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Regional Geotechnical Investigation of the Milton Keynes Area

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Volume 1. Preliminary Report

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REPORT ON FIRST STAGE GEOTECHNICAL INVESTIGATION OF MILTON KEYNES

1. INTRODUCTION

Location

The siting of the designated new city of Milton Keynes was determined by its geographical location in relation to population and commercial requirements. In 1962 it was decided by the Buckinghamshire County Council that a new city with a population of 250,000 in North Buckinghamshire would effectively meet the needs of the locality and of the Greater London area. Though the Council sponsored scheme did not proceed, the initial feasibility study proved a valuable background for the more precise location of the designated area of the new city of Milton Keynes.

Milton Keynes lies across the most important transport route in the country, from London to the north west, about half way between London and Birmingham. The new city is also situated centrally in the main populated and urban part of England and Wales in an area of expanding population and employment. The area is no stranger to development schemes, having successfully fostered the new towns of Wolverton and New Bradwell and the recent expansion of Bletchley.

Importance of Geotechnical Investigation

In any project of this scale geotechnical information must be equal to the demands of the development programme. An overall assessment of the engineering behaviour of the geological units encountered over the area can permit design criteria to be established for both linear structures, such as roadways, tunnels and waterways, and compact structures, such as buildings, bridge piers and dams. A detailed investigation for a particular construction can then establish any amendments to the general design criteria necessary to overcome unfavourable local conditions.

In the case of the development of a new city both linear and compact structures abound.

Their distribution over the whole site is primarily governed by human factors and only in the case of extremely unfavourable ground conditions causing unwarranted extra expenditure need geological conditions interfere with this system. The possibility of trends of engineering properties existing in the various geological units is investigated here with a view to optimising the geotechnical data as it becomes vailable. This study also permits an assessment of the representativity of data from a given unit with respect to surrounding material within that unit so that detailed foundation investigation programmes may be derived for all types of structures.

The Present Investigation

The investigation was carried out under the general supervision of the Engineering Geology Unit of the Institute of Geological Sciences. This arose from discussion between the Milton Keynes Development Corporation and the Institute when the Development Corporation made it clear that they would welcome a survey of the geotechnical properties of the various rock types and superficial deposits found in the area. It was agreed that this survey was a logical development from the recently revised geological mapping of the area by members of the I.G.S. field staff, South of England units. The development Corporation agreed to pay the cost of contract drilling some 30 boreholes and the necessary laboratory testing. The Institute agreed to provide staff for the supervision of the programme and to put down shallow auger holes to obtain samples for additional laboratory testing. It is proposed to incorporate all the borehole and field results obtained within the area up to December 1969 into a final report and series of engineering geology maps or overlays. The present report summarises the findings from the Institute's surveys to date (October 1969) and gives some details of the engineering characteristics of the geological materials found in the area.

The support and co-operation of the Milton Keynes Development Corporation is acknowledged. In particular we are grateful to the staff of the Engineering Section and the Estates Department who assisted greatly in arranging access to land.

We should also like to thank W.S.C. French Ltd., Crailius Co Ltd., and the MPBW Soils Laboratory, Cardington for carrying out the main drilling and laboratory testing programmes.

At the Institute, we are grateful to the Geochemical Division for carrying out sulphate analyses on clay samples.

Mr. P. Grainger and Mr. P. Collins of the Engineering Geology Unit did a considerable amount of soil testing in temporary and often uncomfortable laboratories.

Geological Units

The solid geology within the designated area consists of strata of Jurassic age, dipping gently to the South East. These units are covered in part by recent drift materials of a variable nature. The oldest strata exposed in the area are the Middle Jurassic series outcropping only in the North West around Wolverton and Bradwell Abbey. Above these in the geological succession is the Oxford Clay which makes up the solid geology outcrop over the rest of the area.

Boulder Clay, mainly consisting of derived Oxford Clay, chalk and flint pebbles, sand and gravel provides a blanket of up to 100 ft thick over the majority of the solid material especially in the centre, South and West of the area. In the various river valleys these are irregular deposits of Alluvium, Head and Terrace Deposits. One local feature of special interest is a glacial lake deposit consisting of Varved Clays and silts.

The engineering significance of these units is discussed along with their environments of deposition in the following sections.

System of Geotechnical Mapping

The approach to mapping engineering properties of the various units depends on the type of material. The geotechnical mapping of the solid geological units is based on the knowledge that the beds are fairly consistent in thickness and lithology over the area under consideration. Palaegeographical considerations lead to the conclusion that there probably exists a low amplitude trend of all the engineering properties over the whole area with possible local residual trends, as explained in the following sections. These considerations permit the development of borehole programmes to optimise regional mapping input data and safely reduce further local investigations in these units.

The geotechnical mapping of the drift deposits acknowledges that the units vary considerably in thickness and, often, lithology sometimes over a very small area. From a knowledge of environments of deposition it can be predicted that over the total thickness and extent of any of the drift units there will be a series of high amplitude residual trends of engineering properties disguising or completely overshadowing any general trends. These considerations necessitate the large scale investigation of the engineering properties to determine the degree of confidence in extrapolation from any data collection point. As suggested later the representativity of parameters taken from a practical borehole programme in certain of these units is questionable, while in others it may be valid.

