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CALCULATED AND OBSERVED SETTLEMENT OF A SILO GROUP

TASSEMENT CALCULE ET OBSERVE D UNE GROUPE DES SILOS

ERVIN NONVEILLER, B.Sc.(Eng), Ph.D.

Professor of Soil Mechanics and Foundation Engineering

Faculty of Civil Engineering

University of Zagreb Yugoslavia

IVO KLEINER, B.Sc.(Eng)

Head of Soil Mechanics and Foundation Division

Institute Geoexpert, Zagreb, Yugoslavia

SYNOPSIS A large silo group consisting of four units with a total area of 2560 m² and a total load of 54.000 to was constructed in 1963 for a food industry near Zagreb. The foundation soil consists of interchanging layers of normally consolidated clay and of sandy and gravelly soil. The bearing capacity of the soil was sufficient to support the structures on a shallow slab foundation. A comprehensive settlement calculation yielded a max total settlement of 35 cm. In design differential settlements of about 6 cm from interaction between the individual silo blocks had to be considered. A number of settlement monuments were installed on the foundation slabs and observations are being made since the beginning of construction. A good correlation between predicted and measured settlements of most settlement monuments was established.

INTRODUCTION

The settlement computation of large structures on nonhomogeneous soil always involves uncertainties, and in most cases accurate predictions can not be expected. Among a scattering array of field and laboratory test results, as porosity, compression index, permeability, coefficient of consolidation, variable thickness and sequence of soil strata, the appropriate values must be selected. And even if these data are known precisely on the center lines of bore holes other factors intervene which make the results uncertain. This is so because the interaction between soil and structure produces load redistribution which can be calculated only making some additional assumptions. Higher compressibility and/or higher consolidation rate at some spots cause load reduction at these and corresponding load increase at other stiffer places. As soil settlement is equalized to the deformation of the structure, predicted and observed settlement will not be the same, however precise our theoretical considerations on which settlement calculations are based. It will be of interest therefore to analyse calculated and observed settlements of structures for which reliable exploration was carried out.

A large silo group consisting of four units with a total area of 2560 m² and a total load of 54.000 to was erected near Zagreb. For the foundation of these structures a comprehensive soil exploration was undertaken and the settlement of the characteristic points of the foundation slabs was calculated. A net of settlement monuments was installed and continuous

observations have been carried out since the beginning of construction. The analysis of the results obtained in this case shows a very good agreement between prediction and measurement when the average settlement of every structure is compared. Larger discrepancies are found when individual points and differential settlements are studied.

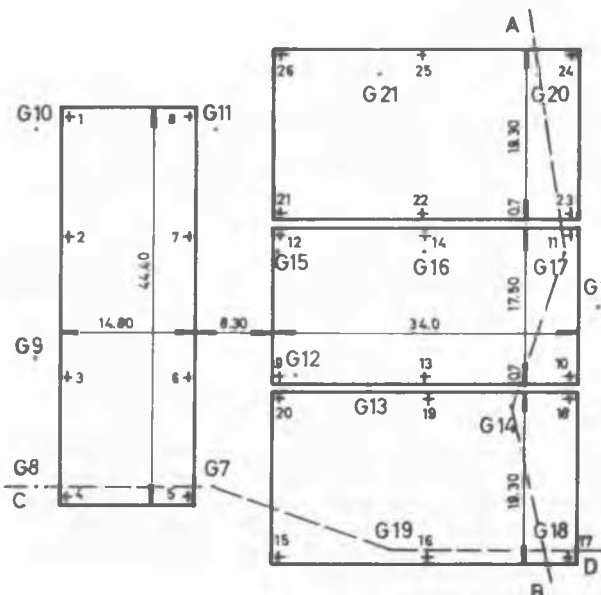


Fig. 1. Foundation slabs of four silos
G10 . exploration bore hole
10 + settlement monument No. 10

SOIL COMPOSITION

Twenty one exploration bore holes between 21 and 48 m deep were drilled for the investigation of the foundation soil, with a total length of 722 m of drilling. In cohesionless strata the Standard Penetration Test was carried out. The undrained shear strength of cohesive strata was measured with a field vane, and undisturbed samples were extracted with a split tube sampler of 89 mm I.D. for laboratory testing. The location of the bore holes is indicated on Fig. 1. Two characteristic soil profiles are shown on Fig. 2. The soil of the site is an alluvial deposit sedimented in the basin of the Sava River. It consists of irregularly bedded sand, gravel and clay beds. Two clay layers of 10 - 12 m and of 4 - 6 m thickness are generally found. The ground water level is 2 - 4 m below ground

medium and stiff with some spots with soft consistency.

