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Effect of Wall Stiffness on Excavation-Induced Horizontal Deformations in Stiff-Hard Clays

Gamze ÜÇDEMIR[1,2*] Sami Oğuzhan AKBAŞ[3]

[1]*Gazi University, Graduate School of Natural and Applied Sciences, Ankara, Türkiye*
[2]*Atatürk University, Faculty of Engineering, Civil Engineering Department, Erzurum, Türkiye*
[3]*Gazi University, Faculty of Engineering, Civil Engineering Department, Ankara, Türkiye*

Keywords

Anchored Deep Excavation
Horizontal Displacement
Stiff-Hard Clay
Support System Stiffness

Abstract

Excavation-induced ground movements are affected by the stiffness of the support system as well as the soil properties. Displacement estimations of deep excavations are generally made using the finite element method (FEM). However, the accuracy and reliability of the results obtained from the finite element calculations will change significantly in proportion with the quality of the parameters employed in the program, thus, the use of probabilistic analysis that considers soil variability's impact has become a popular approach in recent studies. Based on these considerations, this study aims to investigate the influence of wall bending stiffness on excavation-induced lateral displacements for deep excavations in stiff to hard clays and provide a practical methodology to be used in preliminary design. For this purpose, finite element analyses were carried out using various practically achievable support system stiffness values and soil parameters. Considering the inherent variability of the soil, effective stress friction angle and effective cohesion of the soil were randomly generated by Monte Carlo simulations to be used in the finite element analyses. The performance of the analyses was evaluated using results from 22 case histories from deep excavations in stiff-hard clays. The results indicate that, lateral movement in excavations in stiff-hard clays is minimally affected by the stiffness of the wall. Soil variability was found to have a significant impact on the outcome of Monte Carlo simulations, resulting in a wide range of normalized maximum lateral deformations for a given wall stiffness. A new stiffness factor has been proposed that incorporates the horizontal spacing of the support elements, which is capable of covering a wider range of excavation support system types, thus enhancing the accuracy of the analyses.

Cite

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Author ID (ORCID Number)

0000-0002-4274-5823 Gamze ÜÇDEMIR
0000-0002-7872-1604 Sami Oğuzhan AKBAŞ

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1. INTRODUCTION

Deep excavation-induced ground movements can cause severe harm to nearby infrastructure in urban areas if they exceed acceptable limits. Ground movements caused by deep excavations depend on many factors such as soil properties, the type and structural characteristics of the support system, which is usually denoted numerically by its stiffness. Excavation support system stiffness is a variable that is a combination of many factors such as the stiffness of the wall, the horizontal and vertical spacing of the support elements besides the structural strength, and the type of connection between the support elements and the wall (Bryson & Zapata-Medina, 2012).

Prediction of deep excavation-induced displacements are generally made using the finite element method (FEM). But, in engineering practice, simplified charts or empirical design equations are still popular to estimate approximate values of wall deformations, especially before the detailed design phase. Moreover, it is clear that

*Corresponding Author, e-mail: gamzeucdemir@atauni.edu.tr

the accuracy and reliability of the results obtained from the FEM will significantly change as a function of the quality of the parameters employed in the program, thus the incorporation of the impact of soil variability in conjunction with probabilistic analysis has become popular in recent studies. Based on these considerations, this study was performed to investigate the effect of wall rigidity on lateral deformations for excavations in stiff to hard clays. The main aim is to provide a practical methodology to be used in preliminary design. For this purpose, a range of finite element analyses were performed that involve a practical range of support system stiffness values, as well as stiff-hard clay strength parameters. Considering the inherent variability of the soil, the effective stress friction angle (φ) and effective cohesion (c') of the clay were randomly generated using Monte Carlo simulations to be automatically inserted into the finite element analyses using Python programming language. Finally, the performance of the analyzes was evaluated comparatively using measurements reported in 22 well-documented case histories from deep excavations in stiff-hard clays.

This paper is intended to examine the effect of the wall elasticity modulus, which is the support system stiffness parameter, and the soil variability on the displacements. This was achieved by analyzing a range of wall elasticity moduli along with the different soil parameters created separately by Monte Carlo simulations. A novel approach was undertaken by carrying out finite element analyses considering the soil variability, and thus the practical range of the results can be observed. In addition, the obtained data was compared both with other theoretical studies and measurements from case histories, and the adequacy of the system stiffness proposed by Clough et al. (1989), which is widely-used in practice was examined.

This study stands out from others by not only examining the effect of wall flexural stiffness on displacement but also by including the variability in both cohesion and internal friction angle of the soil in the analyses. Additionally, a new stiffness factor has been proposed that incorporates the horizontal spacing of the support elements, which enables covering a wider range of excavation support system types, thus enhancing the accuracy of the preliminary analyses.

2. PREVIOUS STUDIES

One of the most widely-accepted methods to determine excavation-induced displacements was presented by Clough et al. (1989). This method was developed based on excavations in soft clays, and later it was reported to be approximately valid for other soil types. It has the advantage of handling the characteristics of the soil, wall, and the support system together. As a result of studies by Clough et al. (1989), a simple design chart has been proposed for soft to medium stiff clays based on the rigidity of the support system and the factor of safety against basal heave (FOS_{base}). According to this design chart, the support system stiffness, which is defined as a function of wall modulus (E), modulus of inertia (I), and vertical spacing of support elements (s_v) as $EI/\Upsilon_w s_v^4$, has a significant effect on the wall movement in excavations made in soft-medium stiff clays especially for cases where the factor of safety against basal heave is low. In excavations made in stiff clays with high FOS_{base}, the support system stiffness has a less pronounced effect on the wall movement (Clough & O'Rourke, 1990).

The results of the study by Clough et al. (1989) was later updated with the help of a larger database developed by Long (2001). Long (2001) classified the database he created according to low and high FOS_{base} and generated a chart of normalized maximum horizontal displacement as a function of support system stiffness. According to the results obtained in that study, the horizontal displacements of excavations in hard clays are largely distinct of the wall strength and the characteristics of the support elements. In addition, the findings indicate that the support system stiffness has an important effect on the excavations displacement in soft clays with low FOS_{base}, while the influence on systems with high FOS_{base} is less.

Moormann (2004) created an international case history database on deep excavations mostly in soft soils to evaluate the accuracy and reliability of the chart prepared by Clough et al. (1989). According to his analyses, wall lateral displacement was largely independent of the support system stiffness. However, there is no detailed information in the study on factors such as circumambient buildings, geometrical irregularities, quality of workmanship, soil properties at the embedded part of the wall, unforeseen events, ground water circumstances, prestressing of support elements. Because of these uncertainties, Bryson and Zapata-Medina (2012) claimed that the effect of system stiffness on lateral movements should further be investigated by numerical analyses.

In their study, Bryson and Zapata-Medina (2012) created 3-D numerical models that realistically represented the action of the excavation and excavation support systems, to eliminate the uncertainties caused by the lack of information in the Long (2001) and Moormann (2004) databases. In these finite element models, the influences of the wall stiffness, the characteristics of the support elements and different soil conditions on the lateral movement were investigated. Their analyzes showed that in hard clays, the deformations are mostly independent of the support system stiffness at sufficient FOS_{base}, although in soft-medium stiff clays it was greatly affected by the stiffness of the system at low FOS_{base}. Therefore, the results indicate that the effect of the excavation support system on deformations is related to the soil strength.

As can be seen from the results of previous studies, there is a debate on the extent of effect of wall stiffness on excavation-induced displacements, especially as a function of soil strength in stiff-hard clays. In addition, not much effort has been put into investigating the impact of soil variability on the results. These points comprise the main focus of the study presented herein.

3. METHODOLOGY

3.1. Finite Element Modelling

In this study, finite element analyses for deep excavation systems were performed using Plaxis 2D Ultimate software, version 2022. Among the many material models available for modeling soil in the software, the hardening soil (HS), which is an elastoplastic multi-yield surface model (Bryson & Zapata-Medina, 2012) was used. The model uses compression hardening to imitate the permanent compaction of soil during primary compression. Hyperbolic stress-strain relationship showing model behavior is presented in Figure 1 (Plaxis 2D Material Models Manual, 2022).

