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Optimum design of multi-anchored larssen type sheet pile wall for temporary construction works

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Abstract. In some construction works such as multi-basement buildings, subways, deep excavation problems are encountered. In such cases, the shoring walls are used to to prevent damage to the structures next to the excavation area and to provide a safe working environment in the excavation area. In cases where a temporary excavation support is required, sheet pile walls can be more economical comparing to the other walls in the long run due to their reusability. In the present study the analyses were carried out by changing various parametric components such as the number of anchors in vertical row, horizontal and vertical spacing amongst the anchors, anchor angle and excavation depth in LARSSEN type sheet piles constructed temporarily in medium-dense sand. In the analyses, the trapezoidal horizontal earth pressure envelope recommended by FHWA (1999) since the stress concentration occured at the anchor locations. Besides the limit values recommended by FHWA (1999) and BS (1989) was used in the analyses. In total 35488 different sheet pile wall geometry configurations were investigated. According to research results, the lowest costs occur when the horizontal spacing amongst the anchors is 3 m and the angle of the anchors with the horizontal is 15^0. The lowest costs were obtained when the vertical distance of the uppermost anchor to the ground surface is 3 m. Sheet pile sections with optimum cost were modeled in Plaxis 2D to run displacement analyses. Findings showed that the wall displacements were within the allowable limits commonly used in the literature.

Keywords: earth pressure; finite element analysis; multi-anchored sheet pile; optimum design; temporary wall

1. Introduction

Deep excavation problems are frequently encountered in the construction of high-rise buildings, multistorey park ramps, multi-basement shopping centers, subway stations and underpasses which are widely constructed today. A suitable retaining system should be used to prevent damage to the existing structures such as buildings, infrastructure systems, transportation systems, next to the construction site that has deep excavation and to provide a safe working environment in the excavation area. In addition, “Turkish Building Seismic Code (TBSC 2018)” obliged the use of a retaining system for foundation excavations deeper than 1.75 m where sloping excavation can not be performed by giving the appropriate slope angle. The shoring wall types are commonly used in diaphragm wall, reinforced concrete retaining walls, piles, sheet piles and mechanically stabilized earth walls. In the present study, sheet pile walls were selected and investigated. They are relatively light weighted comparing to other retaining systems, they are also able to resist high driving stresses and they are reusabile (Das, 2016). The task of a geotechnical designer is to design an economical and safe retaining system that provides a safe zone within and around the excavation area. Particularly in cases where temporary excavation support is required, sheet pile walls can be more economical in the long run due to their reusability. After the Wenchuan earthquake in China in 2008, a damage investigation carried out on the soil structures show that the prestressed anchored sheet pile walls are an excellent type of seismic structure during the earthquake (Qu *et al.* 2016). On the other hand, sheet pile walls are also used as energy geostructures that embed heat exchanger probes within piles exploit shallow geothermal energy because of providing a renewable energy supply to all built environments (Adinolfi *et al.* 2021). Babu and Basha (2008), Khajehzadeh *et al.* (2013), Das and Das (2015), Mahdi and Ebid (2015) and Kayhan and Demir (2018) are some of studies investigating the optimum design of various shoring walls. Besides, Day (1990), Bhanuchitra and Prusty (2010), Fenerci (2010), Jesmani *et al.* (2011), Bilgin (2012), Amer (2013), Aktan (2014), Alam and Siddique (2014), Cakir (2014), Xie *et al.* (2014), Gazetas *et al.* (2016), Ghazaly *et al.* (2016), Ouria *et al.* (2016), Athira *et al.* (2018), Emarah and Safwat (2018), Jiang *et al.* (2018), Tang *et al.* (2018) and Wang *et al.* (2019) studied shoring walls by using a finite element approach. Qu *et al.* (2016) and Qu *et al.* (2018) developed an analytical method for design of anchored sheet pile walls under dynamic loads using the Winkler Elastic Beam Theory. In the literature, there is a lack in optimum design of multi-anchored sheet pile walls for temporary construction works. With this motivation, the optimum design of multi-anchored sheet pile walls which temporarily retain two different deep excavations with a depth of 15 m and 20 m were investigated. Therefore, sheet pile walls with

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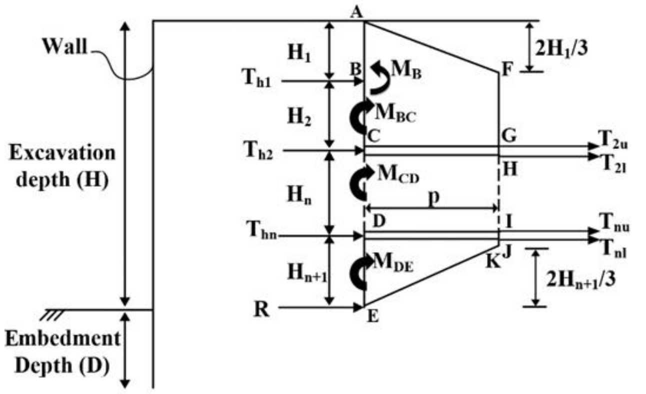

Fig. 1 Earth pressure envelope acting on multiple anchored sheet pile walls (FHWA 1999)

a total of 35488 different geometry configurations were examined by changing the number of anchors in vertical row, the vertical and horizontal spacing amongst the anchors and the angles of anchors and the wall section with the lowest cost was determined. In the analyses, since the stress concentration occured at the anchor locations, the trapezoidal horizontal earth pressure envelope recommended by FHWA (1999) and and the limit values recommended by FHWA (1999) and BS (1989) were used.

The sections with the lowest cost were modeled in Plaxis 2D for displacement analysis since the wall displacements can not be calculated with the method proposed by FHWA (1999) due to the limitations in the proposed methodology. Parametric analyses were carried out to determine the lowest cost sheet pile sections for temporary construction works, and it was aimed to provide a rapid computational methodology to geotechnical designers for optimum design of multi anchored sheet pile walls.

