Vertical and Horizontal Deformations of Foundations and Embankments

Volume 1

Proceedings of Settlement '94

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ABSTRACT

This proceedings, *Vertical and Horizontal Deformations of Foundations and Embankments* (Geotechnical Special Publication No. 40) consists of papers presented at the Specialty Conference sponsored by the Geotechnical Engineering Division of the American Society of Civil Engineers held in College Station, Texas, June 1618, 1994. The prime goals of the conference and the resulting proceedings were: 1) to update the progress made since the 1964 Specialty Conference on Design of Foundations for Control of Settlement on prediction methods and mitigation technologies for both vertical and horizontal deformations of different types of foundations and embankments built on different soils; 2) to provide an effective forum for researchers and practitioners to share research results, current practice and recent technological advances; 3) to recognize the limitations in current practice, identify current and future needs of the profession, and assess the potential and feasibility of innovative technologies; and 4) to provide an effective vehicle for technology transfer. The 137 papers included in this publication cover such topics as: 1) embankments, deep fills, and landfills; 2) shallow foundations; 3) deep foundations; 4) soil improvement; 5) numerical and physical modeling; 6) soil dynamics; and 7) expansive soils, residual soils, and rock. This proceedings provides students, educators, researchers, and practitioners of geotechnical engineering an opportunity to assimilate new information and to meet new challenges.

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SETTLEMENT OF A SILO SUBJECTED TO CYCLIC LOADING

Marco Favaretti[1] and Alberto Mazzucato[2]

ABSTRACT: The paper presents the vertical settlement values for a corn silo located at Ca' Mello, close to Porto Tolle (Italy), and compares it with the theoretical results obtained using a simplified one-dimensional consolidation theory, under cyclic triangular-shaped loading. Settlements of the silo's lateral sides range between two extremes, corresponding to the filling and emptying of the silo. A steady-state condition seems to have been reached after a few loading-unloading cycles.

INTRODUCTION

Some engineering structures, such as storage tanks and silos, are subjected to cyclic loading during their lifetime. Periodic loading and unloading causes consolidation settlement, with the time and average degree of consolidation depending on permeability and the thickness of the clay layer, as well as on the shape of the load-time curve.

This paper presents the vertical settlement values for a rectangular silo 45×71 m wide (Fig. 1), built at Ca' Mello, a small town close to Porto Tolle (Italy), and compares them with the theoretical results obtained using a simplified one-dimensional consolidation theory, under cyclic loading. Consolidation due to cyclic loading is usually studied using a series of cyclic step square/triangular loads and unloads (Baligh and Levadoux 1978; Olson 1977; Wilson and Elgohary 1974), the linearity of the consolidation differential equation solution allows the problem to be solved as a linear combination of single effects.

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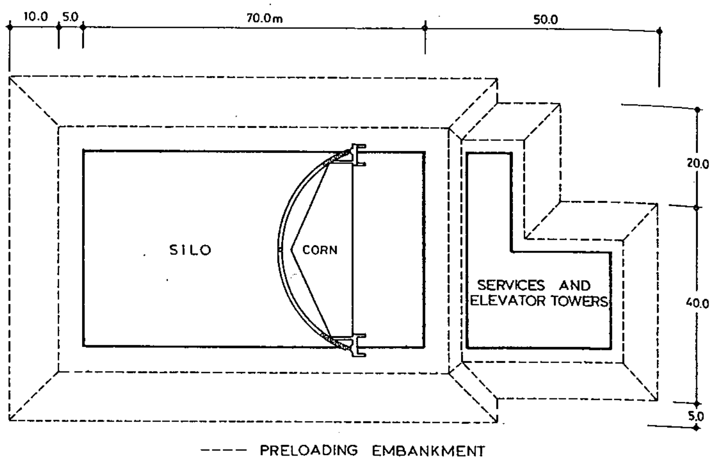

FIG. 1. Site Plan with a Schematic Section of the Silo's Structure

Soil Profile

The most important river in Italy is the River Po. It is 652 km long and its hydrographic basin occupies an area of more than 70,000 km^2, or about two-thirds of the surface area of Northern Italy. The mouth of the river is of delta type extending over approximately 500 km^2, and has been subjected to complex geological and anthropic events during its lifetime.

