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OVERCONSOLIDATION IN SOME FINE-GRAINED SEDIMENTS; ITS NATURE, GENESIS AND VALUE IN INTERPRETING THE HISTORY OF CERTAIN ENGLISH QUATERNARY DEPOSITS

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ABSTRACT

Soil mechanics parameters, such as apparent cohesion, natural moisture content and liquid limit, are useful additional factors in determining depositional and erosional events within non- and partially-lithified sedimentary successions. Overconsolidated beds, caused by desiccation, occur in the marine Quaternary succession of the Essex coast and they indicate at least two important periods of prolonged desiccation during lowered sea levels. The older phase reflects, in part, the late- Devensian - Holocene (Flandrian) interlude of depressed base-level and extended over at least 10,000 years. The younger and shorter phase is intra-Holocene c. 4,500 B.P.

INTRODUCTION

The determination of chronological events from a sedimentary sequence necessitates an appraisal of all the inorganic and organic data presented by the sediments. In Pleistocene and Holocene marine and fluviomarine successions, where the degree of lithification is invariably small, this appraisal has been taken to include soil mechanics information (R o m i n g e r and R u t l e d g e, 1952; K e n n e y, 1963). It has long been appreciated by civil engineers that stratiform soils, that is all non-lithified bedded material resting on lithified bed rock, develop differing mechanical properties depending on their composition, texture, structure and post-depositional history. Among the multiplicity of soils parameters determinable in the laboratory and field there are several, including apparent cohesion, natural moisture content and liquid limit, which give valuable information related to the history of the sediments. In particular, they can collectively substantiate evidence for phases of prolonged emergence of original depositional surfaces only partially inferred from conventional stratigraphic lines of reasoning.

Apparent cohesion is defined as the cohesion between particles in granular soils due to capillary forces (J e r v i s et al, 1958). In part, it is related to the shear strength of soils; in general, the greater the apparent cohesion the greater is the shear strength. Liquid limit (w_l) is defined as the moisture content corresponding to the arbitrary limit between the liquid and plastic states of consistency of a soil. It is the minimum moisture content at which a soil will flow under its own weight.

In silts and clays constituting part of the coastal quaternary marine succession of east Essex, England, the apparent cohesion values vary between 0.1-1.5 kg/cm^2 and the w_l values between 16-89 per cent, though there is no systematic variation through the 35 m thickness of sediment. Detailed study of the petrography, chemistry, grain size, texture and organic content of these sediments reveal that the seemingly random distribution of cohesion and w_l values are a direct consequence of geologically important changes both contemporary with and subsequent to deposition.

OVERCONSOLIDATION

The term 'overconsolidation' refers to a soil layer which has been subject to an effective pressure

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greater than its present overburden pressure; the shearing strength is in excess of the theoretical value calculated for its present overburden. Synonyms are precompression and preconsolidation (Krynine and Judd, 1957; Skempton and LaRochelle, 1965).

The processes leading to the formation of overconsolidated layers can be grouped into those which are essentially mechanical and those where mechanical and physico-chemical factors merge in a complex inter-related fashion. The most fundamental mechanical process is loading, achieved either by superincumbent sediments or, less frequently, by the superimposition of ice-sheets. A good example of the latter is the overconsolidation of the Eocene Little Belt Clay of Jutland (Bjerrum, 1967). In both instances the affected sediments are subject to a loading in which the lowest beds, especially if fine-grained, are generally more compacted than those closer to the surface. Compaction involves a squeezing-out of pore water, a rearrangement of grains resulting in closer packing and a recrystallisation of mineral components. The net result is a decrease in the natural moisture content and increase in the apparent cohesion and shear strength values of the deposit. If consecutive phases of erosion and renewed deposition then occur, the sedimentary succession is marked acros the erosive contacts by sharp, quantifiable changes in the values of natural moisture content, apparent cohesion and shearing strength.

At Bradwell, on the Essex coast, where Holocene marsh clays (shear strength about 0.15 kg/cm^2) rest directly on London Clay (0.5-1.5 kg/cm^2) there is an expected marked change in shear strength across the junction. The shear strength values for the London Clay bear little relationship to the 3.5 m of overlying Holocene sediments and, according to Skempton and La Rochelle (1965), the London Clay was overconsolidated beneath at least 150 m of Tertiary strata which were eroded prior to deposition of the Holocene beds. Under this original Tertiary cover the London Clay was consolidated under pressures estimated at 16 kg/cm^2 greater than the load exerted at present. The Upper Cretaceous Bearpaw Shale of Saskatchewan is another heavily overconsolidated deposit where about 700 m of covering sediment have been subsequently removed.

