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SETTLEMENT OBSERVATION ON FOUR GRAIN SILOS

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SUMMARY.

Towards the end of 1942 a programme was put in hand as an urgent wartime measure to construct in different parts of England a number of silos for the drying and storage of grain. All the structures were to be of similar design but the type of foundation would be varied to suit the site conditions, piling being resorted to when the conditions were obviously unsuitable for a raft foundation. At four of the sites the foundation stratum consisted of a thick bed of clay and the Building Research Station was asked by the chief structural engineer of the Ministery of Works to carry out soil investigations prior to construction to see if a raft foundation could be safely used. Tests were carried out to decide whether the bearing capacity of the soil was compatible with the proposed loading and whether there was an ample factor of safety against failure of the ground in shear. The results of the tests are summarized in the paper and in each case it was concluded that a raft foundation would be suitable.

The site investigation was followed by taking measurements of the actual being settlements of each of the four silos, the first levels taken as soon as each structure was completed and subsequent readings taken at intervals up to the present time. There were, of course, considerable fluctuations in the live loads, the grain load varying at different seasons of the year up to more than 4000 tons. It is interesting to note that the variation in grain load was reflected in the movements of the foundation. Maximum settlement corresponded with maximum grain load followed by an upward movement when the load was removed and these fluctuations were superimposed on the gradual progressive increase in settlement due to long term consolidation. Figures showing settlement-time curves and the corresponding load-time curves are included in the paper.

A comparison between the computed and actual settlements for one of the silos shows that the two are at least of the same order although the complications introduced by the fluctuating load make close comparison difficult.

2. THE STRUCTURE AND LOADING CONDITIONS

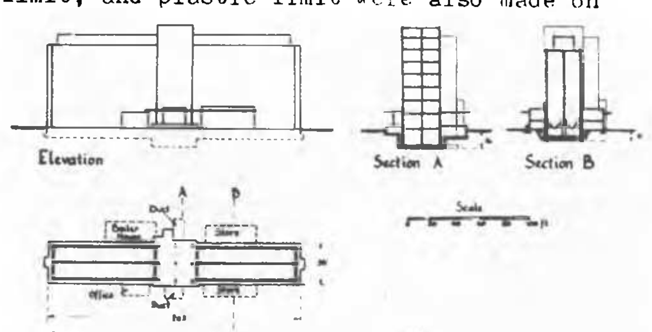
Fig. 1 shows sketch plans of a typical silo constructed in reinforced concrete. The total dead load of the structure amounted to about 7,500 tons and if the bins were ever completely full of grain this would add a total grain load of about 6.000 tons. The design of the structure necessitated that under the central tower the foundation raft should be located at a depth of about 16 ft. below ground level while under the bins the foundation raft for the wings should be about 9 ft. below ground level.

Computations indicated that under the central tower the net pressure on the ground (gross loading minus excavation) was approximately zero. Under the wings the net pressure with the bins empty was about 0.5 tons/sq.ft. but with the bins completely full it increased to about 1.5 tons/sq.ft. The loading conditions were therefore somewhat complicated. While the superstructure of the central tower was separated from the wings by construction gaps, the foundation raft was made continuous. The conditions did therefore permit a certain amount of transfer of load from the wings to the tower foundation but owing to the urgency of the work as a wartime measure and to the need for standardisation of the designs it was not possible for the Chief Structural Engineer to await the receipt of complete soil investigations as affording a more exact means of deciding on the probable distribution of soil pressures affecting the design of the raft. A consideration which militated against the use of independent foundations for the central tower and the bins was the probability of soil water and the necessity to build the basements as completely waterproof structures.