LABORATORY TEST RESULTS

Atterberg limits of the clay samples have shown that inorganic clay of medium and high plasticity prevail (CI and CH) but some samples of clay of low plasticity (CL) occur, mostly as transition from sandy strata to clay. Compressibility of undisturbed soil samples was tested in oedometers of 70 mm diameter and 20 mm high. The usual procedure with load increments doubling the previous load at one day intervals was followed. Some characteristic oedometer diagrams are shown on Fig. 3. It was found that all samples belong to normally consolidated clay. From the oedometer

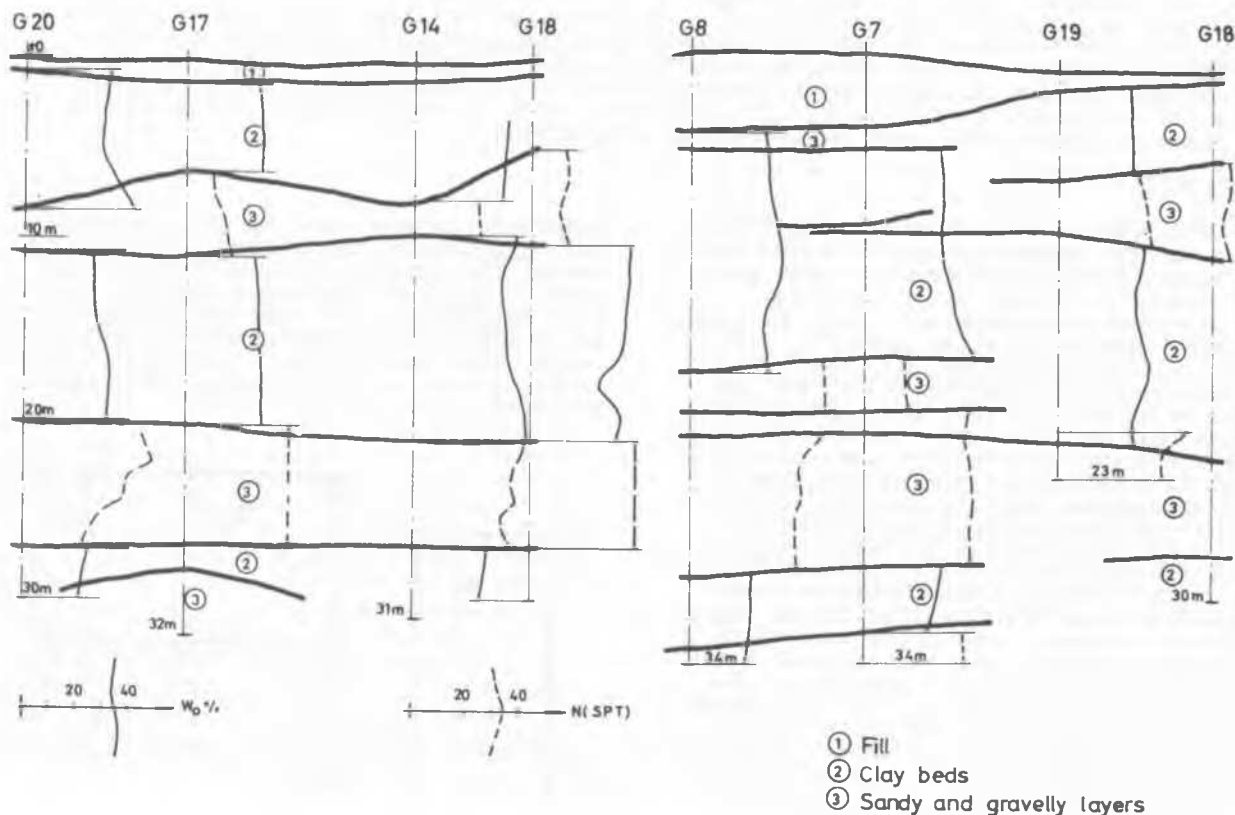
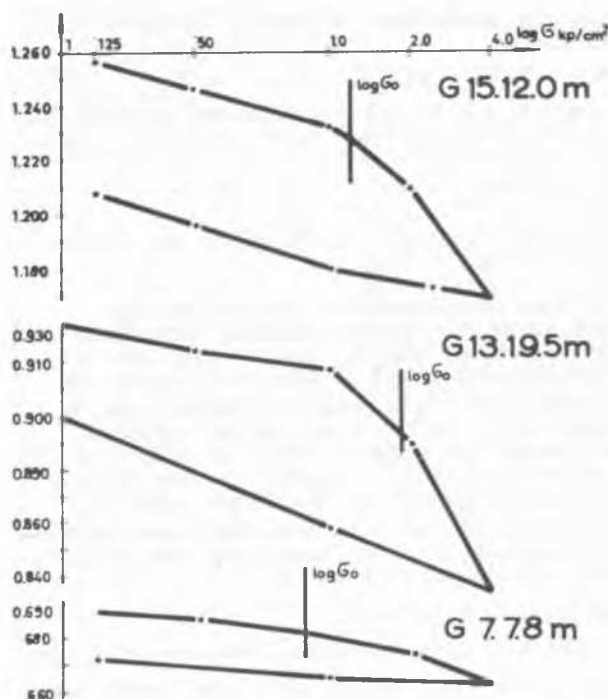


