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ENGINEERING GEOLOGY AND THE THAMES BARRIER PROJECT

– The planning and implementation of the site investigation –

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ABSTRACT

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The Thames Barrier, now under construction, is a structure containing movable gates which will prevent extra high tides flooding London. The majority of the piers are founded in chalk and a few at the northern end of the barrier will be set in the overlying Thanet Sand.

The site investigation in these strata posed problems since the samples from boreholes are only of limited quality and the strata, being mostly under water, cannot be examined *in situ*. The investigation was carried out by boreholes using an extensive series of standard penetration tests and borehole permeability tests, together with tube samples for visual examination and classification testing.

The detailed geological structure beneath the site was inferred from a geophysical survey and from a micropalaeontological investigation and was extended by visual examination of exposures of the strata in adjacent dry land sites.

The results showed that there was a series of faults in the Chalk, but their presence did not appear to affect its engineering properties.

INTRODUCTION

The Thames Barrier, now under construction, consists of ten movable gates set between piers and the river abutments. The site is underlain by Thanet Sand over Upper Chalk. The piers and abutments are set on massive spread foundations, the majority of which will be set in chalk with a few at the northern end being set in Thanet Sand.

This paper describes some of the considerations involved in the planning and implementation of the main site investigation which was carried out in order to derive geotechnical parameters for the detailed design of the structure.

At the time of the work, the authors were representatives of Foundation Engineering Limited who carried out the site investigation and they worked in close association with Messrs. Rendel, Palmer and Tritton, the consulting engineers to the Department of Public Health Engineering of the Greater London Council.

Detailed descriptions of various aspects of the design of the barrier have been given in a London Conference (1978) and a general description of the site investigation has been given by FOOKES & MARTIN (1978).

THE SITE

The barrier is sited at Woolwich on the lower Thames, some 12 km downstream from London Bridge (Fig. 1) and is designed to be closed at times of extra high flood tide, so as to prevent flooding in central London. Downstream of the barrier, the river banks are protected by a continuous line of dykes.

The barrier consists of nine piers and abutments at each bank which support the ten gates. The main gates rotate about horizontal axes and seat in pre-cast concrete sills at riverbed level which span between, and are supported by, the piers. The design calls for strict limitations on differential settlement after the piers have been constructed up to the elevation of the bearings for the gates. Hydrostatic loads on the closed gates impose appreciable eccentric loadings on the foundations. The general plan and elevation are illustrated in figure 2.

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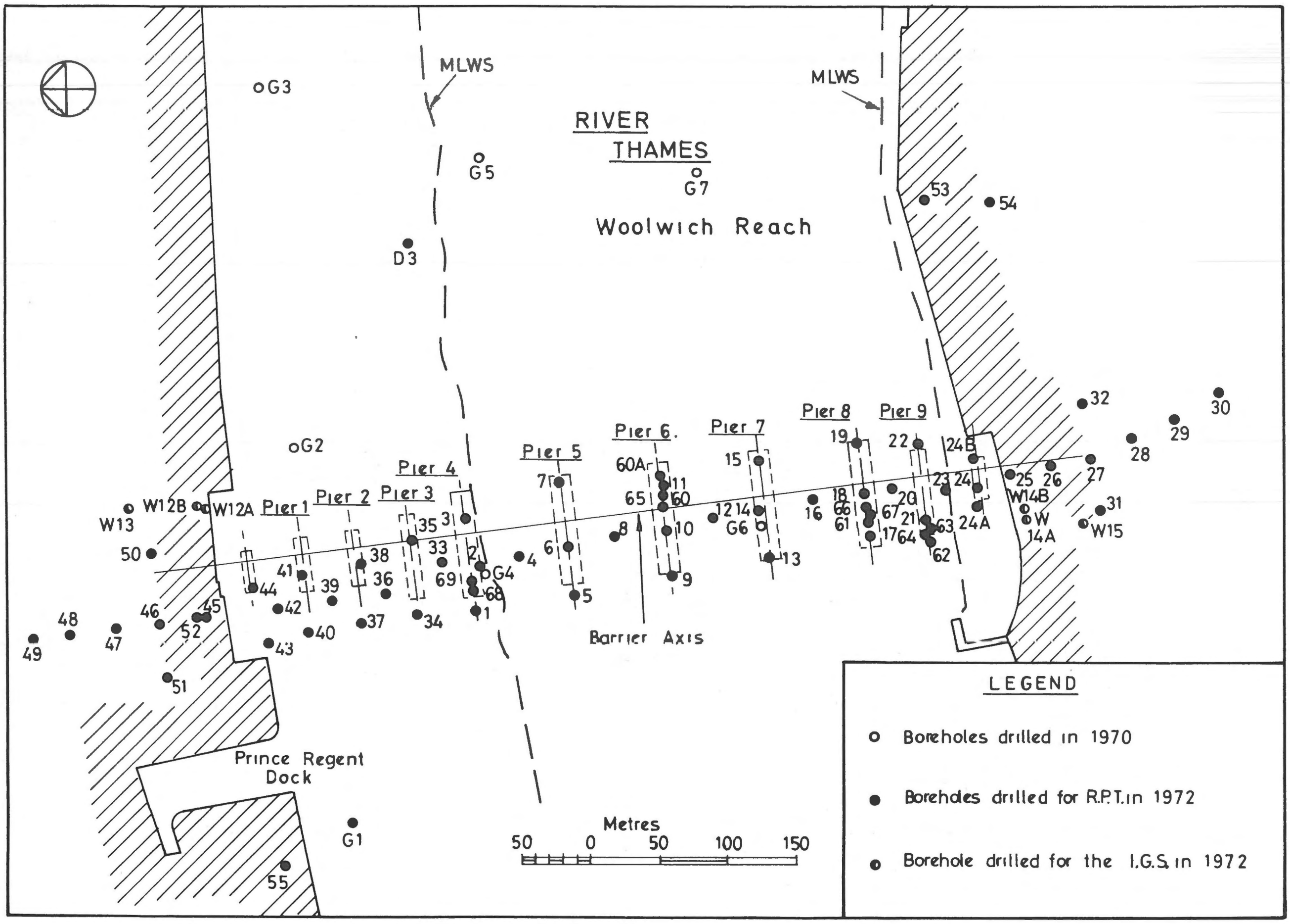


