PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

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Siltation problems in relation to the Thames barrier

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The problems confronting the Siltation Working Party of the Thames Flood Prevention Investigation are stated, the need for an early solution necessitating rigorous limitation of the possible combinations of site, function and design of flood protection structure that could be studied. The reasons for excluding all schemes involving a permanent barrage are given, the Hydraulics Research Station finally being asked to determine the effect on siltation of constructing a barrier at specified sites for use both as a simple surge excluding device and as a continuous half-tide control structure.

The methods adopted by H.R.S. in tackling the problem are described. They include four large-scale estuarine surveys; the establishment of stations for continuously monitoring the suspended solids content of the river; field and laboratory tests to determine the properties of Thames silt; the development of a mathematical model to study the effect of the tide control on the distribution of silt which is carried in suspension, and experiments on a physical model to establish the redistribution of bed sediments in the navigation channel likely to follow barrier construction and continuous half-tide control.

The data from the field surveys demonstrate how current-velocity, suspended silt concentration, salinity and temperature at different depths along the estuary change throughout a spring and a neap tide during both high and low river flows. The results of the silt monitoring exercise supplement the survey data by indicating how the concentrations of suspended sediment in the estuary vary – with tidal range, with position in the bi-monthly spring-to-neap cycle and with seasonal variations in freshwater discharge. The tests to determine the properties of Thames silt provide values for the four parameters describing the processes of silt movement needed to develop the mathematical model.

The indications from the physical model studies are that the construction of a well-designed barrier used only to exclude surges should produce no insuperable siltation problems. Both mathematical and physical model results show that continuous tide control leads to increased siltation, the zone of greatest deposition depending on the barrier site.

1. PROBLEMS OF THE SILTATION WORKING PARTY

At its first meeting on 27 May 1968, the Steering Committee of the Thames Flood Prevention Investigation set up a number of working parties each of which was to be responsible for a different aspect of the investigation. The Pollution and Siltation Working Party comprised representatives from the Greater London Council, Hydraulics Research Station, Thames Conservancy, Port of London Authority, Ministry of Housing and Local Government (now Department of the Environment), Water Pollution Research Laboratory, Central Electricity Generating Board and Messrs Cremer and Warner.

Because of the necessarily wide terms of reference of the investigation, the siltation problems facing the Working Party were complex. Although it was appreciated at a fairly early stage that river bank-raising and/or planned overspill alone would not provide an acceptable form of flood relief and that any permanent solution would involve the erection of a structure across the river, there were still a number of possible sites, functions and designs that such a structure could have. Ostensibly it could be located in at least six places between Southend and Central London; it could take the form of a barrier or a barrage; it could have one or more navigation locks; be equipped with one large gate or several small gates of different design; and so on.

In this context a ‘barrier’ can be considered as a device which is operated only to prevent exceptionally high tides and surges from passing up the estuary when a flood warning is issued: it may be a permanent structure with movable gates or it may be of fabric design. A ‘barrage’ is an obstruction which permanently excludes all tidal flow from the upper estuary and through which the freshwater flow down the river can be passed by sluices when the tide below the structure is ebbing.

Since the resulting changes in the siltation characteristics of the estuary would depend on the site, function and design of structure finally selected, the only completely satisfactory way of comparing the predicted effects of one particular combination of possibilities with those of another would have been to commission siltation studies of all. This would have involved several years' work and was clearly out of the question in view of the urgency of the problem of flood protection. The most promising alternative was therefore to attempt to short-list the possibilities by eliminating those schemes considered likely to produce the most intractable siltation problems.

In view of the serious consequences that can follow man's uninformed adaptation of his environment and the impossibility of studying all of the proposed solutions in the time available, any schemes involving the construction of a purpose-built permanent barrage below Central London were ruled out. Informed opinion considered them likely to produce too large a change in the present hydraulic equilibrium of the estuary to be acceptable to river users.

It was argued that in the extreme case, where the banks and bed of an estuary are composed of deposits of easily eroded sediment, the cross-sectional area of flow at any particular section is directly related to the tidal storage volume upstream. Civil engineering works which reduce the tidal volume will lead to a reduction in the dimensions of the channel carrying the tidal flow. The River Eider in Germany provided an outstanding example of this type of channel deterioration. There, the construction of a tide-excluding barrage 32 km above the mouth resulted in the deposition of over 30×10^6 m^3 of material downstream of the structure within 25 years. The estuary channel shoaled up, first at the barrage and then progressively seawards, attempts to maintain depths by dredging being useless.

It was appreciated that conditions in the Thames differ from those in the Eider, particularly with respect to the nature of the material forming the channel bed and the availability of further supplies of sediment (Inglis & Allen 1957). In the Eider, the bed consisted predominantly of fine sand (Sindern & Rohde 1970), an almost unlimited source of similar material existing off the coast of Schleswig-Holstein. In the Thames the composition of the bed varies from fine silt, several metres thick, in the so-called 'Mud Reaches' downstream of Woolwich, to sandy banks and channels in the outer estuary (figure 1). The reaches between appear to consist of sand or silt, or a mixture of the two, but the thickness of these superficial deposits is not consistent, the inerodible bed underlying the sediment being sufficiently near the surface in some stretches of the river to be exposed by the high current-velocities experienced at certain states of the tide.

'Sand', in the terminology of the hydraulic engineer, is used to denote any sediment, irrespective of geological origin, whose median particle diameter lies between 0.06 mm and 2.00 mm: for values below 0.06 mm the term 'silt' is used.

In a sandy estuary, the distribution of the sediment on the bed depends primarily upon the physical properties of the sediment and the water – particularly on the density and grain size of the sediment and on the velocity of flow of the water. Where, in addition to the sand, there are large quantities of silt, the physico-chemical properties of the sediment and the fluid also assume significance, the salinity of the water affecting the flocculating ability of particles and hence their erosional and depositional properties. Thus, although it was quite reasonable to expect the effect on water movements of a barrage across the Thames to be similar to that of the Eider barrage, sediment movement, although largely dependent on the water movement, was more difficult to predict since the final redistribution of the available material would be affected by phenomena which are incompletely understood. The chances of incurring permanent deterioration in channel widths and depths did, however, seem to be too great to justify the initiation of a lengthy experimental programme of model tests on barrages.

With the purpose-built barrage out of the running, the attention of the Siltation Working Party could be confined to the problems associated with providing a movable barrier.

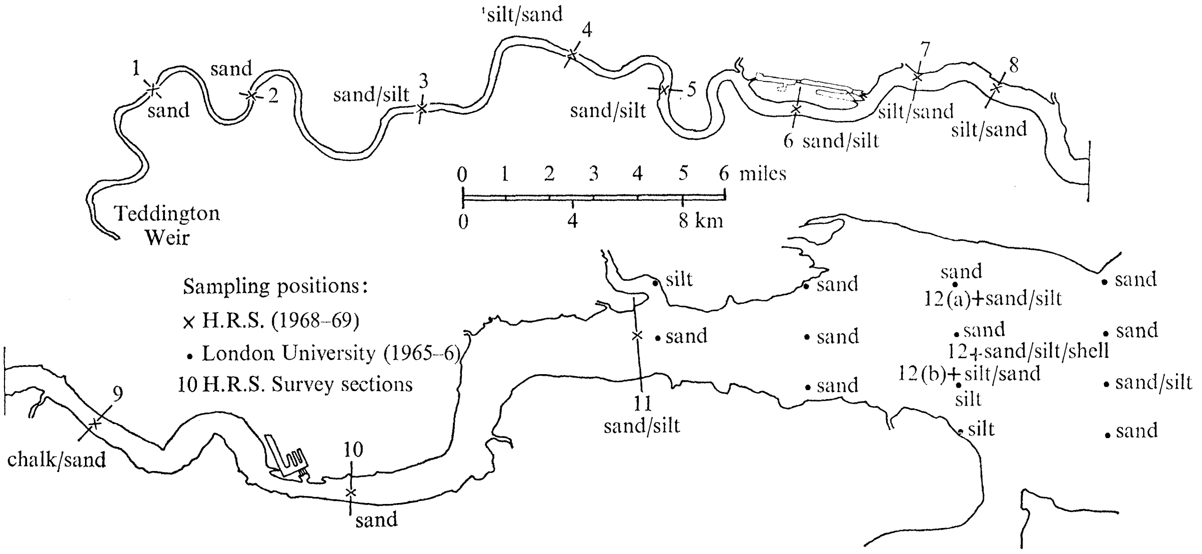

Figure 1. Thames Estuary: composition of the bed.

From hydraulic considerations, a barrier offers considerably more flexibility of function than a barrage. It can be operated solely as a flood protection device, the gates being closed only when a surge warning is issued. Additionally it can be used on a regular basis to control the inflow and egress of the tide, closing at a particular stage during every ebb and opening again at a similar stage on every flood unless a surge is forecast. In this role it can be called a 'tide-control structure', and the 'half-tide barrier' or 'quarter-tide barrier' are simply particular forms of tide-control structure depending on the stage in the tide when the barrier is operated. Finally, if the barrier gates are closed permanently, the structure assumes the role of a full barrage, excluding all tides. It could thus be argued that by opting for a barrier, the barrage concept has been postponed rather than abandoned.

On the face of it the difficulties confronting the Siltation Working Party were reduced. Although it would still be necessary to establish the changes in the configuration of the bed following construction of the barrier, these could be kept small in magnitude and limited in extent provided certain fundamental principles were observed in the design of the structure, the most important being that it should afford minimum obstruction to the flow when fully open.

In practice the problems were less simple, since the decision to concentrate on a barrier was accompanied by pressure to study the effects of using it as a continuous half-tide control device.

Tide control clearly provides an attractive compromise between a full barrage at one extreme and a surge-excluding barrier at the other. It offers the possibility of obtaining some of the benefits in amenity that the former would give, such as concealment of unsightly mud flats in

Central London, while retaining some degree of the tidal flushing provided by the latter. It also eliminates the risk of incurring undesirable increases in downstream water levels caused by reflexions from a barrier closed after the onset of the flood tide.

Because continuous half-tide control would affect the flow characteristics of the estuary considerably less than the presence of a barrage but far more than a well-designed surge-excluding barrier, the magnitude and extent of the consequent changes in the siltation pattern could also be expected to lie somewhere between those produced by a barrage and those resulting from a barrier. Where it had, however, been justifiable to reason from the available evidence that a barrage would in all probability lead to severe siltation, and therefore to delete it from the list of possibilities, the consequences of half-tide control operations were impossible to predict without recourse to detailed siltation studies.

