

**Regulation of the tidal waters of the Elbe**

by

**Dipl. Ing. M. Krause**

Mr G. A. Wilson (Chief Engineer, Port of London Authority) said they were all grateful to the Author for presenting his Paper on the control of a great European river. This was an extremely difficult operation and little enough was known about it, so that the documentation which he had provided for the Institution would be of great value in its records. Mr Wilson also wished to thank the Author for his courtesy when members of the Institution visited the works described in the Paper. Mr Wilson had had the pleasure of visiting them in 1960, and the Author had given up a tremendous amount of his time to making the visit worth while and interesting. Those who took part came away much impressed by what they had seen. It was of great value that a record of the works now existed in the Institution.

48. The work described was a daring enterprise, as Mr Wilson, who had a little to do with rivers, fully realized. He was anxious to know how it had been possible to persuade the Port of Hamburg to accept the barrage, and he would also be interested to know what the effect of the barrage was on the storm surges which came up the estuary of the Elbe.

49. When considering the estuary of the Elbe, he was interested in the agreement, mentioned in § 1 of the Paper, that Hamburg had been able to reach with the Central Government, whereby the Central Government became responsible for deepening the channel in the Elbe to the depth required for shipping using the port. It would be seen that that depth had originally been 10 m, but they had now got it to 11 m, and he understood that they intended to make it 12 m. To those who had seen the estuary of the Elbe that might seem an insuperable problem. He would very much like to know how the open air model of the Elbe estuary, which had a scale of 1 in 500 horizontally and 1 in 100 vertically, and which seemed to cover about half a mile, had progressed and whether or not it had in fact provided information to enable the deepening of the channel to be completed.

50. A little way to the north of the Elbe was the Eider, and when a barrage had been constructed on that river, he thought at Nordfeld but at any rate a little way up the estuary, the estuary had promptly silted up. It would be most interesting to know what the experiments mentioned in § 40 were which had provided the assurance for the port and people of Hamburg that their river would not silt up. He thought that enough was now known to make it possible to predict such things, but, knowing shipping circles, it would be interesting to know how the persuasion had been done. An interesting addition to the Paper would be a reference to where those experiments had been written up, because he had not so far seen any account of them. Possibly it existed only in German.

51. His next point was perhaps a little delicate, because it concerned the catastrophic Hamburg flood in the spring of the present year 1962, which had caused widespread distress in that city. Great consideration must have been given to the

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possibility of a barrage in the river causing an increase in the flood level down river, and it would be most interesting to know what experiments had been done and what records had been made which showed that the flood wave had not been exaggerated.

52. There had been records on the Elbe for 75 years. In this country the fact that there had been records on the Thames for 60 years was regarded as quite outstanding. Mr Wilson sometimes wondered, however, whether or not these earlier records were entirely trustworthy. Certainly on the Thames they had some doubts when they went back to the beginning of the century. Some of the percentages indicated in the Paper for changes were fairly small, and it might be that the records were not entirely reliable. Certainly the method of making the measurements must have improved tremendously since those early days.

53. He had said enough to show the distinction of the Paper, and yet he had not touched on the four sections which were summarized as what had been carried out when the problem had been studied—the construction of the barrage, the construction of the generating station, the navigation canal and its lock, and the pumped storage scheme. Each of those could be the subject of a Paper and each of them was worth recording so that the success of the project could be examined by those who became associated with work of this nature. When he had visited the lock in the navigation canal he had been particularly struck by the control cabin of the lock where one man operated a lock 80 ft wide and 750 ft long. This man saw the craft in, closed the gates and had closed-circuit television to show him what was going on. It would be useful if some progress could be made in operating locks in this country in the same way.

54. Mr Wilson found it interesting that the Author had dealt with pumped storage and said he would like to have some account of how the model experiments had been carried out in relation to the production of cross-currents in the river. That had been touched on to some extent, however, in the film which Dr Krause had shown and perhaps they had seen enough to be satisfied. Mr Wilson had also been interested in the Author's last remark about the continuous sampling and recording of the state of pollution in the Elbe. He would like to know the details of that device.

**Mr C. D. Crosthwaite** (Partner, Freeman, Fox & Partners) wished to discuss primarily the pumped storage project, which he found very interesting. His firm were in process of building a similar project in N. Wales and had encountered a certain number of problems there which he thought must have been met and dealt with on the Elbe.

