Design Example 2.2. Pad foundation with inclined eccentric load on boulder clay

1. Obtaining characteristic value of undrained shear strength

Due to conditions given in the example a decision was made to obtain dimensions of pad foundation in undrained conditions.
In purpose to obtain characteristic value of undrained shear strength c_{uk} results of SPT sounding from all boreholes were used, but with application of different weights due to distance between borehole and centre of foundation. As a weight were used ratios of shortest distance between borehole and centre of foundation to the distance between considered borehole and centre of foundation.

Borehole No.	*Distance [m]*	*Weight factor w [-]*
BH1	*26,33*	*0,25*
BH2	*6,5*	*1*
BH4	*12,5*	*0,52*
BH11	*17,16*	*0,38*
BH13	*30,83*	*0,21*

Local values of c_u were obtained from empirical relation given by O. Sivrikaya and E. Togrol[1]: $c_u = 4{,}75N_{field}$. It was assumed that volume of soil mobilized during potential failure will not reach depth below foundation larger than B meters , so only SPT sounding results from above that depth were used in calculations.

Borehole No.	*Depth [m]*	*N_{field} [-]*	*Weight factor w [-]*	*c_u=4,75N_{field} [kPa]*
BH1	*1,8*	*27*	*0,25*	*128,25*
	3,3	*40*	*0,25*	*190*
BH2	*2*	*55*	*1,00*	*261,25*
	3	*52*	*1,00*	*247*
BH4	*1,8*	*25*	*0,52*	*118,75*
	3,3	*33*	*0,52*	*156,75*
BH11	*1*	*43*	*0,38*	*204,25*
	2	*41*	*0,38*	*194,75*
	3	*64*	*0,38*	*304*
BH13	*1,7*	*48*	*0,21*	*228*
	2,5	*41*	*0,21*	*194,75*
	3,5	*40*	*0,21*	*190*

In a case of pad foundation a volume of soil involved in limit state is large, so results of field investigation have to be averaged over this volume, as value of geotechnical parameter which govern the appearance of limit state is close to average value due to redistribution of stresses in a soil mass.
To obtain characteristic value of undrained shear strength c_{uk} statistical methods were used. The characteristic value was obtained in a way that calculated probability of appearance of less favourable value governing the appearance of limit state should not be greater than 5%. This means that cautious estimate of mean value depend on obtaining mean value of geotechnical parameter from limited set of values with 95% confidence level.

According to „*Designer's Guide to EN 1997-1 Eurocode 7: Geotechnical design – General rules*" R. Frank, C. Baudin, R. Driscoll, M. Kavvadas, N. Krebs Ovesen, T. Orr, B. Schuppener:

[1] "Determination of undrained strength of fine-grained soils by means of SPT and its application In Turkey." O. Sivrikaya, E. Togrol, Engineering Geology 86 (2006) 52 - 69

$c_{uk} = c_{umean} \cdot (1 - k_n \cdot V_{cu})$
$c_{u,mean}$ – weighted mean
V_{cu} – coefficient of variation
k_n – statistical coefficient depending on number of test results, volume of ground involved in the limit state, type of sample population and statistical level of confidence

$V_{cu} = s_{cu}/c_{umean}$
where s_{cu} – standard deviation

Borehole No	*Depth [m]*	*N_{field} [-]*	*Weight factor w [-]*	*c_u=4,75N_{field} [kPa]*	*c_u-c_{umean}*	*$(c_u$-$c_{umean})^2$*	*$w \cdot (c_u$-$c_{umean})^2$*
BH1	*1,8*	*27*	*0,25*	*128,25*	*-84,01*	*7058,38*	*1742,48*
	3,3	*40*	*0,25*	*190*	*-22,26*	*495,69*	*122,37*
BH2	*2*	*55*	*1,00*	*261,25*	*48,99*	*2399,61*	*2399,61*
	3	*52*	*1,00*	*247*	*34,74*	*1206,58*	*1206,58*
BH4	*1,8*	*25*	*0,52*	*118,75*	*-93,51*	*8744,90*	*4547,35*
	3,3	*33*	*0,52*	*156,75*	*-55,51*	*3081,82*	*1602,55*
BH11	*1*	*43*	*0,38*	*204,25*	*-8,01*	*64,23*	*24,33*
	2	*41*	*0,38*	*194,75*	*-17,51*	*306,75*	*116,19*
	3	*64*	*0,38*	*304*	*91,74*	*8415,46*	*3187,68*
BH13	*1,7*	*48*	*0,21*	*228*	*15,74*	*247,62*	*52,21*
	2,5	*41*	*0,21*	*194,75*	*-17,51*	*306,75*	*64,67*
	3,5	*40*	*0,21*	*190*	*-22,26*	*495,69*	*104,51*
		Σ=	*5,30*			*Σ=*	*15170,52*