The delta subsoil is characterized by recent alluvial deposits (Holocene) with alternating soft cohesive and loose granular layers on top. Several studies were carried out, particularly in the fifties when serious subsidence occurred, and in the seventies when the Italian Electricity Generating Board (ENEL) built a large thermoelectric power station in Porto Tolle.

Porto Tolle clay has become well-known due to work of Croce et al. (1973), Bilotta and Viggiani (1975), Garassino et al. (1979), Hansbo et al. (1981), Jamiolkowski et al. (1980, 1984), and Battaglio and Maniscalco (1983). It is a normally consolidated silty clay, very soft and compressible, that conditions the design of any civil structures built in the area. Previous in-situ investigations have enabled a detailed soil profile to be obtained; furthermore it was noticed that the 22 to 24 m thick clayey stratum has a well developed macrofabric, consisting of thin discontinuous seams, lenses and pockets of fine sand and silty sand.

First of all, a piezocone test was carried out to verify the soil profile at Ca' Mello and to check the homogeneity of the thick cohesive stratum; a few permeable thin layers were identified inside the clay stratum, but their planimetric continuity was not certain (Fig. 2). A number of dissipation tests were performed at a depth of from 10 to 25 m during the piezocone test to evaluate the clay's consolidation coefficient ($c_v = 2 \sim 4 \times 10^{-7}$ m^2/s; $c_h = 1 \sim 2 \times 10^{-6}$ m^2/s). The main geotechnical soil

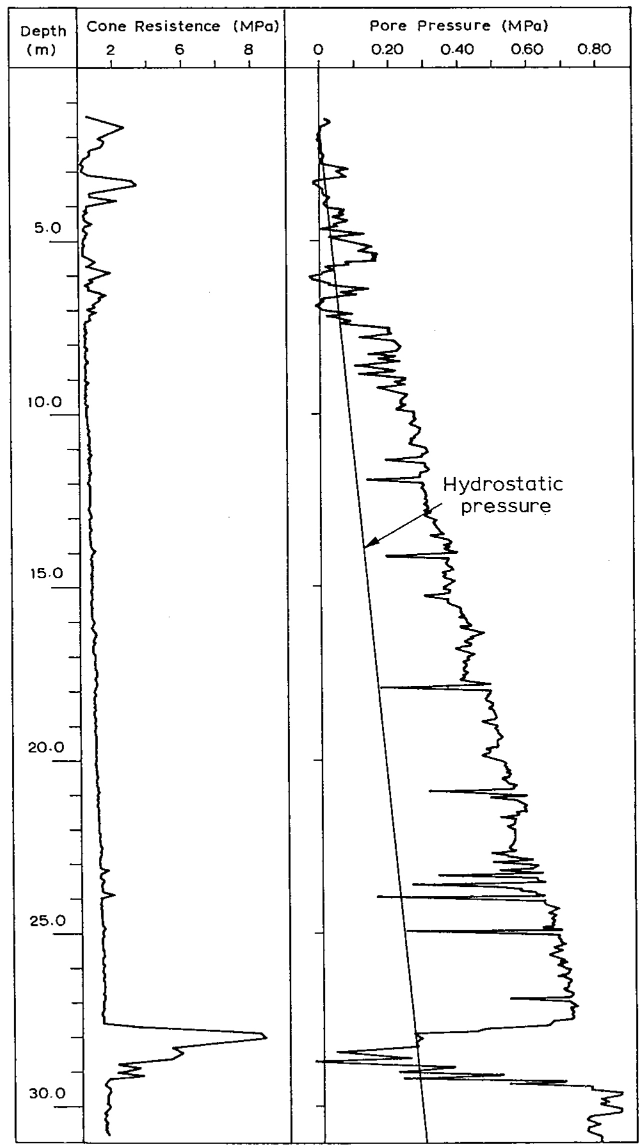

FIG. 2. Pore-Water Pressures Induced during a Piezocone Test

properties (Fig. 3) determined both by in-situ (CPT, boreholes) and laboratory tests (classification, oedometer and triaxial tests) are similar to the results previously published over the last 20 years (see above mentioned references).