On the site of Mystic Power Station, Boston, U.S.A. soil tests proved the presence, in brackish water blue clays, of an overconsolidated layer some 8 m thick and commencing at a depth of 8 m (Kenney, 1963). This layer appears to have consolidated under pressures as high as 9-12 kg/cm^2. Below it, the loading pressures are normal with values between 1.5-4.5 kg/cm^2. As not more than 10 m of sediment have ever rested on the overconsolidated layer it is probable that processes other than normal loading have played some part in its formation.

Terzaghi (1955) reviewed the factors involved in overconsolidation, including desiccation by prolonged surface exposure and the capillary rise of pore water towards the surface at such times. In his view, the capillary pressure generated during this movement has the same mechanical effect as heavy loading and can reach values of several tens of kg/cm^2. If a desiccated layer is again submerged it will retain the character of a heavily overconsolidated layer produced by normal loading (Blight, 1966; Skempton, 1970, p. 393).

The thickness of overconsolidated layers caused by desiccation depends on local climatic circumstances and the position of the free water level within the sediments over a given interval of time. The thickness is likely to increase as exposure is prolonged. Under humic conditions overconsolidation may occur to a thickness of 2-4 m at the surface and, in arid areas, much more. In reclaimed marshland on the Essex coast the surface silty clays are desiccated and overconsolidated to depths of 1-3 m (Skempton and Ward, 1952). The shear strength of these clays is about 0.6 kg/cm^2 decreasing to 0.12-0.22 kg/cm^2 in the underlying 10 m of silty clay. In Canada the late-Pleistocene – Holocene proglacial Lake Agassiz of Winnipeg Province was completely drained between 23,000 and 9,000 B.P. during which time prolonged desiccation occurred. The 'old drying surface', now some 13.5 m below a cover of younger clays and silts, shows overconsolidation characteristics through a thickness of up to 9 m.

OVERCONSOLIDATED LAYERS IN QUATERNARY ROCKS OF ESSEX

The importance of recognizing overconsolidated layers is well exemplified by the Quaternary history of sediments, some 35 m thick, beneath the Essex coast. The nature of these sediments has been revealed in cores from 34 boreholes put down in

TABLE 1.

Borehole	Depth (m)	Sediment type	Apparent cohesion (kg/cm^2)
1	21.2	silty clay	0.73
2	8.7	clayey silt	0.44
3	21.2	clay	1.27
5	29.2	clay	1.27
7	0.6	sandy clay	0.56
	14.0	clay	0.78
8	17.3	silty clay	0.65
10	14.0	sandy clay	0.49
13	14.0	clayey silt	0.86
14	10.3	silty clay	1.05
15	6.1	clayey silt	0.49

1969-1970. Fluviomarine and marine gravels, silts, clays and sands mantle a London Clay (Eocene) surface rendered uneven by sub-surface channels eroded during Pleistocene times (Greensmith and Tucker, 1971). Within the succession there are distinctive levels of environmental and physiographic change which are recognizable using the following criteria:-

(a) a sharp vertical change in lithology e.g. silty clay to medium sand
(b) changes in faunal content e.g. brackish-water fauna to open marine fauna
(c) increased carbon content usually as peat traces
(d) rootlet traces
(e) mottled structure in silty clays caused by rootlets and the burrowing activities of tidal flat organisms
(f) fissuring of silty clays caused by exposure and desiccation
(g) changes in Fe_2O_3/FeO ratio with values rising to 4
(h) colour changes related to the formation of limonite
(i) cementation by limonite, especially in coarse silts and sands

It is generally at these levels that overconsolidated beds occur.