Implications of various environments of deposition

There are essentially four types of depositional environment illustrated by the geological units in the Milton Keynes area. The solid units are representative of sedimentary deposits in a shallow marine and marine environment. The recent alluvium, terrace deposits, glacial gravels and glacial lake deposits are representative of sedimentary deposits in a freshwater environment, some fluviatile some lacustrine. The boulder clay is representative of mechanically lain materials from a dynamic environment beneath or around an ice sheet. The head is representative of physically (and possibly chemically) altered materials from a static or near-static environment, sometimes termed a residual environment.

The over-riding implication of the marine environment is that the depositional conditions were essentially similar over the whole area so that there is a high probability that any trends of properties will be gradual. This should permit their accurate mapping on a regional scale and a very high degree of confidence in their representability.

The primary implication of the freshwater environments is that the depositional conditions varied over even the small areas of the sedimentary basins so that the materials tend to form lenses or discontinuous beds. This implies that trends of engineering properties will be of a higher amplitude and less consistent than for the marine environment, thereby reducing the degree of confidence in extrapolating from a data point. The lacustrine environment prevailing during the deposition of the glacial lake materials provided conditions more constant in areal extent than the other freshwater environments ,but more variable in section.

Outline of Present Investigation

The present investigation attempts to put the above considerations into practice for the designated area of the new city of Milton Keynes. The Middle Jurassic beds are investigated with a particular engineering project in mind, the sewage tunnel through the central high ground. As their outcrop is restricted to the already-built up North West of the area their engineering importance is not very great with the exception of the tunnel project so it was not considered particularly useful to map their geotechnical properties beneath the rest of the site.

The Oxford Clay, which forms the majority of the solid geology outcrop, provides an opportunity to map geotechnical properties of a fairly uniform material. The main object of the undertaking, therefore, is to demonstrate this uniformity and determine any trends imposed upon it. For this purpose a range of boreholes was introduced over the designated area. Unfortunately because of the excessive thickness of overlying drift material over much of the area and the difficulty in determining an individual horizon within the Oxford Clay, it was not possible to examine the trends minutely. Some of the results that are correlatable are mapped in Fig 1 to illustrate the potential of this type of mapping and provide an initial estimate of the variability and trends for one horizon.

The Boulder Clay, which blankets most of the site and is consequently very important to an engineering undertaking of this kind, provides an example of a geological material which is very unpredictable in character. The investigation programme to date has examined the units variability on every scale from sample separations of the order of a kilometre down to sample separation of the order of twenty centimetres. Figs 2 and 3 illustrate the findings and underline the great variability of the material on every scale.

As it would appear that there is to be very little construction on the Recent Alluvium, River Terrace Deposits, Glacial Gravels or Head, a similar investigation of these materials has been withheld until particular engineering projects probably concerned with water works are envisaged. This avoids the study becoming an academic exercise as would otherwise be the case. The exception to this is the Varved Lake material on which it is known there is to be a water retaining structure. When funds become available it is hoped to investigate this unit as an illustration of the application of engineering geology techniques to specific engineering project

2. JURASSIC STRATA BELOW THE OXFORD CLAY

The following is the sequence of strata below the Oxford Clay which outcrop within the Milton Keynes designated area

Kellaways Sands
Kellaways Clay
6 Cornbrash
5 Blisworth Clay
4 Blisworth Limestone
3 Upper Estuarine Series
2 Lower Estuarine Series
1 Upper Lias

The solid strata, which comprise the above beds together with the Oxford Clay, has a general dip to the south-east with this area. Thus these lower strata are exposed in the north and northwest, particularly where the Ouse has cut down below the mean level.

1. Upper Lias. This is the oldest series exposed in the Milton Keynes area and its outcrop is limited to a small area in the Ouse Valley around Stony Stratford and Wolverton. The rocks are uniform clays deposited in an entirely marine environment. For engineering purposes they could be regarded as similar to the Oxford Clay, though the actual values of their properties are slightly different.

The basal beds of the Upper Lias, though not seen at the surface, have been encountered in the Linford gravel workings. They consist of limestones and marls, but it is very unlikely that these would be met except in very deep foundations in the Ouse valley.

The top of the Lias is marked by a major erosion surface. The overlying Middle Jurassic strata were deposited in a variety of environments, ranging from continental to marine. This is reflected in the variability of the beds and consequently their properties.

2. The beds of the Lower Estaurine Series (L.E.S.) are entirely continental. They were waterlain under deltaic and fluviatile conditions. Two facies have been encountered.

a) The white sand facies. This is composed of pure clean sands and silts, occasionally ferruginous.

b) The clay facies. In this one find poorly sorted silty clays, with a few fine sandstones. The rocks are generally dark coloured and sometimes contorted.

These variations in lithology may be encountered both vertically and horizontally within relatively short distances. The properties of the series are exceedingly variable, but they are generally of very low strength. Known thicknesses range from 10 - 40 feet.

