Anticipated and Observed Settlement of a High Chimney

Tassement anticipé et observé d'une haute cheminée

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SUMMARY

The settlement of a 180-m-high chimney, measured and computed after Boussinesq, Westergaard, and Egorov, is considered. The presence of relatively compact silty and silty-sandy Pliocene clays is typical of the subgrade under the foundation. The anticipated and observed values are well within the range of the data published to date and show a fair degree of coincidence. The actual settlement is considerably lower than the permissible maximum values.

SOMMAIRE

On étudie le tassement mesuré et évalué, d'après Boussinesq, Westergaard et Egorov, d'une cheminée haute de 180 m. Le terrain d'assise est caractérisé par la présence d'argiles Pliocènes silteuses et silteuses-sableuses, relativement denses. Les valeurs anticipées et observées cadrent bien dans les limites des données publiées jusqu'à présent, et spécialement celles qui accusent une coincidence entre elles. Le tassement effectif est sensiblement moindre que les valeurs admissibles maximales.

OBJECT AND SITE CONDITIONS

IN THE COURSE of the planned development and uninterrupted growth of the industrial potential, a number of big plants have been built recently in Bulgaria. A 180-m-high factory chimney, whose anticipated and observed settlement is the object of this paper, was constructed at one of these plants.

The soil conditions on the site are given in Fig. 1. The chimney was erected on Pliocene lacustrine deposits, which form a vast kettle depression. The 300 to 400-m-thick sediments rest on a base of crystalline schists. The Pliocene material is divided into three typical horizons. A silty plastic clay complex with sand lenses (below −100 m) is found at the bottom. Isolated, possibly syngenetic, water under overburden pressure, was established in the lenses. The second horizon (between −70 and −100 m) consists of several lignite layers alternating with black schistous clay. The third and highest horizon (between −9 and −70 m) is composed of mixed sandy and sandy-silty clay, with individual wedging-out sand bands, reaching several metres in thickness. The upper layers of this horizon upon which the chimney is situated and with which the investigation was mainly concerned, together with the overlying Quaternary sediments, were studied in detail by drilling and laboratory tests. Data on the physical-mechanical properties of the soils which form the subgrade are shown in Table I.

TABLE I. PROPERTIES OF SUBGRADE SOILS

Layer	Sample	γ (ton/ cu. m.)	w (per cent)	e	w_L (per cent)	I_P (per cent)	S_r	E* (ton/ sq. m.)
5	a	1.90	33.5	0.93	64.0	33.0	0.99	140
6	b	1.93	28.0	0.82	60.5	33.5	0.95	260
7	c	1.74	44.0	1.27	77.0	39.5	0.94	200
8	d	1.81	37.5	1.08	63.0	29.0	0.95	280

*The laboratory values of E are raised in accordance with the experience from simultaneously conducted *in-situ* loading tests with a 5000 sq. cm pressure area.

The geological profile, given in Fig. 1, is as follows: layer 1: diluvial sandy-silty clay, 2.0 to 2.4 m thick; layer 2: alluvial fine- to coarse-grained argillaceous sand, 2.0 to 2.2 m thick; layer 3: alluvial medium-grained gravelly sand, 1.1 to 2.0 m thick, with a thinning-out band of alluvial silty clay (layer 4), up to 1.0 m thick, lying between them on the western side; layer 4: alluvial silty clay, 1.0 to 1.4 m thick; layer 5: almost horizontal Pliocene silty-sandy clay, 6.05 m thick; layer 6: Pliocene silty clay with calcareous inclusions, 4.7 to 5.2 m thick; layer 7: Pliocene silty clay, 3.1 to 4.1 m thick; layer 8: compact Pliocene sandy clay of considerable thickness.

Groundwater was established only in the lower gravelly sand layer of the alluvial sediments at −7.1 m. Water penetration in the lower Pliocene materials is rendered difficult owing to their low filtration properties (coefficient of permeability approximately 10^{-9} cm/sec). On that account, the Pliocene soils are not under water, but just moistened.