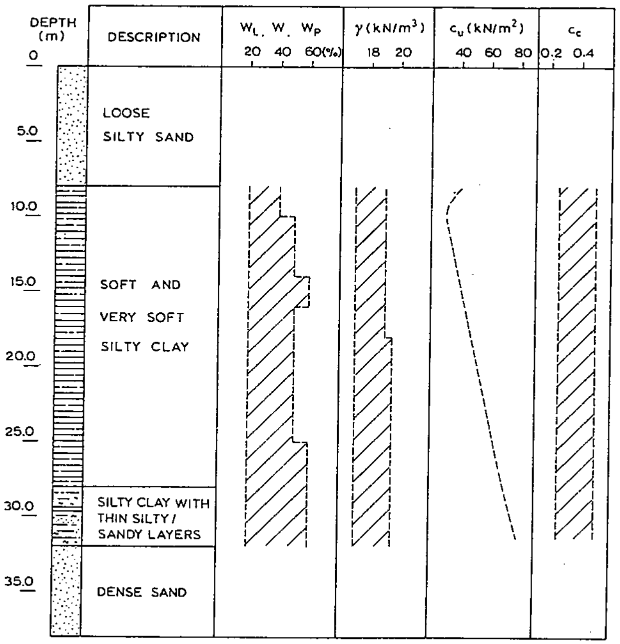

FIG. 3. Subsoil Profile at Ca' Mello with Some Geotechnical Properties

THEORETICAL ANALYSIS

The Terzaghi one-dimensional consolidation theory provides the well-known differential equation, which is valid for a constant surcharge of infinite extent.

If the ground surface load increases linearly and infinitely (for T=0, q=0; for $T=T_c$, $q=q_c$), the excess pore-water pressure u is (Schiffman 1958):

$$u = \sum_{m=0}^{\infty} \frac{2q_c}{M^3 T_c} \sin\frac{Mz}{H}\left[1 - e^{(-M^2 T_c)}\right] \tag{1}$$

The above expression does not have any actual use, since infinitely increasing loading is totally improbable. But it is interesting to note that both its differential and derivatives are linear. Therefore if u_1 and u_2 are the solutions of the consolidation differential equation for the loads q_1 and q_2 respectively, $u = au_1 + bu_2$ (with a, b constant) will be the solution for a linear combination of loads $q = aq_1 + bq_2$.

Let us now consider an isosceles-triangular cyclic loading, with period t_0 (the corresponding time factor is $T_0 = 2T_c$) linearly ranging between 0 (for $t = Nt_0$, T= NT$_0$, with N=0,1,2,...) and q_c (for $t = (2N-1)t_0/2$, $T = (2N-1)T_0/2$, with N = 0,1,2, ...) (Fig. 4).

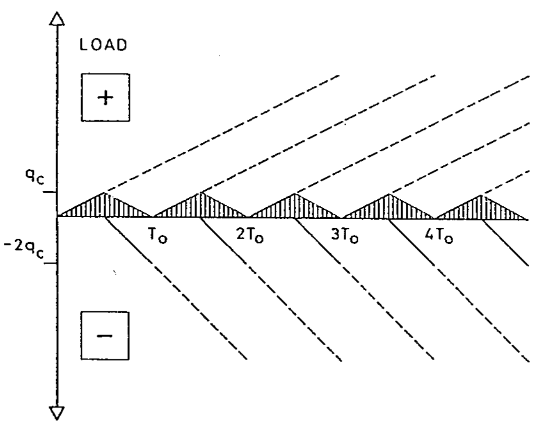

FIG. 4. Triangular-Shaped Cyclic Loading

Terzaghi's hypotheses are still valid; furthermore the coefficients of volume compressibility m_v and consolidation c_v are assumed to be constant, both during loading and unloading. These assumptions are satisfactory for over-consolidated soils, while they are poor for soft normally consolidated soils (Wilson and Elgohary 1974). Actual repeated loading and unloading cycles cause a quasi-preconsolidation effect on N.C. clay.

