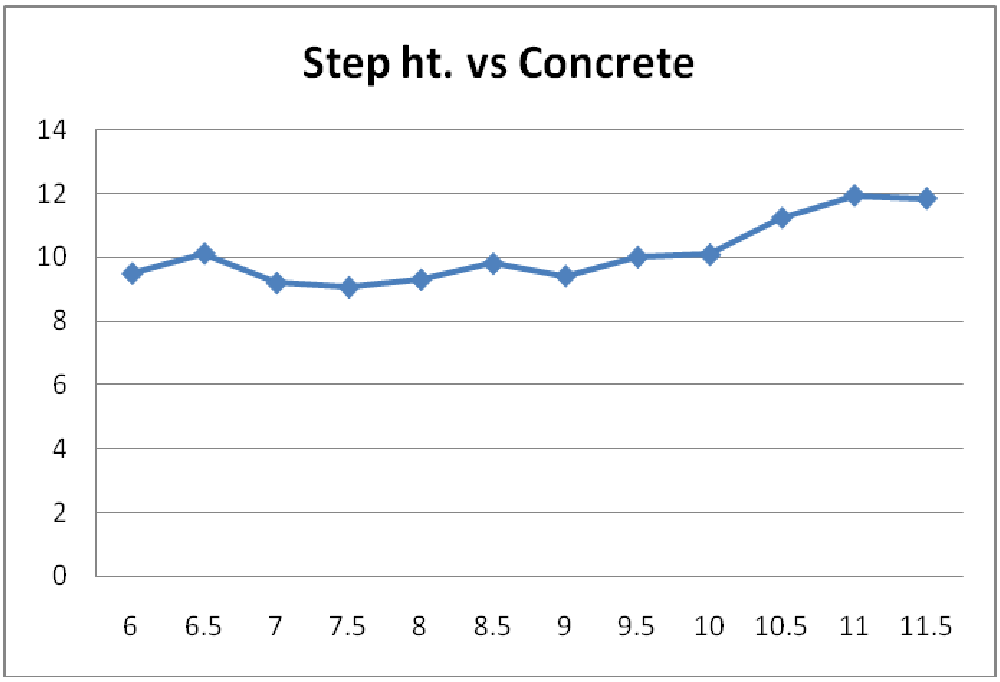
1. Step length embedded in backfill - 6.5 M
2. Step dimensions - 650 x 400 mm

Table 4: Stability analysis and cost comparison for wall ht.12m

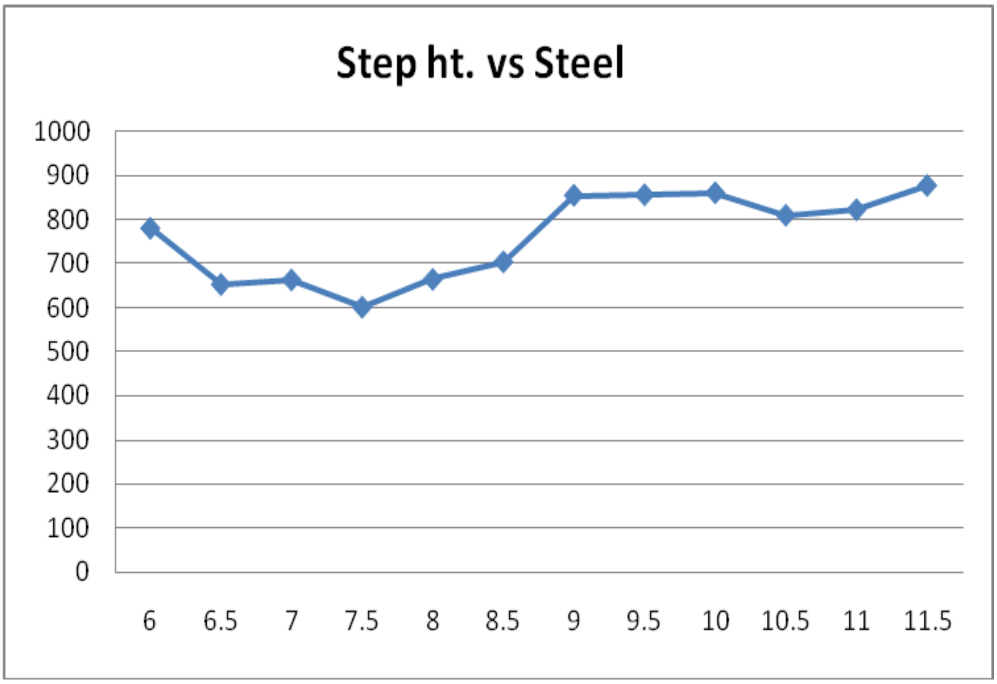
Step from top	Width of toe slab m	Width of heel slab m	Depth of base slab m	Total base slab m
6	2.1	5.9	0.75	8.65
6.5	1.9	6.6	0.75	9.15
7	1.8	6.3	0.65	8.75
7.5	1.65	6.2	0.65	8.45
8	1.5	6.35	0.65	8.45
8.5	1.4	6.1	0.65	8.2
9	1.25	5.85	0.6	7.8
9.5	1.4	5.45	0.7	7.5
10	1.51	5.09	0.7	7.25
10.5	1.6	5.6	0.65	8
11	1.7	5.2	0.65	7.8
11.5	1.8	5.225	0.7	8.1

