Tidal Estuaries: Forecasting by Model Experiments*

By PROF. A. H. GIBSON

THE earliest work on tidal models was carried out by Osborne Reynolds at the University of Manchester in 1885 on scale models of the Mersey estuary. This was followed by an investigation into the general question of the use of such models, in which Reynolds co-operated with a committee appointed for this purpose by the British Association in 1888. The experiments were devoted mainly to an examination of the behaviour of models of the same hypothetical estuary, of symmetrical shape, to different scales. As a result of this investigation, the committee reported in 1891 to the effect that "It would seem therefore that by carefully observing certain [stated] precautions, the method of model investigation may now be applied with confidence to practical problems".

Shortly afterwards, Vernon Harcourt carried out an investigation on a model of the estuary of the Seine, in which the results of improvements made in the estuary since about 1833 are stated to have been reproduced with considerable accuracy. Between 1890 and 1926, very few investigations of this kind appear to have been carried out, and these for various reasons not with any marked degree of success.

Any scale model in which fluid motions are involved must not only be geometrically similar to its original, but also the velocities must be so related to corresponding velocities in the original that all corresponding forces are in the same ratio. The model and its original are then dynamically similar, and all lines of flow and wave formation will be similar. The speeds of model and original at which this condition is satisfied are called 'corresponding speeds'.

In many hydraulic problems, however, viscous forces are unimportant compared with those due to inertia, and in this case it may be proved that the corresponding speeds are proportional to the square root of corresponding dimensions. Thus, in ship model tests the corresponding speeds of model and original are proportional to the square root of their respective lengths. These speeds give similar wave formations. Viscosity, the effect of which is relatively small, prevents exact similarity of the lines of flow in the immediate vicinity of the vessels at these speeds, and this introduces a scalar effect for which a correction can be made.

In the case of a tidal model, the correct propagation of the tidal wave is an all-important factor. The velocity of propagation of such a wave is proportional to the square root of the depth of the water through which it travels, so that the times required for the wave to traverse corresponding distances in the model and the estuary will be proportional to the horizontal scale ratio and inversely proportional to the square root of the vertical scale ratio. This determines the ratio of corresponding times and therefore gives the correct tidal period for the model. If, for example, the horizontal scale ratio is 1 : 40,000 and the vertical scale ratio is 1 : 400, the time ratio is 1 : 2,000, and since the tidal period in Nature is about 12 hours 20 minutes, the correct tidal period in the model is 22·2 seconds.

If the effects of viscosity are small in comparison with those due to inertia, as is the case in a model of suitable size, all velocities will then be in the ratio of the square root of corresponding depths.

DISTORTION OF SCALE

When constructing a river or estuary model, it is seldom possible to adopt the same scale for both horizontal and vertical distances. Especially in tidal models, the horizontal reduction in scale has usually to be considerable in order to keep the model within reasonable dimensions, and a scale of more than 18 in. to 1 mile (1 in 3,520) is unusual, a more common ratio being about 1 : 8,000. If this latter scale were also adopted for the vertical depths in a model of an estuary having a tidal range of say 33 ft., the range in the model would only be 1/20 in. and the current velocities would only be about 1/90 of those in the estuary. In such a model the motion of the water would certainly not be turbulent as in the estuary, and no motion of the bed materials would be likely to occur. To avoid this difficulty, the vertical scale ratio is made much less than the horizontal scale ratio. Thus by making the vertical scale ratio 1 : 200, the tidal range in the case mentioned would be 2 in. and current velocities would be 1/14 of those in the estuary.

Reynolds in his investigations on models of estuaries of simple symmetrical form concluded that, for a model to reproduce estuarine conditions, the product of the cube of its maximum tidal range measured in feet, multiplied by the ratio of the vertical and horizontal scales, should not be less than 0·09, and while, in an estuary of non-symmetrical shape, a smaller value of the criterion may be adopted, it does give an approximate idea of the scales which are likely to give good results in any particular case.

It may be of interest to note that this distortion of scale is usual in Nature, small streams flowing through alluvial ground having much steeper side slopes and gradients than large rivers of similar regime in similar ground. In a very large river such as the Mississippi, the Ganges, or the Irawadi, the maximum depth will rarely exceed 1 : 100 of the maximum width, while in a small stream in similar ground this ratio will seldom be less than 1 : 5.

* From a Friday evening discourse delivered at the Royal Institution on April 13.

