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DESIGN OF THE FOUNDATIONS LOADED BY OVERTURNING MOMENT
STABILITE DES FONDATIONS DE BLOCS SOUMIS A UN MOMENT

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SYNOPSIS: This paper describes the simplified methods of an analysis of the ultimate bearing capacity and load-displacement analysis of the rigid block foundation embedded in soil subjected to lateral loads and an overturning moment. Proposed formulas were developed with regard to soil parameters, geometry of foundation and subsoil surface around the foundation. The proposed method should be used for each rigid foundation with relative depth $0.2 < D/B < 2$ loaded by overturning moment.

RESUME: Le document presente des méthode de calcul actuelles utilisées pour le dimensionnement des fondations de supports aériens et en parti culier, lignes de traction éléctriques.

INTRODUCTION

A directly embedded block as the foundation for supporting structures is still used in the construction of distribution and transmission lines. These uses give us a wide range of different geotechnical conditions, foundation shapes, different geometrical parameters of the soil surface around the foundation. The analyses of the typical use cases indicate that most of them are in the range $0.2 < D/B < 2$ and can be regarded as rigid foundations. The main types of subsoil conditions are:
- foundation is soil medium witn a flat surface,
- foundation on a slope,
- foundation close to a trench.

Considering the rigid block embedded in soil and loaded at the top of the perimeter by a relatively small vertical compressive force Q_V, a relatively small horizontal shear force Q_H and a large overtuning moment Q_M, (load eccentricity $Q_M/Q_H > 6$ meters).

The block will tend to move round to a center of rotation, generating resisting forces by the soil mass. There are lateral resisting forces on the front face of the block above the center of rotation and at the back of foundation below the center of rotation and resisting forces under the base. They are considered to represent the integration of the net stress components (normal and shear stresses) produced by the movement of the block due to applied external overturning moment and compression and shear forces. We should assume that for the block foundation, the side friction on the walls parallel to

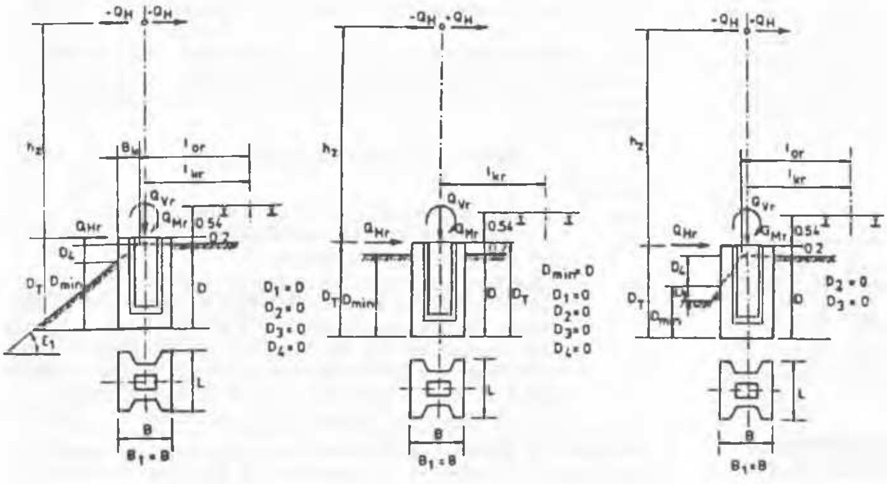

Fig. 1 The main types of subsoil conditions

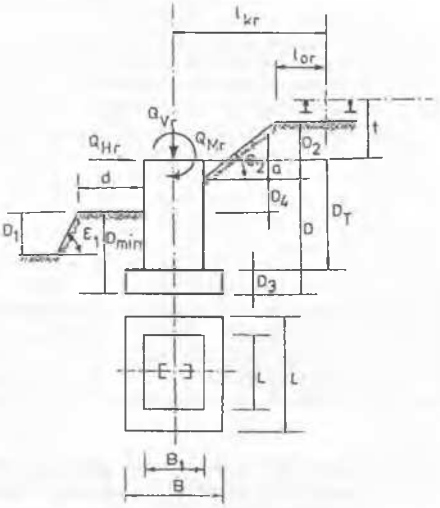

Fig. 2 General scheme of the foundation

the load direction for drilled shaft foundation could be omitted. Observations made in full scale and model tests and numerical analyses indicate that the active pressure on the back side of the perimeter is very small and for cohesive or wet soils does not exist. It means that general model could be simlified by omitting the forces in active zones on the back of half of the perimeter and above the center of rotation and in front of the foundation below this center.