$c_{u,mean} = \Sigma c_{ui} \cdot w_i / \Sigma w_i = 212{,}26 \text{kPa}$
$s_{cu}^2 = \sqrt{((N/(N-1)) \cdot (\Sigma w_i \cdot ((cu_i - c_{u,mean})^2)/\Sigma w_i))}$
$s_{cu} = 55{,}87$ kPa
$V_{cu} = 55{,}87/212{,}26 = 0{,}26$
$k_n = 0{,}56$ – according to Table 2.5 *Values of the coefficient $k_{n,mean}$ for the assessment of a characteristic value as a 95% reliable mean value* w „Designer's Guide to EN 1997-1 Eurocode 7: Geotechnical design – General rules" R. Frank, C. Baudin, R. Driscoll, M. Kavvadas, N. Krebs Ovesen, T. Orr, B. Schuppener.

$\mathbf{c_{uk}} = 212{,}26 \cdot (1 - 0{,}56 \cdot 0{,}26) =$ **180,98 kPa**

2. Ultimate limit states

To solve the example, values of partial factors according to Design Approach 2* were used (combination of partial factors: A1+M1+R2).

Patrial factors for actions		
Permanent unfavourable	γ_G	*1,35*
Variable unfavourable	γ_Q	*1,5*
Partial factors for soil parameters		
Undrained shear strength	γ_{cu}	*1*
Partial factors for resistance		
Bearing capacity	γ_R	*1,4*

Following dimensions of pad foundation were assumed: B=L=3,10m

VERTICAL FORCE (**permanent** loading; **characteristic** value)
$G_{v,k}$ = 1000kN
WEIGHT OF FOUNDATION (**permanent** loading; **characteristic** value)
$G_{pad,k} = B*L*0,8*\gamma_{conc}$ (γ_{conc}=25kN/m^3) = 192,2kN
VERTICAL FORCE (**variable** loading; **characteristic** value)
$Q_{v,k}$ = 750kN
HORIZONTAL FORCE (**variable** loading; **characteristic** value)
$Q_{h,k}$ = 500kN (**Attention:** This force acts 2 meters above upper surface od foundation)
VERTICAL FORCE (**permanent** loading; **design** value)
$G_{v,d}$ = 1350kN
WEIGHT OF FOUNDATION (**permanent** loading; **design** value)
$G_{pad,d}$ = 259,47kN
VERTICAL FORCE (**variable** loading; **design** value)
$Q_{v,d}$ = 1125kN
HORIZONTAL FORCE (**variable** loading; **design** value)
$Q_{h,d}$ = 750kN

CHARACTERISTIC TOTAL VERTICAL FORCE
$G_{v,k}+Q_{v,k}+G_{pad,k}$ = 1942,2kN
DESIGN TOTAL VERTICAL FORCE
$G_{v,d}+Q_{v,d}+G_{pad,d}$ = 2734,47kN1
CHARACTERISTIC BENDING MOMENT DUE TO HORIZONTAL FORCE
$M = Q_{h,k} \cdot 2m$ = 1000kNm
ECCENTRICITY OF VERTIAL LOADING
$e_B = M/(G_{v,k}+Q_{v,k}+G_{pad,k})$ = 0,515m < B/6 = 0,516m

<u>Design value of vertical bearing resistance R_d</u> *<u>- undrained conditions</u>*

$R/A' = (\pi + 2)\cdot c_u\cdot s_c\cdot b_c\cdot i_c + q$

$B'=B-2e_B$= 2,07m
L'= 3,10m
$A' = B' \cdot L'$ = 6,42m^2
c_{uk} = 180,98kPa
c_{ud} = 180,98kPa
$q=h\cdot\gamma_d$=0,8m·21,4kN/m^3= 17,12kPa
Coefficient of foundation shape $s_c = 1 + 0,2\cdot B'\backslash L'$ =1,13[-]
Coefficient of inclination of loading $i_c = 1/2\cdot(1+ \surd(1-(Q_{h,d}/A'\cdot c_{ud})))$ = 0,88[-]
Coefficient of inclination of foundation base b_c = 1[-]

