MULTI OBJECTIVE OPTIMIZATION OF REINFORCED CEMENT CONCRETE RETAINING WALL

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ABSTRACT

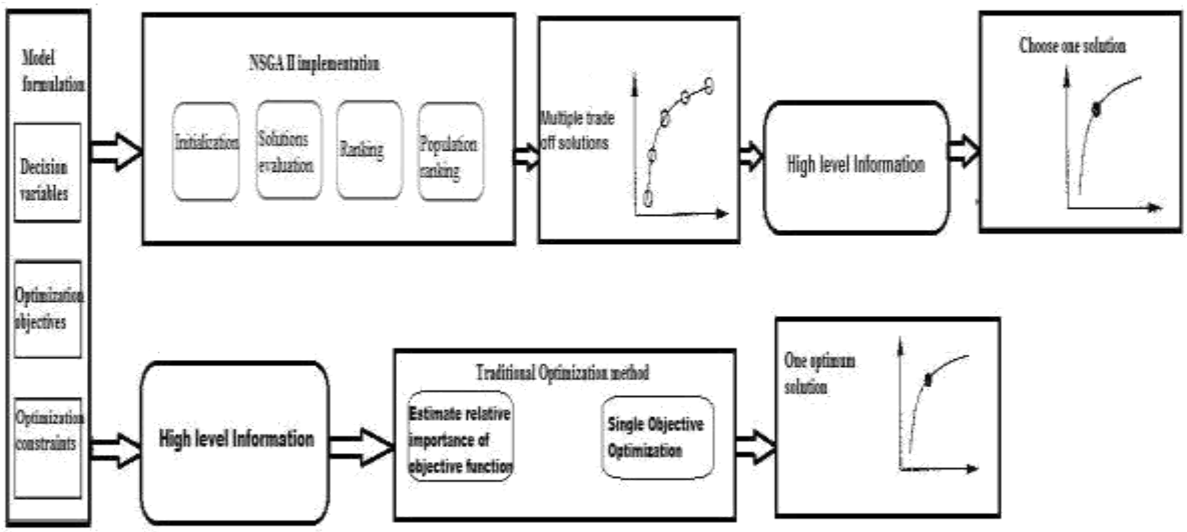
The optimum design of reinforced cement concrete cantilever (RCC) can be solved in the for the minimum cost satisfying required external and internal stability criteria. For high level decision making, an ideal optimization should give the optimized cost vis-a-vis corresponding factor of safety (FOS) against external stability like bearing, sliding and overturning, which is known as multi-objective optimization problem. In the present work multi-objective optimization of the RCC retaining wall is presented with conflicting objectives of minimum cost and maximum factor of safety against external stability. The Pareto-optimal front is presented using an evolutionary multi-objective optimization algorithm, non-dominated sorting genetic algorithm (NSGA-II). The results are compared with that obtained using single objective optimization of minimizing the cost. Based on the results a guideline for the optimum dimensioning of the RCC cantilever retaining wall is presented.

Keywords: *Paretrol-Optimal Front, FOS, RCC Cantilever.*

INTRODUCTION

In structured for supporting a vertical or nearly vertical earth back fill. The other uses of retaining development of roads with constrained inland space in permanent ways, retaining walls is generally include hill side roads, elevated and depressed roads, canals, erosion protection, bridge abutments, etc. The reinforced cement concrete cantilever (RCC) retaining wall is the most common type of retaining wall used in such cases. The design of RCC retaining wall is a trial and error process, in which a trial design with its geometry is proposed (may be as per existing guideline) and checked against different stability criteria [31]. Very often it is an over designed wall with hardly any consideration for optimum dimension. However, the economy is an essential part of a good engineering design and needs to be considered explicitly in design to obtain an optimum section.

The optimum section of a retaining wall can be considered in the framework of an optimization problem and can be solved using the optimization techniques. . In all the above work, the optimization problem has been framed with a single objective of minimizing cost, satisfying the stability against external stability criteria. For high level decision making, an ideal optimization should give the optimized cost vis-a-vis corresponding factor of safety (FOS) against external stability like bearing, sliding and overturning. Hence the more generic problem with a retaining wall is to minimize the cost and to maximize factor of safety (FOS) against external stability. Such type practical optimization problems with more than one conflicting objectives like minimizing the cost and maximizing the FOS against bearing, sliding and overturning is known as multi-objective optimization or vector optimization.



