6. S. P. Peters, "Some Meteorological Aspects of North Sea Floods, with Special Reference to February 1953." Conf. on North Sea Floods, p. 28, Instn Civ. Engrs, 1954.
7. J. R. Rossiter, "The North Sea Storm Surge of 31 January and 1 February, 1953." Phil. Trans. Roy. Soc., vol. 246, p. 371 (Jan. 1954).
8. J. A. Steers, "The East Coast Floods: January 31–February 1, 1953." *Geogr. J.*, Pt. III, vol. 119, p. 280 (Sept. 1953).
9. H. A. Q. v. Ufford, "The Disastrous Storm Surge of 1 February." *Weather*, vol. 8 (1953), p. 116.
10. M. J. Wilkie and G. A. J. Young, "Pneumatic Tide Generator." *Engineer*, vol. 194, p. 133 (25 July, 1952).
11. "Report of the Departmental Committee on Coastal Flooding." H.M.S.O., May, 1954.

The Paper, which was received on the 5th August, 1954, is accompanied by three photographs and six sheets of drawings from which the half-tone page plates, folding Plates 1 and 2, and the Figures in the text have been prepared.

Discussion

Mr F. H. Allen, when introducing the Paper, said that as a result of the publication of the Waverley Committee's Report on the effects of the storm surge, the Ministry of Housing and Local Government had set up a technical panel, called the Thames Technical Panel, to consider the recommendations of the Waverley Committee in relation to the Thames. The further work which the Authors had done since writing the Paper had been carried out in order to assist the Thames Technical Panel.

The Authors had described in the Paper what happened to a surge 1 foot 6 inches higher at Southend than that of 1953. It was found to be 2 feet 3 inches higher at Woolwich and 1 foot 8 inches higher at London Bridge. When they reproduced in the model a surge which at Southend was 3 feet higher than that of 1953 it proved to be more uniform as it travelled up the estuary, being only 3 feet 2 inches higher at Woolwich and 3 feet higher at London Bridge, so that its amplitude remained almost unchanged.

They had also examined the effect of a river flood on the 3-foot-higher surge. The Authors found that the effect of a river flood at Teddington of 20,000 cusecs would be to raise high-water levels in London by $7\frac{1}{2}$ to 8 inches. In the Paper it had been shown that the effect of a similar flood on a $1\frac{1}{2}$-foot-higher surge would be to raise high-water levels in London by the same amount, $7\frac{1}{2}$ to 8 inches.

After that work on a 3-feet-higher surge, they had gone on to examine the behaviour of a surge-reducing barrage, similar to that tested for Long Reach, but situated at Woolwich, where the river was narrower and shallower. The Woolwich position was upstream of the entrance to the

Royal Docks, so that a barrage there might cause less obstruction to shipping. They had carried out their experiments in the same way as those for the Long Reach barrage described in the Paper, and they found that with the 1953 surge, and with the surge 3 feet higher than that of 1953, the Woolwich barrage was almost as effective as the Long Reach barrage in lowering water levels at London Bridge and upstream. The water levels were in fact slightly higher, but by a suitable adjustment of the degree and time of closure the same amount of lowering could be achieved in nearly all cases. The main points to be remembered about a barrage at Woolwich were that it would provide no protection to the relatively valuable and built-up land between the Long Reach site and Woolwich, and also that the reservoir capacity upstream of Woolwich was considerably less than the reservoir capacity upstream of Long Reach, so that in the event of a fresh-water flood the water levels upstream of a Woolwich barrage would rise rather more quickly.

There was no definite evidence at the moment to show that floods in excess of 20,000 cusecs occurred in the Thames, but it had been suggested that a maximum peak flood in the River Thames itself, plus peak flood discharges from its tributaries, might amount to a fresh-water flow of as much as 40,000 cusecs. Because of that suggestion they had carried out certain experiments on the model with a fresh-water flood of 40,000 cusecs, double the 20,000-cusec flood described in the Paper. Those experiments had been carried out only in relation to the barrage at Long Reach. It was stated in the Paper that the effect of the 20,000-cusec flood on water levels in London for any given surge, and for any time and degree of closure of the barrage, was to raise water levels at London Bridge by rather less than one foot. When they reproduced a flood of 40,000 cusecs, they found that its effect was almost precisely double that of a flood of 20,000 cusecs. In other words, if with the 1953 surge they closed the barrage at Long Reach for 90 per cent of the mean tide cross-section 4 hours before high water, with a flood of 20,000 cusecs the water level would be 10 inches higher at London Bridge than it would otherwise be, whilst with a 40,000-cusec flood it would be 1 foot 8 inches higher. So far they had not carried out those experiments with the barrage at Woolwich.

