

High MSE wall design on weak foundations

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Abstract. Retaining structures are one of the most important elements in the stabilization of excavations and slopes in various engineering projects. Mechanically stabilized earth (MSE) walls are widely used as retaining structures due to their flexibility, easy and economical construction. These benefits are especially prominent for projects built on soft and weak foundation soils, which have relatively low resistance and high compressibility. For high retaining walls on weak foundations, conventional design methods are not cost-effective. Therefore, two alternative solutions for different foundation weakness are proposed in this research: optimized multi-tiered MSE walls and single tier wall with foundation improvement. The cost optimization considers both the construction components and the land price. The results show that the optimal solution depends on several factors, including the foundation strength and more importantly, the land price. For low land price, the optimized multi-tiered wall is more economical, while for high land price (urban areas), the foundation improvement is preferable. As the foundation strength decreases, the foundation improvement becomes inevitable.

Keywords: genetic algorithm; mechanically stabilized earth walls; multi-tiered section; optimization; soft soils

1. Introduction

Retaining walls are commonly used for retaining walls, bridge abutments, slope stabilization, seawalls and dikes. Traditionally, retaining structures have been designed as gravity or cantilevered reinforced concrete walls, which are quite rigid and require deep foundations to avoid significant differential settlements. In the contrary to such rigid structures, mechanically stabilized earth (MSE) walls are flexible and cost-effective structures that can tolerate large settlements. MSE walls consist of tensile reinforcing elements embedded in the soil and facing panels that prevent soil failure between the elements, enabling safe construction on nearly vertical slopes. (Burland *et al.* 2012). MSE walls have many advantages, such as simple and rapid construction, no requirement of foundation (except a gravel pad), relatively low cost from using pre-manufactured materials, flexibility, high seismic resistance, and variety of construction materials (e.g., facing elements). These advantages make MSE walls a suitable solution for economical engineering projects such as steep-sided terrain and slope stabilization (Berg *et al.* 2009, Ho 1993, Brooks *et al.* 2010, Han 2015). The main advantage of MSE walls is that they can be built on poor and weak soils, which have

relatively low shear strength and high compressibility. Such soils may cause adverse consequences like excessive deformation and settlement for conventional structures, but MSE walls are very flexible and can withstand differential settlement. Moreover, most of the settlement occurs during construction, which can be compensated in the final grading. Therefore, these features can eliminate the need for soil improvement for projects built on weak soils and reduce the project cost by up to 50 percent (especially for tall retaining walls) (Che Mamat 2013, Dixit 2016, Kempfert and Gebreselassie 2006).

Tall retaining structures built on relatively weak and compressible soils or with site-specific limitations may require alternative solutions to improve their performance and stability. Two possible solutions are: (1) revising the structural geometry and design to reduce both the structure and the foundation stress and deformation, and (2) using ground improvement techniques to increase the bearing capacity and limit the settlement of the foundation soil. The first solution involves reconfiguring the MSE structures from single face walls into tiered walls, which can reduce the lateral earth pressure, increase the stability, and allow the structure to blend into the surrounding topography in urban areas (Sankey and Soliman 2004). The second solution involves applying various ground improvement methods, which can improve the strength and stiffness of the foundation soil and reduce its compressibility.

In this paper, these two solutions are discussed and compared for two different levels of foundation weakness. The comparison considers the financial and construction aspects, such as the ground price and the optimization of the wall geometry. The main purpose and innovation of this paper is to apply the theoretical optimization process to a

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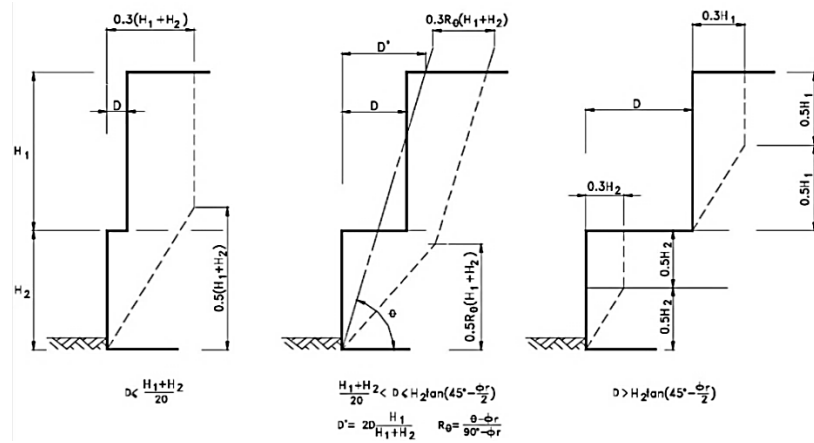


Fig. 1 Effect of offset distance on two tier wall behavior (Berg *et al.* 2009)

real and large-scale project and to evaluate the feasibility of the alternative solutions under different conditions.

2. Multi-tiered MSE wall

2.1 Design considerations and criteria

In MSE wall design, the wall behavior, the internal vertical stresses, and the maximum tension line location depend on whether the wall is designed as a single vertical face or multi-tiered with an offset between tiers. It is proven that as the number of tiers in a multi-tiered wall system increases, the wall behaves more similarly to a reinforced slope rather than a vertical retaining wall (Wright 2005). On the other hand, most design manuals, such as NCMA, ASSHTO and FHWA, only cover two-tier walls. Fig. 1 shows the FHWA criterion for the tier offset of the two-tier walls (Collin *et al.* 2007, Barker and Puckett 1987, Berg *et al.* 2009). It is obvious that this criterion may not work for walls with more than two tiers.