Fig. 1
Plan of barrier site showing borehole positions (after Fookes & Martin, 1978).

GEOLOGY

The geological sequence is:

(4) Alluvium	Contemporary river bed sediments and recent alluvium
(3) Flood-plain gravel	Pleistocene
(2) Thanet Sand	Early Eocene
(1) Upper Chalk	Cretaceous

The alluvium and floodplain gravel lie unconformably on the eroded surface of the Thanet Sand/Chalk and are not considered further in this paper.

There is a gentle dip to the NNE and the interface between the Thanet Sand and the Chalk outcrops in the river bed, the southern boundary lying parallel to the river and about one third of the way across from the north bank. The river bed is lined with mud, but chalk is exposed in the dredged channel on the south side. At low tide, a wide expanse of soft grey mud is exposed on the north side and a sandy shingle beach on the south side of the river. The tidal range is 7 m at springs and 5 m at neaps (Fig. 2).

The Upper Chalk, in its unweathered state, would be described in geotechnical terms as a weak chalk with flints. Lithologically it is a soft pure limestone with abundant flints, often in bands 1-3 m apart or as irregular modules. There is much jointing.

The Thanet Sand rests unconformably on the erosion surface of the Upper Chalk, which shows only minor irregularities and flexuring. It is a fine silty sand, becoming clayey with depth. The lower boundary of the Thanet Sand is marked by a bed up to 0.5 m thick, consisting of irregular greenish coloured flints inbedded in sandy silty clay.