56. The Author's upper reservoir was about 3.3 million cu. m, which was about 112 million cu. ft. The upper reservoir in N. Wales was about half that size, 60 million cu. ft. The Author operated at a head of 80 m, or about 250 ft; they operated at a head of 1000 ft, or about 300 m. The Author's power in ultimate development was 210 MW and their own development was 300 MW. It was apparent therefore that the Author had to deal with very much more water as a rate of flow than they had. Their maximum pumping rate was 2800 cusecs and the Author's would be 4900 when the scheme was complete. Their generation was 4000 and the Author's would be as much as 12 600 cusecs.

57. From Fig. 15 of the Paper it would be seen that the upper reservoir was completely artificial and if by any mischance there was over-pumping the station was going to be washed away. They had precisely the same problem in N. Wales and it had worried them a good deal. To avoid this they had a duplicate system of controls and alarms. First they had duplicated the alarms, so that if the pumping approached the spillway level an alarm went off, and then just before spilling the plant was tripped.

58. Correspondingly (and this was something not immediately apparent) at the end of the generating cycle if generation went on for too long the upper reservoir might be emptied, and then there would be virtually no means of filling it again, because the pumps could not be started by motoring from the system but must be

started by bringing the turbine up and then bringing in the pumps. Where the Author's units reversible or were they, like those in N. Wales, of the more conventional type with turbine and pump on the one shaft?

59. Another question related to the load factor of the system. From what was said in the Paper the Author's load factor would seem to be fairly high; in other words the load system was not 'peaky' as the expression was understood in this country. The Author also referred to the load system of Hamburg itself, which seemed to indicate that the supply system was isolated and not connected to the grid system of the country as a whole. Was that the case or would this peak power be distributed, as in this country, over a much wider area than Hamburg itself?

60. Apparently there was a station for testing the quality of the river water, but it was not clear why it should be necessary to sample the water in that way.

Mr F. J. T. Kestner (Principal Scientific Officer, Hydraulics Research Station), after adding his thanks to the Author for a most interesting Paper, drew attention to two points which were a source of great satisfaction to the hydraulic engineer. The first had already been mentioned by Mr Wilson, the long-continued records of water levels and discharges which had been collected on the Elbe. Information about this was given in § 7 of the Paper, which showed that some of the records went back for almost a century and a half. It must have given the Author great satisfaction to be able to write in § 21:

"It can certainly be established that the fall in the water levels *cannot* be attributed to a decrease in the flow of fresh water."

That very definite statement was fully justified and was made possible because of the excellent records.

62. The second cause for great satisfaction was that in constructing a barrage at Geesthacht the Author had carried out what every civil engineer hoped to achieve, a multi-purpose scheme. The first purpose had been to prevent the fall in low-water level in the upper reaches of the tidal area from spreading further upstream. In the light of the figures which the Author had given that was fully justified in this particular case, but Mr Kestner put in a plea that normally these effects were highly desirable from the point of view of improving the drainage of low-lying land. In this country, especially in the Fenland, where there was a good deal of low-lying land, he wished it were possible, by doing such work, to lower low water and so improve the drainage.

63. The second purpose of the barrage was to generate electricity to supply a peak demand by means of a pumped storage reservoir. As the film had shown, the Elbe had eroded its right bank until it reached ground several hundreds of feet higher than the bed of the river. There was a sudden and almost dramatic change in level. Very skilful use had been made of the topography in this area.

64. The third purpose was briefly indicated in § 32, where it was stated that the barrage was:

"the first step . . . in the fulfilment of Hamburg's wish to possess an inland waterway which is fully navigable at any time for ships of 1000 tons."

Mr Kestner wondered whether that was not perhaps the most important objective of the scheme and whether the presence of the Iron Curtain so close to Hamburg, as Fig. 1 showed, had not completely altered the purpose of the scheme right in the middle of carrying it out.

65. He wished to ask two questions and did so by referring to Fig. 10, which showed the longitudinal section of the Elbe and the fall in bed level due to dredging in the lower Elbe. He wanted to know whether the deepened bed of the Elbe maintained itself or whether continuous or periodic maintenance dredging was necessary. If the bed of the Elbe was self-maintaining, was not the reason for this the fall in low water as shown in Fig. 10? Would the Author agree that a lower bed by itself did not increase the tidal compartment? It was only if there was a fall in low-water

level that the tidal volume could be increased up the estuary, and therefore the tidal discharge.