In this model, when the soil is subjected to primary deviatoric loading, soil strength decreases, and permanent deformation occurs in the soil simultaneously (Bryson & Zapata-Medina, 2012). Soil moduli based on the HS model are determined with the help of the following equations:

$$E_{50} = E_{50}^{ref}\left(\frac{c\ cos\varphi - \sigma_3'\ sin\varphi}{c\ cos\varphi + p^{ref}\ sin\varphi}\right)^m \tag{1}$$

$$E_{oed} = E_{oed}^{ref}\left(\sigma/p^{ref}\right)^m \tag{2}$$

$$E_{ur} = E_{ur}^{ref}\left(\frac{c\ cos\varphi - \sigma_3{}'sin\varphi}{c\ cos\varphi + p^{ref}\ sin\varphi}\right)^m \tag{3}$$

in which, E_{50}= secant stiffness at the point of 50% of the maximum deviatoric stress, E_{oed}= tangent stiffness for primary oedometer loading, E_{ur}= unloading/reloading stiffness, p_{ref}= reference stress equal to 1 atm, m= power for stress-level dependency of stiffness, $E_{50}{}^{ref}$=triaxial loading stiffness modulus at reference pressure p_{ref}, $E_{oed}{}^{ref}$= oedometer loading stiffness module at reference pressure, and $E_{ur}{}^{ref}$= unloading/reloading stiffness module at reference pressure (Plaxis 2D Material Models Manual, 2022). The stress dependent stiffness parameter m used in Eq.1, Eq.2 and Eq.3 varies between 0.5-1.0, with m being 1.0 in soft clay soils and 0.5 in Norwegian sands and silts (Plaxis 2D Material Models Manual, 2022).

The effect of soil variability was also considered in the analyses. In a comprehensive study conducted by Akbaş and Kulhawy (2010) the variability of Ankara Clay (Table 1) was investigated. Ankara Clay is a stiff to hard, semi-saturated, plastic clay red brown in color. It becomes stiffer with depths (Bozkurt, 2017). In the study, the analyses results summarized in Table 1, which can be safely assumed to be representative of hard-stiff clays, was used to determine the mean and coefficient of variation (COV) of the undrained shear strength (c_u) of the clay. The data from the literature was used for estimating the COV of the φ of the clay. In studies by Harr (1984), and Kulhawy (1992), the coefficient of variation of effective stress friction angle varies between 2% and 13%. COV and mean values of c_u and φ used in this study are shown in Table 2.

GU J Sci, Part A 10(2) 113-130 (2023) 10.54287/gujsa.1244790

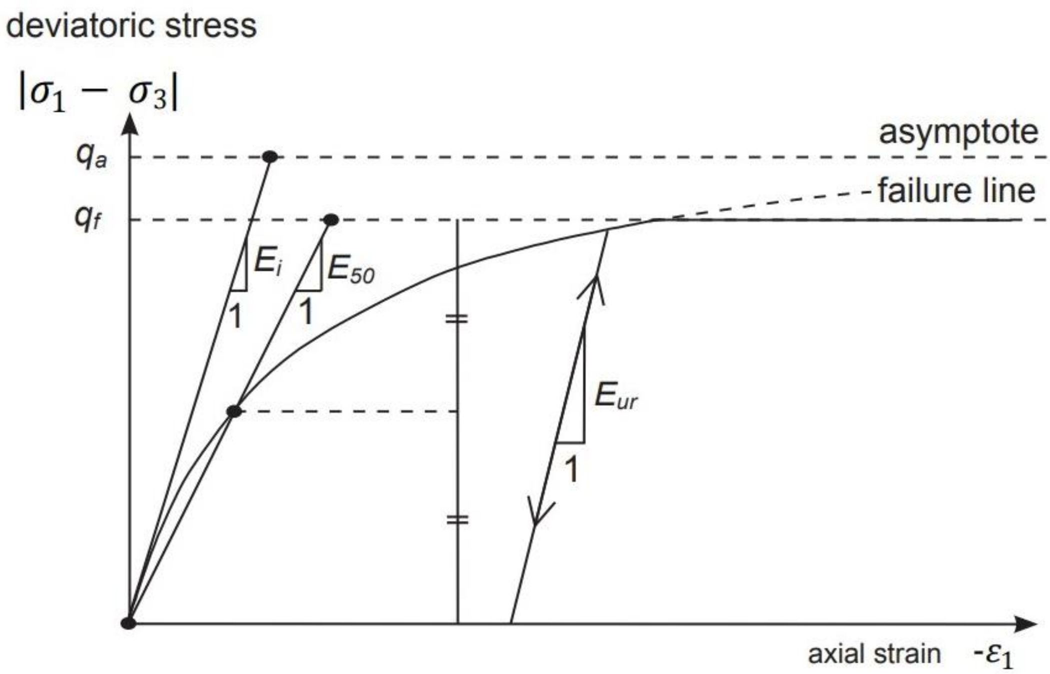


Figure 1. *Hyperbolic Stress-Strain Relation in Primary Loading for a Standard Drained Triaxial Test (Plaxis 2D Material Models Manual, 2022)*

Table 1. *Inherent Variability of Some Geotechnical Properties of Ankara Clay (Akbaş & Kulhawy, 2010)*

Property	**No. of data groups**	**No. of tests per group**	**Property value**		**Property COV(%)**	
				Mean	Range	Mean
w_L (%)	25	4-24	50-79	64	9-22	14
w_P (%)	25	4-25	20-35	26	6-19	12
w_n (%)	26	4-18	23-37	29	12-22	14
PI (%)	25	4-24	21-52	38	13-28	19
e_0	14	4-25	0,65-0,98	0,84	3-16	9
Υ_d (kN/m^3)	20	3-12	14-17	15,8	2-8	5
c_u (kN/m^3)	9	4-8	106-186	148	11-35	23
C_c	7	3-8	0,18-0,38	0,26	14-35	26
SPT *N*	12	6-31	23-60	38	10-46	29

Table 2. *Mean and COV Values for c_u and ϕ*

Parametre	**Mean Value**	**COV (%)**
c_u (kPa)	100	23
ϕ (°)	28	13

After estimating the statistical parameters, Monte Carlo simulations was carried out within the finite element model of the deep excavation system using Plaxis Remote scripting through the Plaxis-Python code software interaction interface (Figure 2).

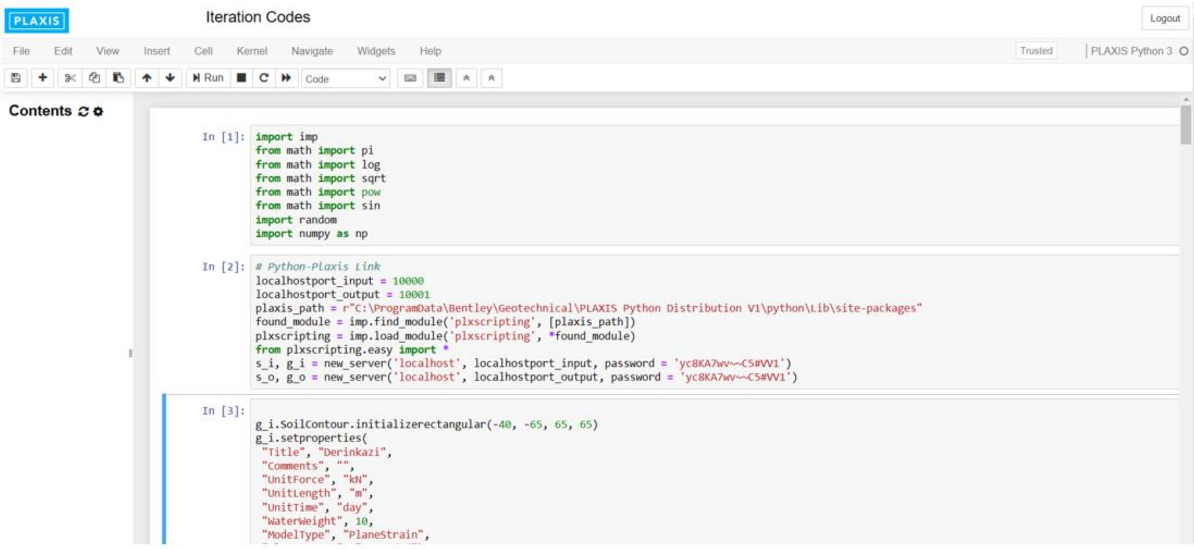


Figure 2. *Plaxis Commands in Python*

In the Monte Carlo simulation method, a variable mathematical or empirical parameter is generated randomly within a certain distribution. The normal or Gaussian distribution is the most usually used type of distribution to determine random variability in a data set in many science disciplines, especially for natural phenomena. However, in asymmetrical distributions, and for cases where negative values are inadmissible, log-normal distribution is more versatile to capture the uncertainty behavior. For this reason, it would be more appropriate to model soil properties as random variables with only positive values using log-normal distribution (Bozkurt, 2017). Therefore, in the analyzes performed in this study, the soil parameter variability was modelled with a log-normal distribution using the aforementioned mean and COV values.