3. SITE INVESTIGATIONS AND SOIL TESTS.

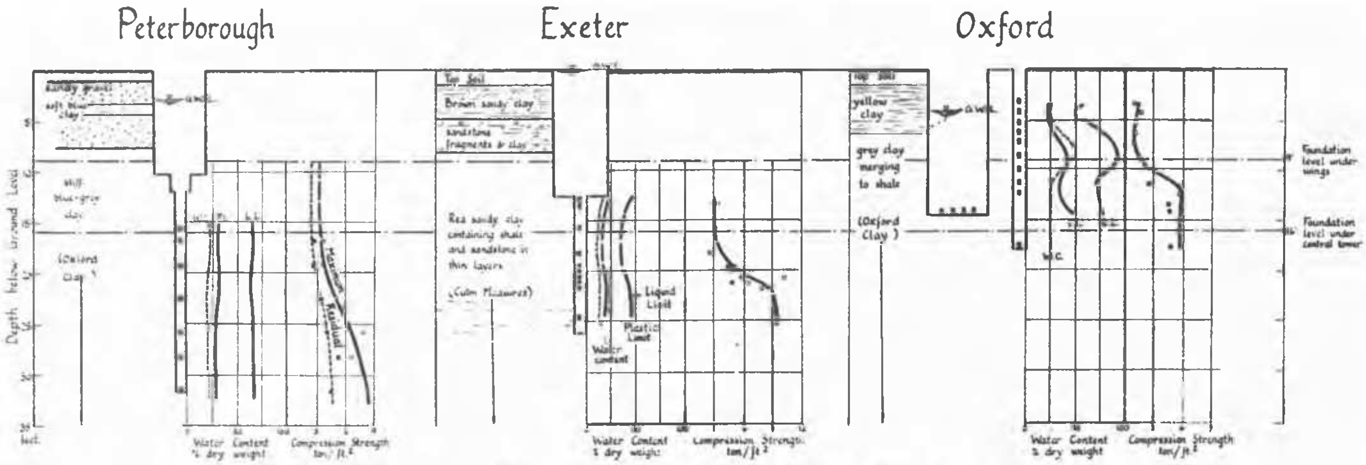
The general procedure adopted in the site investigations was first to look up in the records of the Geological Survey all the relevant geological information and then to supplement this by putting down test pits and boreholes from which soil samples were taken for test purposes.

To follow the variation of strength with depth unconfined compression tests were carried out in the field with the B.R.S. portable compression apparatus.
Tests to measure the moisture content, liquid limit, and plastic limit were also made on



Sketch Plans of Silo.

FIG.1



Site Conditions and Test Results

FIG.2

these samples when they reached the laboratory. In addition larger samples were taken at selected depths and transported to the laboratory for triaxial and consolidation tests.

The four silos for which site investigations were carried out were situated at Peterborough, Oxford, Exeter and Stratford-on Avon. The results of tests on samples from the first three of these sites are shown in Fig. 2. The geological conditions at each of these sites were similar in that the main foundation stratum, covered in three cases by a thin layer of drift, was a bed of clay of the Jurassic period or older. The main body of the clay was in a very tough condition although the top few feet had softened to a certain extent. At Peterborough the Oxford clay stratum was covered by about 8 ft. of drift comprising sandy gravel. At Osford, the same formation (Oxford clay)was met immediately under the topsoil and the depth of softening was of the order of 12-14 ft. At Exeter, the Culm Measure shale of the Carboniferous was covered by about 8 ft. of sandy clay with sandstone fragments. At Stratford the Triassic marl was covered by about 13 ft. of gravels and sands.

Since the design provided for the rafts to be founded below the level of the surface drift the bearing capacity was in each case found to be ample for the proposed structure, the factor of safety against ultimate shear failure being of the order of 5 or 6.