66. That being so, if it was desired to have a self-maintaining estuary, how much lower was it possible to go? Had any calculations been made in that connexion?

67. The second question concerned the effect of high-water levels, and especially on the height of storm tides and storm surges, of deepening an estuary by dredging, as had been done on the Elbe. It had sometimes been suggested that if an estuary was improved by making it deeper, straightening its course and so on, while this made it easier for ships to navigate the estuary, it also made it easier for storm tides and storm surges to penetrate.

68. In view of the record tidal heights reached in Hamburg in the storm surge of February 1962, was there any truth in that opinion or could the Author, on the basis of the records available to him, explode that view, as he had been able to demolish other views by analysing his very good records? It would be most valuable if he would give some indication of the conclusions which he had reached on this matter.

**Mr W. E. Blackmore** (Sir Wm Halcrow & Partners) asked whether the frequent references to the 'tide' represented in all cases what the Author really meant. In particular, in § 33 it was stated that one of the requirements of the barrage was '(b) conservation of the incoming tide in the Ilmenau, Boize and Sude.' From the plan it would be seen that the Ilmenau was downstream of the barrage and the other two rivers were upstream of it. How would it be possible to conserve the tide in the two upstream rivers and in what way would the barrage affect the tide in the downstream one? The upstream level of the barrage, 5·6, would seem to be a little above high tide level, so that the barrage would be an effective barrier against the upstream propagation of the tide. Was that so? Also was it to be assumed that power generation was interrupted at every high tide?

70. His other question concerned the sector gates in the barrage which control the upstream level automatically. He would like to know within what limits those gates could maintain the level. Also did the gates become inoperative when the tide water level rose to approximately the same height as the upstream level?

The following contributions were received in writing:

**Sir Claude Inglis** wrote that he had read the Paper with great interest; the improvements which had been effected in both the tidal and non-tidal lengths of the Elbe during the past 80 years were remarkable. The Paper did not, however, describe the regimen of the estuary, nor detail the methods that had been followed in improving the deep water channel; so that it was not possible to assess either the difficulties that had been overcome or whether the methods followed would be applicable to other estuaries. Such an assessment would, however, be facilitated if the Author supplied the following information, which must, it was believed, be available:

- (a) a survey of the material exposed on the bed of the estuary at the beginning of the century, before much dredging had been done;
- (b) a similar survey for conditions today;
- (c) the present quantity of annual dredging and the total quantity dredged to date; and
- (d) what proportion of this was discharged into the estuary, and what proportion dumped ashore.

72. But, before such data was supplied, it appeared to be justifiable to draw some tentative conclusions:

- (a) the flat slope of the river upstream of the tidal limit indicated that the bed was smooth and that the charge of silt being carried down the river was

small. Under such conditions, any lowering of the bed resulting from scour or dredging would tend to persist; and

- (b) in the tidal portion, however, the reason for the persistence of the improved depths in the channel seemed to have been markedly different. In this portion, the bed material appeared to have been sand, which moved slowly back and forth along the bed of the channel, without appreciable overall progression.

73. It followed that when the channel was deepened by dredging, the velocity decreased, so  $V^2/D$ , and bed movement in the channel markedly decreased. Although some sand was carried into the channel from its flanks to start with, this led to reduced velocities and increased depths over the side slopes, and consequent reduction of movement owing to currents and wave action, so that a new and steeper side-slope regimen was maintained with relatively little dredging. This was on the assumption that the dredged material was either dumped ashore or in such a place that it did not return to the channel.

74. Sir Claude would like the Author to say whether this tentative assessment was correct or needed modification. If correct, it explained why the work done in the Elbe was so successful, and why similar methods would be relatively unsuccessful in estuaries in which the material exposed on the bed was fine. This would be because large quantities of the fine bed material would be scoured into suspension throughout the estuary, much of which would later deposit in the dredged channel due to its increased depth and consequent lowered value of  $V^2/D$ .