LITERATURE REVIEW

The optimum section of a retaining wall can be considered in the framework of an optimization problem and can be solved using the optimization techniques. Keskar and Adidam [19] have used an interior penalty function based nonlinear optimization technique (Deb [12]) for the design of a cantilever retaining wall. Saribas and Erbatur [33] used separate optimization models to find out optimum cost and minimum weight of the cantilever retaining wall using interior penalty functions. Castillo et al. [7], Low [24] and Babu and Basha [3] discussed the optimum design of retaining wall using reliability based method.

Methods for developing low-cost and low-weight designs of reinforced concrete retaining structures have been the subject of research for many years (Fang et al. [16]; Rhomberg and Street [31]; Alshawi et al. [2]; Keskar and Adidam [19]; Saribaş and Erbatur [33]; Low et al. [25]; Chau and Albermani [9]; Bhatti [4]; Babu and Basha [3]). However, the application of heuristic and evolutionary methods to the design of retaining structures is relatively new: Ceranic et al. [8] and Yepes et al. [36] applied simulated annealing (SA); Ahmadi-Nedushan and Varaee [1] used particle swarm optimization (PSO); and Kaveh and Abadi [18] applied harmony search. Recently, Camp and Akin [5] discussed the optimum design of retaining wall using an evolutionary algorithm, big-bang big crunch (BBBC) algorithm. Although the research into the design of retaining structures using evolutionary methods is limited, there are numerous studies on their application to reinforced concrete structures. Coello Coello et al. [11], Rafiqa and Southcombea [29], Rajeev and Krishnamoorthy [30], Camp et al. [6], Lee and Ahn [22], Lepš and Šejnoha [23], Sahab et al. [32], Govindaraj and Ramasamy [17], and Kwak and Kim [20,21] all applied various forms of GAs to the cost-optimization problem. Paya et al. [26], Perea et al. [28], and Paya-Zaforteza et al. [27]

It can be seen that in case of traditional multi-objective optimization, it is converted to single objective optimization problem with importance attached to each objective or taking other objectives as constraints. But an ideal multi-objective algorithm should find out a set of Pareto optimal solution considering all the objectives as equally important. Then one of the solutions is chosen considering higher level information at the decision making level. Population-based evolutionary multi-objective optimization (EMO) is able to generate the required Pareto front in a single run. A comprehensive review of EMO algorithms can be found in Deb [12] and Coello et al. [10]. But, application of multi-objective optimization is limited in geotechnical engineering (Deb and Dhar [13]; Deb et al. [14]). Deb and Dhar [13] proposed a combined simution-optimization-based methodology to identify the optimal design parameters for granular bed–stone column-improved Then the optimization results of retaining wall in multi-objective framework using Elitist non dominated sorting genetic algorithm (NSGA-II) (Deb [12]) are discussed.

ANALYSIS AND METHODOLOGY

The analysis consists of (i) formulation of the optimization problem and (ii) solution of the optimization problem using traditional and genetic algorithms. The formulation of the optimization problem and its solutions are presented as follows.

Formulation of the objective function

In the present formulation for the single objective optimization problem, the total cost (to be minimized), which consists of cost of concrete and cost of steel reinforcement, is considered.

Minimize Total Cost (TC) per meter run

$TC = f\,(L_h, L_t, S, b, t, p_{tt}, p_{th}, p_{ts})$

$TC = c_c Q_c + c_r W_{st}$

Where c_c , c_r are the unit rate of concrete and steel reinforcement respectively and the rates are taken from the Delhi Schedule of Rates 2007 (DSR -2007 [15]). Q_c and W_{st} are the volume of concrete and weight of reinforcement steel, respectively. The cost of shuttering is not considered keeping in mind its effect is minimal in the total cost and it depends on the volume of the concrete. However, if desired it can be considered for the optimum cost design.

The geometric parameters of the retaining wall like top width of stem, heel projection, toe projection and their thickness, percentage of the reinforcement in base slab and stem are considered as the design variables which are varied to reach the optimum cost.

