vertebral disks, the measurements were made along the axial line of the column. The spines were divided in the mesial plane when thoroughly frozen, so that there was no reduction in the depth of the cartilaginous disks through the bulging out of their central soft portions. In the European we find the largest proportion of cartilage in the construction of the lumbar region. In four female spines the average was found to be 35·7 per cent. cartilage to 64·3 per cent. bone.* In the Australian the amount of cartilage is reduced in conformity with the lengthening of the vertebral bodies; the proportion is 30·6 per cent. cartilage to 69·4 per cent. bone. In the Apes, a still further reduction in the amount of cartilage is manifested; even in the Orang with vertebræ proportionally as short as those of a European, the amount of cartilage in the lumbar part of the spine is relatively much less, viz., in the European 35·7 per cent., and in the Orang 27 per cent. In the Chimpanzee, the marked fall in the amount of cartilage is in a measure due to the extremely thin disk which intervenes between the last lumbar vertebra and the base of the sacrum.

In the erect attitude of Man the greater amount of cartilage lessens the shocks transmitted upwards through the column. In the prone or semi-prone position of the trunk the same provision is not so necessary.

"The Principles of training Rivers through Tidal Estuaries, as illustrated by Investigations into the Methods of improving the Navigation Channels of the Estuary of the Seine." By Leveson Francis Vernon-Harcourt, M.A., M.Inst.C.E. Communicated by A. G. Vernon-Harcourt, F.R.S. Received January 19,—Read February 7, 1889.

(Plates 2—4.)

The conditions affecting the training of rivers in the non-tidal portions of their course by jetties, or rubble embankments designated as training walls, are well understood. Training walls substitute a straightened uniform channel for irregularities and varying widths, improving the flow of the current and rendering it uniform, so that scour occurs in the shallow, narrowed portions, and more uniformity

* Aeby gives the proportion of bone and cartilage in the different regions of the European spine at different ages, but as he measured the *front aspect only* of the vertebræ and disks, his results cannot be compared with the above. In front and behind the vertical diameters of the disks and vertebral bodies are modified by the spinal curvatures. To obtain the most accurate information regarding the relative proportion of bone and cartilage in a region, the different elements should undoubtedly be measured along the axial curve.

of depth is attained. In very winding rivers, the additional precaution has to be taken of somewhat reducing the width where the deepest channel shifts over from the concave bank on one side to the concave bank on the opposite side at the next bend lower down, so as to reduce the shoal which is found near the point of contrary flexure by concentrating the current at this place.

The training of the outlets of sediment-bearing rivers into tideless seas is determined by the same principles; for a definite discharge is directed and concentrated between training walls or piers, so as to scour a channel across the bar formed, in front of the outlet, by the accumulation of deposit dropped by the enfeebled issuing current. The increased velocity of the current through the contracted outlet carries the silt into deeper water, where it is either borne away by any littoral current, or again forms a bar, after a lapse of time depending on the depth, which can be removed by an extension of the training works.

The training also of the upper part of the tidal portion of rivers has been effected on similar principles to the non-tidal portion, with satisfactory results, even though the problem is, in this case, complicated by the changes in the direction of the current, and the requisite maintenance of the tidal capacity.

In the lower parts, however, of tidal rivers, where the tidal flow predominates, it is difficult to determine the proper width for a trained channel, which, whilst narrow enough to secure an adequate depth, should not very materially check the tidal flow to the detriment of the outlet. Moreover, where the estuary is large, considerable doubt may exist as to the best direction for the training walls; and the establishment of training walls in a wide estuary, where the flood tide is charged with silt, has resulted in extensive accretions,* and corresponding reduction of tidal capacity, by the concentration of the tidal flow and ebb in the trained channel, and a consequent enfeeblement of the currents at the sides, favouring deposit. The principles, indeed, upon which the training of tidal rivers should be based, are in a very undefined and unsatisfactory condition, as exemplified by the conflicting opinions of engineers whenever important training works through estuaries are proposed, as exhibited with reference to the schemes for training works in the upper estuary of the Mersey,† for which the Manchester Ship Canal promoters sought powers in 1883 and 1884, and as at present exist about the extension of the training works in the Ribble estuary.‡ This is due to the various conditions

* 'Instit. Civ. Engin. Proc.,' vol. 84, pp. 246 and 295, and Plates 4 and 5.

† Evidence before Select Committees of Lords and Commons on the Manchester Ship Canal Bills, Sessions 1883 and 1884, and 'Instit. Civ. Engin. Proc.,' vol. 84, p. 309, fig. 7.

‡ 'Instit. Civ. Engin. Proc.,' vol. 84, p. 260, fig. 1.

involved, which differ more or less in each case, and thus render it difficult to lay down general rules for guidance from arguments based on analogy. One of the most important considerations is the form of the estuary; and in this respect no two estuaries are alike, as their form is the result of complex geological and hydrological conditions; and it suffices to contrast the Mersey and the Ribble, the Dee and the Tay, the Clyde and the Tees, the Seine and the Loire, to indicate the varieties of forms which may have to be dealt with. Other circumstances affecting the problem are the rise of tide, the tidal capacity and general depth, the fresh-water discharge, the silt introduced by the flood tide or brought down by the river, the condition of the sea bottom in front of the mouth, and the direction in which the tidal current enters the estuary. The positions also of ports established at the sides of estuaries require special consideration in determining the proper line for a trained channel. These numerous and variable conditions have often led engineers to enunciate the opinion that each river must be considered independently by itself. This view, however, if strictly adhered to, by excluding the experience derived from previous works, would prevent any progress in the determination of general principles for the improvement of navigation channels through estuaries; each training work would form an independent scheme, based upon no previous experience, and might or might not produce the results anticipated by its designer. Unfortunately also it is impossible to proceed with training works by the method of trial and error; for besides the cost of modifying the lines of training walls, if the desired results are not produced, these works generally effect such extensive changes in an estuary, that it would be impracticable to restore the original conditions, or to modify materially the altered position.

It might be possible to deduce general rules for training works from a careful consideration of a variety of types of estuaries, especially those in which training works have been carried out; and I have commenced an investigation of this kind. This method of inquiry, however, requires a variety of data which it is difficult to obtain for most estuaries, and must depend upon a careful estimate of the relative influence of each of the variable conditions, and a train of reasoning from analogy which might not be accepted by engineers as conclusive. Accordingly, it would be of the very highest value to river engineers, and of considerable interest from a scientific point of view, if a method of investigation could be devised, which might be applied to the special conditions of any estuary, and the results of any scheme of training works determined approximately beforehand, in a manner which could be relied upon from the fact of their depending on an assimilation to the actual conditions of the case investigated, and not on arguments based upon the effects of similar works under

more or less different conditions. The following description is therefore given of the results of investigations, carried on at intervals during more than two years, with reference to the proposed extensions of the training works in the Seine estuary, which appear to afford a fair assurance that a similar method, applied to any estuary, would indicate the effect of any scheme of training works, provided the special conditions of the estuary were known.

Investigations about the Seine Estuary.

The training works in the lower portion of the tidal Seine, commenced in 1848, had reached Berville in 1870, when the works were stopped, in the interests of the port of Havre, on account of the large unexpected accretions which were taking place behind the training walls, and at the sides of the wide estuary below them.* The original scheme, proposed in 1845 by M. Bouniceau,† comprised the extension of the trained channel to Honfleur on the southern side of the estuary, and the prolongation of one or both of the training walls towards Havre at the north-western extremity of the estuary, as in any scheme, the interests of both these ports, on opposite sides of the estuary, have to be considered. The works are acknowledged to be incomplete; and great interest has been evinced, particularly within the last few years, in the question of their extension, so that the shifting channel between Berville and the sea may be trained and deepened, and the access to Honfleur improved, without endangering the approaches to Havre. The objects desired are distinctly defined; but the means for attaining them have formed the subject of such a variety of schemes, that hardly any part of the estuary below Berville has not been traversed by some proposed trained channel, except the portion lying north of a line between Hoc and Tancarville points, which is too far removed from Honfleur to be admissible for any scheme. Altogether, including distinct modifications, fourteen schemes have been published in France within my knowledge, seven of them having appeared within the last five years. The schemes also exhibit great varieties in their general design ‡ (Plate 2, figs. 1 and 3; Plate 3, figs. 1 and 2; and Plate 4, fig. 1), illustrating very forcibly the great uncertainty which exists, even in a special case where the conditions have been long studied, as to the principles which should be followed in designing training works. It is evident that no reasoning from analogy could prevail amongst such very conflicting views; and having had the subject under consideration for a long time, the idea occurred to me in August, 1886, of attempting the solution of this very difficult problem by an experimental method, which might also throw light upon general

* 'Instit. Civ. Engin. Proc.,' vol. 84, p. 241, and Plates 4 and 5.

† 'Étude sur la Navigation des Rivières à Marées,' M. Bouniceau, p. 152, Plate 2.

‡ 'Instit. Civ. Engin. Proc.,' vol. 84, p. 247, and Plate 4, fig. 9.

principles for guidance in training rivers through estuaries. The estuary of the Seine is in some respects peculiarly well adapted for such an investigation, for old charts exhibit the state of the river before the training works were commenced, and recent charts indicate the changes which the training walls have produced, whilst the various designs for the completion of the works, proposed by experienced engineers, afford an interesting basis for experimental inquiries into the principles of training works in estuaries. If, in the first place, it should be possible to reproduce in a model the shifting channels of the Seine estuary as they formerly existed, and next, after inserting the training walls in the model as they now exist in the estuary, the effects produced by these works could be reproduced on a small scale, it appeared reasonable to assume that the introduction, successively, in the model of the various lines proposed for the extension of the training walls would produce results in the model fairly resembling the effects which the works, if carried out, would actually produce.

When the third Manchester Ship Canal Bill was being considered by Parliament in 1885, Professor Osborne Reynolds constructed a working model of the portion of the Mersey estuary above Liverpool on behalf of the promoters of the canal, with the object of showing that no changes would be produced in the main channels of the estuary by the canal works which had been designed to modify very slightly the line of the Cheshire shore above Eastham. This model was, I believe, the first experimental investigation on an estuary by artificially producing the tidal action of flood and ebb on a small scale; and Professor Reynolds' experiment showed that a remarkably close resemblance to the main tidal channels in the inner estuary could be produced on a small scale.