$R_k=A'\cdot[(\pi + 2)\cdot c_{uk}\cdot s_c\cdot b_c\cdot i_c + q]$= 6050,43kN
$R_d=R_k/\gamma_R$= 4321,74kN

$R_d/G_{v,d}+Q_{v,d}+G_{pad,d}$ = 4321,74/2734,47 = 1,58
Utilization factor Λ = $G_{v,d}+Q_{v,d}+G_{pad,d}/R_d$ = 2734,47/4321,74 = 0,63

Following dimensions of footing were taken as correct: $\boxed{B=L=3,10m}$

3. Serviceability limit states

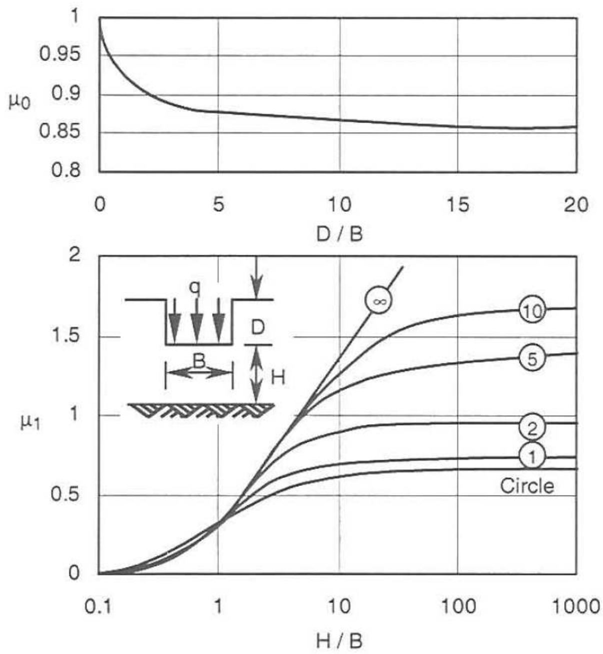
Calculation of immediate settlement

To calculate immediate settlement, simplified method of elastic medium was used:

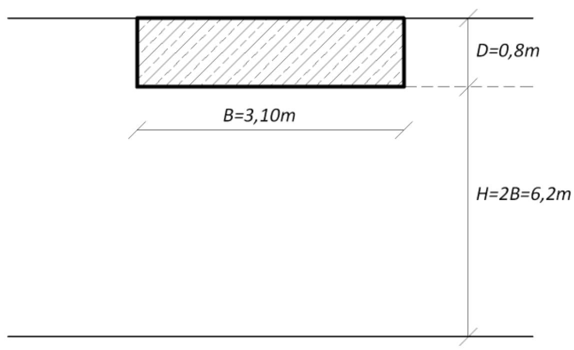
$S_e = \mu_0 \cdot \mu_1 \cdot q \cdot B / E_u$
gdzie:
S_e – settlement
μ_0 – influence factor for depth
μ_1 – influence factor for layer thickness
q – pressure
B – foundation width
E_u – undrained modulus of linear deformation

Settlements are considered only to depth of 2B.

Factors μ_0 i μ_1 are obtained from figure beside (Figure 5.29. Improved influence factors μ_0 and μ_1 for saturated clays (Christian & Carrier, 1978) in *"Soil Mechanics: Basic Concepts and Improvements"* A. Aysen A.A Balkema Publishers 2002).



According to this figure:
D/B=0,8/3,10=0,26 → **μ_0 = 0,96**
H/B=6,2/3,10=2 → **μ_1 = 0,50**



Value of undrained modulus of linear deformation is obtained from relation:
E_u/N_{60}=1,0÷1,2 (MPa) ((Butler, 1975 in „In Situ Testing In Geomechanics. The main tests." Fernando Schnaid, Taylor & Francis 2009).
It was assumed that E_u/N_{60}=1,2

According to O. Sivrikay and E. Togrol[1]:
$N_{60}=0,75 \cdot C_r \cdot N_{field}$
C_r – rod lenght correction factor
It was assumed that C_r=1,0

To determine undrained modulus of linear deformation, the same statistical methods were used as in case of undrained shear strength in ultimate limit state.

