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Settlement Investigations on Grain Silos Founded in Various Soil Conditions in Rumania

Etude sur les tassements de silos de grains construits dans différentes conditions de sol en Roumanie

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SUMMARY

To create additional grain storage in a short space of time, 32 new silos, each having a capacity of 4,300 tons, were constructed near old silos in Rumania during 1962. Most of the new silos were founded on rigid, caissoned rafts. These structures behaved very well, even where large total and differential settlements of the new silos occurred. These settlements were considerably less than those calculated on the basis of compressibility characteristics determined by oedometer tests. Differences were mainly attributed to sample disturbance during sampling, transportation, and test preparation. More accurate results were obtained by adopting the deformation moduli E established by taking account of the physical characteristics of the soil (void ratio and plastic limit). Since differences in results obtained with various computation methods are insignificant, the use of simple methods seems to be preferable.

SOMMAIRE

Pour la réalisation dans un court delai de nouveaux depôts pour les grains, on a construit en Roumanie pendant l'année 1962, 32 nouveaux silos, ayant chacun une capacité de 4300 tonnes et situés à proximité des anciens silos. Presque tous les nouveaux silos s'appuient sur un radier rigide, caissonné. Les constructions de ce type se sont comportées très bien, même dans le cas de tassements totaux et differentiels élevés. Les tassements mesurés des nouveaux silos sont sensiblement plus faibles que ceux calculés sur la base des caractéristiques de compressibilité établies en œdomètre. La non-concordance est attribuée surtout au remaniement des échantillons de sol pendant le prélevement, le transport et la préparation pour l'essai. Des résultats plus exacts ont été obtenus en adoptant des modules de déformation E établis en fonction des caractéristiques physiques du sol (l'indice des vides et la limite de plasticité). Les différences entre les résultats obtenus dans ce cas par diverses méthodes de calcul étant insignifiantes, l'utilisation de méthodes plus simples parait indiquée.

CONSIDERABLE FOUNDATION PROBLEMS always arise in the construction of grain silos. Their effective load, derived from grain load, leads in the case of a rational cell development upon the vertical to a high loading at the foundation level. At present silo foundation problems are very acute in Rumania, as a consequence of an important programme for increasing grain storage initiated in 1961. In the first stage of this programme, finished in 1962 and reported herein, new storage space was obtained by the extension of 32 existing silos erected between 1938 and 1946. Beside the existing silos, new storage facilities were built, each with a capacity of 4,300 tons, connected with the existing silos by a tunnel in the lower part and a gallery in the upper part, with a view to utilizing the same lifting installations.

DESCRIPTION OF STRUCTURES

In order to shorten the design period as much as possible only two silo standard projects were elaborated, in spite of the variation in the physico-mechanical properties of the foundation soil for the 32 sites. These two projects had the following foundation systems: (a) ring-shaped foundations, where a pressure of 4.0 to 8.0 kg/sq.cm. over the foundation soil was permissible; that is, for those sites where the natural soil allows such a pressure, and where total as well as differential settlements are negligible (Fig. 1); (b) rigid raft foundations where a pressure of only 1.5 to 2.0 kg/sq.cm. was permissible (Fig. 2).

NATURE OF SOILS

The 32 investigated structures are situated in south and southeast Rumania. Investigations carried out from 1939 to 1946 as well as new research done in 1961 revealed the following types of soil at these sites: (a) sandy soils—9 sites; (b) clayey soils—12 sites; (c) loess—8 sites; (d) very hard clayey soils—2 sites; (e) rock—1 site. For the sites in the first three soil categories the foundation solution of cais-
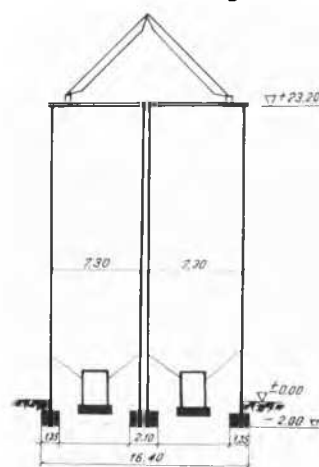

