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Investigation of cantilever retaining walls constructed in Turkey highways

Türkiye karayollarında inşa edilen konsol istinat duvarlarının incelenmesi

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Abstract

In this study, cantilever retaining walls constructed near the highways were investigated according to real project values. Twenty-eight retaining wall projects applied in the site at different regions of Turkey such as Central Anatolia, Marmara and Black Sea were considered. The value of surcharge load, depth of foundation, ground water level, surface slope of soil and wall height were chosen as variable parameters, although properties of base soil, granular backfill and natural soil were considered as constant parameters. Theoretical calculations of factor of safeties were completed against overturning, sliding and bearing capacity according to each case as well as two-dimensional finite element models were solved in Plaxis software to find the maximum horizontal deformations. Rankine active and passive earth pressure theories were used to make static analysis of cantilever walls. If the surcharge load, surface slope of soil, height of wall and ground water level increases, the stability conditions depending on factor of safeties decreases due to results. In addition, a deeper depth of foundation increases the factor of safeties against sliding and bearing capacity, while it does not affect the overturning behavior. The location of ground water stands out as a dominant parameter rather than other external factors. Therefore, the design height of reinforced concrete cantilever retaining wall is not proposed in which taller than 15m due to unsecure and uneconomical conditions, even if other criteria are met.

Keywords: Cantilever retaining wall, Sliding, Overturning, Bearing capacity, Slope stability, Plaxis.

Öz

Bu çalışmada, karayolları kenarlarında inşa edilen konsol istinat duvarlarının gerçek proje değerlerine göre incelenmiştir. İç Anadolu, Marmara ve Karadeniz gibi Türkiye'nin farklı bölgelerinde arazide uygulanan 28 adet istinat duvarı projesi değerlendirilmiştir. Sürşarj yükü değeri, don derinliği, yeraltı su seviyesi, zeminin yüzey eğimi ve duvar yüksekliği değişken parametreler olarak seçilirken; temel zemini, granüler dolgu ve doğal zemin özellikleri sabit parametreler olarak kabul edilmiştir. Her bir duruma göre devrilme, kayma ve taşıma kapasitesine karşı güvenlik sayısının teorik hesaplamalarının tamamlanmasının yanı sıra maksimum yatay yer değiştirme değerlerini bulmak için Plaxis yazılımında iki boyutlu sonlu eleman modelleri çözülmüştür. Konsol duvarların statik analizlerinde Rankine aktif ve pasif toprak basıncı teorileri kullanılmıştır. Sonuçlara göre sürşarj yükü, zeminin yüzey eğimi, duvar yüksekliği ve yeraltı suyu seviyesi artarsa, güvenlik faktörüne bağlı stabilite durumları azalmaktadır. Buna ek olarak, daha derindeki temel seviyesi, devrilme davranışını etkilemezken kayma ve taşıma kapasitesine karşı güvenlik faktörünü arttırmaktadır. Diğer dış etkenlerden ziyade yeraltı suyunun konumu baskın parametre olarak öne çıkmaktadır. Dolayısıyla, diğer kriterler karşılansa dahi, güvensiz ve ekonomik olmayan koşullar nedeniyle 15 m'den daha yüksek betonarme konsol istinat duvarı tasarım yüksekliği önerilmemektedir.

Anahtar kelimeler: Konsol istinat duvarı, Kayma, Devrilme, Taşıma kapasitesi, Şev stabilitesi, Plaxis.

1 Introduction

Retaining walls have been constructed to provide the stability of slopes and to prevent the sliding along the highways, railways, tunnels in addition to bracing applications. Oversized dimensions and insufficient strength capabilities can be encountered during the design and construction steps of retaining walls due to the insufficient data sources. When deciding on the type and dimensions of retaining structure, the planned height is determined depending on the site characteristics, existing building effects, groundwater level, the type of backfill soil, regional conditions and its intended use.

Miscellaneous theoretical and modeling studies can be found in the literature according to different methods and design criteria. Yoo et al. [1] evaluated the position and angle of anti-sliding tooth with a uniformly distributed surcharge load on the backfill surface via FLAC software for the numerical modeling. The limit balance method was used to find the ultimate load causing shear failure of the wall and to compare with conventional limit equilibrium method. Binici et al. [2] examined a collapsed retaining wall to evaluate the possible causes of the failure mechanism. Not meeting of standard requirements, poor material quality and insufficient labor were listed as a reason. Static earth pressure varies according to the seismic acceleration coefficient with linear pressure distribution due to soil depth, while dynamic soil pressure changes abide by seismic acceleration coefficient propagating in the embankment behind the rigid retaining wall and primary waves [3]. Salman et al. [4] carried out the effect of the poisson's ratio and permeability coefficient factors of the base on the behavior of the retaining wall with the finite element software, which includes two-dimensional planar strain analysis. It was observed that the retaining wall built on the saturated compressible clay layer tended towards the embankment rather than moving away from the embankment, contrary to

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the classical soil pressure theories. Liu et al. [5] proposed a new method for finite element optimization based on the definition of additional parameters in the cantilever retaining wall system, which includes horizontal resistance coefficient and the non-linear mass distribution of the soil area in addition to simplified model. Kamiloğlu and Şadoğlu [6] performed a series of failure tests under planar stress conditions of a cantilever retaining wall model that supports two different type of sand layers. It has been emphasized that Coulomb and Rankine theories can be applied to find the active and passive earth pressures with the appropriate shear failure surface assumption of the soil wedge in the case of partial movement of wall. Singhal et al. [7] tested full scaled precast reinforced concrete walls under cyclic loading procedure to observe the out of plane conditions. Effects of backfill density and aspect ratio were presented in addition to the relation between in-plane yield and design capacity. Konal et al. [8] performed shaking table tests for cantilever retaining walls embedded in sandy soils due to saturation. Although limited lateral displacement was reported in the dry sand, this value can be reach up to 12.75% according to the pore water pressure increase. Moreover, geosynthetic reinforced retaining walls and mechanically stabilized earth walls can be used against lateral earth pressure within highway projects [9],[10]. Optimum design criteria of cantilever retaining walls were proposed in some studies based on the geometrical limits, soil and material properties as well as cost analysis with respect to special algorithms [11],[12].

Abood et al. [13] presented the safety factor values of a 4m high reinforced concrete cantilever retaining wall designed according to ACI code against sliding, overturning, and moving problems. Chaliawala and Lokhandwala [14] proposed the optimum design criteria of cantilever and counterfort types of retaining walls at different wall heights in terms of structural performance and cost estimation. Lahande [15] projected a more realistic non-linear seismic active earth pressure distribution behind the retaining wall compared to the static approach due to investigation about the effects of different soil types on the height of the cantilever retaining wall under earthquake behavior. The analytical and finite element modelling of lateral soil pressure within cantilever retaining wall was calculated by Tiwari et al. [16]. It was emphasized that the magnitude of single load and the application point are the most important factor in terms of lateral pressure acting on the wall. Kalateh-Ahani and Sarani [17] tried to adapt the concept of performance-based design in optimization process of 8m high retaining wall. A multi-purpose optimization system has been developed to minimize the cost and permanent deformations. Alias et al. [18] investigated the effect of mesh size on the finite element performance of cantilever retaining walls and compared the results with field monitoring data. Results showed that the effect of mesh size did not make a significant difference and closer values were obtained via fine mesh with respect to field values.

