Estimation of settlements of isolated footings next to suspension supported earth slits

Estimation des tassements de pieds isolés à proximité d'ouvertures de terre en suspension

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ABSTRACT: Due to the building concentration in town centres, the diaphragm wall construction method is being increasingly applied to achieve a deep excavation closure with small deformations. In particular the isolated footings of neighbouring buildings are endangered by settlements resulting from the suspension supported excavation of a diaphragm wall lamella. A simple mathematical method for estimating this settlement will be explained. It proceeds from the comparison of the utilised shear strength in the soil before and after excavating the diaphragm wall lamella. Extensive soil mechanical model tests support the results of this method.

RESUME: En raison de l'aménagement urbain compact, on construit, en ce qui concerne des fouilles profondes, de plus en plus des parois continue en béton moulée pour faire une enceinte avec peu de déformation. La parie continue en béton moulée, étayée avec une suspension à l'état de creusage, a un effet sur les semelles isolées des ouvrages avoisinant. Cettes semelles isolées peuvent se tasser. Ci-après, une méthode par voie de calcul simple est expliquée pour qu'on puisse estimer ces tassements. En ce qui concerne cette méthode, on compare la résistance limitée au cisaillement avant le creusage avec la résistance limitée au cisaillement après. Les résultats de cettes méthodes sont basées sur des essais de mécanique des sols.

1 CONSIDERATIONS FOR THE DERIVATION OF THE PROCEDURE

The considerations for deriving the method are made for a strip footing of a structure next to a very long suspension supported earth slit (plane deformation problem). According to the underlying physical conception, by considering an excavation depth t of the earth slit, settlements of the strip footing arise only then if the soil shear strength, on the (plane) surface connecting the footing edge and the momentary deepest point of the slit, is mobilised on a larger scale than that before excavating the suspension supported slit (fig. 1a). The mobilisation of additional shear strength requires relative deformation in the considered surface.

These deformations manifest themselves in form of a wedge displacement s, which is parallel to the surface, and thus causing settlements s_v of the footing (fig. 1a).

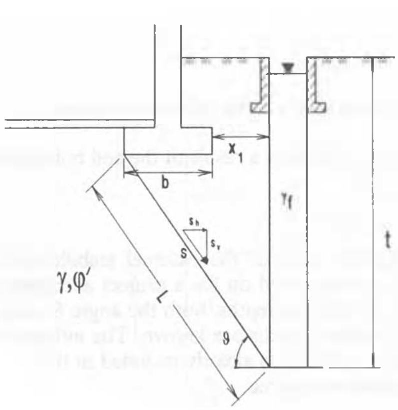

Figure 1a

To determine the mobilised shear strength or its degree of utilisation in the initial state, the state of equilibrium of the forces acting on the earth prism will be considered (fig. 1b), whereby the calculated normal and shear stresses resulting from the strip footing base pressure σ_o, according to the elastic hemisphere theory, in addition to the earth pressure at rest from the soil bulk weight will be applied on the subsequent wall surface of the diaphragm wall trench. The req. φ_o in the initial state can be read out of the illustrated force polygon (fig. 1b) (for the accompanying equations refer to Happe, 1996), so that the degree of utilisation A_o of shear strength in the initial state takes the form

$$A_o = \tan \text{req. } \varphi_o \,/\, \tan \varphi' \quad (1)$$

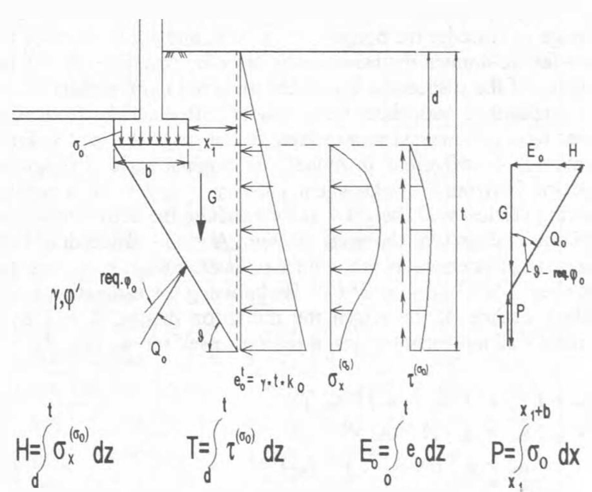

Figure 1b

In the state of suspension support, the above mentioned normal and shear stresses acting on the wall surface of the diaphragm wall trench of the depth t are to be replaced by the pressure of the supporting suspension (fig. 1c), so that the now req. φ_s could be determined from the accompanying force polygon. This - referred to the angle of internal friction of soil - results in the utilisation degree A_s.