Table 1 lists representative firm, overconsolidated silt and clay layers possessing many of the features listed above. The apparent cohesion of these beds varies between 0.44-1.27 kg/cm^2 in contrast to the apparent cohesion of the interbedded soft, plastic silty clays (0.14-0.3 kg/cm^2); the local London Clay varies between 0.88-2.55 kg/cm^2. It is remarkable that the apparent cohesion of some overconsolidated layers equals that of the London Clay. Especially is this so when it is realised that consolidation of the London Clay was achieved under a cover of at least 150 m of later Tertiary sediment, whereas the maximum possible cover for the overconsolidated layers in the Quaternary succession was at maximum only 35 m. Moreover, the superficial silty clays are less rich in montmorillonite ($<$ 10 per cent) than the London Clay (c. 20 per cent), this clay mineral being notable for its marked susceptibility to dehydration under increasing loading.

Values for the natural moisture content and liquid limit are generally lower for the overconsolidated beds when compared with the immediately adjacent beds. When apparent cohesion is plotted against (a) natural moisture content and (b) the liquid limit the accordance between overconsolidation and the lowered values can be appreciated (fig. 1). Overall, the total evidence suggests that the overconsolidation results from prolonged desiccation processes which are additional to normal loading effects. This, in turn, implies varying degrees of emergence of the sediments above sea-level such that these desiccation processes could become fully operative.

The spatial distribution of overconsolidated sediments in the southeast Essex coastal belt is shown in figure 2, together with the levels at which peat fragments are concentrated. The peat concentrations, within a silty clay matrix, are considered to have formed near high-water mark.

The most significant concentration of overconsolidated beds occurs at depths varying between -11.5 and -33 m Ordnance Datum (Newlyn). The apparent cohesion values range between 0.49-1.27 kg/cm^2. Individual seams are up to 3 m thick but the preserved aggregate thickness of beds reaches 5-6 m

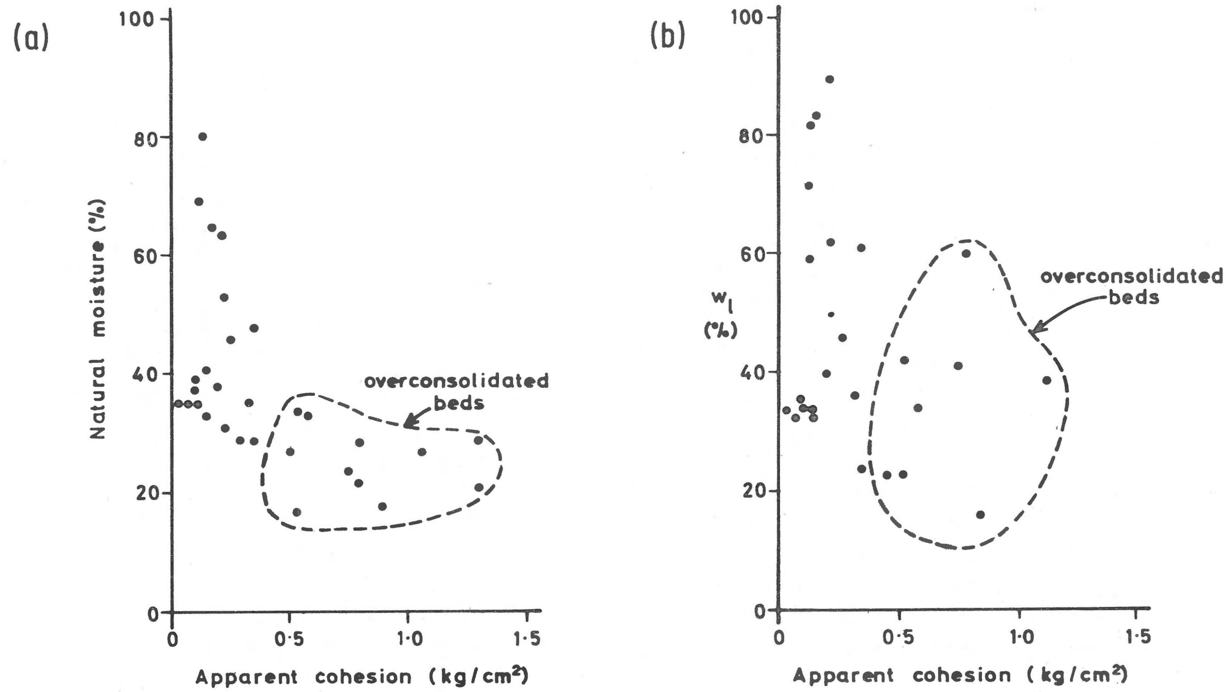

Fig. 1
Soil mechanics data from cores of new boreholes put down in east Essex Quaternary seccession.