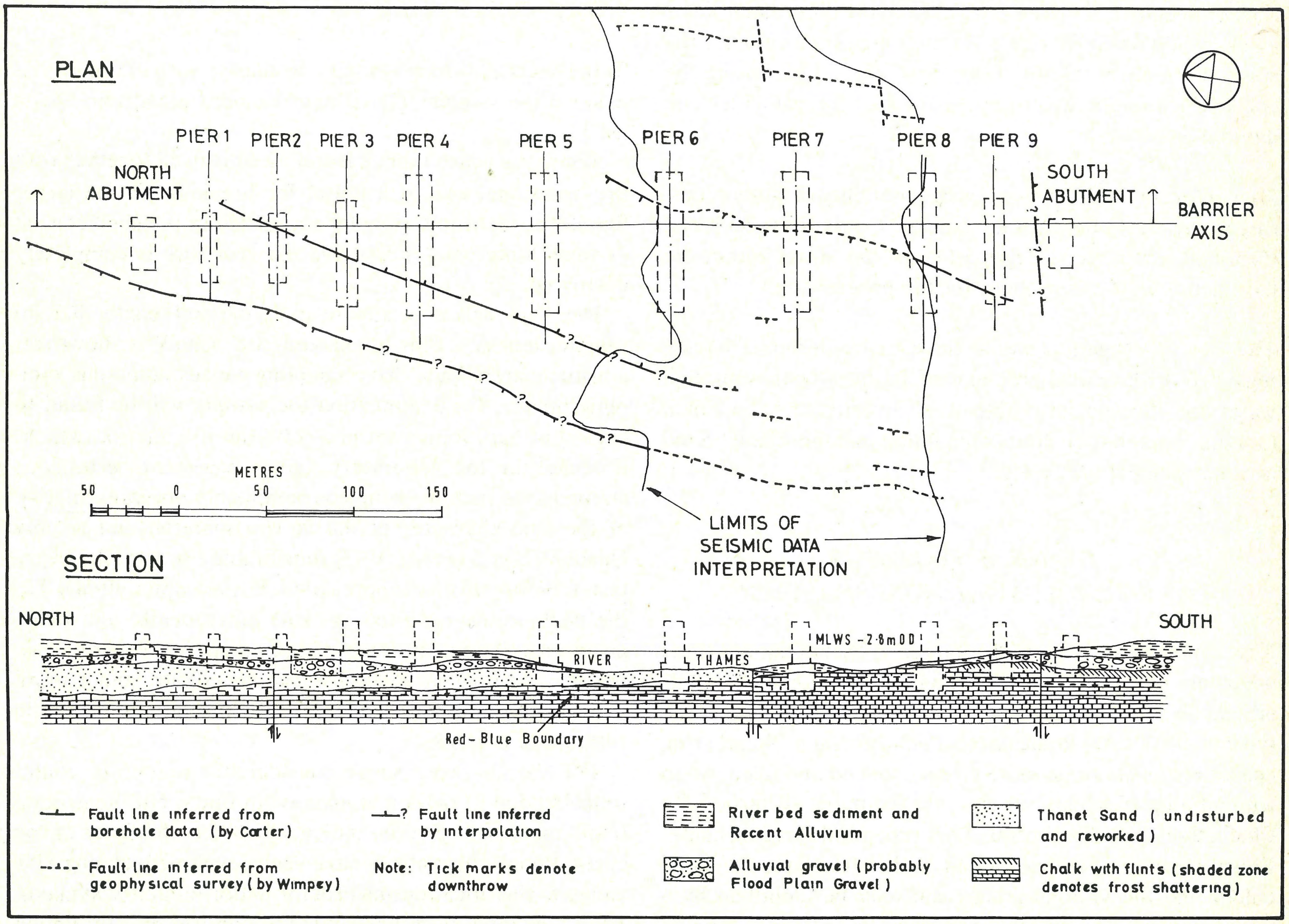


Fig. 2
Geological cross section on the barrier axis and plan showing faults (after Fookes & Martin, 1978).

PREVIOUS INVESTIGATIONS

Small preliminary site investigations have been carried out to study the feasibility of the project and to select the best location. They have mostly been carried out by standard cable percussion methods ('shell and auger') and have given useful experience of the problems of boring, sampling and *in situ* testing in the Chalk.

Immediately prior to the main borehole investigation, a waterborne geophysical survey of the river bed had been undertaken by Wimpey Laboratories Limited, using seismic reflection techniques. Although, for various technical reasons, this did not give reliable data below the river bed, the records for the chalk surface which is exposed in the river bed showed a series of parallel steps, trending at about 30° to the axis of the barrier, which were thought to indicate a series of faults.

REQUIREMENTS FOR THE DESIGN OF THE FOUNDATIONS

Having regard to the already existing knowledge of the geology of the site, there would appear to be three main problems requiring investigation.

(1) Bearing capacity: the piers and foundations would be set on spread foundations subject to eccentric loading; the maximum nett intensity of pressure would be 600 kN/m^2. At what depth should the foundation be set so that there was an adequate factor of safety against the ultimate bearing capacity and so that differential settlements would be within acceptable limits? Settlements were likely to be the most critical consideration and this would require an assessment of the deformation moduli.

(2) Permeability: with the gates closed, the differential water levels would set up seepage through the strata beneath the sills. Were there likely to be any open fissures in the chalk which might lead to excessive seepage velocities and internal erosion?

(3) Uniformity: there was a strong possibility of faults occurring in the strata beneath the barrier. Could these faults be identified and were the properties of the strata within the fault zones worse than those for the general site?

The site investigation would have to be designed having regard to the practical problems of an investigation through water and the special problems of investigating the Chalk (a weak, jointed rock containing flints) and the Thanet Sand (a very compact silty sand).

GENERAL PROBLEMS OF SITE INVESTIGATIONS IN CHALK

The upper chalk is a weak, jointed rock containing flints which are generally 100 - 200 mm in size, but can occasionally be up to 0.5 m. In its unweathered state, the joints are typically about 250 mm apart and tightly closed. Weathering causes the joints to be more closely spaced and open, often with infilling of calcareous clay. On the upper surface of the Chalk, there can often be found reworked (solifluction) chalk. Fresh, weathered and reworked chalk often have the same colour and the various grades can only be identified by a visual examination of the structure, or indirectly from a strength test.

Samples from boreholes are often so badly disturbed, that the character of the *in situ* chalk cannot be determined from a visual examination of the samples.

The quality of results which can be obtained using the standard techniques for site investigations are now discussed.

Cable percussion boring

This concerns borings (shell and auger) with 100 mm diameter drive samples (U_{100}) and standard penetration tests (SPT).

Below the water table a heavy shell is used together with the occasional use of a chisel for breaking up the larger flints. The disturbed samples recovered in the shell consist of small lumps in a slurry and the structure is completely destroyed.

The U_{100} will normally recover the full-length (0.5 m) sample, unless a flint is encountered. Chalk is, however, a brittle material and drive sampling causes numerous sampling breaks. On examination the sample will be found to consist of hard lumps set in a soft cohesive matrix, which, if tested in the laboratory, gives very low erroneous strengths. In fact the sample is completely unrepresentative of the true character of the *in situ* material and is only Quality Class 5 (ROWE, 1972) (unsuitable for any laboratory tests). Before this was appreciated, U_{100} samples often led to the chalk being reported as 'soft putty chalk' and being given an erroneously low bearing capacity. Nevertheless, the U_{100} sample is generally true to colour, and natural joints and fissures can be identified by discolouration on the surfaces of a break.