The above variables are presented in Fig. and are described as follows:

L_h = projection of heel from the base of the stem;

Constraints:

The constraints are considered in terms of criteria for external and internal stability of retaining wall.

The different constraints considered in terms of factor of safety (FOS) are as follows:

External stability

FOS against overturning $FS_{ot} \geq 2.0$

FOS against sliding $FS_{sli} \geq 1.5$

FOS against eccentricity $FS_e \geq 1.0$

FOS against bearing $FS_b \geq 3.0$

Internal stability

As RCC cantilever retaining wall is being considered in this paper, the internal stability in terms of flexure and shear failure are calculated based on IS: 456 -2000 (Indian standard specification for plain and reinforced concrete) using limit state method.

FOS against toe shear failure $FS_{tsh} \geq 1.5$

FOS against toe moment failure $FS_{tm} \geq 1.5$

FOS against heel shear failure $FS_{hsh} \geq 1.5$

FOS against heel moment failure $FS_{hm} \geq 1.5$

FOS against stem shear failure

FOS against stem moment failure $FS_{sm} \geq 1.5$

The details of external and internal stability analysis considered for the proposed study is presented here as followings.

Evolutionary Multi-objective (EMO) Algorithm, (NSGA-II)

The non-dominated sorting genetic algorithm (NSGA), which was proposed by Srinivas and Deb[34], had shortcomings like high computational complexity of non dominated sorting, lack of elitism and need for specifying the sharing parameter. All those issues were overcome in NSGA-II, which is a simple constraint handling EA. It is efficient in handling both single and multi-objective problems.

NSGA-II has some improved features such as fast non-dominated sorting procedure, an elitist-preserving approach and a parameter less niching operator. The brief description of NSGA-II is discussed below and details can be found in Deb [12]. The major steps in implementation of NSGA-II can be described as population initialization, non-dominated sort, crowding distance, selection and GA parameters- crossover and mutation. A flowchart showing the NSGA-II algorithm is presented in fig. 1.

The population is initialized based on the problem range and constraints. Then solution for each objective is found. It is sorted into each front on the basis of non-domination using fast sort algorithm. The first front is completely non-dominant set in the current population and second front is dominated by the individuals in the first front only and so on. Fitness value of each individual is evaluated and they are assigned rank **accordingly** to absolute normalized difference in the function values of two adjacent solutions.

Once the non-dominated sort is complete, the crowding-distance is calculated for each individual. The crowding-distance measures how close an individual is to its neighbors. The crowding computation requires sorting the population according to each objective function value in ascending order of magnitude. Then, for each objective function, the boundary solutions (solution with smallest and largest function values) are assigned an infinite distance value. For other intermediate solutions, they are assigned a distance value equal to the absolute normalized difference in the function values of two adjacent solutions. This is continued with other objective functions also. The overall crowding-distance value is then calculated as the sum of individual distance values corresponding to each objective. Crowding-distance sort is done in order to maintain the diversity in the population. Diversity is an important aspect in EA.

Parents are selected from the population by using binary tournament selection with crowded-comparison operator which is based on the rank and crowding distance. An individual is selected if the rank is lesser than the other or if crowding distance is greater than the other (crowding distance is compared only if the ranks for both individuals are same). The selected population generates offspring from crossover and mutation operators. The NSGA II uses Simulated Binary crossover (SBX) operator for crossover and polynomial mutation. During the process, elitism is ensured by combining the offspring population with the parent population and then selecting individuals for the next generation. Again the combined population was sorted according to non-domination. Then new generation was filled by each front subsequently until the population size exceeds the current population size. The above process is repeated to generate the subsequent generations.