along the axes of some subsurface channels (e.g. boreholes 1 and 5, fig. 2) and 4 m on adjacent interfluves. At Shellhaven, in the Thames estuary and 20 km westwards, a thickness of 3 m has been recorded from a depth of –8 m O.D. (Skempton and Ward, 1952). These thicknesses are residual and the thickness variation in part reflects subsequent phases of erosion. The total evidence suggests that these thick levels of overconsolidation are lateral correlatives and represent a major phase (or phases) of desiccation in the area and, by implication, lowered sea-level. In borehole 10 the overconsolidated surface is overlain immediately by a peat-rich seam dated at 7516 ± 250 B.P. (cf. 7,000 B.P. at Tilbury Docks – in Skempton, 1970) so it is clear that the period of prolonged exposure preceded this date. It is not unreasonable to surmise that this period extended over at least the time between lowest sea-level of late-Pleistocene (Devensian) times (18,000-20,000 B.P.) and local marine inundation during the Flandrian transgression. The time interval may well have been much longer, even extending into pre-würmian times, because in the axial areas of the deepest subsurface channels there is clear evidence of at least two phases of prolonged emergence and desiccation (borehole 1, fig. 2). The thick overconsolidated silty clays are interspersed with soft silty clays and gravels and there are alternations in brackish and marine water facies (Greensmith and Tucker, 1971). It is probable, therefore, that the strongly overconsolidated layer on the interfluves is composite (polycyclic) in origin.

Above this regionally identifiable major surface the overlying Flandrian sediments of the Essex coast are a classic example of a 'coarsening-upwards' marine transgressive sequence. This is most noticeable in the axial parts of the subsurface channels which clearly were the first to be influenced by the Flandrian transgression, and is expressed there by some 23 m of brackish water silty clays passing upwards into silty clays of intertidal origin and, ultimately, sands carrying a fully marine fauna. On the interfluves, however, deposition was discontinuous being indicated by firm overconsolidated beds sometimes closely associated with peat-rich layers (boreholes 8, 12, 14, 15, fig. 2). The apparent cohesion of these firm beds, which attain residual thicknesses of up to 2.5 m, is 0.3-0.45 kg/cm². In view of these thick-