The stability conditions and the design limits of retaining walls are investigated by several researchers with respect to the variable parameters such as height of wall, width of wall, foundation thickness, ground acceleration coefficient, backfill or soil properties, soil surcharge load, cost [19]-[22] The base width required for a safer design against sliding and overturning increases with the increasing of wall height and the unit weight of backfill [19]. On the other hand, the cost of wall can be reduced by increasing of internal friction angle of foundation soil and backfill soil [23]. Even though, actual project details were used in some case studies related about retaining structures all around the world [24]-[28], these parameters are chosen from previous studies or fictive ranges instead of real values, generally. Therefore, actual project values were used within this study to involve the real parameters in terms of structural geometry of retaining wall and behaviour of soil.

In this study, a generalization was made with respect to analytical calculation for design checks such as sliding overturning and bearing capacity problems in addition to finite element modeling. The limit values of cantilever type of reinforced concrete retaining wall were taken from 28 actual projects built in six regions of Turkey. The effects of surcharge load, depth of foundation, groundwater level, and surface slope were investigated due to height of wall from 4m to 19m with a one-meter intervals. Thus, it will be possible to estimate more effective feasibility studies within the boundary conditions in the regions where the project is planned.

2 Actual project parameters

First of all, actual ranges of parameters were taken from twenty-eight real project details, which had been constructed near the Turkey highways. Then, the logical mean values of these limits named as 'used values' in Table 1 were chosen both in the theoretical calculations and the finite element modeling procedure [29],[30].

Table 1. Main parameters of cantilever retaining walls due to the actual project ranges.

Variable Parameters				
Parameter	Unit	Symbol	Actual ranges	Used values
Surcharge load	kN/m^2	q	0-20	0-5-10-15-20
Depth of foundation	m	D_f	0-1.5	0-5-1-1.5
Surface slope	°	α	0-18	0-18
Level of ground water table	m	GWT	min-max	min-max
Height of wall	m	H	4-19	4-19 with one-meter intervals
Constant Parameters				
Parameter	Unit	Symbol	Actual ranges	Used values
Granular backfill				
Cohesion	kN/m^2	c	0-5	3
Internal friction angle	°	$\emptyset$	30-40	35
Unit weight	kN/m^3	γ	18-22	20
Natural soil behind the backfill				
Cohesion	kN/m^2	c	0-5	3
Internal friction angle	°	$\emptyset$	20-40	30
Unit weight	kN/m^3	γ	19-23	21
Base soil underlaying the foundation				
Cohesion	kN/m^2	c	0-10	5
Internal friction angle	°	$\emptyset$	20-40	30
Unit weight	kN/m^3	γ	17-24	20.5

The undrained cohesion, internal friction angle and unit weight were selected as constant parameters in terms of granular backfill, natural soil located behind the granular backfill and base soil. On the other hand, surcharge load, depth of foundation, groundwater level and surface slope of top soil were chosen as variable parameters. Reinforced concrete cantilever retaining walls were designed and modelled according to these boundary conditions, which have a wall height starting from 4m to 19m with an increase of one meter according to real projects. The sample model of retaining wall is given in Figure 1. In total, sixteen cantilever retaining wall geometry were used during analytical and modeling stages regarding to suggested dimensions proportional with the height of wall under design of retaining wall section. While the surcharge load is starting from the top point of wall to the point 'K' as same as the height of wall for each case to provide the lateral surcharge effect along the full height of the wall, the bottom and top locations of ground water table illustrate the horizontal lines located at points 'L' and 'M', respectively. In addition, the mentioned soils in Table 1, which are the granular backfill, the natural soil behind the wall and the base soil underlaying the foundation, are colored as yellow, green and light red, respectively.

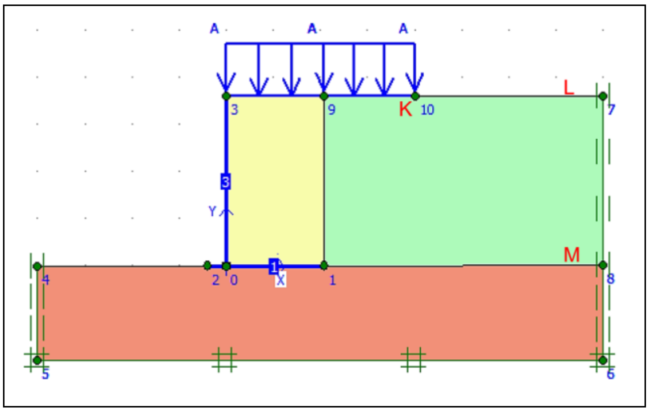


Figure 1. The sample model of retaining wall for analytical analysis and Plaxis model [30].

3 Design of retaining wall

If the proper angle of slope is selected, slope stability can be satisfied without requiring an external structure. However, in cases that do not allow safe design by changing the slope or problematic conditions can be occurred, retaining structures are required to stable design during the construction process and throughout the lifetime [31]. Engineers should consider backfill behind the wall and also soil under the foundation of wall. Some properties such as unit weight (γ), cohesion (c) and internal friction angle ($\emptyset$) of soil should be determined since the lateral earth pressure values must be calculated. However, sometimes retaining structures may be collapsed due to insufficient values of these parameters. Thus, following failure modes may be encountered, a slide potential along the base, an overturn behavior with respect to toe, an inadequate bearing capacity, an excessive settlement or a general failure of retaining wall as given in Figure 2 [32],[33].

The geometrical design of retaining wall is a trial and error process to find the most effective case in terms of application, safety and cost. After the selection of wall type, the dimensions of body and foundation are determined depending on the effective height of wall (H') that represents the distance between top and bottom points at the borderline of the foundation base due to Figure 3. 'H_T' illustrates the total height of retaining wall, while 'H_1' and 'H_2' show the body length and the foundation thickness ($0.1H_T$), respectively. The length of foundation base (B_T) is equal to 0.60H_T, whereas the left side (B_1) and midportion (B_2+B_3) are proposed about $0.10H_T$. While the letter 'A' indicates the width of top portion as a minimum value of 0.3 m, the slope of front face is taken with the horizontal to vertical ratio of 0.02/1.00 [32]. Although 'B_4' is an optional cantilever length of wall depending on the design criteria, the angle of 'η' (Equation 1) is used to find the most effective cantilever length generally [33]. Then, the dimensions of cantilever retaining wall were determined according to the variable height of wall within project ranges.

