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Original Article

Ultimate Bearing Capacity Calculation of Soil with Finite Element Method

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Abstract

Ultimate bearing capacity calculation is one of the most important factors to design foundations in geotechnical engineering. In this paper, ultimate bearing capacity values were calculated with finite element and analytical methods and compared. A case study of silo structure is used for ultimate bearing capacity evaluations. On 30 September 1970, 600-ton weight concrete silo suddenly overturned and failure. After failure, in-situ Vane shear test and laboratory tests carried out to determine soil strength parameters for back analysis. In finite element analysis, Plaxis 2D has been used. From analytical method maximum factor of safety FS= 1,09 from Terzaghi' s bearing capacity equation and minimum factor of safety FS= 0,97 from Meyerhof' s bearing capacity equation. According to finite element analysis results, factor of safety was calculated as FS=0,64. All these results indicate that especially for complex and sensitive soil profiles, finite element analysis method may be used instead of analytical method.

Keywords: Factor of Safety, Plaxis 2D, Ultimate Bearing Capacity, Undrained Shear Strength,

Sonlu Elemanlar Yöntemi ile Nihai Zemin Taşıma Kapasitesi Hesabı

Özet

Geoteknik mühendisliğinde, zemin taşıma gücü hesabı temel tasarımındaki en önemli faktörlerden biridir. Bu çalışmada, zemin taşıma gücü hesapları sonlu elemanlar ve analitik yöntemlerle hesaplanarak karşılaştırılmıştır. Vaka analizi olarak bir silo yapısı incelenmiştir. 30 Eylül 1970 tarihinde, 600-ton ağırlığındaki silo aniden göçmüştür. Göçmeden sonra arazide Vane kesme deneyi ve laboratuvar deneyleri yapılarak zemin mukavemet parametreleri geri analiz yapılabilmesi için belirlenmiştir. Sonlu elemanlar analizinde Plaxis 2D yazılımı kullanılmıştır. Maksimum göçme güvenlik sayısı Terzaghi taşıma gücü bağıntısına göre FS= 1,09, minimum göçme güvenlik sayısı ise Meyerhof taşıma gücü bağıntısına göre FS= 0,97 olarak hesaplanmıştır. Sonlu elemanlar yöntemi analiz sonucuna göre güvenlik sayısı FS= 0,64 olarak elde edilmiştir. Tüm bu sonuçlar, özellikle karmaşık ve hassas zemin profilleri için analitik yöntem yerine sonlu elemanlar analizi yönteminin kullanılabileceğini göstermiştir.

Anahtar Kelimeler: Güvenlik Sayısı, Plaxis 2D, Nihai Taşıma Kapasitesi, Drenajsız Kayma Mukavemeti.

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1. INTRODUCTION

Bearing capacity calculation is very important for foundation design in geotechnical engineering applications. Beside the bearing capacity calculation, settlement criteria should be also satisfied in foundation design. In this study, bearing capacity failure of concrete silo by Bozozuk (1972) [1] is revaluated according to developing in bearing capacity factors and finite element analysis method.

On 30 September 1970, concrete silo suddenly overturned due to first time with corn silage. Silo failure occurred with the estimated 600-ton weight. After failure, in-situ field Vane and laboratory tests were carried out for determination of soil strength parameters. The concrete silo dimensions are as follows; diameter of foundation is B= 7,2 m and height of silo is approximately 21 m. Foundation depth is D_f= 1,52 m. foundation was constructed over soft clay on a ring foundation. Approximately failure profile of silo foundation is given in Figure 1. Its final slope was measured as 50 degrees from the horizontal surface. The exact location of sliding surface was not determined by Bozozuk (1972) [1]. Estimated failure surface extended to a depth of 7 m from the original ground surface.