A moderate distortion of scale, either in an estuary or river model, would therefore appear to be rather an advantage than otherwise, provided that the side slopes which would be necessary in the model to reproduce those in the estuary do not exceed the natural angle of repose of the bed materials. Since this angle is only about 30°, there will usually be points in a model where the sand is unable to stand up to the required slope, and where, in consequence, the depth of the channel or the height of the banks will be less than in the estuary. The actual slopes in most tidal estuaries are, however, very slight indeed, and experience shows that the areas over which the angle of repose would be exceeded in a model do not usually amount to more than a very small fraction of the whole. In such cases, if thought desirable, a slight stiffening of the bed material with an admixture of clay will usually enable the required slope to be maintained.

BED MATERIALS

A criticism often levelled at the use of tidal and river models is that since the actual bed material is usually a not very coarse sand, unless something of the nature of an impalpably fine powder is used in the model, the grain size and textual roughness of the bed will not be reduced in the same proportion as the remainder of the model. The idea that the bed material should of necessity be scaled down in size would appear to be based on two misconceptions. The first is that the resistance to flow is appreciably affected by the surface roughness. Actually, in any model of a large river or estuary having a sandy bed, the resistance is almost entirely due to eddy formation caused by curves and irregularities in the sides, and by irregularities in the depth, the magnitude and effect of which are overwhelmingly greater than that of a change in the textual roughness of the surface itself.

The second misconception is that because the current velocities are reduced in the model, the size of particle which they will move is necessarily correspondingly reduced. This overlooks the well-known experimental fact that a given mean velocity of flow has a much greater scouring effect in a shallow than in a deep channel.

Investigators of the problems of silt and scour in Indian and other rivers and canals have found that rivers and canals of similar cross section but differing in size, and having the same bed materials, are subject to similar scour or siltation if the mean velocity is proportional to d^m, where d is the depth and where the value of m as given by various observers varies from about 0·45 to 0·64. All agree that the value is in the neighbourhood of 0·5, and if it were actually 0·5, two similar channels in the same bed material would scour or silt similarly if their velocities were proportional to the square roots of their depths. But this is the ratio of velocities adopted for purely hydrodynamic reasons in tidal models, so that it would appear that materials of approximately the same grain size and density as comprise the moving sand banks in the estuary or river, should logically be used for the model. Actually the determination of the best material and grain size is a matter for experiment, that which gives the best coincidence with Nature being the one to be adopted.

In some German laboratories, working on problems of one-way river flow, a technique has been developed in which bed material considerably coarser and somewhat less dense than that found in the river is used. At the same time the slope of the bed is increased. This has been found to prevent the formation of sand ripples, which occur with some combinations of sand and velocity of flow. On the other hand, in recent work on models of the Mississippi River at the U.S. Waterways experimental station at Vicksburg, a sand has been used having a diameter (0·0107 in.) about a third of that of the somewhat coarse sand in the river, and has been found to give excellent agreement with observations in the river itself.

THE SILT PROBLEM

Many estuaries carry a considerable amount of silt of a colloidal nature in suspension. This is originally brought down by the rivers feeding the estuary. It tends to coagulate and to be deposited, forming silt banks especially where the fresh river water meets the saline water from the sea, and in a model of any silty estuary this effect needs to be reproduced.

An examination of samples of the river waters enables the proportion of silt carried in by these to be determined, and the introduction of this proportion in the river water supplied to the model does not present any great difficulty. In order to ensure that this shall tend to be deposited at the same place in the model as in the estuary, it is necessary to reproduce, in the correct ratio, the coagulating effects of the sea water. The matter is somewhat complicated by the fact that, while the ratio of the distances through which a given particle has to sink through corresponding depths equals h/H, the corresponding times in which this is to take place are in the ratio $\frac{l}{L}\cdot\sqrt{\frac{H}{h}}$. It follows that the actual rate of fall of a particle in the model should be greater than that in the estuary in the ratio $\frac{h}{H}\cdot\frac{L}{l}\sqrt{\frac{h}{H}}=\frac{L}{l}\left(\frac{h}{H}\right)^{3/2}$. This greater rate of fall can be produced by increasing the size of the particles, either by using silt of greater coarseness, or by using some coagulating medium more effective than the salts in sea water. In the various models I have constructed, the colloidal silt from the estuary itself has always been used, and alum solution has been used as the coagulating medium, experiments having been carried out in each case to determine the exact degree of concentration of this solution required to give the correct rate of deposition in the model.