3.2. Case Study and Soil Properties

The case of a braced excavation with a depth of approximately 19 m in Istanbul has been examined within the scope of this study. For the in-situ wall, 65 cm diameter drilled shafts were installed at 120 cm center to center distance. The deep excavation was supported by 6 rows of prestressed soil anchors with vertical and horizontal spacings of 2.52 m and 1.8 m, respectively (Figure 3). The prestressing load for the anchor strands was determined as 40 tons (Şahin, 2017).

In the field, the exploratory boreholes indicate that, very stiff to hard sandy-silty clay containing yellow-brown fine quartzite pebbles with a thickness of approximately 18 m underlies a fill layer of approximately 3 m from the ground surface. Below the silty clay, a weathered limestone-claystone unit in bluish greenish blackish gray tones was observed as bedrock (Şahin, 2017).

The geometry of the anchored deep excavation is shown as modeled in the finite element model in Figure 4. According to inclinometer readings carried out in the field, it was observed that the maximum horizontal deformations of the in-situ wall in the case of full excavation is approximately 18 mm (Figure 5).

Back analysis of the deep excavation was carried out to obtain the elasticity modulus values reflecting the behavior observed in the inclinometer readings. Duncan and Buchignani (1976) equation was used to obtain the initial modulus of elasticity of the silty clay soil layer:

$$E_u = (300 - 1000) \cdot c_u \tag{4}$$

Using the mean value of the c_u of 100 kPa, a reasonable first assumption for the E_u value was made as 60000 kPa. As a result, initial values for back analyses are shown in Table 3.