Terzaghi (1943), Meyerhof (1963) and Salgado et al. (2004) bearing capacity calculation equations have been used for bearing capacity calculations [2,3,4]. Finite element analysis was carried out with Plaxis 2D. Mohr-Coulomb soil model is used for analysis. Vane correction factor correlations were developed after the publication of Bozozuk (1972) [1]. Bjerrum (1974) [5] and Morris&Williams (1994) [6] suggested vane correction factor correlations which are the function of plasticity index (PI) and liquid limit (LL).

Developments in software technologies allow to calculate engineering calculations reliable and easily. Especially for sensitive soils, this study reveals the importance of finite element method to calculate the beaing capacity of foundation.

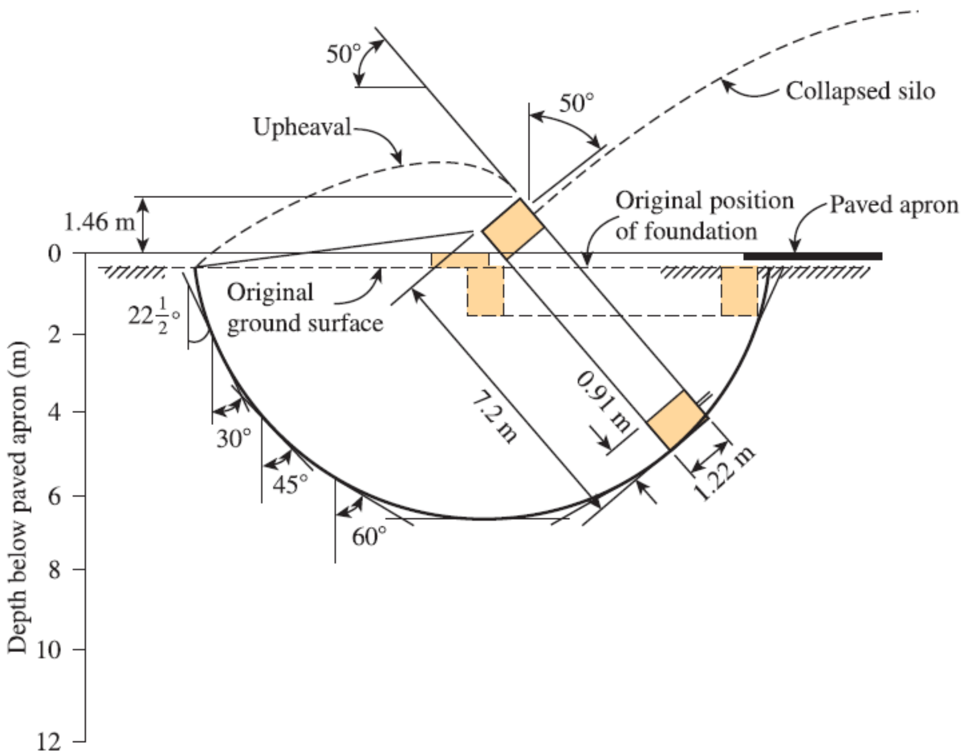

Figure 1. Failure profile of silo based on Bozozuk (1972) [1] (figure has taken from [7])

2. SOIL CONDITIONS

The silo was constructed on very weak and highly compressible clay. After failure of silo, in-situ Vane shear test and laboratory test have been performed to determine engineering properties of soils by Bozozuk (1972) [1]. The soil profile consists of 0,3 m organic soil over 3 m thickness reddish-brown silty clay. Beneath the reddish-brown silty clay, grey silty marine clay continues to end of investigation limit. The grey silty clay contained some black mottling commonly found in the marine clays of the region [1].

In the laboratory tests, Atterberg limit test carried out on soil samples. Liquid limit (LL) values are changing range from %59 to %82 and plasticity index (PI) values are changing range from %34 to %52. Average liquid limit is %65 and average plasticity index is %36 (Figure 2).

According to in-situ Vane shear test results, average undrained shear strength was determined as 28 kPa. In finite element analysis, due to changing of undrained shear strength values with depth, idealized undrained shear strength was determined for each range (Figure 2).