Several studies have been conducted to determine the design procedure for multi-tiered MSE walls. Leshchinsky (2004) studied the effect of various parameters on the required tensile strength, such as offset distance, fill quality and foundation situation. Srivastava *et al.* (2022) compared the factor of safety against total failure of multi-tiered MSE walls with single-tiered ones. Wright (2005) showed the variation of horizontal earth pressure behind the wall with respect to the number and the offset of the tiers. Based on previous studies, it can be concluded that the increase in number of tiers or the offset distance between each tier will decrease the earth lateral pressure and required reinforcement force. According to design procedure of multi-tiered MSE wall, the required reinforcement force for multi-tiered wall is equal to Eq. (1)

$$T_{totals} = \frac{1}{2} K_T \gamma H_{total}^2 \quad (1)$$

In which, T_{totals} is the required reinforcement force for multi-tiered wall, γ is the unit weight of retained soil and H_{total} is the total height of the wall. To estimate the required

reinforcement force for the multi-tiered wall, the key parameter that should be considered is the horizontal earth pressure coefficient (K_T). This coefficient is mainly depends on wall system geometry (number of tiers, offset distance, etc.), reinforcement length, and finally, on vertical distribution of reinforcement forces over the height of the wall (Wright 2005). In Fig. 2, the variation of normalized force coefficient with number and the offset between tiers of wall is presented. Normalized force coefficient is defined as the ratio of the horizontal earth pressure for multi-tiered MSE wall (K_T) to active earth pressure for vertical MSE wall (K_A).

The pseudo-static seismic approach (Bathurst and Cai 1995, Brooks 2010) is used to consider the dynamic forces which consists of dynamic soil thrust at the back of the reinforced zone, and the internal force in the reinforced zone. According to the pseudo-static approach, the incremental dynamic earth force (ΔT_{dyn}) is given by Eq. (2)

$$\Delta T_{dyn} = \frac{1}{2} \Delta K_{dyn} \gamma H_{total}^2 \quad (2)$$

Where ΔK_{dyn} is the incremental dynamic earth pressure coefficient that can be calculated by Eq. (3). γ and H_{total} are defined before.

$$\Delta K_{dyn} = k_v * K_{AE} \quad (3)$$

K_{AE} is the dynamic earth pressure coefficient, and it is equal to Eq. (4)

$$K_{AE} = \frac{\cos^2(\varphi + \psi - \theta)}{\cos \theta \cos^2(\psi) \cos^2(\delta - \psi + \theta) \left[1 + \frac{\sin(\varphi + \delta) \sin(\varphi - \beta - \theta)}{\cos(\delta - \psi + \theta) \cos(\psi + \beta)} \right]} \quad (4)$$

Where ψ is the total wall inclination; δ is the mobilized interface friction angle assumed to act at the back of the wall; β is the back slope angle, and finally, θ is the seismic inertia angle given by Eq. (5)

$$\theta = \tan^{-1} \left(\frac{k_h}{1 \pm k_v} \right) \quad (5)$$

Which k_v and k_h are the vertical and horizontal dynamic coefficients. The total earth force at the back of the wall

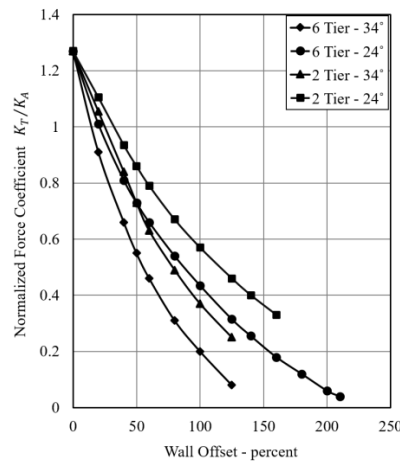


Fig. 2 Variation of normalized force coefficient against number and the offset between tires of wall (Wright 2005)

(T_{total}) is equal to Eq. (6)

$$T_{total} = T_{totals} + \Delta T_{dyn} \quad (6)$$

The final step for accepting any design is checking the factors of safety against the Failure modes. These factors of safety are related to sliding, overturning, bearing capacity, reinforcement tensile failure, reinforcement pullout failure and overall stability. The factor of safety against sliding is defined as Eq. (7) to (9)

$$F.S_{sliding} = \frac{T_{total} + F_{inertia}}{(\sigma'_{v-bottom} L_b) \mu} \quad (7)$$

$$F_{inertia} = k_h V_{reinforced-T} \quad (8)$$

$$\sigma'_{v-bottom} = \gamma H_{total} + q_{loading} \quad (9)$$

In which $V_{reinforced-T}$ is the reinforced volume of the MSE wall, μ is the coefficient of friction between reinforced soil with foundation soil, L_b is the wall dimension at the bottom and $q_{loading}$ is the surcharge load above the retaining wall.

The factor of safety against overturning is calculated with Eq. (10)

$$F.S_{sliding} = \frac{T_{total} d_{total} + F_{inertia} d_{inertia}}{\sigma'_{v-bottom} \frac{L_b^2}{2}} \quad (10)$$

Where d_{total} is the vertical distance between total earth force at the back of the wall and the wall base and $d_{inertia}$ is the vertical distance between internal inertia load and the wall base.

The factor of safety against bearing capacity is equal to Eq. (11) to (13). It must be noted that the bearing capacity stability is controlled by the use of conventional bearing capacity theories. These theories are based on a uniform load distribution with an eccentricity instead of a non-uniform load distribution on the foundation (Das 2015, Bowles 1988)

$$F.S_{bearing} = \frac{q_{ultimate}}{q_{external}} \quad (11)$$

$$q_{external} = \frac{\sigma'_{v-bottom} L_b}{L_b - 2e} \quad (12)$$

$$e = \frac{T_{total} d_{total} + F_{inertia} d_{inertia}}{\sigma'_{v-bottom} L_b} \quad (13)$$

The $q_{ultimate}$ is the maximum bearing capacity of the soil foundation. The factor of safety against reinforced tension for each reinforcement layer is equal to Eq. (14) to (16)

$$F.S_{tension} = \frac{T_{reinforcement}}{F_y w h_{reinf.}} \quad (14)$$

$$T_{reinforcement} = (\Delta K_{dyn} + K_T) \sigma'_v S_v S_h \quad (15)$$

$$\sigma'_v = \gamma H_{reinforcement} + q_{loading} \quad (16)$$

Which F_y is the yield stress of the reinforcement, w is the reinforcement width, $h_{reinf.}$ is the reinforcement thickness, S_v and S_h are the vertical and horizontal spacings of the reinforcement and $H_{reinforcement}$ is the vertical distance between the reinforcement elevation and top of the wall.