Fig. 2. Soil profiles A-B and C-D

surface. In the soil profiles the natural moisture content of the clay beds w_0 % is shown as well as the number of blows N in the Standard Penetration Test performed in gravel and sand layers. The penetration resistance N increases with depth, the natural moisture content varies with depth irregularly, and decreases substantially in the clay bed deeper than 25 m. The consistency of the clay strata varied between

tests the compressibility index C_c was computed for load increase above overburden pressure. On some samples the permeability coefficient was measured and the consolidation index (c_v) was established. Young's modulus was determined from numerous unconfined compression tests and from two undrained triaxial tests on undisturbed samples. Table I shows the result of the executed laboratory tests on undisturbed samples.

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In undrained triaxial compression tests with pore pressure measurement the pore pressure parameters A and B shown in Table II were obtained for the range of stresses to which the sample would be subjected under the silo load.

TABLE II. Pore pressure parameters.

Sample	Pore pressure parameters	
	A	B
G 7-14,5	0,43	1,0
G 10- 7,1	0,54	1,0

The erratic composition of the alluvial sediments shown by the exploration boring was confirmed by the laboratory tests on the clay samples. In order to be able to compute the settlement as accurately as possible it would have been necessary to test a great number of undisturbed samples in oedometers. It is practically impossible to test so many samples to have a complete profile of soil properties at any point where the settlement should be calculated. It was therefore necessary to rely on some correlation between known soil parameters in order to obtain such data from the available test results. Since classification has shown that the clay strata belong

Fig. 3. Typical oedometer diagrams

TABLE I Summary of laboratory test results

Sample hole	depth m	w _o %	w _L %	IP %	Symbol	e _o	E kg/cm ²	C _c	10 ⁸ k cm/s	10 ³ c _v cm ² /s
G1	15,5	32,0			CI ⁽³⁾	0,894	140 ⁽¹⁾		5,0	2,3
G2	13,0	28,4	56,4	23,5	CH	0,880				
G6	14,0	40,1			CL	0,920			0,4	0,12
	18,0	28,1			CL	0,711			14,0	5,62
G7	7,8	28,3					46 ⁽¹⁾	0,0275		
	11,8	28,5			CI	0,788	118 ⁽¹⁾	0,0234		
	14,5	29,8	46,0	22,1	CI	0,793	144 ⁽²⁾			
G10	7,1	31,0	40,4	16,8	CI	0,833	430 ⁽¹⁾			
G13	3,6	30,0	59,4	36,1	CH	0,810		0,0698		
	13,2	28,9	50,8	32,4	CI/CH	0,762		0,1270		
	19,5	22,7	73,0	45,4	CH	0,890		0,1840		
G14	6,8	33,1			CI ⁽³⁾	0,853		0,0597		
	18,3	32,1	61,0	39,5	CH	0,874		0,0840		
G15	12,0	41,0	79,4	53,5	CH	1,230		0,1041		
G16	4,6	29,7	60,6	41,1	CH	0,830		0,0425		
	9,8	24,8	38,8	19,6	CI	0,680		0,0208		
	14,8	25,7	42,6	24,9	CI	0,703		0,1213		
G17	6,3	28,8			CL ⁽³⁾	0,761		0,0339		
	15,7	38,3	66,0	42,8	CH	0,992		0,1715		