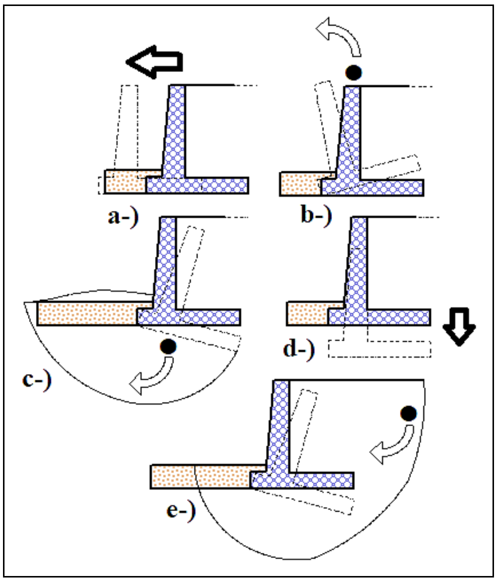


Figure 2. The possible failure conditions of retaining wall.
(a): Sliding. (b): Overturning. (c): Bearing capacity.
(d): Settlement. (e): General failure.

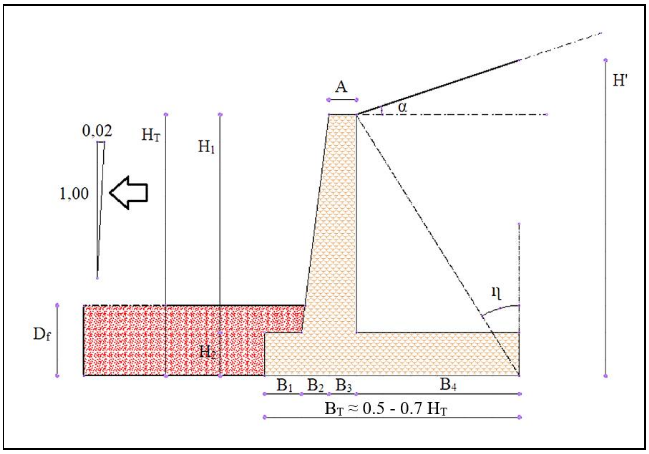


Figure 3. Dimensioning of cantilever retaining wall [33].

$$\eta = 45 + \frac{\alpha}{2} + \frac{\emptyset}{2} + \frac{1}{2} arcsin\left(\frac{sin\alpha}{sin\emptyset}\right) \quad (1)$$

4 Analytical analysis

Rankine active and passive earth pressure theories were used during analytical analysis of retaining walls to calculate the factor of safeties against overturning, sliding and bearing capacity type of failures [33]. Retaining wall can slide along the wall base that occurs between the soil and concrete due to the horizontal active force. Vertical forces or loads which resist wall sliding above the wall base are weight of wall (W_c), weight of soil (W_s), vertical component of active earth pressure ($P_{a(vertical)}$), while horizontal forces which act to the wall as adhesion force (C_a), passive force (P_p) and horizontal component of active earth pressure ($P_{a(horizontal)}$). Factor of safety against sliding can be given as resistive forces divided by sliding forces which should be greater than 1.50 given in Equation 2 with respect to Figure 4.

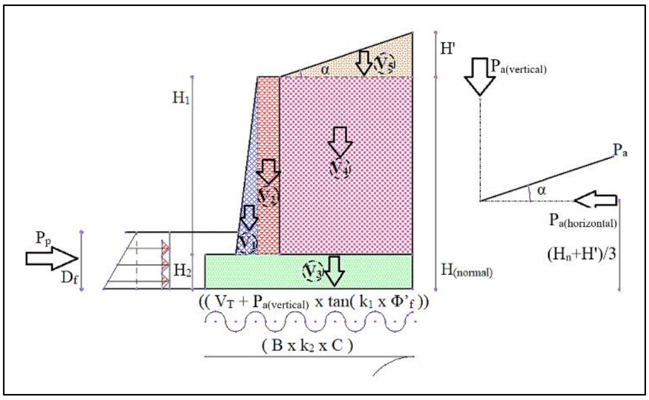


Figure 4. The components of design check against sliding.

$$FS_{sliding} = \frac{(\sum V)\tan(k_1\emptyset') + Bk_2C_a + P_p}{P_a \cos \propto} \quad (2)$$

Where; P_a is an active force, P_p is a passive force, D_f is a depth of foundation, $\emptyset'$ is an effective internal friction angle, B is a width of foundation, α is an angle between topsoil surface and horizontal. '$\sum V$' consists of the weight components from V_1 to V_5 of reinforced concrete wall and soil above the baseline in addition to $P_{a(vertical)}$. 'H' terms represent the height of related portion of retaining wall. 'k_1' and 'k_2' coefficients which change between 1/2 and 2/3.

The wall can overturn in case of instability conditions with respect to point "O" shown in Figure 5. The usual minimum desirable value of factor of safety against overturning is 2.0 according to the ratio between total resistive moments against overturning and sum of the driving moments. The resistive moments are vertical forces from V_1 to V_5 multiplied by their distances from X_1 to X_5 in addition to a moment created by vertical component of active pressure, while driving moments are a moment effect of horizontal component of active pressure in addition to external loading conditions (Equation 3).

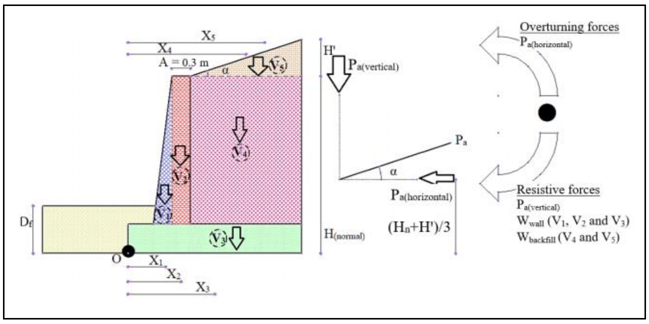


Figure 5. The components of design check against overturning.

$$FS_{overturning} = \frac{\sum M_{resisting}}{\sum M_{overturning}} \quad (3)$$

Bearing capacity of foundation soil should be enough to carry the weight of wall under external loading potentials and environmental effects. Factor of safety against bearing capacity should be greater than 3.0, which defines the ratio between ultimate bearing capacity of soil and maximum bearing capacity at toe, were calculated due to Meyerhof's Theory (Equation 4).

$$q_u = cN_cF_{cd}F_{ci} + qN_qF_{qd}F_{qi} + \frac{1}{2}\gamma B'N_\gamma F_{\gamma d}F_{\gamma i} \quad (4)$$

Where; q_u is an ultimate bearing capacity of base soil, q is a surcharge load, γ is a unit weight of soil and B' is an effective width of foundation. On the other hand, N_c, N_q, N_γ are bearing capacity factors depending on internal friction angle, F_{cd}, F_{qd}, $F_{\gamma d}$ are depth factors and F_{ci}, F_{qi}, $F_{\gamma i}$ are inclination factors [32].