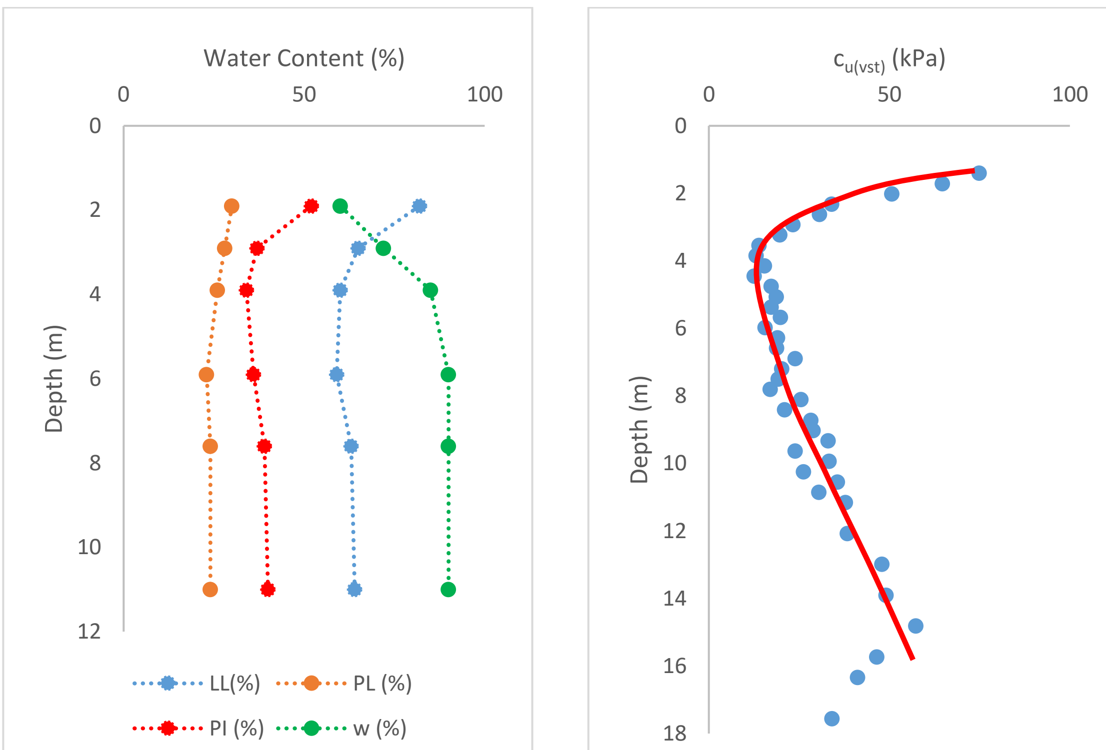

Figure 2. Summary of soil test results [1]

3. BEARING CAPACITY CALCULATION

In this chapter, various bearing capacity calculation methods mentioned. The first researcher about this topic is Terzaghi (1943) has presented a comprehensive theory for the ultimate bearing capacity of shallow foundations [2]. General bearing capacity calculation formula is given in equation (1). Ultimate bearing capacity depends on cohesion (c'), overburden pressure (q), soil unit weight (γ), foundation width (B) and friction angle (ϕ). Bearing capacity factors (N_c, N_q, N_γ) are calculated as function of frictional angle and generally given in tables. Equation (1) have been modified for square (Equation (2)) and circular foundations (Equation (3)).

$$q_u = c'N_c + qN_q + \frac{1}{2}\gamma B N_\gamma \quad (1)$$
$$q_u = 1{,}3c'N_c + qN_q + 0{,}4\gamma B N_\gamma \quad (2)$$
$$q_u = 1{,}3c'N_c + qN_q + 0{,}3\gamma B N_\gamma \quad (3)$$

Apart from that, according to developments in ultimate bearing capacity calculations, some researchers as Meyerhof (1963) [3] and Salgado et al. (2004) [4] has given shape and depth factors. In this paper, soil profile has cohesive character. Hence calculation of these factors are given only for cohesive soils in Table 1. Shape and depth factors are calculated as a function of foundation width (*B*), length (*L*) and depth (D_f). Also [4] gives special coefficients C_1 and C_2 for calculation of Fcs. C_1 and C_2 coefficients are selected from Table 2 with B/L ratio. Therefore, a general bearing capacity may be written in Equation (4).

