then necessary to decide whether the piles could be stopped, if a satisfactory set was reached in the material lying above the thick bed of stiff clay which underlies the site, see Figure "B". Investigation showed that the soft clay bed would cause differential settlement to an extent which would be unacceptable and it was decided to drive the piles through the upper beds (although apparently satisfactory sets might be got there) and to continue driving, until the toes of the piles went into the better strata (i.e. the sand or stiff clay) below the soft clay.

b) Workshop Blocks.

In the workshop blocks the maximum permissible foundation loading was also taken to be 0.7 ton per square foot. Investigation showed that if strip footings were used for the foundations having a maximum loading of approximately 0.6 ton per square foot, for the Western workshop block, there would probably be an average total settlement of 1 inch with a maximum differential settlement of ½ inch, the settlement being about 50% complete in the first three years after the block was built, the differential settlement being caused by the thickness of the underlying bed of soft clay varying from about 16 to 37 feet under this block. The differential settlement for the Eastern workshop was estimated at 1 inch, in this case the soft clay bed only being under part of the building and the settlement is expected to be 50% complete in eight months. The estimated quicker settlement was due to the bed of soft clay being less deep and thinner in this area. These differential settlements might be serious, if they occurred in adjacent sections of the buildings but, as the maximum and minimum settlements would occur in widely separated parts of the buildings, it was decided that well reinforced strip footings would provide the continuity required to prevent the buildings cracking. The strip footings were designed varying from 2'6" to 6'0" in width to keep the foundation pressures uniform and within that permissible on the made ground (0.7 ton per square foot).

8. CONCLUSIONS.

The cost of the test borings, direct loading tests, laboratory examination, etc., was approximately £4,000; this may appear high at first sight but the use of piles in the foundations of the single storey workshops would probably have cost £10,000 more than the strip footings now included in the design. If, however, a thorough investigation of the site had not been made, the risk of using strip footings would have been too great to have been practicable.

On the other hand, apart from the thorough site investigation, the piles for the multistorey blocks might well have been stopped as soon as satisfactory sets were reached in the upper gravel beds, the carrying capacity of individual piles being confirmed by loading tests, in which case there would probably have been serious differential settlement and cracking in the multistorey buildings which would have been very difficult to cure, as the settlement would have continued for some years.

Thus proper site investigation permitted, inter alia, a net saving of approximately £6,000 on the single storey blocks and also prevented a possible heavy future liability being incurred for repairs to the multistorey blocks.

9. ACKNOWLEDGEMENT.

During the investigation much help was received from the Director of the Building Research Station and in view of this, where figures were originally calculated by the Building Research Station but which, when recalculated subsequently gave slightly different results, due to adjustments in design, etc., the original Building Research Station's figures have been used in preference to those calculated more recently.

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SOME EXAMPLES OF FOUNDATION MOVEMENTS DUE TO CAUSES OTHER THAN STRUCTURAL LOADS

L.F. COOLING, M.Sc.,
W.H. WARD, B.Sc.(Eng.). A.C.G.I., A.M.I.C.E.
Department of Scientific and Industrial Research-Building Research Station.

SUMMARY.

In the last five years a very large number of examples of building damage due to foundation movement has been encountered in which the effect of the weight of the building on the ground is negligible. Broadly speaking the damage arises from movement of the ground below the level of the foundations due to either climatic changes or the action of heat from industrial buildings.

The movements may be grouped as follows:

1) Natural Drying
   Drying shrinkage of clays under structures founded at a shallow depth due to:-
   a) Seasonal changes in evaporation and rainfall.
   b) Transpiration of trees and shrubs.

2) Artificial Drying
   Drying shrinkage of clays under industrial buildings (brick kilns, boiler houses, etc.) due to penetration of heat.

3) Artificial Frost Heave
   Frost heave under cold storage buildings due to penetration of frost.
It is necessary to emphasize that these various processes do not only cause purely vertical movements of the ground; appreciable tearing apart of the structure may occur, particularly in groups (1) and (2) where the clay shrinks in all directions.

II. NATURAL DRYING.

a) Seasonal Changes in Evaporation and Rainfall.