RESULTS AND DISCUSSION

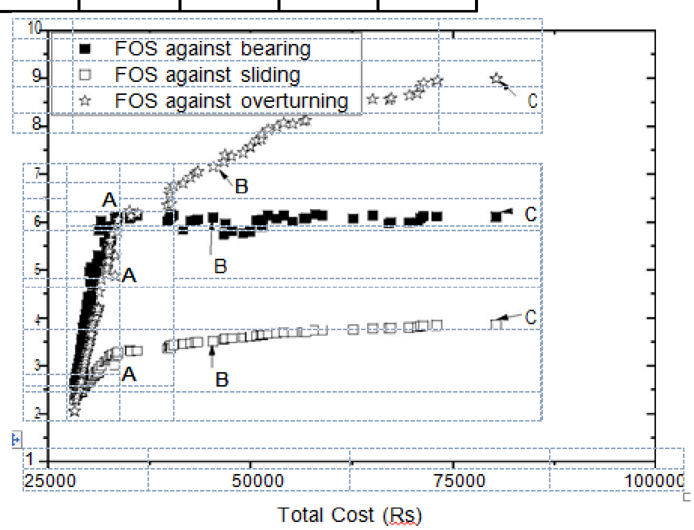
As discussed earlier, the optimized design of retaining wall is considered in both single and multi-objective optimization framework. Hence, the single and multi-objective optimization results are presented and discussed separately. In case of single objective optimization the minimization of cost is taken as the objective with both external and internal stability criteria as constraints as discussed in the previous section.

Table Optimum normalized dimensions of retaining wall of different height for different ϕ values

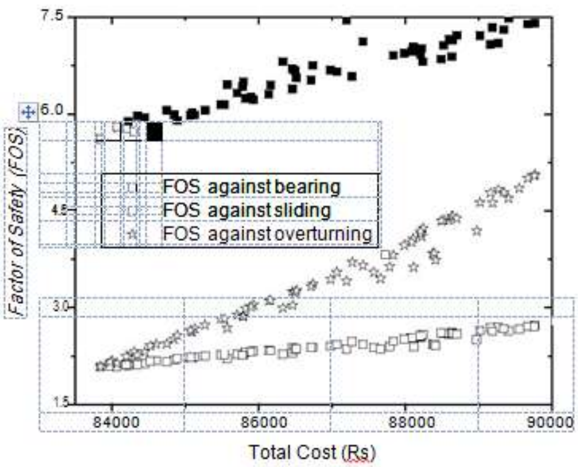
Φ (Degree)	**Normalized Dimensions**	**Height of retaining wall (m)**							
		3	**4**	**5**	**6**	**7**	**8**	**9**	**10**
	S/H	0.05	0.06	0.07	0.08	0.08	0.08	0.09	0.1
	b/H	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.08
20	**L_t/H**	0.33	0.25	0.3	0.33	0.31	0.23	0.22	0.2
	L_h/H	0.21	0.27	0.26	0.28	0.4	0.69	0.78	0.8
	t/H	0.06	0.04	0.05	0.05	0.06	0.08	0.06	0.07
	S/H	0.05	0.06	0.07	0.07	0.07	0.08	0.08	0.08
	b/H	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.1
25	**L_t/H**	0.33	0.25	0.28	0.34	0.33	0.3	0.21	0.2
	L_h/H	0.17	0.2	0.2	0.16	0.24	0.33	0.63	0.75
	t/H	0.04	0.04	0.05	0.06	0.06	0.06	0.05	0.07
	S/H	0.03	0.05	0.06	0.06	0.07	0.07	0.07	0.08

	b/H	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01
30	**L_t/H**	0.33	0.25	0.2	0.31	0.33	0.26	0.26	0.19
	L_h/H	0.17	0.17	0.22	0.13	0.13	0.31	0.33	0.59
	t/H	0.03	0.04	0.04	0.05	0.06	0.06	0.05	0.06
	S/H	0.04	0.04	0.05	0.06	0.06	0.06	0.07	0.07
	b/H	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01
35	**L_t/H**	0.17	0.25	0.2	0.21	0.26	0.3	0.23	0.17
	L_h/H	0.19	0.13	0.16	0.19	0.14	0.13	0.28	0.52
	t/H	0.03	0.04	0.04	0.05	0.05	0.06	0.06	0.05
	S/H	0.03	0.04	0.04	0.05	0.05	0.06	0.06	0.06
	b/H	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01
40	**L_t/H**	0.17	0.25	0.2	0.17	0.21	0.25	0.22	0.19
	L_h/H	0.17	0.13	0.13	0.18	0.14	0.1	0.18	0.3
	t/H	0.02	0.03	0.04	0.04	0.05	0.05	0.06	0.05
	S/H	0.03	0.03	0.04	0.04	0.05	0.05	0.05	0.06
	b/H	0.02	0.04	0.01	0.01	0.01	0.01	0.01	0.01
45	**L_t/H**	0.17	0.13	0.2	0.17	0.16	0.2	0.21	0.19
	L_h/H	0.17	0.14	0.1	0.11	0.14	0.11	0.11	0.17
	t/H	0.02	0.01	0.03	0.04	0.04	0.04	0.05	0.06