$$A_s = \tan \text{req. } \varphi_s \,/\, \tan \varphi' \quad (2)$$

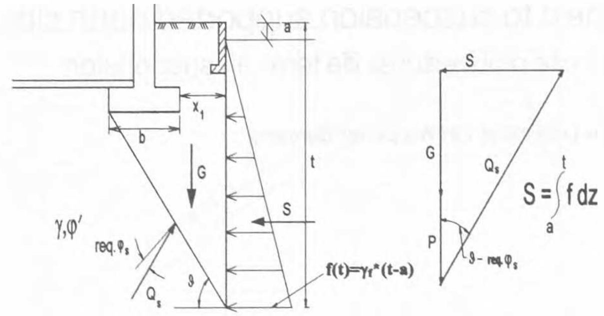

Figure 1c

If $A_o > A_s$, which is possible in case of soils free from ground water and by a big distance of the strip loading from the earth slit, no calculated settlements are to be expected. For estimating the settlements in case that $A_o < A_s$, a realistic mobilising function $A = f(\bar{s})$ is to be applied, whereby $\bar{s}$ is the relative displacement of the triangular rigid soil prism referred to the length L against the soil below (fig.2). The mathematical form of the mobilising function is chosen as a parabola in the domain $0 \leq \bar{s} \leq \bar{s}_m$ (fig. 2):

$$A = 1 - (1 - \bar{s} / \bar{s}_m)^n \tag{3}$$

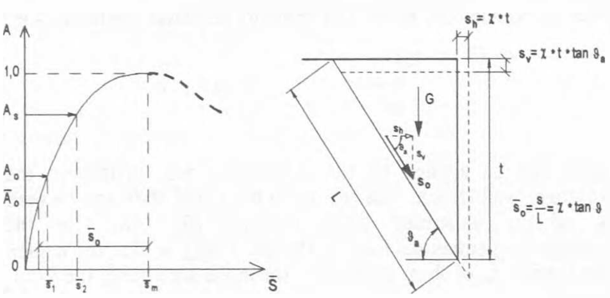

Figure 2

In this, the parameters $\bar{s}_m$ and $\underline{n}$ are to be determined. It is enough to consider the domain $0 \leq \bar{s} \leq \bar{s}_m$ and not to describe the post-failure-domain mathematically, since by reaching $A = 1$ the stability of the suspension supported slit is not more present.

Comparisons with shear force / shear path diagrams from ring-shear tests recommend an exponent in the range $2 \leq n \leq 3$. From numerous examinations in model and original scale it is known that the horizontal displacement path $\chi = s_h / t$ of a parallel moving vertical wall (height = t) for reaching the active limit state (utilisation degree of the shear strength A = 1) - proceeding from the state of pressure at rest with a utilisation degree $\bar{A}_o$ - ranges between $1 * 10^{-3} \leq \chi \leq 3 * 10^{-3}$. By knowing the inclination of the sliding surface ϑ_a, by which the utilisation degree A = 1 by a parallel wall movement arises, it presents itself for $\bar{s}_m$ (fig. 2):

$$\bar{A}_o = 1 - [1 - (\bar{s}_m - \bar{s}_o) / \bar{s}_m]^n$$

$$\rightarrow \quad \bar{s}_m = \bar{s}_o / (1 - \bar{A}_o)^{1/n}$$

$$\rightarrow \quad \bar{s}_m = \chi * \tan \vartheta_a / (1 - \bar{A}_o)^{1/n} \tag{4}$$

The utilisation degree $\bar{A}_o$ of a prismatic soil body, which is defined through the inclination of the sliding surface ϑ_a, is calculated according to fig. 3 to :