Upward soil pressure KN/m2		Effective frictional force KN	Concretem3	Steel quantity Kg/m	Cost Rs/m
Pmax.	Pmin.				
297.29	217.93	213.27	9.4875	780.71	66776.78
295.99	229.29	252.98	10.1125	653.98	63514.89
297.01	224.59	296.07	9.1875	664.01	60708.68
299.91	240.15	342.53	9.055	602.19	57586.67
295.05	249.66	392.37	9.2925	665.24	61129.07

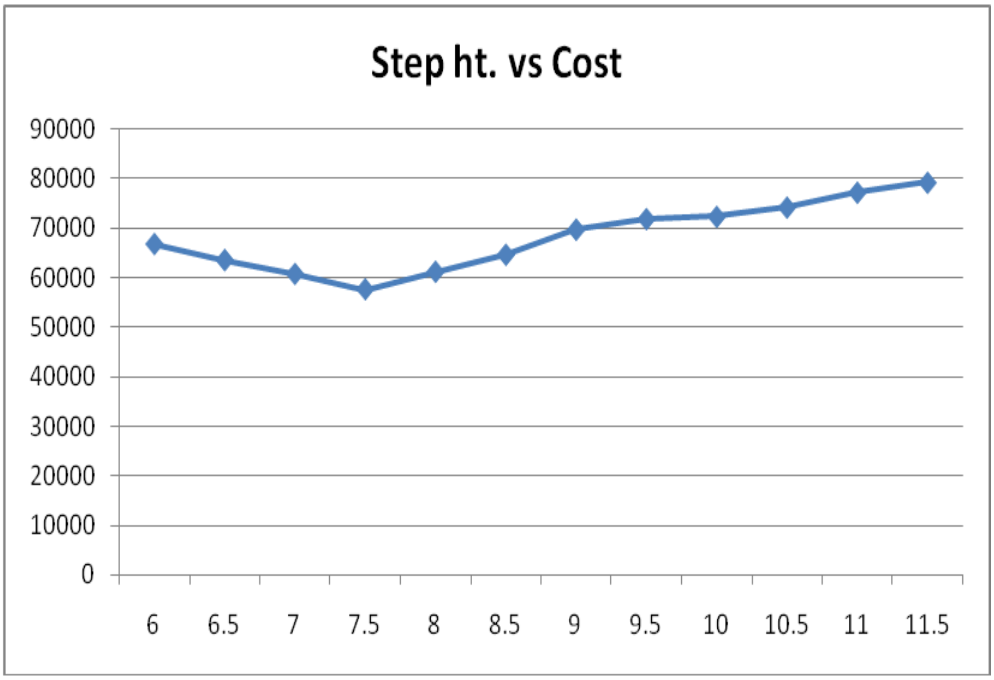
286.61	260.06	445.59	9.7925	704.89	64584.02
270.77	280.76	502.18	9.405	855.36	69697.98
255.28	289.2	562.14	10	856.7	71838.1
240.75	294.08	562.14	10.075	861.16	72292.38
245.75	283.49	692.2	11.2375	810.15	74167.7
244.36	283.43	762.29	11.945	822.89	77191.77
249.26	283.24	835.76	11.85125	877.55	79214.025