As the Mersey model did not extend into Liverpool Bay, the tidal action produced was very definitely directed along the confined channel representing the "Narrows" between Liverpool and Birkenhead; and this tidal flow was not perceptibly influenced by the relatively very small fresh-water discharge. In the Seine, however, there is no narrow inlet channel to adjust exactly the set of the flood tide into the estuary; and the large fresh-water discharge of the Seine, with a basin about eighteen times larger than the Mersey basin, forms an important factor in the result. The tide in a model of the Seine has to be produced in the open bay outside the estuary at a suitable angle which had to be determined; and it was essential for the success of the Seine experiments that accretion should be produced in the model of the Seine estuary under certain circumstances, which was a condition which did not enter into the Mersey problem. Accordingly, the very interesting and valuable results obtained by Professor Reynolds, in his model of the Mersey, could afford no assurance that

experiments involving essentially different and novel conditions would lead to any satisfactory results. I therefore restricted the requirements for my experiments within the smallest possible limits, and contented myself with the simplest means, and the limited space available in my office at Westminster.

Description of Model of the Seine Estuary.—The model representing the tidal portion of the River Seine and the adjacent coast of Calvados, extending from Martot, the lowest weir on the Seine, down to about Dives, to the south-west of Trouville, was moulded in Portland cement by my assistant, Mr. Edward Blundell, to the scales of $\frac{1}{40000}$ horizontal and $\frac{1}{400}$ vertical. The first is the scale of some of the more recent published charts of the Seine—and even at that scale the model is nearly 9 feet long; whilst I made the vertical scale one hundred times the horizontal, as the fall of the bed of the tidal Seine is very slight, and the rise of spring tides at the mouth, being 23 feet 7 inches, amounted to an elevation of the water in the model of only 0·71 inch. There are two banks at the mouth of the estuary, between Havre and Villerville Point, known as the Amfard and Ratier banks, which emerge between half-tide and low water, and divide the entrance to the estuary into three channels. Through all the changes in the navigable channel at the outlet, these banks always appear in some form or other in the low-water charts, either connected with the sandbanks inside the estuary, or detached. On examining the large chart drawn from the survey made by M. Germain in 1880, I found that rock and gravel cropped up to the surface over a certain area on these banks, and accordingly I introduced solid mounds at these places to represent the hard portions of the Amfard and Ratier banks, which are permanent features in the estuary. As a rocky bottom is found near Havre, and also at Villerville Point on the opposite side of the outlet, Amfard and Ratier banks are doubtless the remains of a rocky barrier which in remote ages stretched right across the present mouth of the river. Where the rocky bottom lies bare near Havre and Villerville, the model was moulded to the exact depths shown on the chart of 1880; but in other places the cement bottom was merely kept well below the greatest depth the channel had attained at each place, whilst the actual bed of the estuary in the model was formed by the flow of water over a layer of sand.

Arrangements for Tidal and Fresh-water Flow.—The mouth of the Seine estuary faces west; but the tidal wave comes in from the north-west, and the earliest and strongest flood tide flows through the northern channel between Havre and the Amfard bank; whilst the influx through the southern Villerville channel occurs later, and is stronger towards high water. Accordingly, the tidal flow had to be introduced from a northerly direction, at an angle to the mouth of the estuary; and the line of junction of the hinged tray, producing the

tidal rise and fall, was made at an angle of about 50° to a line running from east to west in the model, so that the tidal flow approached the estuary from a point only about 5° to the west of north-west. The tray was made of zinc, enclosed by strips on three sides to the height of the sides of the estuary; and it was hinged to the model, at its open end, by a strip of india-rubber sheeting along the bottom and sides, so as to make a water-tight joint with sufficient play at the sides to admit of the tray being tipped up and down from its outer end. The rise and fall of the tray was effected by the screw of a letter press, from which the lower portion had been detached, by raising and lowering the upper plate of the press, half of which was inserted under the tray. After the requisite amount of sand had been introduced to raise the bottom to the average level, the model was filled with just enough water for the surface of the water to represent low water of spring tides when the tray was down and the screw at its lowest limit; and the tray was made of such a size that, when the screw was raised to its full extent, the water in the model was raised, by the tipping of the tray, to the level representing high water of spring tides. The water representing the fresh-water discharge of the Seine was admitted into the upper end of the model from a tap in a small tin cistern; and the efflux of a similar quantity of water was provided for at the lower extremity of the estuary, on its northern side near the tray, by a cock with a larger orifice placed at such a level as to allow the water to flow out into a second cistern, of similar size, during the higher half of the tide.

First Results of Working the Model.—The construction of the model was commenced in October, 1886, and its working was commenced in November. Though the Portland cement was convenient for moulding in a small space and in the absence of appliances, it did not prove satisfactory for retaining water at first. The model was purposely made in two halves, and the straight joint was subsequently made water-tight; but, nevertheless, cracks occurred at various places through which the water leaked, and they had to be repaired as they appeared; and the bottom of the model was eventually coated with thick varnish, and after a time the leaks ceased. The flexible india-rubber hinge, from which I had anticipated some trouble, leaked very little from the beginning, and on being fitted with greater care in introducing a tray of somewhat different form, no leakage occurred.

Silver sand was used in the first instance for forming the bed of the estuary. From the outset, the *bore* at Caudebec, indicated by a sudden rise of the water, and the reverse current just before high water near Havre, called the "*verhaule*," were very well marked. The *verhaule* is evidently a sort of back eddy, on the northern shore, occasioned by the influx of the tide, and by the final filling of the estuary from the southern channel; whilst the *bore* appears to

result from the concentration of the tidal rise by the sudden contraction of the estuary above Quillebeuf. The period given to each tide in working was about 25 seconds, which appeared fairly to reproduce the conditions of the estuary.* After the model had been worked for a little time, the channels near Quillebeuf assumed lines resembling those which previously existed; and a small channel appeared on the northern shore, by Harfleur and Hoc Point, which is clearly defined in the chart of 1834. The main channel also shifted about in the estuary, and tended to break up into two or three shallow channels near the meridian of Berville, where the influences of the flood and ebb tides were nearly balanced. The model, accordingly, fairly reproduced the conditions of the actual estuary previous to the commence- of the training walls; though the channel in the estuary did not attain the depth, as represented by the proportionately large vertical scale, which the old channels possessed, owing, doubtless, to the comparatively small scouring influence which the minute currents in the model possess. The sand, in fact, cannot be reduced to a fineness corresponding to the scale of the model, whilst the friction on the bed is not diminished equivalently to the reduction in volume of the current. Silver sand had been used on account of its being readily obtained, its purity, and absence of cohesion, as it was hoped that the water, by percolating freely through it, would more readily shift it. A film, however, seemed by degrees to form over its surface, reducing considerably its mobility; and as the action of the water on it consisted merely in rolling the particles along the bottom, this sand did not prove satisfactory for producing the requisite changes when the training walls were inserted in the model. It became, therefore, essential to search for a substance which the water could to some extent carry in suspension for a short period.

Trial of Various Substances for Forming the Bed of the Estuary.—Some substance was required, not necessarily sand, insoluble in water, easily scoured, and therefore not pasty or sticky, and sufficiently fine or light to be carried in suspension to some extent by the currents in the model, and not merely rolled along the bottom like the silver sand. A variety of substances of low specific gravity, and in powdered form, were accordingly tried in succession during the first half of 1887. Pumice in powder proved too sticky; and flower of sulphur was too greasy to be easily immersed in water. Pounded coke was too dirty to be suitable, and particles of it floated. Violet-powder became too pasty in water; and fuller's earth and lupin seed exhibited similar defects. The grains of coffee grounds were too large in water, and moved up and down in the currents too readily; whilst fine sawdust

* According to the formula in the paper by Professor O. Reynolds, on his Mersey model, read at the Frankfort Congress in August, 1888, the tidal period would be nearly 23 seconds.

from boxwood and lignum vitæ swelled in water, and was carried along so very easily by the stream that no definite channels were formed in it. The powder obtained from Bath brick, which was experimented upon for some time in the model, both without and with training walls, yielded more satisfactory results, as besides affording shifting channels like the silver sand, it accumulated at the sides of the estuary when the training walls were introduced in the model. It, however, gradually became too compact, so that the current could no longer produce much effect on it; but as it is probable that some sticky material is used in the manufacture of Bath bricks, it is quite possible that if I had succeeded in my endeavour to obtain the silt of the River Parret, from which the bricks are made, in its natural state, the material might have proved more subject to scouring influence.

At last, in July 1887, I found a fine sand, on Chobham Common, belonging to the Bagshot beds, with a small admixture of peat. This sand, besides containing some very fine particles, was perfectly clean, so that water readily percolated through it; and it accordingly combined the advantages possessed by silver sand with a considerably greater fineness.

Results of Working Model with Bagshot Sand.—The bed of the estuary having been formed with the sand obtained from Chobham Common, after the model had been worked for some time, the channels assumed a form very closely resembling the chart of the Seine estuary of 1834.* Accordingly, the first stage of the investigation was duly accomplished by the reproduction of a former state of the estuary in the model, with the single exception of a decidedly smaller depth in the channels, except in places where the scour was considerable, which is readily accounted for by the circumstances of the case. It is probable that with a larger model, and especially if the bed was not so nearly level as in the Seine, the depth would approach nearer to the proper distorted proportion as compared with the width.

The close correspondence of the channels in the model with an actual state of the estuary in its natural condition, confirms, in a considerably more complicated case, the results previously achieved by Professor Reynolds with reference to the upper estuary of the Mersey, and affords a fair certainty that, with adequate data, the natural condition of any estuary could be reproduced on a small scale in a model.

Introduction of the Existing Training Walls in the Model.—The second stage of the investigation consisted in the introduction of training walls into the model, corresponding in position to the actual training walls established in the estuary down to Berville. These walls, formed with strips of tin, cut to the corresponding heights at the different places, and bent to the proper lines, were gradually

* 'Instit. Civ. Engin. Proc.,' vol. 84, Plate 5, fig. 1.

inserted in sections; and the model was worked between each addition, to conform, as far as practicable, to the actual conditions. The fine particles of the sand accreted behind the training walls; and the channel between the walls was scoured out, corresponding precisely to the changes which have actually occurred in the estuary of the Seine. The foreshores at the back of the training walls were raised up in some parts to high-water level, whilst in other places the accumulation was somewhat retarded by the slight recoil of the water from the vertical sides of the model, and by the wash over the vertical training walls, these forms being necessitated by the great distortion of the vertical scale of the model. On the whole, however, the accretion and scour in the model correspond very fairly to the results produced by the existing training walls in the estuary. The accretion, moreover, in the model, extended beyond the training walls on each side, down to Hoc Point on the right bank, obliterating the inshore channel close to Harfleur, which had been reproduced in the model, and down to Honfleur on the left bank, corresponding in these respects also to the actual changes in the estuary.* The main channel also, beyond the ends of the training walls, was comparatively shallow, and was unstable, reproducing the existing conditions in the estuary.