5 Finite element modeling

Analyzes were performed in Plaxis 2D software by taking the constant parameters of subbase soil, natural soil behind fill and granular backfill in line with design, while the surcharge load, depth of foundation, groundwater level, surface slope and wall height were selected as variables. Finite element method is the most suitable way among numerical modeling methods in terms of programming, because it allows the solution of complex problems such as boundary conditions, nonlinear material behavior and heterogeneous materials [34]. Plaxis is a finite element program, which is working with mentioned principle, was developed by Delft University of Technology in the Netherlands in 1987 for various analyzes in geotechnical engineering [35]. Mohr Coulomb model was used for soil behavior, which defines the critical combination of normal stress and shear stress at the failure state. The properties of used soils are given in Table 2.

Table 2. Used soil properties in finite element model.

Parameter	Unit	Symbol	Granular backfill	Natural soil	Base soil
Unit weight	kN/m^3	γ	20	21	20.5
Poissons's ratio	-	μ	0.25	0.3	0.3
Modulus of elasticity	kN/m^2	E	120000	80000	100000
Internal friction angle	°	$\emptyset$	35	30	30
Cohesion	kN/m^2	c	3	3	5

The linear elastic type of material was chosen for retaining wall, since the strength parameters of structural members are much higher than soils. Cantilever retaining walls were defined as a plate element, while the modulus of elasticity and Poisson's ratio values were taken as 32000 MPa and 0.15 for C30 class reinforced concrete, respectively [36]. The medium mesh size was defined around the plate elements, while the coarse element distribution was chosen as global coarseness during FEM analyses. The main geometrical model including the boundary conditions is given in Figure 1. It should be noted that the design dimensions change depending on the change in wall height. So, the input geometry of Plaxis models are reorganized for each wall height and sixteen wall models were used, while the ratio between cantilever wall components were kept in same with respect to suggested dimensions given in Figure 3.

A total of 1280 design combinations were modeled in Plaxis software within the limit values of real retaining structures, which are including wall height (H: 4.00-19.00 m), surcharge load (q: 0.00-20.00 kN/m^2), depth of foundation (D_f: 0.00-1.50 m), angle of surface slope (α: 0.00°-18.00°) and ground water level (bottom level and top level of wall). Finally, the maximum horizontal deformations were compared [30].

6 Results

The most basic analyzes in retaining structures are the overturning, sliding, and bearing capacity checks to satisfy the structural requirements. The results of aforementioned design checks were presented in this section due to variable factors while main parameter was selected as a wall height. Four different cases were adopted to the results which are given in Table 3.

Table 3. The change of parameters in scenarios.

Scenario	Surface Slope (°)	Location of Ground Water Table	Level of Surcharge Load (kN/m^2)	Depth of foundation (m)
Case-I	0.00	Bottom	From 0 to 20	From 0 to 1.5
Case-II	0.00	Top		
Case-III	18.00	Bottom		
Case-IV	18.00	Top		

The factor of safety values against sliding, overturning and bearing capacity type of failures were taken as 2.00, 1.50 and 3.0 for all wall heights according to Das [33], respectively. Only one graph was presented for overturning in each case independent from depth of foundation parameter due to there is a limited passive effect caused by the moment arm with respect to point 'O' (Figure 5). Therefore, the average factor of safety values against overturning were obtained as 4.73, 2.45, 2.79 and 1.90 within the scenarios ordering from I to IV, respectively, since the resisting moment of passive component is ignored during overturning calculations. Thus, calculations were made on the safer side and repetition of similar graphs was avoided. On the other hand, it should be indicated that the factor of safeties against sliding, overturning, and bearing capacity are determined according to the given equations under the analytical analysis chapter (Equation 2,3,4) only, and obtained safety factors are used in the investigation for the parametric design of the cantilever retaining wall.

6.1 The effect of depth of foundation (Case-I)

The change in stability checks are given in Figure 6 as a supplement file with respect to the depth of foundation, since other factors were taken constant parameters such as horizontal ground surface (α=0) and without ground water effect. In addition, the results of this case are assumed as a reference one. Designed cantilever retaining walls are safe in all heights in terms of overturning with proper factor of safety values from 4.0 to 7.0 within boundary conditions. On the other hand, the factor of safety against sliding cannot be satisfied when the surcharge load is 20 kN/m^2, depth of foundation is 0.5m and height of wall is above 17m. Although the increase in wall height causes a much sharper decrease in bearing capacity factors compared to other checks, walls are safe for all cases in terms of this phenomenon. If the depth of foundation increases, the factor of safety against sliding and bearing capacity rises above the critical values. This behaviour is identical to that found by several researchers in terms of stability or wall deflection due to the increase of embedment depth [37]-[39].

6.2 The effect of ground water level (Case-II)

The same stability checks are completed in case of ground water level located at the top level of retaining wall (Figure 7), while only the horizontal ground surface (α=0°) is taken as constant. Even though the obtained factor of safety values decreases around 2.50-3.00 with the increase in ground water level, wall is safe for all cases against overturning failure. Retaining walls have insufficient factor of safeties against sliding in almost all cases, except for a foundation depth of 1.5m with a wall height equal and less than 5m. These values are almost same above the wall height of 10m. Moreover, proper results could not be obtained in terms of the factor of safety against bearing capacity taken as 3.00, numerically. When the results of Case-I and Case-II are compared, the average decrement ratios are found as 48.21%, 51.49% and 80.33% with respect to overturning, sliding and bearing capacity factors, respectively. It is seen that the sliding and overturning effects of lateral hydrostatic pressure are dominant rather than the resistive effect of the presence of groundwater on the cantilever member.

6.3 The effect of surface slope (Case-III)

Contrary to the previous scenarios, the surface slope of a soil, that is located at the top portion of retaining wall, is taken as 18° and out of ground water condition within this part (Figure 8). Therefore, these results are compared with Case-I to obtain the effect of surface slope only. Although wall is safe for all heights against overturning that has an average value of 2.80, design checks do not satisfy the sliding and bearing capacity factors after 7 m-12 m and 4 m-10 m, respectively. Factor of safety values increase in the case of deeper foundation level and lower surcharge load. If the factor of safety results of Case-I and Case-III are compared, the average decrement percentages are found as 41.17%, 23.55% and 46.25% due to overturning, sliding and bearing capacity, respectively. It is understood that the stability levels are decreased seriously, because of lateral active pressure increases when the presence of sloped ground surface at the top location of retaining wall.

6.4 The combined effect of surface slope and ground water table (Case-IV)

It is the most critical case since hydrostatical pressure and sloped ground surface enforce the wall together due to given numerical results in Figure 9. Although there are no any problems in previous cases, almost all of the factor of safety values against overturning cannot be satisfied for wall heights out of limited ones up to 7m. Similarly, all of the remaining design checks are not safe for sliding and bearing capacity under focused surcharge loads and depth of foundation levels. Only the factor of safety values of sliding within 4m are enough. The average decrement ratios of overturning, sliding and bearing capacity factors are found as 59.82%, 56.53% and 85.71% according to reference case (Case-I), respectively.