GU J Sci, Part A 10(2) 113-130 (2023) 10.54287/gujsa.1244790

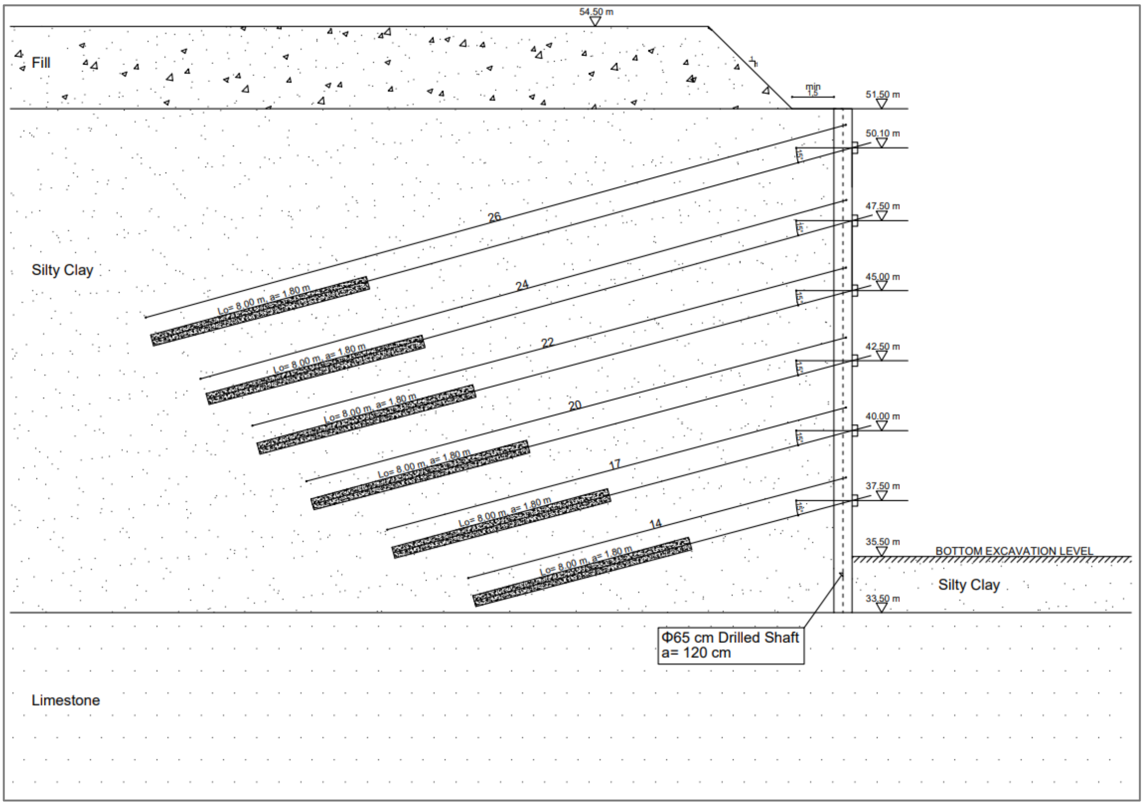


Figure 3. *Cross Sectional View of the Shoring System*

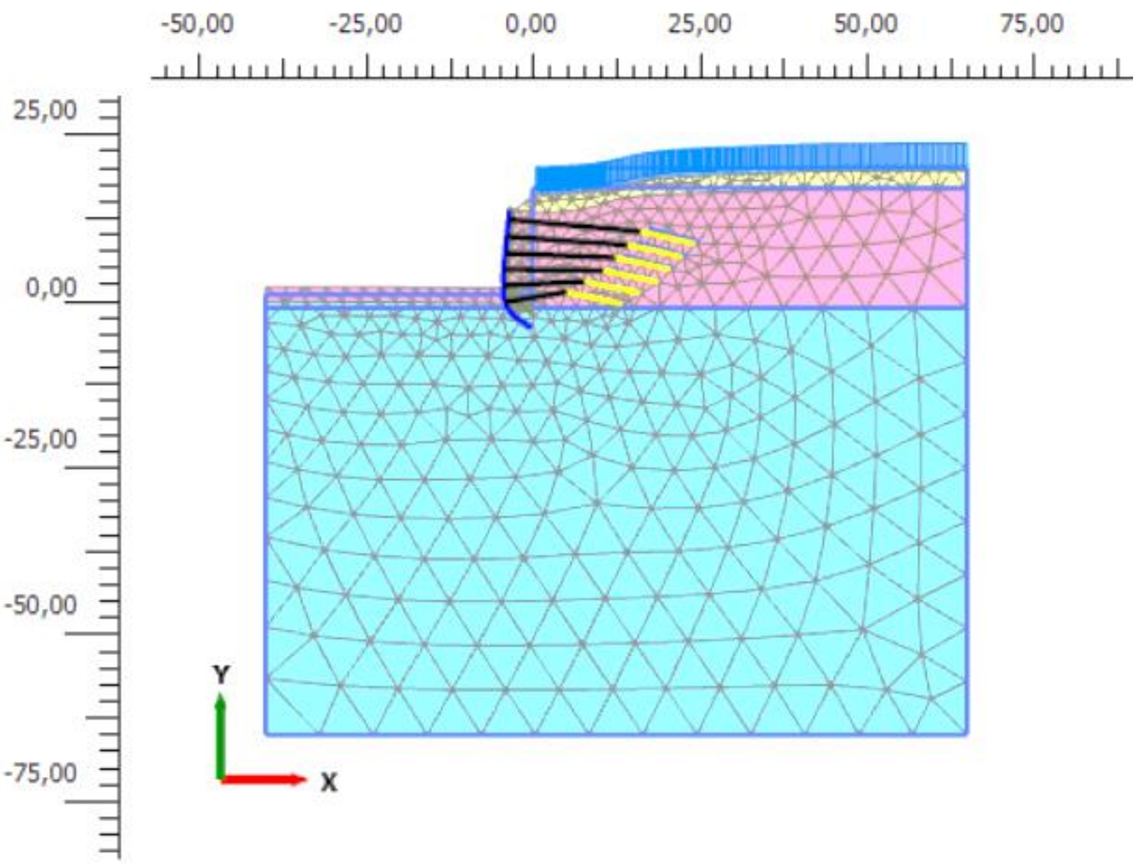


Figure 4. *Finite Element Model of Anchored Deep Excavation*

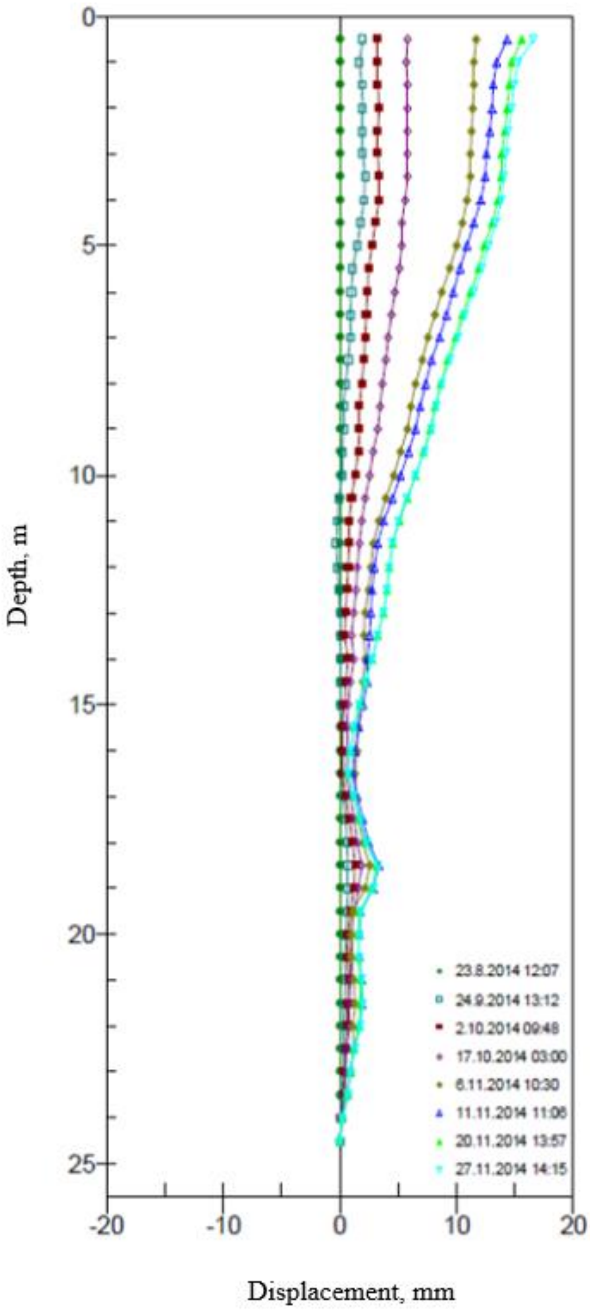


Figure 5. *Deep Excavation Inclinometer Readings (Şahin, 2017)*

Table 3. *Initial Estimates Used in Case Back Analyses (Şahin, 2017)*

Parameter	**Fill**	**Silty Clay**	**Limestone**	**Unit**
Material Model	Hardening Soil (HS)	Hardening Soil (HS)	Hardening Soil (HS)	-
Drainage Type	Drained	Drained	Drained	-
c'	5	10	25	kN/m^2
ϕ'	27	28	35	°
E_{50}^{ref}	12000	42000	200000	kN/m^2
E_{oed}^{ref}	12000	42000	200000	kN/m^2
E_{ur}^{ref}	36000	126000	600000	kN/m^2

GU J Sci, Part A 10(2) 113-130 (2023) 10.54287/gujsa.1244790

The empirical correlations used for the estimation of the geotechnical parameters of the silty clay unit used in the iterative analyzes are presented in Table 4.

Table 4. *Correlations Used in the Determination of Silty Clay Unit Parameters*

Parameter	Silty Clay	Source
E’	0.7 x E_u	Craig, 2004
E_u	600 x c_u	Duncan & Buchignani, 1976
c'	c_u x 0.1	Sorensen & Okkels, 2013

As a result of the back analysis, it was detected that the deformation behavior can be realistically simulated only if the correlation $E_u/c_u \approx 776$ value is used for the silty clay unit, as with this value a horizontal deformation of about 18 mm that was observed in the field has also been determined by the finite element analysis (Figure 6). The calculations of the reference elasticity moduli besides the geotechnical parameters obtained as a result of back analysis and used in finite element analyses are presented in Table 5.

Table 5. *Parameters Found as a Result of Case Back Analysis*

Parameter	Fill	Silty Clay	Limestone	Back Analysis Correlations/Calculations
Material Model	Hardening Soil (HS)	Hardening Soil (HS)	Hardening Soil (HS)	$c'=0.1c_u$ c_u=100 kPa
Drainage Type	Drained	Drained	Drained	$E_u/c_u=776$
ϒ (kN/m^3)	18	19	21	E_u= 100*776=77600
c' (kN/m^2)	5	10	25	E_u/E’=0.7
ϕ' (°)	27	28	35	E’=0,7*776000≈ 54350
E_{50}^{ref} (kN/m^2)	12000	54350	200000	E_{50}^{ref}=E’=54350
E_{oed}^{ref} (kN/m^2)	12000	54350	200000	$E_{oed}^{ref}=E_{50}^{ref}$
E_{ur}^{ref} (kN/m^2)	36000	163050	600000	$E_{ur}^{ref}=3E_{50}^{ref}$
Power (m)	0.5	0.5	0.5	-
R_{inter}	0.7	0.8	0.8	-

Figure 6. *Lateral Displacement of Drilled Shaft Wall as Obtained from the Back-Analysis ($\delta_{maxlateral} \cong 18$ mm)*

4. RESULTS AND DISCUSSION

4.1. Influence of Wall Bending Stiffness

In this study, 8 different coefficients called α as defined by Bryson and Zapata-Medina (2012) were used to represent walls with various rigidities that can be constructed in the field. The drilled shaft rigidity was determined according to the α coefficients produced. The typical drilled shaft wall conditions and geometries used to determine the lower and upper limits of the α coefficient are given in Table 6. Based on Table 6, the α coefficient range was determined to have a range between 0.05 and 50.

Table 6. *Upper and Lower Limits for α Coefficient*

Drilled Shaft Properties	**Upper Limit for α**	**Lower Limit for α**
Concrete Class	C35	C16
Pile Diameter (cm)	φ160	φ30
Pile Spacing (m)	0.8	1.5
I: Moment of Inertia (m^4)	0.3217	$3.9761*10^{-4}$
E: Elasticity Module (kN/m^2)	33200000	27000000
Rigidity: EI (kNm^2/m)	13350512.14	7156.94
Baseline EI (kNm^2/m)	220000	220000
α=EI/Baseline EI	60	0.04

For each of the wall rigidity determined using 8 different α coefficients, 100 Monte Carlo simulation-based finite element analyzes, that is, a total of 800 anchored deep excavation analyzes, were carried out to also determine the influence of soil variability on the results. In the analyzes carried out for the anchored deep excavation, the bored pile element is modeled as a solid element, which has both bending and axial rigidity, and is assumed to exhibit linear elastic behavior. With the assumption of elastic behavior, high moment capacity (Mp) and axial capacity (Np) values are automatically assigned to the wall element by the finite element program, so that the solid element exhibits elastic behavior in all cases, regardless of the section effects.