The Hydraulics Research Station, Wallingford, was accordingly asked to provide answers to the following comprehensive question.

What would be the effect on siltation in the Thames estuary of constructing a barrier at specified sites for use, first as a simple surge excluding device, and secondly as a continuous half-tide control structure?

2. Methods employed in tackling the problems

In view of the need for early results, the Hydraulics Research Station proposed that in addition to constructing a physical hydraulic model of the Thames on which to carry out a detailed test programme, it should initiate complimentary studies designed to increase the understanding of the behaviour of water and sediment in the estuary. The information thus obtained might enable the otherwise lengthy model experimental programme to be cut.

The suggested studies included an attempt to set up a mathematical siltation model designed to examine the effect on the distribution of suspended silt in the estuary of continuous half-tide barrier control at different sites. It was emphasized that, to the best of the Station's knowledge, no one had so far been successful in establishing a mathematical model to study siltation and so the outcome was problematical. The decision to take the step, though somewhat adventurous, was justifiable on the grounds that where the material in the natural estuary consists of both sand and fine silt or mud, a physical model could not provide a complete guide to the new distribution of sediment following barrier operation. It could reproduce only the behaviour of material which in nature moves on, or just above, the bed, although in stating this it must be added that most of the sediment-transport in a channel occurs in these regions. The mathematical model, however, could supply information on the movement of very fine material in suspension, both near to the bed and throughout the depth of flow; it could thus both supplement and to some extent confirm the physical model results.

In addition to the mathematical siltation model, four large-scale field surveys were proposed. Simultaneous measurements of current velocity, salinity and suspended silt content of the water, made at a number of river sections throughout four selected tides, would meet two important requirements. They would provide a comprehensive knowledge of conditions in the estuary during a spring and a neap tidal cycle at times of both high and low river flow, and at the same time produce some of the basic data needed to set up the mathematical model.

The third complementary study involved the establishment of stations for continuously monitoring the amount of silt in suspension in different parts of the estuary. Such an exercise would supplement the information obtained on the field surveys by indicating how the concentration of sediment in suspension varied – first during a particular tide, secondly during the progression of the 28 tides through the bi-monthly spring-to-neap cycle, and thirdly with the continuous variation in river flow which accompanies seasonal changes. The distribution of suspended silt recorded in the estuary during a specific tide and a particular river flow could eventually be used as input data to the mathematical model to establish the effect of tide-control under a variety of conditions.

The fourth and final study would consist of carrying out tests on Thames mud to determine the constants and coefficients of erosion and deposition needed for the mathematical model.

3. Field surveys

The two 'dry weather' surveys, mounted during the spring and neap tides of 24 and 30 September 1968, respectively, were planned to coincide with the low freshwater flow normally experienced in the Thames at this time of the year. The English climate being reliably unpredictable provided the river with exceptionally high discharges during the fortnight preceding the surveys. The maximum flow recorded at Teddington Weir, the tidal limit of the estuary, was 50×10^6 m^3 a day compared with the mean daily flow for September of just over 2.3×10^6 m^3 a day. Although the river discharge had fallen again by the time of the surveys (7.7×10^6 m^3 and 11.8×10^6 m^3 a day for the 24 and 30 September respectively), the volume of freshwater still in the estuary was very much greater than usual. This was demonstrated by the fact that the upstream limit of intrusion of saline water lay in the vicinity of Woolwich instead of about 13 km further up-river near the Tower of London.

The 'wet weather' surveys which had been planned for the following February were accordingly postponed until 26 September and 6 October 1969, when the river conveniently maintained a steady flow rate of less than 2.3×10^6 m^3 a day (i.e. below the mean daily flow for the period) both before and during the spring and neap surveys.

The length of river surveyed extended from Richmond to Southend, a distance of 96 km, and for each survey the river was divided into 12 sections which are shown on figure 1. The spacing of the sections was determined partly by the requirement to station each survey vessel as far away as possible from bends in order to minimize the effects of local topography on flow, and partly by the need to obtain greater coverage of conditions in the middle part of the estuary than elsewhere. This second requirement arose because the most likely sites for barrier construction lay in the centre stretches of the river between Upper Pool and Long Reach. Furthermore, the major siltation zone in the Thames, known as the 'Mud Reaches' is located here in Gallions, Barking and Halfway Reaches, and it was necessary to have as much information as possible on conditions in the Mud Reaches in order to establish the mathematical siltation model and verify its performance.

At each of the 12 river sections the velocity of currents was measured every 10 min throughout a tide and the direction of currents every 20 min, at 0.15, 0.3, 0.6 and 1.2 m ($\frac{1}{2}$, 1, 2 and 4 ft) above the bed. It is in these lower layers of the flow that a high proportion of the total sediment transport in the estuary occurs, where the rate of change of current velocity with depth is at a maximum. It was therefore of especial interest to record the velocity gradient during a tide in this zone. A photograph of the equipment developed for this purpose is shown in figure 2. Throughout the remainder of the depth, the direction and the velocity of the flow were measured at 3 m intervals once every 20 min. The concentration of suspended sediment was determined in the laboratory from pumped water samples collected at each survey section every 30 min throughout the tide at positions 0.6, 1.5 and 3 m above the bed and thereafter at 3 m intervals to a point 1.5 m below the water surface. Measurements of the salinity and temperature of the river were made at the same positions and times as the water samples were collected.

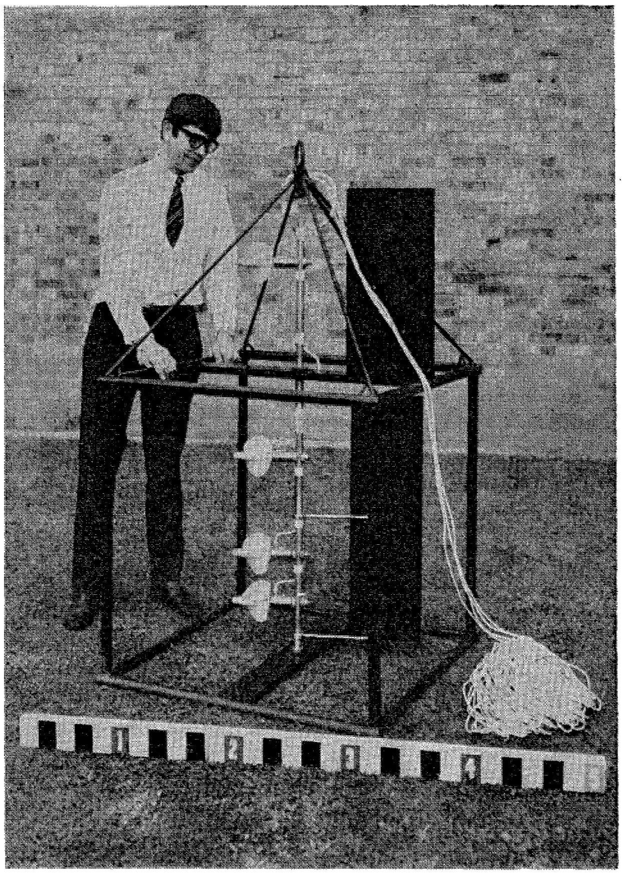

Figure 2. Current meter array.

In addition to the data on current velocity, suspended sediment, salinity and temperature, the Thames surveys provided measurements of tide level, water depth, water pollution and information on the composition of the estuary bed, the data return on all four surveys being over 90 %.

Because of the large scale of the operation and the number of measurements required, the organizer, Mr J. D. G. Smart of the Hydraulics Research Station, was assisted by the loan of staff and survey equipment from several interested authorities, including the Greater London Council, the Port of London Authority, the Medway Conservancy, the Ministry of Agriculture, Fisheries and Food, the Ministry of Defence and Southampton University. Most of the data collected were processed by computer and are being printed with the information from each survey section contained in one volume. They are presented in the following form:

(*a*) Current velocity/time plot of raw data for each depth.
(*b*) Salinity/time plot of raw data for each depth.
(*c*) Suspended solids concentration/time plot of raw data for each depth.

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(*d*) Current velocity/depth plot of interpolated data at each time interval.

(*e*) Salinity/depth and suspended solids concentration/depth plots of interpolated data at each time interval (shown on the same graph).

4. Suspended silt monitoring

Reliable measurement of suspended sediment in the field by automatic means presented considerable difficulties. Because there was no suitable system on the market with a short delivery time and an economic price, all available measuring heads and data-logging equipment were examined and a specification was drawn up marrying two 'Partech-WPRL' sensing heads to a 'd-mac' data logger and control unit.

The sensing heads each consist of a central light source compartment and two photo-electric cell compartments. The river water flows through a gap between each photo-cell and the light source: the light transmission detected by the photo-cell is thus a function of the turbidity of the water. The lengths (a, b) of the two gaps between the light source and the two photo-cells are unequal so that the difference between the two photo-cell voltages is a function of the turbidity of a filament of water of length ($a-b$). This arrangement eliminates the possibility of any inaccuracies due to uniform clouding of the compartment lenses between routine inspections. The relation between the voltage difference and the concentration of suspended solids of the water is obtained by empirical calibration. Each sensing head can be set to one of three possible ranges – 0 to 1000, 0 to 2000 or 0 to 3000 parts/10^6.

The data logger and control box contains a clock, the control circuits, and a magnetic tape-recorder. The clock switches on the sensing heads at 15 min intervals and records the instantaneous voltage difference of each head on magnetic tape, together with a number identifying the time. The magnetic tape is later retrieved and translated into punched paper tape suitable for computer analysis.

Each monitoring set is self-contained and operates from 12 V dry cell batteries for a minimum period of 35 days without requiring attention. After this interval the sets are serviced, which involves inspecting the sensing heads and cleaning them if necessary, checking their calibration, monitoring battery voltage levels and replacing the magnetic tape.

Since March 1970, Mr M. F. C. Thorn of the Hydraulics Research Station has been operating four such sets of silt monitoring equipment in Halfway Reach, Long Reach, Gravesend Reach and Sea Reach; respectively 21, 34, 41.5 and 69 km below London Bridge. At each site, two heads are mounted on a convenient pile at levels 0.6 and 3 m above the apparent river bed. They are connected by cable to the logger and control box housed in a nearby building.