3. The Upper Estaurine Series (U.E.S.) contains two lithologies:

a) A calcareous group of marls, fossiliferous clays and limestones, together referred to as the Upper Estaurine limestone. This lies at, or within a few feet of, the base of the U.E.S. The limestones which usually predominate are in some places hard and massive, in others argillaceous and weak. Usually 6-10 ft thick.

b) The remainder of the U.E.S. is composed of variegated multicoloured green-grey clays with some silts and calcareous bands. The lithology is very variable vertically, but tends to fall into cycles. The properties may be expected to show similar variability to those of the L.E.S. but on the whole the rocks are slightly stronger.

The series as a whole was deposited under lagoonal and deltaic conditions with some marine incersions, notably the Upper Estuarine Limestone. The thickness of the whole series has been seen to range from 30 to 40 ft.

4. The Blisworth Limestone is entirely calcareous, in the main being a hard massive limestone. Marl and clay bands, up to 2 ft in thickness are quite common. The formation is wholely marine and in thickness varies from 20 to 30 ft. Although joint spacing appears to be quite frequent, the bedding planes may be several feet apart. This fact, together with the extreme hardness of the rock in some places, would make it a very difficult formation to excavate, except within about 10 ft of the surface, where it weathers to a flaggy limestone. In tunnelling operations, the hard, massive parts of the formation would be difficult to excavate but may be expected to stand without too much overbreak. Problems may be encountered where marl and clay bands occur.

5. The Blisworth Clay is a variable group deposited under lagoonal and deltaic conditions, with infrequent marine phases. In most respects it is comparable to the clay facies of the Upper Estaurine Series. In the lower two thirds it is usually a purple brown very plastic clay while the upper third is often grey-green and somewhat siltier. At outcrop it produced plastic clays, which are usually less silty than those of the U.E.S. Known thicknesses range from 12 - 20 ft.

6. The Cornbrash is in many respects similar to the Blisworth Limestone, but the proportion of clay is much lower and there are no marls. In lateral extent it is a very uniform formation, having been deposited under entirely marine conditions. In the Peterborough district it is generally a good founding material but it weathers easily to a rubble and in the Milton Keynes Area it appears to be well jointed and fractured so that it may not perform so well under foundations. On the other hand it would be a much easier material to excavate than the Blisworth Limestone. Its thickness varies between 2 and 8 ft.

7. The Kellaways clay is a thin, very uniform clay deposited in a marine environment. It is generally strong and its properties compare closely with those of the Oxford Clay. 3 to 6 ft thick.

8. The Kellaways Sands comprise a variable sequence of fine sands and silts. The properties show a limited range of variation, though greater than for the adjacent clays. Occasionally some cemented pockets of sand are encountered; these are referred to as 'doggers'. This marine formation is 10 - 15 ft thick.

3. OXFORD CLAY.

Environment of Deposition

The depositional environment of the Oxford Clay was shallow marine to marine depending on the individual horizon. The lower beds are of shallow marine sediments, containing typical near-shore clastic materials with consequent reduction in the microfaunal population. Another feature of these conditions is the occasional channelling on the sea bed which reflects itself presently as a change in the thickness of the now-consolidated beds over a range of several tens of metres. A further consequence of this channelling is the apparent occurrence of frequent low amplitude residual trends on the general offshore trend of properties. The major problem, from the point of view of obtaining correlatable results, is that it is very difficult to determine exact boundaries between the lithological units within the lower Oxford Clay because of the scarcity of type microfossils.

The higher beds are of marine sediments, with much less coarse clastic material and consequently a greater deeper-water microfaunal population. The conditions of deposition of these beds, being further from the ancient shoreline, were more quiescent. This permitted a less-interrupted gradation of material in an off shore direction, which should be presently reflected by a low amplitude trend of engineering properties from North West to South East over the designated area.

Engineering Implications of General Properties

Unfortunately the higher beds outcrop only in the South East of the designated area and are then often covered by drift. The lower beds, which are not so readily correlatable outcrop in a broad South West to North East arc through the centre of the site, often covered by extensive drift deposits. The lower beds are of considerable engineering importance because of their extent over the designated area and a preliminary geotechnical map has been prepared (Fig 1 - See Appendix 1 for interpretation technique) for one of the most precisely defined horizons. Five sites were specially chosen for this pilot study and it is thought that the initial success, even with this loosely defined zone, justifies an extension of this method to other horizons and a closer separation of data points.

From the map of geotechnical properties it can be seen that the general trend of engineering properties from North West to South East is very gradual and of small amplitude; for example, the total range of Liquid Limit can be seen to be only 8%. The other index properties exhibit a similar range and general trend. Superimposed on the general trend is a residual (or local) trend in the neighbourhood of present day Simpson. This appears as a "clay sink" by interpretation of the engineering properties, suggesting a possible deeper trench in the near-shore environment in that area at the time of deposition. This supposition requires further investigation before compiling a final geotechnical map. Similar trends would be expected in other horizons within the Oxford Clay but with fewer residual trends and any that exist would be of a lower amplitude, i.e. the range of properties would be lower.

It is stressed that all the properties quoted are used as index parameters at present. It would be unwise to use the undrained strength values in design without ascertaining the degree of weathering and other possible disturbance to the samples. Such alterations to in situ unweathered material can cause reductions in strength of an order of magnitude.