In compliance with structural requirements and geological conditions it was decided to lay the foundation of the chimney at −7.85 m on an artificial sand cushion, 1.20 m thick, consisting of carefully vibrated medium- to coarse-grained pure quartz river sand (Fig. 1, layer 9). The object of the sand cushion is to accelerate the time of consolidation of the Pliocene silty sandy clay and to distribute uniformly the load of the foundation over a wider surface.

COMPUTED SETTLEMENT

The anticipated settlement of the chimney was computed on the basis of the geological profile, laboratory tests, and structural details.

The overburden pressure p_γ was determined and plotted left of the centre line in Fig. 1. The loading, p_0, which causes the settlement is obtained by substracting the weight of the trench excavation from the weight of the building which includes the fill and the sand cushion.

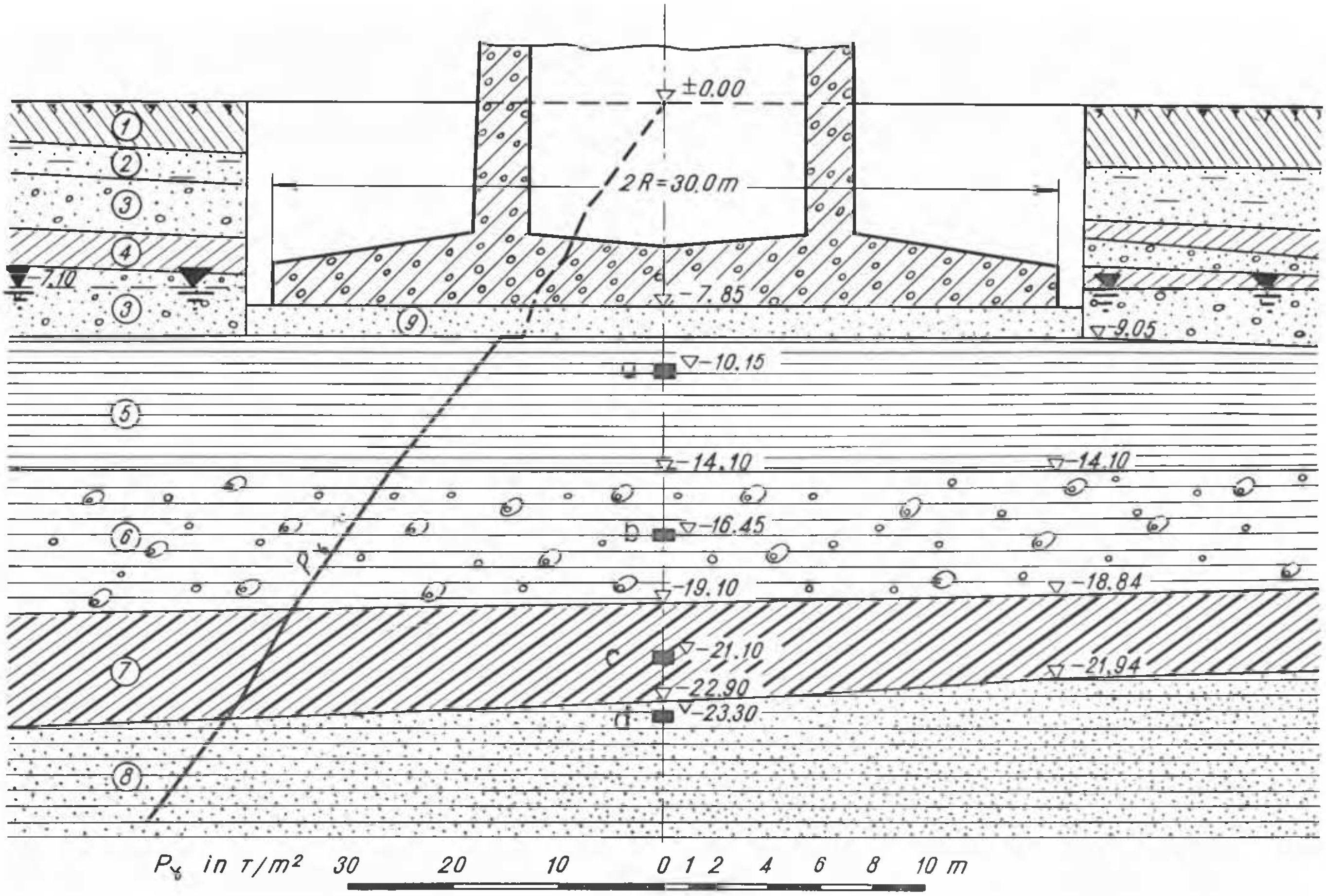

FIG. 1. Geologic-lithologic cross-section of the subgrade under the chimney: 1, sandy-silty clay; 2, argillaceous sand; 3, gravelly sand; 4, silty clay; 5, silty-sandy clay; 6, silty clay with calcareous inclusions; 7, silty clay; 8, sandy clay; 9, sand cushion; a, b, c, d, undisturbed samples; p_γ overburden pressure.

The distribution of the stresses σ_z in depth along the centre line of the circular foundation ($2R = 30$ m), uniformly loaded with $p_0 = 9.3$ tons/sq.m., was determined (Fadum, 1948; Egorov, 1961). The pressure distribution diagrams obtained are given in Fig. 2. The significant depths h_B and h_W, according to Boussinesq and Westergaard respectively, are assumed according to *Norms and Technical Instructions for Designing the Subgrade* (1955) at such a vertical distance from the foundation, where the condition $\sigma_z = 0.2p_\gamma$ is satisfied within ± 0.5 tons/sq.m.

The settlement is calculated by the formula

$$S = \sum_1^n \frac{F_i}{E_i},$$

where F_i is the area cut from the respective pressure diagram by the layer with No. i, whose modulus of linear deformation is E_i (Fig. 2).