6.5 The horizontal displacement values obtained in finite element modeling

The results for 1280 combinations of cantilever retaining wall are given in this section. The stability of the wall was checked by comparing the maximum horizontal deformation values of the retaining walls with respect to allowable limit deformation as a 0.2% of total wall height [40],[41].

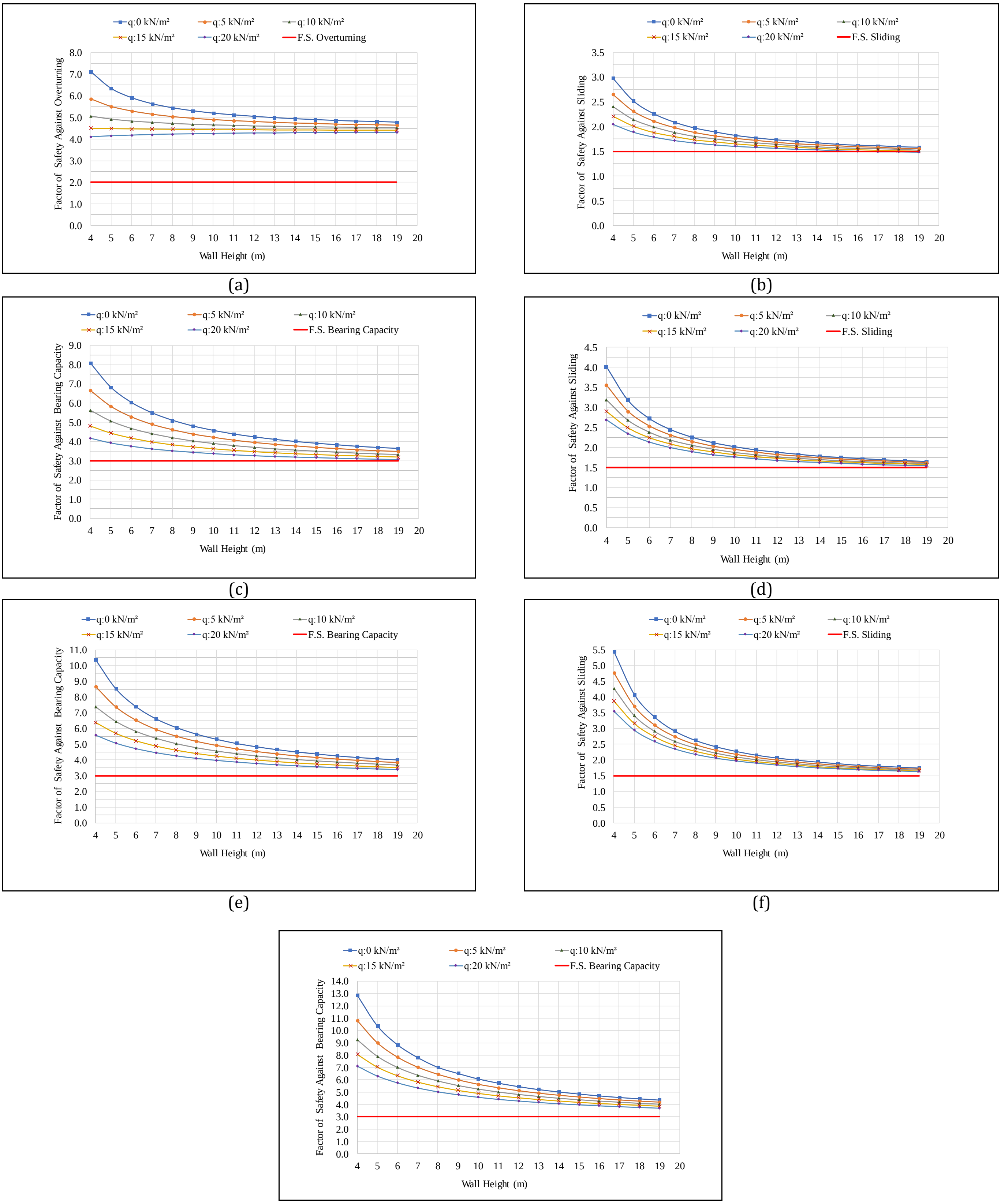
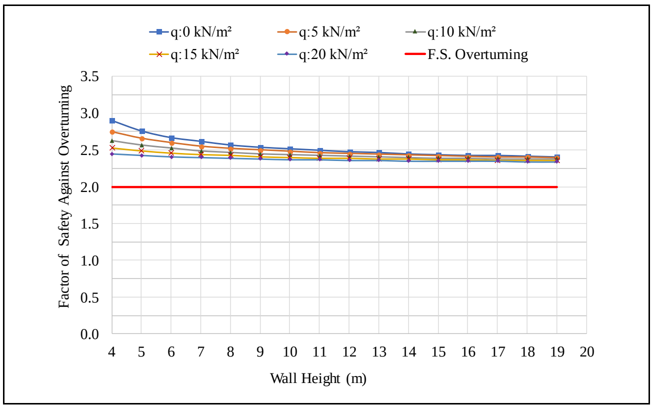
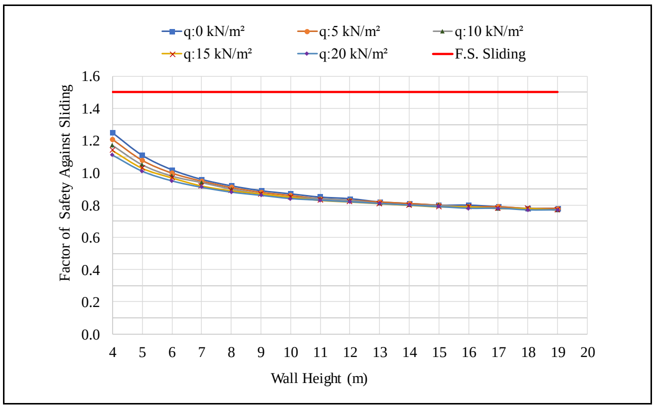


Figure 6. The change in overturning, sliding and bearing capacity factors due to the depth of foundation in case of horizontal ground surface and no ground water condition (a-c): D_f=0.5 m, (d-e): D_f=1.0 m and (f-g): D_f=1.5 m.