The experiments relating to this stage extended over a year and a half, taking up all the time that could be spared to them by myself and my assistant during that period; they formed the turning point of the investigation, and have the interest of being, as far as I am aware, the first attempt at putting training walls in a model, and obtaining the resulting accretion on a small scale. Without the accomplishment of this stage, it would have been useless to continue the investigation; and its satisfactory attainment proved so difficult in actual practice, that for a long time it seemed probable that the attempt must be abandoned.

Application of System to Ascertain the Probable Effects of any Training Works.—As the first and second steps in the investigation, by the aid of the model, had furnished results which corresponded very fairly with the actual states of the estuary of the Seine before and after the execution of the training works, the final stage of the investigation, for ascertaining the probable results of any extensions of the training walls, could be reasonably entered upon. In selecting the lines of training walls to be experimented on, it appeared expedient to adopt those which have been designed, after careful study, by experienced engineers, both on account of the results from these being far more interesting than those of a variety of theoretical schemes, and also in the hope that some assistance might thereby be rendered to French engineers in the prosecution of this important

* 'Instit. Civ. Engin. Proc.,' vol. 84; compare Plate 5, fig. 1, and Plate 4, fig. 1.

work. Moreover, the schemes exhibit sufficient variety to admit of their being taken as types of schemes for throwing light upon the principles on which training works should be designed in estuaries. Accordingly, the third stage in the investigation consisted in extending the training walls in the model, in accordance with the lines of some of the schemes proposed; and, after working the model for some time with each of the extensions successively, the several results were recorded, as shown in Plates 2 and 3, and Plate 4, figs. 1 and 2. The lines of training walls experimented on in the model were taken, with one exception, from five out of the seven most recent schemes proposed, as these five schemes are, I believe, the only ones which are still put forward for adoption. The lines shown on Plate 4, fig. 3, represent merely a theoretical arrangement of training walls, inserted for a final experiment in the model, to ascertain the effect of the most gradual enlargement of the trained channel which the physical conditions of the estuary would have admitted of at the outset, whilst maintaining the full width at the mouth.

Scheme A.—The first arrangement of extended training walls introduced into the model was taken from a scheme, some of the main features of which were proposed in an earlier scheme in 1859,* and which was put forward in an amended form in 1886.† The design, as inserted in the model, consisted of an extension of the parallel training walls from Berville down to Honfleur, and the formation of a breakwater across the outlet, from Villerville Point on the southern shore of the estuary, out to the Amfard bank, thus restricting the mouth to the channel between Amfard bank and Havre. The lines of these works were formed in the model with strips of tin, as shown on Plate 2, fig. 1; the northern training wal was kept low, and the southern wall was raised to the level representing high water of neap tides; whilst the strip representing the breakwater was raised above the highest tide level, thus forcing all the flood and ebb water to pass through the Havre Channel. The results obtained in the model with these arrangements, after working it for about 6000 tides, are indicated on the first chart (Plate 2, fig. 1). The channel between the prolonged training walls had a fair depth throughout, partly owing to the concentration of the fresh-water discharge between the walls, and partly from the retention of some additional water in the channel at low water, by the hindrance to its outflow offered by a sandbank which formed in front of the ends of the training walls. A deep hole was soon scoured out in the narrowed outlet by the rapid flow of the water filling and emptying the estuary at every tide. The absence, however, of connexion between the direction of the flood tide current

* 'La Seine comme Voie de Communication Maritime et Fluviale,' J. de Coene, 1883, p. 11, and Plate 7.

† 'Projet des Travaux à faire à l'Embouchure de la Seine,' L. Partiot, Paris, 1886.

through the outlet and the ebbing current from the trained channel, aided by the accretion of sand in the sheltered recess behind the breakwater, led eventually to the formation of two almost rectangular bends in the channel, one just beyond the training walls, and the other near Hoc Point in the model. This tortuous channel, moreover, was shallow, except at the bends and the outlet; and a bar was formed a short distance beyond the outlet. The contraction of the mouth of the estuary by the breakwater interfered so much with the influx of the tide into the estuary as to render it impossible to raise the tide inside to its previous height; and the reduction in height of the tide was clearly marked at Tancarville Point in the model. Sediment accumulated in the estuary beyond the trained channel, being brought in by the rapid flood current, and not readily removed by the ebb, except in the trained channel and near the outlet; and this accretion, by diminishing the tidal capacity, gradually reduced the current through the outlet, and consequently the depth of the outlet channel. A considerable accumulation of sand took place outside the breakwater, along the southern sea-coast, so that the bank opposite Trouville in the model was connected with the shore, and the foreshore advanced towards the end of the breakwater (Plate 2, fig. 1).

Scheme B.—The second arrangement of training walls inserted in the model, below Berville, was taken from a scheme proposed in 1888, representing a modification, by another engineer, of the design from which Scheme A was copied.* It comprised the retention of the breakwater from Villerville Point to the Amfard bank, the most essential feature in Scheme A; but the extension of the northern training wall was dispensed with, whilst the southern training wall was prolonged, in a continuous curve, from Berville to Honfleur (Plate 2, fig. 2), and eventually to the Amfard bank, connecting it there with the extremity of the breakwater (Plate 2, fig. 3). A slight widening out of the existing trained channel, by an alteration of the end portion of the northern training wall, completed the arrangement of the model. The results obtained by inserting the training wall down to Honfleur, and then working the model for about 3500 tides, are shown in Plate 2, fig. 2; and those obtained after the prolongation of the southern training wall to the breakwater, and working the model for about 3700 tides, are shown in Plate 2, fig. 3. The channel followed pretty nearly the concave line of the prolonged southern training wall, between Berville and Honfleur in the model, except near Berville; but the depth of water was less regular than in the previous experiment, owing to the diminished concentration of the ebb from the absence of the northern training wall. The channel

* 'Mémoires de la Société des Ingénieurs Civils,' Mars, 1888, Paris, pp. 257 and 273, and Plate 162, fig. 2.

between Honfleur and Amfard was tortuous as before, but its direction was different. The deep hole at the outlet, the bar beyond, and the advance of the southern foreshore beyond the breakwater, reappeared again with very similar features to those in the first scheme, except that the sandbank did not quite reach the outside face of the breakwater at low water. (Compare fig. 2 with fig. 1 in Plate 2.)

The results which followed from working the model with the southern training wall prolonged to Amfard, are shown in Plate 2, fig. 3. The main alteration from the former experiment naturally occurred between Honfleur and Amfard in the model, a continuous channel being formed along the new piece of concave training wall; whilst the general depth inside the estuary was improved as far as the meridian of Hoc Point. The channel, however, above Honfleur was not improved, owing apparently to the want of uniformity between the directions of the flood and ebb currents in the model. The other features remained very similar to the former case, except that the end of the sandbank beyond the breakwater was slightly eroded, whilst deposit took place between the extended training wall and the breakwater. (Compare fig. 3 with fig. 2 in Plate 2.)

Scheme C.—The third arrangement of training walls experimented upon in the model was chosen from a design published in 1885.* It consisted of an enlargement of the original trained channel below Quillebeuf, by a modification of the southern training wall from Quillebeuf, and of the northern training wall from Tancarville, and the extension of the northern wall to Amfard and Havre, and the southern training wall to Ratier, as shown on Plate 3, fig. 1. The trained channel was thus given a curved, gradually enlarging form, and was directed into the central channel of the model, between Ratier and Amfard, the Villerville and Havre channels being practically closed near low water. The effects of working the model for about 6500 tides with this arrangement of training walls are indicated on the chart (Plate 3, fig. 1). The main channel kept near the concave southern training wall for some distance below Berville, and then gradually assumed a more central course between the training walls towards the outlet, passing out just to the south of the Amfard bank. The channel thus formed had a good, tolerably uniform depth, together with a fair width, owing apparently to the flood and ebb tides produced in the model following an unimpeded and fairly similar course. Deposit occurred behind the training walls on each side; and the foreshore advanced in front of Trouville in the model, in consequence of the shutting up of the Villerville Channel.

Scheme D.—The fourth arrangement of training walls adopted in

* 'La Seine Maritime et son Estuaire,' E. Lavoinne, Paris, 1885, p. 140, and 'Instit. Civ. Engin. Proc.,' vol. 84, p. 248, and Plate 4, fig. 9.

the model was selected from the most recent design* proposed by an engineer who had previously submitted schemes in 1881† and 1886.‡ The trained channel was widened out by an alteration of the southern wall from Quillebeuf, and the northern wall from Tancarville, more than trebling the width between the training walls at Berville in the model; and the walls were extended in sinuous lines to Havre on the northern side, and Honfleur on the southern side, as shown on Plate 3, fig. 2, thus forming a winding trained channel rapidly enlarging near its outlet. The model, with these lines of training walls, was worked for about 5000 tides, with the results indicated on the chart. Deep channels were scoured out close along the inner concave faces of the training walls in the model; but shoals appeared over a considerable area of the newly trained channel; a bar stretched across the deep channel where it shifted over from the south to the north training wall, about half way between Berville and Honfleur; and a large sandbank, emerging above low water, occupied the centre of the outlet opposite Honfleur. Deposit also occurred at the sides of the estuary behind the training walls.

As it was of importance to ascertain to what extent accidental modifications in the arrangement of the sand in the preparation for an experiment might affect the result, the lines of training walls described above were inserted a second time in the model, after the subsequent scheme E had been experimented upon, rendering it necessary to replace afresh both training walls, and to remodel the sand so as to represent approximately the present condition of the estuary. The model was prepared for this second experiment in the usual way, without any special endeavour to secure coincidence with the first experiment in the initial arrangement of sandbanks and channels. The condition of the low-water channels in the model, after working the model with this arrangement of training walls for the second time for about 5400 tides, is shown on Plate 3, fig. 3. The main features of the trained channel in the charts of the two experiments exhibit a very fair resemblance, considering the modifications which any alterations in the initial condition might produce, and the naturally variable state of the channels in a wide outlet. The deep channels reappear in the second chart at the inner concave faces of the training walls, with intervening shoals; a large sandbank is again visible at low water along the north training wall, opposite La Roque and Berville in the model; and the sandbank in the centre

* 'Déposition de M. Vauthier devant la Commission des Ports et Voies Navigables de la Chambre des Députés,' Paris, 1888, p. 17, and Plate 4.