2. Materials and methods

"Excavation Safety and Precautions Circular" part in TBSC obliged the use of a retaining systems for foundation excavations deeper than 1.75 m where sloping excavation can not be performed by giving the appropriate slope angle. The Circular states that seismic effects can be neglected in the design of retaining structures that will be used for less than 2 years. The research was carried out for the economical and safe design of a multi-anchored sheet pile wall which are temporarily constructed (for less than two years) in medium-dense dry sand soil. Sheet pile walls were preferred in the analyses since the reusability would have a decreasing effect on the cost in the long term. In the LARSSEN type sheet pile section to be used for two different deep excavations with a depth of 20 m and 15 m in an excavation area of 15x12 m^2, the analyzes were carried out by changing the number of anchors in the vertical row, the anchor angles, the vertical and horizontal spacing of the anchors. As a result of the analyzes, 19200 different sheet pile wall geometry configurations for 15 m excavation depth and 16288 different sheet pile wall geometry configurations for 20 m excavation depth were examined and the costs of each case were calculated. Consequently, sheet pile section having the lowest cost was determined. Rankine and Coulomb earth pressure envelopes, which are commonly used in traditional soil mechanics, were not used in the analyses, because they do not take the stress concentration that occured in the anchor locations into account. Instead, a horizontal earth pressure envelope recommended by FHWA (1999) was used for multi-anchored sheet pile walls constructed in medium-dense sands (Fig. 1). FHWA (1999) stated that the maximum bending moments for the flexible walls constructed in competent soils such as medium-dense sand and hard clay, occur on the exposed part of the wall above the excavation subgrade and the anchor forces and bending moments can be estimated within reasonable limits with the use of this pressure envelope (Fig. 1). FHWA (1999) also assumed that a hinge with zero bending moment developed at the excavation subgrade and that a reaction force (R) as a horizontal support acts on the elevation of the excavation base (Fig. 1). The p value representing the maximum ordinate of the pressure envelope in Fig. 1 is calculated by Eq. (1) (FHWA, 1999).

$$p=\frac{0.65K_a\gamma_n H}{H-\frac{1}{3}\left(H_1+H_{n+1}\right)} \tag{1}$$

$$K_a = \tan^2\left(45-\frac{\varnothing}{2}\right) \tag{2}$$

Here γ_n is the natural unit weight of soil, H is the excavation depth, H_1 is the vertical distance of the uppermost anchor to the ground surface, H_{n+1} is the vertical distance of the lowest anchor to the base of excavation and K_a is the active earth pressure coefficient.

To determine the anchor forces in the hyperstatic system of Fig. 1, the hinge method proposed by FHWA (1999) was used. The hinge method assumes that a hinge developed at the excavation subgrade and at all anchor locations except the top anchor. After the hyperstatic system in Fig. 1 is solved by using hinge method, i. anchor forces (T_{hi}) per unit width of the wall are calculated by Eq. (3). Also, since anchor forces in Fig. 1 are horizontal component of anchor forces per unit width of the wall, total horizontal forces (T_{thi}) acting on the anchors in the excavation area are calculated from Eq. (4).

$$T_{hi} = T_{iu} + T_{il} \quad (i = 2,3,.....,n) \tag{3}$$

$$T_{thi} = T_{hi} * s \quad (i = 1,2,,.....,n) \tag{4}$$

where s is the horizontal spacing amongst the anchors and n; is the number of anchors in the vertical row. The total anchor force (T_i) to be used in the design of the anchor bond zone and in the selection of the number of strands is calculated by Eq. (5).

$$T_i = \frac{T_{thi}}{\cos\theta} \quad (i = 1,2,,.....,n) \tag{5}$$

where θ is the angle of inclination of the anchor with the horizontal. According to FHWA (1999) water and surcharge effects, if any, should be added in addition to soil pressures. M_B is the negative bending moment that occurs in the uppermost anchor location in Fig.1. Maximum bending moment is calculated with the moment equilibrium at the point where the shear force is zero. Calculated moment value is compared with the moment of M_B. Larger moment value is considered as the maximum bending moment acting on the wall. Using the maximum bending moment value acting on the wall, the choice of sheet pile wall's section is made with the help of Eq. (6).

$$S_{min} = \frac{M_{max}}{\sigma_{all}} \tag{6}$$

where S_{min} represents the minimum section modulus used in the selection of the sheet pile wall's section and σ_{all} represents the allowable bending stress of the steel sheet pile. σ_{all} can be calculated with the aid of Eq. (7) (FHWA 1999).

$$\sigma_{all} = 0.55F_y \tag{7}$$

where F_y represents the yield stress of the steel sheet pile wall.

Steel sheet pile walls with a yield strength of 248 MPa or 345 MPa are generally preferred in common practice (FHWA 1999). Within the scope of this study, types of sheet piles in Table 1 and the unit costs include driving and removing works, costs of material and equipment and all labor costs recommended by Constructive Power of Turkey were used. In addition, according to the minimum section modulus value calculated with the help of Eq. (6), the appropriate sheet pile section was selected from Table 1. The minimum number of strand required for the anchor depending on the magnitude of the anchor force calculated from the Eq. (5) is determined as given in Table 2. Furthermore the inequality proposed by FHWA (1999) for medium-dense sands and presented in Eq. (8) was used for the calculation of the minimum bond length to will resist the anchor force calculated from Eq. (5). The minimum diameter values required for the bond zone depending on the number of strands to be used in the anchor is given in Table 3 for 1st class corrosion protection (FHWA 1999).

$$T_i \le 145L_{bond(i)} \qquad (i = 1, 2, ,....., n) \tag{8}$$

where $L_{bond(i)}$ is the anchor bond length.

In the shoring wall, waling beams are used for the anchors in horizontal row to work together with the sheet pile wall. For the unit cost per 1 ton of the waling beams \$295.27, which is recommended by Constructive Power of Turkey, was used in the calculations. Depending on the number of strands, the unit costs commonly used for anchors in the building industry, including the cost of materials and equipment and all labor costs, are given in Table 4 (Yazici and Keskin, 2019).

According to FHWA (1999), the embedment depth is calculated to retain the R force in addition to the active forces acting on the part of the wall below the excavation subgrade. The free body diagram in Fig. 2 was used to calculate the embedment depth and the Eq. (9) was generated by using free earth support method.

$$\frac{\gamma_n * K_p * D^2}{3} = \frac{\gamma_n * K_a * D^2}{2} + R + q * K_a * D \tag{9}$$

$$K_p = \tan^2\left(45 + \frac{\varnothing}{2}\right) \tag{10}$$

Table 1 The section modulus and and unit costs of Larssen (U section) sheet pile

Sheet pile type	**Minimum section module (S_{min}) (cm^3)/m)**	**Unit cost (\$/m^2)**
Larssen 22	1260	41.26
Larssen 23	2000	45.23
Larssen 24	2500	47.63
Larssen 25	3040	51.36
Larssen VI	4200	61.45
Larssen VII	5010	63.86

Table 2 Properties of 0.6" (15 mm) diameter prestressing steel strands (FHWA 1999)