Since the silt concentrations measured in Sea Reach, at the estuary entrance, have remained consistently low (less than 50 parts/10^6), this site is now being discontinued in favour of a new location in Woolwich Reach, between the proposed barrier and the free ferry terminals.

Computer processing and presentation of the recorded data is presently in progress, the first set of results demonstrating a strong correlation between silt concentration and tidal range.

5. Determination of properties of Thames silt

To develop the mathematical silt model it was necessary to estimate the value of four parameters describing the cycle of silt movement – a cycle which involves the processes of erosion, transport in suspension and deposition.

The first parameter was the *critical shear for erosion*, or the force exerted on the bed by a particular current velocity gradient immediately above the bed at which silt movement is initiated. The second parameter was the *erosion constant*, that is the rate of increase of the erosion rate with shear force. The third parameter was the *limiting shear for deposition*, or the value of shear force at which materials start to deposit out of suspension on to the bed. The fourth parameter was the *settling velocity* of the silt.

The first three values were obtained by flume tests, using two identical flumes originally built for a long-term basic research project to study the properties and behaviour of cohesive silts under conditions similar to those found in estuaries. The reason for having two flumes was that testing could proceed in one while a silt bed was being consolidated in the other, long periods of inactivity thereby being avoided.

The critical shear for erosion and the erosion constant were obtained by pumping a slurry of silt and water of measured concentration and volume into the working section of one of the flumes and allowing the silt to settle to form a bed. For this operation the roof and sides of the working section could be temporarily raised to provide a 1.8 m deep settling tank. The bed was left to consolidate for 3 days, the surplus water was slowly drained off and the flume returned to its normal dimensions for testing.

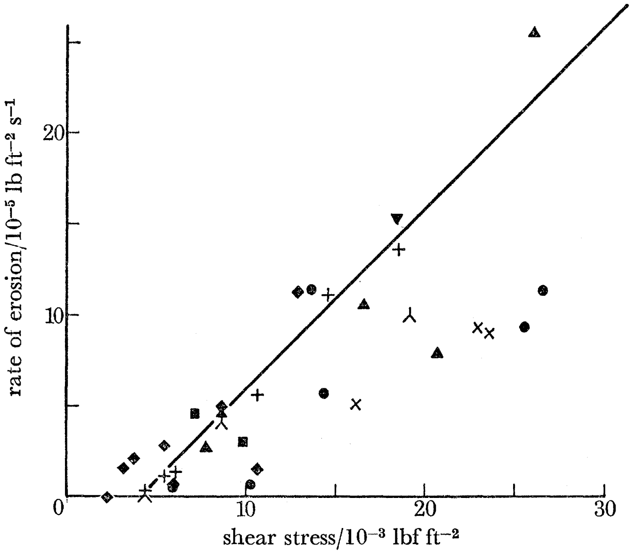


FIGURE 3. Flume tests to determine critical shear erosion and erosion constant. (1 lb ft^{-2} s^{-1} $\approx$ 4.88 kg m^{-2} s^{-1}; 1 lbf ft^{-2} $\approx$ 48 N m^{-2}.) The different symbols indicate different tests.

Starting at a low value, a constant discharge was passed through the flume for 1 h during which regular measurements were made of discharge, head loss across the working section and concentration of suspended sediment.

The discharge was gradually increased and the process repeated successively until all the silt had been eroded from the bed. The results obtained from eight series of tests are plotted on figure 3. Although the results of any tests with naturally occurring cohesive materials are always difficult to reproduce with much accuracy, there are additional reasons for the large scatter of points here.

The results at a particular flow depend to some extent on the amount of material previously eroded from the bed, the general belief being that as the erosional process continues, the bed becomes more resistant to further erosion. Values obtained from the runs with higher discharges would therefore tend to indicate less erosion than they should. This could have been avoided by depositing a new silt bed for each discharge tested – an extension of the procedure which was not possible in the time available for the study. The determination of this particular curve was thus rather subjective, assisted by visual observation and first-hand experience of the tests.

The critical shear for erosion is given by the intercept of the curve with the shear stress axis: the erosion constant, or rate of increase in erosion rate with shear, is given by its slope.

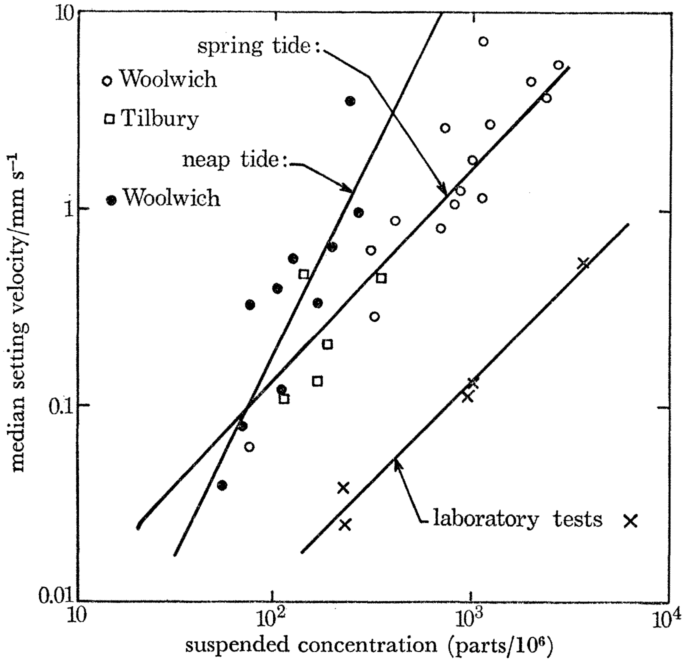


FIGURE 4. Settling velocity tests.

The third parameter obtained from the flume tests, the *limiting shear for deposition*, involved a test procedure which was virtually a reversal of that adopted for the erosion studies. The flume was run at a very high discharge for half an hour to thoroughly disperse the slurry that was pumped in from a mixing tank. The discharge was then reduced and held constant for an hour. A bed started to form and its thickness was measured at regular intervals at the glass side of the flume. In addition, records of discharge, head loss and concentration of suspended silt were obtained as in the previous tests. Successively lower discharges were passed through the flume until the water became almost stationary. The results thus gave the shear stress on the bed and the corresponding rate of deposition and, when analysed, indicated that no significant deposition occurred at a shear stress above 0.00125 lbf/ft^2 (0.06 N/m^2). This was the initial value used for the mathematical model.

The fourth parameter required for the mathematical silt model study, the *settling velocity* of Thames silt, was not obtained from flume tests but, in the first instance, from settling tests undertaken in the laboratory. Subsequent field tests led to modification of the values used in the mathematical model.

The settling velocity of a given silt is a complex function of concentration, salinity and turbulence but the effect of turbulence cannot be satisfactorily reproduced in the laboratory. There has thus been a general tendency in the past to ignore it. However, in July 1969, during the course of this investigation, Mr M. W. Owen developed a new field instrument (Owen 1971) which enabled settling velocity to be calculated directly from field observations, thus including the effect of any turbulence which might be present at the site.

Tests carried out with this instrument at Woolwich and Tilbury during both spring and neap tides indicated that under conditions of turbulent flow salinity has very little effect on the settling velocity of Thames silt. They also showed (figure 4) that on neap tides the settling velocity increased approximately with the square of the concentration, whereas on spring tides the increase was linear. Finally they demonstrated that although the spring tide tests gave roughly the same rate of change in settling velocity with concentration as the laboratory tests, the actual values were approximately ten times greater.

6. Mathematical silt model studies

With the information collected in field and laboratory an attempt could be made to develop the mathematical silt model.

During the early stages the principal object was to simplify wherever possible in order to establish a working model: refinements and modifications could be made later as experience was gained. The estuary was thus treated as an idealized estuary, rectangular in section (figure 5), whose width varied exponentially with length. In view of the geometry of the Thames, these simplifications were reasonable.

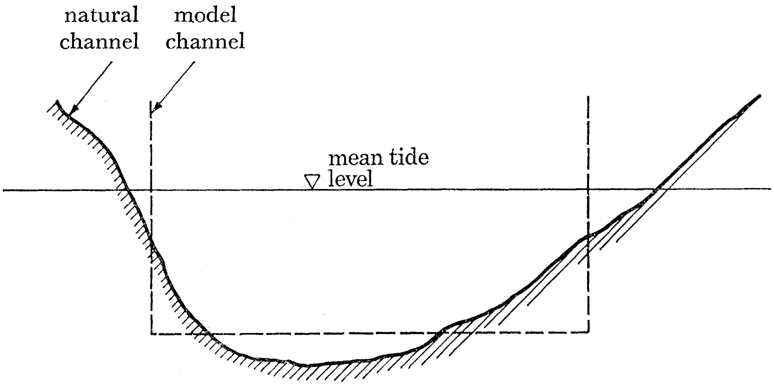


Figure 5. Schematization of channel section. Vertical distortion 20:1.

The development of the model divided naturally into two stages – the simulation of water movement and the simulation of silt movement, the former being a prerequisite of the latter.

In the first, or water movement stage, calculation based on the fundamental laws of momentum and continuity were carried out, section by section, throughout the estuary at successive time intervals. When the channel geometry and roughness are known accurately, it is not particularly difficult to verify a 'bulk flow' model of water movement: even with rather inadequate information on channel roughness, a few runs with different values of friction will usually produce satisfactory agreement with field results. However, a simple bulk flow model assumes uniform distribution of properties throughout the depth – too unrealistic a simplification in the light of the Thames field measurements, which demonstrated significant changes in current velocity and concentration of suspended silt with depth, particularly near the bed. In the lower few feet, the current velocity increases from zero at the bed to almost mainstream value, while the suspended silt concentration decreases from a very high value near the bed to virtually the average value.

The model flow was therefore divided into two horizontal layers with a common boundary 1.2 m above the bed. The total flow throughout the depth and the flow in the lower layer were both calculated, the difference between the two giving the flow in the upper layer. All properties within each layer were assumed to be uniformly distributed with depth at their respective average values.

Figures 6 and 7 show the resulting schematization of the profiles of velocity and suspended silt concentration used in the model.