TABLE II. COMPUTED SETTLEMENTS

Diagram of the vertical stresses after		Computed settlement, S (cm)
Boussinesq		5.2
Westergaard		3.5
Egorov	h_B	5.5
	h_W	4.2

Since Egorov's method applies only to a layer of limited thickness, it is necessary to determine the distribution of the vertical stresses and the settlement after this method, separately for each significant depth h_B and h_W. The final results of the computations are shown in Table II.

OBSERVED SETTLEMENT

The actual settlement of the chimney was determined periodically through precise geodetic measurements. The first observations were made immediately after casting the concrete foundation. For this purpose four check levelling benchmarks, numbered 1, 2, 3, and 4 (Fig. 3) were placed on the ends of two almost perpendicular diameters of the foundation. Thus, with one more check mark the inclination of the foundation can also be followed. The benchmarks were used up to the completion of the foundation concreting at the level ± 0.00. Then new benchmarks were located on the chimney shaft, corresponding to the initial ones, and measuring still continues.

The levelling of the benchmarks, intended to determine the settlement, is always conducted with a closed circuit. The initial benchmarks, R_{III} and R_{IV}, (Fig. 3) are placed about 50 m from the chimney and their levels are checked by a double (direct and reverse) closed circuit from the basic benchmarks, R_I and R_{II}, which are respectively 300 and 150 m away from them.

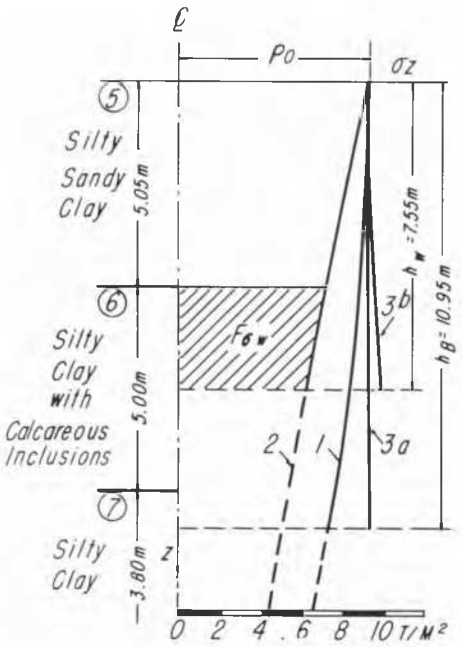

FIG. 2. Vertical pressure distribution in the subgrade along the centre line. 1, pressure diagram after Boussinesq; 2, pressure diagram after Westergaard; 3a, pressure diagram after Egorov for the significant depth h_B after Boussinesq; 3b, pressure diagram after Egorov for the significant depth h_W after Westergaard; 5, 6, and 7, layers from which undisturbed samples were taken; F_{6W}, stress diagram area after Westergaard, governing the settlement of layer 6 (as example).