Num. of 15 mm diameter strands	**Cross section area**	**Ultimate strength**	**Prestressing force**		
			$0.8f_{pu}A_{ps}$	$0.7f_{pu}A_{ps}$	$0.6f_{pu}A_{ps}$
	(mm^2)	(kN)	(kN)	(kN)	(kN)
1	140	260.7	209	182	156
3	420	782.1	626	547	469
4	560	1043	834	730	626
5	700	1304	1043	912	782
7	980	1825	1460	1277	1095
9	1260	2346	1877	1642	1408

Table 3 The relationship between the number of strand and bond zone diamater

Number of 15 mm diameter strands	**Recommended minimum diameter (mm)**
4	150
7	165
9	178
11	191
13	203
17	216

Table 4 Unit costs used for anchors

Num. of 15 mm diameter strands	**Unit cost (\$/m)**
3∅0.6 "	13.04
4∅0.6 "	15.28
5∅0.6 "	18.61
7∅0.6 "	23.09
9∅0.6 "	27.57

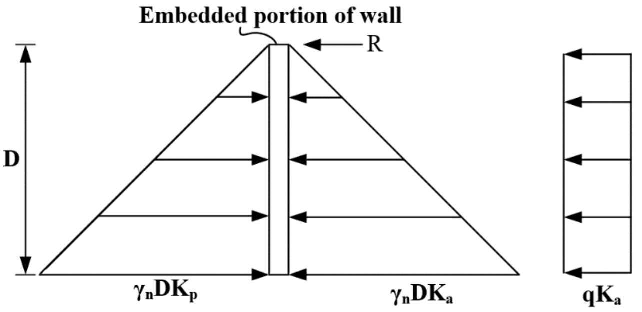

Fig. 2 Free body diagram fort the calculation of the embedment depth

where q is the surcharge load, D is the embedment depth of the wall and ϕ is the internal friction angle of soil and K_p is the passive earth pressure coefficient.

The boundary conditions recommended by FHWA (1999) were also used for the anchors. Eq. (11) is formed by utilizing the geometry of Fig. 3 to calculate the minimum anchor unbonded length required for the anchor bond zone to extend beyond the potential failure surface (Yazici 2019).

$$L_{ub}[j]=\left(\frac{\left(H-\left[\sum_{i=1}^{j}H_i\right]\right)*\sin\left(45-\frac{\varnothing}{2}\right)+x}{\sin\left(45+\theta+\frac{\varnothing}{2}\right)}\right) \tag{11}$$

Here, $L_{ub}[j]$ represents the minimum unbonded length required for the jth row anchors from the ground surface, H_i represents the vertical distance of the anchors shown in Fig. 1. Also x is 1.5 m or 0.2H, whichever is greater.

BS (1989) suggested that the vertical spacing between each anchor should be greater than 2 m. Furthermore, Fig. 3 shows that the horizontal spacing amongst the anchors should be greater than 1.2 m. As seen in Fig. 3, the anchor unbonded length should be minimum 4.5 m as the strand is used in the anchor body in this study. In addition, an overburden of at least 4.5 m over the center of the bond zone of the anchor closest to the ground surface should be (FHWA 1999).

To check if the overburden condition is met, Eq. (12) is created by using the geometry as given in Fig. 3.

$$H_1 \geq 4.5-\left(\frac{L_{bond_1}}{2}+L_{ub_1}\right)*\sin\theta_1 \tag{12}$$

where L_{ub1}, L_{bond1} and θ_1 are the anchor unbonded length, anchor bond length and anchor inclination of the uppermost anchor, respectively. If the boundary condition in Eq. (12) cannot be achieved, the bond length and/or unbonded length and/or angle of the uppermost anchor should be increased until the condition is satisfied. In this study, the bond length of the uppermost anchor is increased until the condition in Eq. (12) is met.

In the present study, the natural unit weight and internal friction angle of the soil which the sheet pile wall will be constructed is taken as 18 kN/m^3 and 36^0, respectively. It is assumed that the groundwater level is far below the lower end of the wall. LARSSEN type sheet pile sections given in Table 1 with yield strength of 345 MPa were used in the analyses. For the waling beams, a cross-sectional area of 86.82 cm^2 and unit volume weight of 7.8 t/m^3 used in the example in PLAXIS 3D Foundation Tutorial Manual Version 2 were used in the calculations. In addition, Type 270 prestressed strands with a diameter of 15 mm having a modulus of elasticity of 196.5 MPa proposed by Aaron (2016) were used for the anchors. In the analysis, a surcharge load of 5 kPa representing the construction machines and material weights around the excavation area was also acted on the wall. Because at least 3 strands are generally used in the anchors in the field, if the number of strands required for the anchors is less than 3, the number of strands is taken as 3. In the analyzes, the vertical spacings amongst the anchors were taken equal (H_2=H_3=…=H_n). In the calculations, the modulus of elasticity of concrete used for the anchor bond zone is 32 Gpa and the modulus of elasticity of steel is 200 Gpa. The total cost of the anchored sheet pile wall consists of the total cost of the sheet pile wall, the total cost of the anchors and the total cost of the beams used in the excavation area (Eq. (13)). The cost of the wall is obtained by multiplying the total length of the wall (H+D) by the sheet pile unit cost and the perimeter of the excavation where the wall is built. The anchor cost is obtained by multiplying the total anchor length (L_{ub}+L_{bond}) by the anchor unit cost and the number of anchors in the horizontal row. The beam cost is obtained by multiplying the total beam weight by the beam unit cost.

$$TC=ATC+BC+PTC \tag{13}$$

$$PTC=2*(B+L)*(H+D)*PUC \tag{14}$$

$$ATC=\left(\sum_{i=1}^{n}\left(L_{ub}[i]+L_{bond}[i]\right)*AUC[i]\right)*N \tag{15}$$

$$BC=BUC*n*BW \tag{16}$$

$$R_{inter}=\frac{\tan\delta}{\tan\varnothing} \tag{17}$$

$$\delta=\frac{2\varnothing}{3} \tag{18}$$

where B is the excavation width, L is the excavation length, TC is the total cost, ATC is the anchor total cost, BC is the waling beam cost, PTC is the sheet pile total cost, PUC is the unit cost of the sheet pile wall, AUC is the unit cost of the anchor, BUC is the unit cost of the waling beam, BW is the weight of waling beam, n is the the number of anchors in the vertical row, N is the the number of anchors in the horizontal row, R_{inter} is the soil-wall interface strength, δ is the angle of friction between soil and wall, $L_{ub}[i]$ and $L_{bond}[i]$ values are the anchor unbonded length and the anchor bond length in ist row, respectively. The flow chart of the methodology described above for the preliminary design is shown in Fig. 4.