The development of the second, or silt movement stage of the model was more complicated than the simulation of the water movement since the basic principles involved are still not completely understood. Continuity of the flow of silt had to be maintained, the empirical expressions based on the experimental results of field and laboratory tests being used to describe the processes of erosion, transport in suspension and deposition.

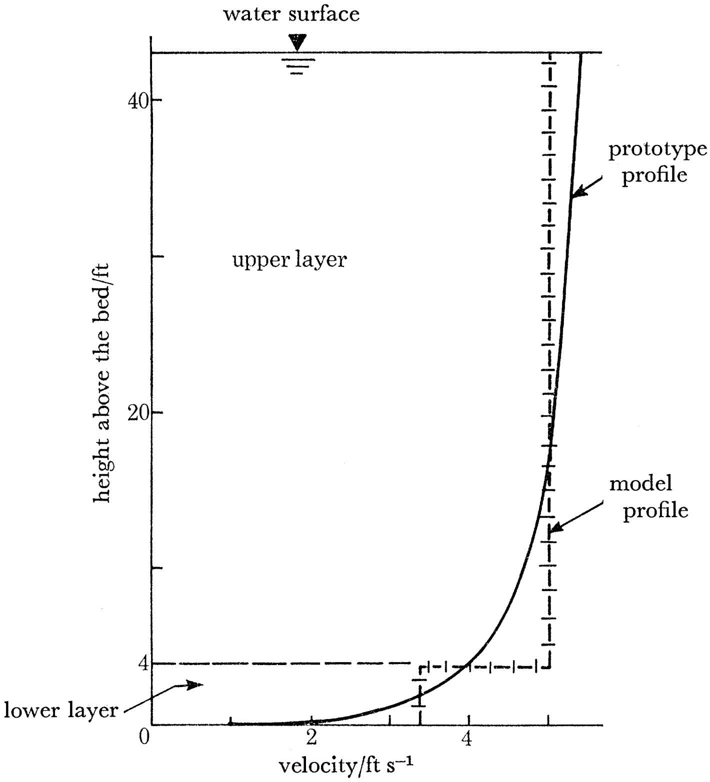


Figure 6. Schematization of velocity profile (1 ft ≈ 0.3 m).

Once eroded from the bed, the silt was assumed to move in suspension with the water in the lower layer, diffusing gradually into the upper layer. Although the concentration with depth within a layer was assumed to be constant, it was assumed to vary continuously with distance along the estuary. The relative distribution of silt between the lower and upper layers depended on the amount settling downwards and the quantity moving upwards due to mixing at the interface. Once on the bed, material was assumed to consolidate immediately, no account being taken of the effect of consolidation time on erosive strength of the bed.

By making these assumptions and considering the expressions for the processes involved in silt movement, equations of continuity of flow of silt in each layer could be formulated. Combining these with the continuity equations for water movement gave equations describing the changes in concentration of suspended silt in each layer.

Table 1 shows the calculation procedure adopted for both stages of model testing.

The model was first verified for reproduction of water movement.

At Teddington, the upstream limit, the river flow observed at the time of the field measurements was introduced, and at Southend, the seaward limit, the observed changes in tidal height with time were simplified to give a sinusoidal curve of the correct tidal range and period. The observed longitudinal salinity distribution at mean tide and the instantaneous water surface profile at low tide level were also introduced. The model then calculated the tidal propagation throughout the estuary, settling down after two tides to give repeating results in good agreement with the field measurements of water movement. Detailed descriptions of the mathematical silt model are given in Owen & Odd (1970).

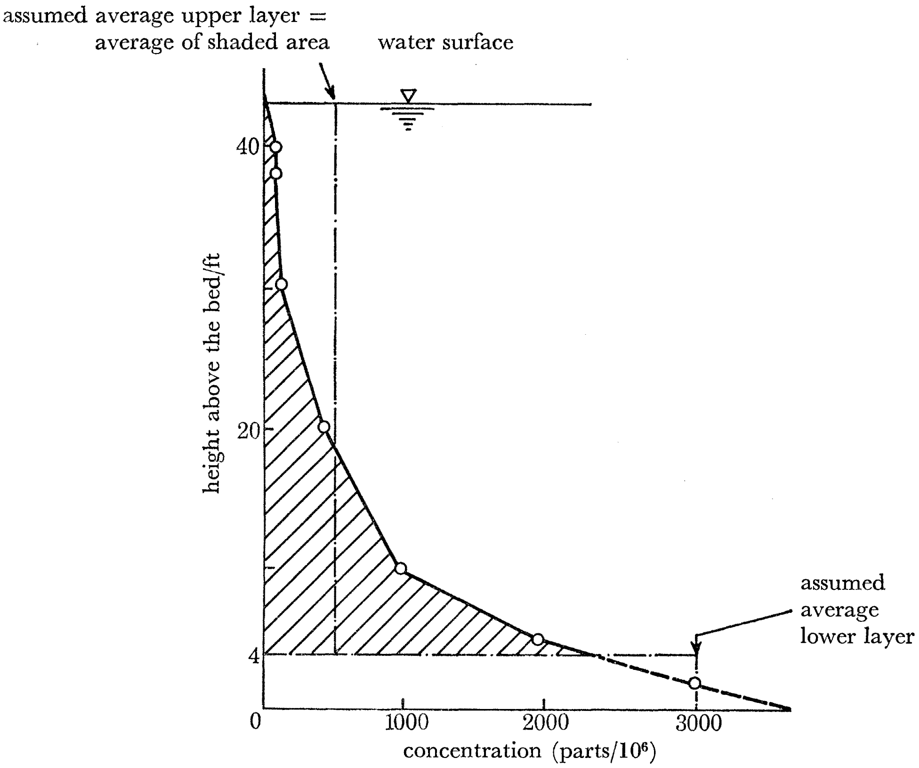
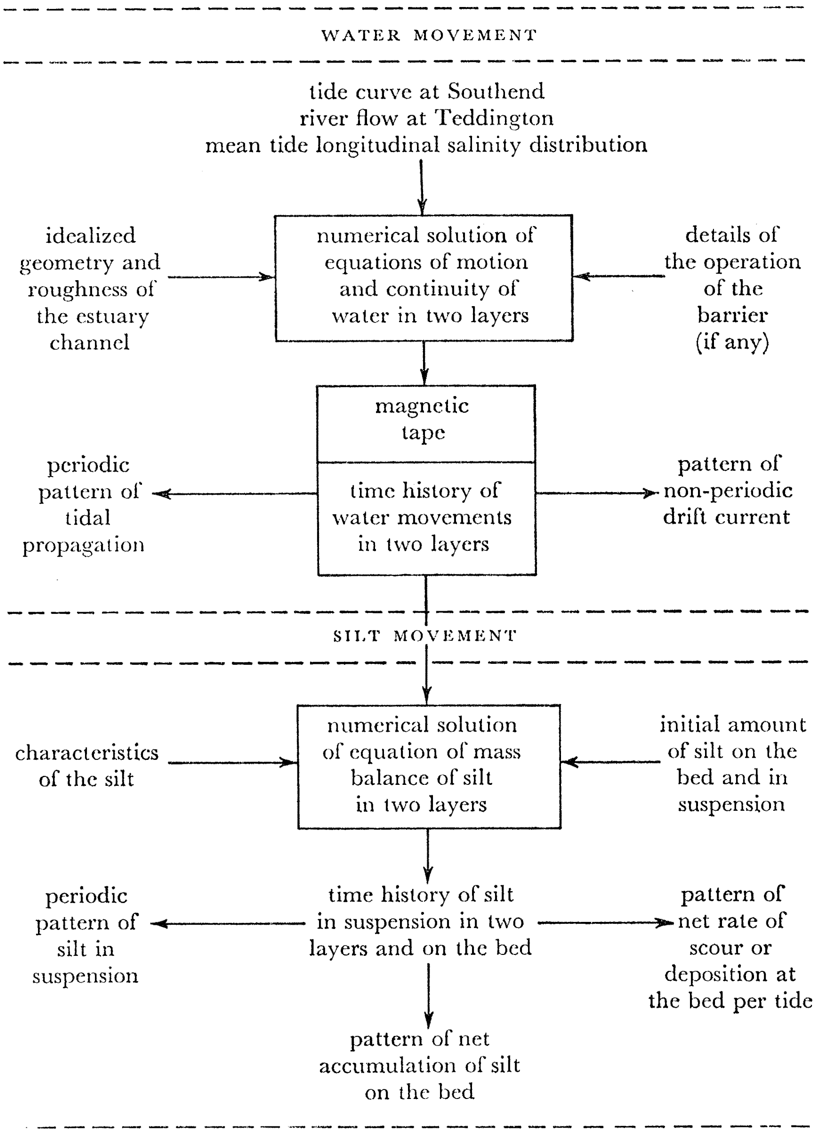


FIGURE 7. Schematization of suspended concentration profile (1 ft ≈ 0.3 m).

The starting conditions for the tests to verify the reproduction of silt movement were the concentrations in each layer measured at low tide level during the surveys, and a uniform thickness of potentially active silt (amounting to about 230000 tons dry mass of material) spread over the whole bed of the estuary. This represented the amount of silt actively engaged in movement during a spring-to-neap tidal cycle and not the total quantity stored in the estuary. Four tides were run to permit the model to redistribute the material to form 'hard' and muddy reaches and the fifth was analysed to check the silt concentrations in each layer. The criteria for comparing model results with field measurements were: first, the variation of the average concentration in each layer throughout the tide with distance along the estuary, and secondly the variation of concentration in each layer with time at the surveyed river sections. Figures 8 and

9 demonstrate respectively the agreement reached on spring and neap tides after several trials with various values of each of the silt constants. The main difference between silt movement on spring and neap tides was one of degree only, the amount of silt in suspension during a neap tide being about 90 % less.

Table 1. Calculation procedure



In view of the complexity of the problem and the simplifications made, the agreement between model and nature was considered acceptable. The model had reproduced the peak of the average concentrations in the correct stretch of the estuary – the Mud Reaches – and, with few exceptions, the absolute values were not too dissimilar. The discrepancies between the extremely high individual concentrations recorded in the Mud Reaches during the spring tide survey (over 50000 parts/10^6) and the more modest maxima from the model (over 3000 parts/10^6) were almost certainly due to the formation of a thick layer of fluid mud on the bed of the estuary round the sampling instrument. At high concentrations suspended silt exhibits hindered settling and behaves more like fluid mud than a suspension of flocculated silt particles.