SPT values show some considerable scatter in chalk, probably due to random contact with flints, but the general trend appears to give an indication of the character of the chalk. Rough correlations have been developed relating SPT values to classification and to deformation moduli (WAKELING, 1970), and later work has tended to confirm the correlation (CAMBRIDGE, 1974). The classification is given in table I.

The SPT is a reasonably sensitive test in the range of 0-40, but above this it is doubtful if the recorded value has much additional significance. In fact, values quoted in excess of 40 are often extrapolated, the test having been stopped before the full 300 mm penetration was obtained. Hence SPT values in excess of 40 are of little use in attempting to compare the harder types of chalk.

Table I
Chalk classification.

Grade	SPT values	Description
VI	< 8	Extremely soft, structureless chalk, consisting of unweathered and partly weathered, small angular chalk fragments set in a matrix of deeply weathered remoulded chalk.
V	8-15	Soft structureless chalk, consisting of unweathered and partly weathered, angular blocks and fragments, set in a matrix of weathered remoulded chalk; bedding and jointing absent.
IV	15-20	**Soft, friable to rubbly chalk possibly weathered with bedding and jointing present. Joints and small fractures** from 10-50 mm apart are present. The joints are commonly filled with remoulded chalk and small unweathered fragments.
III	20-30	Rubbly to blocky, unweathered medium chalk with joints 60-200 mm apart.
II	30-40	Medium chalk with widely spaced closed joints more than 200 mm apart.
I	> 40	Hard, brittle chalk with widely spaced joints similar to Grade II but harder.

Rotary core drilling

The largest size that can normally be employed with the rigs used in routine site investigations is 100 mm diameter hole-size, giving a core of about 80 mm diameter. In unweathered chalk with flints, this often yields poor-quality samples with less than 50% solid core being recovered. The main problem is that the chalk matrix is relatively weak and the flints tend to break loose beneath the diamond bit and destroy the core. Weathered chalk, grades IV to VI, is generally too friable to yield solid cores.

Some improvement in core quality can be obtained using larger-core, more powerful drill rigs and special coring bits containing large carbons, with high resistance to shattering, in place of diamonds.

Down-the-hole logging

This is an adaptation to civil engineering requirements of equipment developed for logging exploration boreholes in the oil industry and uses acoustic and nuclear emissions. It was tried out, unsuccessfully, at the Barrier site in a 150 mm diameter borehole. The lack of success was probably due to the presence of disturbed material around the wall of the borehole which absorbed too much of the energy. A down-the-hole television camera was also used but it was found that the chalky water completely obscured the vision.

GENERAL PROBLEMS OF SITE INVESTIGATION IN THANET SAND

Thanet Sand presents the standard problem of a very dense sand in which the SPT's often meet refusal. The general practice is to use alternating SPT's and U_{100}'s, thus detecting any less dense zones and recovering some samples for visual examination and grading tests.

THE MAIN SITE INVESTIGATION

A site investigation will generally be required to determine the following objectives:
(1) the character of the strata, e.g. stratification, faulting, etc.;
(2) the ground-water condition;
(3) the engineering properties of the strata.

In rocks, it is necessary to examine the macro-structure of the strata in large exposures and at the Barrier, where the site is under water, this was impracticable. Hence, it was necessary to examine adjacent dry-land exposures and reference the stratigraphy to that of the Barrier.

Site work

The river boreholes were done using two combined cable percussion and rotary rigs (Pilcon Wayfarer) mounted on barges. Cable percussion borings were done in 200 mm and 150 mm diameter boreholes with alternating U_{100}'s and SPT's. Rotary drilling was done using a hydraulic drive and coring in 'H' size in a 100 mm diameter hole, the core diameter being 75 mm.

On land, similar equipment was used together with one larger rotary rig, drilling a 150 mm diameter hole.

The Chalk

Boreholes in the chalk were done by cable percussion methods with alternate U_{100}'s and SPT's at close intervals of depth. Frequent borehole permeability tests were carried out by falling-head procedures using the borehole casing as a seal against the surrounding strata. These tests all had limited accuracy, but the aim was to obtain the maximum number of observations in the hope that the existence of weaker zones (due to weathering and fault shattering etc.) would be detected by the SPT values and that open fissures would be detected by the borehole permeability tests.

An analysis of the microfossils in the borehole samples was carried out (CARTER & HART, 1977), and this enabled some recognisable horizons to be traced across the site. The work of Carter on the microfauna has shown up the gentle folding of the Upper Chalk which was not revealed in the borings. It is similar to that found elsewhere in the Chalk in the south-east of England. There are two sets of folds almost at right angles; one monoclinal, with folds trending SE-NW and the other, weaker folds, trending NE-SW superimposed.