In the study, the wall bending stiffness values were obtained by multiplying the bending stiffness in the sample case with different α coefficients determined by considering the possibility of the various wall geometries and construction qualities that can be realized in the field. The baseline bending stiffness value used to improve the various wall stiffness is 220000 kNm^2/m. Table 7 displays the wall stiffness values utilized in the probabilistic analyses.

Table 7. *Wall Bending Stiffness Values*

α	**α × EI ($kN.m^2/m$)**
0.05	11000
0.5	110000
0.75	165000
1	220000
5	1100000
10	2200000
25	5500000
50	11000000

Note: *Baseline EI = 220000 kNm^2/m*

While evaluating the impact of wall stiffness on displacement, Clough et al. (1989) used a variable named as the system stiffness factor, which is defined as $EI / \Upsilon_w s_v^4$ where E=Young's modulus of the wall, I=moment of inertia per unit length of the wall, s_v=average vertical support spacing, and presented its relationship with lateral wall movement normalized with excavation depth (Figure 6). In this study, first, the Clough et al. (1989) design chart shown in Figure 7 was compared with the deterministic analysis of the deep excavation (Figure 8). Note that stiffness-normalized horizontal displacement is defined as δ_H(max) / H, where $\delta_H(max)$ is the maximum horizontal wall movement, and H is the maximum excavation depth.

Deep excavation FOS_{base} can be calculated by

$$FOS_{base} = \frac{N_c c_u + \sqrt{2} c_u \left(\frac{H+D}{B}\right) + 2 c_u \left(\frac{D}{B}\right)}{\gamma H} \tag{5}$$

where N_c is the bearing capacity factor, c_u is the average undrained shear strength of the retained soil, H is the height of the excavation; B is the width of the excavation; D is the depth of embedment below the excavation bottom, and γ is the unit weight of the soil above the excavation (Carswell & Siebert, 2021). Since the length of the excavation is not known, it is assumed to be infinite. But the width, B, is restricted because a stiff stratum, i.e., weathered limestone-claystone is near the bottom of the excavation (Sabatini et al., 1999). Therefore, B is equal to depth D= 2 m. The minimum N_c value is determined as 5.14 according to the continuous foundation property and conservatively assuming H/B=0. As a result, the deep excavation FOS_{base} is calculated to be approximately as 6.

Current practice is to use a FOS_{base} greater than 2.5 for permanent works and 1.5 for support of excavation works (Sabatini et al., 1999). The FOS_{base} calculated indicates that the deep excavation is very safe against basal heave.

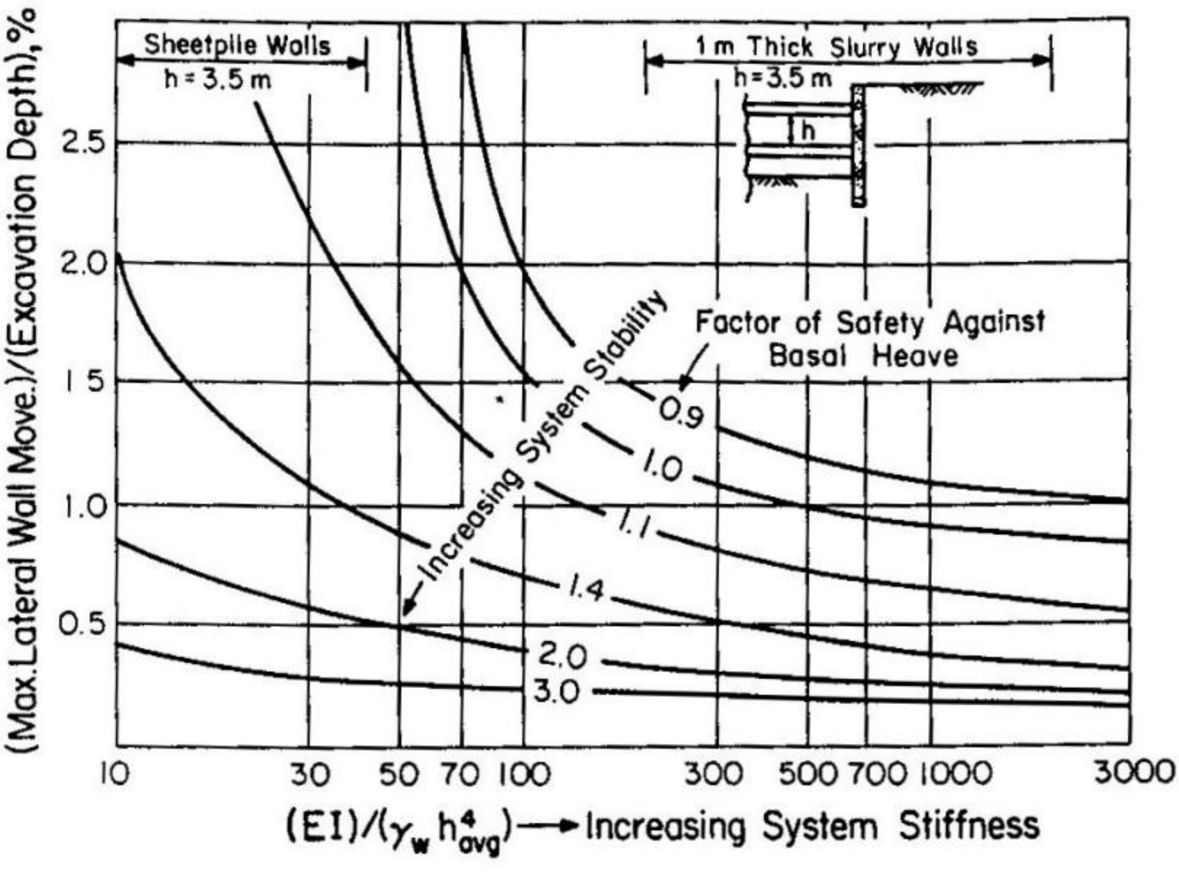


Figure 7. *System Stiffness-Normalized Maximum Lateral Deformation (Clough et al., 1989)*