Graph 9: Step location Vs concrete cum/m for wall Ht. 12m



Graph 10: Step location Vs steel kg/m for wall Ht. 12.0 m



Graph 11: Step location Vs cost per meter for wall Ht. 8.0 m

5) Stepped Retaining Wall of Height 15m

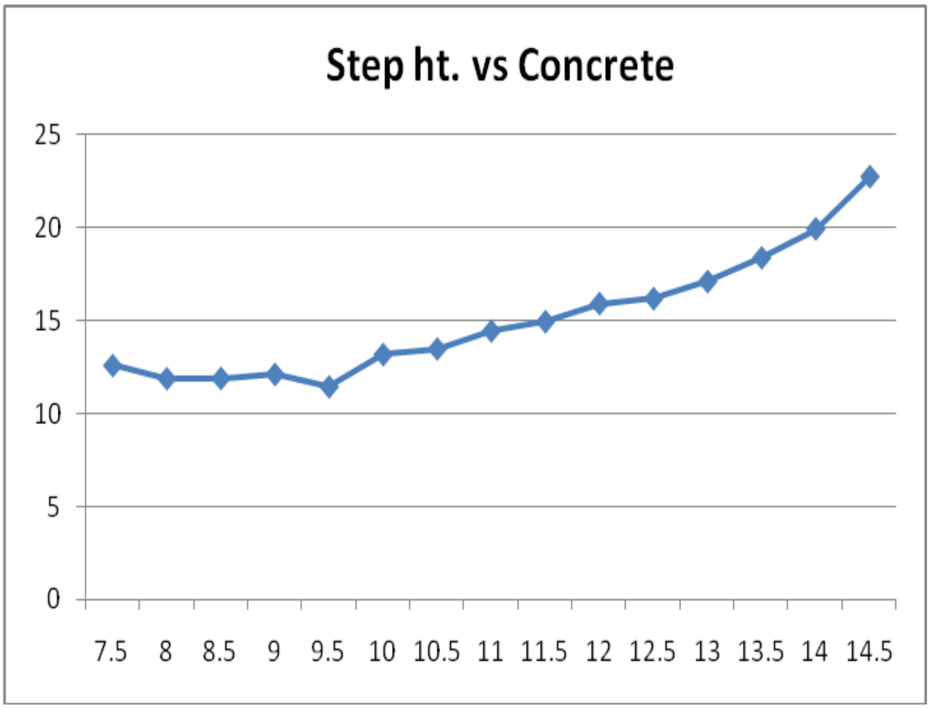
Assumptions

1. Step length embedded in backfill – 7.5m
2. Step dimensions - 700 x 450 mm

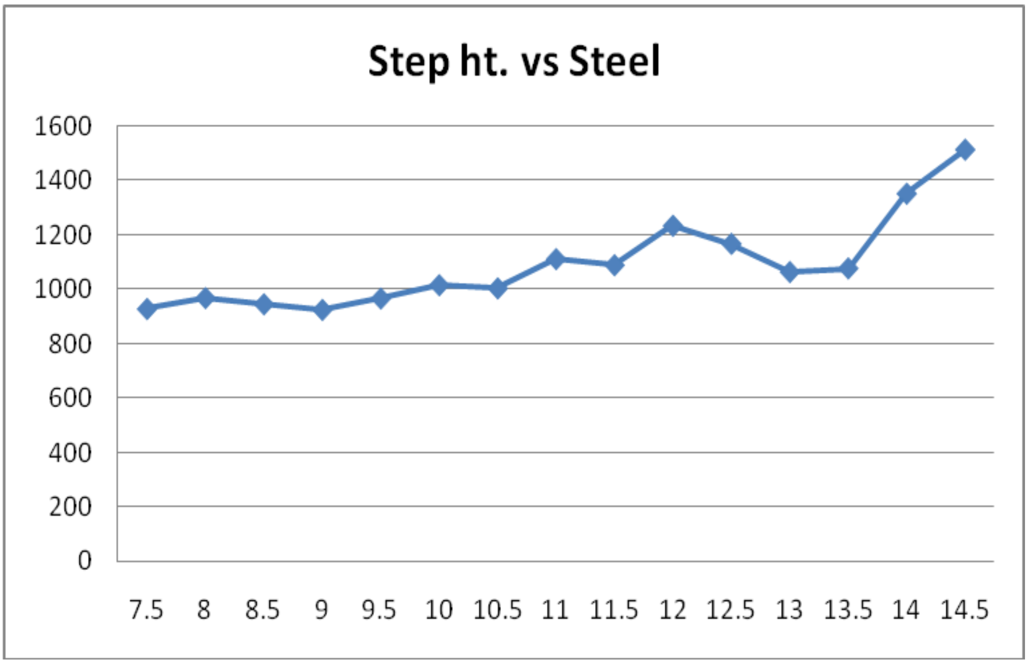
Table 5: Stability analysis and cost comparison for wall ht.15m

Step from top m	Width of toe slab m	Width of heel slab m	Depth of base slab m	Total base slab m	Stem thickness in m top	Bottom.
7.5	2.1	6.3	0.75	9.5	0.35	1.1
8	2.15	6.1	0.75	9.15	0.35	0.9
8.5	2.12	5.73	0.75	8.75	0.35	0.9
9	2.12	5.46	0.75	8.5	0.35	0.92
9.5	2	5.33	0.72	8.15	0.35	0.82
10	2	5.225	0.8	8.195	0.35	0.97
10.5	2	4.7	0.75	7.8	0.35	1.1
11	2.1	4.15	0.75	7.5	0.35	1.25
11.5	2.2	3.75	0.75	7.25	0.35	1.3
12	2.25	4.45	0.75	8	0.35	1.3
12.5	2.4	4.1	0.75	7.8	0.35	1.3
13	2.6	4.2	0.785	8.1	0.35	1.3
13.5	2.8	4.4	0.85	8.5	0.35	1.3
14	2.9	5.1	0.9	9.3	0.35	1.3
14.5	3	6.05	1	10.4	0.35	1.35