Triangular cyclic loading can be obtained by superposing two different series of infinitely and linearly increasing loads, alternately positive and negative, and shifting the origin of each load of $+T_0/2$ along the T-axis, as shown in Fig. 4. The general solution can be found in this way, by adding to Schiffman's solution (valid for a single infinitely increasing loading) infinite times, and by paying attention to the correct sign (positive/negative) (Soranzo 1985). The limit of the average consolidation degree, at half-cycle (U_{hc}-lim) and end of the cycle (U_{ec}-lim), for $N \to \infty$ and T_0 ranging from 0.01 to 10 (valid for usual applications), are shown in Fig. 5.

The curves of U_{hc}-lim and U_{ec}-lim are symmetrical in relation to the horizontal line U=0.5; they both tend to 0.5 for $T_0 \to 0$, and to 1 and 0 respectively for $T_0 \to \infty$. The difference between two curves increases with increasing T_0. The average degrees of consolidation U, for different T_0, during the first three cycles (N =1,2,3) and at N = 100-cycle, are shown in Fig. 6. Several cycles are necessary to produce a steady state condition for low values of T_0, while a few cycles are suffice for high T_0 values.

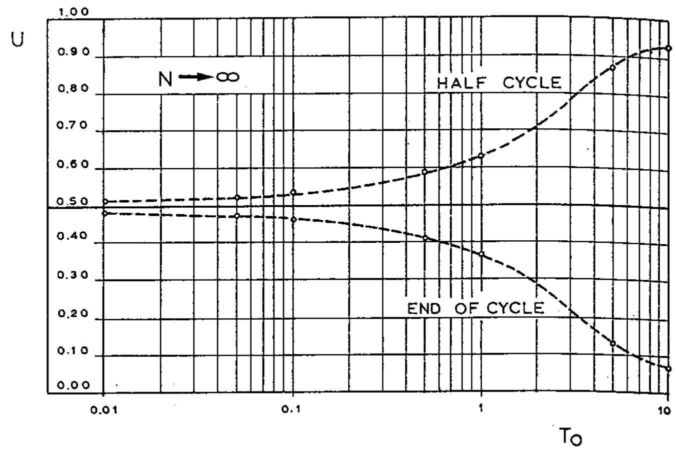

FIG. 5. Average Degree of Consolidation Limit at Half Cycle and End of Cycle

EVALUATION OF THE SILO SETTLEMENTS

The shallow strip foundation structure carries out a twofold function: as retaining structure of the stored corn, and as support of the three-hinges arc steel roof (Fig. 1). It is composed of a reinforced concrete slab (1.00 m thick and 4.00 m wide) with two lateral keys (0.80 m thick and 3.00 m deep) founded on improved base coarse material, 4.00 m thick. The flexible bituminous pavement of the silo presents a series of small transversal trenches, where hot air jets are located to prevent moulding of the stored corn. The success of these devices is assured only if the pavement distortions are lower than 1/300 and the absolute settlements are lower than 150 mm.

Now a comparison between actual and predicted settlements, which occurred along the longitudinal lateral sides of the silo, is presented. Evaluation of the theoretical settlements was carried out considering the following three compressible layers: one shallow (1), one medium (2), divided in two parts (A and B) by a thin permeable layer 23 m deep, one deep (3), and two different loading conditions:

(1) a preloading earth-embankment (H = 5 m; γ = 16.5 kN/m^3), wider than the silo area (Fig. 1);

(2) silo completely filled with corn (γ = 8.5 kN/m^3).

Design data (H_0 is the initial thickness and CR the compression ratio of each layer) and expected settlements s (evaluated at the end of the primary consolidation) for both conditions are summarized in Table 1.

The rate of consolidation of the cohesive layers 1, 2B and 3 is relatively high, due to their small drainage length.