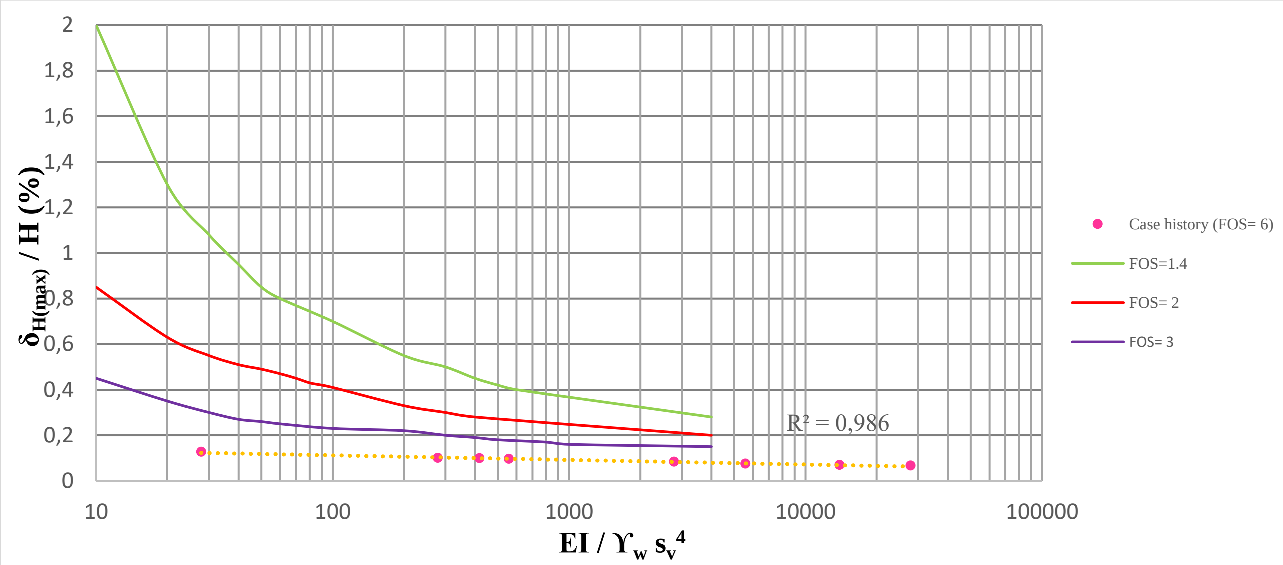


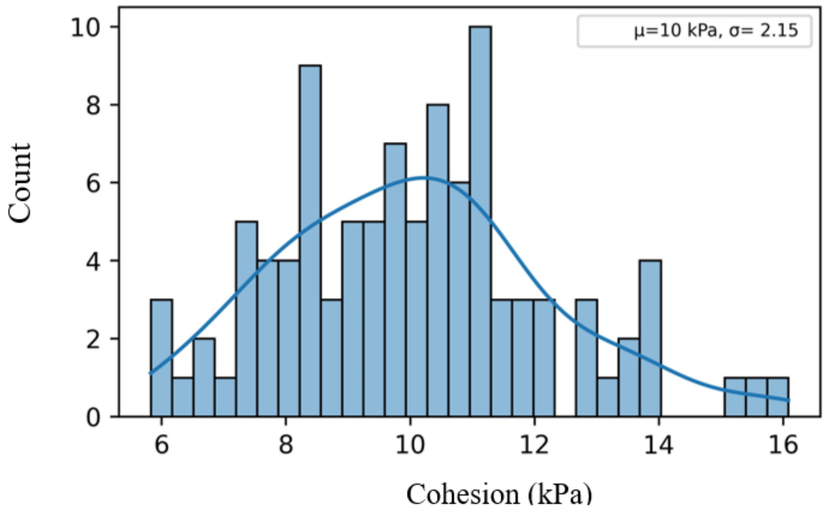
Figure 8. *Comparison of the Deterministic Analysis with the Clough et al. (1989) Design Chart*

As can be seen from Figure 8, the design curve obtained as a result of deterministic finite element calculations has a similar trend with those asserted by Clough et al. (1989) for hard-stiff clays, i.e, those with high FOS_{base} values. Note that for the cases investigated herein the system stiffness varies between about 27.8-27800, while the displacement value varies within a very low range of about 0.126%-0.066%, as expected. As can be seen from these results, stiffness of the support system has a very low effect on displacements in stiff-hard clays for all practical purposes.

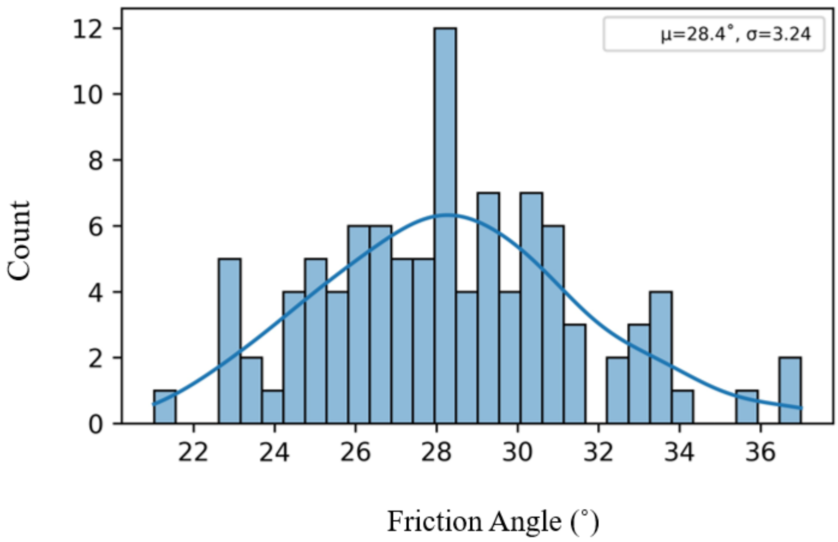
The deterministic analysis results indicate that, as the system stiffness factor increases 1000 fold, the normalized lateral deformation decreases only from 0.13% to 0.07%. The results obtained support the findings of Clough and O'Rourke (1990), who stated that wall stiffness and support element spacing have a minimal effect on wall lateral movement in stiff-hard clays.

In addition, for estimating the effect of soil variability on deformations, 100 analyzes performed for each wall stiffness, i.e., for each α value using Monte Carlo simulations. The distribution of simulated values for soil modulus as well as the horizontal displacements are shown in Figure 9 for α = 5 and the results for all α are plotted on Figure 10 in terms of system stiffness vs. normalized maximum lateral deformation. As can be seen from Figure 10, soil variability, which is inevitable, results in quite a large range in the obtained values of normalized maximum lateral excavation deformation for any given wall stiffness. To compare the analytical results with those measured from case histories, data reported from anchored deep excavations in stiff clays obtained from different studies (Table 8) as well as the results of the parametric study by Bryson and Zapata-Medina (2012) (Table 9) are also plotted on the Figure 10.

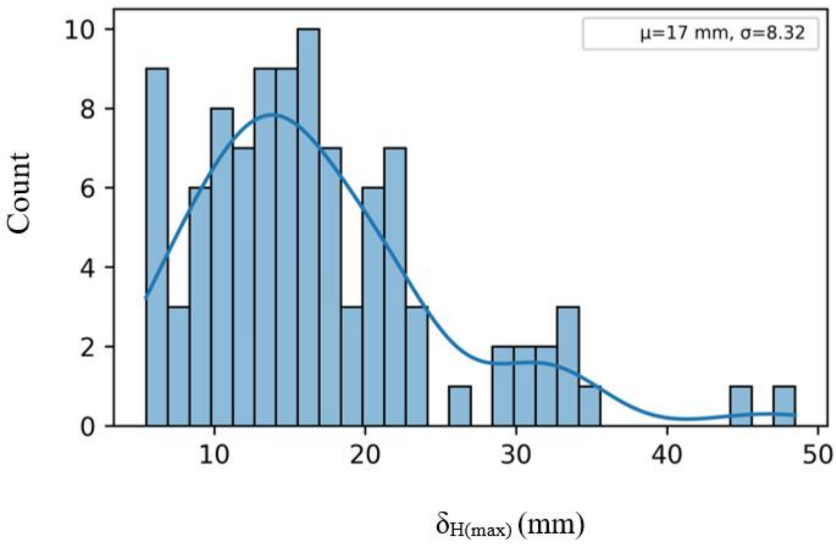
A close look at Figure 10 indicates a similar trend of slightly decreasing normalized maximum deformation with increased system stiffness both for finite element analysis results and case histories for stiff-hard clays. It is interesting to observe that the boundaries defined by the probabilistic analyses captures most of the deviation from the trend lines observed for the case histories, except two of them. Note that in one of these outliers $\delta_{H(max)}/H$ value is 0.62, which corresponds to a high horizontal deformation of 125 mm, even though the support type is a quite rigid diaphragm wall. A close look at this case history indicates that, although the clay was classified as stiff-hard, the undrained modulus is reported to be only 15300 kPa, which may be the reason for this relatively large displacement. A similar conclusion was reached for the second outlier in the data with $\delta_{H(max)}/H$ value of 0.51. For the results of the parametric study carried out by Bryson and Zapata-Medina (2012), it is seen that except for three, the data lies within the borders defined by probabilistic analysis. The three values that are left out has α coefficients that are out of the range employed herein. For the data points with normalized displacement values of 0.253% and 0.268%, the sheet pile walls behaved quite flexibly, and for the data point with a low normalized displacement value of 0.066%, the thick diaphragm wall is extremely rigid.