Once the model was deemed to reproduce silt movement satisfactorily, tests were carried out to determine the effects of continuous half-tide control with a barrier located first in lower Woolwich Reach and then in Blackwall Reach. The barrier was programmed to close instantaneously at mid-ebb and to open again when water levels on either side equalized, at about mid-flood.

As the model had not been developed to the stage where it could reproduce salinity variations in the estuary, the longitudinal salinity distribution near the bed at mean tide was assumed to be unaffected by barrier operation. The upstream limit of intrusion of saline water was, however, adjusted to remain immediately downstream of the barrier instead of just upstream as during the field survey. These assumptions were justified by subsequent tests in the physical model.

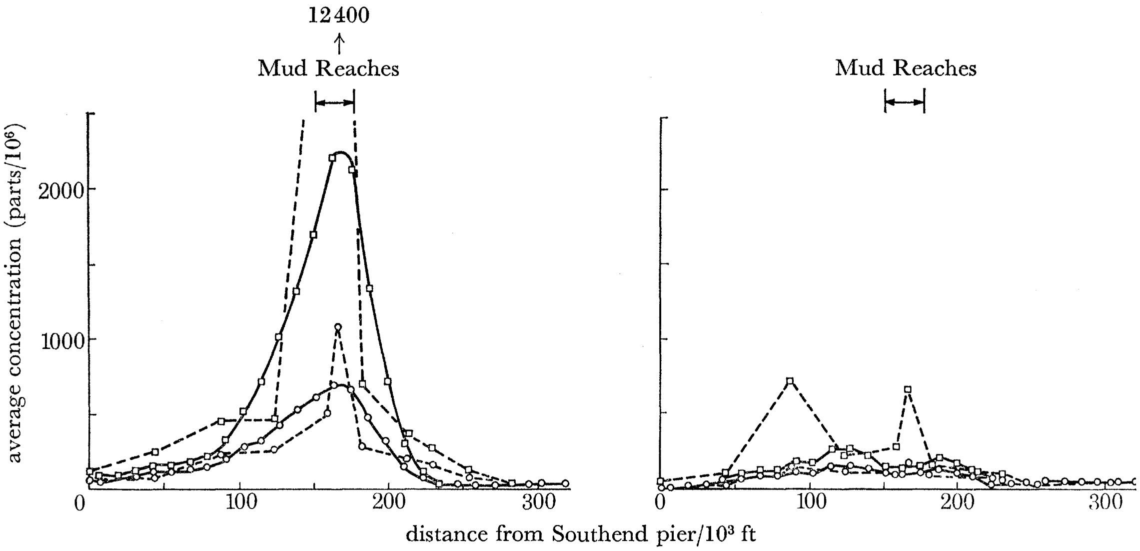


FIGURE 8

FIGURE 9

FIGURES 8, 9. Proving tests of spring tide (figure 8, left) and neap tide (figure 9, right). Model: ○—○, upper and □—□ lower layers; prototype: ○---○, upper and □---□, lower layers.

The effect of continuous half-tide control on water levels and current velocities upstream and downstream of the barrier are typified by the curves in figures 10 and 11 respectively. From the standpoint of siltation the most important change was the large reduction in current velocity which occurred. This in turn influenced the quantity of material in suspension in the estuary, concentrations in the Mud Reaches being many times lower than before barrier operation. Figures 12 and 13 show the effect on the distribution of average concentrations of tide control at Woolwich and Blackwall respectively.

Although the immediate effect of barrier operation at either site was the rapid deposition of suspended sediment in the Mud Reaches, the continuation of tide control resulted in differences in the longer-term distribution of siltation which were dependent on the barrier site.

With the Woolwich barrier, continuous half-tide control led to the gradual erosion of the material initially deposited in the Mud Reaches after the first closure, the quantity transported downstream during successive ebb tides exceeding the amount brought into the area during the same number of flood tides. The continuation of this process led to the formation of a new deposition zone approximately 10 km down-river. By contrast, the seaward displacement of the Mud Reaches by closure of the Blackwall barrier was only about 1.5 km, sediment eroded from

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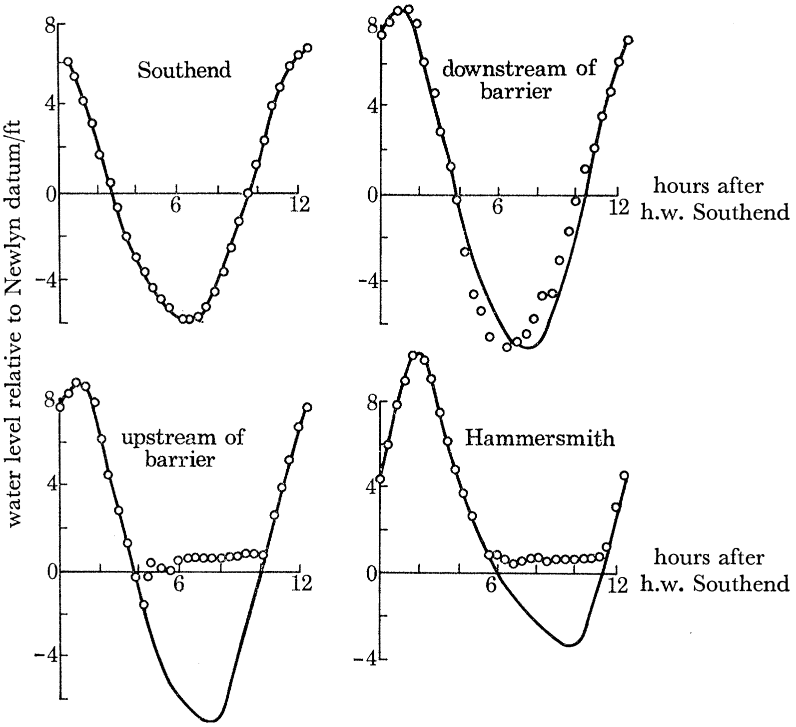

FIGURE 10. Specimen tide curves typifying the effect of half-tide control. —, unrestrained flow; o, half-tide control. Mean tide: upland flow 42 m³/s.

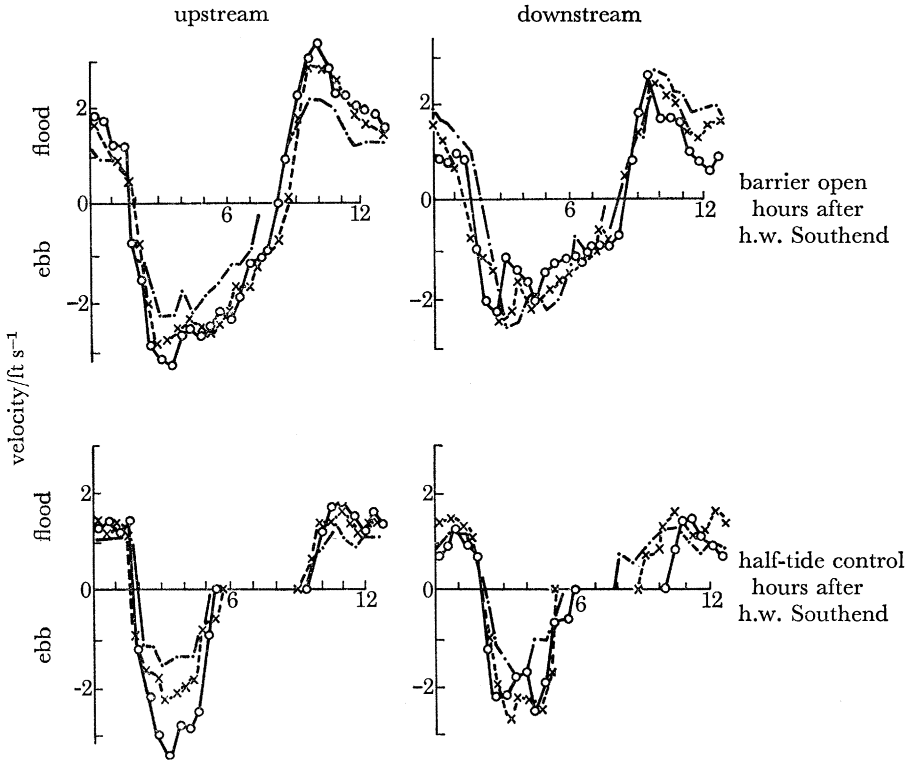

FIGURE 11. Current veolcity curves typifying the effect of half-tide control (mean tide). o—o, 1.5 m below surface; × --- ×, mid-depth; ·—·—·, 0.6 m above bed.

the upper end being deposited immediately downstream of the present seaward limit of the deposition zone.

By logging the quantities of silt involved in the exchange processes of erosion and deposition, the net gain or loss of silt on the model bed could be determined. This is plotted before and after tide control with each barrier on figures 14 and 15 for spring and neap tides respectively.

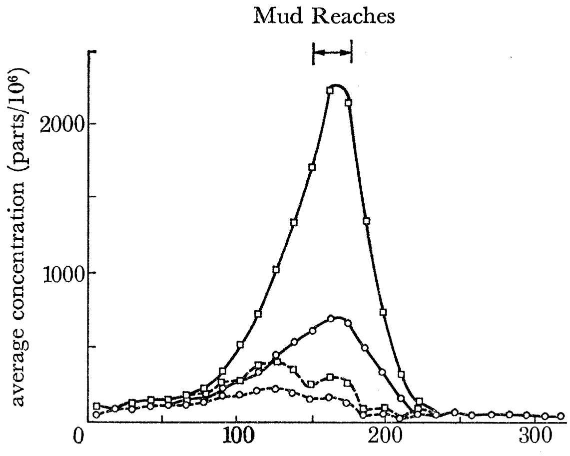

FIGURE 12

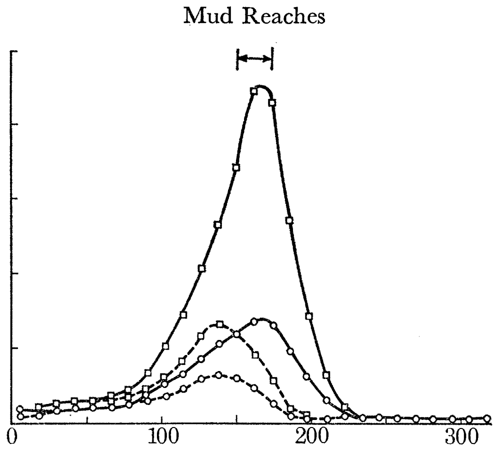

FIGURE 13

FIGURE 12. Woolwich barrier tests.