The general theoretical model was developed by Bolt (1976) and more precisely described in works by Dembicki and others (1977,1978), Bolt and others (1989), Bolt (1991). It is assumed that the foundation is rigid, in this method. For all practical purposes the straight foundation has to be categorized as a rigid one when:

$$\frac{D}{EJ/k} < 2 \tag{1}$$

where:

EJ - bending stiffness of the foundation,
k - horizontal modulus of subgrade reaction of the soil foundation system.

THE ULTIMATE BEARING CAPACITY ANALYSIS

The general scheme of foundation and description taken in proposed method are shown in figure 2.

The ultimate equilibrium condition

The ultimate equilibrium of the calculated value of applied forces or moments and ultimate capacity of the soil surrounding the foundation requires the achievement of the following condition:

$$\gamma_n \cdot Q_r \le Q_f \tag{2}$$

Table 1. The strength reduction factor m

No	Foundation technology	Method of evaluation for soil parameters		
		A	B	C
1.1	Poured concrete,drilled shafts,direct embedment	0.8	0.75	0.7
1.2	Prefabricated foundation inserted in the borehols or to excavation and the space between the walls of excavation and foundation filled with concrete or other strong materials			
1.3	Directly embedded foundation into the wide excavation and filled with controlled densities of the fill material			
2.	Directly embedded foundation into the wide excavation and filled with soil without controlled densities	0.75	0.65	0.6

where:

Q_r - the design value of the applied resultant loads (resultant horizontal load Q_{Hr}, resultant vertical compressed load Q_{Vr}), kN; or applied resultant moment Q_{Mr}, kNm;
Q_f - the design value of ultimate bearing capacity of soil-foundation system with regard to the variability of the soil properties and strength,kN;

$$Q_f = m \cdot Q_{nf} \tag{3}$$

γ_n - factor of the consequences of failure, (in each case for a value over one a special economic and statistical analysis is needed);
Q_{nf} - characteristic value of ultimate capacity of soil-foundation system;
m - a strength (resistance or capacity) reduction factor with regard to the variability of the soil properties and strength.

The external load selection

The loads for foundations of supporting structures can be classified as steady-state loads (those that are imposed on a structure for a long or continuous period, transient loads imposed on a structure for a short time duration), construction loads (imposed during the erection of structure and during the erection of structure and during wire installation), maintenance loads (a result of maintenance activities).

The design value of the applied resultant load Q_r according to the Polish standard PN-80/B-03322 can be achieved by selecting a load factor γ_f corresponding to the particular load component as follows:

$$Q_r = \sum_{i=1}^{n} \gamma_{fi} \cdot Q_{ni} \tag{4}$$

where:

Q_{ni} - the characteristic value of the component of applied load kN,
γ_{fi} - load factor applied to component i according to table 2.

Table 2. Values of the load factor γ_f

Load	Load factors γ_f for working conditions	
	normal	accidental
Dead loads (loads for structure,foundation and soil on enlarged base)	1.1(0.9)	1.0
Ice loads	1.4	
Wind loads	1.3	
Tension loads	1.3	

Evaluation of the ultimate bearing capacity

The ultimate bearing capacity of the foundation Q_{Mnf} is expressed as the ultimate resultant moment around the center of rotation at the depth z_0 by the following formula:

$$Q_{Mnf} = v_1 \cdot v_2 \cdot v_3 \cdot v_4 \cdot N_\beta \cdot \gamma_D \cdot D_{min}^4 \tag{5}$$

where:

D_{min} - minimal embedment length of foundation, m;
γ_D - average effective unit weight of soil above the embedment depth, kN/m;
N_β - diamensionless bearing capacity factor established as ultimate moment $N_\beta = M_{ult}/\gamma_D \cdot D_{min}^4$ for rigid square foundations with the dimensionless vertical load factor v_5 = 1 as function of the characteristic value of soil internal friction ϕ and relative width of the foundation base $\beta = B/D_{min}$ in range $0.2 < B/D_{min} < 2$. Values of N_β are shown in table 3.