In addition to this folding Carter also located five faults which are shown on figure 2. These follow two main directions, namely NE-SW and NNE-SSW. One of the latter was first detected by the Wimpey Geophysical Survey as a step in the Chalk surface. The NNE-SSW faults are aligned *en echelon* at a small angle to the line of the Barrier. They are described by Carter as steep-angled normal faults with lateral displacements of up to 50 m, which he interprets as tear faults with a fairly small vertical throw of up to 5 m. They may occur in the chalk surface as steps, but they were not located in the borings.

Although slickensiding was observed in the core of several boreholes, it is not possible to correlate these with the faults shown up by the microfauna and one may conclude that other less prominent faults may also be present.

Since there was no visible evidence of faulting at Northfleet, a visit was made to the chalk cliffs at Pegwell Bay, Kent, where a number of faults can be seen. The chalk is from the Upper Chalk series and the Thanet Sand interface can be seen at the western end of the section. The geological study suggested that the chalk may be from a different horizon to that of the barrier site, but from a visual inspection, its

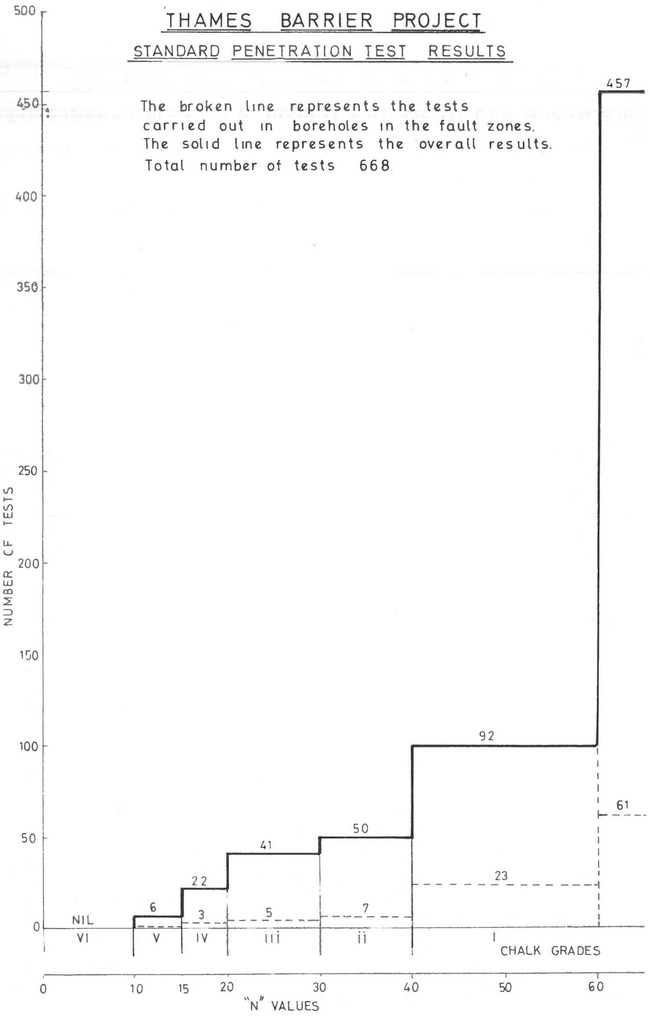


Fig . 3
Standard penetration test results in chalk shown as total number of values in each grade.

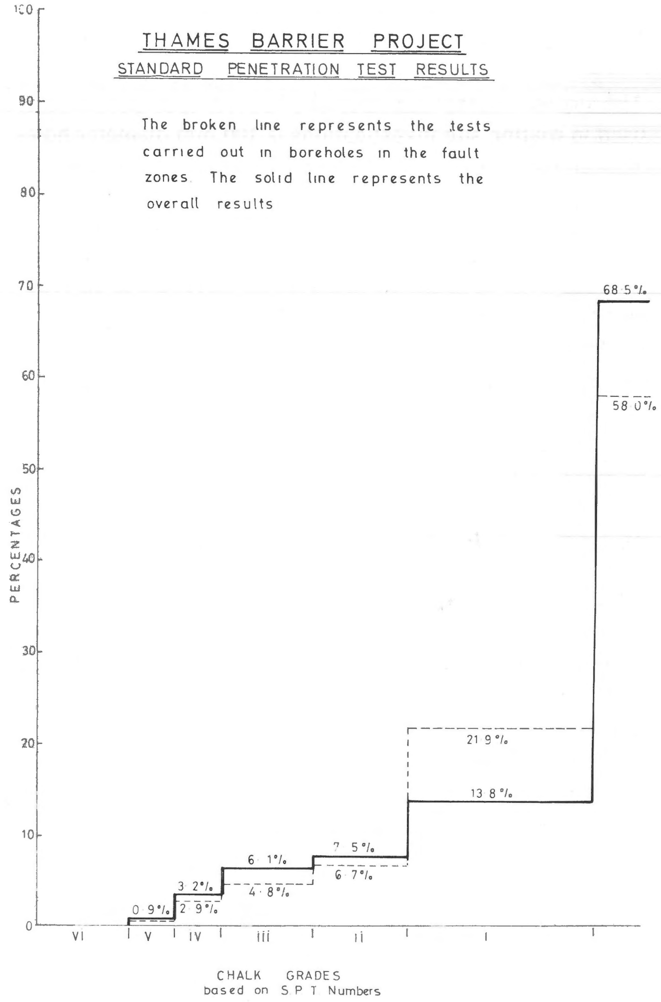


Fig. 4
SPT results in Chalk of each grade shown as percentages of total number of tests carried out.

engineering properties would appear to be similar.