FIGURE 13. Blackwall barrier tests. Spring tide. No barrier: ○—○, upper layer; □—□; lower layer. Barrier: ○---○, upper layer; □---□, lower layer.

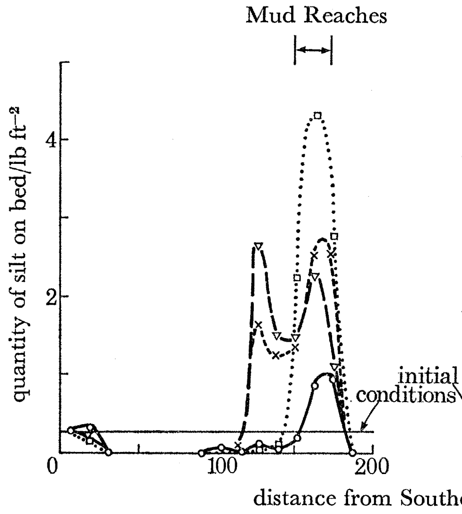

FIGURE 14

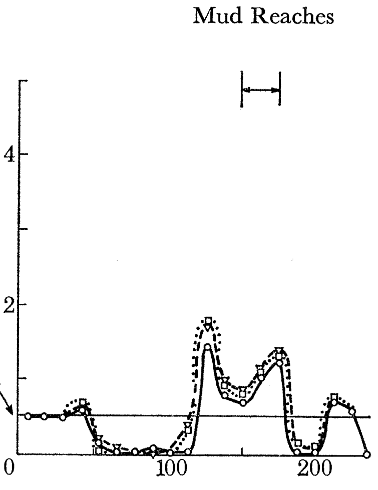

FIGURE 15

FIGURES 14, 15. Distribution of silt on bed; figure 14 (left), spring tide; figure 15 (right) neap tide. ○—○, proving test; ×---×, Woolwich barrier (5th tide); □··□, Blackwall barrier (5th tide); ▽--▽, Woolwich (10th tide).

On both spring and neap tides, continuous barrier operation reduced current velocities and suspended silt concentrations, but there the similarities ended. Whereas spring tide control resulted in increased siltation, neap tide control produced virtually no change in the distribution of sediment, the silt which deposited after the first barrier closure remaining as a thin layer over the middle reaches of the estuary throughout subsequent closures.

The Hydraulics Research Station were urged to quantify the results of this study in terms of siltation rates, which they did, but not without emphasizing the need to treat the figures cautiously in view of the assumptions which had been necessary in the development of the mathematical silt model.

7. Physical model studies

The mathematical model studies provided a general picture of the new longitudinal distribution of zones of erosion and deposition following changes in the movement of suspended silt due to tide control. The physical model tests, carried out under the supervision of Mr B. V. Derbyshire, performed a similar function in rather more detail for sediment which moves on or immediately above the bed. In addition they demonstrated the effect of the barrier structure, gates fully open, on the distribution of material in the navigation channel in the reaches nearest the barrier.

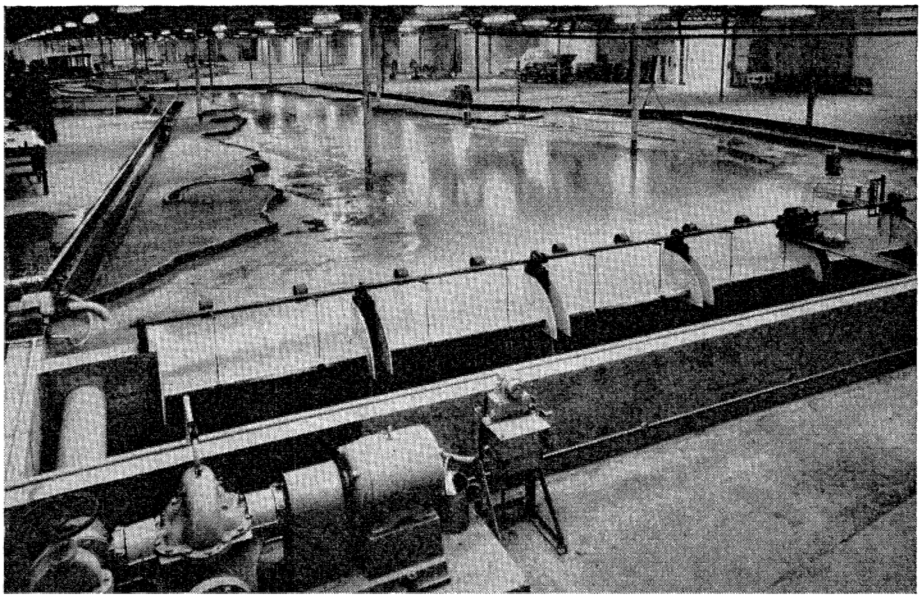

Figure 16. Thames model.

The model, shown on figure 16, was 115 m long, 12 m wide, had a horizontal scale of 1/600, a vertical scale of 1/60 and included the Thames estuary from Southend-on-Sea to Teddington Weir. It was equipped to reproduce any particular tide repeatedly or any combination of tides of varying range, any river flow from zero to the equivalent of 90×10^6 m^3 a day, and the natural salinity distribution as measured in the estuary.

As with the mathematical model it was relatively easy to verify the physical model for simulation of water movement, the tests being carried out with the estuary bed fixed in cement mortar. Verification of its ability to reproduce the natural topography of the river bed was confined to the stretch between the Isle of Dogs and Long Reach, an area which included the major deposition zone – the Mud Reaches. Granulated perspex of density 1.18 g/cm^3 and median grain diameter 0.3 mm was screeded over the correctly moulded cement mortar bed and a spring-to-neap cycle of 28 tides was generated repeatedly until successive surveys made at a given stage in the tidal cycle indicated the model bed to have reached a state of dynamic equilibrium. A perturbation was introduced by dredging a large area in Barking Reach and leaving the model running until again there was no tendency for bed levels to change. The resulting topograph was sensibly similar to that of the predredged model river.

In addition to providing a check on the repeatability of the model, this exercise permitted comparison of the sediment infill rates of the dredged channel in model and nature from which a model time-scale for sediment movement could be derived. It was thus possible to make approximate quantitative assessments of siltation rates following different barrier schemes (H.R.S. 1970).

Figure 17 compares the model equilibrium survey with the river survey of August 1966. Bed levels in the model study area were generally about 0.6 to 0.9 m higher than in the field because the thickness of the sediment screeded over the cement mortar bed was equivalent to 0.75 m.

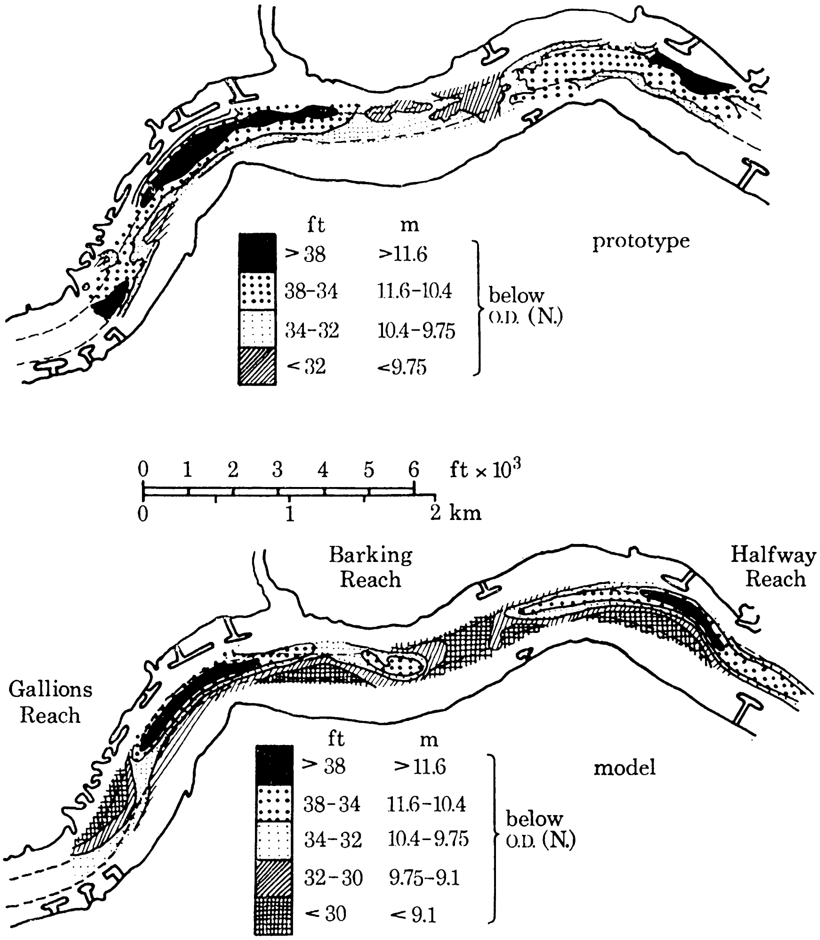

FIGURE 17. Prototype and models surveys.

A barrier was installed in the model in lower Woolwich Reach (figure 18) and tides were generated with the gates fully open until a new state of dynamic equilibrium was achieved.

Finally, the barrier was operated as a half-tide control device, the gates being closed during the ebb tide to impound the water upstream at a level of ordnance datum (Newlyn) and reopened when the following flood tide reached a similar level at the barrier. These operations were carried out on successive tides until yet another state of dynamic equilibrium was attained.

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The complete series of tests was repeated with barriers in Blackwall Reach and at Silvertown (upper Woolwich Reach). The two accretion/erosion charts on each of the figures 19 to 21 demonstrate the resulting changes in the distribution of sediment in the navigation channel. The model equilibrium survey before barrier construction is compared with that after barrier construction on the upper chart, and with that after about three months of continuous half-tide control on the lower chart.