Since the displacements of the sheet pile system could

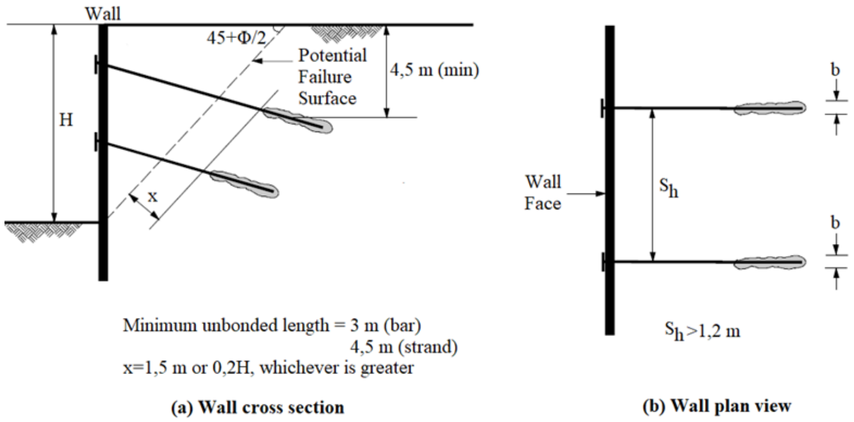

Fig. 3 The boundary conditions for anchors (FHWA 1999)

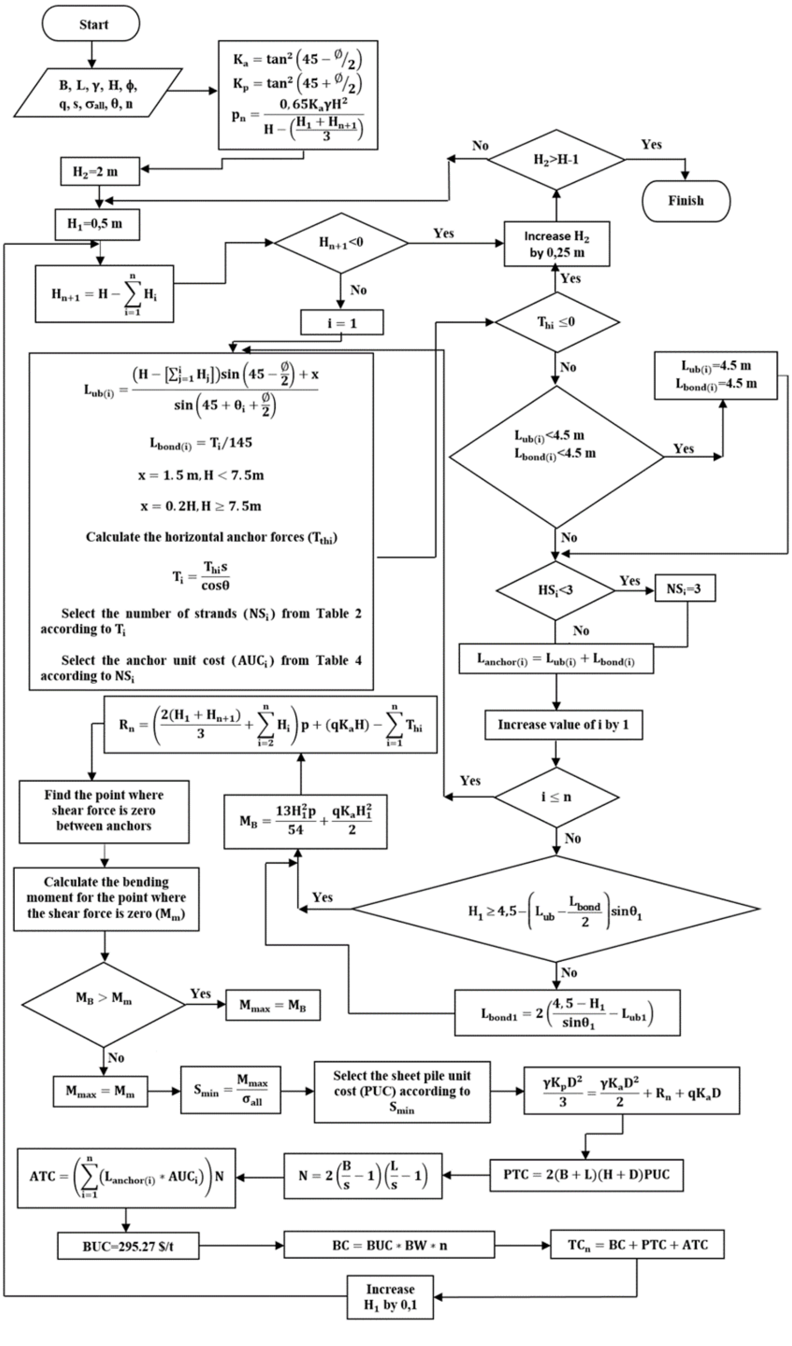

Fig. 4 Flow chart of multi-anchored sheet pile wall design

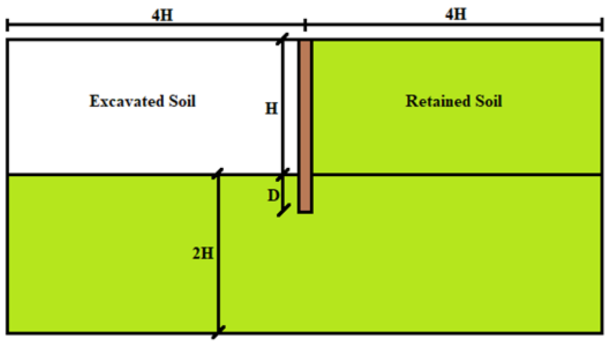

Fig. 5 Minimum model limits for sheet pile wall (Bilgin, 1994)

not be calculated by the method proposed by FHWA (1999), the lowest cost wall sections having excavation depths of 15 m and 20 m were analyzed with Plaxis 2D which use two-dimensional plane strain conditions. The model limits proposed by Bilgin (1994) and shown in Fig. 5 are taken into consideration in Plaxis 2D model. In addition, the analyses were carried out considering fully drained conditions since the soil is cohesionless. Hardening Soil model which is an extended version of a hyperbolic stress-strain method proposed by Duncan and Chang (1970) was used to model the soil because it helps to create a more realistic model.The model takes the change in stiffness of the soil with depth into account by using three different stiffnesses, i.e. secant stiffness, unloading-reloading stiffness and oedometer tangent stiffness (Liong, 2014, Hsiung and Dao, 2014). Because of the stress concentration in and around the sheet pile wall, a finer mesh was used in this study. In addition, staged construction analysis was used in the calculations in order to be consistent with the field application. “Plate”, “Node to node anchor” and “geogrid” options was used for the modeling of the sheet pile wall, anchor unbonded length and anchor bond zone, respectively. The interaction between the sheet pile and the soil is modeled with the help of an interface. Eq. (17) proposed by Khoiri ve Ou (2013) for granular soils was used for the strength reduction coefficient of the interface element.