It can be seen from the profiles of various engineering properties for boreholes 16 and 24 that it would be possible to misinterpret such profiles in terms of engineering significance if samples were taken at too great a separation in profile. This is illustrated quite well by comparing the profiles of, say, Liquid Limit for the two series of tests performed for each hole, one with samples at a separation of about ten feet the other of about three feet. The profiles are distinctly different and any zonation for design purposes based on this would differ in each case. As it must be accepted that the closer separation of data provides the most accurate profile, this serves as a strong recommendation for close separation sampling even in fairly uniform materials.

Engineering Implications of Trend and Range of Properties

The total range of index parameters for the horizon illustrated suggest that for that bed, and therefore, by inference for all those above it in the Oxford Clay it could be considered as a uniform material over the designated area for the purposes of engineering design. Therefore, it would appear that over this area the low amplitude trend in these beds has no significance to engineering projects. However, again by inference from consideration of the depositional environment, it would appear that there could be a greater range of properties and more local trends in the lower beds of the North West of the area. This greater variability could be of engineering significance, especially as one particular property, the cohesion, could become locally very low so that the safety of short term excavations designed on general values would be suspect. This is, therefore, a field for further detailed investigation, requiring new techniques for correlation.

The average properties for the Oxford Clay in this area suggest that it is generally a stiff fissured silty clay.

4. BOULDER CLAY

Environment of Deposition

Boulder clay, or till, is an omnibus term given to products of the erosional and depositional activities of glacier ice. Eroding ice picks up rock fragments of all shapes and sizes as it advances together with rock-flour resulting from ice abrasion. In general deposits laid down directly from ice have not been subjected to the action of water and consequently are characteristically unsorted and unstratified. Till is deposited largely near the margins of ice sheets where the ice is relatively thin (measured in hundreds of feet compared to thousands of feet near centres of accumulation).

Two general types of till are recognised - ablation till and lodgment till. Ablation till accumulates on the surface of a glacier by the melting out of englacial material. It is characterised by the presence of abundant angular and unstriated boulders, a high proportion of sand and gravel and small amounts of clay; the texture is loose and it therefore oxidises rapidly and is commonly brown or yellowish brown in colour. Lodgment till by comparison is very compact and contains fewer and smaller stones which are rounded and striated. The proportion of silt and clay present is high and consequently permeability is low; oxidation proceeds very slowly and this till is usually grey in colour.

Although tills appear to be heterogenous, unsorted and unstratified masses structures may be present which affect strength and permeability. These include the parallel orientation of silt and clay particles and the preferred orientation of the long axes of pebbles and boulders - generally in the direction of ice movement. Compact bands or irregular bodies of sand and/or silt resulting from the activity of englacial water may also be present. Oblique joints often occur, resulting from marginal shearing in the ice sheet or post-depositional dessication, and they may be faced with thin layers of compacted sand.

Engineering Implications of General Properties

The cover of Boulder Clay is of sufficient extent to merit special attention with respect to engineering construction on it. It was decided that, as much of the proposed new construction is planned for sites covered by the Boulder Clay, the investigation should cover the whole area with extra consideration given to the tentative new city centre near Little Woolston. With this in mind a shallow borehole programme was carried out over the whole area on a system which, when coupled with the rest of the borehole network, provided a grid with separation of data points at about five hundred metre intervals. The results of this demonstrated the variability of the unit to be large over the whole area as can be seen by scanning the borehole logs containing Boulder Clay (in Appendices)

As no trends were immediately apparent on the small scale a trench, twenty metres long by one metre wide by four metres deep, was dug near Little Woolston exposing a section of Boulder Clay. The results of index testing on a one metre interval grid are shown on Fig 2 for a longitudinal section of the trench. It can be seen that the usual index tests (Atterberg Limits and Specific Gravity) show consistent trends in profile but these trends are generally of an order of magnitude less in extent than a building foundation. To further examine the variability of this material a one metre square within the grid was further divided by sampling at twenty centimetre intervals. Fig 3 shows that the range of the index parameters is as great over this scale as over that of the trench and generally over the whole of the designated area.

It was decided to adopt a convention of cross-hackering that shows clayey zones as more heavily hackered in every case for the Boulder Clay properties. At a glance it is therefore evident that there is strong agreement between all the index properties except the Bulk Density. Moderate agreement is to be expected but such a close relation lends extra confidence to the testing accuracy.

Assuming the accuracy of the Bulk Density determination to be equally accurate it must be accepted that there exists greater variation in it. Generally there is a trend similar to that of the other index properties but with different residual trends upon it. There is an overall vertical trend superimposed on this system. It would be expected that this overall trend would extend over the whole designated area as indicated by other boreholes. The occasional residual trends, contrary to normal expectations of sandy zones being more dense than clay, support the accepted concept of dynamic placement without much consequent over loading.

The major engineering implication of the results of this investigation is that any practical borehole programme in Boulder Clay will generally not give results that are representative of neighbouring areas only a metre or so away. Consequently the usual borehole technique is reduced to a tool for exploring the total thickness of the unit and finding excessive anomalies of engineering importance, e.g. buried glacial lakes, very large boulder, etc.

It would be expected that the variability of engineering properties would decrease with depth and removal of the more variable material above may be an economic proposition for major construction in many cases. In other cases, large scale in situ testing could be most valuable.