It was observed that S/H ratio increased with increase in height of retaining wall, but is almost independent of ϕ value. Though L_t/H does not vary much with height of the wall, but there is a substantial increase in L_h/H value with the height of the retaining wall for different ϕ value. The stem thickness ratio t/H varies from 0.04 to 0.07.



Showing the variation of FOS (factor of safety) against bearing, sliding and overturning with total cost (For height of 6.0m and angle of internal friction of 30^0)



Variation of factor of safety with total cost against bearing, sliding and overturning Figure for the RCC RW of height 6m and ϕ of 20^0

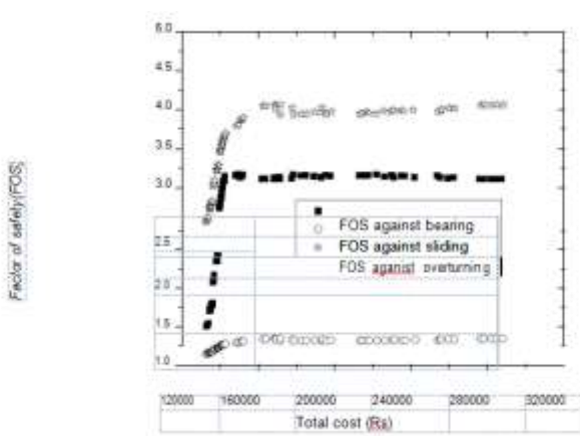
It is evident that due to in decrease in ϕ value, the total cost increased. It is also observed that, the increase in FOS against sliding is very less as compared to the FOS against bearing and overturning.

Table The dimensions of the retaining wall and the percentage of reinforcement for the RW of 7m and ϕ of 20^0

L_t	L_h	t	S	B	P_{ts}	P_{th}	P_{tt}
1.883549	2.826453	0.991749	0.653579	0.101565	0.001200	0.001262	0.001204
2.724518	1.908309	0.999704	0.649582	0.108120	0.004540	0.006221	0.001266
2.890437	1.900427	0.997153	0.502223	0.104399	0.005327	0.007548	0.004870
2.871614	1.900679	0.973811	0.502223	0.101379	0.004165	0.001253	0.004870
2.517208	2.148268	0.994184	0.654817	0.101862	0.002432	0.001568	0.003554
2.247351	2.634007	0.984631	0.655261	0.102117	0.001200	0.001233	0.001239
2.742916	1.840739	0.942169	0.658667	0.103244	0.001650	0.001202	0.001209
3.014428	1.776613	0.996187	0.485006	0.100028	0.003643	0.002659	0.001769
1.543815	2.599614	0.989476	0.653528	0.101315	0.001200	0.001241	0.001202
2.250558	2.392585	0.981639	0.655385	0.100504	0.001200	0.001341	0.001231
1.551913	1.413553	0.991764	0.652005	0.100090	0.001200	0.001204	0.001201
2.681107	1.625418	0.998167	0.651592	0.108334	0.001200	0.001245	0.001201