Notes: (1) from unconfined compression test,
(2) from triaxial undrained test,
(3) from visual field classification.

predominantly to clay of medium and high plasticity (CI and CH) it was tried to correlate the compressibility index C_c to the natural moisture content. This correlation is shown on Fig. 4. and a large scatter of the results is apparent. Nevertheless the results were grouped around two curves, the lower for samples up to the depth of 10 m the upper for samples from the depth of more than 10 m. From such correlation compression indices for settlement calculation were obtained.

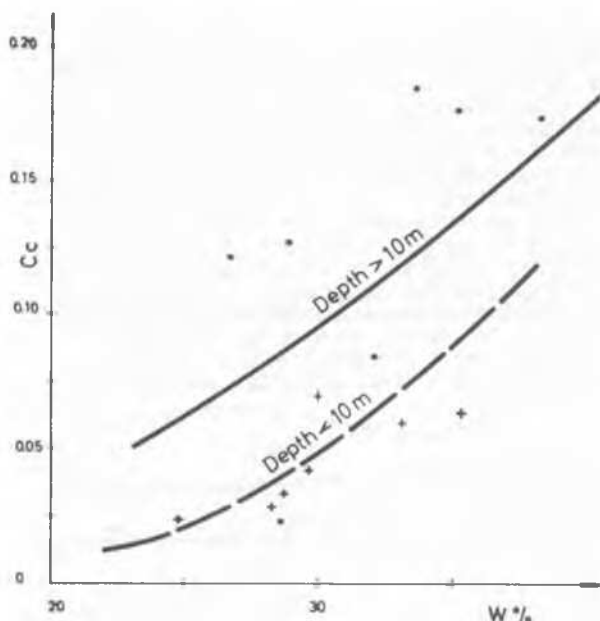


Fig. 4. Correlation between natural moisture content w_0 % and compression index C_c
 + samples 0/10 m depth
 . samples more than 10 m depth

SETTLEMENT CALCULATION

The settlement of the silos was calculated for all characteristic points of the foundation slabs indicated on Fig. 1, i.e. 16 points all together. The vertical stress distribution for these points and the settlement were calculated on an electronic computer with loads on various surface areas and with soil properties in different strata as input data.

The settlement calculation of total final settlement was made as proposed by SKEMPTON and BJERRUM (1957). Immediate settlements of the sandy and gravelly strata were calculated with compression indices derived from the standard penetration test values (N) as suggested by NONVEILLER (1963) from correlations proposed by BOGDANOVIC (1959). The immediate settlement of the clay beds was computed with Young's moduli E obtained in the undrained triaxial and unconfined compression tests.

Consolidation settlement was calculated from the oedometer settlement reduced by the factor

$$A = A + (1 - A) \dots \dots \dots (1)$$

From Table 2 in the publication by SKEMPTON and BJERRUM, and with $z/B = 30 : 60 = 0,5$, $\alpha = 0,5$ and $A = 0,5$

$$R_c = 0,75 \rho_{oed} \dots \dots \dots (2)$$

The results of the calculation are summarised in Table III.

The time development of consolidation settlement was computed using Terzaghi's consolidation theory. The coefficient of consolidation (c_v) of the tested samples scatter in a wide range of values, which means great differences in the computed settlement at a given time. In order to reduce the possible error the coefficient of consolidation for the silos A and B₂ was computed from the observed time settlement curves for dead load, and the following values were obtained:

$$\text{Silo A } c_v = 0,5 \cdot 10^{-3} \text{ cm/sec}$$

$$\text{Silo B } c_v = 0,8 \cdot 10^{-3} \text{ cm/sec}$$

It is seen that they are in the lower range of laboratory tests.

With these values the average degree of consolidation (U) was computed for every point, and from this the consolidation settlement in December 1968 as

$$\rho_{c,t} = U \rho_c \dots \dots \dots (3)$$

The average degree of consolidation was calculated with the gradual load application as proposed by Terzaghi. Every clay bed was considered separately and the settlements were added. The resulting consolidation settlement until December 1968, when the last settlement observation was made are shown in column (6) of Table III.