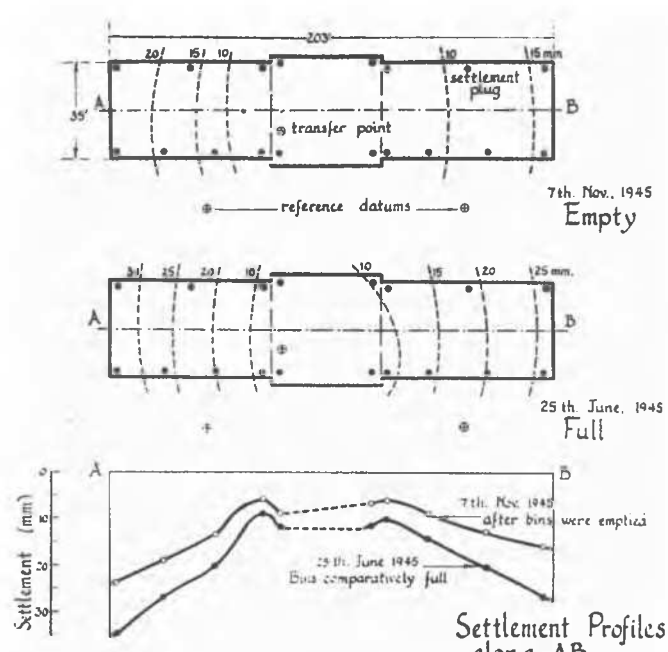
It was however necessary to recognise that these older clays are particularly liable to soften and slake if left exposed for any length of time to water and therefore precautions were taken during the excavation for and the casting of the concrete raft to prevent undue softening of the clay.

4. SETTLEMENT OBSERVATIONS.

At a convenient time during construction settlement plugs (eighteen in number) were installed in the raft at positions shown in Fig. 4. By using a transfer point fixed in the first floor of the central tower, the levels of the plugs could be compared with two outside reference datums. The datums were placed in suitable positions at a short distance away from the structure and were of the rod type with the bottom of the rod fixed at a depth of several feet (8 to 10 ft) below ground surface. Levels were taken by means of a precision level and a special scale graduated in millimetres. By this method it was found possible to carry out readings to an accuracy of about $\frac{1}{2}$ mm.

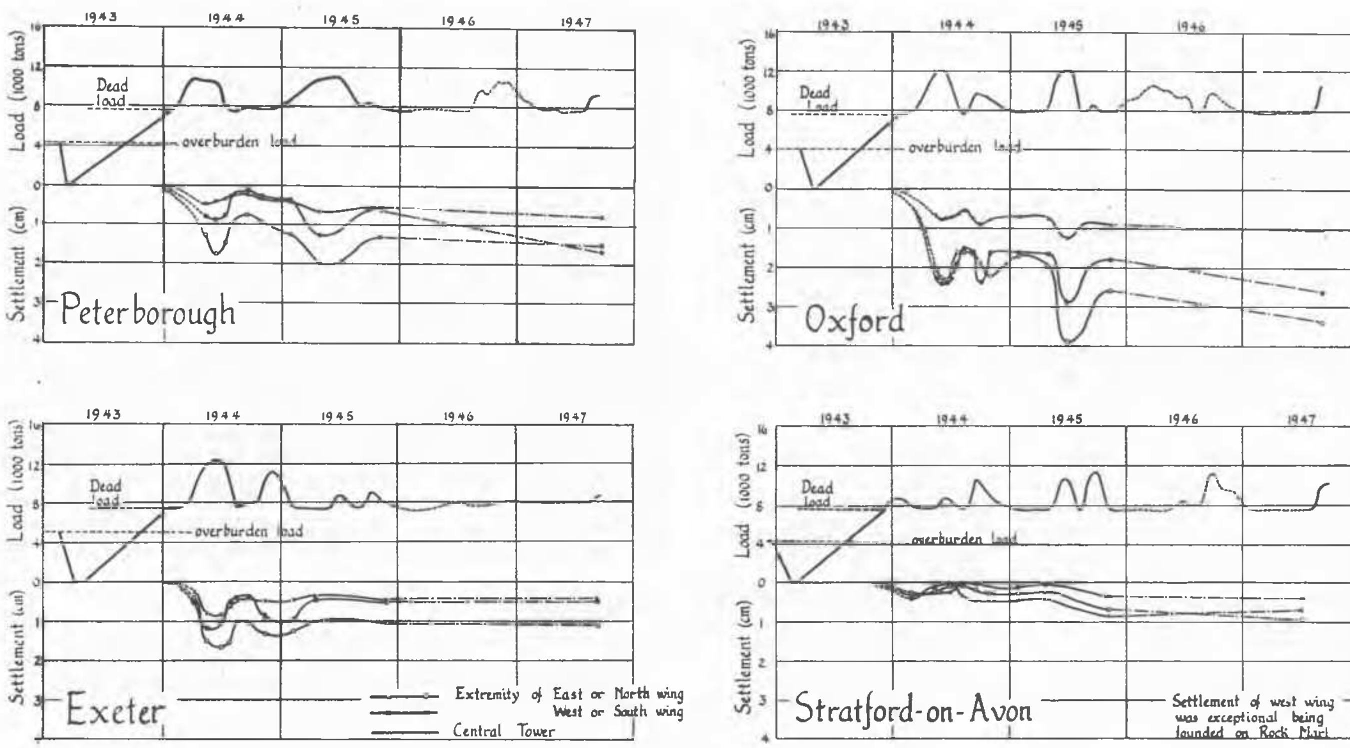
Unfortunately it was not convenient to take readings until after the structures were completed and in some cases the first levels were not taken until after a small quantity of grain had been placed in the bins. There. after levels were taken at intervals and a record of the grain in the bins was obtained over the period of levelling. The fluctuations in the live load were considerable the grain load varying at different seasons of the year from zero up to more than 4.000 tons.