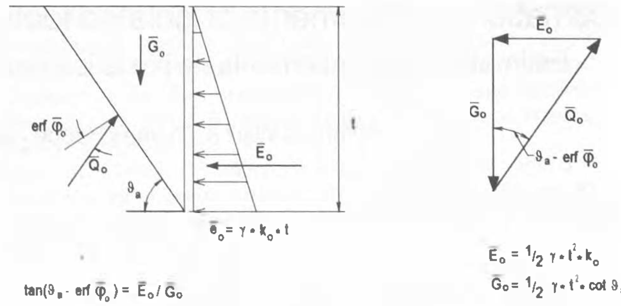

Figure 3

$$\bar{A}_o = \tan [\vartheta_a - \arctan (k_o * \tan\vartheta_a)] / \tan\varphi' \tag{5}$$

k_o = coefficient of earth pressure at rest, e.g. $k_o = 1 - \sin \varphi$

The used inclination of the sliding surface ϑ_a is valid for a vertical ($\alpha = 0$), suspension supported ($\delta_a = 0$) earth wall by a horizontal ground ($\beta = 0$) as a rule, so that $\vartheta_a = 45° + \varphi/2$ is to be applied.

For a certain excavation depth t of the slit the utilisation degree A_o before the excavation, that A_s by reaching the depth t and then, by means of the mobilising function according to fig. 2, the relative displacement paths $\bar{s}_1$, $\bar{s}_2$ and herewith

$$\bar{s}_s = \bar{s}_2 - \bar{s}_1 \tag{6}$$

are to be determined. The footing settlement is the vertical component of the displacement path $s_s = \bar{s}_s \cdot L$.

2 SETTLEMENTS OF ISOLATED FOOTINGS NEXT TO SUSPENSION SUPPORTED EARTH SLITS OF LIMITED LENGTH

The utilisation degree A_s is defined over the mean angle of friction that is mobilised on a plane surface connecting the footing back edge and the momentary deepest point of the suspension supported slit to maintain equilibrium. By means of equation (2), A_s is the reciprocal value of a safety coefficient $\eta_\varphi = \tan \varphi' / \tan$ req. φ which is defined over the angle of friction. As Walz et al., 1980 presented, the numerical value of η_φ in the domain of interest $1{,}0 \leq \eta_\varphi \leq 1{,}5$ is approximately identical with the used safety definition in the proof of the external stability of a suspension supported earth wall according to DIN (German institute for standardisation) 4126

$$\eta_k = S_w / E^r_a$$

S_w = effective supporting pressure force of the suspension

E^r_a = spatial earth pressure force as a result of the soil bulk weight and footing load.

Would the mathematical proof of the external stability of the suspension supported slit be carried on for a project according to DIN 4126 for several excavation depths, both the angle ϑ and the safety coefficient η_k for these depths are known. The influence of an isolated footing next to the slit is already included in this safety coefficient or in the utilisation degree

$$A_s = 1 / \eta_k$$

respectively.

The utilisation degree A_o before excavating the slit is calculated for the surface defined through ϑ, whereby for the simplicity and with regard to the magnitude of settlements conservatively only the soil bulk weight (without influence of footing) is considered. Analogous to the derivation in fig. 3 :

$$A_o = \tan [\, \vartheta - \arc\tan (\, k_o * \tan \vartheta \,)] / \tan \varphi' \qquad (7)$$

Thus, by means of A_s, A_o and ϑ, all the elements for estimating the settlement are known.

3 EXAMPLE

Beside an isolated footing (a * b = 1,5 m * 2,0 m) (fig. 4) bearing a load of 700 kN, a 4,5 m long diaphragm wall, at a distance 1,0 m from the footing, is to be excavated up to a depth t = 20 m. The footing is founded 2,0 m beneath the ground surface. The soil parameters and the remaining geometrical boundary conditions are to be taken from fig. 4.