Foundation geometry and geometry of surrounding soil, influence of vertical components of applied loads and cohesion in cohesive soils are expressed by factors $v_1, v_2, v_3, v_4, v_5, v_6$.

$$v_1 = 1 + \bar{c} \cdot \left(1 - \ln\frac{B}{D_{min}}\right) \tag{6}$$

where: $$\bar{c} = \frac{c_{uD}}{\gamma_D \cdot D} \qquad (7)$$

Table 3. Bearing capacity factor N_β

β \ Φ	5°	10°	20°	25°	30°	35°	40°
0.20	0.10	0.13	0.14	0.19	0.27	0.41	0.64
0.30	0.16	0.19	0.22	0.29	0.41	0.61	0.97
0.40	0.22	0.26	0.29	0.38	0.54	0.82	1.29
0.50	0.27	0.32	0.36	0.48	0.68	1.02	1.91
0.70	0.43	0.50	0.57	0.72	0.97	1.39	2.11
1.00	0.84	0.97	1.10	1.31	1.65	2.20	3.14
1.20	1.26	1.44	1.64	1.91	2.31	2.96	2.96
1.50	2.19	2.49	2.81	3.18	3.71	4.54	5.92
2.00	4.63	5.21	5.98	6.60	7.40	8.60	10.52

A shape factor v_2 incorporates possible changes in the width of the foundation perimeter by relation B_1/B and L_1/L and in the shape of its cross section by coefficient μ_3 shown in table 4 using the following formula:

$$v_2 = \left(1 + \frac{B_1}{B}\right)\left(1 + \frac{L_1}{L}\right) \cdot \mu_3 \qquad (8)$$

Vertical load component factor v_3:

$$v_3 = 1 + \frac{1}{3}\,\frac{B}{D_{min}}\,(v_5 - 1) \qquad (9)$$

where:

$$v_5 = \frac{Q_{Vno}}{\gamma_D \cdot D_{min} \cdot B \cdot L} \qquad (10)$$

$$Q_{Vno} = V + G_f + G_s \qquad (11)$$

V - vertical component of applied load, kN;
G_s - weight of soil on the foundation base, kN;
G_f - weight of foundation, kN

The geometry of the soil surface factor v_4 can be obtained by the following formula:

$$v_4 = \left(1 - \frac{\varepsilon_2}{\psi} \cdot \sin\varepsilon_2\right) \cdot \left(1 - \sin\Phi_{uD}\right) \cdot \left(\frac{D_2 + D_4}{D_{min}}\right) \cdot n_1 + \exp\left[\left(\frac{d}{D_{min}} - \frac{4}{3}\right) \cdot \frac{D_1}{D_{min}} \cdot \frac{\varepsilon_1}{\psi} \cdot n_2\right] \qquad (12)$$

where:

n_1, n_2 - from table 5;
$\psi = \arctan(\tan\phi_{uD} + \bar{c})$ (13)

for $\frac{d}{D_{min}} \geqslant \frac{4}{3}$ computing values is $\frac{d}{D_{min}} = \frac{4}{3}$

for $\frac{D_1}{D_{min}} \geqslant 1$ computing values is $\frac{D_1}{D_{min}} = 1$

for $\frac{D_2 + D_4}{D_{min}} \geqslant 0.5$ computing values is $\frac{D_2 + D_4}{D_{min}} = 0.5$

for $\varepsilon_1 > \psi$ it is necessary to use reduction of the shelf width
$d' = d + D_1 \cdot [\cot\varepsilon_1 - \cot\psi]$ and $\varepsilon_1 = \psi$;
Φ_{uD} - undrained angle of internal friction at the depth D.