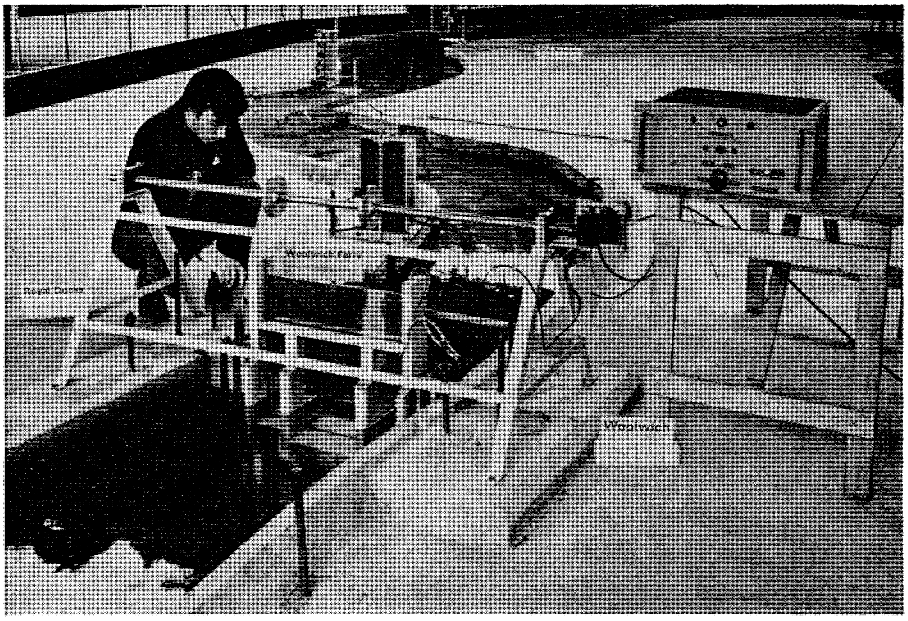


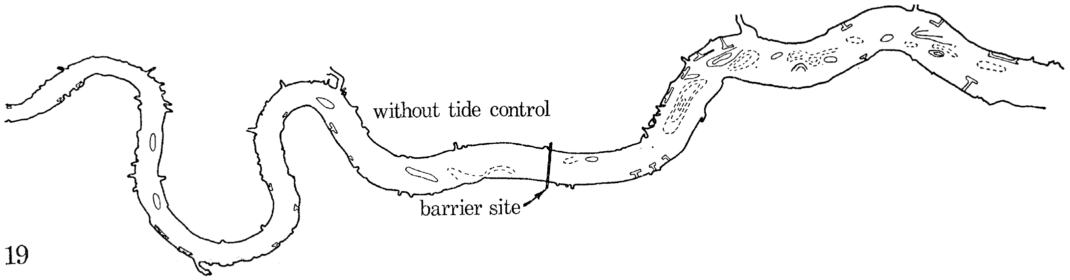
Figure 18. Woolwich barrier tested on model.

Changes on all three upper charts are small, signifying that the presence of the structure has relatively little effect on navigation channel depths. The three lower charts, however, indicate that tide control with any one of the three barriers produced considerable changes in depth.

The Woolwich barrier caused erosion in the upper Mud Reaches, the material passing downstream to deposit as far down-river as upper Long Reach: the Blackwall barrier resulted in increased deposition within the Mud Reaches and Woolwich Reach: the Silvertown barrier produced effects reflecting its intermediate position, increased siltation within the Mud Reaches being accompanied by accretion beyond the usual seaward limit of the deposition zone. Continuous tide control at any of the sites led to an increase in the rate of siltation, and hence in the maintenance dredging rate, at the entrance to the Royal Group of Docks in Gallions Reach, the Woolwich barrier giving the highest rate, the Blackwall barrier the lowest.

8. Conclusions and implications

Two main conclusions have emerged at this stage of the siltation studies. The first is that, if used only to exclude surges, a barrier could be sited at Woolwich, Blackwall or Silvertown without disturbing the present hydralic equilibrium of the estuary. Local changes in the siltation pattern would be likely to occur due to the effect of the structure on flow behaviour in the vicinity of the barrier: these effects would be entirely dependent on its detailed design – sill



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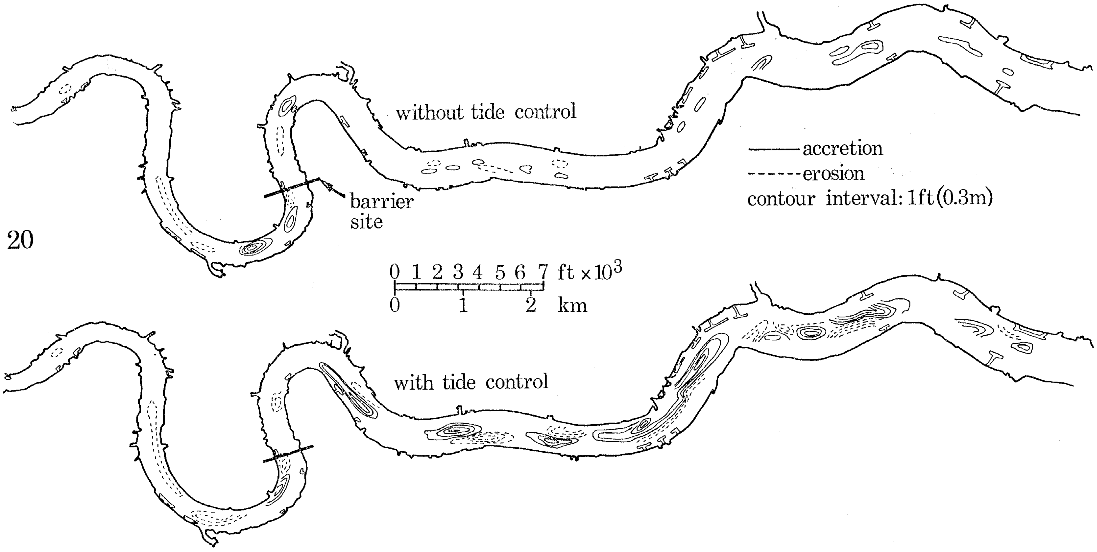

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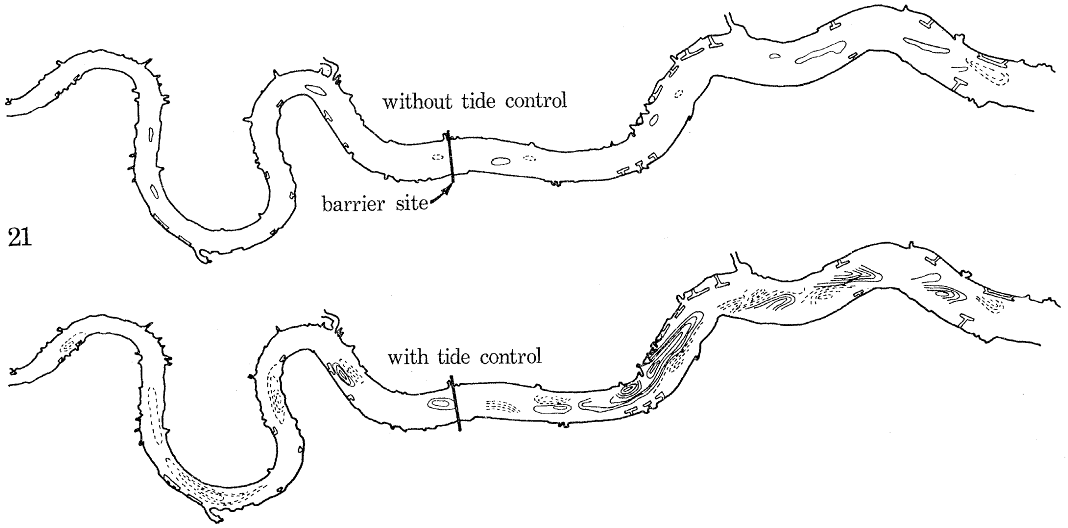

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Figures 19 to 21. Effect of (19) Woolwich barrier, (20) Blackwall barrier and (21) Silvertown barrier on accretion and erosion.

level, length and alinement of piers, number of gate-openings, etc., and could be minimized by applying the findings of large-scale model tests.

The second conclusion is that continuous half-tide control by any of the barriers tested would radically change the siltation characteristics of the estuary – either by decreasing depths in the present major deposition zone or by creating a new deposition zone further seaward. The evidence available so far suggests that siltation would be greater, the further down-river the barrier site.

The acceptability of the changed river-bed topography created by continuous tide control will obviously depend on future requirements. At present no dredging is necessary within the confines of the navigation channel: if it is of paramount importance that this situation should continue but that depths should nowhere be less than they are today, then continuous tide control is out of the question. If, however, other, non-navigational, considerations carry greater weight, then either reduced depths and continuous maintenance dredging must be faced or some modified form of intermittent tide control must be devised which ensures that undesirable siltation is kept to a minimum. The second alternative should be possible to achieve with the aid of further tests on the hydraulic models.

Acknowledgements are due to Mr R. C. H. Russell, Director of the Hydraulics Research Station, for his permission to submit this paper, and to Mr W. A. Price whose advice, based on long association with hydraulic problems on the Thames, was generously given.