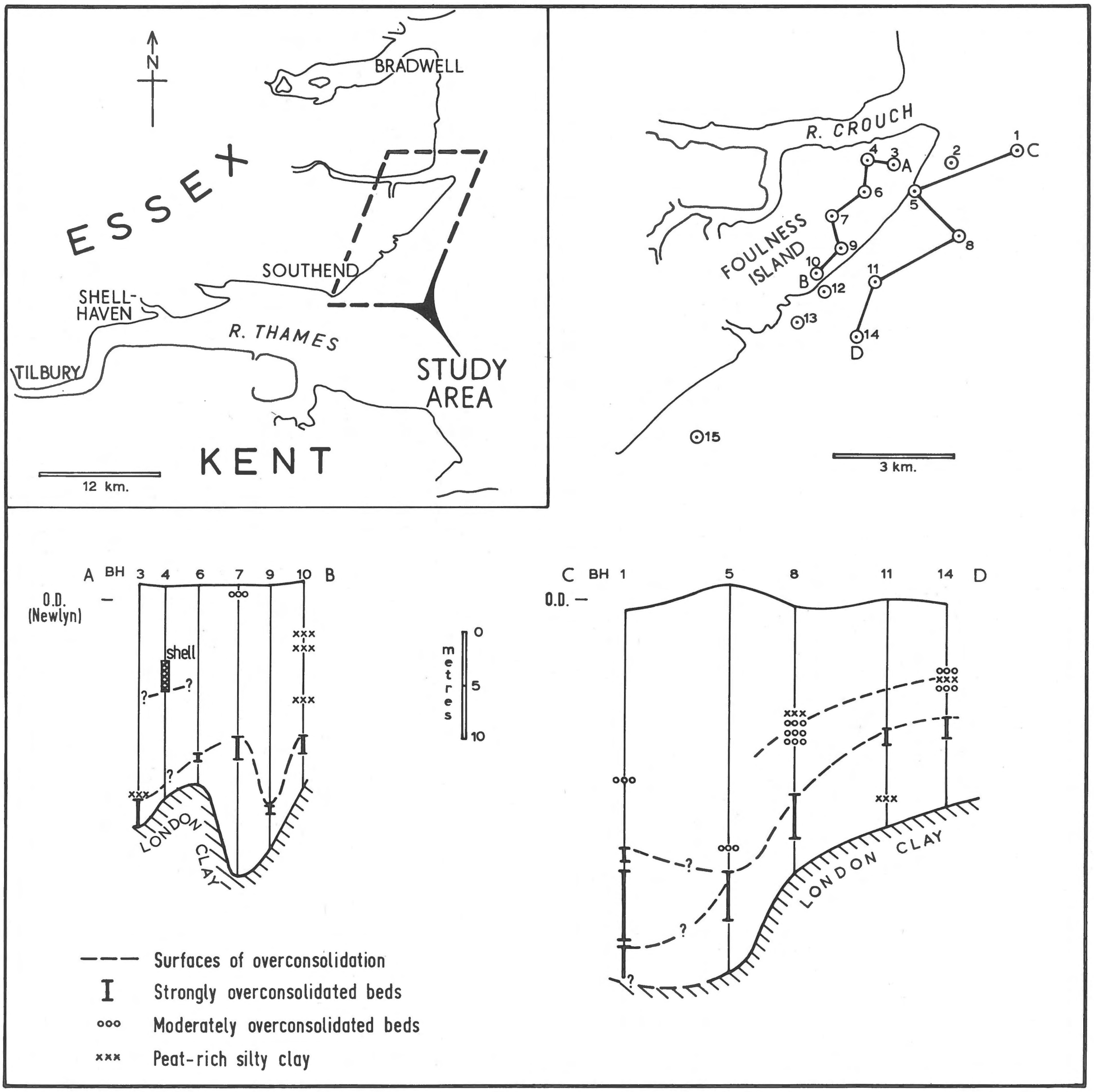

Fig. 2
Location map and sections in the east Essex Quaternary successions showing the proposed correlation of the major overconsolidated levels.

nesses it is likely that the firm beds again reflect episodes in the history of the area when sea-level was lowered. The dating of these episodes of intra-Holocene lowered sea-levels is difficult to assess but, with regard to what is probably the most important episode, the age appears to pre-date c. 3,900 B.P. (boreholes 4, 8, 14, fig. 2). An intertidal shell bank at a depth of –8.5 m O.D. in borehole 4 yielded radiocarbon dates of 3580 ± 175, 3912 ± 110 B.P. At Tilbury, some 40 km westwards in the Thames estuary a peat bed at –5 m O.D. was dated at 3940 ± 110 B.P. (Godwin et al, 1965). It is possible, therefore, that this lowering may equate with the 'Bahama emergence' of Fairbridge (1958, 1961) during which, he suggests, eustatic sea-level fell by 3 m (maximum) during the interval spanning 4,000-5,000 B.P.

CONCLUSIONS

Soil mechanics data when used in conjunction with conventional stratigraphic information are powerful tools in the interpretation of complex marine successions of Quaternary age. At least two major episodes of overconsolidation of silty clays can be recognized in east Essex and the thicknesses of strata affected suggest that this overconsolidation was not a short term desiccation effect due to a phase of low tides in a dry climatic period (contrast Skempton, 1970, p. 387). It is much more likely to have been long term desiccation measurable in hundreds (or thousands) of years and caused, fundamentally, by lowered sea levels. The lowest and areally most widespread overconsolidated level recognized in the Essex succession is probably composite in origin and was formed prior to 8,000 B.P. and the onset of Flandrian sedimentation. It represents an exposure period of at least 10,000 years.

The intra-Holocene overconsolidated beds generated at c. 4500 B.P. strongly suggest prolonged emergence and they appear to support the view that sea level has not risen consistently through Holocene times. Hence, the conclusions of Umbgrove (1947) and Zwart (1951), among many others who favour a Subboreal fall in sea-level, seem to be justified. The contrary opinion of no fluctuation during Holocene times is not supported (see Jelgersma, 1961, p. 46-47 and de Jong, 1967, p. 382).

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