The resultant horizontal ultimate resistance of the systems can be computed as:

$$Q_{Hnf} = \frac{Q_{Mnf}}{h + z_0} \qquad (14)$$

where:
Q_{Mnf} - ultimate resultant moment from equation (5), kNm;
h - height of application of horizontal load Q_{Hn} above the soil surface, m;
z_0 - depth to the center of rotation below the soil surface, m;

The position of the center of rotation can be established from the following approximate formula:

$$z_0 = D_{min} \cdot \xi_0 \cdot v_6 \qquad (15)$$

where: $$\xi_0 = \left(\frac{\mu_0 + v_5^{3/4}}{10}\right) \cdot \exp\left[0.15 \cdot \frac{B}{D_{min}} \cdot (1 - 2 \cdot \sin\Phi_{uD}) - 0.1 \cdot \bar{c}\right] \qquad (16)$$

$$v_6 = \left[\mu_1 + 0.1 \cdot (0.7 \cdot \bar{c} - \mu_2) \cdot \frac{B_1}{B}\right] \qquad (17)$$

$\mu_0 = 5$ for cohesive soils ($c_u > 0$)
$\mu_0 = 6$ for cohesionless soils ($c = 0$)
μ_1, μ_2 - coefficients from table 4.

Table 5. Values of coefficients n_1, n_2

Load direction	n_1	n_2
from slope to crest	1	$\frac{1}{2}$
to slope	$\frac{1}{4}$	1

Table 4. Values of the coefficients $\mu_1, \mu_2, \mu_3, \mu_4$

Coefficient	▭→	□→	◇→	○→
μ_1	1.22	1.22	1.20	1.16
μ_2	2.00	2.00	2.00	1.80
μ_3	0.25	0.25	0.30	0.20
μ_4	1.00	1.00	0.00	0.50

LOAD DEFLECTION ANALYSIS

Stiff foundation is subjected to rotation against the center of rotation under the applied horizontal load. The rotation angle and the foundation displacement in a ground level are assumed as characteristic displacement values.

Relationships between lateral stress transmitted to the ground and displacement is described by a formula:

$$\sigma_H = K_H \cdot u \qquad (18)$$

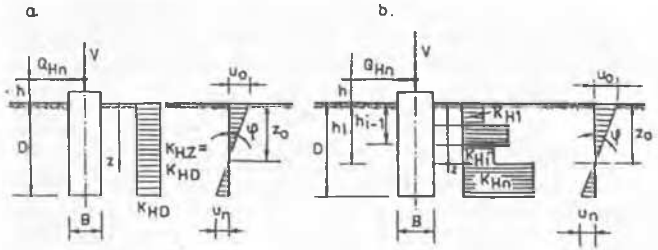

Fig.3 Displacement schemes for foundations loaded by horizontal force a - homogeneous soil, b - multi-layerd soil

where:
u - foundation displacement at depth z,m;
σ_H - lateral stress induced by applied load,kPa;
K_H - coefficient of lateral soil displacement,$kN/m^2/m$;

Coefficient of the lateral soil displacement (Davidson and others (1982)) for a certain soil layer is described by a formula:

$$K_{Hi}=\frac{5.7\cdot E_{pi}}{L_i}\cdot\left(\frac{L_i}{D_{min}}\right)^{0.4} \qquad (19)$$

where:

E_{pi} - modulus of deformation as would be measured with a pressuremeter test, kPa;
L_i - foundation width, m;
D_{min} - foundation embedment depth, m;

It is assumed that the value of K_H coefficient is constant in the given soil layer (fig.3).