**Dr D. M. McDowell** (Chief Hydraulic Engineer, Calcutta Port Commissioners) wrote that the gradual increase in the tidal range of the River Elbe as a result of deepening the approaches to Hamburg and the effect that this had on the river upstream was a fascinating story which added to the knowledge of the behaviour of estuaries. The title of the Paper led Dr McDowell to believe that it would include some data on the changes that have taken place in tidal propagation and on the calculated effect of the new barrage at Geesthacht. The only data regarding the tides, however, referred to local extreme values plus changes in the average mean and low-water levels. Some reference to the speed of propagation of the tidal wave due to typical spring and neap tides together with information regarding the rate of transport of solids at various stations would have been valuable. It was particularly unfortunate, therefore, that so much of the data presented with the paper was difficult to follow owing to mistakes in presentation. There were obvious errors in the titles of the vertical columns of figures to the right of Figs 2, 3, and 4. There was no vertical scale for Figs 2, 3, 4, and 5 and the significance, if any, of the irregular spacing of the horizontal lines was not clear. The graphs in these figures showed re-entrant curves in places. What did the figures down the centre of Fig. 5 convey and where were the lowest tide levels referred to in the title? Headings were missing from the second and fourth columns of figures in Table 3. Fig. 1 was much too small and would have been improved if it had been turned through  $90^\circ$  and enlarged to occupy a full page.

76. In spite of these errors, there was much of interest in the paper. The Author referred to calculations and model tests that showed that there would be no effect on water levels in the Hamburg Port area due to the barrage of Geesthacht. This was to be expected because the sectional area there was so much smaller than at Hamburg and it might be inferred from Fig. 10 that the tidal range was also much less. There would, however, be appreciable changes in tidal range at the barrage itself and these would have an effect on local bed levels. How far would these effects be likely to extend downstream and had any attempt been made to solve the difficult problem of the ultimate bed levels and tidal ranges when the bed has stabilized itself to the new conditions?

77. Figs 2 and 4 showed a cyclic variation in mean and low-water levels averaged

over 5-year periods. The discharge observations at the Darchau gauge appeared to show a similar trend, but full analysis of the gauge data and corresponding rainfall in the catchment would be required before any firm conclusions could be drawn. Had the Author any comments regarding these cyclic variations?

78. The mean-water levels and low-water levels averaged over 19-year periods also showed pronounced drops round about the water years 1865 and 1925 and, in fact, if these trends were taken into account, there was little evidence of lowering the mean-water level at any station above Hohnstorf. The gauge recordings at stations near Hamburg did not go back far enough to include the first drop of level so that it was difficult to draw any conclusions from them. What were the reasons for these pronounced falls of level? Would the Author please explain how the depressions of average-water levels and low-water levels were obtained as these did not appear to correspond with the levels shown in the graphs of Figs 3 and 4.

**Mr L. Johnson** (Senior Assistant Engineer, Central Electricity Generating Board) wrote that as the Elbe had in the past been subject to bed erosion, it was possible that the water still carried a silt burden upstream of the Geesthacht barrage. Would the Author say if any signs were apparent that silt deposition had occurred anywhere in the pumped storage scheme? Turbine discharge could also cause scour and it would be interesting to know if any special precautions were necessary to avoid this.

80. In order to encourage a smooth flow pattern for the discharge between river and power station, it had been necessary to provide an unsymmetrical channel between the two. One would have thought that under these conditions vortex formation might occur in the power station forebay, during the pumping cycle; would the Author say if this problem did in fact arise?

**Herr Krause**, in reply, referred first to § 49 of the discussion. The large open-air model of the Elbe was constructed in 1939. Its primary object was research into the conditions in the outer Elbe, to improve and stabilize the navigable waterway below Brunsbüttelkoog. Owing to the outbreak of the war in 1939, the work was interrupted for a long period. After the war, various separate investigations were carried out. The decision had then to be taken to reconstruct the model on another site, as it became apparent that the reliability of the investigations was very doubtful, owing to the shifting nature of the subsoil, for the model was sited on sandy soil deposited in 1928. Mr Wilson had already inspected the new model installation during his visit to Hamburg in 1960. After extended trials to establish the accuracy with which the model represented actual conditions in the river, research work was recently begun.

82. Before deepening of the navigable waterway was begun, the Hamburg Water and Navigation Authority had had an expert opinion worked out by Professor Walter Hensen, who urged the construction of the large Elbe model in 1939, and who for some ten years has been Director of the Franzius Institute for Foundation Engineering and Hydraulics at the Technical College in Hanover. It would be going too far afield to delve into details of this very comprehensive investigation. However, it led to the conclusion that the main navigable waterway of the Elbe from Hamburg to Cuxhaven could, without difficulty, be deepened to at least 12 m below M.L.W.S., as the tidal flow in the Elbe would not be appreciably altered by such deepening. The cross-sectional widening operations necessary for deepening to 12 m over the whole Lower Elbe were so small—the enlargement of cross sectional area varied from 0.5 to 1.5%—that one need only expect an alteration in tidal lift of a few centimetres, which might perhaps fall below the limits of measurement of the current model investigations.