The Factor of safety against the pullout failures is equal to Eq. (17) to (19).

$$F.S_{pullout} = \frac{T_{reinforcement}}{2 f^* \sigma'_v w l_{bond}} \quad (17)$$

$$l_{bond} = l_{reinf.T} - l_{in} \quad (18)$$

Where f^* is the pullout resistance factor, $l_{reinf.T}$ is the total length of the reinforcement and l_{in} is the length of the reinforcement between the maximum tension line and the wall face. It must be mentioned that based on the numerical studies on the behavior of multi-tiered MSE walls and the

FHWA guidelines, the criterion of the maximum tension line for the two-tier wall configuration (Fig. 1) can be generalized to walls with more than two tiers (Liu *et al.* 2014, Yoo and Jung 2004).

2.2 Optimization

Optimizing the design variables of the multi-tiered MSE wall to achieve the most economical design is the major aspect that is discussed in this paper. Site-specific costs of MSE structures, which are subjected to the optimization, are functions of different factors, such as temporary or permanent application, in situ soil layers, wall type and size, and facing element. Another factor that has a significant role in the optimization is the cost of the wasted area by the tier offset. The importance of the last factor increases when the project is located in an urban area. In recent studies, changing the wall configures into a tiered one is recommended for high retaining structures; however, the cost of the wasted area has not been considered in cost evaluations.

Limited studies have been undertaken to optimize and improve the design of MSE walls. Ghassian and Aladini (2009) researched on the optimization of single-faced MSE walls by using the genetic algorithm and the limit equilibrium analysis to evaluate the effects of different design variables on the final cost of the retaining wall. In conjunction with the previous research, Bagheri and Derakhshani (2019) adopted the swarm optimization method and the Multi-Verse optimization algorithm to optimize the design of single-face MSE walls and evaluate the effects of different design variables in final results. Ponterosso and Fox (2000) also researched on the optimization of reinforced soil embankments with geogrid reinforcements by using the genetic algorithm based on the design method put forth by the UK Department of Transportation. The aim of their research was to optimize the reinforcement layout for the desired slope specifications and the total cost. In other research, Basudhar and Vashista (2009) used the sequential unconstrained minimization technique in conjunction with conjugate direction and quadratic fit methods for multi-dimensional and uni-directional minimization to obtain the optimal cost of geosynthetic MSE walls. The aforementioned researches have shown reductions in construction costs ranging from roughly 7 to 15 percent.

2.2.1 Genetic algorithm

Genetic algorithms are a type of numerical optimization algorithm inspired by the natural selection process and Darwin's theory of survival of the fittest. Genetic algorithms are categorized as metaheuristic algorithms and just the same as other similar algorithms, they have two important features:

1. Selection of the best, leading to the optimum solution.
2. Randomization that leads to a search for the optimum solution all over the domain of the problem.

Another striking feature of the genetic algorithm is the

conversion of the input parameters into binary codes, which can be applied to both continuous and discontinuous problems. The potential solutions are encoded as binary strings, called chromosomes or individuals. The population of such chromosomes, representing the generation in every cycle, is evaluated by the fitness function. After the fitness of each chromosome was analyzed; the next generation from the former chromosomes was produced by the algorithm's transition components which are:

- Elitism: choosing the best individuals for the next generation.
- Selection: the mechanism of selecting individuals.
- Crossover: merging the genetic information of two proper individuals.
- Mutation: random deformation of the string with a certain probability.

The reproduction and development of generations continued in each cycle in order to obtain the optimum solution (Coley 1999, Man *et al.* 1996, Shahbaz Khan *et al.* 2015).

2.3 Simulation and optimization model

To reach the optimum configuration for multi-tiered MSE walls, a simulation with an optimization model are required. A model that evaluates every chromosome, which is a set of design variables and represents a possible design section, also considers the constraints (internal and external stabilities) by using a penalty function. Finally, each chromosome is ranked by the optimization function, which is the total cost of the design section in the construction type of problems. The total cost of MSE wall structures mainly consists of reinforcement, reinforced wall fill, backfill, facing unit, construction, and installation. The price of site ground is also included as a cost function element because it is high compared to other factors, especially reinforcement, in urban areas. The facing element, construction, and installation costs generally remain unchanged; therefore, they can be omitted from cost optimization. Eventually, the total cost of MSE wall structure (C_T) will be formulated as Eq. (8)

$$C_T = C_R + C_S + C_B + C_G + P \quad (8)$$

Where C_R is the total cost of reinforcement, C_S is the total cost of reinforced soil fill, C_B is the total cost of backfill soil, C_G is the total cost of wasted ground by wall's tier offset, and P is the penalty value which is equal to Eq. (9)

$$P = p(FS_{fg} - FS_g) \quad (9)$$

FS_{fg} is the minimum required factor of safety and FS_g is the factor of safety for the each solution. The penalty value is considered to eliminate the solutions that have an insufficient factor of safety or are overdesigned by increasing their total cost and reducing their fitness value. Fig. 3 shows the flowchart of the design and optimization procedure.

