Statistical Evaluation of Settlement Observations

Evaluation Statistique des Observations des Tassements

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SYNOPSIS The results of settlement observations for 148 foundations were evaluated together with the soil parameters and loading history. All types of soil and foundations are represented except pile foundations. For the calculation of the final settlements, 10 calculation methods were chosen and compared with the results of the extrapolated final settlement observations. In order to compare the results, the calculations were made for the characteristic point, in which the settlement of a rigid and a flexible foundation are the same. Settlement influence value charts were calculated for different values of Poisson's ratio and for a modulus of compressibility increasing linearly with depth. Based upon a preliminary examination, the best ratio of compressible layer to width of foundation was found to be 1 for rafts and 2 for single footings. The mean value of the ratio of calculated to observed settlement and the correlation coefficients of the calculated correcting functions permit a judgement of the different calculation methods.

INTRODUCTION

The calculation methods used for settlement predictions show a large scatter of results when compared with the results of settlement observations. Discrepancies between measured and predicted performances not only arise from the theoretical assumptions which have been made but also from the scatter of soil properties on the site, so that an evaluation of the cause of these discrepancies is extremely difficult. The value of the modulus of compressibility E_s for example can vary by more than 100 %, according to the method used for its determination or the location on the site for which it has been determined. A statistical evaluation of different settlement calculations compared with the results of observed settlements was considered useful to clarify the influence of the different parameters and their determination.

EVALUATED DATA

For 148 foundations data concerning settlement observations was gathered, whereby pile foundations were excepted, as the settlement analysis of these foundations is not comparable to that of shallow foundations. The main part of the data concerns raft foundations (112 buildings), the smaller part single footings (29 values) and strip foundations (7 values). Besides information about settlement behaviour, the corresponding loading history and soil parameters were evaluated. All kinds of soil are represented, beginning with heavily overconsolidated clays over soft clays and silt to sand and gravel; in each of these groups there are about the same number of values. The size of the foundations varies from single footings of 1.0 x 1.0 up to large raft foundations of 60.0 x 100.0 m. The gross foundation pressure varies, according to the kind of soil from 20 kN/m² for a very soft organic clay up to 1263 kN/m² for a dense sand. For a comparison with calculation methods the final settlements had to be extrapolated, if not observed. The extrapolated results obtained in the time-settlement regression analysis with a mean correlation coefficient of r = 0.93, show that the extrapolated final settlements can be assumed to be rather accurate.

CALCULATION METHODS

The chosen calculation methods are based either upon compression tests or in situ testing, calculation methods which use results of triaxial tests could not be included because there was not sufficient data. One of the main problems in estimating settlements is the determination of the soil compressibility, and therefore a series of tests was run to see which evaluation of sounding tests suited the data best. It was found that the equation given by d'Appolonia (1970)

$$E_s = 21.600 + 1.060\ N_{30}\ [kN/m^2] \quad \cdots (1)$$

was the most suitable expression for the calculation of the modulus of compressibility E_s for sand with Standard Penetration Tests. The calculation of E_s for static penetration tests was found to be the best for the equation given by Sanglerat (1972):

$$E_s = 4 \cdot q_s \ [kN/m^2] \cdots \cdots \cdots \quad (2)$$

for silts and soft clays. It was not possible to evaluate the original stress-strain curves of the oedometer tests as they were not obtainable, so that the evaluated values of E_s given by the projecting engineer had to be used. For all foundations the according above named calculations were carried out, depending on the type of test which had been made. All settlement calculations were carried out for the characteristic point (DIN 4019) as the settlement of this point is the same for calculations assuming a rigid foundation or a flexible foundation. Furthermore, the settlement of this point is more or less the mean settlement obtained in settlement observations. Therefore a comparison between calculation methods and observed settlements is possible, no matter what assumptions are made concerning the rigidity of the foundation. The most common method for estimating settlements is the equation

$$s = \int_{z_1}^{z_2} \frac{\sigma_z}{E_s} dz \cdots \cdots \cdots \quad (3)$$

In this expression, either one of the arguments or both σ_z and E_s can be varied with z, (z = depth coordinate). In the first three calculation methods chosen, the modulus of compressibility E_s was held constant with depth, whereas the distribution of σ_z was varied. Then the equation (3) was integrated according to three different specifications:
1) Poisson's ratio $\mu = 0$ and concentration factor (Fröhlich 1934) $\nu = 3$. This is the calculation method according to DIN 4019.
2) Poisson's ratio $\mu = 0$ and concentration factor $\nu = 5$.
3) Poisson's ratio $\mu = 0.3$ and concentration factor $\nu = 3$.
The corresponding equation is:

$$s = \frac{p \cdot B \cdot i}{E_s} \cdots \cdots \cdots \quad (4)$$

with $i = f(\mu, \nu)$ as given above and p = mean foundation pressure. The influence values i for equations (4), case 2) and 3) are given in Fig. 1. In the next three calculation methods the same stress distribution as above was chosen, but the value of E_s was assumed to increase linearly with depth:

$$E_s = E_o \ (1 + k \cdot z/b) \cdots \quad (5)$$

E_s = modulus of compressibility at ground surface and k = increasing factor. In this case, k was chosen to be 0.6, although a variation of **k** with the soil type seems indicated and evaluations in this direction are taking place. The influence values i for k = 0.6 are given in Fig. 2. The other four chosen calculation methods are the

