PREDICTION OF SETTLEMENTS FROM EVALUATED SETTLEMENT OBSERVATIONS FOR SAND

PREVISION DU TASSEMENT PAR DES MESURES DE TASSEMENT EVALUEE POUR LE SABLE

ПРОГНОЗ ОСАДОК НА ОСНОВЕ РАСЧЕТА И ОПЫТНЫХ ДАННЫХ ДЛЯ ПЕСКА

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SYNOPSIS

Within the scope of a general research work 48 settlement measurements at building and industrial constructions have been evaluated with regard to an improvement of the prediction of settlement for sand. Partially, measurements were effected for this purpose, partially, measurements already existing were compiled which either had been put at disposal by other authorities or had been taken from literature.

By the measurements, primarily the compressibility of the soil within and after the building time was determined in form of pressure-settlement curves. From this, the modulus of subgrade reaction and - for a known layer thickness - an ideal modulus of compressibility are resulting. The latter is related to the results of the standard penetration tests resp. the static sounding tests, to the foundation widths as well as to the depth of foundations below ground level. By means of multi-correlations formulas were developped for the calculation of settlement. From this, the influence of the foundation width to settlement is appearing with particular clarity, that is the settlement is increasing approximately with the root of the foundation width. The results of the work are compared with known methods to determine the settlements by means of sounding tests.

1. INTRODUCTION

As you know, settlement calculations for constructions on sand according to the methods usual for clay soils - in the Federal Republic of Germany e.g. according to DIN 4019 - are leading to unsatisfactory results, because the soil law of sand cannot be gripped by the compression tests normally used for settlement calculations. The compressibility of sand does not only depend on the vertical pressure, but also on the lateral pressure which is influenced by the foundation width, the foundation depth, the construction length and the contact pressure. Though formulations exist to obtain on the basis of triaxial pressure tests a better mathematical interrelationship for the compressibility of sand (e.g. Brinch Hansen 1966, Kérisel/Quatre 1968), these owing to their difficult performance did not find access to practice yet. Therefore, for quite a time already another course has been adopted by fully refraining from compression tests resp. triaxial tests and calculating settlements of such buildings on the basis of the results of penetration and static sounding tests (Buisman 1944, Terzaghi/Peck 1948, Meyerhof 1956 and 1965, Schmertmann 1970, de Beer 1965, Bazaraa 1967). The results of these investigations are scattering (fig. 4).

Rise to take up this question again was given by an extensive testing program for the evaluation of settlement observations at constructions on various soils, in recent years having been carried through in Aachen (Sherif 1972). From this program, in the following 48 constructions on sand will be cited for which sufficient settlement observations, but also penetration or static sounding tests are at disposal in a sufficient number.

2. EVALUATION METHODS

When evaluating the 48 objects for which settlement observations are at hand - partly from our own projects, partly from literature (table) - the methods hitherto usual were followed up as widely as possible. For the calculation of settlements in the elastic-isotropic half-space the equation applies:

$$s = \frac{p \cdot B}{E_s} \cdot f_n \, (d_s/B, \; L/B, \; \nu) \qquad (1)$$

In this are

B (cm) = width of foundation

L (cm) = length of foundation

d_s (cm) = thickness of the compressible layer ≤ 2 B s (cm) = the mean settlement under the foundation considered for its final state. As far as a time-settlement curve is existing, the final settlement can be exterpolated from the hyperbolic course of the time-settlement curve (fig. 1) (Sherif 1970). Namely, the time-settlement curves were showing that in case of sands, too, settlements had not always subsided upon termination of the building time.