Based on the optimization procedure and the internal

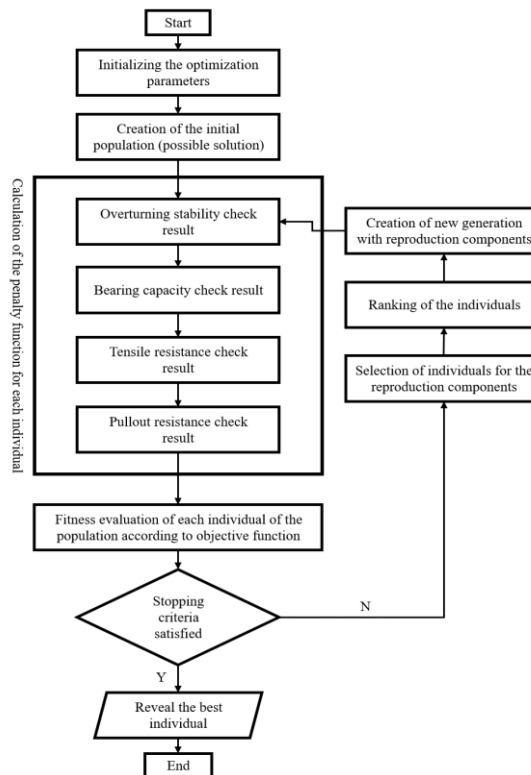


Fig. 3 Genetic algorithm optimization flowchart

and external stability checks, a computer program is developed in MATLAB® software. The program finds the optimal solution (wall design section) from the given input parameters and wall component costs.

2.4 Input parameters

Two different types of soils (weak and very weak soils) are used as the foundation soil in the present work. Table 1 shows the foundation soil properties. The reason for weak and very weak labeling is the relative weakness of subsurface soil condition for construction of a high retaining wall. In other words, the definition of weak and very weak foundation depends on amount of insufficiency of foundation soil strength relative to required strength. Foundation soil parameters in this paper are based on laboratory test results from WTC project in Tabriz, Iran. A three-tiered wall with three different heights was considered for the design and optimization procedure. For the wasted ground value, a wide range of high-value ground prices (urban areas) and low-value ground prices (suburban areas) are employed to clarify the effect of ground price on the design solution. The MSE wall’s input parameters and unit costs of components are tabulated in Table 2.

2.5 Validation

The outputs from optimization must be validated by comparing them with a similar optimized wall. To attain this purpose, the results from (Basudhar *et al.* 2008) are

Table 1 Some geotechnical parameters of soils

Soil	γ_f (kN/m ³)	C_f (kPa)	ϕ°
Weak soil	15	50	20
Very weak soil	15	30	15
Reinforced soil	21	0	36
Backfill soil	18	1	30

Table 2 Input and cost parameters

parameter	value
Wall height (m)	19 to 25
Number of tier	3
Vertical spacing of reinforcement (mm)	750
Horizontal spacing of reinforcement (mm)	375 to 1000
Reinforcement strip width (mm)	60
Reinforcement strip thickness (mm)	3 to 7
Reinforcement yield stress (N/mm ²)	240
F. $S_{sliding}$	>2
F. $S_{overturning}$	>1.5
F. $S_{bearing}$	>2
F. $S_{tension}$	>1.5
F. $S_{pullout}$	>2
Reinforced wall fill cost (\$/m ³)	2
Backfill cost (\$/m ³)	1.6
Reinforcement cost (\$/m ³)	5
Ground value cost (\$/m ²)	137.4 to 1374

used as the validation criterion. In this paper, the design cost of a 5-meter single face MSE wall with the geogrid reinforcement, without considering overburden and seismic

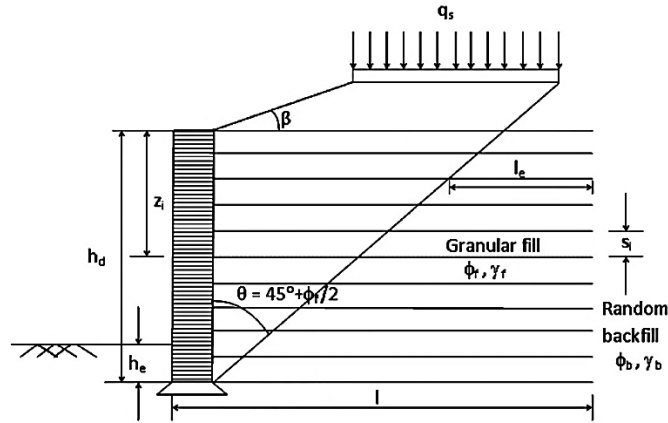


Fig. 4 Validation criterion for optimization (Basudhar *et al.* 2008)

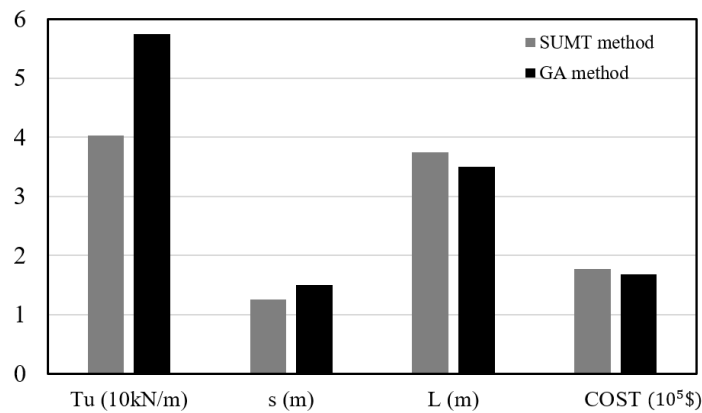


Fig. 5 Comparison of outputs between SUMT and GA optimization methods

Table 3 Input parameters of validation problem

parameter	value
T_u (reinforcement tension) (kN/m)	30 to 60
L_{min} (m)	1
S_{min} (m)	0.2
φ °	34
γ (kN/m ³)	20
Wall fill cost	\$3/1000 Kg
Geogrid reinforcement cost	\$(0.02T_u+2)/m^2
Cost of facing unit	\$60/m ²
Min. overturning factor of safety	2
Min. sliding factor of safety	1.5
Min. bearing capacity factor of safety	2
Min. reinforcement strength factor of safety	1.5
Min. reinforcement pull-out factor of safety	2

loads, is optimized by using the sequential unconstraint minimization technique (SUMT) (Fig. 4). The same design procedure, limit equilibrium work stress method, and input parameters (Table 3) are considered in the optimization process.