3. Results and discussion

As a result of the research, the graphs showing the variation of the maximum bending moments, minimum embedment depths and total costs versus the change of the vertical spacings of the anchors are presented below.

When each curve in Figs. 6-7 is examined, the maximum bending moments decrease with increasing H_1 up to a certain value and then increase. In the graphs, the maximum bending moments in the decreasing zone occur between the excavation subgrade and the lowermost anchor. The bending moments of the increasing zone occur in the first anchor location as a result of the anchor group being too close to the excavation subgrade. And these moments equal to M_B. The magnitude of M_B depends on H_1 and p (Fig. 4). The reason for each curve in the growing zone of

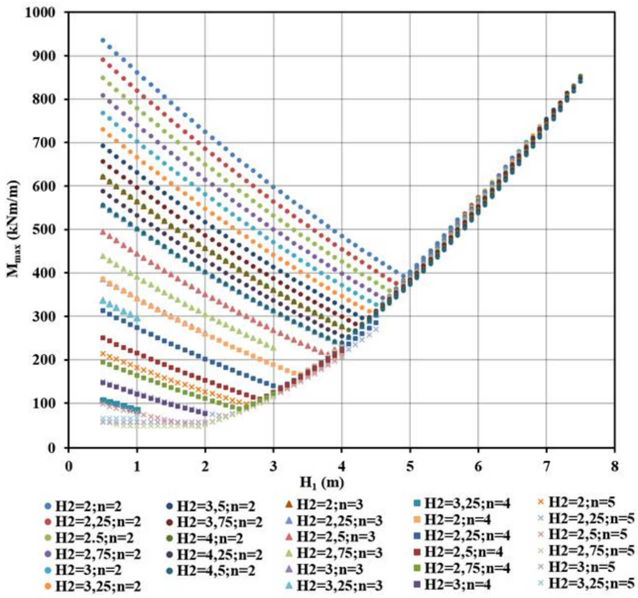

Fig. 6 Maximum bending moments versus the change of vertical spacing of anchors for 15 m excavation

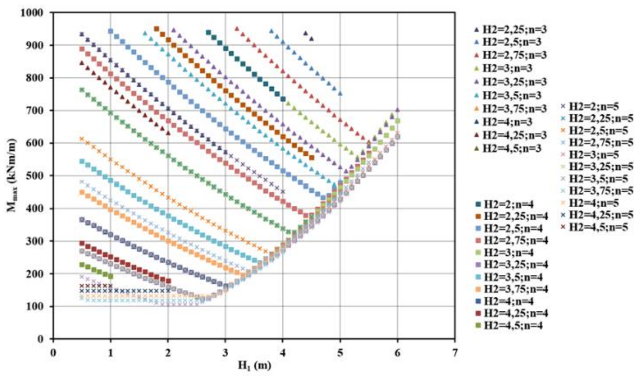

Fig. 7 Maximum bending moments versus the change of vertical spacing of anchors for 20 m excavation

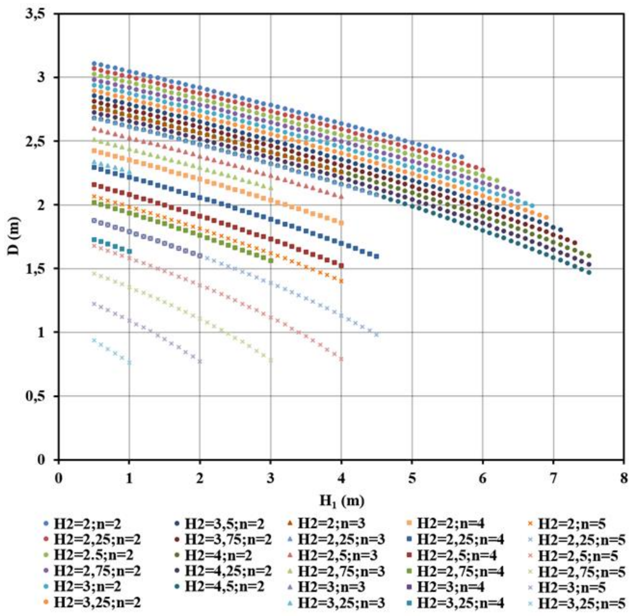

Fig. 8 Minimum embedment depths versus the change of vertical spacing of anchors for 15 m excavation

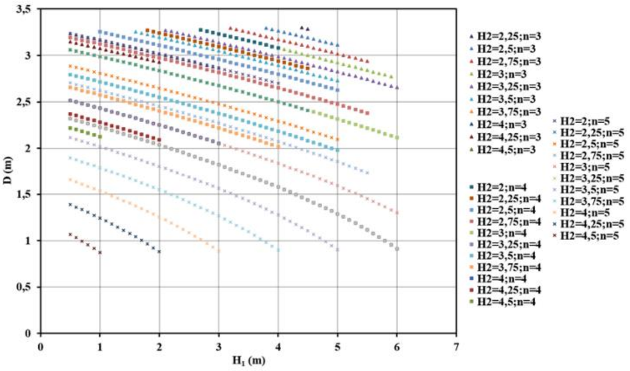

Fig. 9 Minimum embedment depths versus the change of vertical spacing of anchors for 20 m excavation