This group relates mainly to dwelling houses which in Britain have foundations consisting essentially of strip footings extending to a depth of about 1 ft. 6 in. to 2 ft. below ground level and loaded to about \( \frac{1}{2} \) ton/sq.ft. The thickly populated parts of S.E. England occupy an area which largely consists of fat stiff-fissured clays of Tertiary, Cretaceous and Jurassic age and fat boulder clays derived therefrom. The index properties of all these clays is of the order of:-

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid limit</td>
<td>75</td>
</tr>
<tr>
<td>Plastic</td>
<td>25</td>
</tr>
<tr>
<td>Shrinkage</td>
<td>17</td>
</tr>
</tbody>
</table>

The mean annual rainfall over the area varies from about 21 to 30 in. and the annual evaporation from a grass surface is equivalent to about 19 in. of rainfall. The seasonal change in water content at a depth of 6 in. varies from about 40 per cent. to 15 per cent. and measurable changes extend to a depth of about 5 ft., where the water content remains at about 28 per cent. These moisture variations cause volume changes of the clay and the vertical movements of a series of plates buried in a grass field in undisturbed clay at the Building Research Station are shown in Fig. 1.

b) Transpiration of Trees and Shrubs.

The drying effects of the transpiration of trees and shrubs are superimposed on the seasonal conditions mentioned above whenever the root system approaches the shallowly founded structures. The root systems of isolated trees generally spread to a radius greater than the height of the tree and have been observed in southern England to cause significant drying of fat clay soils to a depth of about 10 ft. Differential movements of 4 in. or more have been observed in houses 80 ft. from a row of black poplars and movements of 1 to 2 in. are quite common, see Fig. 3.

The problem arises broadly in two ways:–

1) At the time of construction, fast growing trees, e.g. poplar, elm, etc., are often planted in English suburban gardens. Within 5 or 6 years the roots extend a distance of 60 ft. or so and dry out the clay abnormally below the foundations of the nearest part of the house. The drying appears to be more than a purely seasonal effect and a permanent depression of the ground surface is produced during the early period of rapid growth when the tree demands more water than is available from the rainfall less evaporation and runoff.

2) The problem also arises when a mature slower-growing tree exists and a house is constructed over part of its root system. The damage arising from this set of conditions does not appear to be as widespread as in the previous case. Examples of damage to houses have even been encountered within 30 ft. of mature oak trees. The trouble appears to arise because the sheltering effect of the house on the roots induces them to deplete the moisture normally stored in the ground.

Abnormal spells of dry weather have much more serious effects when trees are present than was mentioned previously; the clay not only receives directly less rainfall and suffers...
greater evaporation, but the increased radiation on the trees in full leaf causes the transpiration to increase and the root system to spread. For example towards the end of the 4 year period 1942 to 1945 the S.E. of England was short of one whole year’s rainfall and again in 1947 only just over one inch of rain fell between the end of July and the middle of November, see Fig. 1. The damage to modern dwelling houses during these periods became very extensive. Many examples of cracking and settlement of partly completed foundations and houses have been noted during construction in the autumn of 1947.

III. ARTIFICIAL DRYING.

Examples examined recently have revealed the long term nature and magnitude of the movements associated with high temperature drying of fat clays beneath hot process buildings. A brick kiln 200 x 100 ft. in area constructed on 9 ft. of brick rubble overlying stiff-fissured Oxford clay (liquid limit 70, plastic limit 28) worked continuously for about 30 years and was then demolished. Four years later a cold process building (pan grinding shed) was constructed over part of the same site and 7 years later had settled up to 13 in. in one corner and risen 7 in. elsewhere. At this time a trial pit and borings showed that:-

a) The heat from the old brick kiln had penetrated at least the full thickness of the Oxford clay (65 ft.) causing it to shrink and crack.

b) The temperature gradually increased from 70°C. at a depth of 16 ft. to 390°C. at a depth of 35 ft., when further excavation of the trial pit was impossible owing to the intense heat.

c) The clay was oxidised to a depth of 48 ft. Some of the heat had probably been generated within the clay owing to slow combustion of the organic content (ignition loss 17 per cent. of dry weight). The observed movements of the trial pit and shed are due to the following causes:- (a) the rise of the foundations in part of the structure due to the gradual swelling of the clay as the ground water re-enters at the edge of the dried zone, (b) the settlement of the foundations in other parts due to the slaking of clays and silt-impregnated lenses as their boundaries become lubricated x).

In connection with some large extensions to another brick kiln, which had settled and cracked on dried Oxford clay, it was suggested that the possibility of damage could be reduced by constructing the retort walls of small circular brick tunnels. These tunnels provide a natural circulation of air beneath the kiln floor and thus reduce the heat reaching the ground. A series of thermocouples have been installed under both new and old kilns and the temperature conditions under the old kiln and those of the new kilns firing are given in Fig. 4. The new kilns are not yet in operation. The old kiln is about 1200 ft. long and consists of a series of chambers 15 ft. long and 50 ft. wide. The fire, rising to a maximum temperature of 1050°C. travels along the whole kiln and the firing cycle in any one chamber occupies about 12 days. It will be noted in Fig. 4 that the heat cycles are noticeable at a depth of 4 ft., and about % cycle out of phase. The temperature is apparently constant at a depth of 16 ft. in., but observations over a period of years are likely to show a steady rise in temperature at this depth.