Table 1. Shape and depth factors

Factor	Meyerhof (1963) [3]	Salgado et al. (2004) [4]
F_{cs}	1+0,2 (B/L)	$1+C_1 (B/L)+C_2 (D_f/B)^{0,65}$
F_{qs}	1	1
$F_{\gamma s}$	1	1
F_{cd}	$1+0{,}2 (D_f/B)$	$1+0{,}27 (D_f/B)^{0,5}$
F_{qd}	1	1
$F_{\gamma d}$	1	1

Table 2. C_1 and C_2 coefficient from Salgado et al. (2004) [4]

B/L	C_1	C_2
Circle	0,163	0,210
1,00	0,125	0,219
0,50	0,156	0,173
0,33	0,159	0,137
0,25	0,172	0,110
0,20	0,190	0,090

$$q_u = c'N_c F_{cs} F_{cd} + qN_q F_{qs} F_{qd} + \frac{1}{2}\gamma B N_\gamma F_{\gamma s} F_{\gamma d} \quad (4)$$

F_{cs}, F_{qs}, $F_{\gamma s}$: Shape factors

F_{cd}, F_{qd}, $F_{\gamma d}$: Depth factors

4. ANALYSIS AND CALCULATIONS

4.1 Analytical Calculation

Ultimate bearing capacity calculations are made according to the ultimate bearing capacity calculations described developed by various researchers in previous chapters.

Parameters for ultimate bearing capacity are determined as; soil unit weight γ= 18 kN/m^3, average undrained shear strength from Vane shear test $c_{u,vst}$= 28,2 kPa, plasticity index PI= %36, liquid limit LL= %60, foundation depth Df= 1,5 m, foundation width B=L= 7,2 m. Average value of vane shear test correlation factor is determined from Table 3 as λ= 0,71. Design undrained shear strength $s_u = \lambda\, c_{u,vst}$= 0,71x28,2≅ 20 kPa. Shape and depth factors calculation is given in Table 4. Bearing capacity factor N_c is determined as 5,7 from Terzaghi (1943) [2] and 5,14 from Meyerhof (1963) [3]. N_q is equal to 1,0 and N_γ is equal to zero. Ultimate bearing capacatiy calculation results are shown in Table 5.

Table 3. Vane shear test correction factors calculation

Correlation	λ	Reference
λ=1,7-0,54log(PI)	0,859597	Bjerrum (1974) [5]
$\lambda=1{,}18e^{-0{,}08(PI)}+0{,}57$ (PI>5)	0,636239	Morris and Williams (1994) λ=f(PI) [6]
$\lambda=7{,}01e^{-0{,}08(LL)}+0{,}57$ (LL>20)	0,627691	Morris and Williams (1994) λ=f(LL) [6]

Table 4. Shape and depth factors calculation

Coefficient	Meyerhof (1963) [3]	Salgado et al. (2004) [4]
F_{cs}	1,2	1,172
F_{cd}	1,0416	1,123

Table 5. Ultimate bearing capacity calculations

Coefficient	Terzaghi (1943) [2]	Meyerhof (1963) [3]	Salgado et al. (2004) [4]
N_c	5,7	5,14	5,14
N_q	1	1	1
N_γ	0	0	0
F_{cs}	-	1,2	1,17
F_{qs}	-	1	1
$F_{\gamma s}$	-	1	1
F_{cd}	-	1,04	1,12
F_{qd}	-	1	1
$F_{\gamma d}$	-	1	1
q_u (kPa)	**175,2**	**155,2**	**161,7**