Obtaining representative value of number of blows in SPT sounding

Borehole No.	Depth [m]	N_{field} [-]	Weight factor w [-]	$N_{field} \cdot w$ [-]	N_{field} - $N_{field,mean}$	$(N_{field} - N_{field,mean})^2$	$w \cdot (N_{field} - N_{field,mean})^2$
BH1	1,8	27	0,25	6,67	-28,85	832,53	205,52
	3,3	40	0,25	9,87	-15,85	251,34	62,05
	4,8	38	0,25	9,38	-17,85	318,75	78,69
	6,3	45	0,25	11,11	-10,85	117,80	29,08
BH2	2	55	1,00	55,00	-0,85	0,73	0,73
	3	52	1,00	52,00	-3,85	14,85	14,85
	4,5	77	1,00	77,00	21,15	447,17	447,17
	6	93	1,00	93,00	37,15	1379,85	1379,85
BH4	1,8	25	0,52	13,00	-30,85	951,95	495,01
	3,3	33	0,52	17,16	-22,85	522,29	271,59
	4,8	41	0,52	21,32	-14,85	220,63	114,73
	6,3	43	0,52	22,36	-12,85	165,22	85,91
BH11	1	43	0,38	16,29	-12,85	165,22	62,58
	2	41	0,38	15,53	-14,85	220,63	83,57
	3	64	0,38	24,24	8,15	66,36	25,14
	4,5	67	0,38	25,38	11,15	124,24	47,06
	6	97	0,38	36,74	41,15	1693,03	641,30
BH13	1,7	48	0,21	10,12	-7,85	61,68	13,00
	2,5	41	0,21	8,64	-14,85	220,63	46,52
	3,5	40	0,21	8,43	-15,85	251,34	52,99
	4,5	37	0,21	7,80	-18,85	355,46	74,94
	5,5	33	0,21	6,96	-22,85	522,29	110,12
	6,5	36	0,21	7,59	-19,85	394,17	83,10
		Σ=	10,23	555,60		Σ=	4401,76

$N_{field} = \Sigma N_{field} \cdot w_i / \Sigma w_i = 54{,}33$
$S_N^2 = \sqrt{((N/(N-1)) \cdot (\Sigma w_i \cdot ((N_{field} - N_{field,mean})^2) / \Sigma w_i))}$
$S_N = 20{,}29$
$V_N = 20{,}29/54{,}33 = 0{,}37$
$k_n = 0{,}37$

$\mathbf{N_{field,k}} = N_{field,mean} \cdot (1 - k_n \cdot V_N) = 54{,}33 \cdot (1 - 0{,}37 \cdot 0{,}37) = \mathbf{46{,}82}$
As representative value of blows from SPT sounding were taken 47 blows.

$N_{60} = 0{,}75 \cdot C_r \cdot N_{field} = 0{,}75 \cdot 47 = 35{,}25$
$E_u = 1{,}2 \cdot N_{60} = 1{,}2 \cdot 35{,}25 = 42{,}3\text{MPa}$

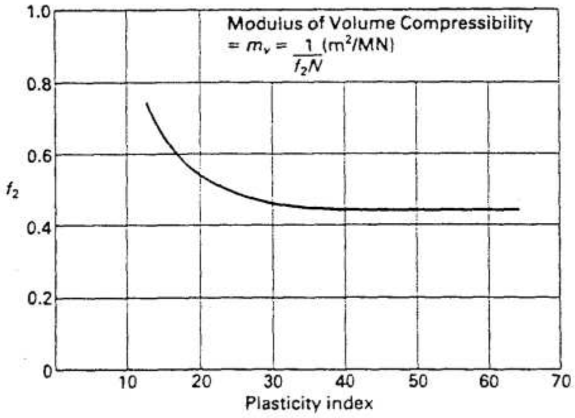
To calculate pressure under foundation characteristic value of loading was used:
$G_{v,k} + Q_{v,k} + G_{pad,k} = 1000 + 750 + 192{,}2 = 1942{,}2\text{kN}$
then:
$\mathbf{q = 1942{,}2/3{,}10^2 = 202{,}10kPa}$

$\mathbf{S_e = \mu_0 \cdot \mu_1 \cdot q \cdot B / E_u = (0{,}96 \cdot 0{,}5 \cdot 202{,}10 \cdot 3{,}10)/42300 = 0{,}007m = 7mm}$

Calculation of settlement resulting from consolidation

Settlement resulting from consolidation were calculated from relation $s_c = (\Delta\sigma \cdot \Delta h)/M$. The soil was divided into calculation layers. Increments of stresses caused by foundation loading in each of these layers were calculated using centre points method.