SEVERN MODEL

In 1926, the Severn Barrage Committee of what was then the Department of Civil Research decided that the only way to investigate the probable effect of a proposed tidal power barrage across the Severn estuary was to construct a working scale model. Such a model, to a horizontal scale of 1 : 8,500 and a vertical scale of 1 : 200, was made in the Engineering Laboratories at the University of Manchester.

The information required from the model was: (1) The effect of the barrage on the tidal levels above and below its site, at all points between Barry and Gloucester. (2) The effect on the tidal currents. (3) The effect on the configuration of the sand banks and especially of the navigable channels. (4) The effect on siltation above and below the barrage. (5) The effect on sewage disposal. (6) The effect on flooding in times of flood discharge from the rivers entering the estuary.

The available data comprised details of a survey of the upper estuary carried out by Capt. Beechey in 1849, along with Admiralty charts of the lower estuary of about the same period, and some tidal observations from Penarth and Avonmouth and a few points in the upper estuary.

These were supplemented in 1927 by the Hydrographic Department of the Admiralty, which took samples of the water at various points in the estuary, from which the salinity and silt contents were determined; samples of the bed materials; additional tide curves; float and current observations; observations on the Severn bore; and, finally, a detailed survey of a large part of the estuary above and including the site of the barrage. This, in conjunction with Admiralty charts of the lower estuary, enabled the general configuration of the estuary at two times approximately seventy-eight years apart to be compared, and these two surveys were used as a basis of calibration of the model.

In the first place, the bed of the model was moulded in sand to the 1927 survey, after which a series of tidal observations were made at its seaward end, at the point corresponding to Penarth. The mechanism and the form of the plunger producing the tides were adjusted by successive trial and error until the correct tidal curves were obtained at the seaward end of the model. As the tidal wave advances up the estuary, considerable changes take place in its height and form, and a comparison with observations in the estuary shows that these changes are closely reproduced in the model.

A comparison of the distances travelled by floats dropped at corresponding points in the estuary and model also shows a very close agreement, while the behaviour of the Severn bore, which was well developed in the model, shows an almost uncanny agreement, both as regards its height and rate of travel, with the behaviour of the original as determined by the Admiralty Survey party.

After having obtained the correct tides, tests were carried out to determine the best bed material. Twelve materials were tested in all, ranging from powdered pumice on one hand to emery on the other. In each case the bed was moulded to the Beechey survey of 1849, and was surveyed after the number of tides (55,200) required to bring the date to 1927. The material which gave the closest agreement with the estuary survey of 1927 was found to be a silica sand about 25 per cent finer in grain than the sand in the estuary, and this was then used for all further work. With this particular sand a comparison of the configuration of the model and of the estuary at the end of the period showed a good general agreement, especially in that part above the site of the barrage. The general agreement, in fact, was such as to indicate that when modified by the introduction of the barrage, the effect of this in the estuary might be expected to be very similar to that in the model.

The tests to determine the effect of the barrage are carried out in pairs. In the first of each, the bed of the estuary is moulded to represent the 1927 contours, and a test is carried out without the barrage, surveys being taken at the end of each 10, 20, 30, . . . years. The bed is then remoulded to the original state, and the test is repeated with the barrage installed and in operation, surveys being taken at the same intervals of time as before. The complete results of these experiments have been embodied in an appendix to the report of the Severn Barrage Committee of the Economic Advisory Council.

GENERAL REMARKS

The successful use of a tidal model depends largely on its being of a suitable scale, and on the possibility of being able to reproduce with reasonable accuracy the physical factors tending to produce movement of the bed materials. As regards the scale, the largest scale which the available space permits is advisable. This is partly because the necessary distortion of scale becomes less as the scale is increased, and partly because it enables details to be developed and studied more accurately.

Much also depends on the conformation of the estuary and on the tidal range, but for the average estuary, for investigating the effect on the navigable channels, the horizontal scale should not be less than about 9 in. to the mile (1 : 7,040). With a tidal range of 30 ft., the Reynolds' criterion in such a model will be satisfied if the vertical scale is about 1 : 214, giving a vertical exaggeration of scale of 33 : 1. If circumstances permitted of a horizontal scale of 18 in. to 1 mile, the vertical scale could be 180 : 1, which would reduce the exaggeration to 19·6 to 1 and obviously increase the usefulness of the model.