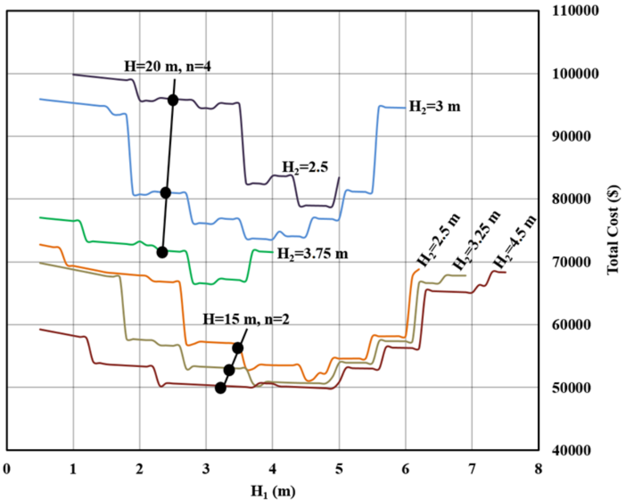

Fig. 10 Total cost versus change of vertical spacing amongst anchors for 15 m and 20 m excavation depth

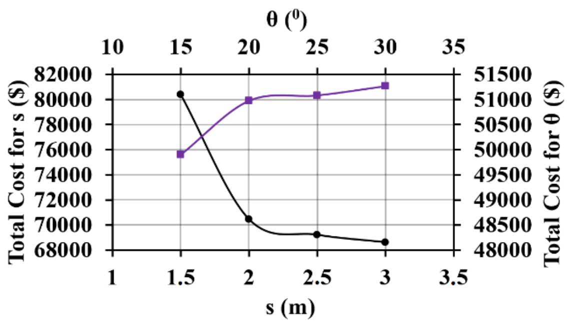

Fig. 11 Total costs versus anchor horizontal spacing

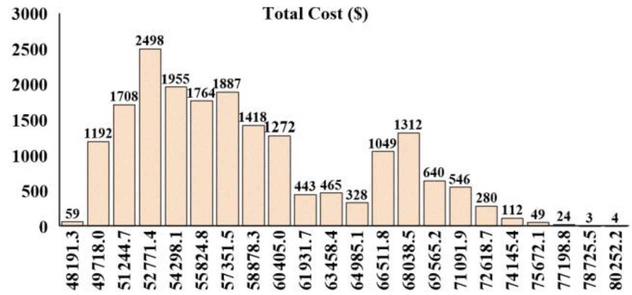

Fig. 12 Total costs for 15 m excavation depth

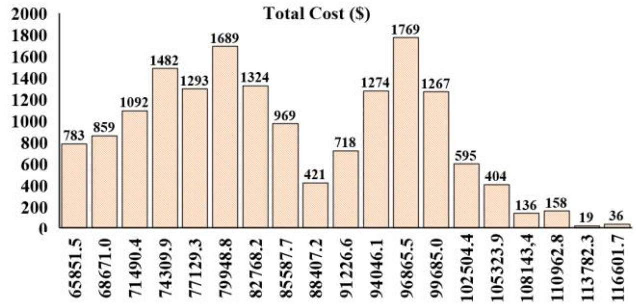

Fig. 13 Total costs for 20 m excavation depth

the Figs. 6-7 is close to each other is that the variation of the p calculated from Eq. (1) with respect to H_1 and H_2, is to small. In the case where $H_2 \geq 4$ m and n=5 in Fig. 7, the maximum bending moments occur amongst the anchors, and they are not affected by the change of H_1.

As the anchors in the vertical row comes close to the excavation base or the vertical distance (H_2) between the anchors increases, the total of the anchorage forces increases. Consequently, the R-value calculated from the horizontal equilibrium in Fig. 1 decreases. As given in Eq. (9), the embedment depth is directly affected by the change of R. This situtations explains why the embedment depths of the sheet pile are reduced as the H_1 and H_2 values increase (Figs. 8-9).

The variation behaviour the depending on H_1 and H_2 values of the costs of different geometries examined for 15 m and 20 m of excavation depths is similar to each other. And some of the curves representing this behavior are given in Fig. 10. When each curve in Fig. 10 is examined, costs decrease to a certain value of H_1 and then increase. In the increasing zone of Figs. 6-7, the maximum bending moment occurs in the 1st anchor location and this moment value only increases with the rising of H_1. This explains the behavior of the zone where costs increase with the rise of H_1 in Fig. 10. Besides, with the increase of H_2, the costs are generally reduced as the embedment depth and the maximum bending moment values decrease. In addition, sudden increases and decreases occurred in the curves in Fig. 10. The reason for these sudden increase and decrease is the change in the required sheet pile section as a result of the increase or decrease of the maximum bending moments due to the change in the vertical spacings of the anchors. As a consequence of this change, the unit cost of the sheet pile wall is changed and the increase and decrease in the unit cost causes the increase and the fall in total costs, respectively.

With the increase of the horizontal distance between the anchors, the T_{thi} values increase and as a result, bonded length of the anchors and total cost increases. In addition, if the number of strands in anchors increases with the increase of the Tthi, this situation will also increase the total costs. Besides, the total cost decreases as the number of anchors in the excavation area decreases with the increase in the horizontal distance between the anchors. As a result, the dominant one of the above situations, which has an increasing or decreasing effect on the cost, determines the value of the total costs. On the other hand, with the increase

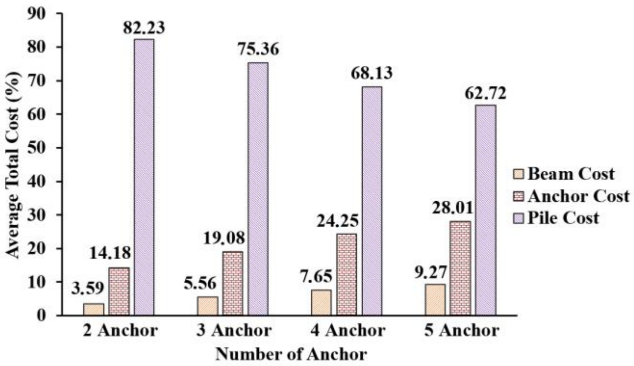

Fig. 14 Percentages of anchor, waling beam and sheet pile costs for 15 m excavation depth

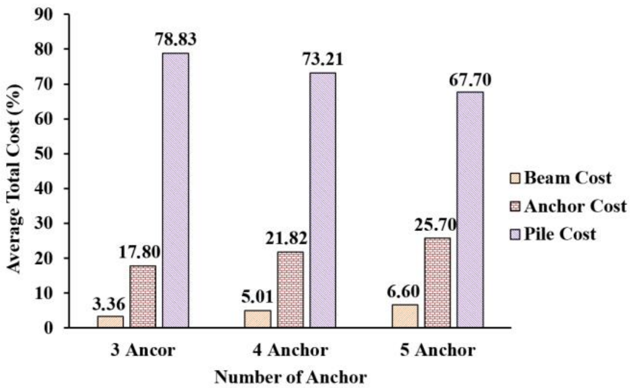

Fig. 15 Percentages of anchor, waling beam and sheet pile costs for 20 m excavation depth