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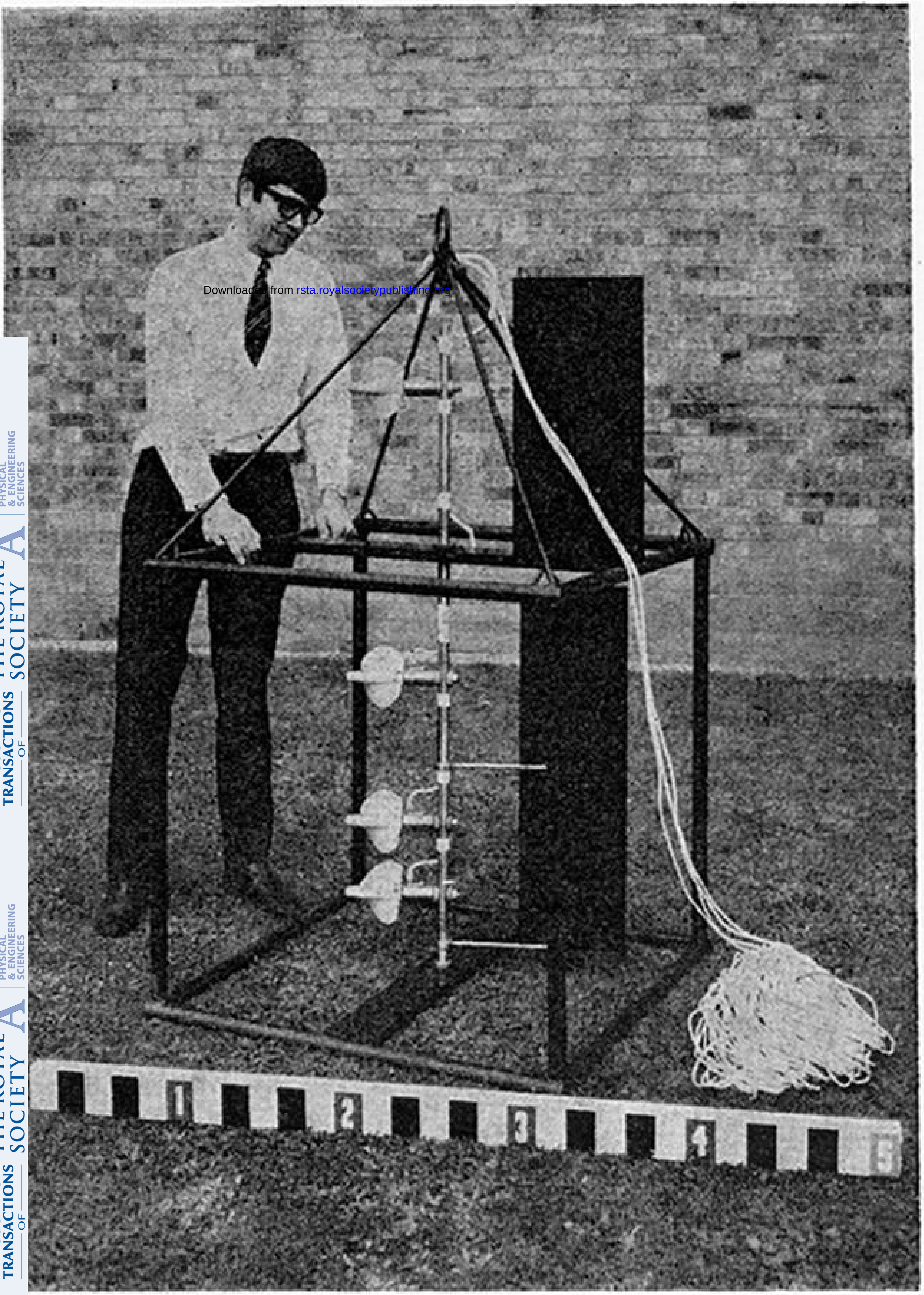

FIGURE 2. Current meter array.

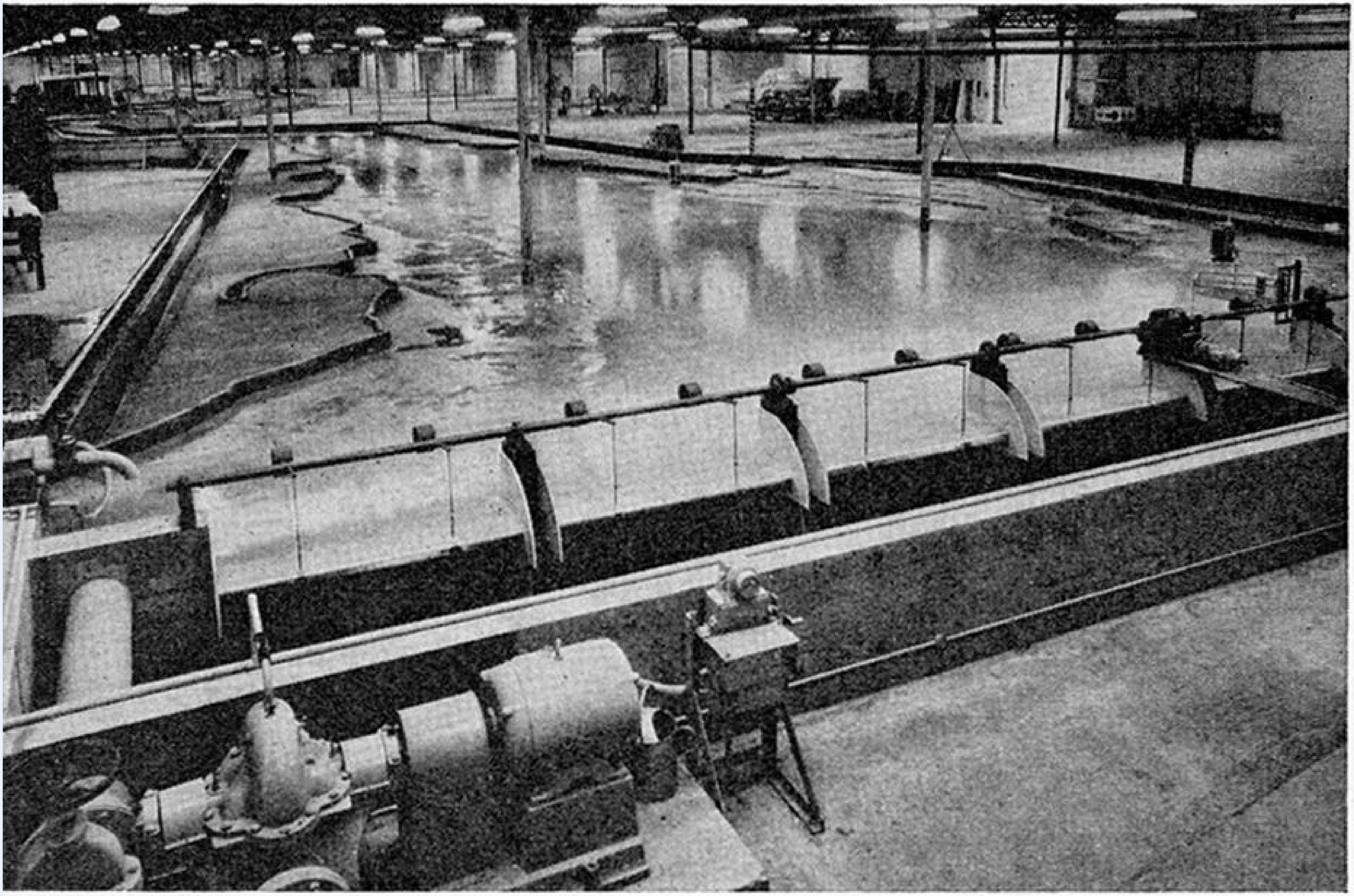

FIGURE 16. Thames model.

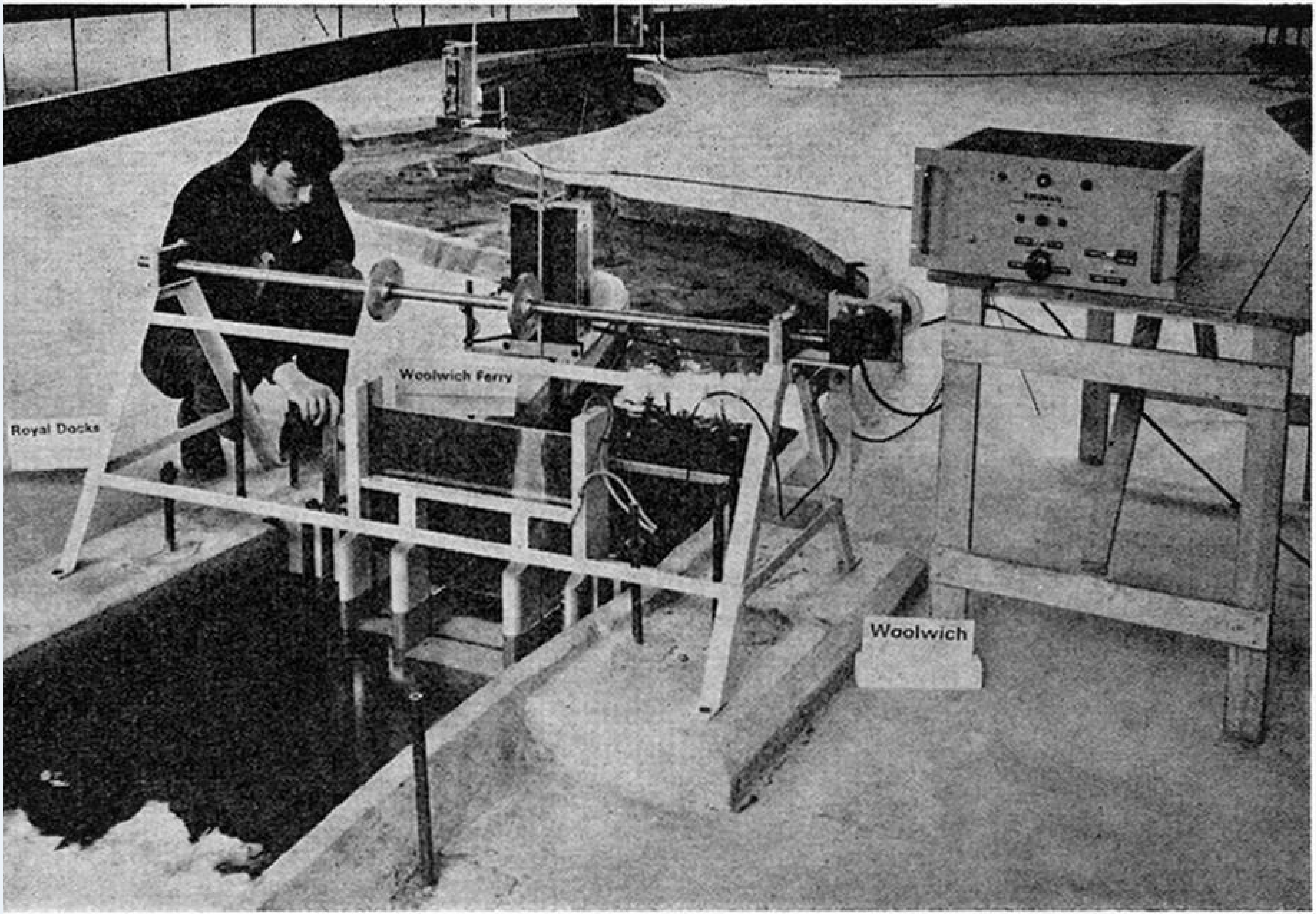

FIGURE 18. Woolwich barrier tested on model.