(a)



(b)



(c)

Figure 9. *100 Analyzes Histograms for α= 5*
a) *Cohesion,* ***b)*** *Friction Angle,* ***c)*** *Maximum Lateral Displacement*

Table 8. *Extracted Case History Data*

References	c_u (kN/m^2)	EI (kNm^2/m)	s_v (m)	s_h (m)	H (m)	$\delta_{H(max)}$ (mm)
Bahadır & Onur, 2018	100	328000	2.4	1.6	19	21.86
Bahadır & Onur, 2018	150	219000	3.25	1.8	17	12.96
Bahadır & Onur, 2018	150	219000	3.25	1.8	14.5	5.8
Bryson & Zapata-Medina, 2012	140	970313	2.45	2.45	12.2	14.75
Bryson & Zapata-Medina, 2012	190	2500000	3.08	3.08	18.5	30
Bryson & Zapata-Medina, 2012	76.5	2300000	3.8	3.8	20	124.76
Bryson & Zapata-Medina, 2012	105	468000	3.3	3.3	11.8	44.53
Bryson & Zapata-Medina, 2012	77.5	1177600	2.65	1.92	15.7	81.37
Cavlaz, 2017	125	312161	2.5	1.87	18	12
Cavlaz, 2017	200	477522	2.5	1.3	29.5	50
Çalışan, 2009	200	263000	2.5	2	20	26
Engin, 2019	95	573027	2	1.7	25	35
Karatağ, 2012	200	263000	2.5	2	13.6	8.6
Kökten & Yıldız, 2018	190	249728.5	2.5	2	13.6	13
Özyürek, 2019	190	603200	2.125	1.63	33	23
Şahin, 2017	100	220000	2.5	1.8	18.5	18
Şahin, 2017	100	220000	2.2	1.5	20	15
Şahin, 2017	100	220000	2.52	1.8	19	18
Ünver & Ünver, 2021	170	520933.2	2.8	1.1	25	42
Ünver & Ünver, 2021	170	520933.2	2.8	1.1	24	40
Ünver & Ünver, 2021	170	520933.2	2.8	1.1	19	65
Yeler, 2019	200	280400	2.5	2	14	12.7

Table 9. *Parametric Study by Bryson and Zapata-Medina (2012)*

Stiff Clay (c_u=125 kPa, E_s=14847 kPa, FOS$_{base}$= 3.52)			
Model	$EI/\Upsilon_w s_v^4$	$s_v s_H \Upsilon_w H^2/EI$	$\delta_{H(max)}$ (mm)
1	264	61.53	24.64
2	264	39	22.69
3	264	78	26.09
4	2150	36.46	22.07
5	897	45.37	23.01
6	4229	30.79	21.29
7	897	45.37	23.07
8	13	1231.45	32.67
9	26	615.73	30.93
10	66	246.29	28.52
11	132	123.15	26.56
12	1322	12.31	20.06
13	2643	6.16	17.83
14	6608	2.46	14.79
15	66080	0.25	8.07

Note: *System stiffness factors were calculated using the following values: H= 12.2 m; s_v= 3.8 m; s_H= 6 m*

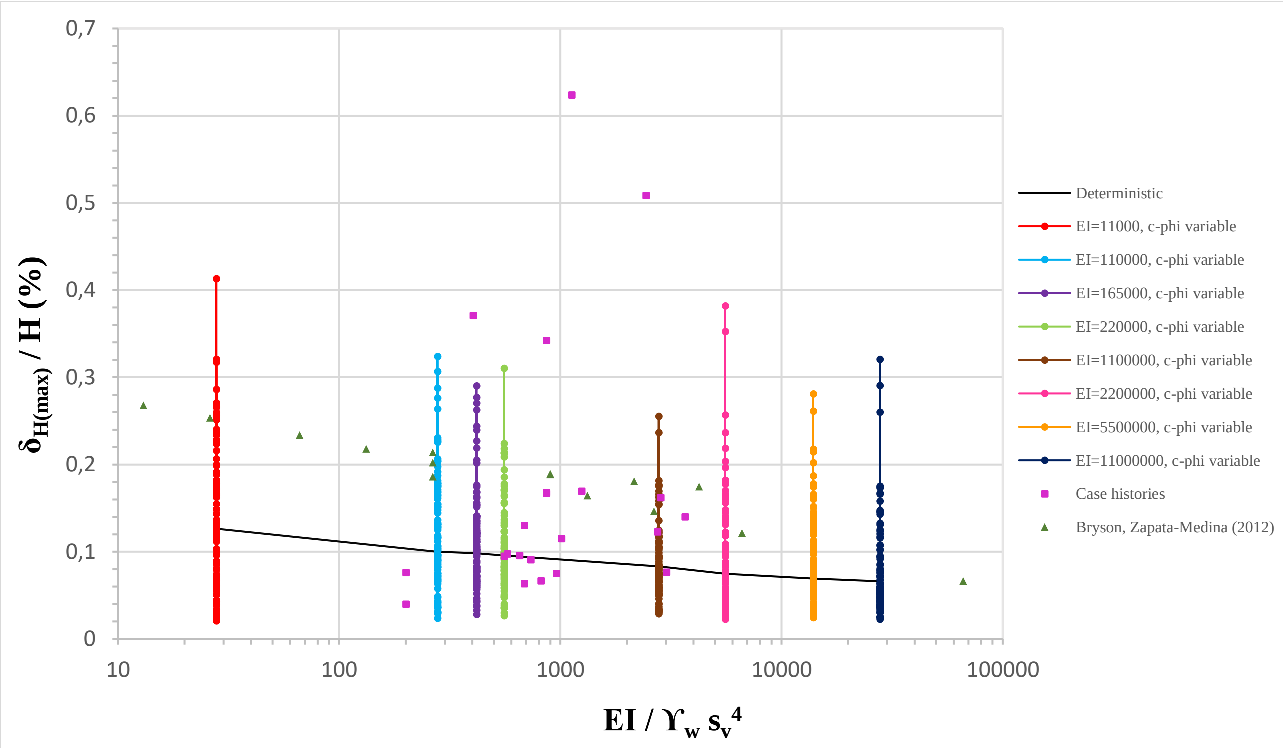


Figure 10. *$\delta_{H(max)}$ / H (%)- EI / Υ_w s_v^4 Graph of all Data*

It is important to note that the Clough et al. (1989)-defined system stiffness factor, which was also used in the preparation of Figure 10, may not be able to fully symbolize the real nature of deep excavation behavior, because this factor uses just the vertical spacing of the support elements. The Clough et al. (1989)-suggested system stiffness factor includes the wall stiffness and the support element vertical spacing, but not the horizontal spacing. Figure 11 illustrates the relationship between the horizontal distance between anchors and the lateral deformation of the deep excavation examined. According to the results of the analysis, when the horizontal spacing of the anchor is reduced by about 1 m, the lateral deformation is reduced by about 16 mm. Considering that the maximum horizontal deformation as recorded by the inclinometer measurements for the excavation was 18 mm, the horizontal spacing of the anchor seems to have about as much effect as the vertical spacing on the lateral deformations. Since Clough et al. (1989) uses only the vertical spacing of support element in the system stiffness factor, this approach can be considered only as a 2D approach. However, as seen in Figure 11, it is more likely that the system stiffness factor is 3D due to the effect of horizontal spacing (Bryson & Zapata-Medina, 2012).

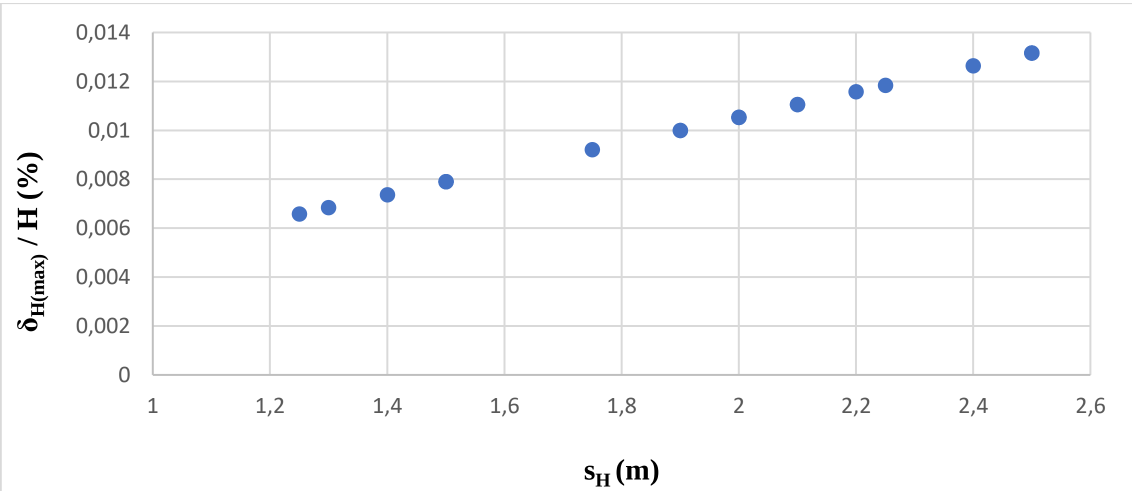


Figure 11. *Influence of Horizontal Support Element Spacing on Deep Excavation Lateral Deformation*