1.657036	1.770498	0.992759	0.652844	0.100206	0.001200	0.001203	0.001213
1.653559	1.590260	0.988023	0.652844	0.100212	0.001200	0.001201	0.001216
2.571273	2.158902	0.999900	0.655705	0.103483	0.002763	0.001208	0.004126
2.968490	1.683329	0.990773	0.574165	0.102607	0.001766	0.001207	0.001275
2.968976	1.604528	0.995872	0.567651	0.100987	0.001766	0.001229	0.001756
1.526285	1.494612	0.991899	0.652807	0.101414	0.001200	0.001207	0.001218
1.820907	1.775813	0.981876	0.655223	0.100002	0.001200	0.001207	0.001203
2.724518	1.908309	0.999704	0.640369	0.108120	0.003942	0.006221	0.001250
2.578879	2.148268	0.970256	0.639916	0.105978	0.001886	0.001236	0.001229
2.723648	1.908309	0.999356	0.640369	0.110883	0.003942	0.006221	0.001250
2.571273	2.158902	0.999900	0.655649	0.103483	0.002763	0.001208	0.004126
1.586715	2.123870	0.982184	0.655142	0.101425	0.001200	0.001204	0.001205
2.136024	1.683382	0.979715	0.655223	0.101285	0.001200	0.001205	0.001200
1.624900	1.574350	0.988023	0.652844	0.100016	0.001200	0.001201	0.001228
2.733506	1.908309	0.999899	0.624764	0.114858	0.003496	0.005584	0.001273
1.960392	1.693114	0.991721	0.652686	0.101042	0.001200	0.001257	0.001201
3.014428	1.776613	0.996288	0.485006	0.100028	0.003643	0.002659	0.001769
2.905046	1.631478	0.991501	0.660778	0.105116	0.001544	0.001327	0.003785
2.305351	1.625418	0.998167	0.651114	0.107852	0.001200	0.001245	0.001201
1.577054	2.554409	0.991479	0.652005	0.100319	0.001200	0.001369	0.001201
2.186129	2.644198	0.979715	0.655275	0.101285	0.001200	0.001249	0.001200
2.724518	1.907397	0.985873	0.649837	0.103610	0.004540	0.006160	0.001212
2.733506	1.908309	0.999899	0.624764	0.115718	0.004540	0.004925	0.001267

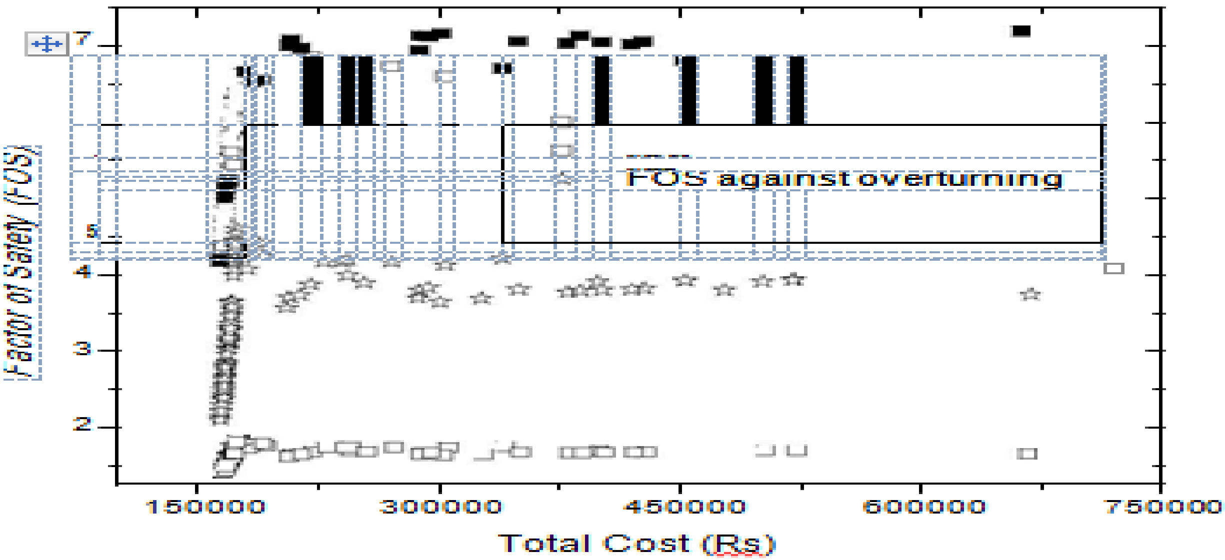
2.103489	2.479744	0.984914	0.654216	0.101492	0.001200	0.001204	0.001206
1.966080	2.766232	0.991749	0.653590	0.101583	0.001200	0.001220	0.001213
1.948256	1.563248	0.995422	0.652005	0.100075	0.001200	0.001228	0.001202
2.545496	2.226513	0.997519	0.640502	0.100855	0.001354	0.001230	0.006173
2.890439	1.908309	0.998933	0.502223	0.107686	0.004735	0.006771	0.002053
2.710802	1.927983	0.999618	0.649400	0.108120	0.001886	0.001365	0.001211
2.196958	2.479493	0.984205	0.653528	0.102721	0.001201	0.001228	0.001206
2.733506	1.908309	0.999957	0.624764	0.115718	0.004540	0.004925	0.001267
2.197613	1.711894	0.980869	0.655385	0.103077	0.001200	0.001212	0.001208
1.847724	2.113309	0.992056	0.655636	0.100075	0.001200	0.001201	0.001201
1.921335	2.087780	0.991749	0.655636	0.100075	0.001200	0.001254	0.001202
2.256970	1.683382	0.979715	0.655223	0.101802	0.001200	0.001201	0.001207
1.421447	1.597749	0.989698	0.653505	0.100257	0.001200	0.001244	0.001202
1.847860	1.696476	0.991106	0.652686	0.100016	0.001200	0.001202	0.001204
2.136024	1.683382	0.979715	0.655223	0.101285	0.001200	0.001205	0.001200
1.653559	1.590260	0.999642	0.652844	0.100212	0.001200	0.001201	0.001216