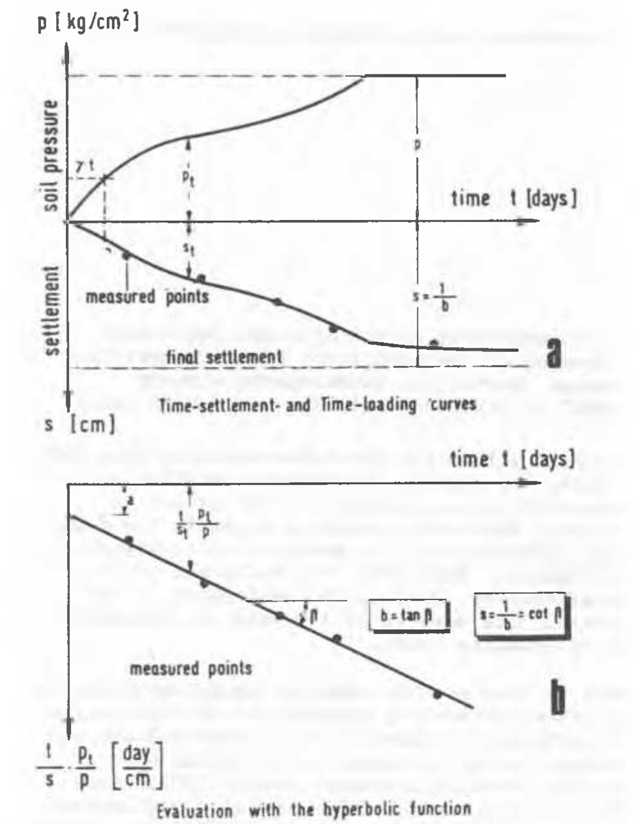

Fig. 1: Extrapolation of the end-settlement of foundations

p (kg/cm^2) = mean contact pressure under the foundation considered without reduction of the excavated material $\gamma \cdot t$. The evaluation of settlement observations has shown that the reduction of $\gamma \cdot t$ theoretically to be expected does not make itself felt at the measurement of settlements. Therefore, the following investigations always apply to the full mean contact pressure.

f_n = influence factor for the settlements (fig. 2) according to the usual tables for the elastic-isotropic half-space (e.g. Steinbrenner 1934, Kany 1959 etc)by a Poisson's ratio $\nu = 0$. The factor is depending on the ratio d_s/B which for larger compressible layers was never substituted larger than 2, as according to experience no essential influence of the construction can be expected any more underneath this depth. Therefore, the following considerations either apply to $d_s/B = 2$ or, in case the compressible layer is smaller, to a ratio which is correspondingly smaller.

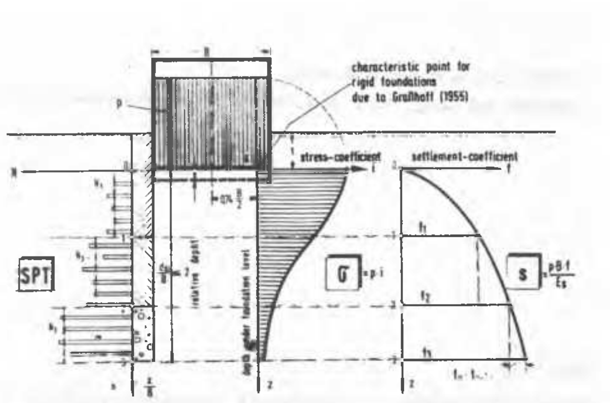

Fig. 2: Scheme of the evaluation of settlement observations

3. LAW FOR THE COMPRESSIBILITY OF SAND

The quantity E_s (kg/cm^2) = modulus of compressibility occurring in the question which is usually taken from the compression test can for sand no more be won in this way. Therefore, after several tests the following statistical formulation is introduced which in the essential introduces as a measure for the compressibility of sand the number of blows N of the standard penetration test instead of the results of the compression tests.

$$E_s = k_1 \cdot N^{k_2} \cdot (B/B_1)^{k_3} \cdot (p/p_1)^{k_4} \cdot (1+k_5 \cdot t/B) \qquad (2)$$

In this are

N = number of blows of the standard penetrometer for a penetration of 30 cm. For constructions for which no standard penetration tests, but static sounding tests were existing, the number of blows N was estimated from the point resistance of the static penetrometer according to Schmertmann (1970) (table column α). Relevant is the arithmetic mean of the blows on the layer thickness d_s drawn on. In case of several layers are found above the depth d_s, the mean value of N is formed under consideration of the weights f (fig. 2) of the various layers. Hereby, you are proceeding on the assumption that approximately the compressibility E_s and the number of blows N linearly depend on each other, thus that k_2 at least approximately is equal to 1 (see as well fig. 4). You then obtain for the mean value

$$N = f_n / \sum_{1}^{n} \frac{f_n - f_{n-1}}{N_n}$$

n = number of the layer concerned (fig. 2)
B_1 = unit of width (1 cm)
p_1 = unit of contact pressure (1 kg/cm²)