The calculated time settlement curve of point E, the observed time settlement curve of the corresponding monument 9 and of some other monuments are shown on Fig. 5 together with the rate of loading.

ANALYSIS OF RESULTS

The calculated average total settlement of all points is 17,4 cm against 14,9 cm from measurement, which is 14,3 % in excess of observation. The total settlement calculated in the usual way from the oedometer tests would be 20,2 cm i.e. 26 % in excess of observed settlement. The application of the procedure proposed by SKEMPTON and BJERRUM gives a more reliable settlement estimate. Considering all assumptions which had to be made in such a calculation on one hand and the small volume of tested soil samples compared to the total stressed volume on the other, the agreement between predicted and measured settlements obtained

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TABLE III. Comparison of calculated and observed settlements

Silo & char- acter- istic point	Corr- espon- ding monu- ment	Total load to/m ² P_1	Settlement in cm				Obs- erved P_m	Mean settlement of silo, cm		Difference							
			P_c	U_{P_c}	U_{P_c}	$P_1 + U_{P_c}$		calcu- lated	obser- ved	cm	%						
1	2	3	4	5	6	7	8	9	10	11	12						
A A B B C C D D	4 5 1 8	17,9	4,8 7,3 6,2 8,3	8,3 9,0 11,5 15,5	4,5 4,9 6,2 8,5	9,3 12,2 12,4 16,8	11,6 11,9 10,7 12,4	12,6	11,4	1,2	9,5						
	B ₂ E F F G G H H	9 12 10 11	15,4	8,5 6,8 8,3 11,6	15,9 17,5 15,6 11,7	9,1 10,1 14,9 6,7	17,6 16,9 23,2 18,3					17,2 16,5 18,5 19,0					
		B ₁ I J J K K L L	15 17 20 18	22,0	10,0 10,8 10,4 9,3	12,1 12,3 18,8 28,2	7,0 7,1 10,3 15,2					17,0 17,9 20,7 24,5	13,2 20,1 12,4 18,7	20,0	16,1	3,9	19,5
			B ₃ M N N O O P P	21 23 26 24	21,3	10,3 11,4 7,9 10,8	20,1 13,6 10,9 12,7					11,2 7,8 6,2 7,3	21,5 19,2 14,1 18,1				

ined in this case can be regarded as very satisfactory. In the calculation of immediate settlement of silo B₂ and B₃ the settlement which occurred during construction of the silos A and B₂ was not subtracted. This amounts to about 2,5 cm on the points K, L, M and N (it is negligible on the other points). Considering this the agreement would be better on these two silos also.

Another detail which deserves attention is the fact that the differences between calculated and observed settlements are much greater when single points are considered (calculated settlement up to 40 % in excess of observed). It is also remarkable that the points of the silos B₁ and B₃ adjacent to silo B₂ settled essentially not more than the other points, thus the expected larger settlement of points adjacent to the middle load was not observed. This fact can be explained by the previously mentioned effect of load redistribution due to different soil properties, which increases the settlement of stiffer and reduces that of more compressible areas.

The calculated time settlement curve of point (E) shows a general agreement with the observed development of settlement (Fig. 5). It is remarkable that the calculated settlement for dead load is much greater than the observed one while calcu-

lated and measured total settlement are in good agreement. A very similar picture was obtained for the other points. Two factors could contribute to this discrepancy:

- The rate of loading is very high for every load increment in the oedometer test. The loading rate of the silos was of the order of 5-10 g/cm²/day, i.e. the loading rate in the oedometer is 10-20 million times greater than this. This could contribute to destroy some diagenetic bonds between clay particles in the oedometer test at much lower load levels than under the silos, thus increasing the compressibility at lower load.
- The settlement of the normally consolidated clay beds was computed with the compression index C_c of the virgin load branch of the oedometer curve. BJERRUM (1967) has shown that this can lead to a great overestimate of settlement on some normally consolidated clays. The settlement should be computed with the swelling index C_s for load increments smaller than the plastic resistance due to achieved secondary consolidation of the clay beds. Since these details were not studied at the time when the laboratory tests for the settlement computation were made their influence could not be evaluated.