The optimized solution based on the GA method is compared with the SUMT method in terms of design

parameters and overall costs, as shown in Fig. 5. The comparison reveals a close agreement between the costs, although there are differences in reinforcement design parameters.

2.6 Design output of the multi-tiered wall

The optimization of the design parameters (Fig. 6) and the estimation overall costs of the retaining wall are performed based on the input parameters and site condition, and the optimized outputs are obtained. In Tables 4 and 5, the results are presented for weak foundation site with low and high ground prices, respectively. The final costs are for unit length of the wall section. For medium weakness soil, a tiered section is an economical solution. However, the ground price is a dominant parameter that affects the total cost and other design parameters significantly. As the ground price increases, the tier offset decreases and the wall section dimensions increase (Tables 4 and 5).

The global stability of the designed sections is assessed for both low and high ground price conditions. The global factor of safety is calculated using the limit equilibrium methods. Table 6 presents the factor of safety results.

The situation is entirely different for a very weak foundation soil. Due to the subsurface soil's excessive

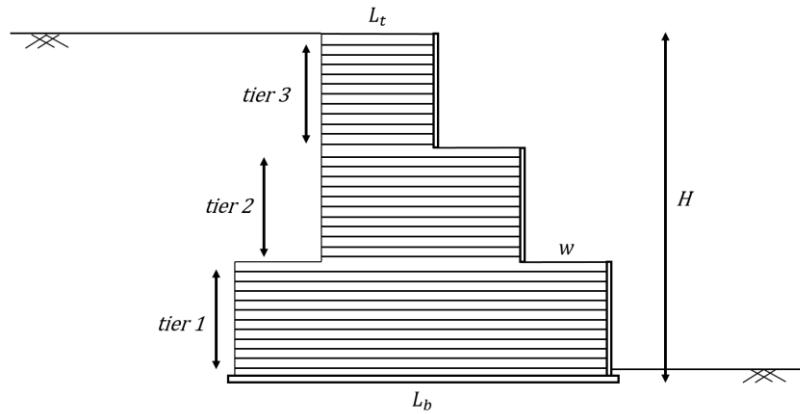


Fig. 6 Designed tiered wall configuration

Table 4 Multi-tier wall section parameters in low price ground value

H (m)	L_b (m)	L_t (m)	W (m)	tier 1		tier 2		tier 3		cost (\$/m)
				Width (mm)	H. space (m)	Width (mm)	H. space (m)	Width (mm)	H. space (m)	
9	13.3	8.5	2.4	3	1	3	0.5	4	0.375	3478
22	17	7.3	4.8	3	1	4	0.5	5	0.375	4517.2
25	19.5	7.3	6.1	3	1	3	0.375	6	0.375	6443.8

Table 5 Multi-tier wall section parameters in high price ground value

H (m)	L_b (m)	L_t (m)	W (m)	tier 1		tier 2		tier 3		cost (\$/m)
				Width (mm)	H. space (m)	Width (mm)	H. space (m)	Width (mm)	H. space (m)	
19	13.7	10.2	0.6	3	1	4	0.375	5	0.375	5711
22	16.7	10.8	0.75	3	1	4	0.375	6	0.375	7745.4
25	19.5	11.4	0.85	3	1	4	0.375	6	0.375	8922.4

Table 6 Overall factor of safety for multi-tiered wall

Wall height (m)	FS (Overall)	
	Low price	High price
19	1.88	1.67
22	1.53	1.86
25	1.75	1.56

weakness and inability to tolerate external loads, MSE walls taller than 15 m are not feasible. Furthermore, the wall section dimension ratio is uneconomical. The only way to design a high retaining wall under such conditions is to improve the foundation.

3. Improvement of foundation soil

The alternative solution for projects facing a problem of soil weakness is improving the strength of the foundation soil. Different methods are available with regard to improvement of weak foundations such as deep soil mixing, grout injection, rigid inclusion and crush stone columns. Crush stone columns are advantageous due to their relatively low cost and available material, cost effective and

easy implementation, and flexibility. The analogous features of MSE retaining walls and stone columns, including their flexibility and cost efficiency, make the combined structure economical and resilient against static and seismic loads (Garini *et al.* 2017).

3.1 Crushed stone column improvement

Crushed stone column improvement involves the partial replacement of subsurface soil with compacted vertical columns of crushed stone material. In this method, usually 15 to 35 percent of the weak soil area is replaced by filled and compacted granular columns that lead to an area with a composite material with lower compressibility and higher strength. The other advantages are increase of bearing capacity, reduction in total and differential settlements, increase in time rate of settlement, and transferring the embankment loads to more competent subsurface layers.

These advantages make the crushed stone column technique a practical way to support structures on soft soils (Barksdale and Bachus 1983, Fattah *et al.* 2016, Hugher and Withers 1974, Schaefer *et al.* 2017, Biswas *et al.* 2022).