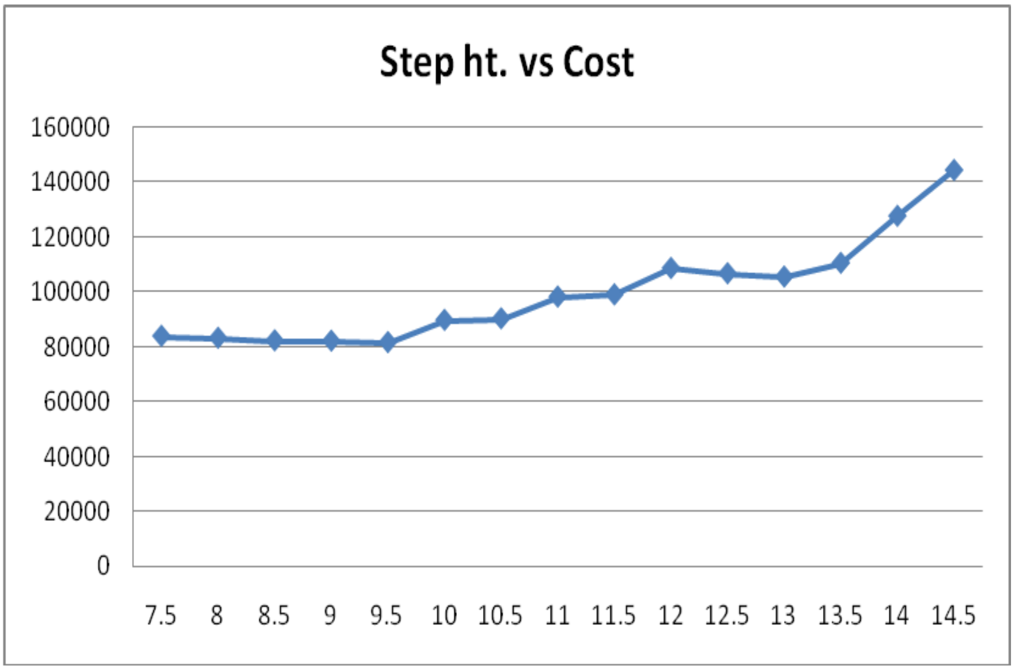
Upward soil pressure KN/m2		Effective frictional force KN	Concretem3	Steel quantity Kg/m	Cost Rs/m
Pmax.	Pmin.				
297.9	290.8	299.8	12.5625	928.64	83900.27
298.52	284.82	348.86	11.8625	968.68	83171.99
295.9	282.2	401	11.875	946	82240.5
291.9	275	457.9	12.09	925.5	82111.5
300	283.5	517.88	11.4255	967	81570.25
292.9	272.8	581.5	13.156	1015.9	89729.7
282	280.35	648.73	13.4625	1004	90290.75
264.5	276.8	719.6	14.425	1111	98260.5
238.88	283.5	794.12	14.925	1089	99064.5
267.8	271.9	872.19	15.9	1233	108669
234.5	286.35	954	16.1625	1167	106749.75
223.5	290.75	1040	17.0835	1064	105544.25
213	299	1128.5	18.3625	1077	110579.75
225	300	1221	19.92	1350	127770
246.25	300	1317.5	22.725	1511	144510.5



Graph 12: Step location Vs concrete cum/m for wall Ht. 15.0 m



Graph 13: Step location Vs steel kg/m for wall Ht. 15.0m



Graph 14: Step location Vs cost per meter for wall Ht. 15.0m

3. RESULTS AND DISSCUSSIONS

Example

The example of analysis and design of stepped cantilever retaining wall are given below.

Data Assumptions

Data assumed for the stability calculation of stepped cantilever retaining wall

- Free Board not necessary
- The backfill is enough compacted to develop necessary friction.
- Bearing Capacity of soil: 300 KN/Sq. m
- Water level is much below the level of base and effect of soil moisture is ignored.
- Dry density of soil: 18 KN/Cubic m.
- Angle of internal friction: 300
- Coefficient of friction: 0.60

- Stability is checked for sliding and overturning.
- Factor of safety against sliding = 1.5
- Factor of safety against overturning = 2.0

The moment and reinforcement provided for various heights are as shown in table

3.1 Counter fort Retaining wall

The structural analysis of counter fort Retaining wall is done as per routine analytical practices. Generally these walls are use for span more than 6m, but here in order to compare the results analysis and design of these counter fort retaining walls is done for Heights 6m to 15m. The mechanism of this wall is different from cantilever wall and here Base slab is more important design aspect.

Table 6: Dimensions of Counter fort Retaining Wall

Ht of wall m	Total Base Slab M	Width of Toe Slab	Width of Heel slab	Base slab Thk. M	Stem Thk. m	
					Top	Botm.
6	3.5	0.3	3.0	0.28	0.2	0.2
8	4.25	0.5	3.45	0.35	0.3	0.3
10	5.6	1.0	4.25	0.45	0.45	0.35
12	7.75	1.25	6.05	0.5	0.45	0.45
15	10.0	2.75	6.70	0.77	0.55	0.55

Counter fort Details

Spacing	4.0	3.5	3.0	3.0	3.0
Thickness	0.3	0.375	0.4	0.45	0.55

The analysis of Base slab for wall is presented in table Here Toe slab is designed as cantilever slab spanning from stem. The upward soil pressure will be act as major load on toe slab. But the heel slab will be designed as simply supported slab in between two adjacent counter forts. Sometimes when toe projection is larger and if there is possibility of stress reversal in stem, the counter forts are also provided on toe slab at that time Toe slab design will also be as heel slab design .The major load for heel slab will be effective load from average Upward pressure and Retained soil load on heel slab.