83. § 50. There need be no fear of danger of silting up the Lower Elbe. The conditions in the Eider are different, inasmuch as the lock at Nordfeld in the vicinity of the mouth was constructed in the brackish water zone and thus decisively altered the whole of the tidal conditions in the Eider. The dam in Geesthacht, on the other

hand, was situated some 140 km above the mouth of the Elbe at the tidal limit, where the tide no longer made itself felt by its flow but only by the backwash of the upper waters.

84. The model investigations described by the Author in § 40 of the Paper therefore did not deal with silting up of the Lower Elbe. Research was only directed to the changes to be expected, as a result of the construction of the weir, in the tidal water levels in the stretch below the weir with normal tides, with storm tides, and with east wind tides. In addition, they served to establish the most favourable site for the weir and necessary dimensions for the weir and foreland openings to ensure a safe run-off of high water.

85. The model investigations carried out for the damming of the Elbe at Geesthacht had not been published. No difficulty would be encountered in obtaining accurate details, however, if the interested parties would apply either to the Franzius Institute or to the Government Establishment for Hydraulics (Bundesanstalt für Wasserbau) at Karlsruhe.

86. Various papers had appeared in the German Technical Press on the subject of the Eider and some of them were listed at the end of the Discussion.<sup>1-3</sup>

87. § 51. It was in character that a rise in the flood level down river should be expected, particularly during storm tides, after erection of the dam at Geesthacht. Appropriate storm-tide investigations were undertaken in a model, to be able to estimate the influence of raised tides and storm tides and the extent of any claims, e.g. for the raising and strengthening of dykes. In an endeavour to base the investigations on the most unfavourable conditions, the representation of observed storm tides in the model was abandoned and, instead, the storm tide of 22/23 December, 1954 was combined with various highest volumes of headwaters. (The investigations were carried out in the spring of 1961, before the catastrophic storm tide of 16/17 February, 1962.) Thus it was also possible to obtain information on the effect of the headwaters on the storm tide water levels. This would not have been possible by selection of natural tides, as the different wind conditions for individual storm tides permitted no comparisons.

88. Unfortunately, it was not possible within the limits of this short reply to go further into the many details of the investigations carried out. Herr Krause would therefore confine himself to the overall result. The question of whether the safety of the dykes would be reduced by the damming of the Elbe could be answered with a clear 'No'. With storm tides, as with average tide conditions, the damming of the Elbe would produce a noticeable effect only in the upper region, i.e. on a stretch of some 20 km below the weir. With an increase in the upstream discharge, the tide lifts, and therefore the reflexions as result of the damming, fell off, i.e. the lifts of the flood level down river were less, the greater the upstream discharge. With an upstream discharge from about 1000 m<sup>3</sup>/sec, practically no further rise in the "Thw" took place. This was at first surprising. However, since at this upstream discharge the weir was designed not to increase the impounded water above the amount before the damming, the storm tide ran almost unhindered through the weir openings.

89. The investigations had also shown that the security of the dykes against overflowing during storm tides after damming was increased by an artificial deepening of the river bed, for this resulted in a fall in the water level. After commencement of deepening of the bed, a reflux certainly took place at the weir. The increase in amplitude thereby arising was not, however, sufficient to counterbalance the fall in the flood level down river caused by the deepening of the river bed. A measure of this kind was, in any case, cheaper than a general raising of the dykes. It was, moreover, carried out in order to ensure sufficient depth of water for shipping.

90. In § 53 Mr Wilson had invited discussion of design details of the various works. A series of articles by the Author and Herr Reuter on the Geesthacht works was at present appearing in the *Die Wasserwirtschaft* and would be completed by the end of 1963.<sup>4</sup>

91. In reply to the question, raised in §§ 54 and 60, of contamination of the Elbe and testing the quality of the river water, the following observations were put forward.