(a)



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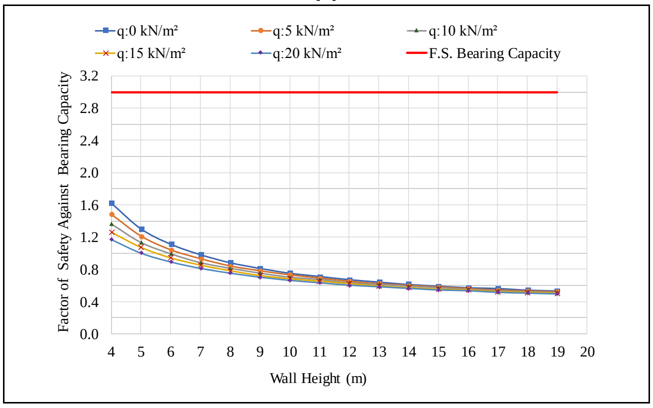

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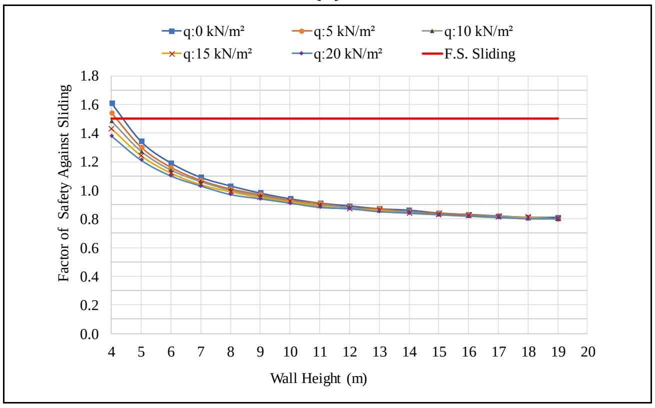

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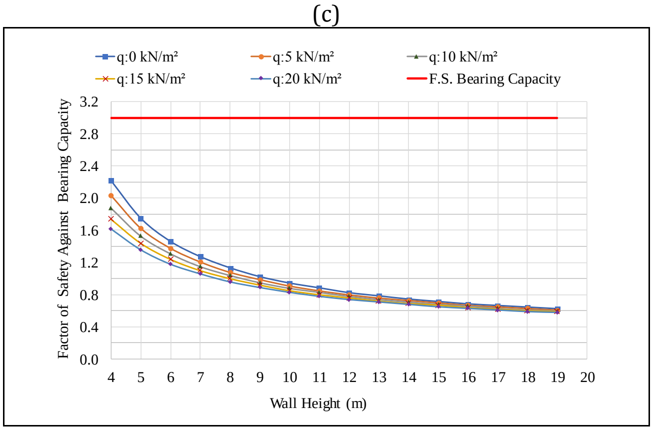

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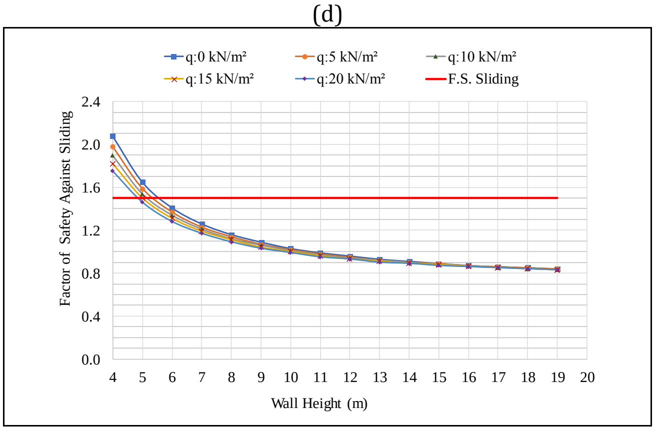

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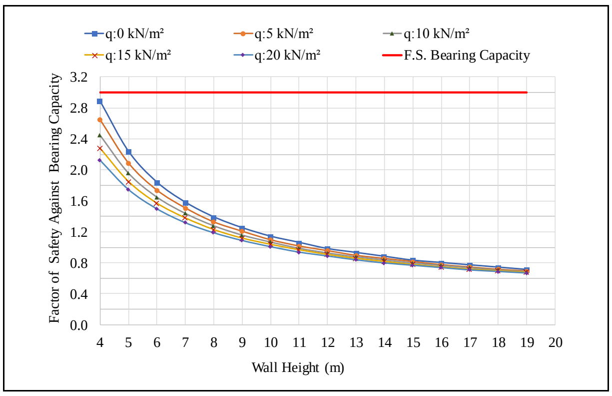

(g)

Figure 7. The change in overturning, sliding and bearing capacity factors due to the depth of foundation in case of horizontal ground surface and ground water condition (a-c): D_f=0.5 m, (d-e): D_f=1.0 m and (f-g): D_f=1.5 m.