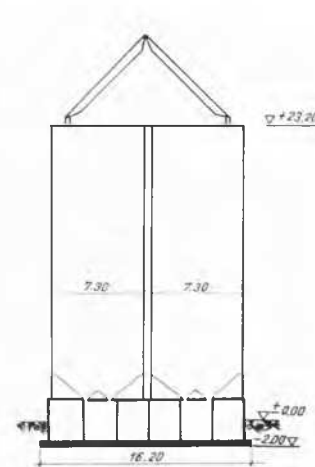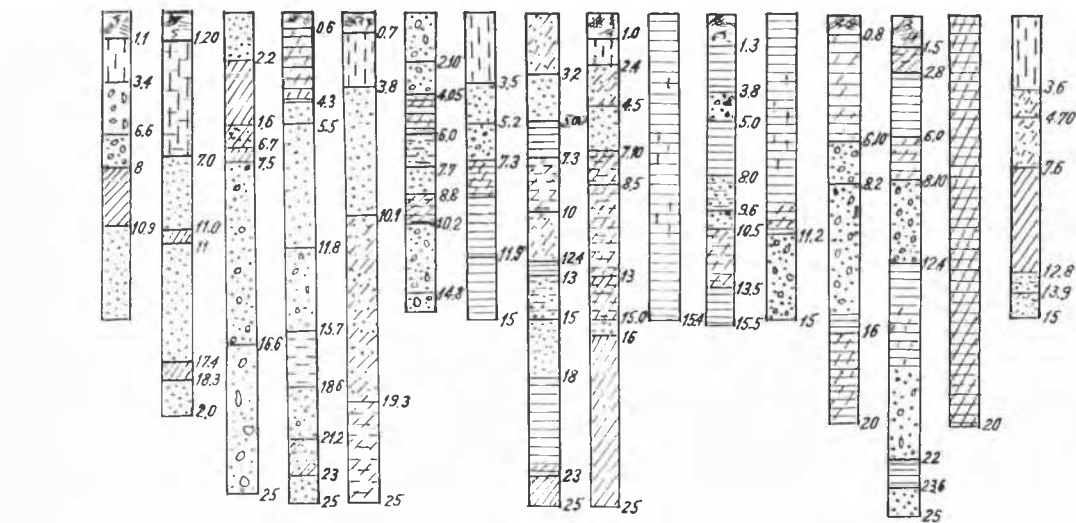FIG. 1. Section through silo, ring foundation.

FIG. 2. Sections through silo, caissoned raft foundation.

SETTLEMENTS IN CM

SILO No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
a	4.80	4.0	1.7	6.2	5.0	3.0	6.4	6.3	6.2	5.0	2.5	2.5	2.65	8.0	4.0	10.6
b	10.0	11.7	—	—	—	6.11	9.8	5.75	—	10.78	13.5	7.3	6.4	12.7	14.4	16.3
c	8.5	10.3	—	—	—	5.7	9.8	6.5	—	9.5	10.9	7.0	6.2	9.9	12.2	16.2
d	7.6	6.5	6.15	7.35	9.0	4.5	8.4	6.7	8.6	8.0	6.3	5.14	4.5	2.0	7.10	12.2
e	6.6	6.50	6.10	7.5	8.4	3.9	8.15	5.6	10.2	7.5	6.10	4.8	4.2	6.10	7.0	11.8
f	5.0	6.0	5.5	6.5	7.25	3.5	6.6	6.0	7.10	7.10	5.15	4.0	4.75	5.5	7.0	9.7
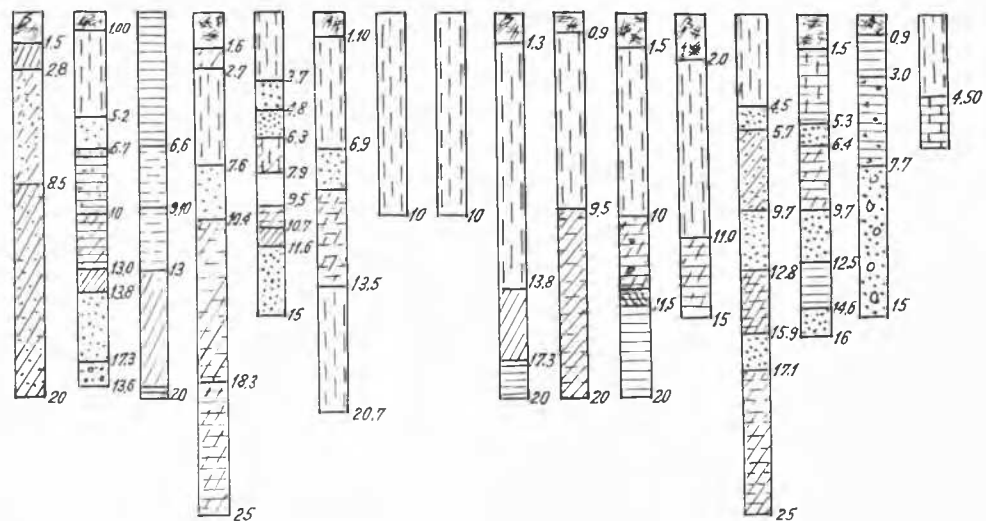
SETTLEMENTS IN CM