4. DETERMINATION OF THE CONSTANTS

You obtain from eq. (1) by transformation

$$E_s = \frac{p \cdot B}{s} \cdot f_n \, (d_s/B,\ L/B,\ \nu) \qquad (3)$$

This fictitious value of E_s can be calculated from the dimensions of the footings, the given contact pressure and the measured settlement. In eq. (2) it can then be substituted as a known quantity. By this, the quantity E_s practically is eliminated. Equation (2) can then be written in the logarithmic form

$$\log \frac{E_s}{(1+k_5 \cdot t/B)} = \log k_1 + k_2 \log N + k_3 \log (B/B_1) + k_4 \cdot \log (p/p_1) \qquad (4)$$

For the determination of the five constants, 48 pairs of values are at disposal so that k_1 to k_5 can be determined by means of a multi-correlation. Here it was proceeded in a way that for
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the parameter k_5 by way of trial values between 0,34 and 0,46 were introduced. By means of the calculation program BMD 02R of the Computation Center of the TH Aachen correlations were made and that parameter k_5 chosen which supplies the largest correlation coefficient. The final result was k_1 = 1,71 kg/cm², k_2 = 0,87, k_3 = 0,50, k_4 = 0, k_5 = 0,4, so that the final equation for the calculation of settlements is reading as follows:

$$\frac{p \cdot B}{s} \cdot f_n(d_s/B,\ L/B) = (1{,}71 \pm 0{,}55) \cdot N^{0,87} \cdot \sqrt{B/B_1} \cdot (1 + 0{,}4\ t/B) \qquad (5)$$

or:

$$s\ (\text{cm}) = \frac{p\ (\text{kg/cm}^2) \cdot f}{1{,}71\ (\text{kg/cm}^2) \cdot N^{0,87} \cdot \sqrt{B/B_1}} \cdot \frac{1}{(1 + 0{,}4\ t/B)} \cdot B\ (\text{cm}) \qquad (6)$$

The correlation coefficient is r = 0,938, thus relatively high. With regard to the result it is interesting that according to this equation the settlement is increasing linearly with the contact pressure p, thus that the constructions show a constant modulus of subgrade reaction $k_s = p/s$. This has been proved by settlement observations for quite a number of constructions with regard to the variable load p within the building time (Schultze 1962 and 1963).

5. PRACTICAL APPLICATION

In order to simplify settlement calculation with eq. (6), the parameter (settlement coefficient) $\frac{s \cdot N^{0,87}}{p}$ (1 + 0,4 t/B) was plotted as a function of the width B for various side ratios L/B and d_s/B = 2 (fig. 3). At a smaller layer thickness settlements have to be multiplied by the given reduction factors.