† 'Rapport sur les Améliorations dont sont encore susceptibles la Seine Maritime et son Estuaire,' L. L. Vauthier, Rouen, 1881, p. 46, and Annex 29.

‡ 'Dire à l'Enquête ouverte sur l'Avant-projet des Travaux d'Amélioration de la Basse-Seine, 1886,' L. L. Vauthier, Paris, Plate 1.

of the outlet of the trained channel opposite Honfleur emerges again, though smaller in extent owing to alterations in the channel; and the deep place at the end of the southern training wall, close to Honfleur, is the same in both charts.

Scheme E.—The fifth arrangement of training walls introduced into the model was taken from a design* published in 1888, which is a modification of a scheme, presented in 1886, by a Committee of experts appointed by the French Government to consider the question.† In the scheme as laid down in the model, the trained channel in the bend between Quillebeuf and Tancarville, where the depth was greatest, was enlarged in width by setting back the southern training wall; the original width of the channel was retained at the point of inflexion opposite Tancarville, and the channel was widened out below La Roque by a modification of the lines of both training walls down to Berville. The training walls were also extended beyond Berville in sinuous lines, as shown on Plate 4, fig. 1, the southern wall being carried down to Honfleur, and the northern wall not quite so far. The portion forming the last bend of the northern training wall was kept low, whilst the others were made high, according to the design. Both in this and the preceding arrangement of training wells experimented on, the expanding trained channel was somewhat restricted in width along the portions near the changes of curvature, to make it conform to the principles which experience has laid down for training winding rivers in their non-tidal course, as previously mentioned. The results obtained, after working the model for about 3700 tides, are represented on the chart (Plate 4, fig. 1). The channel between the training walls was somewhat shallow in places; and though a deep channel was formed along the inner concave face of the southern wall between La Roque and Berville, a shoal emerging above low water appeared along the concave face of the last bend of the northern training wall. This bank appeared to be due to the protection the extremity of the bend afforded from the action of the flood tide in the model; whilst the ebb followed the central flood-tide channel, instead of passing over to the concave bank as would have occurred with the current of a non-tidal river. The main channel beyond the training walls, which, though of fair depth, was somewhat narrow and winding, was also unstable; for in the early part of the experiment, its outlet was in the central channel between Ratier and Amfard in

* 'De l'Amélioration du Port du Havre et des Passes de la Basse-Seine,' Baron Quinette de Rochemont, Paris, 1888, excerpt 'Mémoires de la Société des Ingénieurs Civils,' 1888, p. 324, Plate 162, fig. 1.

† 'Commission d'Étude des Améliorations à apporter au Port du Havre et aux Passes de la Basse-Seine,—Rapport de la Commission,' Paris, 1886, p. 61, and chart.

the model, whilst at the close of the experiment it had shifted, as shown, to the Havre channel. Accretion occurred behind the training walls in the model; and some silting up took place in the Villerville Channel and along the foreshore in front of Trouville, owing apparently to the preference of the main channel for the other outlets, and the diminished capacity of the estuary resulting from accretion.

This arrangement of training walls was further investigated by working the model for about 6300 tides more, with the results shown on Plate 4, fig. 2. The chief features of the estuary in the model showed only slight changes from the state previously recorded (Plate 4, fig, 1), with the exception of the main channel which had shifted again to the central outlet; whilst the northern foreshore above low water extended over part of the former site of the channel. The two conditions of the estuary, represented by Plate 4, figs. 1 and 2, have therefore the interest of exhibiting in the model a shifting channel, such as actually exists at the present time in the Seine estuary below Berville.

Scheme F.—The last experiment was made on an arrangement of training walls inserted in the model, making the trained channel expand as gently as practicable between Aizier and the sea, whilst retaining the natural width at the outlet (Plate 4, fig. 3). This is the form of channel which theory indicates as the most suitable;* for whilst it facilitates the influx of the flood tide, it prevents, as far as possible, the abrupt changes in the velocity of a river in passing from its estuary to the sea, which are so prejudicial to uniformity of depth in a channel. It was therefore of interest to ascertain what results would be produced by this theoretical arrangement of training walls in the model, which, in order to leave the outlet free, and thus avoid favouring a progression of the foreshore outside, had to provide a wide channel near Honfleur compared with the restricted width available at Quillebeuf. The direction of the channel between Aizier and Quillebeuf, together with the cliffs bordering the river at Quillebeuf and Tancarville Points, determined the maximum width obtainable at Quillebeuf, and the direction of the channel from Aizier to Tancarville; and the extension of the training walls in the model from this point was regulated by the necessity of passing close to Honfleur at the south, and not impeding the approach to Havre on the north. The effects produced in the model by working with this arrangement of training walls for about 7300 tides are indicated on the chart (Plate 4, fig. 3). The southern training wall was kept above high-water level all the way to its termination at Honfleur in the model, but the northern training wall was gradually reduced in height from nearly opposite Honfleur towards Havre. The trained

* 'Rivers and Canals,' L. F. Vernon-Harcourt, p. 236.

channel had a good width at low water throughout, in spite of the distance apart of the training walls in the model, the whole channel being below low-water level, except near the southern wall between Berville and Havre, and against the northern wall nearly opposite Hoc Point, where banks emerged slightly above low water. The channel, moreover, was distinctly, though slowly, improving with the continuance of the working, and the banks diminishing. There was also a fair depth in the channel, the shallowest place being opposite Berville, whilst a deep place was formed just above, near the southern wall between La Roque and Berville. The depth in all the outlet channels was well maintained; and though deposit naturally took place behind the northern training wall, no accretion was visible along the foreshores outside.

Considerations affecting Experimental Training Works.

The value of experiments resembling those just described depends entirely upon the extent to which they may be regarded as producing effects approximately corresponding, on a small scale, to those which training works on similar lines, if carried out in an estuary, would actually produce. If the effects of any training works could be foreshadowed by experiments in a model, the value of such experiments, in guiding engineers towards the selection of the most suitable design, could not be overestimated.

Some of the influences at work in an estuary cannot possibly be reproduced in a model—such as winds and waves. Winds coming from different quarters are variable in their effects; but the direction of the prevailing wind indicates the line in which the action of the wind has most influence, which may be exerted in reinforcing the flood or ebb currents, and may aid or retard accretion by blowing the silt-bearing stream more into or out of the estuary. Waves are the main agents in the erosion of cliffs along open sea-coasts, and in stirring up sand in shallow places; and the material thus put in suspension may be transported by tidal currents, aided by wind, into an estuary, and be deposited under favourable conditions. These circumstances affect the rate of accretion, which cannot be investigated experimentally, as it is impossible to reproduce in a model the proportion of silt in suspension, which, moreover, varies in any estuary with the state of the weather and tide, and the volume of fresh water discharged. Inside an estuary, also, waves in storms may erode the shores at high tide, and modify the low-water channels; but the first effect is very gradual, and the second is intermittent—only occasionally occurring.

The main forces acting in any tidal estuary are the tidal ebb and flow and the fresh-water discharge, which are constantly at work; and they regulate the size of the channels in an estuary, and for the most

part their direction, as well as the limits of accretion. These are the forces which can be reproduced in miniature in a model, as proved by the close concordance in the channels obtained by experiment with the actual conditions of the Mersey, and with a previous state of the Seine estuary; and this similarity of results would not have occurred if the other influences noticed above were at all equally potent.

Training walls mainly modify the direction and action of the tidal ebb and flow and fresh-water discharge; and, therefore, it is reasonable to suppose that the results in a model, due to these alterations, would correspond to their actual effects in an estuary, provided the important element of accretion could be also reproduced. This was satisfactorily accomplished in the second stage of the investigation, proving that the miniature influences produced in the model corresponded, in this case also, with the forces acting in the estuary. Accretion is promoted by training walls in an estuary where matter is carried in suspension; but the action of waves in modifying the channels is stopped by the intervention of training walls. Accordingly, the further the training walls are extended, and the more an estuary is protected by works such as those indicated in Plate 2, the more is the modifying influence of waves eliminated, and therefore the more are experiments in a model likely to correspond with the conditions of estuaries under similar conditions.

Other considerations also afford grounds for supposing that the effects observed with training walls in a model fairly correspond with the results which such works would produce in an estuary. The charts of the experiments show that definite results followed from certain lines inserted in the model, and that modifications in these lines were followed by modifications in the results. (Compare Plate 2, figs. 1, 2, and 3, and Plate 3, fig. 2, with Plate 4, fig. 1.) Moreover, the results produced with the model agree very closely with the results which, in the two earliest schemes experimented upon, it was stated, before the experiments were begun, would follow, if the works indicated by lines in the charts were actually carried out in the Seine estuary.*

* Compare the observations relating to Scheme A and Plate 2, fig. 1, with the following extract from 'Instit. Civ. Engin. Proc.,' vol. 84, p. 356 :—" The narrowing of the mouth of the estuary of the Seine would at first promote scour, and increase the depth in that part of the channel, and for a little distance above and below. This contraction, however, would impede the influx of the flood tide, and cause changes in the velocity of the current through the narrow neck, and in the wide estuary above, promoting the deposit of silt brought in by the tide. This accretion would be greatly aided by the prolongation of the training walls to Honfleur, so that eventually the greater portion of the estuary comprised between Tancarville, Hoc Point, and Honfleur would be raised to high-water level. This large reduction in tidal capacity would reduce the tidal current through the narrowed entrance, and consequently diminish again the depth in the channel. Moreover, this reduction of

It would be impossible to determine by experiment the time any changes in an estuary would occupy. The figures, in fact, giving the number of tides during which each experiment was worked, are not even intended as an indication of the rate of change in the model, and much less as any measure of the period required for such changes in an estuary, but merely as a record of the comparative duration of each experiment. It was observed, however, that the changes were most rapid where the modifications effected by the lines of walls inserted in the model were greatest (Plate 2), and slowest where the lines in the model produced the least alterations. (Plate 3, fig. 1, Plate 4, fig. 3.)

Principles for Training Tidal Rivers deduced from Experiments.