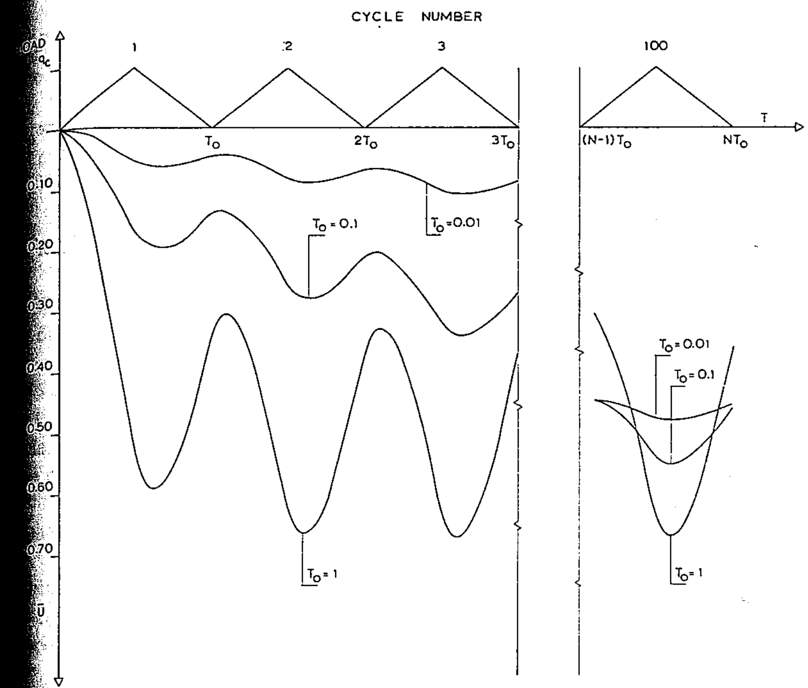

FIG. 6. Average Degree of Consolidation versus Load as a Function of Time Factor T_0

During loading-unloading cycles, layers 1-2B-3 behave elastically like an overconsolidated cohesive soil (Fig. 7a), whereas layer 2A shows, in addition to elastic deformation, a residual primary consolidation settlement, gradually decreasing over time (Fig. 7b).

A preloading embankment was previously built on the area and maintained for 15 months in order to limit the absolute and differential settlement of the silo during its lifetime and reach satisfactory consolidation both at the center and along the sides of the silo.

An embankment settlement of 0.57 m was measured along the longitudinal strip corresponding to the lateral sides of the silo; this situation, pertaining to loading condition 2 (only corn loading) would correspond to an average degree of 100% consolidation for layers 1, 2B and 3, and 80% for layer 2A. Therefore a residual consolidation settlement equal to 50 mm of layer 2A was expected to occur gradually and fully developed during the first loading-unloading cycles.

TABLE 1. Consolidation Settlement along the Silo Sides

Layer	H_0 (m)	CR	σ_{v0}' (kPa)	σ_v'(kPa)		s_∞ (m)	
				(1)	(2)	(1)	(2)
1	4	0.16	40	70	32	0.28	0.16
2A	15	0.20	140	50	30	0.40	0.25
2B	5	0.15	185	45	28	0.07	0.05
3	2	0.15	248	40	26	0.02	0.01
				total settlement		0.77	0.47

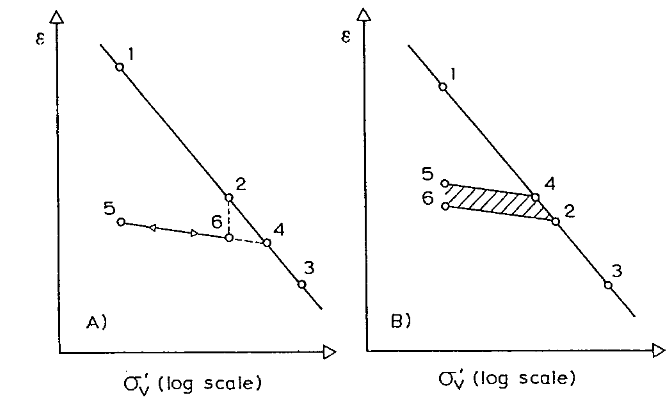

FIG. 7. Schematic Representation of the Behaviour of Layers 1-2B-3 (A) and 2A under Cyclic Loading (B): (1) initial condition; (2) U = 100% for constant loading of corn; (3) U = 100% for constant preloading; (4) before removing the embankment; (5) after removing the embankment. CONDITION A: each cycle moves between 5 and 6. CONDITION B: cycles initially move within the marked zone tending after a few cycles to settle on the line 6-2

In addition to the residual consolidation settlement, each cycle causes an elastic settlement s_{el} (Table 2):