SILO No	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
a	7.80	4.10	14.5	16.7	6.0	2.80	6.0	6.70	25	22	80.9	43	28	4.5	1.5	0.5
b	14.8	18.5	76.0	23.0	16.00	16.30	22.00	3.50								
c	16.7	15.10	25.5	21.0	16.2	14.9	17.7	18.0								
d	10.7	7.5	14.6	16.5	9.0	8.3	8.5	11.6								
e	9.0	7.4	16.50	16.0	8.4	8.0	8.4	12.4								
f	10.8	7.2	14.40	14.4	7.75	7.0	7.8									

SYMBOLS

Sand   Silt   Silty clay

Clay   Loess   Gravel

Sandy silt   Clayey sand   Chalk

FIG. 3. Soil profiles for the 32 studied sites, as well as the following settlement values: (1) measured (line "a"); (2) computed on the basis of oedometric modulus E, either by summing deformations of elementary layers (line "b") or with Yegorov's formula (Eq 1) (line "c"); (3) computed on the basis of deformation moduli E established function of e and w_p, with Eq 3 (line "d"), Eq 1 (line "e"), or Eq 4 (line "f").

soned raft with a 1.5–2 kg/sq.cm. pressure on the soil was used, and for the other sites the ring-shaped foundation solution was used.

INVESTIGATIONS OF SILO SETTLEMENTS

Twenty-nine of the 32 silos were founded on compressible soils; therefore their behaviour in operation and their settlement were of considerable interest. To this end settlement marks were fitted on all the new silos and control marks were fitted on the existing silos, at a distance of 4 to 6 m, from the extended works, in order to outline the new structure loading influence over the former structure settlements. The settlement measurements began after the foundation and the walls had been erected to a height of 2 m. This height corresponds to a pressure of 0.3 kg/sq.cm., approximately equal to the load of the soil excavated for the foundation.

The silo was filled carefully in order to retain symmetry of loading. The depth of filling trenches for each cell was ⅙ of the available height. After filling all the cells to half of the available height (i.e., at a silo loading of about 2,000 tons), the levels of the control mark were measured; the constant loading was afterwards maintained during a 30-day period. In this way the soil's deformation from before loading to capacity was measured.

In the cases where, after the first loading, a silo showed a tendency to tilt—as a consequence of the non-homogeneity of the foundation soil, or of local moistening in the case of loess soils—further loading was conducted asymmetrically, so as to reduce the tilting of the structure as much as possible. After loading to capacity, successive sets of control-mark levels were noted over several months. After this, as a function of the load-settlement curve shape, the normal operation of the structure was authorized. These observations have continued, two readings being made annually. Fig. 3, line "a", shows the stratification and settlement values of the 32 structures, as measured in April, 1964, about 16 months after the start of the operation. The largest settlements were registered for the silos which were founded on loess. At five of the eight loess-founded silos (Nos. 25, 26, 27, 28, and 29), the settlements were appreciably larger than those estimated on the basis of the soil compressibility in natural state. These settlements, to a great extent, are a consequence of the fact that the loess was considerably wetted during the foundation construction period.