Crushed stone columns are divided into two different types: end bearing and floating. End bearing crushed stone

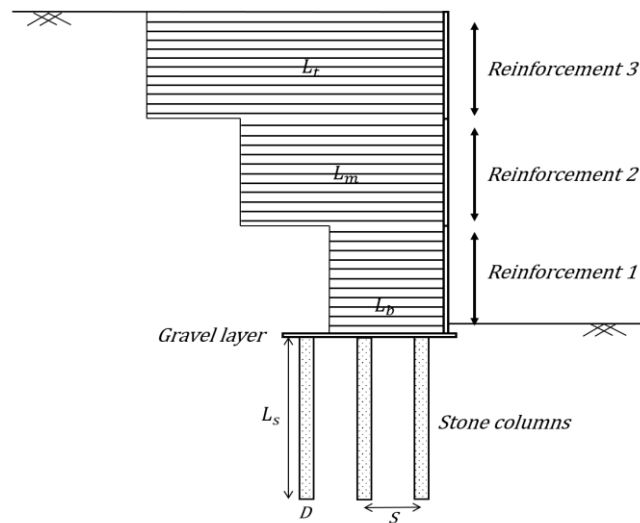


Fig. 7 MSE wall with an uneven reinforcement length over the height in addition to stone column arrangement

columns transfer all the external loading to a firm subsurface stratum that exists beneath the soft soil layer. On the other hand, in the case of the existence of a deep soft soil layer, the crushed stone columns are classified as floating columns (Etezad *et al.* 2015, Ng and Tan 2014).

Various parameters influence the performance of floating stone columns. The most important ones are the geometry of the crushed stone columns (length, diameter, spacing and arrangement), and the strength properties of the crushed stone and surrounding soil (Biswas *et al.* 2022, Hanna *et al.* 2019).

3.1.1 Design considerations and criteria

For floating crushed stone system, different design theories and methods have been proposed in which considering a group of crushed stone column and surrounding soil as a composite material is the most applicable. According to the mentioned theory, the bearing capacity of the foundation soil that is improved by stone columns is determined by Eq. (10), using the general bearing capacity equation with revised factors specified for the soil-stone column system as follows (Etezad *et al.* 2015)

$$q_u = \frac{1}{2} \gamma_{comp} B N_\gamma + q N_q + C_{comp} N_c \quad (10)$$

Which, q_u is the ultimate bearing capacity of the composite foundation, B is the total width of the composite area, q is the overburden pressure, C_{comp} and γ_{comp} are the cohesion and the unit weight of the equivalent composite system, and are given as follows (Eqs. (11) and (12)).

$$C_{comp} = A_S C_{stone} + (1 - A_S) C_{foundation} \quad (11)$$

$$\gamma_{comp} = A_S \gamma_s + (1 - A_S) \gamma_{foundation} \quad (12)$$

Where, C_{stone} , $C_{foundation}$, γ_{stone} and $\gamma_{foundation}$ are the cohesion of crushed stone column, the cohesion of foundation soil, the unit weight of crushed stone column

Table 7 Stone column parameters

Stone column parameter	value
γ_{stone} (kN/m ³)	20
ν_s	0.35
φ_s °	40
C_{stone} (kPa)	0

and the unit weight of foundation soil, respectively. A_S (the replacement ratio) is equal to Eq. (13)

$$A_S = \frac{A_{col}}{S^2} \quad (13)$$

Where, A_{col} is the cross section of the crushed stone column and S is the spacing between the columns. N_γ , N_q and N_c are the bearing capacity factors that are a function of the shearing resistance of the equivalent soil - stone column material, $\frac{C_{comp}}{C_{clay}}$ and $\frac{\gamma_{comp}}{\gamma_{clay}}$ (Etezad *et al.* 2015).

3.2 Foundation improvement Input Parameters

The same foundation soil and MSE construction materials given in Tables 1 and 2 are considered, along with the stone column material properties shown in Table 7. The stone column arrangements have constant spacing, and the reinforcements have uneven length over the height of the MSE wall as illustrated in Fig. 7.

3.3 Design outputs of foundation improvement

The design results of the MSE wall and the stone column configuration for weak and very weak foundation soils are tabulated in Tables 8 to 10. According to the results, maximum spacing is required for foundation soil with moderate strength. However, as foundation weakness increases, the column arrangement becomes more congested. The impact of foundation weakness extends

Table 8 MSE wall section with an uneven reinforcement length for weak foundation soil

H (m)	L_t (m)	L_m (m)	L_b (m)	Reinforcement 1		Reinforcement 2		Reinforcement 3		Cost (\$/m)
				Width (mm)	H. space (m)	Width (mm)	H. space (m)	Width (mm)	H. space (m)	
19	12.5	10	7.5	3	0.5	5	0.5	5	0.375	4092.73
22	15	12	9	3	0.5	5	0.5	6	0.375	6072.72
25	16.5	13	9.5	3	0.5	5	0.375	7	0.375	8519.24

Table 9 MSE wall section with an uneven reinforcement length for very weak foundation soil

H (m)	L_t (m)	L_m (m)	L_b (m)	Reinforcement 1		Reinforcement 2		Reinforcement 3		Cost (\$/m)
				Width (mm)	H. space (m)	Width (mm)	H. space (m)	Width (mm)	H. space (m)	
19	16.8	14	11.2	3	0.5	5	0.5	5	0.375	5872.24
22	18.3	15	11.7	3	0.5	5	0.5	6	0.375	7175.82
25	19.7	16	12.3	3	0.5	5	0.375	7	0.375	9706.6

Table 10 Stone column configuration for weak and very weak foundation soil

Wall height (m)	Weak soil			Very weak soil		
	D (m)	S (m)	L_s (m)	D (m)	S (m)	L_s (m)
19	0.8	4	5	0.8	2	5
22	0.9	4	5.5	0.9	2	5.5
25	1	4	6	1	2	6

Table 11 Overall safety factor of trapezoidal MSE wall

Wall height (m)	Weak soil	Very weak soil
19	1.81	1.849
22	1.65	1.61
25	1.64	1.504

beyond improvement; it also affects the minimum dimensions of the wall section. The weaker the foundation soil, the larger the wall section required. The global stability of the designed sections is investigated using the limit equilibrium analysis method, presented in Table 11.