Table 5 Soil and interface properties used in Plaxis 2D

Soil unit weight above phreatic level	18 kN/m^3
Secant stiffness (E_{50}^{ref})	35000 kN/m^2
Tangent oedometer stiffness (E_{oed}^{ref})	35000 kN/m^2
Unloading/reloading stiffness (E_{ur}^{ref})	105000 kN/m^2
Power for dependency of the soil stiffness to the stress level (m)	0.5
Cohesion (c)	1 kPa
Friction angle ($\emptyset$)	36^0
Dilatancy angle (φ)	6
Poisson's ratio (ϑ_{ur})	0.2
Interface reduction factor (R_{inter})	0.613

of the anchor angle, the total costs increase as the T_{thi} values and bonded length of the anchors increase. As seen in Fig. 11, the total costs decreased with the increase in the horizontal distances between the anchors and the decrease in the anchor angles.

When all the costs obtained from analyzes are shown in a histogram (Figs. 12-13), it is seen that the sheet pile system has a cost between \$48191 and \$81778 for 15 m excavation depth and it has a cost between \$65851 and \$119421 for 20 m excavation depth. For instance, Fig. 12 shows that there are 59 different sheet pile sections with costs between 48191 and \$49718. It can be seen from Figs. 12-13 that with the optimum design of the sheet pile wall, a saving of approximately 2 times is achieved compared to the wall section with the highest cost. In addition, with the increase of excavation depth from 15 m to 20 m, the costs increased by 37~46%.

Table 6 Plaxis 2D parameters for all anchor unbonded length for 15 m excavation depth and for 2nd and 5th anchor unbonded length for 20 m excavation depth

Type of behaviour	Elastic
Normal stiffness (EA)	82530 kN
Spacing out of plane	3 m

Table 7 Plaxis 2D parameters for all anchor bond length for 15 m excavation depth and for 2nd and 5th anchor bond length for 20 m excavation depth

Type of behaviour	Elastic
Normal stiffness (EA)	176134 kN/m

Table 8 Plaxis 2D parameters for the 1st, 3rd and 4th anchor unbonded length for 20 m excavation depth

Type of behaviour	Elastic
Normal stiffness (EA)	110000 kN
Spacing out of plane	3 m

Table 9 Properties of the sheet pile wall

Type of behaviour	Elastic
Normal stiffness (EA)	3150000 kN/m
Flexural rigidity (EI)	42840 kNm^2/m
Weight (w)	2.4 kN/m/m
Poisson's ratio	0

Table 10 Plaxis 2D parameters for 1st, 3rd and 4th anchor bond length for 20 m excavation depth