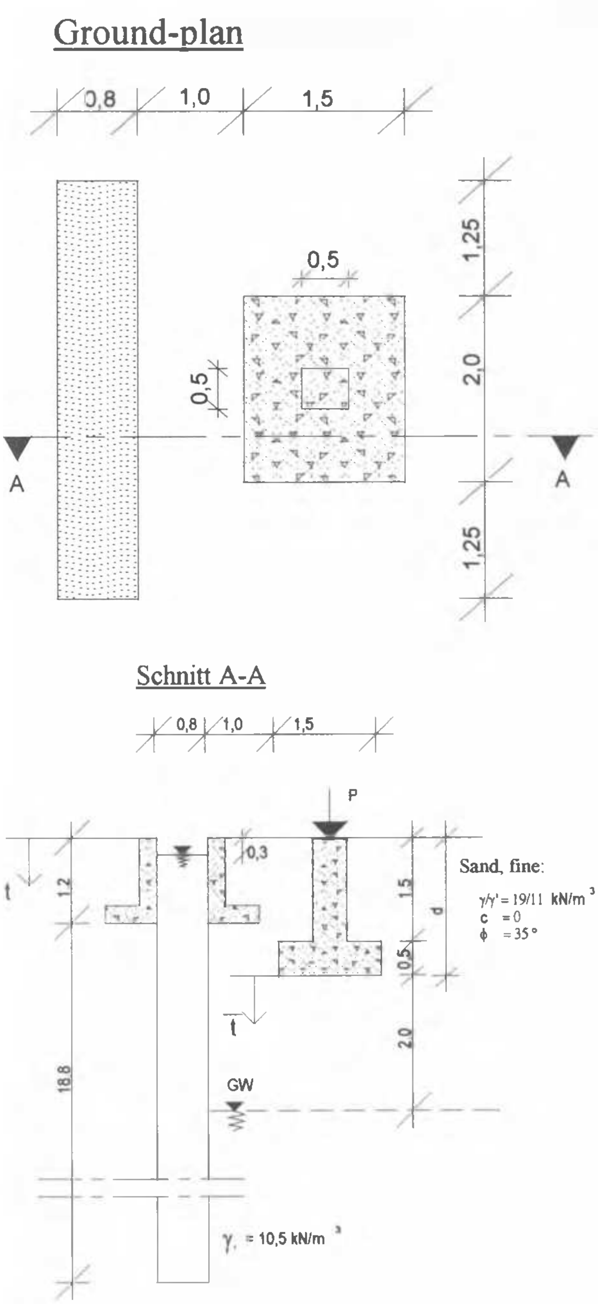

Figure 4

For the mathematical proof of safety against failure of the diaphragm wall trench, since the existing soil is fine sand, it will be proceeded on the assumption that the suspension supporting force possesses a membrane-like effect. According to DIN 4126, the spatial earth pressure force E^r_a acting on a prismatic rupture figure model will be determined, the length of which is equivalent to the footing dimension parallel to the slit, thus amounts to l_a = 2,0 m (unfavourable case for the safety coefficient).

For the calculation of the stability coefficient η_k, the commercial program VERTREN was applied, the results of which are given in columns 2 and 4 of the following table. In column 3 the utilisation degree A_o is given according to the equation (7), whereby the governing inclination of the sliding surface ϑ proved in column 2 was applied. The column 5 includes the utilisation degree A_s, after constructing the slit, as a reciprocal value of the safety coefficient η (column 4). As long as $A_s < A_o$, the footing will not settle. The equation for calculating the displacement path $\bar{s}_s$ parallel to the sliding surface results from the equation (3) which is solved according to $\bar{s}$

$$\bar{s} = \bar{s}_m * [1-(1-A)^{1/n}]$$

by applying equations (6) and (4)

$$\bar{s}_s = \chi * \tan \vartheta_a / (\, 1 - \bar{A}_o \,)^{1/n} * [\, (1-A_o)^{1/n} - (1-A_s)^{1/n} \,] \qquad (8)$$

with ϑ_a = 45° + φ/2 and $\bar{A}_o$ according to equation (5). The footing settlement is then

$$s_v = \bar{s}_s * L * \sin \vartheta = \bar{s}_s * \bar{t} \qquad (9)$$

($\bar{t}$ in column 6: $\bar{t}$ = t - d = t -2,0)