Infiltration under the foundation also occurred, caused by the sidewalk inclination towards the silo, after the first settlement. The wetting of the loess has caused an additional settlement phenomenon, characteristic for this soil type. Taking into account the particular foundation rigidity, no measurements were taken for diminishing loess sensitivity to wetting (surface or deep tamping, thermal or chemical treatment, etc.), considering that, even if differential or large settlements do occur, the superstructure will be in no way damaged. The truth is that neither the maximum registered inclination (4.7 per cent), nor the maximum settlement (43 cm), has had any effect on the structure. Only a periodic back levelling of the conveyors common to both the new and the old silos was required, to maintain an undisturbed operation. Ring-founded silos (Nos. 30, 31, 32) have shown negligible settlements.

In view of these facts, a discussion of the magnitudes of the actual and the computed settlements, is of interest only in the case of the other 24 silos.

COMPARISON BETWEEN REAL AND COMPUTED SETTLEMENTS

The calculation of the probable settlements was carried out in conjunction with structure design, taking into account the estimated settlement value and establishing the initial level of the conveyors in the new construction. The calculation was done by summing deformations of elementary layers, standardized in Rumania, for the "characteristic point" defined in concordance with DIN 1054. The results are given in Fig. 3, line "b", for 20 silos where soil compressibility tests were done by an oedometer.

Smaller values are systematically found for real settlements compared with the computed ones. In one case, silo no. 8, the ratio of the real to computed settlement was 1:1; this discrepancy is due to the non-consideration of the compressibility of the sandy soils found at the site which certainly also contribute to the settlement. In all the other cases the ratio was below 0.6, and in 8 of the cases was even below 0.4.

To determine to what extent the other settlement values are influenced by the method used, a computation was carried out in accordance with the elasticity theory for a non-homogeneous medium (Yegorov, 1949). In this method the settlement is computed taking into account all three normal stresses. In the case of a multi-layered soil, the settlement computation for a rectangular loading surface is made with the help of the formula

$$s = 2ap \sum_{i=1}^{k} \frac{K_i - K_{i+1}}{E_i} M \qquad (1)$$

where $2a$ is the foundation width; p is the net foundation pressure; E_i is the deformation modulus of the ith layer; K is the number of layers within the compressible zone; K_i is a non-dimensional distribution coefficient—e which is given in dependence of $n = 2b/2a$ and $m = Z/a$; $2b$ and $2a$ represent the foundation length and width, and Z the considered depth; M is the over-unity correction coefficient with respect to stress concentration due to the presence of a rigid layer at the active zone limit and is given depending on the H/a ratio, H being the comparable zone thickness. Similar E values, as in the preceding computation (Eq 1), were used, determined on the basis of the compression curves obtained within the oedometer. The results are inserted in Fig. 3, line "c". It is established that the settlements thus obtained—even if they are a little smaller—do not approach the real settlement values. These results justify the conclusion that the non-agreement between the measured and the computed settlements is related to soil deformation characteristics which are introduced in the computation, and not to the method itself.

As the laboratory tests were carried out upon samples whose structure is considerably disturbed during the sampling process, transportation and placement in the oedometer, the deformation moduli obtained through these tests are sensibly modified in comparison with the real values. The difference is greater in the case of silty soils and soils of high strength.

The problem is to establish E values which are more in agreement with reality. One procedure is to start from the measured settlement values and then introduce them into Schleicher's well-known formula concerning the settlement of a loading plate situated in an infinite, continuous half-space:

$$s = \alpha[p \sqrt{F}(1 - \mu^2)/E]. \qquad (2)$$

The E values, obtained by this formula on the basis of measured silo settlements, are still too large for the natural and physical state of the respective soils, because the foundation soil model, as an infinite half-space which can be adopted in the case of some usual plate loadings or of certain

block foundations, becomes inadequate in the case of extended loading surfaces.