The chalk in the Pegwell Bay cliffs is heavily jointed and there are a number of steeply inclined joint systems. At Pegwell Cove to the eastern end of the section, a line of flints showed the existence of faults having vertical throws of 2-3 m. The fault surfaces were steeply dipping with a series of parallel surfaces extending over a width of about 1 m. A close examination of these showed that all the fault and joint surfaces were tightly closed. Following the examination of these faults, a re-examination of the remaining part of the cliff section showed that there were in fact an appreciable number of other faults on all of which the joint surfaces were closed. A visual examination of the chalk exposed in the cliffs would have placed the solid chalk in grade III and the faults would not be obvious.

The Thanet Sand

Boreholes in the Thanet Sand were by standard cable percussion methods with alternate U_{100}'s and SPT's at close intervals of depth. Borehole permeability tests were also carried out.

RESULTS

The Chalk

The SPT's indicated that the chalk is sound and unweathered where it is covered by the Thanet Sand. Elsewhere, where it is covered by the flood-plain gravel, or by contemporary river-bed alluvium, there is some indication of softening in the upper layers. However, in every borehole, hard chalk of grade II quality (SPT greater than 30) was encountered within 10 m below the top of the chalk. The most severe softening was noted in the riverbed adjacent to the south bank and beneath the gravel under the south bank where there were occasional pockets of grade V quality chalk (SPT value 8-15). The numerical distribution of the SPT values for all the tests carried out at the chalk is shown in figures 3 and 4, and it will be seen that approximately 90% of all the results indicate hard chalk of grade I or II quality.

A comparison of the results of the SPT's carried out in the boreholes near faults, with the corresponding results for the entire site, indicate that the faulting appears to have no significant effect on the test results. However, there is a suggestion that in boreholes 47 and 48, which lie close to a presumed fault, there is an increase in the proportion of grade III quality chalk indicating a closer spacing of the joints.

In situ permeability tests done in the normal site investigation boreholes, using only the borehole casing as a seal against the surrounding ground, have only a limited accuracy. The results of this series of tests are shown diagrammatically in figure 5. There is a considerable scatter of results with a general trend between the coefficient of permeability limits, 5.10^2 and 10.10^{-7} m/s. More precise tests were carried out in borehole 52 on the north bank in which three test lengths were established by perforated standpipes sealed in with grout. The test lengths were established in zones where the borehole cores suggested that there might be fissuring. The results show that the coefficient of permeability in this borehole was not greater than 0.5×10^{-7} m/s.

The principal objective of the borehole permeability tests was to detect any open fissures which would have given considerably greater coefficients of permeability. Considering together the results of the rising and falling head determinations for each test set-up, there is no indication that any such fissure was penetrated by the boreholes. This does not preclude, however, their existence elsewhere on the site.

The results of the permeability tests carried out in the boreholes which were thought to be near or in the fault zones indicate that the chalk in these zones is not significantly different from that of the rest of the site. This is illustrated in the plots of the test results (Fig. 5).

The engineering properties of the chalk, as determined from the boreholes near the fault zones, were not different from those of the chalk over the whole of the site. In view of this, the sinking of trial pits or inspection shafts at any location in order to make a visual inspection of the chalk *in situ*, was not considered justified. A number of pits would be required in order to obtain useful results and the cost would have been considerable. It was, however, felt worthwhile to try and find other sites where chalk from a similar horizon was exposed and showed faulting.