The foregoing investigations, viewed merely as experiments, without any reference to their bearing on the Seine, may serve for indicating some general principles applicable in training tidal rivers through wide estuaries. Direct experiment for each estuary is undoubtedly preferable to abstract reasoning, where such experiment is possible, as it reproduces the special conditions of the estuary to be investigated. Nevertheless, general principles may be of value in guiding the choice of designs to be investigated, so as to avoid waste of time in testing unfavourable schemes, and also in cases where the conditions of an estuary are not sufficiently known to afford a correct basis for experiment.

The experiments may be divided into three classes, namely:—

(1.) Outlet of estuary considerably restricted, and channel trained inside towards outlet. (Plate 2.)

(2.) Channel trained in sinuous line, expanding towards outlet, but kept somewhat narrow at changes of curvature. (Plate 3, figs. 2 and 3, and Plate 4, figs. 1 and 2.)

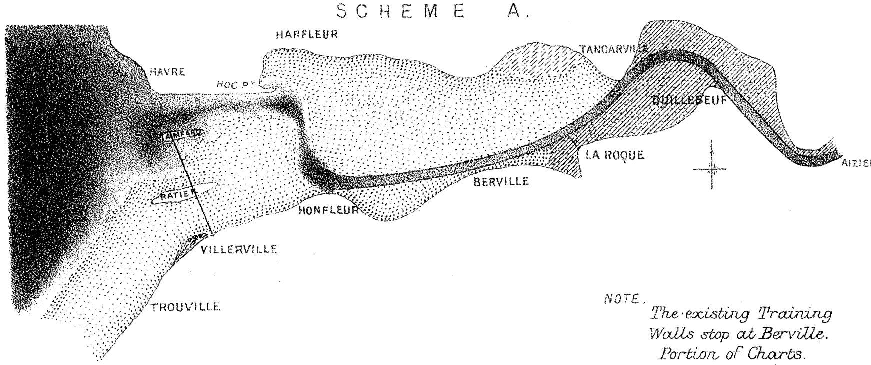
(3.) Channel trained in as direct a course as practicable, and expanding regularly to outlet. (Plate 3, fig. 1, and Plate 4, fig. 3.)

The experiments of the first class exhibited a deep outlet, and a fairly continuous channel inside, where the training works were prolonged to the outlet. The channel, however, was irregular in depth

tidal flow in and out of the lower estuary would favour the natural heaping-up action of the sea on the sands outside; so that eventually, not only would the initial deepening of the narrowed outlet be lost, but the good depths in the bay outside the estuary would be imperilled."

Compare also Plate 3, fig. 1, with the following extract from 'Instit. Civ. Engin. Proc.,' vol. 84, p. 250:—"The continuously concave southern training wall, whilst very favourable to Honfleur, will unduly keep the ebb current to that side, and therefore away from Havre. Also, the extension of the wall along the Ratier Bank will act like a groyne, and, arresting the silt-bearing southern current, will connect Trouville Bank with the shore, and lead to a large accumulation of deposit in front of Trouville . . . . and also the low walls proposed will not prevent accretion."

Fig. 1.
SCHEME A.



NOTE. *The existing Training Walls stop at Berville. Portion of Charts below L. W. O. S. T. is chalk shaded.*

Fig. 2.
SCHEME B1.

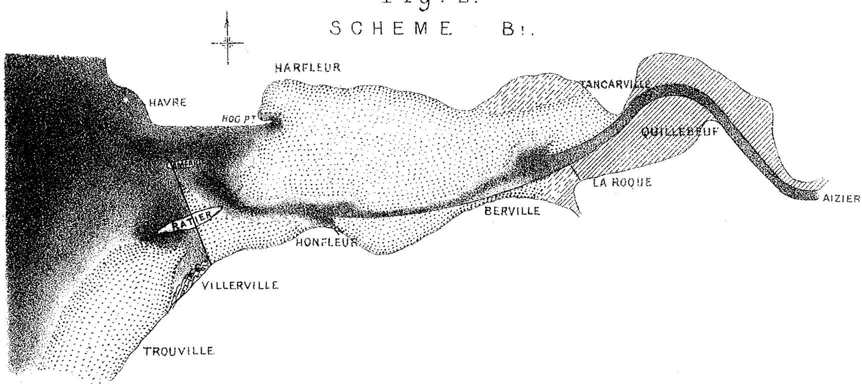
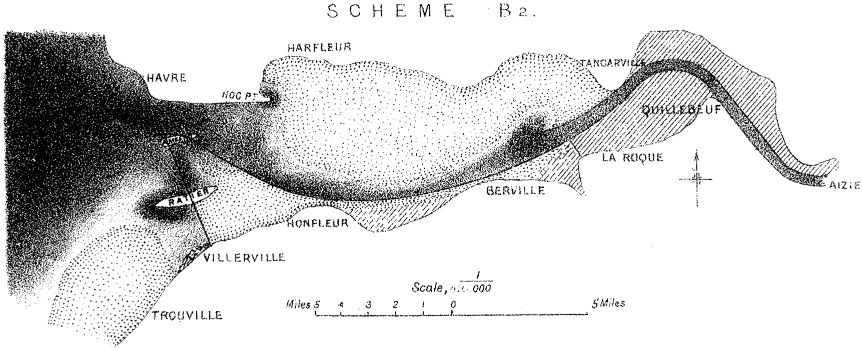


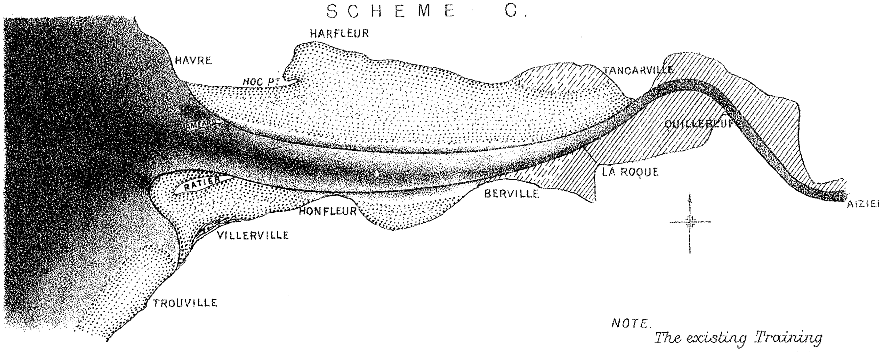
Fig. 3.
SCHEME B2.



West, Newman & Co. lith.

Fig. 1.

SCHEME C.



NOTE.
The existing Training Walls stop at Berville. Portion of Charts below L. W. O. S. T. is chalk shaded.

Fig. 2.

SCHEME D.

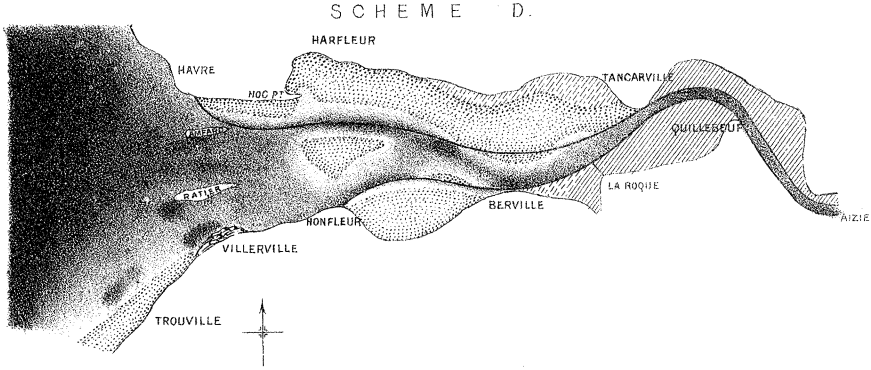
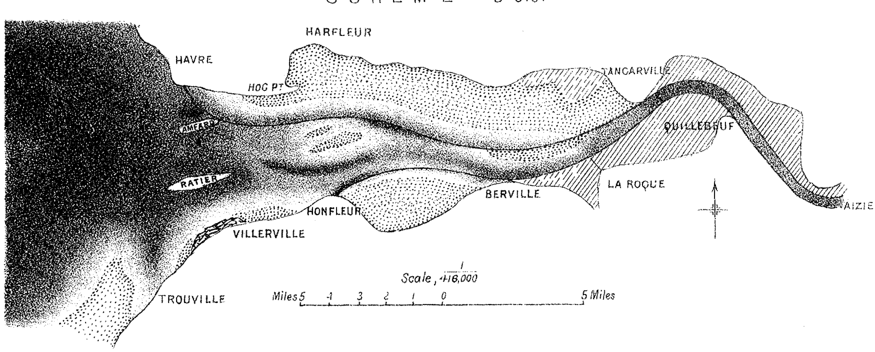


Fig. 3.

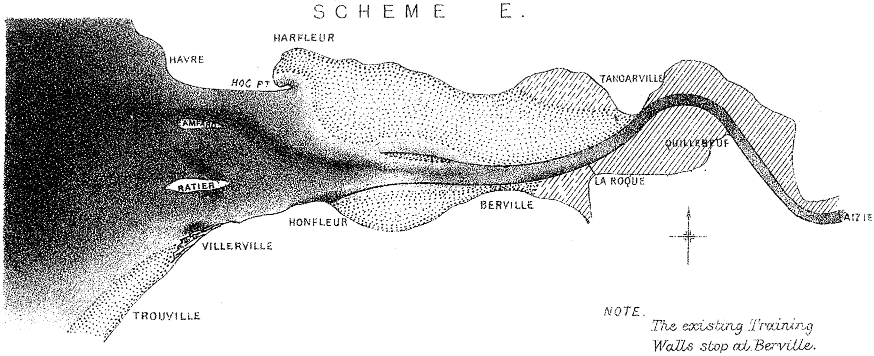
SCHEME D bis.



West, Newman & Co. lith.

Fig. 1.

SCHEME E.



NOTE. *The existing Training Walls stop at Berville. Portion of Charts below L.W.O.S.T. is chalk shaded.*

Fig. 2.

SCHEME E bis.