In the Paper the Authors had not been concerned with the type of structure to which they referred as a "surge-reducing barrage." It was, however, fairly obvious that some type of multi-gate or multi-span structure would be required, and it had been suggested that in operation the smaller spans at the sides might be closed before the wider spans in the centre, so as to cause less interruption to shipping. They had carried out some observations in the model to find out what velocities might be reached in the central gaps before the main gates were lowered. Using a barrage similar to that described in the Paper, they cut two gaps in the centre, each equivalent to a width of 350 feet, and measured the maximum velocities which occurred through those gaps when the barrage was lowered at definite times before high water of the surge. They found that with a surge similar to that of 1953 the maximum local velocities reached at the Long Reach site were between 7 and $7\frac{1}{2}$ feet per second when the barrage was fully open, but that if the side spans were lowered with two gaps left open in the centre the maximum velocity through the gaps was of the order of 10 feet per second.

Mr Allen concluded his remarks by showing some photographs taken shortly after the storm of 1953.

Mr W. A. Price, continuing the introduction, described some of the instruments used in the model experiments. Among them were tide gauges of a design similar in principle to certain full-scale instruments. A spherical float (for which a motor-car headlamp bulb was used) rose and fell with the tide in a well connected to the model by a short length of pipe. The float carried a varnished balsa-wood scale graduated in model feet, and the scale was viewed by a fixed telescope fitted with a fine horizontal cross-wire. By this method rising or falling water levels could be read to $\pm$ 0·01 inch, and at high water and low water, when the levels remained almost constant for a few seconds, they could be read to $\pm$ 0·005 inch.

For the observations of the velocity of flow to be expected at the barrage, a miniature propeller current meter, recently developed at the Hydraulics Research Station at Wallingford, had been used. The propeller, of approximately $\frac{3}{8}$-inch diameter, was made of polystyrene, and by counting the number of revolutions in a given time it was possible, by previous calibration, to obtain the velocity of flow. There was no mechanical linkage between the propeller and the counter. The blades of the propeller, passing between two fine electrodes, created electrical pulses which were counted by an electronic counting and recording device.

Referring to some practical aspects of the model experiments, Mr Price pointed out that for certain tests it had been essential to construct the model embankments to represent conditions on the night of 31 January 1953, as accurately as possible. It had been done by reproducing the longitudinal profile of the bank on lengths of brass strip, which were then filed down in the workshop and subsequently set at the appropriate level in cement mortar.

Dr A. T. Doodson remarked that there were occasions when tide models could be used to considerable advantage, and, so far as the type of model used by the Authors was concerned, he was quite satisfied that its indications might be relied upon.

His principal difficulty was that in connexion with tide models the frictional terms in the tidal equations needed very careful consideration. Some years previously he had endeavoured to set forth from the tidal equations theoretical reasons for showing that it was very necessary to bring in artificial friction, but the Authors' model had satisfied that condition, and he thought satisfied it very well. The wire mesh which the Authors had used was rather better than placing a lot of small stones over the bed. He was quite happy, therefore, to accept the results of the Authors' model experiments.

He thought that, in all probability, the model had given quite precise quantitative statements with regard to the amounts which were spilled over the banks. Qualitatively it was well known that if water was spilled over the embankments of a river there must be some diminution of the oscillation. It was, of course, a general principle which was worth taking into account in all work of that kind that what could be measured was known precisely but knowledge of what could not be measured was meagre and very unsatisfactory. That, it would be recalled, had been Lord Kelvin's dictum, and recently Dr Doodson had had many opportunities of impressing it upon people in relation to storm surges. In his view, therefore, the quantitative indications of the Authors' model could be relied upon.