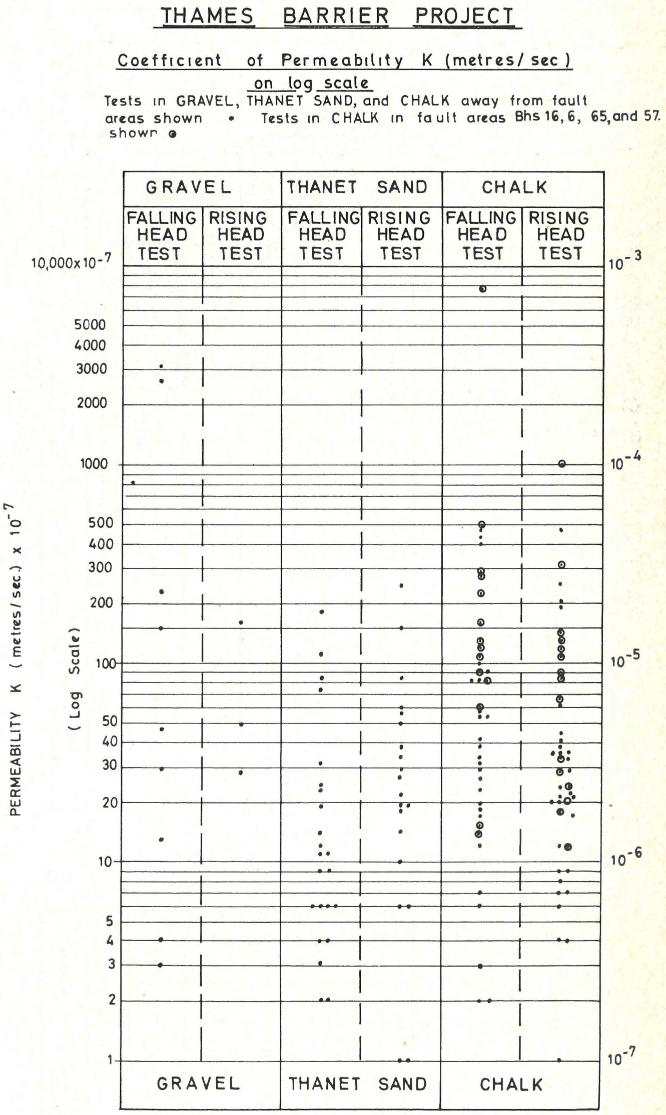


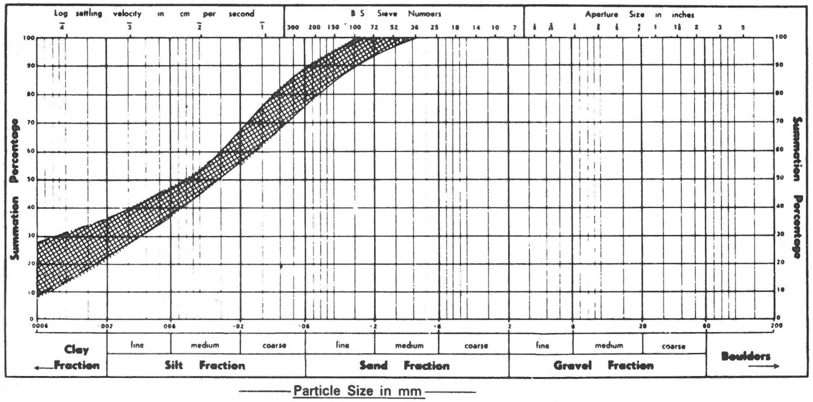
Fig. 5
Borehole permeability tests.

It is very likely that the faults at the barrier site are similar in character to those visible at Pegwell Bay and this, together with the results of the site investigation, leads strongly to the conclusion that the faults at the barrier site are unlikely to have had any major effect on the general engineering properties of the chalk stratum. Hence, it was concluded that the chalk at the barrier site was comparable with that encountered elsewhere in the Upper Chalk stratum, and that its character was likely to be similar to that inferred from the standard penetration test classification system. This would place most of the unweathered chalk in grades I and II, with a certain amount of grade III occurring at the top of the unweathered material, and possibly also in the fault zone. As such, the unweathered chalk is likely to be traversed by a pattern of closed joints with the joint spacing related to the quality classification. The major joint systems in the region tend to be vertical, but there are also likely to be

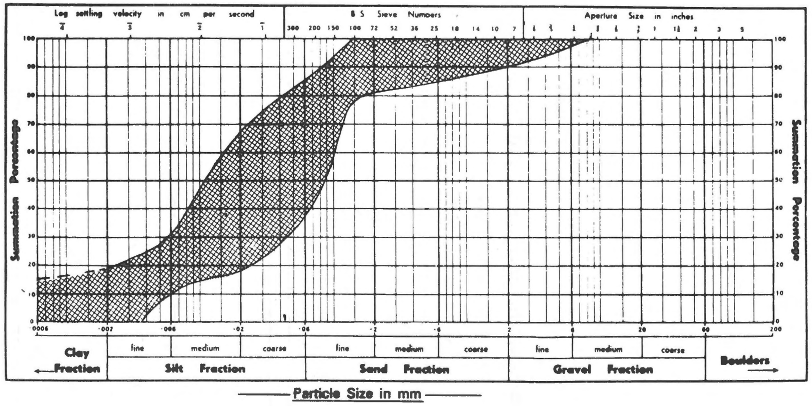
PARTICLE SIZE DISTRIBUTION
(ENVELOPES)

CONTRACT: THAMES BARRIER PROJECT DATE: June 1972

(a) Recent alluvium - river bed sediment.