Type of behaviour	Elastic
Normal stiffness (EA)	188500 kN/m

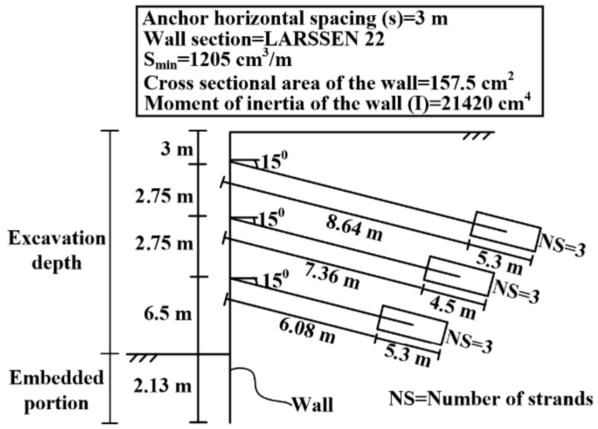

Fig. 16 Wall geometry having the lowest cost for 20 m excavation depth

The charts displaying the percentage of the anchor,

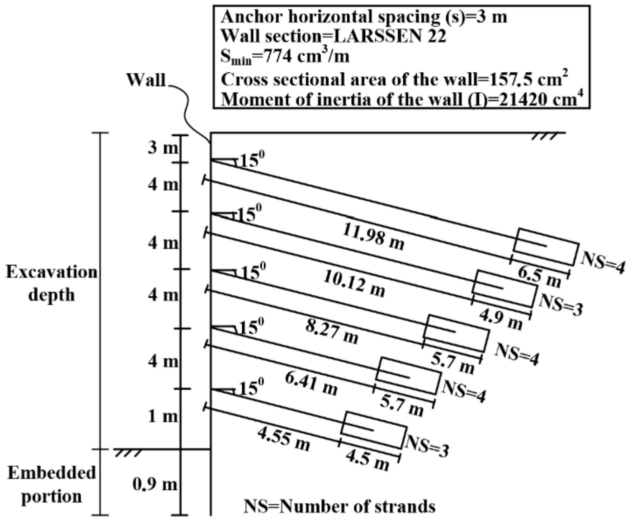

Fig. 17 Wall geometry having the lowest cost for 15 m excavation depth

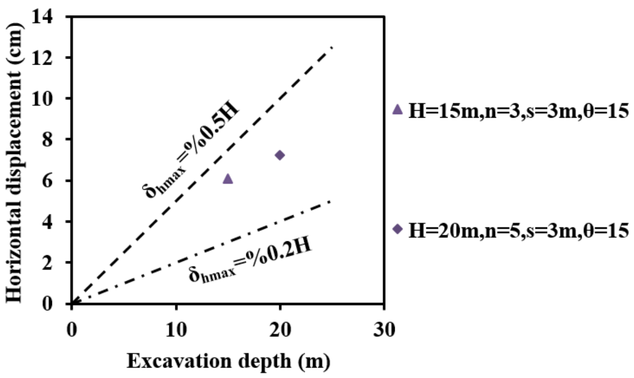

Fig. 18 Horizontal displacements of sheet pile walls

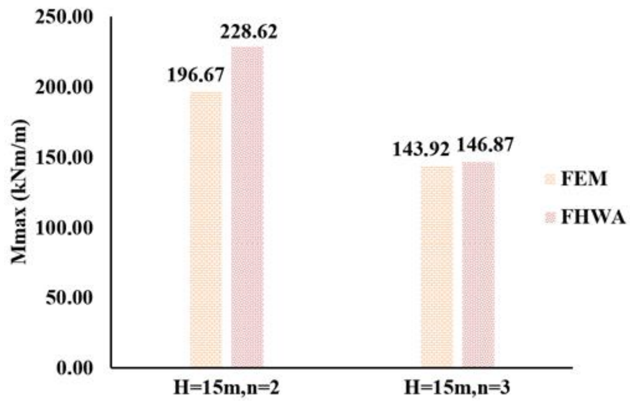

Fig. 19 Comparison of maximum bending moments

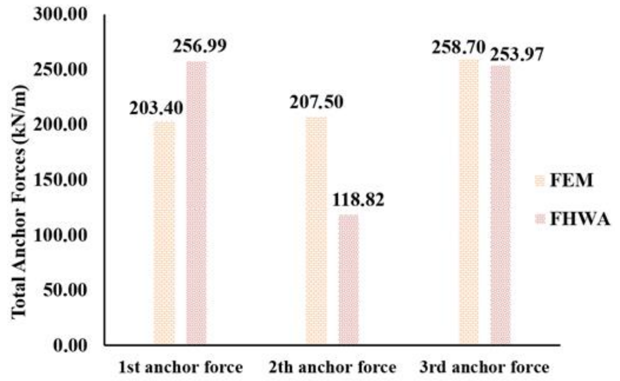

Fig. 20 Comparison of anchor forces for 15 m excavation depth

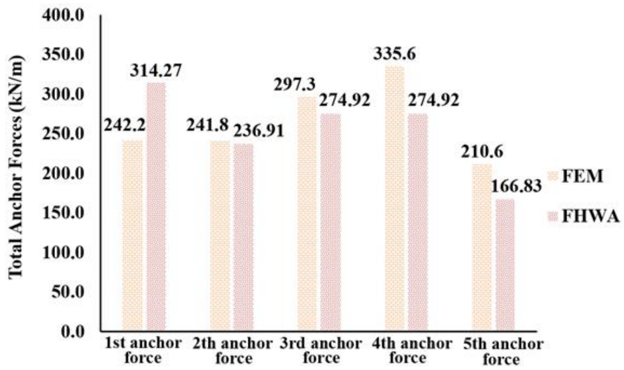

Fig. 21 Comparison of anchor forces for 20 m excavation depth

waling beam and sheet pile costs are given in Figs. 14-15.

When the Figs. 14-15 are examined, the biggest part of the total cost is the wall cost. Considering their share in the total cost, the cost changing from higher to smaller are; the cost of sheet pile wall, the cost of anchor, and the cost of the waling beam. Additionally, the cost of the sheet pile wall is decreased and the cost of anchor and waling beam increases with the increase of the number of anchors in the vertical row.

In the analyses, the anchor angles were changed between 15-30^0. It is concluded that the lowest costs occur when the anchor angle is 15^0.

The geometries of the sheet pile walls which have the lowest cost among all examined wall sections for 15 m and 20 m excavation depth are given in Figs. 16-17. These cross-sections, which are shown in Figs. 16-17 and have the lowest cost, are modeled in Plaxis 2D by using the parameters in Tables 5-10 for displacement analysis. In the analyses, the Elasticity Modulus value of 35 MPa which is used by Bilgin (2012) for medium-dense sand is used. In addition, Gouw (2014) stated that the value of m, which controls the dependency of the soil stiffness to the stress level is generally equal to 0.5 for sands. Therefore, the value of m was chosen as 0.5 in this study.

The horizontal displacements obtained from Plaxis 2D are shown in Fig. 18. Clough and O'Rourke (1990) and Ou *et al.* (1993) suggested that the value of the maximum horizontal displacement of the sheet pile walls remained between 0.2% and 0.5% of the excavation depth. In consequence of the analysis, the maximum horizontal displacement values calculated for the sheet pile sections with optimum cost were within these recommended limits (Fig. 18). In addition, the anchor forces and bending moments obtained from the finite element analysis were compared with ones obtained from the method proposed by FHWA (1999) (Figs. 19-21). In Fig. 19, the bending moments obtained by using the method proposed by FHWA (1999) are greater than those obtained by the finite element method. In addition, Figs. 20-21 show that the FHWA (1999) method calculates the 1st anchor force greater than one calculated in the finite element method. On the other hand, the results for the other anchor forces found with the finite element analyses are greater than the method proposed by FHWA (1999).

4. Conclusions

In the present study, a parametric study was carried out for the optimum design of temporary multi-anchored sheet pile walls in dry sand soils. The effects of the number of anchors in the vertical row, the horizontal and vertical distances between the anchors, the anchor angles and the excavation depth on the embedment depth, the maximum bending moment and cost of the sheet pile wall were investigated. In addition, using the methodology proposed by FHWA (1999), it was checked whether the displacements of the sections with the lowest cost for different excavation depths remained within the allowable limits. The anchor forces and bending moments obtained by Plaxis 2D were compared with the ones obtained by the method proposed by FHWA (1999). The main findings from this research are as follows:

- When the vertical distance of the uppermost anchor to the ground surface is generally 3 m, the sheet pile sections provides the lowest cost.
- The cost varying from higher to smaller of elements used in a multi-anchored sheet pile wall are sheet pile cost, anchor cost and waling costs. As a result, since the wall section is the most important parameter that controls the change in total cost, The lowest costs occurred in the type of Larrsen 22 wall.
- The lowest costs occurred when the horizontal spacing amongst the anchors was equal to 3 m.
- The lowest costs occurred when the angle of the anchors with the horizontal was generally 15^0.
- It has been observed that the costs have increased by approximately 42% with the 33% increase in excavation depth.
- According to the results obtained from the finite element analysis, the maximum bending moments and the uppermost anchor force are calculated conservatively by using trapezoidal horizontal earth pressure envelope and boundary conditions proposed by FHWA (1999) for the design of multi-anchored sheet pile walls constructed in medium-dense sands. Additionally, the anchor forces calculated by using FHWA (1999) method except for the anchor in the first row were smaller than those obtained from the finite element analysis.
- As the vertical spacing amongst the anchors increases, the anchor forces increase and the embedment depth decreases.
- When the number of anchors in the vertical row increases, wall costs decrease and anchor and waling costs increase.
- Geotechnical designers can determine the lowest cost sheet pile sections by using the method proposed by FHWA (1999) during the preliminary design of multi-anchored sheet pile walls. Then they can carry out safe and economical sheet pile wall design by using one of the finite element methods to calculate the displacements of the lowest cost sections. In this way, geotechnical designers can save time by not examining tens of thousands of geometrik configurations by finite element method.

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