92. The pollution of rivers by waste waters from large towns, and more especially and increasingly from industrial works, had caused the authorities concerned with river management to pay special attention to the science of the properties of water. As a rule, the hydrological data needed for an evaluation of a water comprised configuration of bed, water level, river discharge, and qualitative basic properties. The latter included in the main, temperature, salinity, turbidity, pH value, hardness, and acid content. The effects of water are not concerned with static conditions but with constantly changing developments and trends. Recognition of this fact had for a long time led to continuous observations of water levels and amounts of river discharge. The qualitative basic properties of the water, on the other hand, were nearly always obtained by single tests carried out on the water at longer or shorter intervals of time. In order to obtain a series of continuous observations for this purpose, the Hamburg Water and Navigation Authority took the opportunity afforded by the reconstruction of the Lauenburg railway bridge in 1950 to arrange for an underwater research chamber in the single pier. To the extent that automatic measuring procedures and equipment were not yet available, they were developed in this chamber during the course of the year. During the construction of the weir at Geesthacht, and following successful experience at Lauenburg, an underwater research chamber was likewise built into a weir pier.

93. The sampling system for the Elbe water consisted of eight steel tubes with a diameter of 150 mm, which were fixed one under another at a spacing of 1 m in the direction of the longer axis of the pier. The water was sampled at the desired depth from time to time and led through a downpipe to the measuring installation. A tube of 150 mm dia. served for the run-off which discharged at the lower end of the pier below the lowest normal low-water level.

94. The installation was so arranged that the water could be sampled over the whole range of fluctuation from highest high-water level to lowest low-water level. The measuring appliances were connected to the flow through the chamber by short pieces of pipe. A centrifugal pump with a normal delivery of 100 m<sup>3</sup>/h was fitted at the end of the discharge main, in order to produce in the piping a velocity similar to that in the river. This pump worked intermittently. The velocity of the water in the piping was measured by venturimeters. The velocity of flow in the river was measured in the usual way by an impeller. It was, moreover, related to the water level.

95. Monthly survey trips were also carried out, to check the qualitative conditions of the Elbe, in which samples were taken at intervals of 2 km on the stretch of river from the boundary of the region as far as Cuxhaven. The samples were examined on board the survey ship. The results are plotted as longitudinal profiles. On these survey trips, amongst other things, bacterial and biological investigations were also carried out, i.e. researches on pathogenic germs, phenol and detergents. In addition, since 1957, the radioactivity of the Elbe water had been ascertained by taking test samples at several marked places.

96. Mr Crosthwaite, in § 56, by his comparative calculations, might think that the amount of fall at Geesthacht was uncommonly small. This much smaller fall in comparison with Wales had to be compensated for at Geesthacht by a larger volume of water.

97. § 57. The level of the reservoir was continuously indicated in the control room and in the turbine room. This was done by a step-by-step indicator graduated in centimetres and a continuous indicator over a potentiometer, both of which obtained their impulse from a float. The values could be read on a scale in each case and were simultaneously transmitted to a recorder. On reaching the highest or the lowest reservoir levels, light and acoustic extreme-position signals are actuated.

98. The electricity load-despatcher also received information on the water level as

a continuous indication of stored energy. The pumping time was settled, in accordance with the demand for water, between load-despatcher and management, before starting to run the pumps. Then followed the switching on of the pumps. Switching off the sets at the end of the pumping process took place in succession, normally at intervals of 15 to 30 min, so that at the end only one pump was running. Even if this pump should, by inadvertence, be allowed to run on over the desired highest water level in the reservoir, of 90.6 m above lowest water level, a period of several hours would be required to bring the reservoir to the point of overflowing. But in this case the pumping time would be considerably extended into the region in which the turbine plant would normally be driven, or the sets shut down.

99. These plant conditions were continuously watched from three positions, namely the load-despatch room, the control room, and the power house attendant. Thus sufficient security against overflowing of the reservoir was ensured.

100. Emptying of the reservoir in the case of a burst pressure pipe was prevented, because with the resultant rise in the normal velocity of the water in such a case, the tripping mechanism of the throttle clack valve in the intake structure was released through a measuring orifice impulse. In addition, the emergency stopvalve could be closed from the control room in under 60 seconds.

101. § 58. The horizontal-shaft power-units each consisted of a turbine, a motor generator, and a pump for working at 214 rev/min, the runaway speed being 435 rev/min.