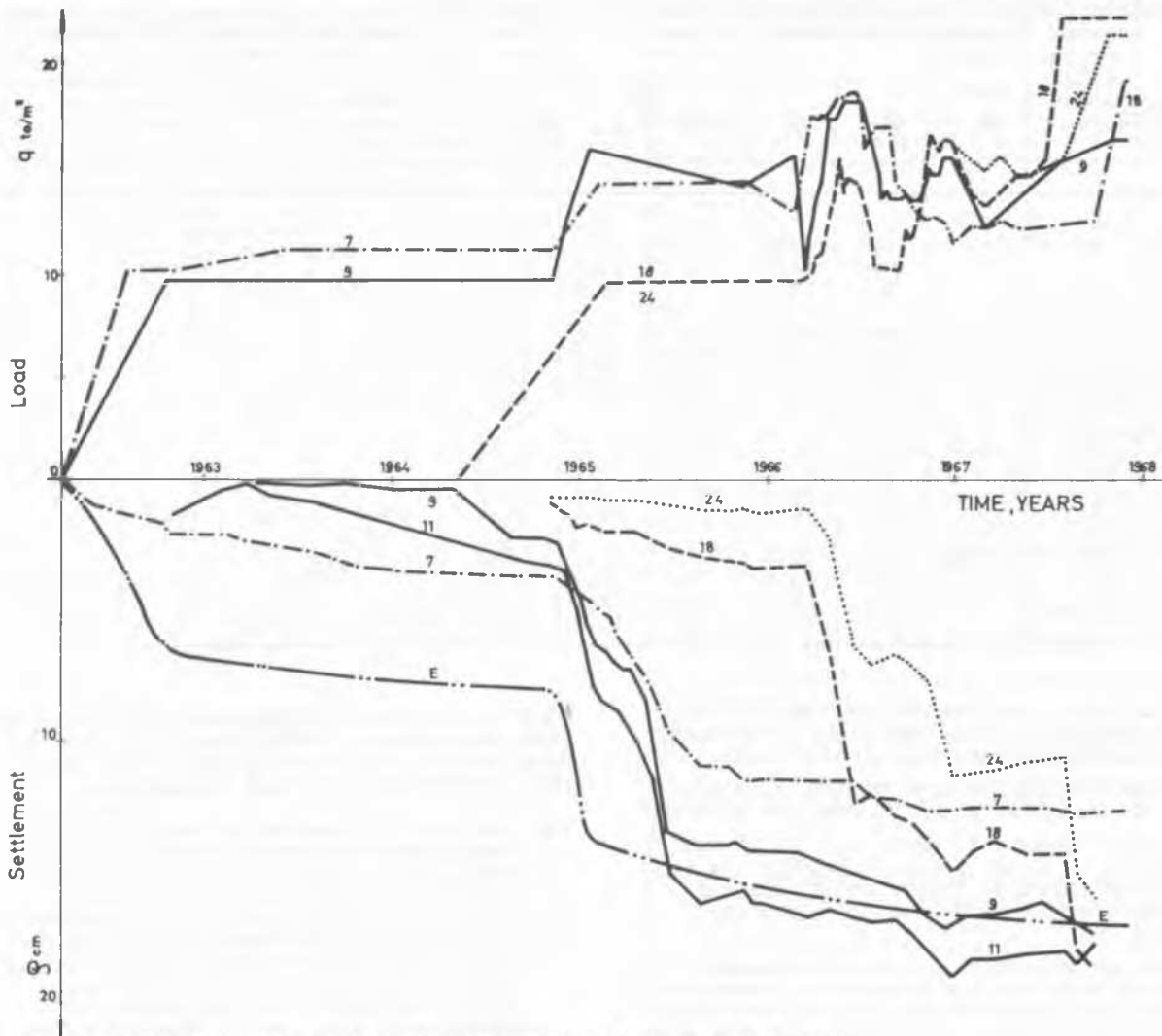


Fig. 5. Loading diagram, observed and computed time settlement

CONCLUSIONS

1. The calculated average total settlement for each of the four silos is between 6 to 21 % in excess of the average observed settlement although the compressibility indices were deduced from a widely scattering correlation with the natural moisture content of the clay beds.
2. The difference between calculated and observed total settlement of single settlement monuments is much greater, and computation of differential settlements between adjacent structures is less reliable than computation of average settlement.
3. The fact that the settlement under dead load is much less than the computed whereas the settlement for full load

agrees with the observation can be explained only partly, and more investigation into this point is necessary. It is possible that oedometer tests with much smaller loading increments would reproduce better the compressibility of normally consolidated clay.

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