He had very little to say with regard to that part of the estuary which lay between the site of the barrage and London Bridge and which would be protected by the barrage. It seemed to him that the results obtained were quite reasonable; he had looked for defects but could find none. There were, however, several things he wished to mention with regard to the portion of the estuary between the barrage and Southend. Before touching on that, however, he said it would be very valuable to have some idea of the amount of silt which might possibly be removed whilst the barrage was down. It was known that there must be high velocities, and the question to which he would like to have a quantitative answer was: would there be such an amount of silt transferred while the barrage was down as would cause difficulties to navigation in the river when the barrage was re-opened? It was really a matter of how many tides would need to flow before equilibrium would again result. He had not been able to find anything in the Paper dealing with that side of the matter.

Fig. 9 on p. 69, showed 100-per-cent closure; he wished to deal with that because it was the extreme case; he was not thinking for one moment that it would be proposed to have 100-per-cent closure. Taking Tilbury between the hours of -4 and -2, it would be seen that there was almost a minor surge with a bore of about 10 feet. That steep rise, in the event of the barrage being completely shut down, would be a menace to shipping, and that would need to be borne in mind when the barrage was operated.

Another point of note in Fig. 9, in the diagram relating to 750 feet downstream of the barrage, was the oscillation of water level during a 2-hour period. He wondered if that was a real oscillation, and whether it would be real in nature. The Authors had said that the reflected wave caused by the barrage travelled down the estuary towards Southend at the rate at which low water travelled, which meant at the natural rate pertaining to the depth of the river. It seemed that there were indications that when that wave had reached the input it was reflected again towards the barrage, so that there was to-and-fro oscillation. It would be seen that there were at least three oscillations at Tilbury of diminishing amplitudes. It was possible, therefore, that in nature the conditions might not be quite so bad as the diagram seemed to indicate. For instance, the second oscillation at Tilbury tended to put up the height of high water—not very much, but appreciably. He thought that in nature there would be a reflected wave travelling from the barrage itself out towards the open sea, and that instead of being reflected backwards once more it would continue to travel outwards, so that the second and third oscillations might not occur. In Fig. 8 those oscillations were still present, but the slopes were by no means so steep. If ever the barrage was constructed, care would need to be taken that it was not closed right down to the bottom.

He had asked himself whether there were any dangerous conditions upstream of the barrage, and he was glad to say that he did not find any dangerous conditions indicated by the diagram, which was a very satisfactory result. Indeed, he would not expect them, because the question of a reflected wave would not come into consideration at all. The water which had been travelling forward up the Thames would continue to go forward, and there would not be that difficulty of a reflected wave.

Mr J. I. Taylor said that the point which interested him most was the spill over the embankments and the effect of that spill on the surge levels, particularly in London. In Table 5, p. 60, spill gave only a very small part of the actual flood volume, averaging in fact only 25 per cent of the flood volume. Mr Taylor showed some slides of how the prototype worked on the 1st February, 1953.

The first showed the breach in the embankment just upstream of Littlebrook power station in area C, where the model had shown that out of a total flood volume of 4,130 acre-feet, only 330 acre-feet resulted from spill. That corresponded to the impression that the River Board engineers had formed from the flood, that had there not been breaches the flooding would have been very much less. The slide was proof of the great rush of water which came through a breach of the type in question.

A further slide showed a breach up Dartford Creek into the same area, C. It was mentioned in the Paper as the only one known to have occurred just before the top of the tide. It showed the debris strewn across the marsh, far into the marsh, which was an indication of the great flow of water which took place through such a breach.

In another slide Mr Taylor showed part of area B, where the model had indicated that almost the entire volume of water was by spill. In fact no breaches had been made, because the model and calculation showed a greater volume of flood water by spill than the volume observed. That was one point to be borne in mind, that the flooding by spill accounted for only about 25 per cent of the total volume.

The Authors had also pointed out, on p. 62, that the flooding which occurred after high water had passed was of no benefit in reducing the tide level farther upstream. Only one-eighth of the volume of flood water had been of any value, as it were, for the relief of the flooding in London ; the remaining seven-eighths had had no beneficial effect.

Mr Taylor was surprised at the effect which had been obtained with an 18-inch-higher surge. It would be seen from the figures given on p. 61, that in the case of such a surge, 18 inches higher than that of 1953, the overtopping of the banks as they had been in January 1953, would reduce the tide level at London Bridge by 15½ inches ; instead of the surge being 20 inches higher than in 1953, it would be only 4½ inches. That was, of course, a very large reduction, but, in case it should tempt anyone to think of spill as a means of relieving London of danger, there were a few points which he would like to make.