TABLE 2. Evaluation of the Elastic Settlements

Layer	1	2A	2B	3
$s_{elastic}$ (mm)	30	37	13	3

The simplified one-dimensional consolidation theory under cyclic loading was only applied to the layer 2A. The design values assumed for the calculation of the time factor T_0 and the average degree of consolidation are:
c_v (coefficient of consolidation) = 1.5×10^{-6} m²/s;
t_0 (loading-unloading cycle period) = 365 days;
H (maximum drainage length) = 7.5 m; and inserted in the following expression:

$$T_0 = \frac{c_v t_0}{H^2} = 0.84 \qquad (2)$$

The coefficient of consolidation c_v was evaluated using oedometer tests, performed with repeated loading and unloading cycles, and dissipation tests carried out during piezocone tests.

A steady-state condition is reached after only three cycles. The minimum and maximum average degree of consolidation is respectively equal to 0.34 and 0.48 for the first cycle, 0.38 and 0.60 for the second cycle, 0.38 and 0.61 for the third cycle. The predicted settlements of the silo are reported in Fig. 8 as a function of time and loading.

COMPARISON BETWEEN ACTUAL AND PREDICTED SETTLEMENTS

The embankment was removed and construction of the silo was completed within a few months. The silo is generally filled with corn at harvest time (September-October), and gradually emptied during the spring; so that the cyclic loading period varies from 10 to 12 months.

The graphical relationship between the corn load and average settlement along the lateral sides of the silo, measured by levelling for four years at regular intervals, is shown in Fig. 8.

Settlement values were only measured along the sides due to the difficulty involved in checking settlement at the center of the silo. The trend clearly shows positive and negative peaks corresponding to the filling and emptying of the silo respectively. A steady-state condition already seems to have been reached after only three cycles; this is the typical behavior of consolidating layers characterized by a high time factor T_0.

Theoretical trend fits well maximum settlements, corresponding to the filling of the silo, whereas underestimates the minimum values.

CONCLUSIONS

A simplified one-dimensional consolidation theory under cyclic loading was applied to the case of a silo, periodically filled and emptied with corn. This theory assumes that both the coefficient of consolidation c_v and of volume compressibility m_v are constant: this can only be satisfactory with homogeneous overconsolidated cohesive soils.

The subsoil at Ca' Mello features a 22 to 24 m N. C. thick clayey stratum, very similar to the Porto Tolle clay, spaced with thin permeable layers. It was subjected to preloading for 15 months, which induced a very high degree of consolidation all over the construction area.

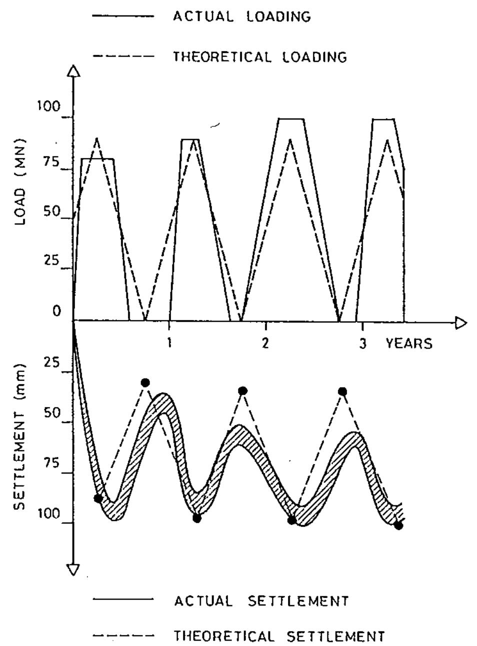

FIG. 8. Comparison between Theoretical and Actual Settlements of the Lateral Sides of the Silo as a Function of the Load

The comparison between actual and predicted settlement was made only along the lateral sides of the silo, where it is relatively simple to measure the actual settlement.

Theoretical trend of settlement fits well actual values measured along the silo's sides, though in the considered case minimum settlements are slightly underestimated. However such a comparison suffers of some uncertainty regarding the exact amount of corn, stored inside the silo, and its actual storage time.

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APPENDIX - REFERENCES

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