The relationship between the normalized displacement and a suggested updated system stiffness factor in the form of $s_V s_H \Upsilon_w H^2/EI$, which includes support element horizontal spacing s_H and maximum excavation height H are presented in Figure 12. A comparison of Figure 12 with Figure 10, which is created with Clough et al. (1989)-proposed system stiffness factor, firstly indicates that the two outliers aforementioned above could not be captured by the newly defined system stiffness factor also. Thus, these two cases, as previously indicated, have some unusual behavior, which cannot be reasonably explained theoretically. On the other hand, with the use of the newly proposed system stiffness, all the data from the parametric studies performed by Bryson and Zapata-Medina (2012), except one, are now within the limits of finite element analysis results. The diaphragm wall with high stiffness remains out of the range for the same reason. But the case histories with flexible sheet pile walls moved inside the smaller range since the horizontal spacing of the support elements is 6 m, and the vertical spacing is approximately 4 m. Thus, a larger range and different types of support elements are now more easily captured, meaning that proposed the new definition is a more meaningful way to describe design results as illustrated with case histories.

Table 10 shows a statistical evaluation of the system stiffness factor for the case histories. If the system stiffness factors are to be evaluated according to statistical parameters, the range of the system stiffness value suggested by Clough et al. (1989) is 3450.7, while that of the new system stiffness factor is 66.7. In addition, while the standard deviation and the coefficient of variation of the system stiffness value suggested by Clough et al. (1989) are 998.43 and 81.03%, respectively, the standard deviation and the coefficient of variation of the new system stiffness factor are 20.76 and 48.86%, in order. As it can be understood from here, the new system stiffness factor changes within a narrower range and when the standard deviation and coefficient of variation are taken into account, the values are closer to each other.

Thus, with the use of the newly proposed system stiffness factor, unlike the Clough et al. (1989) proposition, most of the case histories, i.e. typical designs, are concentrated in the range where the system stiffness is between 14.6 and 73, with a normalized displacement of approximately 0.04% ~ 0.18%. Thus, successful designs in practice can be expected to lie within this smaller range for stiff-hard clays, which is a useful information for preliminary calculations.

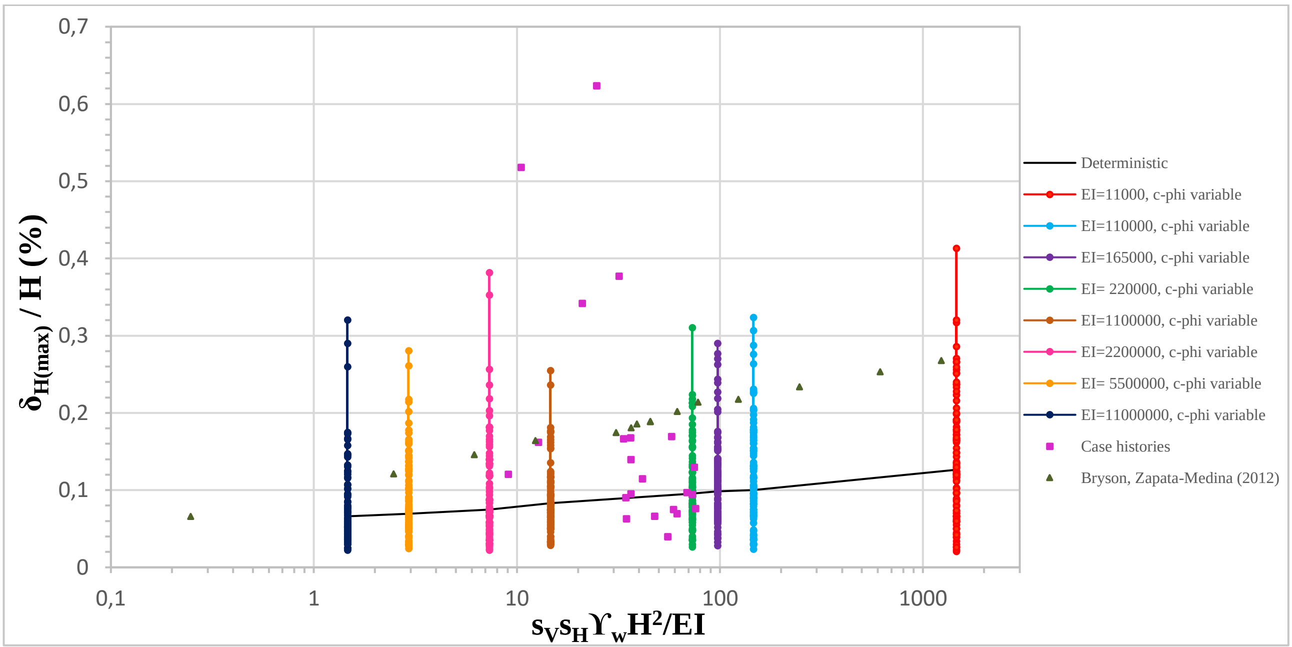


Figure 12. *The Newly Created System Stiffness and Normalized Lateral Deformation Graph for all Data*

Table 10. *Statistical Evaluation of the System Stiffness Factors*

Statistical Parameters	**$EI/\Upsilon_w s_v^4$**	**$s_v s_H \Upsilon_w H^2/EI$**
Range	3450.7	66.7
Mean	1232.2	42.5
Standard Deviation	998.43	20.76
Coefficient of Variation (%)	81.03	48.86

5. CONCLUSION

In this study, the effect of wall stiffness on lateral displacements was investigated for excavations in stiff to hard clays. For this purpose, a series of systematic finite element analyses were carried out that involve a practical range of support system stiffness values, as well as stiff-hard clay geotechnical parameters. A practical methodology in terms of a chart to be used in preliminary design was presented. Considering the inherent variability of the soil, the φ and c' of the clay were randomly generated using Monte Carlo simulations to be automatically inserted into the finite element analyses using Python programming language. Finally, the performance of the analyzes was evaluated comparatively using measurements reported in 22 well-documented case histories from deep excavations in stiff-hard clays.

The results indicate that for a 1000-fold heighten in the system stiffness factor, the decrease in the mean normalized lateral deformation is only about 0.06%. Thus, wall stiffness and spacing of support elements have a small influence on wall lateral movement in stiff-hard clays. On the other hand, Monte Carlo simulations demonstrated that soil variability has a large influence, and results in quite a large range in the obtained values of normalized maximum lateral excavation deformation for a given wall stiffness. This range was observed to explain the variability of the lateral deformations observed in well-documented case histories.

Finite element analyses designate that the horizontal spacing of the anchor has about as much effect as the vertical spacing on the lateral deformations. Widely-used Clough et al. (1989) definition of system stiffness uses only the horizontal center-to-center spacing, thus can be considered as a 2D approach. A new definition of system stiffness is recommended in this study, and it captures a larger range and different types of support elements are now more easily captured, and thus can be considered as a more robust and simple approach to describe the expected performance of excavation wall design.

In deep excavations in stiff-hard clays, the main factor affecting the maximum lateral wall displacement is the soil parameters, regardless of the bending stiffness of the support system. In fact, this study has indicated clearly that relying solely on the stiffness of the support system to determine the lateral displacement in deep excavations may not be reliable. Another contribution of this study is to demonstrate that the variability of soil parameters and the support system stiffness can lead to significant variations in the expected displacements. Therefore, probabilistic analyses that consider the variability in both soil parameters and support system stiffness should be conducted during the design phase to determine the magnitude of displacements and appropriate measures should be taken accordingly.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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