Engineering Implications of Trend and Range of Properties

The range of index properties is generally about four or five times as great over an area as small as one square metre as it is at any given horizon in the Oxford Clay over the whole designated area. The range of engineering design parameters would be even greater because the standard methods employed on the index testing require only the small fraction of the material in general. The overall range of properties includes those associated with almost pure clay, uniform silt or sand, well graded sandy gravel, and rock and clay admixtures. The lensed nature of these materials would required their removal from beneath water retaining structures.

Trends of properties are often general over a distance of several metres with more local trends superimposed on them. All the trends can be very abrupt no matter what their amplitude. For design purposes this distribution of properties requires that no one value of any property may be assumed for any foundation problem unless it is a generalised property determined for the whole of the material affected by that foundation.

The establishment of economical design criteria was further complicated by the discovery of a local slip plane cutting the trench along a local bedding plane. The slip was in a very weak clay layer between a coarse sand in a clay matrix and a firm clay. The weak layer was only about one milimetre thick and certainly indistinguishable in disturbed borehole sampling and to all but the very practised eye in undisturbed sampling. The slip was down dip at about 15° to the horizontal. Any such plane beneath a foundation designed on even a general average porometer could prove catastrophic.

5. ALLUVIUM

Environment of Deposition

The depositional environment of alluvium is freshwater. In the Milton Keynes area the alluvium was laid down by the present river system which has since altered only slightly by local meandering so that the unit occupies only ribbons up to half a mile wide about the existing rivers. The material is graded by the local currents and deposited on the river bed. As can be seen by analogy with present small rivers the material tends to be deposited in the slack water and eroded from the fast run around meanders. This type of deposition results in the formation of lenses of material. However, fluvial regimes of this scale provide a fairly uniform range of materials so the lenses are barely distinguishable for engineering purposes. The exception to this is the occasional silt lens corresponding to a historic flood time. A practical borehole programme should discover any such lens of engineering significance. The environment has basically not changed in this area during the deposition of the alluvium so no erosion of the recent material has taken place, leaving it in a normally consolidated state.

Engineering Implications of General Properties

As the alluvium occupies only the borders of the present river network it is of importance only to water retaining structures and occasional roadway foundations and small buildings. It has not, therefore, been investigated in detail as it should be grouped with the several other units beneath it when investigating the foundations for specific water retaining structures. However, in general terms there are two main engineering implications of such materials in this context. The consolidation characteristics of alluvium generally indicate a large amount of settlement under even normal engineering loads and, if there is too great a thickness of it for economic removal, embankments on it should be designed to accommodate this settlement to avoid breaches in dams or cracking of road surfaces. The presence of occasional large lenses of more permeable material could provide a natural water bypass beneath a water retaining structure, especially if excessive settlement caused cracking in the surface material to provide easy access to a lens. A further property of engineering significance is the general weakness of material but fortunately the weakness is obvious and general.

Engineering Implications of Trend and Range of Properties

The range of properties for these materials is not generally great except in the occasional permeable lenses. This usually permits the assumption of generalised design parameters over the limited area between the data input points of a practical borehole programme. In this particular regime it would be expected that any regional low amplitude trend would be overshadowed by residual trends of the scale of a compact structure but, apart from silty and sandy lenses, no trends should be of a high enough amplitude to defeat normal engineering site investigation methods.

Any permeable lenses of engineering significance should become evident from a normal practical borehole programme along with their properties, the most significant being grain size distribution and permeability. Generally there is an abrupt division between these lenses and the surrounding material, reflecting the depositional conditions so they are not predictable by the onset of a gradual local trend.

6. RIVER TERRACE DEPOSITS AND GLACIAL GRAVELS

Environments of Deposition

River Terrace Deposits

Sands, gravels and silts are deposited in the middle and lower reaches of a river valley due to the loss of load bearing capacity of the river resulting from a reduced velocity of flow. Reduction in flow velocity occurs in one or both of two circumstances: the lower elevation above base level and greater width of the river channel in the lower reaches of a valley, and/or raising of the base level resulting from a rise in sea level.

Terraces which develop in the lower reaches of a river valley are thalassostatic, i.e. they result from the response of the river to fluctuations in sea level. A permanently flowing river, under stable eustatic conditions, is in a permanent state of erosion. Terraces are formed by the interruption or intensification of vertical erosion due to the rise or fall of sea level.

The periodic general lowering of sea level during the Pleistocene period is correlated to periods of extensive glacier expansion as also are the cutting of erosional benches of rivers. A rise in sea level following a glacial episode is correlated to an amelioration of climate and the aggradation in the lower reaches of a valley largely takes place under temperate conditions. In general terms river terrace deposits were laid down during temperate or warm periods and river channel benches were cut during cold or glacial phases. Often the first materials to be laid down on a river bench were solifluction deposits, indicative of a cold climate, these are poorly sorted and unstratified. The later temperate fluviatile aggradation consists of sands, gravels and silts, often coarser towards the base, well sorted and stratified. Channelling and reworking of the deposits is common.

Glacial Gravels

Glacial sands and gravels are deposited from melt waters issuing from the margins of a glacier. Sub-glacial and englacial debris is laid down both in and above the level of local standing water to form sheets of outwash in which sorting has occurred and where stratification is more or less regular. Grain size of these deposits depends on the outwash load and the distance from the melt water source; the coarsest grades are deposited near the source and the finest further down stream.