Table 7 showed what a large volume of water spilled into the lowland areas on such a surge. Although only half the volume shown in column 2 need be considered as effective flooding—effective in the sense of reducing the tide in London—a limit must quickly be reached beyond which the lowland areas would not receive water. Taking in particular, for example, area G, in 1953 the volume of flood water had been 4,200 acre-feet, and it was mentioned earlier in the Paper that the depth of flooding had then been 6 feet. That area was in Essex, and he did not know what it was like, but he assumed that the ground level was about 6 O.D., so that the level of the flood water must have been about 12 O.D., leaving very little more depth for still greater flood water to enter. The landward side of the marshes usually rose relatively steeply, and increased depth did not give much increase in area over which the flood water could spread.

If deliberate flooding of lowlands were to be considered as one method of relieving London of danger—an urgent problem—then it ought to be done not by spilling over embankments but rather by discharging under control through sluices into selected flood areas. He made that point because the Essex and Kent River Boards had, immediately after the flood of 1953, raised their Thames-side embankments by 3 or 4 feet where very vulnerable and important areas were concerned, and it had been said that London might suffer in consequence. He suggested that the idea of using embankments as spillways should not be contemplated, and that the embankments should not be limited in height for that reason. If flooding was to be a method of relief it should be done in some other way and under control.

He was a little puzzled by the figures given after the first paragraph on p. 57, which showed that with the 20,000-cusec upland flood the level at North Woolwich in the model was 10½ inches higher than without the flood, but at London Bridge only 9 inches. He wondered whether the reason for that difference could be explained, because the effect of the flood water might be expected to be greater upstream than at Woolwich. That again raised the question of the use of flood areas. If that were to be a method of relief to London, then presumably it would mean holding back upland water as well as diverting the tide water.

Mr W. E. Doran observed that it had been very fortunate that the Thames pilot model had been in being and available for carrying out tests on the 1953 surge, and doubly fortunate that the model happened to be equipped with a pneumatic tide generator which made it possible to reproduce the tides of 31 January to 2 February and to carry out various alterations on the model, such as making up the banks, allowing the banks to breach and so on, without affecting the tides. If the model had been fitted with a plunger for generating the tides, those experiments would not have been possible; even had it been a cam-operated model they would have been very difficult.

Apparently, very strong apprehensions existed in certain quarters about the effect on surge levels in London of raising the flood defences downstream. It was a very controversial question, and those feelings would have been extremely difficult to combat without the aid of the model, particularly if those who held those ideas strongly were not easily convinced by mathematical proof, and such people were apt to hold their opinions more strongly than did others. The model had demonstrated in a very convincing manner that protection downstream had not been carried out at the expense of London. The Kent and Essex River Boards must feel very pleased that they were absolved from any blame in that connexion, although Mr Taylor seemed slightly apprehensive that there might still be designs on his area for spilling future surges. It was to be hoped that that would not happen.

Another interesting point which had emerged from the model experiments was the confirmation of previous calculations of the effect of an upland flood upon surge levels.

With regard to the amount of water which it was assumed would be spilled or would escape through the breaches, his own experience on the River Ouse in the surge confirmed what had been said by the Authors, namely, that the banks tended to fail about or after high water, and then failed progressively, so that the main effect of the spill was at existing bank level. Similarly, the flooded areas went on increasing progressively. There was a tendency, of course, at each tide for the breaches to widen and deepen and, therefore, for the flooded areas to become greater. On the model the whole of the spill had been assumed to occur on one tide. He thought that that assumption would mean that the model results were certainly on the safe side, and that the real increase would definitely be less than had been shown on the model.

Mr Doran was not quite clear from Mr Price's remarks exactly how the spill had been arrived at. Apparently the banks had been made out of brass strip cut to the appropriate profile; presumably the spill section had to be abbreviated, because it would not be possible to have all the various spill sections which occurred; or perhaps that referred only to the breaches. Mr Doran wondered whether, if the Authors had used a brass strip, which was in effect a sharp-crested weir, and a distorted scale on the model, the discharge over that sharp-crested weir would be volumetrically correct by comparison with the real discharge. In Table 4 the agreement seemed extraordinarily good between the calculated and the observed figures. The model figure was 25 per cent and the calculated 30 per cent, so that apparently good agreement had been obtained there.