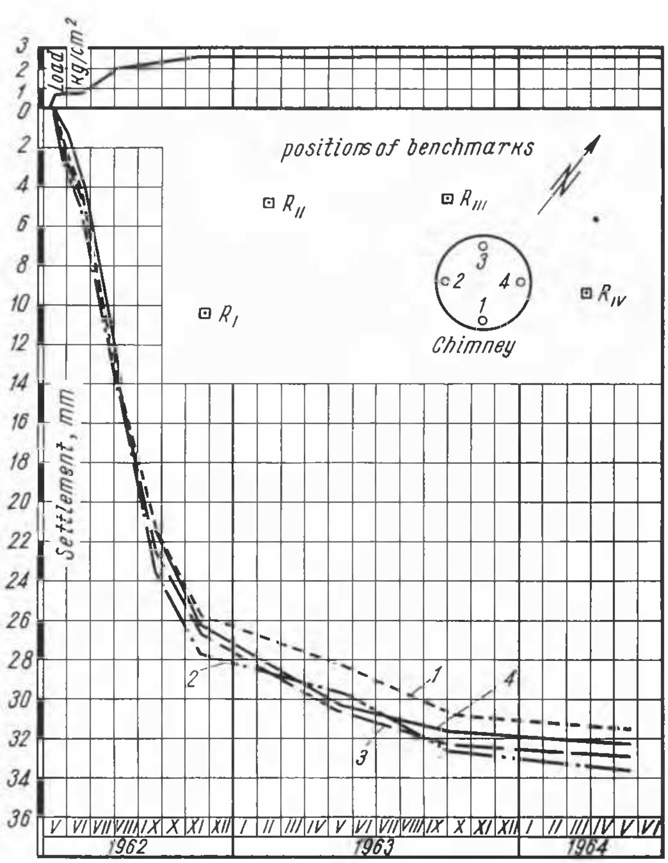

FIG. 3. Observed settlement of the check benchmarks *versus* time: 1, 2, 3, 4, check levelling benchmarks; R_I, R_{II}, basic levelling benchmarks; R_{III}, R_{IV}, initial levelling benchmarks.

The levelling is carried out with a precision instrument (Zeiss Ni 004) and with an invar levelling staff, equipped with a prop and a liquid level for vertical fixing. The sights are not longer than 25 m. The average error for a twice-levelled distance of 1 km for the basic and initial benchmarks (R_I, R_{II}, R_{III}, and R_{IV}) is less than 0.4 mm.

The average error of the level difference measured at the levelling of the check benchmarks (1, 2, 3, and 4), determined with the formula $m_p = \sqrt{[\Sigma(w/n)/N]}$, does not exceed 0.02 mm, where w is the non-coincidence of the closed levelling circuit, n is the number of stations, and N is the number of closed levelling circuits.

The results of the observations at the check benchmarks and the load increase during construction are given in Fig. 3. As shown there, the settlement of the chimney has almost been completed. The final settlement, towards which the average measured value of the four check benchmarks approaches asymptotically, with fair approximation may be assumed to be 3.4 cm. This value is considerably smaller than the permissible settlement for such a building, which according to Table 6 of *Norms and Technical Instructions* etc. (1955) is 30 cm. The maximum inclination of the foundation is about 0.00005 and is also much smaller than the permissible one, which according to Table 7 of *Norms and Technical Instructions* is 0.004.

CONCLUSION

The anticipated settlement, calculated by various methods, and the observed settlement are of the same order. The settlement calculated after Westergaard is closest to the average measured value. If the rigidity of the foundation is also taken into account in the computation, then the settlements calculated after Boussinesq and Egorov also approach those observed. The method for determining the significant depth, suggested in *Norms and Technical Instructions*, is completely adequate in this case. The necessity of raising the laboratory values of the modulus of linear deformation is confirmed. The sand cushion under the foundation has served a positive purpose for the distribution of stresses, as well as for the acceleration of consolidation.

REFERENCES

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