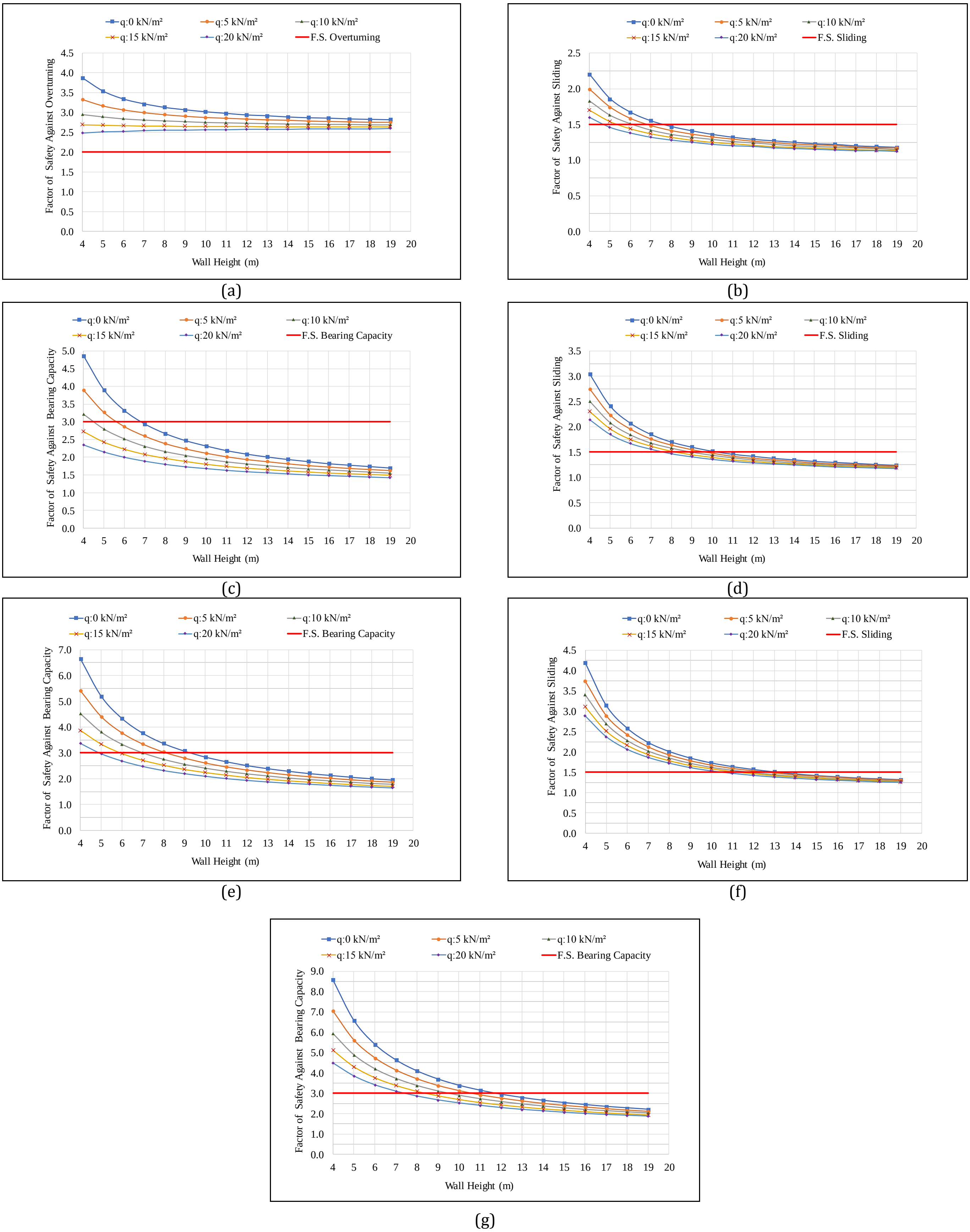

Figure 8. The change in overturning, sliding and bearing capacity factors due to the depth of foundation in case of sloped ground surface (α = 18°) and no ground water condition (a-c): D_f=0.5 m, (d-e): D_f=1.0 m and (f-g): D_f=1.5 m.

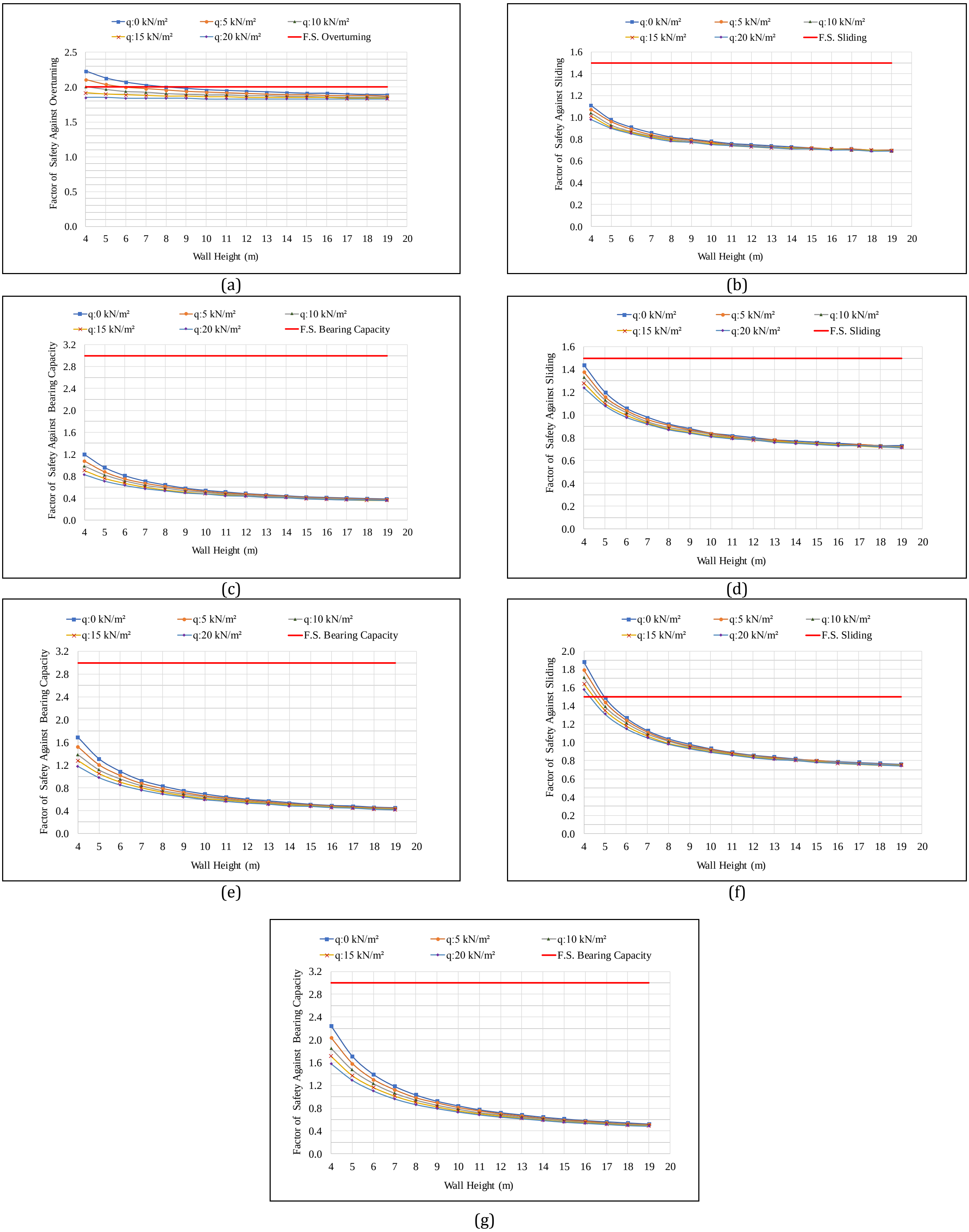

Figure 9. The change in overturning, sliding and bearing capacity factors due to the depth of foundation in case of sloped ground surface (α = 18°) and ground water condition (a-c): D_f=0.5 m, (d-e): D_f=1.0 m and (f-g): D_f=1.5 m.

The obtained maximum horizontal displacement values of Case-I and Case-III, which have out of ground water effect, are given in Figure 10. The displacement values reduced in the case of increment of depth of foundation as well as decrement of surcharge load, if horizontal ground surface slope case were focused Figure 10(a)-(c). Even though the trend of curves were close to linear behavior up to 15 m wall height, the sharp increase was seen after this level. This proves that the passive effect caused by the foundation depth or the resistive moment provided by cantilever part are insufficient against the active forces behind the wall heights of 15m and beyond. On the other hand, it is seen that the deformation values increased seriously, when the surface slope increases from 0° to 18° due to Case-III Figure 10 (d)-(f). The curves reach the critical reference line after 7 m to 11 m with respect to the depth of foundation. Similar with the Case-I the higher rate of displacement increase was seen after 15 m on the curves.

The displacement results of Case-II and Case-IV, which contains ground water effect, are given in Table 4 as a form of numerical data since stability failure were observed at all wall heights except the first 4-5 m and unreasonable curves were obtained. The extension of the heel section makes great contributions to the overall stability due to increase in the preventive effect against overturning and sliding, generally.