As for the probability of higher surge levels occurring, he hoped that some guidance would be available as a result of research on the subject, but it seemed abundantly clear that London had no margin whatever with regard to tidal surges. The London defences had been designed on the basis of the surge of 1928, and in the 25 intervening years there had been a loss of about 3 inches, owing to rise of sea level. In the Appendix to the Waverley Committee's Report the estimate was given of a loss of 12 inches per century, and in the Paper the Authors mentioned 9 inches. There had, therefore, been a loss of about 3 inches in the past 25 years, and in another 25 years that would have risen to something like 6 inches, which was quite appreciable when considering spill. When, in addition, the effect of high floods in the river on raising the surge was considered it became an extremely serious problem, to which special consideration should be given, even if the scheme suggested as a remedy was very expensive. Records were made to be broken. Experience in the examination of river floods, for example, showed that the record of the last highest flood was always exceeded; thus, it was almost certain that the 1953 flood surge level was not the highest possible.

Apart from other considerations, the great value of the proposed barrage was first that it gave positive control of the level by means of its operation, by the time and the amount of closure, and secondly, whereas the cost of raising existing defences by 1 foot or 2 feet might be prohibitive, in the case of the barrage the cost of giving some extra protection was probably proportionately less. For example, if it were decided that the London defences ought to be raised by 18 inches as a reasonable maximum, they could probably be raised by more than that on the barrage without a proportionate increase in cost.

The Authors had not mentioned the depth and width of the river at Long Reach. If they would give those figures it might afford some idea of the magnitude of the problem involved in the construction of a barrage.

Mr E. A. G. Johnson remarked that Mr Allen had shown some slides which indicated the extent of the development along the banks of the Thames, and the Ministry of Agriculture and Fisheries and the River Boards had been faced at a very early stage after the emergency works, in fact, even before they had been finished, with the task of making some decision on what form the permanent repairs should take and how high they should be. It had been obvious, and had also been made very clear to them by the residents of Canvey Island and other urban areas along the

Thames, by industrialists, owners of oil refineries, and so on, that it would not be satisfactory if the defences were put back just as they had been before the flood, and so targets had to be set. The targets set would raise the walls in all important industrial and urban areas to a level which would be a safe-guard against a flood of the 1953 magnitude, but so far as agricultural areas were concerned, unless they were of special importance, nothing more would be done for the moment than good restoration. He had been very glad to find that the Waverley Committee, having considered all the evidence, concluded that those had not been bad decisions, though taken in a hurry. The Ministry and the River Boards did not entirely disregard London ; they thought very hard, in the limited time available to them, about suitable reservoir areas which could be flooded by spill or by sluices, but it was very difficult to find any areas along the Thames without considerable development, or railways. Where there was such an area, it was very low down the estuary.

As Mr Doran had said, they had been very fortunate in having the Thames model available, and the Waverley Committee, as soon as it got to work, quickly devoted its attention to the problem of London. The results of the model experiments had indicated that the works which had been done would not have a great effect with another tide of the size of that of 1953. Mr Johnson thought, however, that the salient point was that, although with a tide 18 inches higher than that of 1953 the overtopping of banks would have a substantial effect, nevertheless the position in London would not be satisfactory. Table 8 showed that at Blackwall there would still be 11 inches to be dealt with, so that even if they had done nothing about raising the downstream walls and had neglected Canvey Island and the industrial areas along the Thames London would still have its problem to which a solution would have to be found.

The engineers' fundamental difficulty was to know just how high a surge to expect. The limited records available suggested a frequency of about once in 200 years for tides as high as that in 1953 but there was at present no scientific evidence to show that there could not be considerably higher water levels. It was thought that there might be inter-actions between the tide and the surge which would prevent a combination of maximum tide height with maximum surge height, but there seemed to be no proof of that.

As a matter of interest it might be mentioned that an Oceanographic Committee had been set up as a result of the work of the Waverley Committee. That Oceanographic Committee would settle the subject matter of researches to be made on behalf of the Government by the Liverpool Tidal Institute, the National Institute of Oceanography, the Meteorological Office, and the Hydrographic Department of the Admiralty. Those researches might afford an indication of what the maximum tides could be, but until that was known engineers were left in considerable difficulty.