4. Results and discussion

In this article, different solutions for building a high retaining wall on weak foundation soil are compared and the key factors for each solution are identified. According to the comparison of both solutions in weak foundation soil (Fig. 8), the most critical factor that can dramatically increase the final cost and which may lead to changes in the final decision is the ground value.

As illustrated in Fig. 8, a wide range of ground values can make using a multi-tiered MSE wall an economical solution under low ground value conditions. However, under high ground value conditions, improving the soil conditions is more suitable. This factor also influences the design parameters. The change in wall offset influences not only the dimensions of the wall section and required reinforcement, but also the total cost of the wall. So,

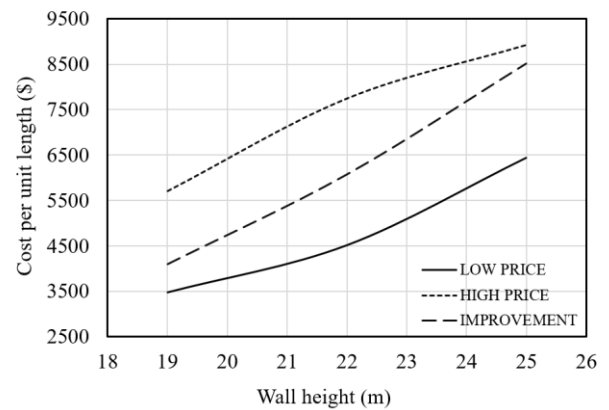


Fig. 8 Cost comparison in weak soil condition

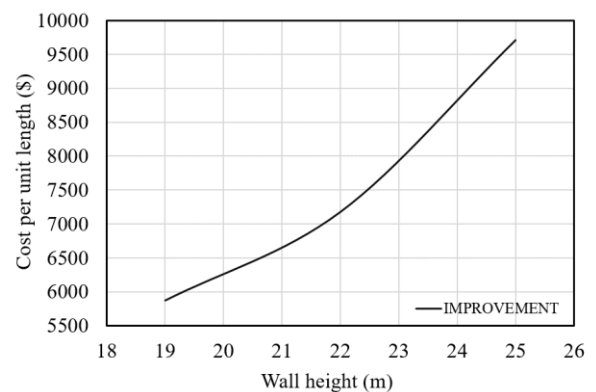


Fig. 9 Cost evaluation in very weak soil condition

contrary to the related design codes and references, changing the wall configuration may result in more construction expenses in comparison to foundation improvement in special cases like urban areas.

The Situation differs, in terms of excessive weakness of the foundation soil. Despite the advantages of using a multi-tiered wall configuration, this solution is impractical for

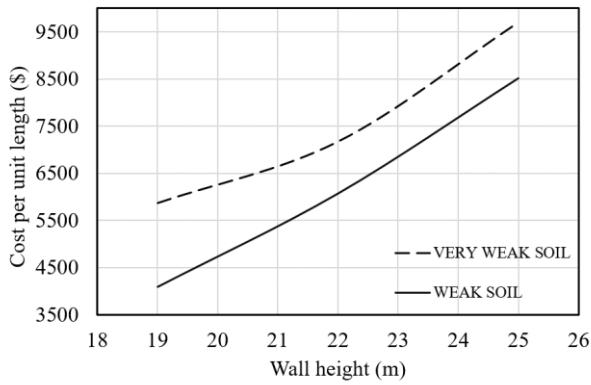


Fig. 10 Effect of soil weakness on cost evaluation of wall section and improvement

such conditions. Therefore, improving the foundation is the only solution. The cost evaluation of the improvement method and the related retaining wall is presented in Fig. 9.

Finally, we can conclude that the foundation weakness influences not only the arrangement and diameter of the stone column, but also affects the required dimensions of wall section. As it presented in Fig. 10, increase in foundation soil weakness ends to more congested arrangement of crushed stone columns, larger wall section and eventually higher costs.

5. Optimization case study

For further investigation and more assurance of optimization process, a full-scale project which is a 22-m high, multi-tiered wall, designed and constructed next to the World Trade Center (WTC) tower in Tabriz, is optimized and the result compared with the constructed section (Fig. 11). The World Trade Center (WTC) Tower of Tabriz is one of the most outstanding commercial buildings in Tabriz. The H-shaped tower is Iran’s first trade, service and tourism center with a high of 152 meters and a large dome with 35 floors. The foundation soil of the WTC project was marl. In many sub-tropical and tropical and regions of the world, marly soils (marls) and lime or cement stabilization of marl soils are used as a convenient and expedient means for development of foundation base courses and inexpensive wearing courses for transport purposes. The failure of many of these natural and stabilized marls to perform their function has been reported (Ouhadi 1997, Ouhadi and Yong 2003, Ouhadi and Yong 2008). According to previous studies the initial parts of the marl are weathered and its strength properties are very weak. The middle layers have better strength properties. At deep layers, the strength properties are improved according to the mentioned cases and also according to the conducted geotechnical studies in the study area. The geotechnical boring log in the study area and the project location are shown in Figs. 12 (a) and 12(b) respectively. The foundation condition was the same as a weak foundation soil. The project pictures are shown in Fig. 13.