Outwash deposited above local water level builds up fans with irregular surfaces which are channelled by small streams. Sub-aqueous deposits form deltas showing more regular sedimentation built up of the coarsest parts of the load shed by the melt waters. Further downstream rafting by ice may introduce coarse materials into finer sediments.

Outwash fans vary in size depending on the number and size of melt water streams, load and length of time of formation. Some outwash plains are pitted by kettleholes indicating that when the ice front receeded blocks of ice were left in the accumulated sediment. Outwash deltas have more even surfaces which are formed from the topset beds. If outwash is confined to a pre-existing valley a valley train may be built up by aggradation of the melt water load and terraces may be cut in the infilling as a result of the lowering of the local base level of the proglacial stream.

Engineering Implications of General Properties

From the point of view of engineering constructions on these materials there are only a few problems resulting from the general properties; these are related to the absence of fine material. The presence of any of these materials in a natural condition beneath or in the flow path around a water retaining structure would render the scheme economically unviable, owing to the excess drainage through the more permeable material. Both sorts of coarse grained material tend to be in beds that are continuous over the extent of a compact engineering construction or in large lenses often of equal extent. Another feature, particularly of the Glacial Gravel, is the common occurrence of well sorted zones of material from coarse gravel, sometimes in a matrix of silt, down to silts. When subject to hydraulic gradients greater than critical these materials assume a quicksand condition. This is not an insoluble problem and it can be predicted and overcome in virtually every case at very little cost provided one is aware of its possible occurrence. In certain cases, moderately sorted material subject to high hydraulic gradients can become devoid of fines, the smaller fraction, so that it supports "pipes", or local quicksand conditions, which can cause excessive leakage and/or catastrophic collapse in or near water retaining structures or deep excavations below water table level.

A further implication of the particle size distribution of these materials relates to their strength under various conditions. In free drainage cases the gravels and sands will not stand freely in excavation except in the very short term case. When there is a finer fraction included in the matrix it will prevent very short term drainage and permit the material to stand freely for a little longer until it drains. This is the most dangerous in that it can offer a false sense of security. In normal drained bearing conditions all these materials make excellent foundations, having a high strength and low settlement properties.

Engineering Implications of Trend and Range of Properties

The important properties are mainly the grain size distribution and permeability. Any trends determined for permeability would permit major leakage channels to be predicted and counteracted. The range of permeability would cover several orders of magnitude in these materials but it would be difficult to grout only the most permeable zones against leakage. Therefore, the whole of the profile through the unit would have to be grouted and a knowledge of any trends in permeability would permit a close estimate of grout take.

Trends of grain size distribution would not only permit a prediction of zones likely to be liable to adopt a quicksand condition but would also be economically useful in forecasting the optimum sites for gravel and sand exploration.

7. HEAD

Environment of Formation

These materials were formed essentially in position from indigenous materials, either by physical and/or chemical alteration of local materials in situ or by the slow accumulation of material from hillside creep or late glacial mud flows. The regime has remained largely unaltered since their formation. They have been subject to little or no erosion and are, therefore, essentially normally consolidated. There exists a remote possibility that some of the material in this unit may never have been completely below a water table nor completely waterlogged since its formation so that it could be locally metastable. This is a condition that would occasion excessive settlement after the completion of an engineering construction if it were later flooded.

Engineering Implications of General Properties

The engineering behaviour of this unit is likely to be similar to that of Alluvium. It is likely to be moderately compressible but will generally be found to be stronger than Alluvium in all drainage conditions. However, there is less likelihood of the existence of lenses of highly permeable material. The possibility of any of the material being metastable should be explored for specific engineering projects as it is likely to be only a local phenomenon. As the unit is not to form the foundation material of an intensely built upon area it has not yet been investigated to this effect.

Engineering Implications of Trend and Range of Properties

It is likely that trends within this unit are mainly in profile as indicated in the present borehole logs. The range of properties could be high but only down to just below the subsoil so that economic removal of unsuitable surface material should be possible. Below that level engineering design should be able to proceed with generalised parameter determined in profile from boreholes. If the unit is to be considered in relation to a water retaining structure a preliminary investigation should be made to determine the amount, if any, of altered clay minerals that could have swelling properties upon the introduction of water.

8. VARVED LAKE DEPOSITS

Environment of Deposition

Varved deposits are rhythmically banded sediments formed where glaciers discharge melt water into still water - usually a lake but may also be a bay of the sea or even a quiet river. During the recession of an ice front melt waters from the surface of the glacier sink down through crevasses to the bottom of the ice where they flow under pressure in tunnels. Where these over loaded sub-glacial rivers reach still water, clear of the ice margin, sand is deposited which becomes finer and is interbedded with clay; eventually at great distance from the ice front only clay is deposited. Deposition of varves is periodic - usually annual.

Each varve consists of two parts: a thick, light coloured coarse layer - the product of deposition from summer melting, followed by a thin, dark coloured layer consisting largely of coloidal matter and clay deposited during winter. The thickness of the individual varve and the size of the constituent mineral particles depends to a large extent on the proximity of the ice front.