variation of factor of safety with total cost against bearing, sliding and overturning Figure For the RCC RW of height 10m and ϕ of 20^0

It can be seen that the optimum cost is different, but the trend in variations of total cost with the FOS are similar. It can also be seen that there is an optimum point upto which the FOS can be increased with the cost, but then after the increase in dimension of the retaining wall increased the cost, but with minor changes in the FOS value.

It was found in the table that there are some points very close to each other as part of the Pareto set. This is due to the fact that in case of a population based approach, few solutions may be very close. It can be seen that in comparison to L_h value there is wide variation in L_t value (2.05 to 3.86). Similarly, the thickness of base slab is almost constant, but there is a change in the 'b' corresponding to increase in cost and FOS value. To compare the effect of angle of internal friction value, the variation of cost and FOS for a retaining wall of 10m height and $\phi = 40^0$ is shown in Fig..



Variation of factor of safety with total cost against bearing, sliding and overturning Figure for the RCC RW of height 7m and ϕ of 20^0

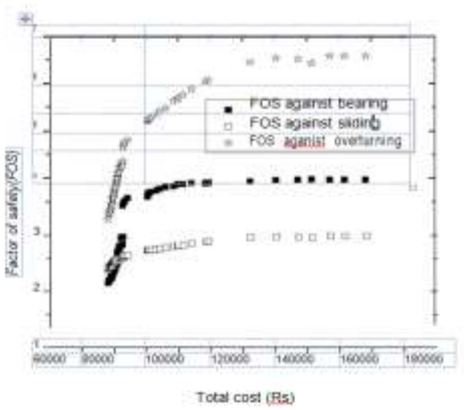
From the graph, it is observed that though there is very marginal increase in the FOS against sliding. But the peak increase in the FOS against overturning and bearing with increase in cost of Retaining wall It can be seen that as expected the total cost increases with increase in height of the wall and decreased with increase in ϕ value. It can be seen that there is a significant decrease in the cost with ϕ value and height of wall beyond 5m. Hence, optimum dimension of retaining walls up to 5.0m can be considered as one group and walls above 5.0m can be considered as another group.

The variation in the FOS against the external stability criteria; overturning, sliding, eccentricity and bearing with different angle of internal friction of backfill soil for various heights are presented as follows. Fig. 6 shows the variation in FOS against overturning with ϕ value for different heights of the retaining wall.