The base slab depth is provided as per required for maximum Bending Moment while reinforcement is provided as per actual requirement for Toe and Heel slab.

Table 7: Structural Analysis of Counter-fort Retaining wall (Base slab)

Height of wall m	Bending moment (KN.m)		Depth of base slab required mm	Depth of base slab Provided mm
	Toe	Heel		
6	12.67	158.98	240.03	400
8	47.58	232.12	290.00	450
10	187.55	419.80	390.00	550
12	288.36	534.34	440.00	600
15	1152.18	1391.32	710.00	850

The reinforcement provided for base slab i.e. Toe slab and various locations is shown in table 8

Table 8: Design of Base slab of counter fort retaining wall

Ht. Of wall m.	Base slab Thick. Mm	Main Steel.			
		Toe slab		Heel slab	
		Ast. mm2	Bar Dia. & Spacing	Ast. mm2	Bar Dia. & Spacing

6	400	168.73	ϕ10 @150mm	1172.70	ϕ20 @150mm
8	450	297.07	Φ12 @150mm	1538.54	ϕ20 @150mm
10	550	981.27	Φ16 @150mm	2317.76	Φ25 @150mm
12	600	1399.52	Φ20 @150mm	2724.55	Φ25 @150mm
15	850	4183.46	Φ25 @115mm	5194.55	Φ32 @150mm

The mechanism of stem of counter fort retaining wall and Cantilever retaining wall is not same. In cantilever retaining wall, stem was acting as free cantilever with span equal height of wall while in counter fort, stem acts as simply supported slab spanning in between two adjacent counter forts. The effective span for this will be span of counter fort along length of wall. The dimensions of stem are reduced due to this mechanism. The bending moment of the vertical wall is maximum at the junction of stem (wall) with Base and reduces to the zero at the top of the wall.

The moments and reinforcement provided for various heights are as shown in table 9

Table 9: Moment and Reinforcement details along length of stem for counter fort wall

Ht. of wall m.	Moments along length of stem(KNm)	Steel prov. In Vertical wall			
		Stem Thickness			
		Dreq. mm	Dprov. mm	Ast mm2	Bar Dia. & Spacing
6	72	161.51	200	1130.09	Φ10 @70mm
8	73.5	163.19	300	1736.00	Φ12 @65mm
10	67.5	156.39	350	552.52	Φ16 @150mm
12	81	171.31	450	510.83	Φ20 @150mm
15	101.25	191.53	550	520.35	Φ25 @150mm

The counter forts act as self-supporting structural elements for retaining wall. It takes reactions, both from the stem as well as Heel slab. The counter fort may be considered to bend as a cantilever, fixed at heel slab. The counter fort acts as an inverted T beam of varying rib depth. The structural analysis of counter fort is done based on above assumptions. The Max. Depth of this cantilever beam is width of heel slab. The steel reinforcement is provided as per requirement for tensile stress induced in it due to soil load on stem.

The moments and connection of counter fort details for various wall heights are as shown in table 10

Table 10: Moment and Connections of counter fort with Heel slab

Stamm.	Moment	Bar Dia. And Spacing	Connections of counter fort with Heel Slab		
			Horizontal Force	Bar Dia.	Spacing of Stirrups
6	864	Φ20 @100mm	144	Φ8	100mm
8	1792	Φ20 @100mm	168	Φ8	100mm
10	3000	Φ25 @100mm	180	Φ10	100mm
12	5184	Φ25 @100mm	216	Φ10	100mm
15	10125	Φ32 @100mm	270	Φ12	100mm

The main stress along counter fort is tensile. The connection of counter fort with base slab and stem is important for all assumed mechanism. The steel reinforcement provided is in the form of two legged stirrups of required diameter steel. The saving in steel reinforcement can be done as per curtailment / Reduction in number of stirrups from bottom to top side of wall.

3.2 Stepped Cantilever Retaining Wall

The stepped cantilever wall is new type suggested in this thesis. Here concrete steps are provided on stem projecting into backfill. The pressure compacted backfill will anchor the concrete plate/step and will develop frictional resistance force; this will act as indirect support for cantilever retaining wall. In short stem will act as propped cantilever and thus will reduce the destructive forces on stem / retaining wall.