A brief summary of the results is given in Fig. 3. In order to simplify the drawings the movements of only three points in each silo are given, the points being the extremity of each wing and the central tower. The tendency in each case was for the central tower to settle least and for the settlement to increase linearly as the distance increas-



Distribution of Settlement, Full & Empty Oxford Silo

FIG.4



Observations on Silos - Time-Settlement Curves

FIG.3

ed outwards in the direction of the wings being greatest at the extremities of the wings (see Fig. 4). In order to estimate the first part of the settlement curve it has been necessary in each case to extrapolate back to a zero time which was taken as that when half the net dead load (total dead load minus excavations) was acting on the raft. This initial portion of the curve (which is small in each case) is shown dotted while the remainder of the curve obtained directly from the settlement readings is shown as a full line.

The striking feature of these curves in Fig. 3 is the way in which the variation in the grain load is reflected in the movements of the foundations. It will be noted that when the grain bins are full the settlement is a maximum and that on removing the load by emptying the bins there is a definite upward movement of the foundations.

Also although the central tower was subject to neglible variation in grain loading, the levels of the points located there too reflect the variation in grain load but to a smaller degree than the wings. This indicates that there was a certain amount of transfer of load from the wings to the centre through the foundation raft. The curves also show a gradual increase in settlement due to long term consolidation in which the fluctuations due to elestic movements under the action of the grain load are superimposed.

The elastic movements due to grain load are shown more clearly in Fig. 4 which gives contours of the settlement of the Oxford grain silo at two states of loading, the first when the bins are comparatively full of grain and the second when the bins were subsequently emptied.

5. COMPARISON BETWEEN OBSERVED AND COMPUTED SETTLEMENTS.

In the case of the Oxford silo the foundation raft for the wings was located at a level still within the upper softening zone of the clay. An estimate was therefore made of the probable consolidation settlements and for this purpose consolidation tests were carried out on selected samples. The results gave the following values for the consolidation characteristics of the clay in the zone which would control the consolidation settlements over the first few years:

Compressibility coefficient$\left(\frac{a}{1+\varepsilon}\right)$=0.034 ft.^{2}/ ton)
Consolidation " 0.0008 in.^{2}/ min.)

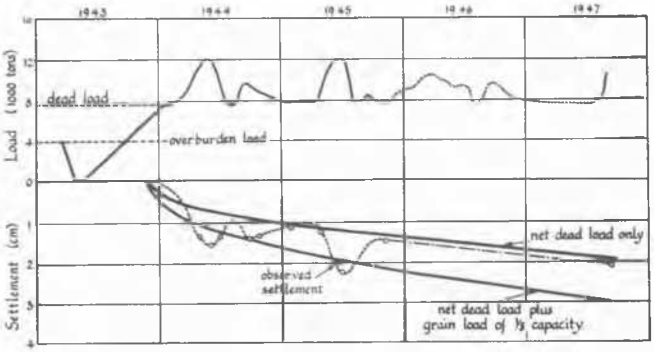
Since the main clay bed was of considerable thickness it was assumed that drainage would take place through the upper surface only.