(b) Recent alluvium



PARTICLE SIZE DISTRIBUTION
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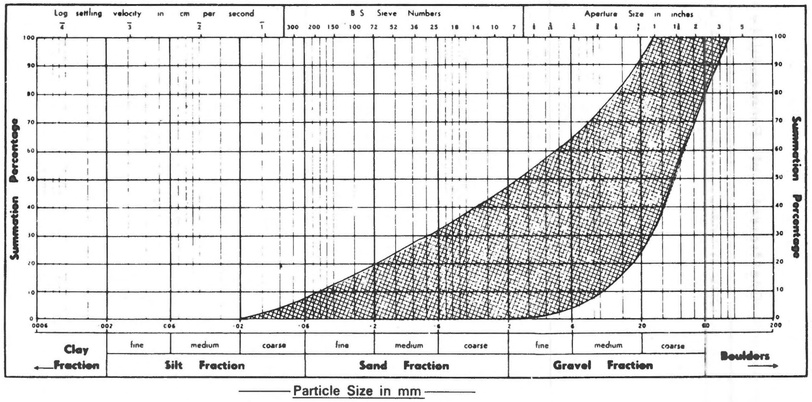
CONTRACT: THAMES BARRIER PROJECT DATE: June 1972

(c) Flood plain gravel.



(d) Thanet sand

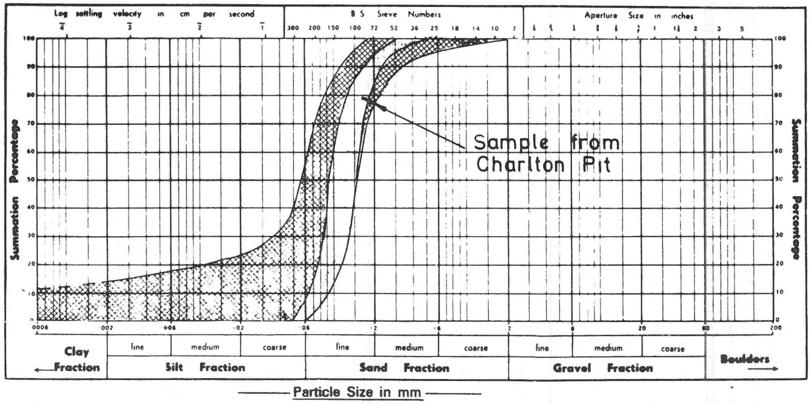


Fig. 6
Grain-size distribution. a: recent alluvium and river bed; b: recent alluvium; c: flood-plain gravel; d: Thanet Sand.

inclined joints associated with the faults.

The deformation moduli for the chalk were estimated from the SPT values (WAKELING, 1970) and it was considered that in general the foundations should be set in grade II chalk (SPT value not less than 25) and that E could be assumed to be at least 1000 MN/m^2.

The Thanet Sand

Beneath the north bank (generally to the north of borehole 33), the SPT values are mostly in excess of 60, which, in terms of the Terzaghi & Peck classification system, indicate a compact to very compact consistency. There is some small reduction in the SPT value in the upper three metres of the stratum, immediately below the flood-plain gravel where the minimum observed values were about 30. This reduction possibly indicated the effect of some sort of weathering.

The Thanet Sand beneath the river bed (generally to the south of borehole 33), shows a reduction in SPT value to about 20 or less. This probably indicates a higher degree of some form of weathering, or even that some of the material has been redeposited by the river. These blow counts indicate a medium-dense consistency. There is no significant evidence that the fault zones have had any effect on the results.

The results of *in situ* permeability tests are shown diagrammatically in figure 5 and indicate a general trend of coefficient of permeability between the limits 5 and 50.10^{-7} m/s. These results are comparable to those observed for the Thanet Sand at other sites, and there is no significant evidence that the fault zones have any effect on these results.

CONCLUSIONS

(1) The geological structure of the Upper Chalk in the area is reasonably well known and it was necessary only to determine the presence or otherwise of faults beneath the actual pier positions and to assess their probable effect on the barrier.

(2) Because of the difficulty of taking good undisturbed samples and the very high cost of obtaining direct access to the Chalk for visual examination, the investigation was carried out by boreholes with numerous standard penetration tests and permeability tests *in situ*.

(3) The investigation revealed the presence of five minor faults *en echelon* at an oblique angle to the centre line of the barrier, but it was concluded that they had little effect on the engineering properties of the Chalk or on the overlying Thanet Sand.

ACKNOWLEDGEMENTS

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REFERENCES

Cambridge 1974: Various papers on foundations on chalk. Published as Proc. Conf. Settlement of Structures (Cambridge) - Pentech Press. (London).

Carter D. J. & M. B. Hart 1977 Micropalaeontological investigations for the site of the Thames Barrier, London - Quart J. Eng. Geol. 10 (3).

Fookes P. G. & P. L. Martin 1978 Paper 4 Thames Barrier Design Symposium - Inst. Civ. Eng. London

Rowe P. W. 1972 Relevance of soil fabric to site investigation practice - Geotechnique 22: 195-300

Wakeling T. R. M. 1970 Proc. B. G. S. Conf. on in-situ investigation in soils and rocks (London): 17-22

Plate IV
Enclosing dam with drainage sluices of Kojima Bay, Okayama Prefecture in Japan. A tidal embayment was dammed off from the sea by the construction of the enclosing dam. The enclosed area has been partly reclaimed; the remaining water area constitutes a fresh-water reservoir from which water for supplemental irrigation can be withdrawn.