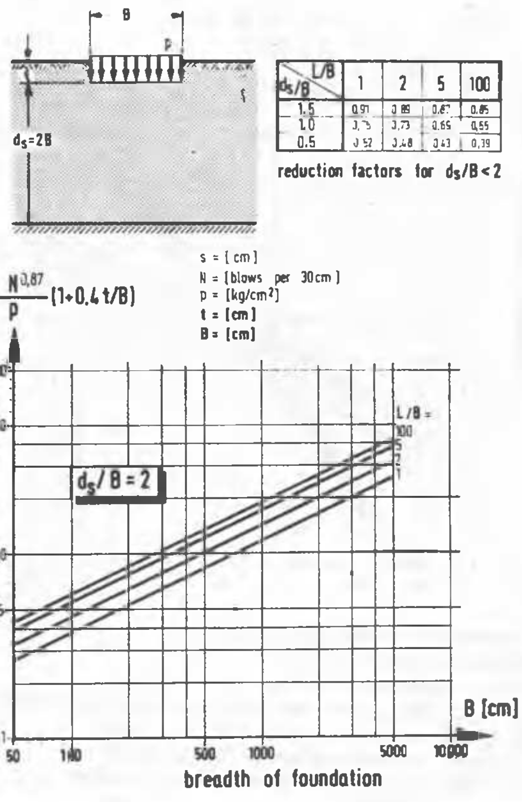


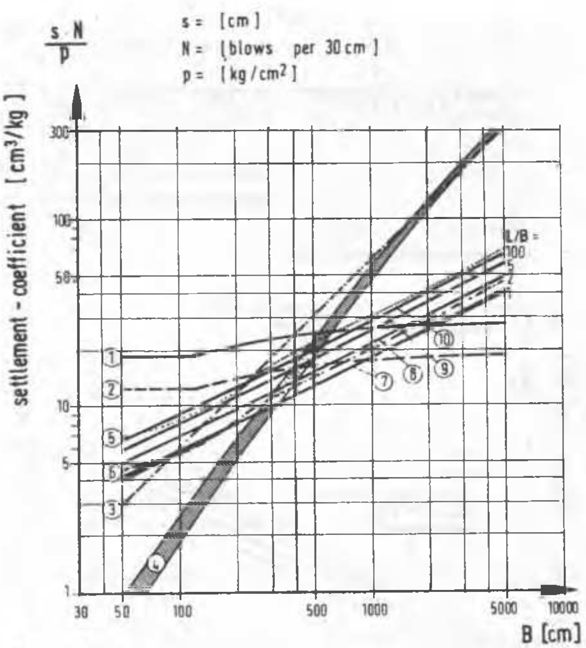
Fig. 3: Settlement calculation with help of the blows of the standard penetration test

6. COMPARISON WITH THE RESULTS OF OTHER METHODS

As most methods are working with a linear dependence E_s on N, thus with a factor $k_2 = 1,0$, an equation was established for this case, as well by means of a multi-correlation. You then obtain

$$s(cm) = \frac{p\ (kg/cm^2)\cdot f}{1,14(kg/cm^2)\cdot N\cdot\sqrt{B/B_1}}\cdot\frac{1}{(1+0,4\ t/B)}\cdot B(cm) \quad (7)$$

The correlation factor diminishes by this alteration of factor k_2 from r = 0,938 to r = 0,873. By this formulation it is possible to plot the various suggestions in a combined form in which s · N/p is chosen as vertical axis (fig. 4). The diagram reveals a very good conformity of the method here developped (curves 7 - 10) with the formulations 5 and 6 by Terzaghi/Peck (1948), Meyerhof (1956 and 1965) with the corrections according to Bazaraa (1967). Moreover, the eq. (6) and (7) are permitting a refinement of these suggestions with regard to the influence of the side ratio L/B. The other suggestions 1 to 4 are out of place.

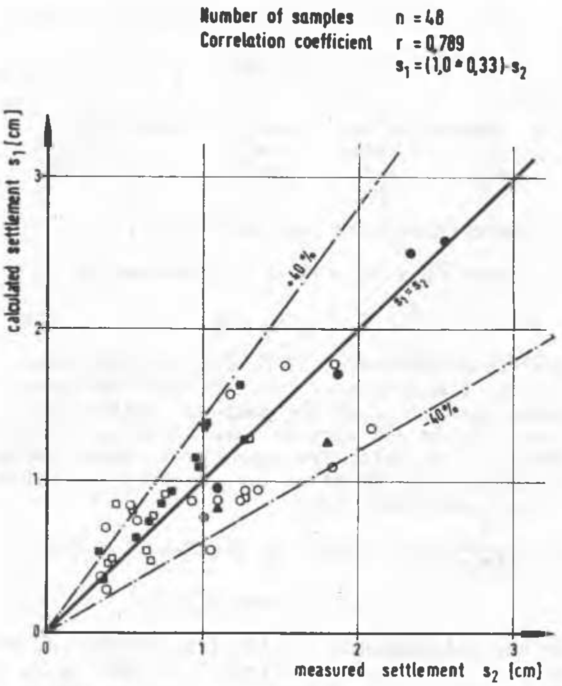


①= Terzaghi / Peck (1948), Meyerhof (1956)
②= Meyerhof (1965) = ① × 2/3
③= Schmertmann (1970) N = 5 q_s
④= Buisman (1944), De Beer (1965) (N=5q_s, p = 2 kg/cm, γ = 1-2 t/m³)
⑤= ① with correction due to Bazàraa (1967), γ = 2 t/m³
⑥= ② with correction due to Bazaraa (1967), γ = 2 t/m³
⑦——⑩ = new results from the evaluation of settlement observations

Fig. 4: Comparison between the new results from the evaluation of settlement observations for sand and other methods

7. ACCURACY OF THE SETTLEMENT CALCULATION

To obtain a general view of the accuracy attained with eq. (6), the 48 measurements of settlement the investigations are basing upon were checked one by one and compared with the observed amounts (fig. 5). The correlation factor is r = 0,789, the calculated settlements nearly without exception lie within a range of ± 40 % of the measures values. Such relative accuracy is about corresponding to that you obtain for cohesive soils with usual compression tests. However the settlement for sand is very lower and therefore the absolute accuracy is higher.