The dried Oxford clay beneath an identical kiln which had been fired for 6 years was examined 3 months after it was closed down. At a depth of 14 ft. below the kiln floor the clay had only just dried out and could not have been raised to a temperature much above 100°C. The ground was highly cracked and many striated "slickensides" were noted due to differential movement during drying. A strong current of air issued from the cracks owing to convection and this may augment the rate of drying. The general distortion of brick kilns bears out the fact that the heat penetrates deeper under the centre of the heated area than at the boundaries. One point of practical use is that the tall chimney’s constructed in the centre of the kiln only settle and scarcely tilt, whereas those constructed at the edge of the kiln gradually tilt towards the centre of the heated area and may fall over or have to be pulled down to avoid dangerous collapse. In addition the chimneys being founded at a deeper level than the rest of the kiln (15 to 20 ft. below) are liable less than the kiln and severe cracks occur near the chimney bases.

A battery of three Lancashire boilers, each 9 ft. diameter and 10 ft. long had been in service for two winter seasons (9 weeks firing and 5 weeks damped down each year) when signs of strain in the steam and water mains suggested that settlement was taking place. A section through the structure is shown in Fig. 5, together with the temperature and water content conditions in the underlying London Clay.
Temperature and Water Content Conditions under a Group of 3 Lancashire Boilers.

FIG. 5

Half Cross Section of a Basement Cold Store.

FIG. 6

don clay (liquid limit 74, plastic limit 28, shrinkage limit 16). The boiler raft had sunk about 6 in. at the centre and 3 in. either side. The water content curves show that drying had extended to a maximum depth of 5 to 6 ft. below the foundations at the end of the second heating cycle. The normal ground temperature at a depth of 15 ft. is only 11°C.

IV. ARTIFICIAL FROST HEAVE.

Large quantities of food had to be stored for long periods during the war at low temperatures, -10°C. or lower, in basement cold stores, which prior to 1940 were used for short term transit storage at about -6°C. or higher. The long term pre-war average temperature was

severe temperature conditions the insulation normally used (6 in. of baked cork slab) was not sufficient to prevent the frost from penetrating several feet into the ground in the course of 3 or 4 years. This caused the floor and foundations to heave (4). Fig. 6 shows an example of the extent of the frost penetration, the isothermals and the frost heave after the store had been maintained at -10°C. for about 4 years. The ground was very satisfactorily sampled in an undisturbed frozen state by means of the sampling tube shown in Fig. 7 and
Soil Sampling Tube for Frozen Soil.

FIG. 7

Soil Sampling Table for Frozen Soil from under Cold Stores.

FIG. 9

Particle Size Distribution of Frost Heaved Soils from under Cold Stores.

FIG. 10
the thermocouple rods which were soil grouted into 2 in. diameter boreholes are shown in Fig. 8.

The temperature gradients (about 0.2°C/ft) and the rate of penetration of the zero isothermal (about 1 to 2 ft./year) under cold stores are much less than appears to occur generally under freezing conditions in nature, the comparable figures being 1°C/ft. and 2 ft./month in England. With this slow rate of frost penetration, water can move at a sufficient rate for ice lenses to grow even in comparatively fine grained soils and under these conditions ice lenses grow to abnormal thicknesses. The particle size distributions of frost heaved soils from under cold stores are given in Fig. 9; the clay in soils 1, 2 and 3 is comparatively inactive. Ice lenses up to 5 in. thick were found in soil 2.

The store illustrated in Fig. 6 was slowly thawed out to avoid exceptional settlement. The movements of a typical stancheon base and a point on the floor are shown in relation to the depth of the zero isothermal in the ground and the room temperature in Fig. 11. About 30 stancheons lifted 1 to 7 in. in this building and they all settled within 1 in. of design level on thawing the ground slowly.

The simplest way to avoid heaving under cold stores, where the ground conditions are favourable for frost heaving, is to build the structure above ground with a free air space beneath. The basement store is however more conservative thermally, but it is difficult to dispose of condensation if air circulation is used below the basement floor. The store illustrated in Fig. 6 has been equipped with a low temperature electrical heating grid placed just below the 6 in. of cork insulation. The electrical energy supplied amounts to about 0.15 watts/ft.² and the input is controlled by relays operated by thermocouples embedded in the soil surface so as to keep the temperature just above freezing point. This appears to be an economical method and does not reduce the headroom in the store.

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REFERENCES.