t [m]	ϑ [°]	A_O [-]	η [-]	A_S [-]	$\bar{t}$ [m]	s_v [mm]
0,000	38,200	0,510	99,999	0,010	0,000	0,000
0,800	64,760	0,595	2,032	0,492	0,000	0,000
1,600	66,800	0,575	2,150	0,465	0,000	0,000
2,400	68,800	0,551	2,678	0,373	0,400	0,000
3,200	70,320	0,529	3,240	0,309	1,200	0,000
4,000	55,440	0,626	2,043	0,489	2,000	0,000
4,800	60,240	0,622	1,546	0,647	2,800	0,241
5,600	63,200	0,607	1,416	0,706	3,600	1,282
6,400	64,760	0,595	1,362	0,734	4,400	2,240
7,200	66,000	0,584	1,326	0,754	5,200	3,288
8,000	67,520	0,567	1,303	0,767	6,000	4,468
8,800	69,800	0,536	1,309	0,764	6,800	5,579
9,600	71,800	0,504	1,335	0,749	7,600	6,436
10,400	73,440	0,473	1,376	0,727	8,400	7,019
11,200	74,800	0,445	1,424	0,702	9,200	7,461
12,000	76,000	0,418	1,482	0,675	10,000	7,747
12,800	76,960	0,395	1,540	0,649	10,800	7,987
13,600	77,760	0,375	1,614	0,620	11,600	7,953
14,400	78,600	0,354	1,669	0,599	12,400	8,308
15,200	79,240	0,337	1,742	0,574	13,200	8,320
16,000	79,760	0,322	1,828	0,547	14,000	8,132
16,800	80,400	0,304	1,883	0,531	14,800	8,498
17,600	80,960	0,289	1,970	0,508	15,600	8,464
18,400	81,400	0,276	2,048	0,488	16,400	8,476
19,200	81,760	0,265	2,117	0,472	17,200	8,540

By slit depths t > 4,0 m, mathematical settlements arise which run up to approx. 8,5 mm by an end depth of excavation t = 20 m. For estimating this settlement according to equation (8) and (9), the parameters n = 3 and $\chi = 2 * 10^{-3}$ were applied:

$$\bar{A}_o = 0{,}6114$$
$$\bar{s}_s = 5{,}26 * 10^{-3} * [\, (1-A_o)^{1/3} - (1-A_s)^{1/3} \,] \quad [m]$$

4 COMPARISON OF THE RESULTS OF THE CALCULATION PROCEDURE WITH THAT OF MODEL TESTS

Numerous model tests in scale 1:10 and 1:20 were carried out, by which a suspension supported earth slit next to a loaded isolated footing was, as realistic as possible, excavated (refer to Waldhoff, 1991 and Happe, 1996). A typical test result is shown in fig. 5a, whereby the settlements of a footing model (5 cm * 10 cm) located at a distance of x_1 = 12,5 cm from a suspension supported slit of length l_s = 20 cm are plotted as a function of the slit depth for different footing loads. Fig. 5b presents the footing settlements calculated according to the above mentioned procedure. Both the coarse and the magnitude of the measured settlements can be with satisfaction reproduced through the explained mathematical method.

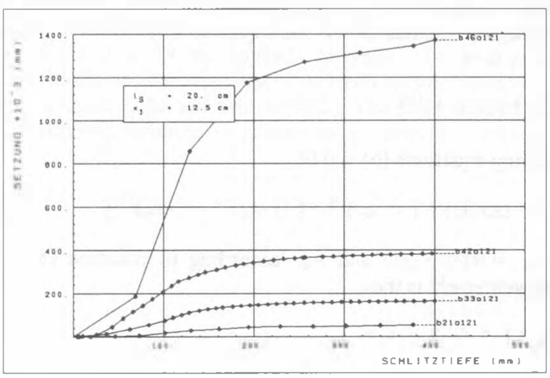

Figure 5a

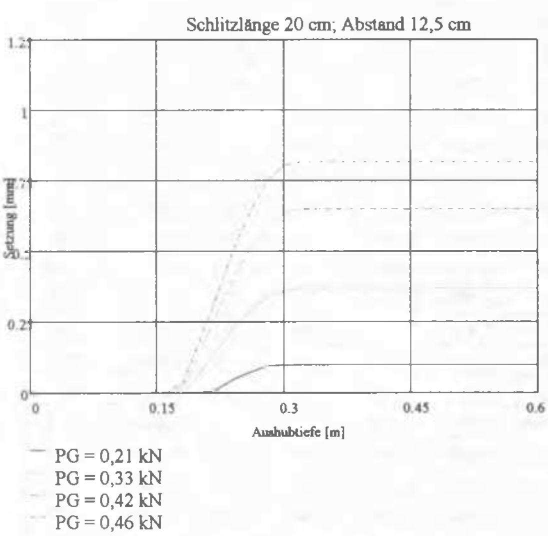

Figure 5b

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