Table 11: Summary of Dimensions of Stepped Cantilever Retaining Wall

Ht. of wall m	Total base slab m	Width of Toe Slab M	Width of Heel slab m	Base slab Thk. m	Stem Thickness	
					Top	Bot
6	2.85	0.65	1.9	0.4	0.2	0.3
8	5.25	0.95	3.9	0.4	0.2	0.4
10	6.5	1.5	4.4	0.60	0.25	0.6
12	8.5	1.65	6.2	0.65	0.3	0.65
15	10.5	2.0	7.3	0.9	0.5	1.2

Concrete Steps				
Total	Spacing	From Top	Width m	Depth m
3.5	2	4.00	0.45	0.3
4.5	2	6.0	0.45	0.5
6.0	2	8	0.6	0.5
6.0	1.5	8	0.6	0.65
5.75	1.25	7.75	0.75	0.7

There is reduced soil load on base slab of wall firstly due to decreased base slab width and secondly due to reduction in load of soil resting on concrete steps/plates in backfill. In this case of wall interestingly it was the case that, wall was stable at shorter dimensions but the stem was pulled inside backfill due to assumed frictional force hence the structural dimensions were not much reduced to keep balance between self weight and resisting forces.

The forces acting and analysis and design of base slab for this new stepped cantilever retaining wall are as shown in Table12

Table 12: Structural Analysis of Stepped cantilever Retaining wall (Base slab)

Ht. Of wall m.	Bending moment (KNm)		Thickness Required mm	Thickness Provided Mm
	Toe	Heel		
6	72.03	105.00	195.05	400
8	205.34	800.88	538.68	650
10	581.84	987.57	598.18	750
12	656.00	1112.92	618.55	800
15	979.98	1553.13	750.15	900

Table 13: Design of Base slab of Stepped cantilever Retaining wall

Ht. of wall m.	Base slab Thick. Mm	Main Steel.			
		Toe slab		Heel slab	
		Ast. mm2	Bar Dia. & Spacing	Ast. mm2	Bar Dia. & Spacing
6	400	505.63	ϕ12 @150mm	741.68	Φ16 @150mm

8	650	887.99	Φ20 @150mm	3623.94	ϕ25 @135mm
10	750	2217.81	Φ25 @150mm	3854.36	Φ32 @150mm
12	800	2343.51	Φ25 @150mm	4069.80	Φ25 @150mm
15	900	3130.30	Φ32 @150mm	5079.49	Φ36 @150mm

Ast. mm2	960	1560	1800	1920	2160
Bar Dia. & Spacing	Φ10 @80 mm	Φ12 @75 mm	Φ16 @100mm	Φ16 @100 mm	Φ16 @90mm

The R.C.C. steps / plates projecting in backfill are main key elements in this type of wall. The Resisting force developed due to these steps is function of depth of these steps below top of wall, surface roughness of concrete plates, degree of compaction of backfill and specific weight of backfill. The steps are developing frictional force due to their anchorage in backfill and steps are reinforced with sufficient steel required for tensile stress developed in it due to pulling effect. Though these steps are standing as free cantilever in backfill, they will not be designed as cantilever as it is assumed as backfill is compacted.

The details of forces acting and design of these concrete steps is as shown in Table 14

Table 14: Concrete Step analysis and design details

Ht. of wall m	Step Dimensions		Location	
	Width	Depth	Depth below Top	In Fill Embedment
6	0.4	0.3	4.0	3.5
8	0.5	0.3	5.5	4.5
10	0.6	0.3	6.5	5.5
12	0.65	0.4	7.5	6.5
15	0.7	0.45	9.5	7.5

Reinforcement Details		Step spacing along length	Frictional force developed
Dia	No		
12	4	2.0	67.68
12	6	2.0	151.47
12	8	2.0	244.30
12	12	1.5	342.23
16	10	1.25	517.10

In this type of wall the nature of moment variation will be similar as that of Cantilever retaining wall but there will be drastic change in moment at the point where concrete step is projected inside backfill. Up to this point the moment will be function of height of backfill but below this the moment will be algebraic sum of both resisting and destructive moments i.e. Destructive moment due to backfill and resisting moment of frictional force developed due to step.

The steel reinforcement will be provided not only adhering to moment values but with also consideration to minimum steel quantities and Practical site considerations also.

The table 15 and 16 shows the moment variation and steel reinforcement provided for this stepped cantilever wall

Table 15: Moment Variation Along length of stem for Stepped cantilever Wall

	6m		8m		10m	
	Moment KNm	D Prod Mm	Moment KNm	D Prod mm	Moment KNm	D Prod mm
0-L/4	3.375	225	8.0	250	15.63	300
L/4-L/2	27.0	250	64.0	300	125	400
L/2-2L/3	91.12	275	216.0	450	421.87	600
2L/3-L	35.52	300	310.04	550	674.27	750

	12m		15m	
	Moment KNm	D Prod mm	Moment KNm	D Prod Mm
0-L/4	27.0	350	52.7	400
L/4-L/2	216.0	500	421.9	700
L/2-2L/3	729	750	1423.8	1000
2L/3-L	1385.77	1000	2944.08	1400

Table 16: Reinforcement details along Height of stem

Ht. of wall m.	Moment Variation along length of stem(KNm)	Steel prov. In Vertical wall			
		Stem Thickness			
		Dreq. Mm	Dprov. Mm	Ast mm2	Bar Dia. & Spacing
6	35.52	138.94	300	500.82	Φ12 @150
8	310.04	410.49	500	2732.36	Φ20 @115mm
10	674.27	605.35	700	4274.66	Φ25 @115mm
12	1385.77	867.83	950	4238.38	Φ25 @115mm
15	2944.08	1264.93	1350	9803.36	Φ32 @80mm

3.3 Unit Cost per Meter of Wall

A) Counter fort Retaining Wall:

The cost of counter fort retaining wall includes cost of concrete for stem, counter fort and base slab is added, and the steel quantity is calculated from actual steel used with some provision for wastage also. For counter fort retaining wall, the cost of wall is calculated for total spacing of counter forts and from this per meter cost of wall is calculated.