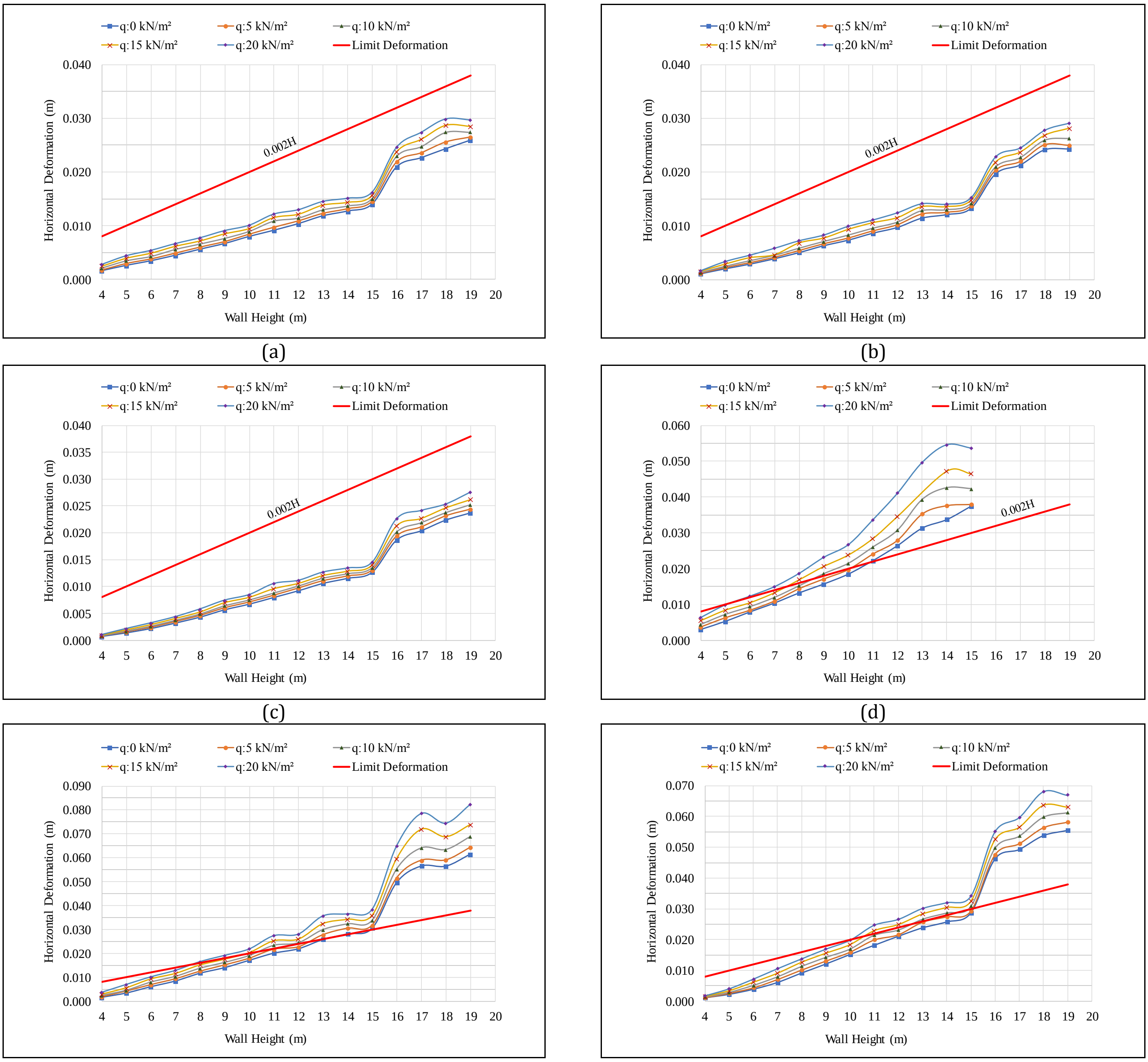

Figure 10. The maximum horizontal deformation values of finite element modeling due to the depth of foundation is equal to 0.5m, 1.0 m and 1.5 m respectively; (a-c): Case-I, and (d-f): Case-III.

Table 4. The maximum horizontal displacement values for Case-II and Case-IV.

Scenario	Height of wall (m)	Depth of foundation (m)	Horizontal displacement (mm)	Increase due to change in surcharge (%)
Case-II	≥4	0.5	Stability failure	-
	4	1	5.43	43.57
	5		10.70	29.56
	>5		Stability failure	-
	4	1.5	2.96	35.70
	5		6.94	28.64
	6		10.89	28.61
	7		16.88	11.00*
	>7		Stability failure	-
Case-IV	≥4	0.5	Stability failure	-
	≥4	1	Stability failure	-
	4	1.5	5.83	74.20
	5		19.07	55.71**
	>5		Stability failure	-

*: Out of 15.00 kN/m^2 and 20.00 kN/m^2. **: Out of 20.00 kN/m^2 due to failure.

Although vertical component of the water pressure located above the cantilever part provides a positive effect, its active pressure more critical after a limited wall height. If the depth of foundation increases from 0.5 m to 1.5 m, stability failure conditions can be shifted up to 7 m wall height. This behavior proved that ground water effect is the most critical external factor. Moreover, the increase percentage in horizontal displacement were calculated in the case of applied surcharge load increased from unloaded case to 20 kN/m^2. The sloped ground surface created much more displacement rather than horizontal case.

7 Conclusions

In this study, design and stability checks of cantilever retaining wall was investigated with respect to variable external factors such as surcharge load, depth of foundation, ground water level and slope of soil behind the wall. Internal parameters of backfill materials and natural soils were taken from actual project values in addition to external ones. Factor of safety checks and finite element modeling were completed within the range of wall height values between 4 m and 19 m with a one-meter intervals.

It was observed that while there was a linear increase in curve trends up to the first 15m wall height, an excessive increment was observed in factor of safety values as well as horizontal displacements after this. Based on these results, wall heights up to breaking points around 15 m in reinforced concrete cantilever retaining walls will be more reliable and economical than taller walls. In addition, it was noted that the cross-sectional analyses must be completed to satisfy the reinforced concrete requirements.

The effect of surcharge load and depth of foundation can be taken as one group, and the effect of water level and surface slope can be classified as another group due to similar effects within finite element models. On the other hand, the hydrostatic pressure caused from the ground water table is the most critical external factor. Therefore, drainage conditions must be satisfied behind the retaining wall via weep holes and permeable materials. Although the data presented in the study is a generalization for the cantilever retaining walls built in highways, it should be noted that the characteristics such as seasonal effects, precipitation regimes, and local loading conditions should not be marked. On the other hand, no collapse potential has been encountered in the actual projects where the data were taken, even some failure conditions were obtained in fictional overloaded cases within study.

8 Author contribution statements

In the scope of this study, the Şule ACARCA in the literature review and modeling procedure; the İbrahim KELEK in the theoretical calculations; Burak EVİRGEN in the formation of the idea, assessment of obtained results and writing an article; the Ahmet TUNCAN the checking the article in terms of content were contributed.

9 Ethics committee approval and conflict of interest statement

“There is no need to obtain permission from the ethics committee for the article prepared”.

“There is no conflict of interest with any person / institution in the article prepared”.

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