Table The dimensions of the retaining wall and the percentage of reinforcement for the R of 10m and ϕ of 40^0

L_t	L_h	t	S	b	P_{ts}	P_{th}	P_{tt}
1.032	2.840	0.437	0.721	0.054	0.577	0.672	0.519
1.013	2.690	0.437	0.721	0.054	0.577	0.672	0.526
1.416	3.000	0.558	0.962	0.575	0.314	0.158	0.266
1.745	2.988	0.486	0.757	0.081	0.522	0.313	0.753
1.786	2.993	0.486	0.756	0.100	0.522	0.302	0.753
1.786	2.994	0.486	0.756	0.142	0.522	0.302	0.753
1.147	2.999	0.432	0.994	0.999	0.308	0.243	0.377
1.619	3.000	0.559	0.937	0.229	0.337	0.266	0.387
1.046	2.962	0.437	0.721	0.055	0.577	0.672	0.529
1.573	3.000	0.559	0.952	0.164	0.323	0.209	0.371
1.313	3.000	0.432	0.918	0.763	0.345	0.264	0.467
1.003	2.804	0.451	0.691	0.051	0.643	0.639	0.508
1.237	2.884	0.444	0.721	0.062	0.577	0.551	0.731
1.282	2.954	0.440	0.722	0.050	0.577	0.586	0.793
1.014	2.828	0.438	0.721	0.053	0.577	0.664	0.508
1.416	3.000	0.558	0.962	0.528	0.314	0.158	0.266
1.090	3.000	0.423	0.721	0.056	0.577	0.715	0.689
1.065	2.922	0.438	0.721	0.052	0.577	0.672	0.548
1.350	3.000	0.452	0.938	0.705	0.345	0.237	0.566
1.026	2.818	0.437	0.721	0.054	0.577	0.672	0.519
1.423	2.958	0.443	0.718	0.052	0.593	0.496	0.892
1.416	3.000	0.558	0.962	0.546	0.314	0.168	0.266
1.533	3.000	0.556	0.953	0.360	0.317	0.186	0.329
1.248	2.998	0.434	0.971	0.804	0.304	0.301	0.488
1.123	2.999	0.365	0.984	0.994	0.305	0.320	0.523
1.676	2.998	0.506	0.764	0.210	0.521	0.358	0.658
1.003	2.699	0.451	0.691	0.053	0.643	0.639	0.508
1.530	3.000	0.536	0.967	0.379	0.317	0.211	0.388
1.090	3.000	0.423	0.721	0.051	0.577	0.715	0.675
1.123	3.000	0.365	0.971	0.979	0.304	0.301	0.517
1.003	2.699	0.451	0.691	0.051	0.643	0.639	0.508

In comparison to Table , it can be seen that the dimensions like Lt corresponding to $\phi = 40^0$ is less than half of that corresponding to $\phi = 20^0$, but the variation in Lh is very marginal. Similarly, though the thickness of the base slab reduced, the variation in thickness of stem slab is very less. Such a study gives the opportunity to the professional engineers not only to choose the suitable FOS and the corresponding cost, but also the corresponding footing dimensions and percentage of reinforcement



Variations of factor of safety with total cost against bearing, sliding and overturning for the RCC RW of height 10m and ϕ of 40^0

It can be seen that due to increase in ϕ value, the total cost reduced, but the trend is similar with FOS against sliding is critical. It can be mentioned here that, the increase in FOS against sliding is very less compared to FOS bearing and overturning.

CONCLUSIONS

The present study discussed about the optimum design of RCC cantilever retaining wall in a single and multi-objective framework using genetic algorithm, NSGA-II. Based on the results and discussion thereof, following conclusions can be made.

A set of effective Pareto optimal set was observed, indicating the efficacy of NSGA-II in finding out distinct and number of Pareto solutions. It was observed that there is a steady increase in FOS against bearing to increase in cost upto FOS 4.0 , then after the FOS does not change appreciably with increase in cost. It was also found that FOS against sliding is the controlling factor for the considered retaining wall.

It was also observed that in the Pareto solutions, there is wide variation in Lt value (2.05 to 3.86), though variation in L_h value is marginal. Similarly, the thickness of base slab is almost constant, but there is a change in the 'b' corresponding to increase in cost and FOS value.

It was observed that for a wall height of 10m, the dimension like Lt corresponding to $\phi = 40^0$ is less than half of that corresponding to $\phi = 20^0$, but the variation in Lh is very marginal. Similarly, though the thickness of the base slab reduced, the variation in thickness of stem slab is very less.

Such a study gives ample opportunities to the professional engineers not only to choose the suitable FOS and the corresponding cost, but also the corresponding footing dimensions and percentage of reinforcement.

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