4.2 Finite Element Analysis Calculation

Since the silo foundation is circular, in software foundation was modelled as axisymmetrically. Mohr-Coulomb soil model is selected in analysis. The Mohr-Coulomb model is a simple soil model and is used to get a first approximation of the soil behavior. It is a linear elastic perfectly plastic model and used widespread in design. Hooke law is valid for elastic range. The perfectly plastic part is based on failure criterion by Mohr-Coulomb. With plastic behavior, irreversible strains develop while with elastic behavior, the strains will be reversed when unloading. The Mohr-Coulomb model requires six input parameters as Young modulus (E), Poisson’ s ratio (ν), cohesion (c), soil friction angle (ϕ), dilatancy angle (ψ) and tension-cut off (σ_t) [8].

Soil profile is divided by 8 layers due to changing of undrained shear strength. Correction factor λ= 0,71 is applied to determine design undrained shear strength. Soil elasticity modulus is calculated according to Table 6 by formula E= 500 s_u. Undrained shear strength and elasticity modulus values are shown in Figure 3. Soil parameters are given in Table 7.

Table 6. Elasticity modulus calculation [9]

Plasticity Index	Elasticity Modulus
PI > 30 or organic	Es= (100 to 500) s_u
PI < 30 or stiff	Es= (500 to 1500) s_u

Table 7. Soil parameters

Layer	Depth (m)	s_u (kPa)	E (MPa)
Clay-1	0-3	14	7,1
Clay-2	3-5	8	4,2
Clay-3	5-7	11	5,6
Clay-4	7-9	15	7,5
Clay-5	9-11	17	8,5
Clay-6	11-13	28	14,2
Clay-7	13-15	34	17
Clay-8	15-18	25	12,7