The Dutch found themselves in much the same position. In the Third Interim Report of their Delta Commission—a counterpart of the Waverley Committee, except that he believed it consisted wholly of engineers—it was stated that :— " Even the old method, i.e., adjusting the height of the retaining walls, in this case the dykes, to the last known highest water level, would now mean raising the retaining wall by at least 1 metre. We cannot consider this sufficient, however, as we must assume that still higher levels than those already known, however exceptional the levels of 1st February, 1953, may have been, can occur along our coasts. The various factors which cause storm flooding may occur in still more unfavourable fashion, and in a still more unfavourable combination, than they did on 1st February, 1953. It has been impossible, however—as our studies and calculations have shown—to arrive at any exact figures for higher storm flooding or for the frequencies involved, but we may safely assume that a storm flood level of this nature may occur sooner or later, even though exceptionally, and it is therefore our duty to raise the dam now more than the metre mentioned. If we also remember the continuous relative fall in the level of our country, we shall have to base plans for improving the seaward retaining wall in southwest Holland, where this must be done now, on increases in height of at least $1\frac{1}{2}$ to 2 metres, according to circumstances."

The Dutch were afraid of a tide considerably higher than that of 1953.

Mr A. S. Quartermaine said that as a member of the Waverley Committee he desired to emphasize what had been said by Mr Doran and confirmed by Mr Johnson. When Mr Doran referred to those who could not be convinced by mathematical calculations he perhaps had the Waverley Committee in mind ! Mr Doran's views on that matter accorded with Mr Quartermaine's, namely that the existence of the Thames model, and the opportunity of having the staff of the Hydraulics Research Station, under the skilful guidance of Sir Claude Inglis, available at the precise time when it was needed by the Waverley Committee, had enabled that Committee to make decisions which it could scarcely have done if it had not had the backing of the experimental work carried out on the model.

If the model had not been available Mr Quartermaine was sure that the Waverley Committee would have had some doubt about suggesting that an investigation should be made into the question of building a surge-reducing structure across the Thames, lest the mathematical experts proved that doing so would obviously result in something quite abnormal in the way of resulting water levels ; by skilled use of the model, however, the Committee had in a very short time been able to say quite definitely that serious consideration should be given to the question of a surge-reducing structure.

Mr M. N. Medrington, commenting on what had been said by the Authors about the rapid rise in water level downstream following the closing of the barrage on the model, said it appeared that with 100-per-cent closure about 2 hours before the time of high water there was a reflected wave downstream which attained a maximum about $1\frac{1}{2}$ hour before high water just downstream of the gates. In other words, about half an hour after the gates were closed the maximum effect immediately downstream of the gates was reached. There was, in fact, what was almost a surge—perhaps it might be described as a " baby surge "—going in the opposite direction to the normal tide-cum-storm surge.

He thought there must be a possibility of that small surge travelling downstream coinciding in time with the tide and the storm surge travelling upstream. He had looked at the diagrams in the Paper which dealt with that, but they were to a small scale and not very extensive. The speed of the reflected wave travelling downstream, however, could be judged by what had been said on p. 70, and it could therefore be stated that the reflected wave downstream would take approximately 45 minutes to get from Long Reach to Southend. Normally, high water from Southend to Long Reach took about 40 minutes, and from those two facts the conclusion could be reached that the maximum effect of the reflected wave and of the highest water level of the tide would be experienced together downstream more or less in accordance with the following formula. By taking the time in minutes from the closure of the barrage to high water, deducting 30 minutes and then dividing by 4 the answer obtained in miles would give the point of coincidence of the two surges downstream of the gates. That meant that with a closure 2 hours before the time of high water the coincidence would take place beyond Southend.

It was stated in the Paper that the Authors held no brief for Long Reach as the site of the barrage, and in the discussion it was said that consideration had been given to the possibility of siting the barrage farther upstream. If the barrage was sited farther upstream, was there not a possibility that the coincidence of the reflected wave going downstream and the tide travelling upstream would take place, say, in the Tilbury area, or somewhere like that, where it would be significant ?

The Authors' reply to the Discussion will be published in the Proceedings, Part III, August, 1955.—SEC.

The closing date for Correspondence on the foregoing Paper was the 1st January, 1955, and no contributions other than those already received at the Institution will be accepted.—SEC.