102. The Francis turbines were coupled direct to the generators and delivered about 59 000 h.p. or 43.5 MW. The rated output of the generators of 35 MW could be obtained with heads down to about 76 m and fell to 32 MW with the lowest head.

103. The single-stage storage pumps, with two intake elbows, deliver about 33 cumsecs at mean delivery head. Three of these pumps could fill the storage reservoir in  $9\frac{1}{4}$  hours. The pump was coupled to the motor-generator, when stopped, by means of a disconnectable dog clutch. A starting turbine for the pump had proved expensive and unnecessary for the above mentioned conditions of operation. Starting up of the set had therefore to be carried out by means of the turbine which, after paralleling-in of the synchronous motor, ran with it, open to atmosphere.

104. § 59. The purpose of the pumped-storage works at Geesthacht was the economic solution of the peak load problem, in the first instance for the administrative area of Greater Hamburg. The grid was not, however, isolated, but permanently linked to the entire national grid. Since the coming into service of the pumped-storage works, it had been proved not only that the installation served to cover the peak demand, but that it also provided an excellent instantaneous stand-by, especially in case of damage or sudden shutting down of a set in one of the large national steam power stations. The Hamburg Electricity Supply Company, in their present plan for extending the pumped-storage works, therefore envisaged the installation of modern pumps with higher output, so as to be able to refill the reservoir more rapidly.

105. The Author considered that it was not within the scope of his Paper to give full details of the pumped-storage works. Those interested could, however, refer to Dr Ing R. Meister or Dr Ing Cl. Brandenburg, both of the Hamburg Electric Supply Co., (Hamburgische Electricitäts-Werke) Hamburg 1, Gerhart-Hauptmann-Platz 48.

105. § 64. The Geesthacht dam was first proposed at the beginning of 1950, at a time when the 'Iron Curtain' was already in existence. The provision of an efficient inland waterway link to the Port of Hamburg was not the most important objective of the project and did not alter the aim of the project during its execution.

106. Thorough investigations carried out by the Author in recent years had shown that canalization of the Elbe in the interests of navigation was not possible, on account of the very difficult hydrological conditions. The only problem which

arose was the construction of a lateral canal, branching off from the area of dammed water above the Geesthacht weir. The investigations in this matter had been carried out without taking into account the prevailing situation of a divided Germany.

107. § 65. In general, the navigable waterway depths on the Lower Elbe maintained themselves. Over large stretches, the cross-section was reduced by the construction of stagings and embankments, so as to increase the scouring action. In places where natural enlargements of the cross-section occurred—for example, where the channel divided or branches led off—deposits of mud or sand were apt to form, owing to reduction of the velocity of flow. Dredging had therefore to be carried out every year at these places. The self-maintenance of the Elbe bed was not solely due to fall in the low water level (see Fig. 10), but was in the first place due to the river training works, to which the fall in the low water level was certainly attributable. It was correct to say that a lower-lying bed did not by itself increase the effect of the tides.

108. § 66. The problems which Mr Kestner had put forward unfortunately extended far beyond the scope of the Paper. It was therefore not possible to give a short reply to them, particularly if one distinguished between the Lower Elbe and the Outer Elbe in the enormously extended estuary of the Elbe. The real lower river of the Elbe, which tended to delta formation, was so much divided up into channels that it was scarcely possible to make serious calculations. In such an estuary, one had finally to rely on the experience of the hydraulic engineers operating there.

109. §§ 67 and 68. The deepening of the Elbe below Hamburg—grading and shortening of its course were not undertaken—had had no noticeable effect on the height of storm tides. Only the time of propagation of the tidal wave was accelerated. Thus storm tides arrived in Hamburg nowadays some 10 minutes earlier than they did before the training works on the Lower Elbe.

110. The Author regretted that the very far-reaching questions put by Mr Kestner can only be dealt with very superficially. He would gladly reply to him thoroughly in detail if Mr Kestner would write to him.

111. § 69. Mr Blackmore was quite correct in his doubts. There was here an apparent confusion in the translation. The German word 'Vorflut' had been translated as 'incoming tide', which was clearly incorrect and therefore gave a completely different meaning. Unfortunately, it had not been possible for Herr Krause to discover the equivalent English expression. 'Vorflut' was understood to mean the property of a watercourse of receiving, and carrying off without damage to soil conservation, the surface water and, in some cases, raised subsoil water, from its catchment area on both sides, whether by natural fall or with the aid of pumps for overcoming differences in level.