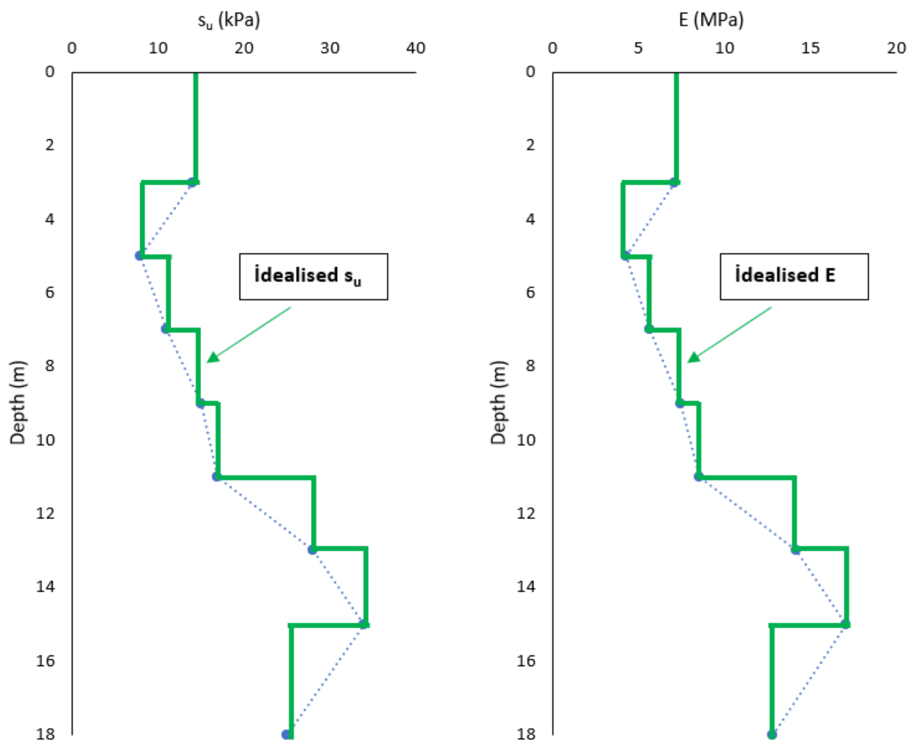

Figure 3. Undrained shear strength (s_u) and elasticity modulus at soil profile

Finite element model which is created with Plaxis 2D is shown in Figure 4. Construction stages are defined in software and listed below. Silo load 160 kPa is applied to foundation. According to analysis result, total displacements (u) diagram is shown in Figure 5. Total displacement of foundation has been calculated as 33,48 m. Under service load, this deformation is not realistic. Hence very soil big deformations point out to failure of foundation of silo. Maximum Mstage value is calculated as 0,64 in Figure 6. According to this chart, approximate failure of foundation starts from when total displacement is equal to 0,50 m.

Construction stages:

- Phase 1: Initial phase

- Phase 2: Construction of silo
- Phase 3: Application 160 kPa building load

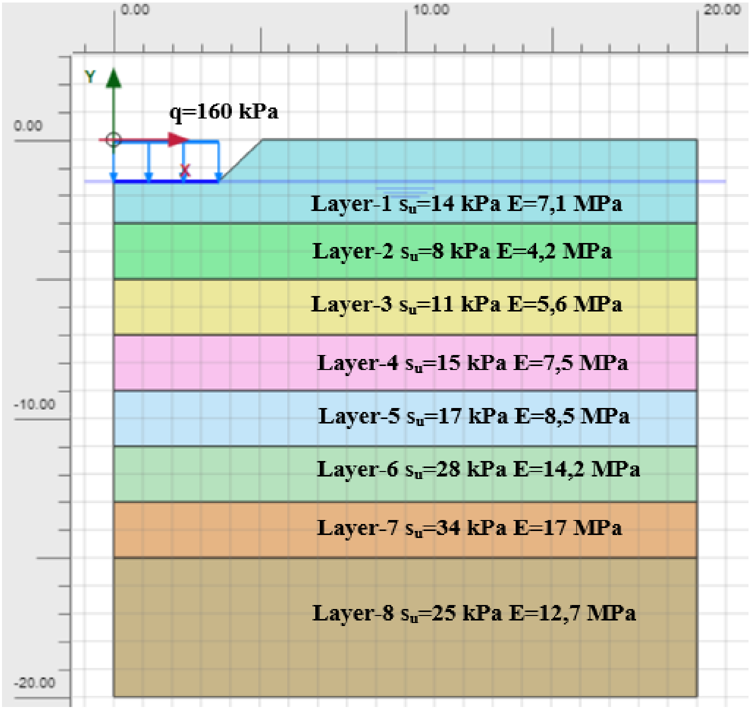

Figure 4. Plaxis 2D analysis model

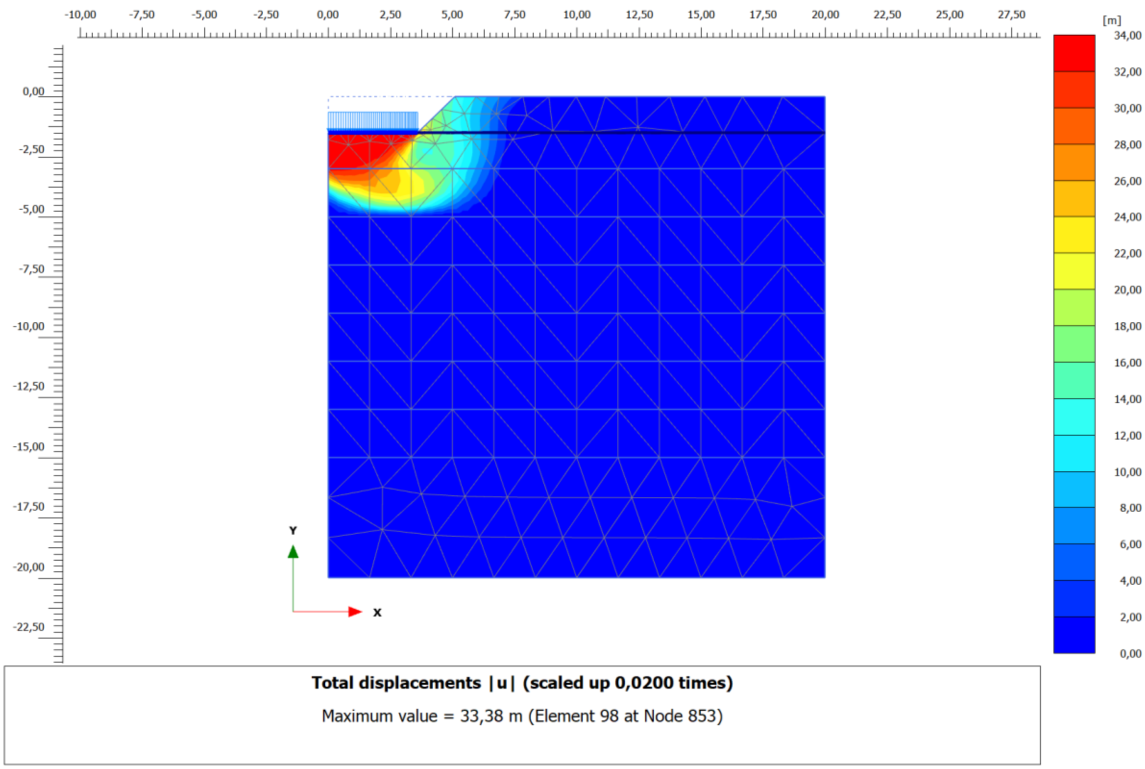

Figure 5. Analysis result- total displacement contours

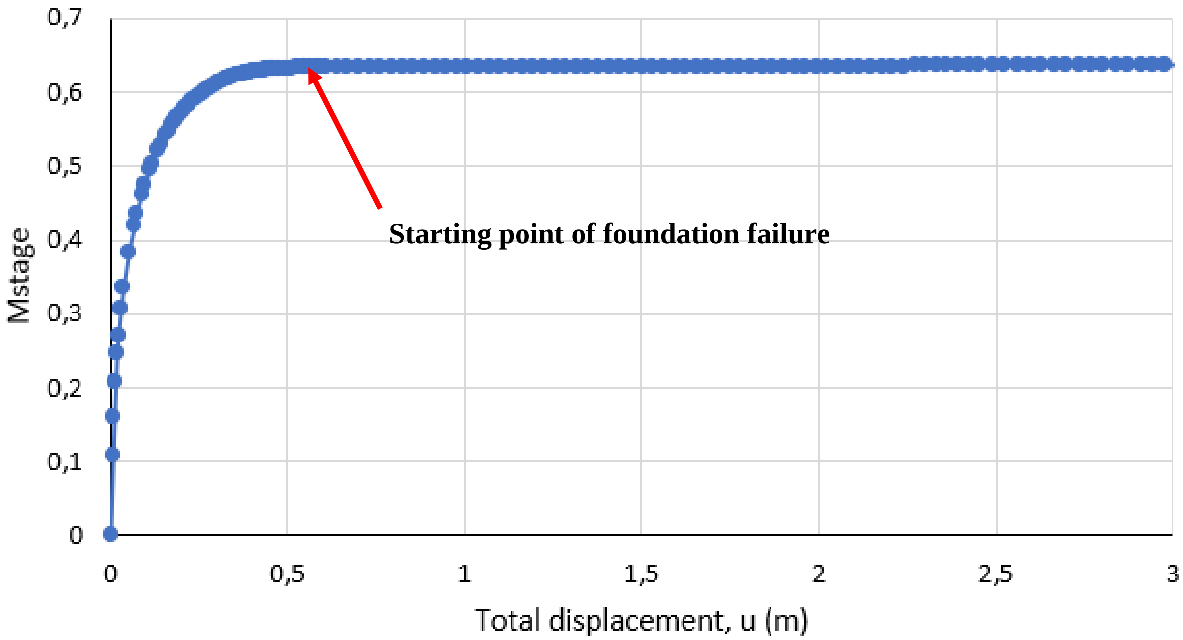

Figure 6. Mstage- total displacement chart

5. RESULTS

Bearing capacity calculation results are presented in this chapter. Factor of safety (FS) is calculated as ratio of ultimate bearing capacity to maximum pressure. Factor of safety (FS) values are calculated FS= 1,09 from Terzaghi' s bearing capacity equation, FS= 0,97 from Meyerhof' s bearing capacity equation, FS= 1,01 from Salgado et al. bearing capacity equation and FS= 0,64 from Plaxis 2D analysis result. The results are summarized in Figure 7.

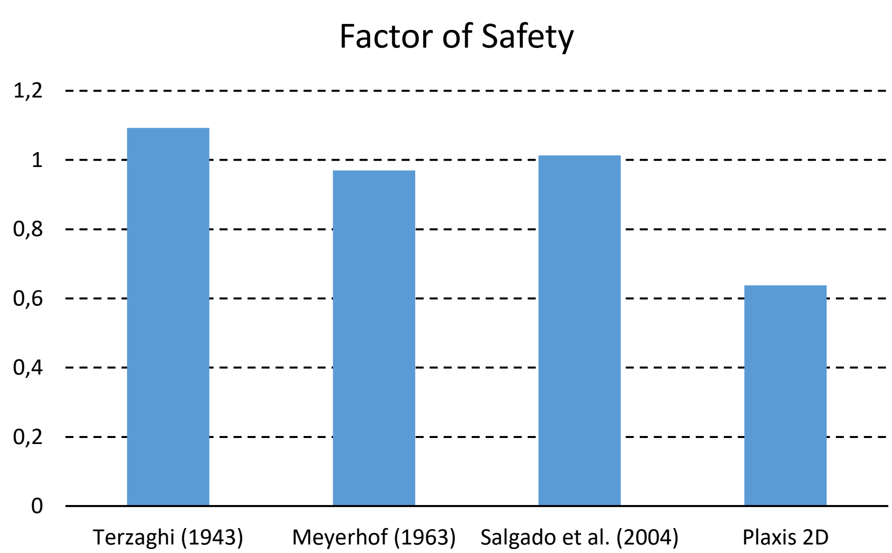

Figure 7. Factor of safety (FS) calculations

6. CONCLUSION

In this paper, ultimate bearing capacity calculation revaluated according to analytical and finite element method. Bozozuk (1972) [1] is selected as case study for this purpose. On 30 September 1970, silo suddenly overturned and failure with approximately 600-ton weight. Maximum pressure was observed as 160 kPa while silo failure. After failure, in-situ Vane shear test and laboratory tests carried out to determine soil strength for design. Soil profile consists of very weak and high compressible clay layer. Vane shear test corrections for design undrained shear strength value are calculated from Bjerrum (1974) [5] and Morris&Williams (1994) [6] correlations. Terzaghi (1943) [2], Meyerhof (1963) [3] and Salgado et al. (2004) [4] bearing capacity equations and finite element analysis software Plaxis 2D is used for bearing capacity calculations. Analytical method solution values are calculated close to each other abut FS=1,0. Minor differences for analytical solutions occurred from bearing capacity factors, shape and depth factors. Minimum factor of safety is calculated as FS=0,64 from finite element analysis result. Finite element result remains safe side for ultimate bearing capacity calculation. Advantages of finite element method are summarized below:

- Soil profile can be divided sub-layers according to soil parameters
- Ground water table level considered sensitively
- Deformation parameters of soil are defined

Because of the safest result for examined case study from finite element method, author suggests to use finite element analysis method for complex and sensitive soil profiles instead of analytical method. In future studies, this paper can be contributed by using finite element method for different soil properties and geometries.

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