Finally, numerous tests were carried out to correlate the mechanical characteristics of the soils with the physical ones gained through experimental data. A similar correlation example is given in the table included in the Soviet norms (Snip, 1962). From this table, for all the clay layers in the silo sites studied, the values of deformation moduli E drawn, as a function of void ratio, e, and of plastic limit, w_P.

With the values of E thus obtained, the settlements were computed by several methods.

1. The summation of deformation of elementary layers, with the formula

$$s = \sum_{i=1}^{n} \frac{\rho_{zi} h_i}{E_i} \beta, \qquad (3)$$

where n is the number of layers included within the active zone; ρ_{zi} is the half-sum of the normal vertical efforts appearing at the upper and lower face of the ith layer, as a consequence of the pressure transmitted to the soil; h_i is the thickness, E_i is the deformation modulus for the ith layer; and β a coefficient equal to 0.8 which tends to the correction of the simplified scheme admitted in the computation considering only the normal vertical stress and the lateral deformation completely free (Snip, 1962).

2. With Yegorov's formula (Eq 1).

3. With the approximate method recommended by Brinch Hansen (Brinch Hansen and Dundgren, 1960), on the basis of the conventional hypothesis of stress distribution into the soil through planes 30° inclined towards the vertical. The settlement computation formula according to this method is

$$s = 2.30 P/E(L - B) \log (B + H)L/(L + H)B, \qquad (4)$$

where P is the total foundation load, and B the rectangular foundation sizes, and H the compressible layer thickness.

The values obtained by means of these three methods are given in Fig. 3, lines "d", "e", "f".

From the data obtained the application of the three methods has led to settlement values of a similar magnitude and values relatively close to the measured values. It must be stated that, although in some cases real settlements half as large as the calculated ones have been obtained (ratio 0.4 to 0.5 cm), this difference occurred especially at sites with less compressible soils, where the actual settlements had small values and therefore the differences between the actual and computed settlements are of the same order of magnitude. In similar situations the deviation is of no practical importance. That closer agreement between real and calculated settlements was obtained for sandy soils is also a result of the fact that settlements in the clayey soils are not yet complete.

CONCLUSIONS

1. It was pointed out from the experience accumulated during the construction of 32 silos, that foundations in the shape of caissoned rigid raft are recommended for soils sensitive to large and/or differential settlements. The rigid raft considerably diminishes the risk of superstructure degradations, as a consequence of soil deformations.

2. A comparative analysis of measured and computed settlements demonstrated that the principal reason for the lack of agreement between the two values is the disturbance of the soil samples during their sampling, transport, and preparation in the laboratory. Thus the oedometer results are not completely representative of the soil studied.

By using some compressibility characteristics obtained in an indirect way, and depending on other physical characteristics of soils for computed settlements, very close agreement with the real values is obtained. This fact is not surprising as for the correlation tables between the deformation modulus E, the void ratio e, and the plasticity limit w_P are statistics abstracted from a great number of tests carried out to determine the compressibility characteristics by plate loading in the field, and not by oedometer tests.

3. As long as a doubt still exists regarding the compressibility characteristics, the use of certain more accurate methods, which require more complex calculations is not justified, since similar results were obtained from the method derived from the elasticity theory and from an approximate method based on the assumption that stress distribution in the soil occurs in planes inclined 30° towards the vertical.

4. For the improvement of silo design, it is necessary that, on the one hand, as extensive information as possible should be obtained (with the help of depth marks) on the active zone extending below the foundation and that, on the other hand, direct pressure measurements on the foundation level should be carried out with the help of pressure cells. A measurement schedule in this direction is in the course of development in the new stage of the silo construction campaign, which started in 1963, in which the construction of silos of 15,000 to 30,000 tons capacity are contemplated.

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