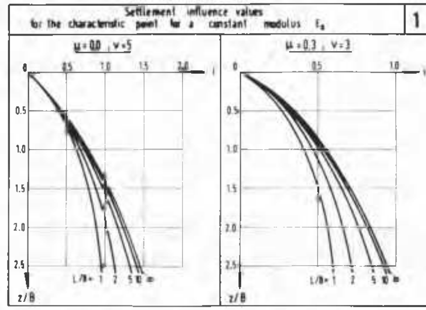

Fig. 1 Settlement Influence Values

following:
1) The equation given by Kerisel (1975), using a circumference load factor

$$s = 3.5 \cdot \frac{p \cdot R_H}{E_s} \cdots \cdots \cdots \quad (6)$$

with R_H = hydraulic radius (area/perimeter)

2) The integration of the linear decreasing stress distribution suggested by Jaky (1944)

$$s = \frac{L \cdot B \cdot p}{E_s(L+B)} \cdots \cdots \cdots \quad (7)$$

3) The proposition of Kezdi (1970), assuming a simplified stress distribution

$$s = 2.3 \frac{p}{2 E_s (L-B)} \cdot \log\left(\frac{2B+z}{2E_s+z} \cdot \frac{L}{B}\right) \cdots \quad (8)$$

4) The empirical approach proposed by Schmertmann (1970)

$$s = \frac{p \cdot B \cdot 0.6}{E_s} \cdots \cdots \cdots \quad (9)$$

The above named calculation methods are listed in Table I. Using the results of a preliminary examination, a factor of z/B = 1.0 was found the best for the thickness of the compressible layer for rafts and a factor of z/B = 2.0 was found

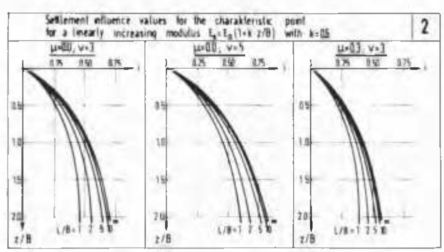

Fig. 2 Settlement Influence Values

Table I

Nr.	Calculation method author	Factor common to all calculation methods: $s = \frac{p \cdot B}{E_s}$	multiplication factor
1	DIN 4019		$i = f\ (\mu = 0,\ v = 3)$
2	Fröhlich		$i = f\ (\mu = 0,\ v = 5)$
3	-		$i = f\ (\mu = 0.3, v = 3)$
4	-		$i = f\ (\mu = 0,\ v = 3,\ k = 0.6)$
5	-		$i = f\ (\mu = 0,\ v = 5,\ k = 0.6)$
6	-		$i = f\ (\mu = 0.3, v = 3,\ k = 0.6)$
7	Kerisel		$\frac{1,75}{(1 + B/L)}$
8	Jaky		$\frac{B}{B + L}$
9	Kezdi		$\frac{1.15}{(1 - B/L)} \cdot \log(\frac{2B + z}{2L + z} \cdot \frac{L}{B})$
10	Schmertmann		0.6

appropriate for single footings, except for the calculation methods where other specifications for z/B are given (Kerisel, Jaky, Schmertmann).

CALCULATION RESULTS

The mean value of the ratio s/s_o varies from 0.55 to 3.7 for method 9 and method 7 respectively. Also there is a Poisson distribution of the ratio s_{cal}/s_{obs} and the inverse ratio for all 148 foundations, with differences of the mean value and the standard deviation (Fig.3). A reason for this is the fact, that many ratios lie near 1.0. When divided into the three groups
1) raft foundations (112 values)
2) single footings (29 values)
3) strip foundations (7 values)
the frequency distribution changes significantly. While there is no remarkable change in the frequency distribution for rafts, and no statistical valid interpretation is possible for strip foundations (too large scatter), the results for the single footings show a normal distribution for all ten methods. The variation coefficients show smaller values after being divided into the three above named groups (Table II). The mean values of equation 7 and 9 show a significant difference when compared with the results of the other computations, whereby the division into the three groups plays no matter at all.