Values of foundation displacements are described by the following formulae:

a) homogeneous soil:

A horizontal foundation displacement at the ground level, m:

$$u_o=\frac{2\cdot Q_{Hn}}{v_4}\cdot\left\{\left[\frac{D_{min}+3\cdot h}{6\cdot a_4+D_{min}^2\cdot K_H\cdot L\cdot v_7}\right]+\frac{1}{K_H\cdot L\cdot v_7\cdot D_{min}}\right\} \qquad (20)$$

A horizontal displacement of foundation at its base, m;

$$u_n=\frac{2\cdot Q_{Hn}}{v_4}\cdot\left[\frac{D_{min}+3\cdot h}{6\cdot a_4+D_{min}^2\cdot K_H\cdot L\cdot v_7}\right] \qquad (21)$$

A rotation angle of the foundation:

$$\varphi=\arctan\left(\frac{u_o+u_n}{D_{min}}\right) \qquad (22)$$

where:

$$a_4=v_7\cdot\frac{B^3\cdot M_{oD}}{D_{min}}\cdot\left(\frac{L}{D_{min}}\right)^{0.4} \qquad (23)$$

v_7 - influence of cyclic loading sequence (for static load equal 1);
Q_{Hn} - characteristic horizontal component of the resultant load, kN;
h - height of application of the resultant horizontal force Q_{Hn} above lower surcharge, m;
B - foundation width, m;
z_o - embedment of the instantaneous rotation center of foundation below the lower surcharge from (15), m;
v_4 - coefficient according to (12);
K_H - coefficient of lateral deformation according to (19), kN/m;
M_{oD} - oedometric modulus of compressibility under the foundation base, kPa;

b) multi-layerd soil

A horizontal a foundation displacement at the ground level u_o and horizontal displacement of the foundation at its base u_n can be achieved from equations, m;

$$u_o=\frac{2\cdot Q_{Hn}}{v_4}\cdot\left[\frac{3\cdot a_2\cdot h+2\cdot(a_3+3\cdot a_4\cdot D_{min})}{4\cdot a_1\cdot(a_3+3\cdot a_4\cdot D_{min})-3\cdot a_2\cdot(a_2+2\cdot a_4)}\right] \qquad (24)$$

$$u_n=\frac{2\cdot Q_{Hn}}{v_4}\cdot\left[\frac{6\cdot a_1\cdot D_{min}\cdot h+3\cdot a_2\,(D_{min}-h)-2\cdot a_3}{4\cdot a_1\cdot(a_3+3\cdot a_4\cdot D_{min})-3\cdot a_2\cdot(a_2+2\cdot a_4)}\right] \qquad (25)$$

where:

$$a_1=\sum_{i=1}^{n}v_{7i}\cdot K_{Hi}\cdot L_i\cdot(h_i-h_{i-1}) \qquad (26)$$

$$a_2=\sum_{i=1}^{n}v_{7i}\cdot K_{Hi}\cdot L_i\cdot(h_i^2-h_{i-1}^2) \qquad (27)$$

$$a_3=\sum_{i=1}^{n}v_{7i}\cdot K_{Hi}\cdot L_i\cdot(h_i^3-h_{i-1}^3) \qquad (28)$$

a_4 - according to (23);
n - the number of soil layers from the lower surface of subsoil to the foundation depth;
u_o,u_n - the values of a horizontal foundation displacement at the ground level u and horizontal displacement of foundation at its base, m;
K_{Hi} - coefficient of the lateral deformation for the layer i according to (19), kN/m;
h_i,h_{i-1} - depth of the layer i and the layer i-1 from the lower soil surface (for i=1 $h_{i-1}=0$), m;
B - width of foundation base, m;
L_i - foundation legth in the layer i,m;
Q_{Hn} - characteristic horizontal component of resultant load kN;
ϕ - rotation angle of the foundation according to (22).

COMPARISON OF MODEL RESULTS WITH FIELD DATA

The Geotechnical Laboratory of the Gdańsk Technical University in cooperation with COBIRTK of Polish Railways conducted full scale test in different soil conditions and for different types of subsoil conditions. These field test data on 18 foundations were used for a comparison of the proposed method results with the field test data and give quite reasonable results.

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