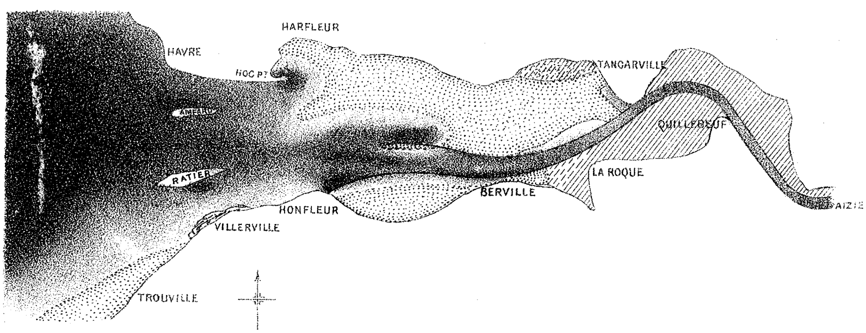
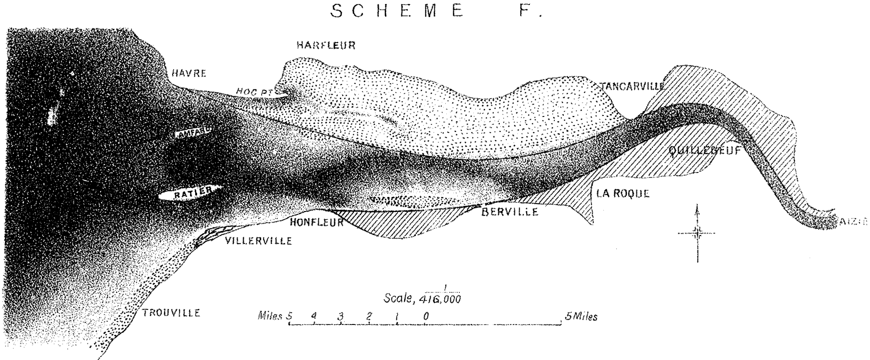


Fig. 3.

SCHEME F.



West, Newman & Co. lith.

near the outlet; and a bar appeared in front of the outlet outside. The breakwater also, extending across part of the outlet, favoured deposits both inside and outside the estuary, by producing slack water in the sheltered recesses.

The second class of trained channel was designed to profit by the scour at the concave face of bends, so clearly exhibited at the first bend of all the charts, and to continue the depth thus obtained by restricting the width between the bends, on the principle adopted for winding non-tidal rivers. Experiment, however, did not bear out the advantages anticipated from this system, probably owing to the variable drection of the flood tide at different heights of tide, its being checked in its progress by the winding course, and not acting in unison with the ebb from the difference in its direction and the width of the trained channel near the outlet. The main stream in a non-tidal winding river always follows a tolerably definite course; whereas the flood tide tends gradually, as it rises, to assume as direct a course as possible. The difference, therefore, in the conditions of a non-tidal and tidal river, in this respect, is considerable.

The third class of trained channel afforded a wide, tolerably uniform channel in the experiments; the flood tide was less impeded in its progress than with the other forms of training walls, and appeared to act more in concert with the ebb.

The experiments, accordingly, indicate that the only satisfactory principle for training rivers, through wide estuaries with silt-bearing currents, is to give the trained channel a gradually expanding form, with as direct a course as possible to the outlet. The rate of increase of width between the training walls must be determined by the special conditions of the estuary. If the outlet is very wide, and the gradual expansion in width cannot be commenced a considerable distance up an estuary, some restriction in width at the outlet may be expedient to avoid a too rapid expansion. It is evident that the widening out adopted in the last experiment (Plate 4, fig. 3) was carried to its utmost limits, from the continuance of sandbanks inside the trained channel, and that, regarding merely the improvement of the channel, it might have been preferable to restrict its width at the outlet as effected in Scheme C (Plate 3, fig. 1). At the same time, it must not be inferred, from the existence of these sandbanks, that the distance apart of the training walls was much too great in the last experiment; for the width apart of the training walls necessitated the inclusion of a greater extent of sandbanks within the trained channel at the outset, and also rendered the rate of improvement in the channel more gradual, so that the improvement in the channel both in direction and depth was still progressing at the close of the experiment, and the sandbanks in the channel were in process of removal, and not being formed. The choice in such cases, where the

widening out cannot be commenced far up, appears to lie between the utmost improvement of the channel at the expense of accretion on the foreshores outside, and the maintenance of the depths over the foreshores beyond the outlet accompanied with a somewhat less good channel in the estuary. In some cases, deposit on the foreshores at the side beyond the outlet might be of no importance, and then the river channel should be primarily considered; but if, on the contrary, accretion on the foreshores outside is undesirable, the outlet must be maintained by a greater widening out of the training walls. The actual direction of the training walls must be determined, in each case, by the general direction of the channel above, the situation of ports on the estuary, the position of the outlet, and the set of the flood tide at the entrance.

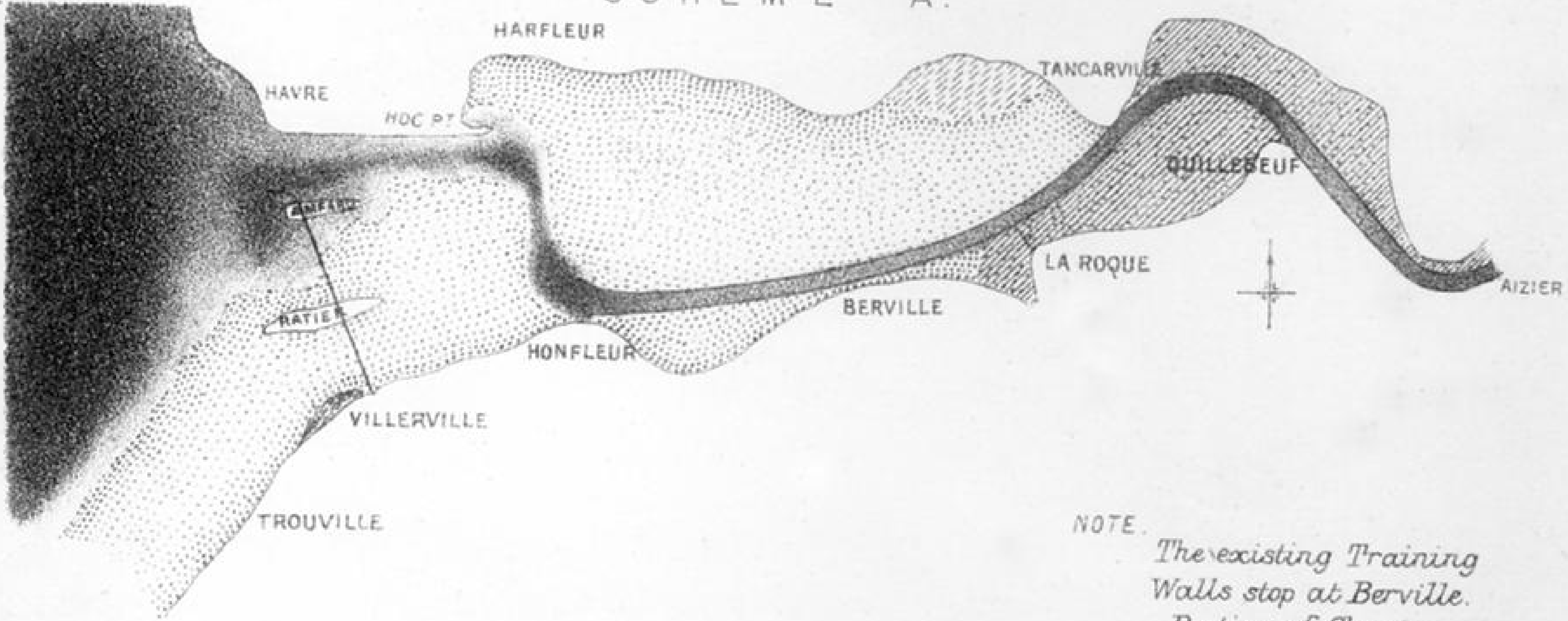
Concluding Remarks.—In terminating this record of my investigations, and the general principles for training works which they seem to indicate, I desire to acknowledge the care with which my assistant, Mr. E. Blundell, has carried out the tedious task of working the tides in the model, and prepared the charts of the experimental results from which the illustrations accompanying this paper have been drawn out. Eddies at sharp edges, due to distortion of scale, appear to have excessive scouring effect in a model; whilst the action of the more regular currents exhibits a deficiency in scouring power, as previously noted. Though the actual depths of the channels, however, are too small for the distorted vertical scale, reliance, I think, may be placed on the general forms and relative depths of the channels obtained in a model. It is possible that the inadequate depth might be remedied by the employment of a finer or lighter material for forming the bed of the model, or by using a liquid of greater density than water; but sand and water have the unquestionable advantage of being the substances which actually effect the changes in estuaries.

"On the Cranial Nerves of Elasmobranch Fishes. Preliminary Communication." By J. C. EWART, M.D., Regius Professor of Natural History, University of Edinburgh. Communicated by Professor BURDON SANDERSON, F.R.S. Received February 22,—Read March 7, 1889.

Although the cranial nerves of *Hexanchus*, *Echinorhinus*, and *Scyllium* have been fully described, and the segmental value of the nerves of Elasmobranch fishes repeatedly considered, the nervous system of *Læmargus* has hitherto escaped notice. This is probably to be accounted for by anatomists taking for granted that *Læmargus* agreed in the arrangement of its nerves with *Echinorhinus* and other *Spinacidæ*.

Fig. 1.

SCHEME A.



NOTE.

The existing Training Walls stop at Berville. Portion of Charts below L.W.O.S.T. is chalk shaded.

Fig. 2.

SCHEME B1.