The cost per running meter for counter fort retaining wall for various retain heights is as shown in table

Table 17: Cost per Running Meter for Counter fort Retaining

Ht. of wall	6m		8m	
Location	Concretem3	Steel kg	Concretem3	Steel kg
Stem	1.2	76.08	2.4	137.6
Base slab	0.98	66.16	1.49	80.08
Counter Forts	2.7	137.2	5.18	234.05
Total	4.88	279.44	9.07	451.73
Rate	3500	43	3500	43
Amount	17080	12015.9	31745	19424.39
Sum	29095.9		51169.4	
	29100		51170	

10m		12m		15m	
Concretem3	Steel kg	Concretem3	Steel kg	Concretem3	Steel kg
3.5	156.8	5.4	251.52	8.25	439.7
2.52	139.86	3.9	229.82	7.7	475.28
8.5	527.98	16.34	765.5	27.64	1810.55
14.52	824.64	25.64	1246.84	43.59	2725.53
3500	43	3500	43	3500	43
50820	35459.52	89740	53614.12	152565	117197.79
86279.52		143354.1		269763	
86280		143360		269770	

B) Stepped Cantilever Retaining Wall:

As like for counter fort retaining wall, the cost of stepped cantilever retaining wall will be calculated firstly as per spacing of steps in backfill along length of wall and hence it is transferred to per meter cost. The construction practice for stepped cantilever wall will not be very special than cantilever wall hence except extra amount for backfill compaction, no any extra provision is made in cost calculation.

Table 18: Cost per running meter for Stepped Cantilever Retaining Wall

Ht. of wall	6m		8m	
Location	Concretem3	Steel kg	Concretem3	Steel kg
Stem	3	142.78	4.8	476.72
Base slab	2.28	84.91	4.2	370.71
Steps	0.25	8.2	0.39	16.63
Total	5.53	235.89	9.39	864.06
Rate	3500	43	3500	43
Amount	19355	10143.3	32865	37154.58
Sum	29498.3		70019.58	
	29500		70000	

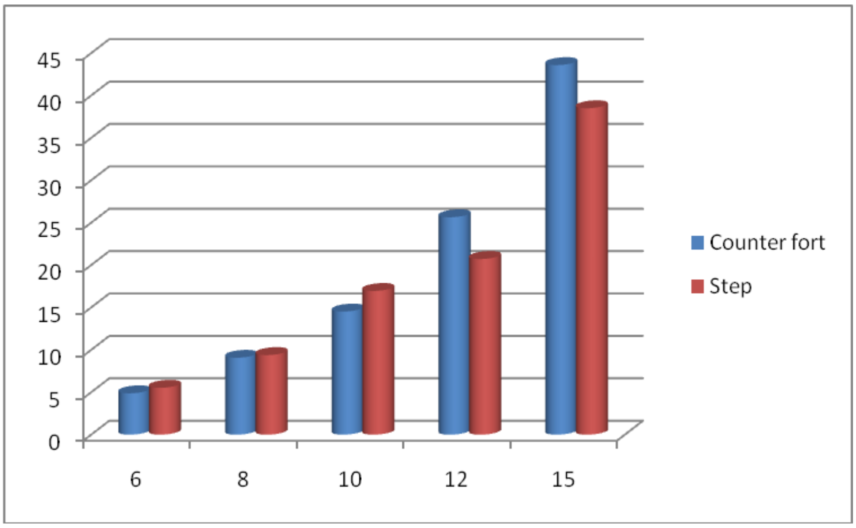
10m		12m		15m	
Concretem3	Steel kg	Concretem3	Steel kg	Concretem3	Steel kg
8.6	972.2	11.52	602.65	25.5	1688.23
7.8	623.21	8.29	500	11.8	850.07
0.55	26.18	0.9	59.69	1.2	100.88
16.95	1621.59	20.71	1162.3	38.5	2639.18
3500	43	3500	43	3500	43
59325	69728.4	72485	49981	134750	113485
129053		122466		248235	
129050		122470		248240	

3.5 Cost Comparison:

The cost per meter for all these three proposed types is tabulated above. In table 6.19 the comparison of concrete quantity per meter for different wall heights and different wall types are shown.