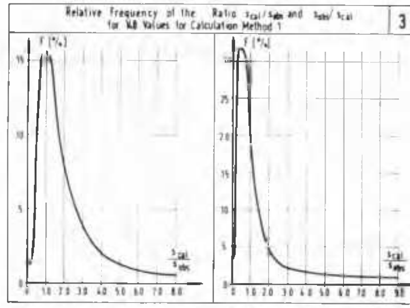

Fig. 3 Relative Frequency Distribution

Regression functions were computed with the observed settlements as dependent variable and the calculated settlements as independent variable. The results show that all computed regression functions go nearly through the point 0/0, and only the gradient b varies (Fig. 4). The regression functions were calculated for a safety factor of 95 % and they are significant except for the strip foundations, where the scatter is too large to allow a significant regression function to be computed. The regression functions for rafts and for single footings are given in Table III, and can be used as correcting functions. The settlement is calculated according to one of the listed methods and then this value is multiplied by the corresponding correcting function i.e.:

$$s_{obs} = a + b \cdot s_{cal}$$

This method allows for a scatter of soil

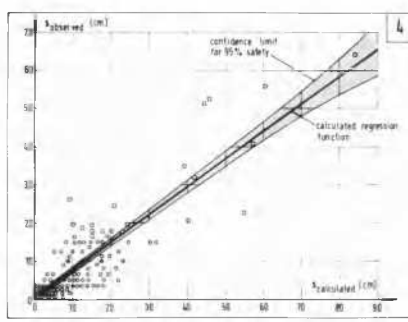

Fig. 4 Calculated Regression Function for 148 Values (Method 1)

Table II: s_{cal}/s_{obs}

calcu-lation method	all values (148)			raft foundations(112)			single footings (29)			strip found.(7)		
	mean	stand. dev.	variat. coef.	mean	stand. dev.	variat. coef.	mean	stand. dev.	variat. coef.	mean	stand. dev.	variat. coef.
1	1,82	1,43	0,79	1,99	1,54	0,78	1,51	0,79	0,52	0,52	0,35	0,67
2	2,16	1,66	o,77	2,28	1,78	o,78	2,07	1,05	0,51	0,57	0,38	0,67
3	1,49	1,15	0,77	1,60	1,24	0,78	1,31	0,69	0,52	0,40	0,27	0,67
4	1,41	1,12	0,79	1,56	1,21	0,77	1,05	0,52	0,50	0,40	0,27	0,67
5	1,63	1,27	0,78	1,78	1,37	0,77	1,36	0,66	0,49	0,44	0,29	0,67
6	1,13	0,89	0,78	1,24	0,96	0,77	0,89	0,44	0,50	0,31	0,20	0,67
7	3,71	3,37	0,91	4,30	3,64	0,85	2,05	1,05	0,51	1,26	0,82	0,66
8	1,70	1,45	0,85	1,92	1,58	0,82	1,06	0,49	0,46	0,72	0,47	0,66
9	0,55	0,49	0,90	0,64	0,53	0,82	0,35	0,16	0,46	0,005	0,006	1,19
10	2,02	1,75	0,87	2,31	1,90	0,82	1,27	0,59	0,46	0,47	0,31	0,67

properties and the not exactly known stress distribution.

CONCLUSIONS

The computations show that the calculation methods 7 and 9 cannot be considered to estimate settlements with a satisfactory degree of accuracy. The results of the evaluations s_{cal}/s_{obs} and the regression functions indicate that f r single footings the stress distribution is not so important, furthermore that the scatter of soil paramete E_s is not very large, as the compressible layer z is not very thick. The scatter of results for raft foundations is partly due to the fact that raft foundations cover a large area and have a larger compressible layer. Therefore the paramete E_s shows a larger scatter. It also seems indicated that the anisotropy of the soil and further differences between theoretical assumptions and actual soil behaviour play a greater part in the calculations of settlements of large foundations than for single footings.

Table III
$s_{obs} = a + b \cdot s_{cal}$

cal. meth.	raft foundations			single footings		
	r	a	b	r	a	b
1	0,867	-0,002	0,734	0,872	0,005	0,439
2	0,864	-0,001	0,631	0,877	0,005	0,325
3	0,864	-0,001	0,897	0,871	0,005	0,509
4	0,864	-0,003	0,933	0,883	0,006	0,613
5	0,861	-0,002	0,812	0,889	0,005	0,4[illegible]2
6	0,861	-0,002	1,155	0,884	0,005	0,730
7	0,852	-0,005	0,354	0,874	0,006	0,300
8	0,906	0,005	0,699	0,895	0,006	0.5[illegible]5
9	0,906	0,005	2,0[illegible]6	0,895	0,006	1,694
10	0,906	0,005	0,5[illegible]2	0,895	0,006	[illegible],471

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