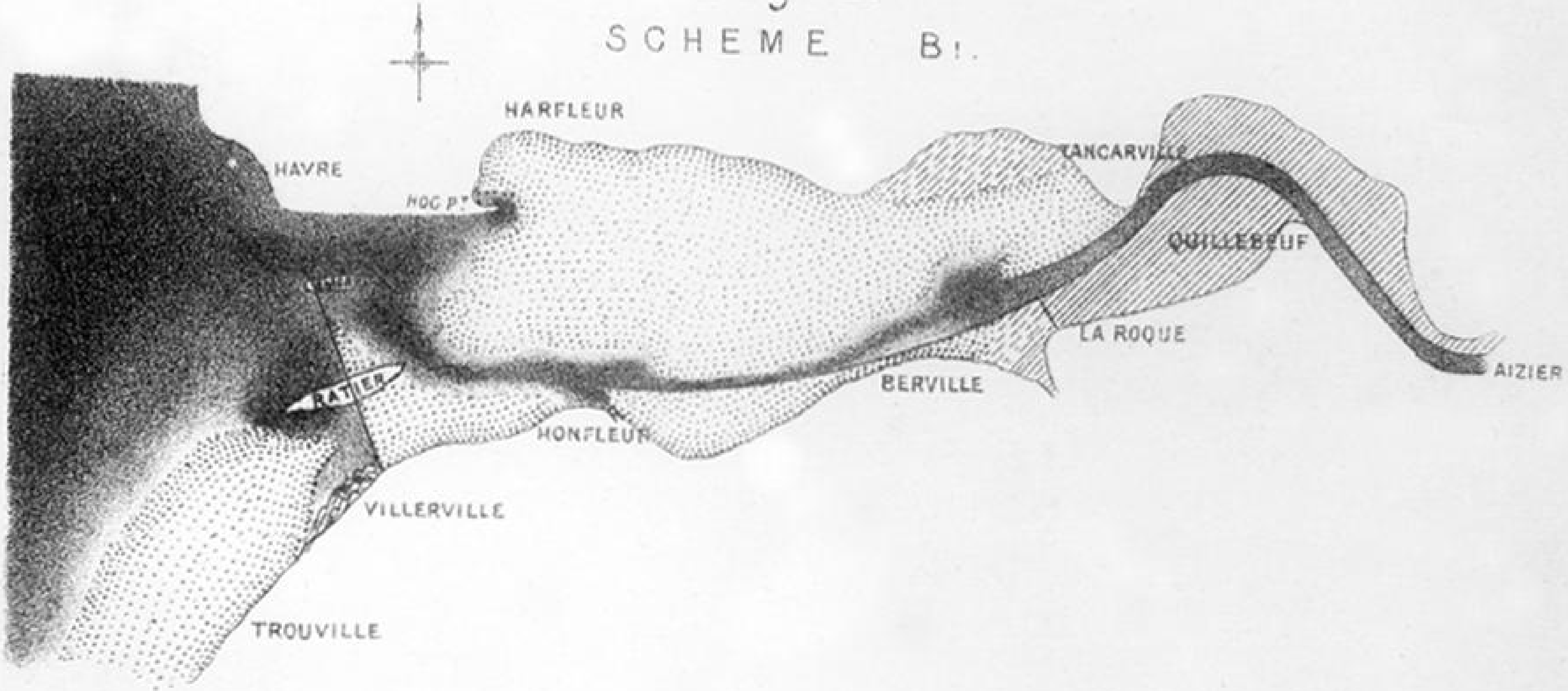


Fig. 3.

SCHEME B2.

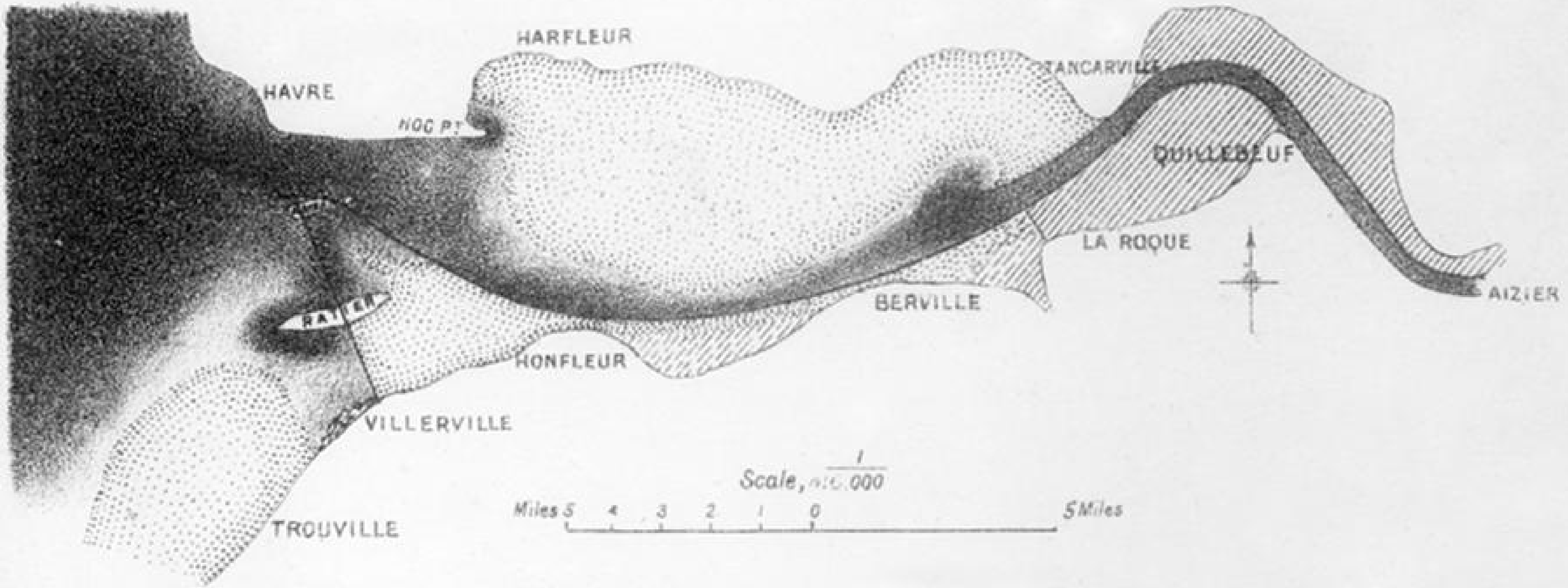
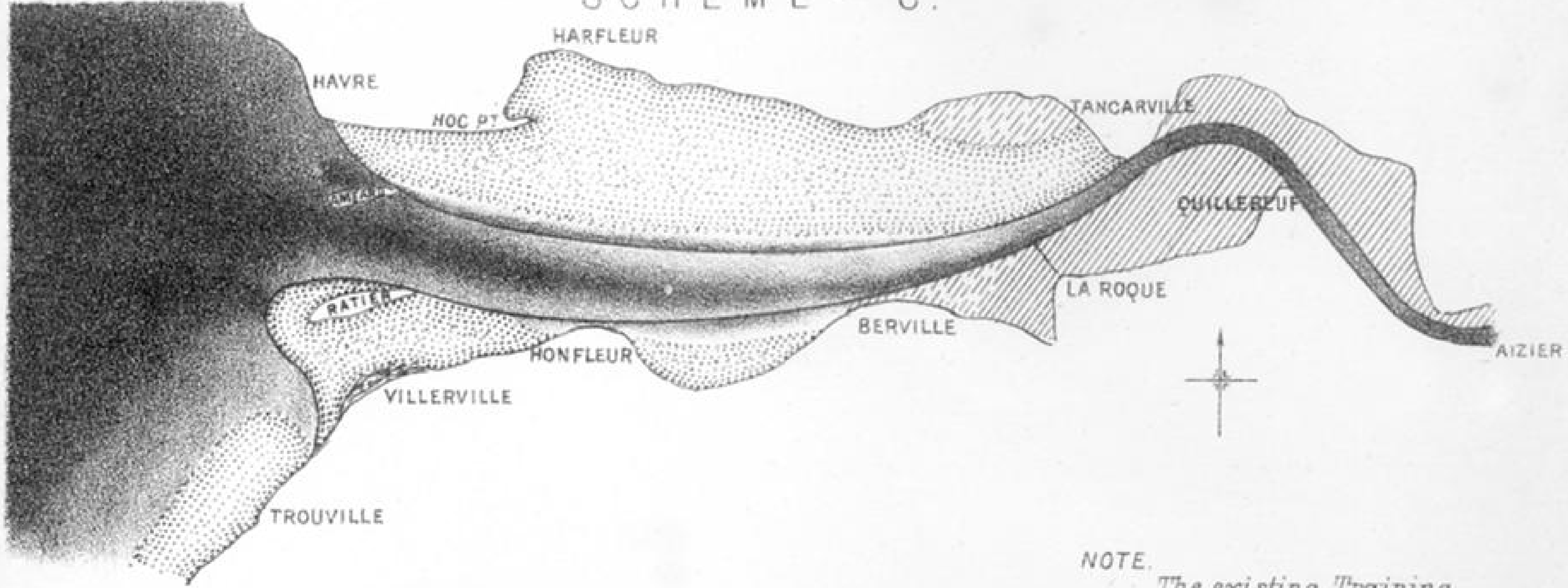


Fig. 1.

SCHEME C.



NOTE.

The existing Training Walls stop at Berville. Portion of Charts below L.W.O.S.T. is chalk shaded.

Fig. 2.

SCHEME D.