Owing to the complications introduced by the fluctuating grain load, the problem was simplified for the purposes of settlement analysis and settlement curves were computed for the following two limit conditions:

a) One wing was considered as acting by itself (i.e. separated from the central tower) and it was assumed that the net dead load only caused consolidation.
b) The same as (a) but with a load acting all the time equal to the net dead load plus a proportion of the maximum grain load estimated at 1.000 tons (1/3 capacity of the wing).

The settlement curves for these two conditions are given in Fig. 5 and for comparison purposes the average settlement of a wing is included as a dotted line. Although the fluctuations due to the grain load complicate the curve for the measured values it can be seen that the measured and computed values are at least of the same order.

Owing to the uncertainties at present associated with the theoretical estimation of elastic movements, no prior attempt was made to indicate the probable movements under the grain load except to indicate that on the



Comparison between Observed and Computed Settlements Oxford Silo.

FIG.5

basis of past experience they were not likely to be much more than a quarter of an inch. During the course of testing however a series of triaxial compression tests were carried out on Oxford clay samples and it is interesting to see how theoretical values based on these results compare with the actual movements. The tests indicated that the modulus of elasticity was of the order of 150 to 200 tons/sq. ft. From an analysis based on elastic theory the theoretical movement under a grain load of 0.6 tons/sq.ft. would be of the order of 2 in. whereas in actual fact the measured movement was only about 0.3 in.

This result tends to confirm the suggestion put forward by Dr. Terzahi 1) that, particularly for buildings supported on a raft foundation at a depth of more than about 8 ft. below the ground surface, there exists a great resistance against lateral yield of the stratum which substantially reduces the elastic settlement.

ACKNOWLEDGEMENTS.

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1) K. Terzaghi "Settlement of Structures" Paper F.16 Vol III Proc. 1st.Int.Conference on Soil Mechanics and Foundation Engineering Harvard 1936.

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LOADING TESTS ON TANKS IN PERSIA

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The subject of this paper is the method employed and the results achieved in the investigation of the bearing power of two areas consisting chiefly of soft, silty and highly varved soil in Persia, which were proposed for the erection of important plant.

It was known that this plant, which, it was assumed, will be constructed on semi-rigid reinforced concrete slab foundations, would impose on them, during its operation, loads of an intermittent and surging nature which would be somewhat akin to those caused by high structures under wind pressure.

It was also known that any unequal settlement of these foundations which might occur would have extremely serious effects on the operation of this plant.

It was sought to ascertain the working load which, under these circumstances, might be placed with safety on the soil.

Further, it was realised that there did not exist sufficient theoretical equipment for estimating, to any useful degree of accuracy, the amount and type of settlement which might occur on such soil under incremental loading imposed during construction, especially having regard to its heterogeneous nature.

For this reason, and also on account of the large capital loss which might be incurred if a faulty decision was made, it was decided to employ soil investigation and loading tests of a size which, it is believed, have few, if any, precedents.

As a preliminary to these loading tests, borings were made on these sites to a depth of about 100 ft. and undisturbed samples were taken and tested.

SOIL INVESTIGATION.

The site borings taken on these two areas disclose the types of soil which have a striking similarity, both in their properties and sequence, in both cases displaying, (a) a surface stratum of laminated light brown clay from 12 to 15 feet in thickness, lying over a soft, silty clay deposit about 50 ft. thick, closely laminated or varved, and containing silty and sandy partings with occasional shelly fragments and also black particles of a peaty nature. Near the base of this latter deposit, erratic inclusions of peat were found.

This deposit, in each case, is followed by a stiff mottled clay, the strength of which rapidly improves with its depth.

SHEAR VALUES.

The samples from the surface stratum of clay had a shear value varying between 1200 and 400 pounds per square foot respectively at its surface, when dry, and at its lower horizon 12 to 15 feet below ground level.

The succeeding silt and clay varved deposit varied in shear strength between about 250 and 450 pounds per square foot, according