Table 19: Comparison of Concrete for Different Walls

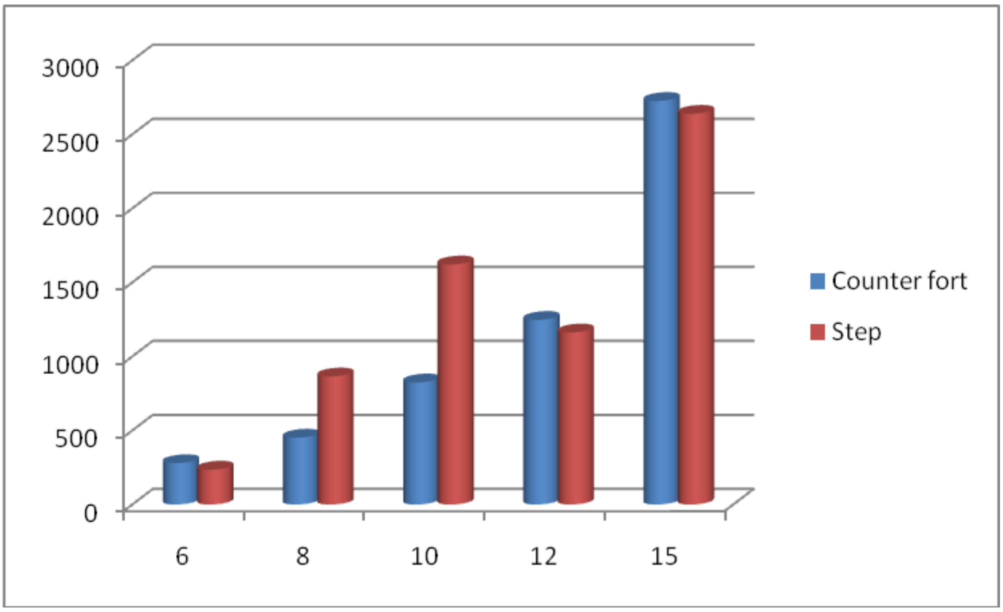
Wall Ht. m	Counter fort wall	Stepped Cantilever wall
6	4.88	5.53
8	9.07	9.39
10	14.52	16.95
12	25.64	20.72
15	43.59	38.5



Graph15: Concrete Quantity Comparison

Table 20: Steel reinforcement per meter of wall

Wall Ht. m	Counter fort wall	Stepped Cantilever wall
6	279.44	235.89
8	451.73	864.96
10	824.64	1621.59
12	1246.84	1162.34
15	2725.53	2639.18

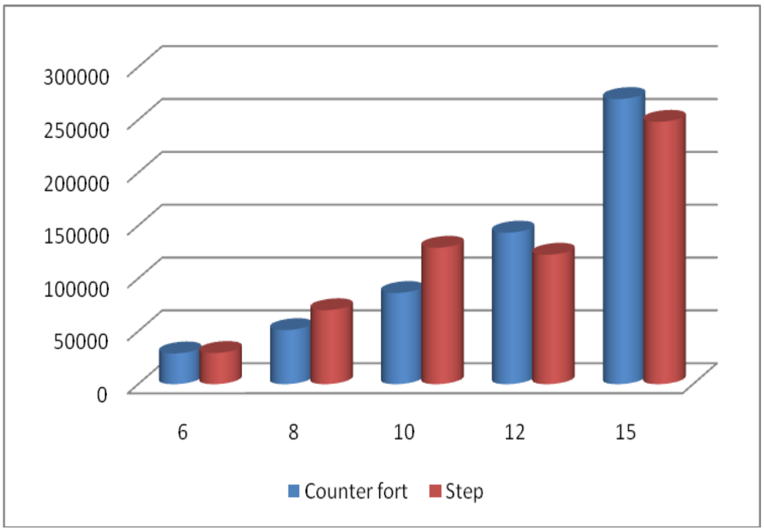


Graph 16: Reinforcement Quantity Comparison

The table 21 shows final cost comparison of all these wall types for same heights and graph 17 showing variation.

Table 21: Final Cost Comparison

Wall Ht. m	Counter fort wall	Stepped Cantilever wall
6	29100	29500
8	51170	70000
10	86280	129050
12	143360	122470
15	269770	248240



Graph 17: Final Cost Comparison

It is clear from table that for heights from 8.0 M to 10.0 M counter fort retaining wall is giving economical results. Hence counter fort wall is better alternative for retaining heights up to 10.0 M. Other wall types may also be checked depending on actual site conditions.

The stepped cantilever is giving best result for height more than 10.0 M, from this height counter fort retaining walls are being uneconomical.

5. CONCLUSION

Cantilever retaining walls are economically suited for wall heights up to 6.0 M and hence for height up to 6.0 M, no other alternative is necessary.

Counter fort retaining walls are suitable for retaining wall heights 8.0 M to 10.0 M for standard site conditions assumed. The other types of wall may also be tried for different site conditions.

At first instant, Stepped cantilever Retaining wall are economically best suited for wall heights from 11.0 M to 15.0 M. this is proving to be better alternative for large wall heights as more than 11.0 M. Its mechanism is proven and used in many civil engineering structures.

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