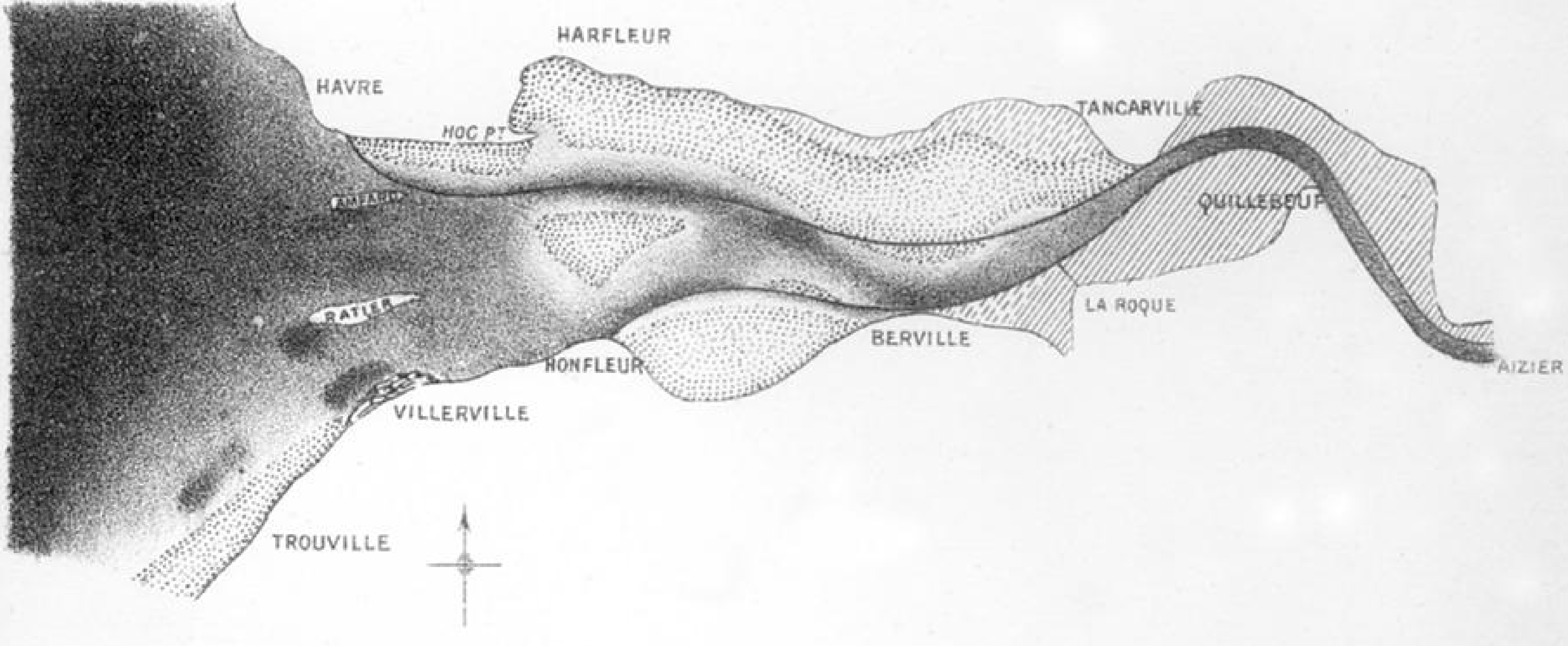
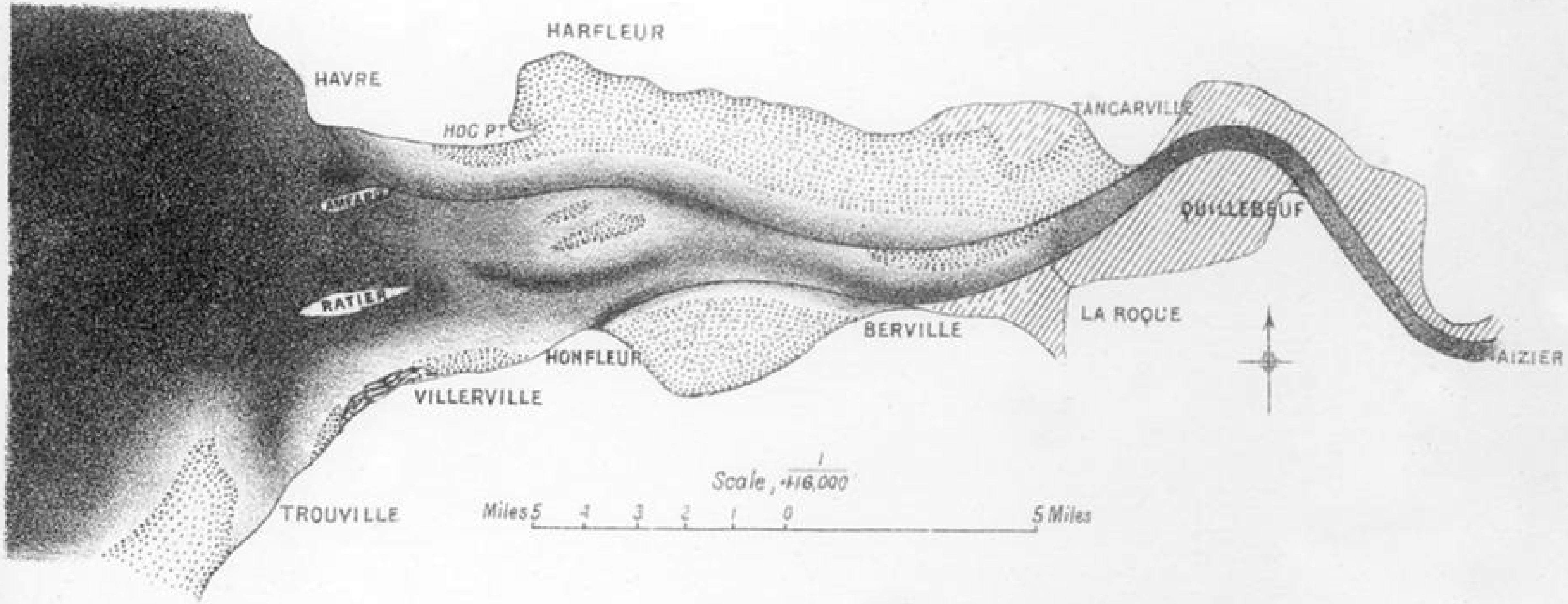


Fig. 3.

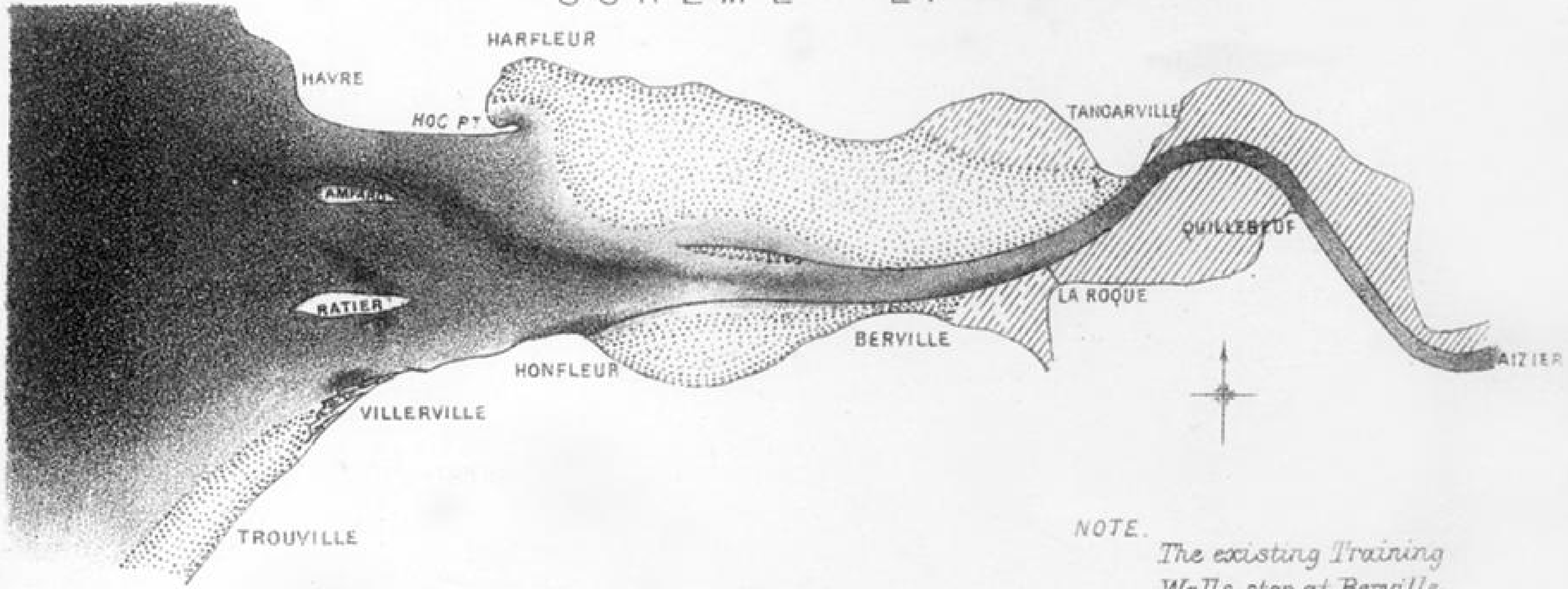
SCHEME D bis.



West, Newman & Co. lith.

Fig. 1.

SCHEME E.



NOTE.

The existing Training Walls stop at Berville. Portion of Charts below L.W.O.S.T. is chalk shaded.

Fig. 2.

SCHEME E bis.

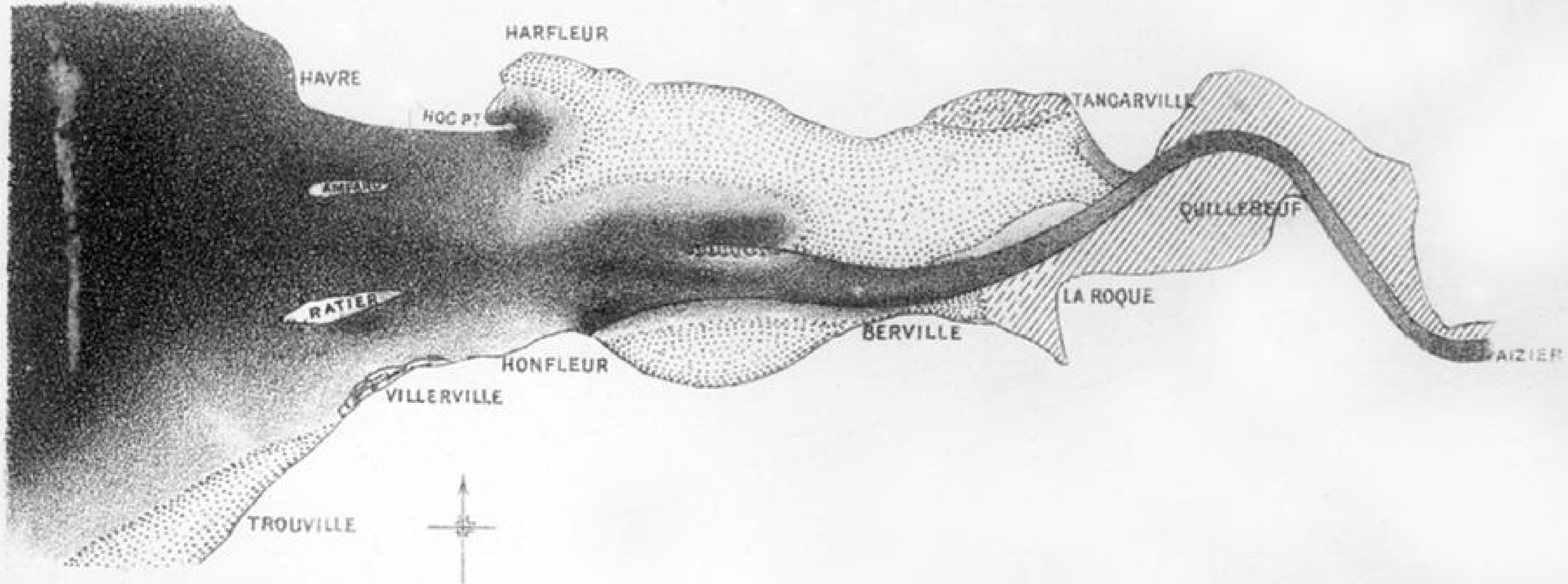


Fig. 3.
SCHEME F.