● Standard Penetration Test, Aachen
○ Static Cone Test, Muhs (1961)
■ Standard Penetration Test, D'Appolonia and others (1968)
□ Static Cone Test, Schmertmann (1970)
▲ other structures (see Table)

Fig. 5: Comparison between calculated and measured settlements

SUMMARY

By evaluating the settlement observations at 48 structures on sand for which at the same time sounding tests are existing, the possibility resulted to calculate the settlements as a function of the number of blows of the standard penetration test instead of compression tests which for sand soils represent no sufficient model. An equation was derived in which apart from the mean number of blows of the penetration tests for a depth d_s/B = 2 there are still occurring the unreduced mean contact pressure p as well as the foundation

Table: List of data for the investigated structures

No	p	B	L/B	t/B	d_s/B	q_s	$\alpha = q_s/N$	N	s	mention of somces
	kg/cm^2	m	(1)	(1)	(1)	kg/cm^2	1	(1)	cm	
1	2,99	2,55	4,20	0,37	2	-	-	37	1,09	Institut für Grundbau und Bodenmechanik, TH Aachen
2	1,84	1,70	> 10	0,94	2	-	-	43	1,92	
3	2,90	17,60	4,80	0,60	0,80	-	-	18	2,55	
4	2,62	16,00	2,69	0,45	0,75	-	-	15	2,33	
5	2,56	14,20	1,00	0,25	2	-	-	30	1,86	
6	1,91	23,00	1,17	0,13	2	150-200	7	30	1,52	Muhs (1961)
7	2,35	1,80	1,00	1,67	2	150-200	7	30	0,34	
8	2,35	1,35	1,00	2,22	2	150-200	7	30	0,39	
9	2,90	2,20	1,00	1,36	2	150-200	7	30	1,05	
10	1,82	22,40	1,49	0,13	2	150-200	7	30	1,84	
11	1,99	4,50	1,27	0,67	2	150-200	7	30	0,39	
12	0,83	15,00	4,86	0,20	2	150-200	7	30	0,54	
13	2,55	1,60	7,90	0,24	2	150-200	7	30	0,93	
14	2,55	1,15	11,00	0,24	2	150-200	7	30	1,00	
15	3,00	0,80	23,00	0,29	2	150-200	7	30	0,58	
16	2,10	1,80	13,40	0,12	2	150-200	7	30	1,69	
17	1,70	23,60	1,10	0,13	2	150-200	7	30	1,17	
18	1,56	21,70	1,00	0,14	2	150-200	7	30	2,08	
19	3,10	3,30	1,73	0,91	2	225	7	33	1,10	
20	3,10	3,30	1,73	0,91	2	225	7	33	1,22	
21	3,10	3,60	1,75	0,83	2	225	7	33	1,27	
22	3,10	3,60	1,75	0,83	2	225	7	33	1,36	
23	3,10	4,50	1,51	0,67	2	225	7	33	1,83	
24	1,76	36,00	1,00	0,00	0,32	-	7	18	1,80	Baker (1965)
25	2,18	2,60	8,80	0,77	2	40	4	10	3,25	de Beer/Martens (1956)
26	1,90	8,60	1,74	0,29	2	190	4	45	1,10	de Beer (1957)
27	1,32	3,00	1,6	1,00	2	-	-	20	0,34	D'Appolonia/ D'Appolonia/Brissette (1968)
28	1,32	3,00	1,6	0,50	2	-	-	20	0,58	
29	1,57	4,00	1,6	1,00	2	-	-	20	0,66	
30	1,57	4,00	1,6	0,50	2	-	-	20	0,73	
31	1,82	4,90	1,6	1,00	2	-	-	20	0,80	
32	1,82	4,90	1,6	0,50	2	-	-	20	0,97	
33	2,06	5,80	1,6	1,00	2	-	-	20	0,95	
34	2,06	5,80	1,6	0,50	2	-	-	20	1,01	
35	2,31	6,70	1,6	1,00	2	-	-	20	1,02	
36	2,31	6,70	1,6	0,50	2	-	-	20	1,24	
37	2,24	1,00	1,0	0,00	2	135	3,5	39	0,36	Schmertmann (1970)
38	2,24	0,50	4,0	0,00	2	100	3,5	29	0,40	
39	3,36	0,50	4,0	0,00	2	100	3,5	29	0,67	
40	5,75	1,00	1,0	0,50	2	180	3,5	51	0,44	
41	5,75	0,50	4,0	0,50	2	150	3,5	43	0,42	
42	3,47	1,00	1,0	0,50	2	70	3,5	20	0,55	
43	1,31	0,60	1,0	0,55	2	18	3,5	5	0,69	
44	2,30	0,60	1,0	1,50	2	22	3,5	6	1,27	
45	1,36	0,90	1,0	0,30	2	20	3,5	6	0,76	
46	1,15	0,90	1,0	1,00	2	23	3,5	7	0,64	
47	2,02	1,20	1,0	0,17	2	27	3,5	8	1,30	
48	2,74	1,20	1,0	0,75	2	32	3,5	9	1,27	