There are three main ways in which the fine extra-glacial sediments may be deposited. Melt waters rise to the surface of the lake and spread out widely dropping the sedimentary load through the standing water below. The sediment may be carried out along the bottom of the lake by, and be deposted from, a turbidity current. The melt waters may spread out gradually becoming mixed with the entire body of standing water and then deposit sediment. The salinity, temperature and density of the standing water into which the melt water was discharged determined whichof these processes took place, or which dominated in a combination.

Small stones and concretions are sometimes abundant in varved deposits, and are usually confined to the coarse layers. Angular fragments of till are also quite common in some deposits and these are usually confined to the lower varves of a sequence. Deformation of varves, particularly in the upper part of a deposit is common, this can be due to wave action, calving of ice bergs, turbidity currents, recent or penecontemporaneous slumping or over-riding by glacier ice.

Engineering Implications of General Properties

The implications of the properties of the individual layers, or varves, are greatly overshadowed by the those of the combination of the layers. The general properties of the individual layers are generally those apertaining to a silt or those apertaining to a clay. Any layer considered on its own would therefore behave as a silt or as a clay. Collectively, however, the behaviour of the unit is a complicated mixture of the two and a few extra characteristics are introduced. The problems inherent in this unit again involve both strength and drainage characteristics. The major problem from the point of view of stability is that, though the silt layers are essentially capable of immediate free drainage in a vertical direction, the drainage path in that direction is blocked by the intervening clay layers. This means that upon the rapid application of a load to the surface the total load is taken by the pore water pressure in both silt and clay. The clay, being a cohesive material, even if weak, can often withstand the load more than the non-cohesive silt which can in effect act as a fluid immediately outside the loaded area until the excess pressure can dissipate laterally. This is a particularly relevant point to consider in programming the construction of massive water retaining structures.

A further implication of the layered nature of the unit is that the horizontal permeability of the overall unit will be considerably higher than the vertical. This is an important consideration in predicting seepage from water retaining structures and amount and time of consolidation beneath any structure.

Engineering Implications of Trend and Range of Properties

The union of the layers is so overwhelmingly important compared with the individual layers that it is not pertinent to consider them separately. Therefore, though the range of properties is sure to be high for the unit as a whole, it is only the range of behaviour characteristics of the whole unit that is significant to engineering construction. By considering the environment of deposition it is thought that lateral trends of the properties of the individual layers and the whole unit will be found to be of a low amplitude and insignificant.

9. DISCUSSION

Summary of Engineering Implications of the Geological Units

With the exception of the Middle Jurassic beds are relatively free of engineering problems except for difficulties in tunnelling through hard limestone bands and the rapid introduction of groundwater through joints in this material and problems associated with the clayey silts of the Lower Estuarine Series. The Oxford Clay, representing the Upper Jurassic beds, is a typical stiff over-consolidated silty clay. The engineering problems inherent in it will be those typical of engineering projects on similar British marine clays, e.g. Gault and London Clay (though the latter is more clayey). Experience gained in these materials, on which there has been much more engineering construction, should prove invaluable.

The Boulder Clay provides a far greater engineering problem. The excessive variability of the unit and the consequent impossibility of obtaining representative design parameters by laboratory testing will involve large projects in the extra expense of in situ large scale testing for strength and consolidation characteristics. The widespread occurrence of slip planes like the one unearthed in the only trench dug, at Little Woolstone, could necessitate a very expensive investigation programme for all large projects.

The Recent Alluvium should not provide any insurmountable problems provided engineering constructions are designed to take account of its high compressibility and low general strength. Occasional permeable lenses of engineering significance should be found in a conventional borehole programme.

The engineering problems involved in the River Terrace Deposits and Glacial Gravels are that they will often "boil" when subjected to high hydraulic gradients. This can take the form of a quicksand condition in deep excavation (or boreholes and trial pits, etc) or of piping through or around water retaining structures.

The engineering problems associated with the Head are essentially the same as those associated with Recent Alluvium. There is a remote possibility that the unit may be locally metastable.

The major problems proposed by the Varved Lake Deposits result from its varved nature. There is the possibility of a "blow out" beside a large rapidly built engineering construction. It should also be noted that consolidation characteristics found in a conventional oedometer will be very inaccurate.

Suggested Methods of Overcoming these Problems (with particular consideration given to safety and economy)

The difficulty of removing the hard Middle Jurassic limestones in the tunnel should be easily overcome by normal mining techniques. The excessive introduction of groundwater through its joints could still be important, even if only for its nuisance value. However, it would be uneconomical to dewater the whole bed so it is suggested that seepage water is collected at appropriate intervals in the tunnel and intermittently pumped out.

The problems involved in working on the Oxford Clay will include estimating the effect of fissuring on the reduction of the intact strength and similar hitherto unanswered questions. The strongest recommendation possible is that the experience gained in neighbouring marine clays should be implemented and general design criteria tempered by local considerations, e.g. local fissure pattern.

There is no way of safely avoiding large scale in situ testing in Boulder Clay. At some scale, probably less than that of the construction foundation, truly representative average design parameters will be found. It is an economical proposition to try to find this optimum scale before large scale construction begins. It is also recommended that an attempt be made to establish the frequency of occurrence of near-surface slip planes in this material and whether their effect can be incorporated in the "lump" design parameter establish from less-than-fullscale in situ testing.