112. § 70. The weir gates were so designed that their mobility was positively dependent on the slowly changing headwater and the more rapidly alternating tail water (tide). They were so stabilized that the prescribed pool elevation of +4 m above mean sea level was maintained at all times. With an upstream discharge of  $\geq 1100$  cumecs the gates were lowered; the same was naturally the case if storm tides from below reached the level of the upper pool water.

113. §§ 71–74. The inquiries made by Sir Claude Inglis were certainly very interesting, but Herr Krause had regretfully to refrain from giving an answer here, as they were peripheral to his chosen subject. If Sir Claude Inglis wished it, he would be glad to reply to them personally at any time.

114. § 75. Unfortunately, the Author was not in a position to give Dr McDowell data immediately on the velocity of propagation of tidal waves and on the amount of sedimentary material transported. The investigations carried out by the Author were exclusively confined to the bed erosion steadily progressing upstream, resulting from the deepening of the Lower Elbe. In this connexion, the effect on the tide of

the dam was naturally examined in the model investigations. Moreover, it was foreseen that, with normal tides, the high tide level would rise and the low tide level sink as a result of reflexion from the dam. The site for the dam was then chosen so that these changes in the water level would die out in the region of Hamburg harbour. The dam had no effect of any kind on the velocity of propagation of the tidal wave, as it was sited more than 140 km upstream, in the vicinity of the tidal limit.

115. Investigations of the amount of sedimentary material transported had not been made. It was known that the sands shifted downstream; the amount of sedimentary material was, moreover, so small that silting up of the large area of dammed water was not to be feared within the foreseeable future. The transport of sand from the North Sea into the mouth of the Elbe was certainly considerable, but it did not reach nearly as far as Geesthacht, but remained in the area of the mouth.

116. The captions of the vertically-arranged series of figures on the right of Figs 2, 3, and 4 were correct. These figures indicate the lowering of the water level at the given level marks since commencement of recording the levels concerned. The curves in the original drawing were, of course, shown to scale; in the reduced reproduction, giving the scale would have had little meaning. It was indeed only intended to indicate the trend of development. In order to make it more easily understood, horizontal lines were drawn in, the position of which was arbitrary and which otherwise had no further meaning. The curves were arranged below each other so that they did not intersect, and the vertical spacing of the level positions (left side) was therefore not to scale.

117. The numerals in the middle of Fig. 5 represented the absolute values of the lowest water-levels, referred to sea level, — 5.0 m, about 1885–1890, before the beginning of the large construction works of the Lower Elbe. The curves indicated low-water levels and were in fact averages spread over 19 years.

118. The Author did not understand what captions Dr MacDowell had missing in Table 3. He had, however, noticed an error in the first column where (1888) should read (1895).

119. § 76. For the model researches, no model was available with a shifting bottom, only one with a firm bottom. The lowering of the river bottom below the weir would, however, remain within small limits in accordance with the data available.

120. § 77. It was obvious that the data needed for a complete analysis were much more extensive than was possible in a treatise affording only a hurried review.

121. § 78. The drops in water level in 1865 and 1925 had also attracted the attention of the Author, without his being so far able to find a plausible explanation. It would appear that there was a certain degree of periodicity involved, but the space of time covered by the observations and records was clearly as yet too small to make a decisive assertion on the subject. What mattered in any consideration of the present case was merely the phenomenon of the general falling tendency of the water level.

122. §§ 79 and 80. From the first it was clear to the Author that the connexion of the power-station tail race at the pumping installation to the course of the Elbe was of special importance. It was precisely for this reason that very thorough model tests were carried out. Most careful investigation was made as to how far the possibility of larger deposits of sand had to be reckoned with in the vicinity of the pumping installation and to what extent the undertow and backwater surge could be dangerous to passing shipping. The investigations resulted in a very slim opening of the power-station tail race, with a small base sill. In the five years during which the pumped-storage installation had been in operation, the model investigations had been fully vindicated. So far, no sand deposits had appeared which could have interfered with the fairway channel of the Elbe and thus with passing shipping. Even with unfavourable water conditions, no adverse effects on shipping occurred from cross-currents, as the measured cross current did not amount to more than 0.1 m/sec.

123. The turbine discharge had caused no scouring. There was a large stilling basin connected to the power house, and the energy was very largely absorbed, so that the tailrace, some 300 m in length, had so far shown no change.

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