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depth t, the foundation width B, the thickness of the compressible layer d_s and the length of the footing. The accuracy attained is ± 40 %.

REFERENCES

BAKER (1965) - Discussion of "shallow foundations" by Meyerhof. Proc. ASCE, SM 6, p. 119.

BAZARAA (1967) - Use of the standard penetration test for estimating settlements of shallow foundations on sand. Ph.D.thesis, University of Illinois.

BRINCH HANSEN (1966) - Improved settlement calculation for sand. DGI 20.

BUISMAN (1944) - Grundmechanica, p. 171. Delft.

D'APPOLONIA/D'APPOLONIA/BRISSETTE (1968) - Settlement of spread footings on sand. Proc. ASCE, 94, SM 3, p. 735.

DE BEER (1965) - Bearing capacity and settlement of shallow foundations on sand. Proc. Symp. Duke University, April 1965, p. 15.

DE BEER/MARTENS (1956) - Discussion of "Penetration tests and bearing capacity of cohesionless soils" by Meyerhof. Proc. ASCE, Oct. 1956, 1095, p. 7.

GRASSHOFF (1955) - Setzungsberechnungen starrer Fundamente mit Hilfe des "kennzeichnenden" Punktes. Bauingenieur 30, p. 53.

KANY (1959) - Berechnung von Flächengründungen, p. 142. Berlin, Wilh. Ernst & Sohn.
s.a. FF (1959) - Flächengründungen und Fundamentsetzungen. Erläuterungen und Berechnungsbeispiele für die Anwendung der Normen DIN 4018 und DIN 4019 Blatt 1. Berlin, Wilh. Ernst & Sohn.

KÉRISEL/QUATRE (1968) - Settlements under foundations. Calculation using the triaxial apparatus. Civ. Eng. Publ. Works, Rev. 63, p. 531 and 661.

MEYERHOF (1956) - Penetration tests and bearing capacity of cohesionless soils. Proc. ASCE 82, SM 1, 866, p. 1.

MEYERHOF (1965) - Shallow foundations. Proc. ASCE 91, SM 2, p. 21.

MUHS (1961) - Ergebnisse der Setzungsmessungen an den Hochhäusern im Hansaviertel und am Hochhaus "Heiselberger Dreieck" in Berlin. Berlin, Mitt. Degebo, 15, p. 1.

SCHMERTMANN (1970) - Static cone to compute static settlement over sand. Proc. ASCE 96, SM 3, p. 1011.

SCHULTZE (1962) - Probleme bei der Auswertung von Setzungsmessungen. Vorträge der Baugrundtagung Essen, p. 343.
s.a. Mitt. VGB 27.

SCHULTZE (1963) - Beispiele für die Setzungsbeobachtungen in bindigen und nichtbindigen Böden. Proc. Europ. Baugrundtagung, Wiesbaden, I, p. 143.
s.a. Mitt. VGB 29, p. 3.

SHERIF (1970) - Zur Auswertung von Zeitsetzungslinien von Hoch- und Industriebauten. Mitt. VGB 46, p. 223.

SHERIF (1972) - Setzungsmessungen an Industrie- und Hochbauten und ihre Auswertung. Diss. TH Aachen (not yet published).

STEINBRENNER (1934) - Tafeln zur Setzungsberechnung. Straße 1, p. 121.
s.a. Grundbautaschenbuch, I, p. 92. Berlin, Wilh. Ernst & Sohn, 2. Edition.

TERZAGHI/PECK (1948) - Soil mechanics in engineering practice, p. 423. New York, John Wiley.