To calculate compressibility modulus a relation given by Stroud (1974)[2] was used, for determining coefficient of volume changes:
$m_v = 1/f_2 \cdot N$ [m^2/MN]



Values needed to calculate it are representative values of blows from SPT sounding for each calculation layer and representative value of plasticity index.
The table below presents SPT soundings used to calculate compressibility modules for each calculation layer. Soundings marked with pluses are those which although being beyond considered range, were included in it because of localization of sounding in respect of centre of foundation.

Range	*Soundings which were used(depth [m])*	*Representative number of blows*
0,00 – 1,80	*BH1(1,8), BH2(2,0)(+), BH4(1,8), BH11(1,0), BH13(1,7)*	*32*
1,80 – 2,80	*BH1(3,3), BH2(2,0), BH4(1,8), BH11(2,0), BH13(2,5)*	*31*
2,80 – 3,80	*BH1(3,3), BH2(3,0), BH4(3,3), BH11(3,0), BH13(3,5)*	*39*
3,80 – 4,80	*BH1(4,8), BH2(4,5), BH4(4,8), BH11(4,5), BH13(4,5)*	*45*
4,80 – 5,80	*BH1(4,8), BH2(4,5)(+), BH4(4,8), BH13(5,5)*	*38*
5,80 – 7,00	*BH1(6,3), BH2(6,0), BH4(6,3), BH11(6,0), BH11(6,5)*	*51*

Obtaining representative value of plasticity index

I_P [%]	$I_P - I_{P,mean}$	$(I_P - I_{P,mean})^2$
8,5	-3,40	11,56
13,5	1,60	2,56
9,5	-2,40	5,76
14,5	2,60	6,76
13,5	1,60	2,56
11,5	-0,14	0,02
10,5	-1,14	1,31
	Σ=	30,86

$I_{P,mean} = \Sigma I_{P,i}/n = 11{,}64\%$
$S_{Ip}^2 = (1/n-1) \cdot \Sigma(I_{P,i} - I_{P,mean})^2$
$S_{Ip} = 2{,}27\%$
$V_{Ip} = s_{Ip}/I_{P,mean} = 2{,}27/11{,}64 = 0{,}19$

[2] "The standard penetration test in insensitive clays and soft rock" Stroud M. A. (1974) Proceedings of the 1st European Symposium on Penetration Testing, Stockholm, Sweden, vol. 2(2), pp. 367-375

$k_n = 0{,}75$
$I_{P,k} = I_{P,mean} \cdot (1 - k_n \cdot V_{Ip}) = 11{,}64 \cdot (1 - 0{,}75 \cdot 0{,}19) = 9{,}94\%$

Following value of plasticity index was assumed as representative value: $I_P = 9{,}94\%$.

For $I_P=9{,}94 \rightarrow f_2=1$

Depth below base of foundation z_i[m]	*z_i/B*	*$\eta = f(L/B;Z/B)$*	*Stress resulting from foundation loading $s_{zq}=\eta * q$ kPa*	*M_i kPa*	*Average stress$_{z\,si}$ kPa*	*Hi*	*S'_i cm*
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
0,00	*0,00*	*1,000*	*202,10*				
				32000	*189,19*	*1,00*	*0,591*
1,00	*0,32*	*0,872*	*176,28*				
				31000	*145,43*	*1,00*	*0,469*
2,00	*0,65*	*0,567*	*114,57*				
				39000	*92,83*	*1,00*	*0,238*
3,00	*0,97*	*0,352*	*71,09*				
				45000	*58,70*	*1,00*	*0,130*
4,00	*1,29*	*0,229*	*46,31*				
				38000	*39,13*	*1,00*	*0,103*
5,00	*1,61*	*0,158*	*31,96*				
				51000	*26,90*	*1,20*	*0,063*
6,20	*2,00*	*0,108*	*21,84*				
						Σ=	*1,595*

S_c = 16mm

So:
$S = S_e + S_c = 7 + 16 = 23$mm

Because for standard construction with separate foundations total settlements of 50mm are allowed, assumed dimensions of foundation B=L=3,10m are considered as correct.