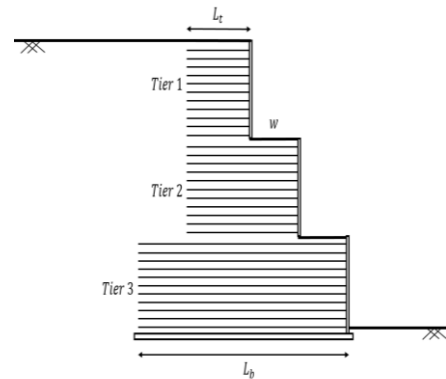
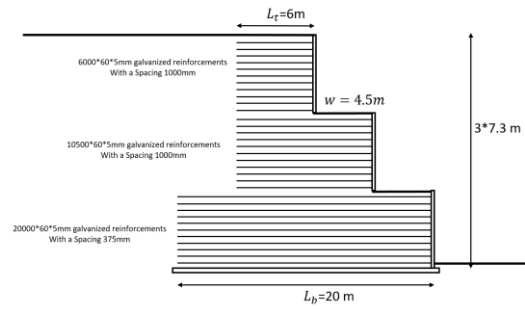


Fig. 11 The constructed multi-tiered MSE wall details next to the WTC tower in Tabriz (Iran) against the optimized wall section

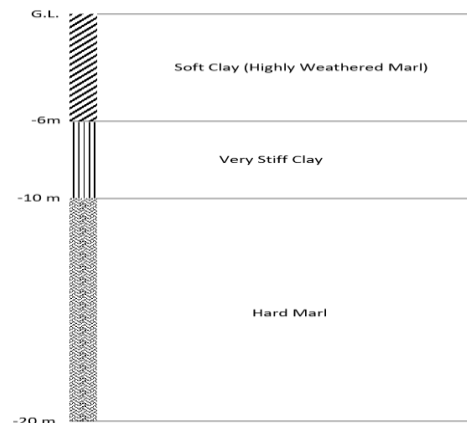


Fig. 12 (a) The boring log and (b) the location of the WTC tower in Tabriz (Iran)



Fig. 13 The World Trade Center (WTC) tower in Tabriz (Iran)

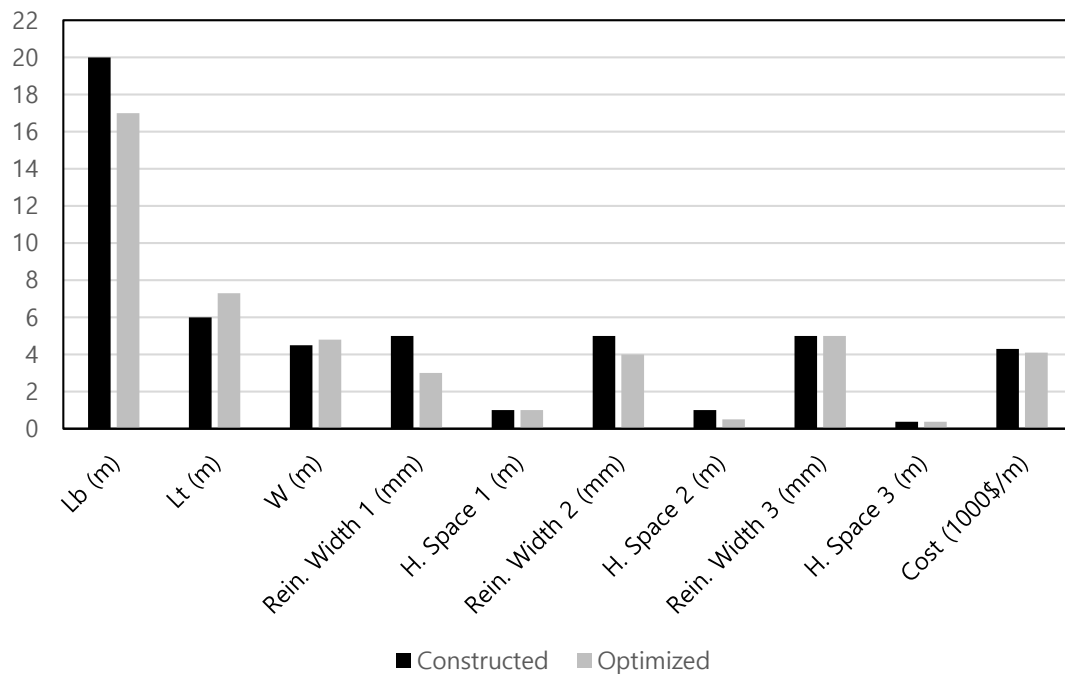


Fig. 14 The Results comparison of optimized vs constructed wall

The optimization process leads to a design section that is compared against the constructed section in Fig. 14. The results show that the lower dimension is reduced, but the tier width and the top dimension are increased. Also, the reinforcement in the two upper tiers is decreased. These changes lead to about a 5% decrease in the total cost, which is significant for a large-scale project like this.

6. Conclusions

In this research, different key factors in the design of high MSE walls on weak foundation soils are discussed. For different foundation weaknesses, possible design solutions are investigated and the GA optimization algorithm is used

to obtain best fit results. Based on the results of the current research, it can be concluded that:

- The optimization algorithms are an applicable tool in the design procedure, not only do these algorithms reduce the total cost of the project, but the algorithm procedures also allow the evaluation of the importance of different factors.
- In the design and construction of a high retaining wall in relatively weak foundation soil, each design factor relevant to the project must be determined, and its influence on different design solutions must be evaluated. Especially, the ground value in urban areas has a critical influence and can change the project's design decisions. Under specific circumstances, costly improvement

techniques can become more economical than multi-tiered MSE walls.

- In the case of weak foundation soil, the increase in ground price will lead to a reduction in tier width and an increase in wall section dimensions. The effect is so noticeable that it can make the foundation improvement solution more economical.
- In a case of excessive weakness of foundation soil, the Multi-tiered MSE wall is not applicable and foundation improvement is inevitable.
- The increase in foundation weakness leads to not only a more congested crushed stone column arrangement, but also an increase in required wall dimensions.
- Using the method that was proposed in the present research in the design of a retaining wall beside the World Trade Center (WTC) tower leads to about 5% decrease in total cost, which is essential in a large-scale project like this.

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