As regards the factors tending to produce movement of the bed material, the one factor which is continuously in operation is the scour of the tidal currents, and these can be reproduced with sufficient accuracy in a model. The currents, especially in the riverine part of the estuary, are modified by seasonal changes in the river flow, and this factor can also be reproduced, given a knowledge of the probable magnitude and sequence of floods and dry periods. Where the estuary is exposed to some prevailing wind, the action of this can also be reproduced by means of fans adjusted so as to produce surface waves of the required height.

One factor which cannot be reproduced is the effect of violent gales, the incidence of which, both as regards time and direction, is casual. It is true that over a long period, where there is no prevailing gale direction, the effects of such extraneous forces may be expected partially to counteract each other, but on the other hand one such gale may produce changes in an exposed estuary greater than would occur in months or even years of normal ebb and flow.

For this reason, close agreement between model and estuary over a definite period of years is scarcely to be anticipated. Close agreement can only be expected where the estuary is comparatively sheltered and where the effect of the ebb and flow currents is all-important. For this reason, a model is likely to be more successful of an estuary in which the physical features are such as to give rise to well-defined currents, and in which the tidal range is large so that the strength of these currents is also large. From this point of view the upper Severn estuary, with its 40 ft. tidal range and current velocities approximating 10 knots at places, is an almost ideal subject for model investigation.

Another difficulty in attempting to reproduce all the changes in an estuary over a long period of time is that of reproducing coastal erosion. In many cases this is comparatively small in Nature, but where it is large the difficulties of finding a material which will erode at approximately the correct rate are great. Where this is necessary, it can only be done by extended experiment. In spite of the difficulty, however, experiments now in progress on a model of the Rangoon estuary (by Sir Alexander Gibb at University College, London), show that it is possible to reproduce this effect. This model, in which the effects of coastal erosion and of the monsoon gales have been incorporated, represents probably the most remarkable investigation of this type yet attempted.

Generally speaking, the great usefulness of an estuary or river model lies in its power to indicate the probable effect of artificial changes such as may be produced by the introduction of a barrage ; or training walls ; or bridge piers. Such changes affect the tides and the set and velocity of the currents to an extent and in a manner which is reproduced with close accuracy in a model. In so much as an increased velocity causes scour, and a reduced velocity causes deposition, if the bed material is moved the movement caused by the change will be in the same direction and of the same general kind as in Nature, and experience shows that in favourable circumstances good general agreement, both quantitative and qualitative, can be obtained.

Some estuaries, owing to their physical characteristics, are not suitable subjects for model investigation, but at the worst such an investigation gives information as to the changes in the velocities and directions of the currents, from which valuable deductions as to the probable effects on the bed may be made.

South African Plants Poisonous to Stock

THE subject of plants poisonous to cattle is of perennial interest to pastoralists, which is receiving in South Africa the scientific attention it needs. The Veterinary Services and Animal Industry Branch of the Department of Agriculture of the Union of South Africa now has a team of workers (Onderstepoort Veterinary Research Station) consisting of Drs. Steyn and Quin, veterinary research officers, Dr. Claude Rimington, chemist working as a research fellow under the Empire Marketing Board, and Dr. A. C. Leeman, botanist attached to the Division of Plant Industry, Pretoria. The first two numbers of the *Onderstepoort Journal*, which is to be issued quarterly in continuation of the annual reports of the Station, contain several interesting papers on the subject.

In a series of six papers in the first issue, Dr. Steyn deals on broad lines with poisonous plants. It is shown that it is possible to develop in animals a considerable degree of tolerance to certain poisonous plants by feeding them with small, but increasing, quantities, whilst with other plants continued ingestion of small quantities may even cause sensitisation or produce cumulative effects. An interesting side-issue is the proposal to use sodium chlorate as a weed-killer for the rag-worts (*Senecio* spp.), which are responsible for poisoning stock, both in New Zealand and South Africa. Before adopting it, its toxicity to stock has been carefully tested and found so low that it is regarded as a safe means of destroying these weeds.

It is still uncertain whether the disease known as 'lathyrism', common in certain parts of India, is due to use of *Lathyrus sativus* peas as a foodstuff, and for that reason a proposal to use *L. sativus* hay as a feeding-stuff in South Africa has been investigated. The hay proved innocuous to rabbits, sheep and cattle even when fed in comparatively large amounts, but was poisonous to horses. Great care was taken to make sure that the hay was entirely derived from *Lathyrus sativus*, and these observations support the view that this plant is the cause of 'lathyrism', and that horses are particularly susceptible to its action.