The compressible, weak Alluvium could be economically removed beneath the occasional water retaining structures to be built on it provided it is not more than about five metres thick. In the event of its being of greater thickness superimposed structures could be designed to have sufficient plasticity to accommodate the settlement. Significant permeable lenses could be economically filled by chemical grouting. For large projects in which the removal of the material would never-the-less be excessively uneconomical it would probably be necessary to preconsolidate the unit by drainage and perhaps preloading before constructing a major embankment on it.

To prevent boiling of the Terrace Deposits and Glacial Gravels it would almost always be an economic necessity to reduce the hydraulic gradient by lowering the water table by pumping from wells around the offending area. It would probably be more economical to deal with the problem when it arose rather than do extensive tests to predict it, other than sinking trial boreholes first to see if they strike "running sand". Piping in indigenous material could be dealt with in the same way and filters should be designed to prevent it in water-retaining structures.

The metastability of Head can be established cheaply by laboratory tests. Other problems in it can be overcome in the same way as for alluvium. In the unlikely event of swelling materials being present Head should not be used as a fill material.

The "blow out" problem over Varved Lake Deposits can be overcome by slowing down the construction programme according to consolidation requirements that can be obtained either by in situ testing or by laboratory testing using aparatus that provides scope for lateral drainage. This same aparatus should provide all the necessary consolidation characteristics needed for design on such thinly varved materials.

Some Suggested Further General Investigations

It is suggested that investigation of the following topics would prove valuable to later construction within the designated area of Milton Keynes.

1. The effect of fissure intensity and orientation on the stability of engineering earthworks.

2. The scale at which in situ testing in Boulder Clay provides representative design parameters.

3. The correlation of laboratory and in situ parameters for the varved materials.

4. The amplitude of trends of engineering properties in the Lower Oxford Clay.

5. The affect of weathering on engineering properties.

The preparation of the geotechnical maps presented here is primarily to illustrate the variability of Boulder Clay and relative consistency of Oxford Clay. Two techniques are used; that shown in Fig 2 is simply to plot individual index parameters separately, each on a different diagram. This has the advantage that the individual trends are readily digested. If the maps (in this case, sections of a trench) were superimposed a picture could be built up that would permit an overall comparison of these trends; however, it would become cumbersome. An advance on the overlay system would be to plot all the index parameters on one map, sacrificing individual clarity and gaining the advantage of being able to compare trends easily without any encumbrance of overlays. Once the eye is familiar with accepting this kind of mapping it readily translates the map in terms of combined trends. The experienced engineer or geologist will at the same time infer a lithological interpretation.

To assist the lithological interpretation the individual parameters may be sacrificed in favour of meaningful ratios of them. Examples of this are shown in Figs 1 and 3. Fig 3 is shaded such that the lithological interpretation is already done. If the individual parameters were required, as they would be if this technique were developed for design parameters, they could be derived from the map by solving a series of simple simultaneous equations given in the index with each map. With experience this takes only a little longer than interpreting from the direct mapping of individual parameters - a small price to pay for a general lithological interpretation at a glance. It should be understood that the present submission of maps is intended to be primarily an illustration of technique.

The table of selected engineering properties and significance of the main geological units is composed from the information available from the borehole survey tempered with previous experience of these materials. It should be understood that the values given are representative of about 95% of samples tested, the rest being badly tested or from an unreliable source. It should also be noted that the effects of weathering, physical and/or chemical, can be either to soften, usually by mineral alteration, or to harden, usually by dessication, any unit so that its engineering properties fall outside the given ranges.

UNIT	LITHOLOGY	AVERAGE RANGE OF SELECTED ENGINEERING PROPERTIES					MAIN ENGINEERING PROBLEMS
		PL* %	LL* %	LB/FT^3	S.G.*	Cu LB/FT^2	
Middle Jurassic	Highly variable, including beds of sand, clay, limestone and frequent mixtures	-	-	-	-	-	In text
Oxford Clay	Stiff fissured silty clay	20-25	55-75	125-135	2.6-2.8	3000-15000	Reduction of intact strength by fissuring
Boulder Clay	Heterogenous, unsorted admixture of sand, gravel and flint and chalk pebbles in silty clay matrix	15-22	30-60	115-135	2.5-2.7	500-5000	Acquisition of representative engineering design parameters. Occurrence of very weak slip planes.
Alluvium	Soft compressible clayey silt with some sand, occasionally in lenses	15-25	30-55	95-120	2.4-2.7	500-2000	High compressibility. Low strength.
River Terrace Deposits and Glacial Gravels	Compact, cohesionless, often uniform sand and gravel	-	-	125-145	2.6-2.8	-	Quicksand conditions
Head	Compressible admixture of silty clay with some sand and pebbles	15-25	30-65	100-120	2.5-2.7	500-3000	High compressibility. Low strength. Metastability.
Varved Lake Deposits	Thinly laminated clays and silts	15-20	35-55	115-130	2.5-2.7	1000-3000	"Blow out" under rapid loading. Anisotropic seepage.

* Standard tests on material passing No 36 seive.