PAPER No. 173.

A STUDY OF THE FLOW OF WATER UNDER WORKS ON SAND FOUNDATIONS BY MEANS OF MODELS.

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I.—Introduction.

The literature available on the subject of the flow of water under works is not of great extent nor does it contain any considerable amount of experimental evidence upon which the theories connected with constructional practice have been based. This may be due to the difficulties encountered in experimentation.

The study now to be described is naturally divisible into two sections :—

(*a*) The course of the flow of water under a work,

and (*b*) The pressures on the work due to the head of water.

The two sections need entirely different methods and apparatus for their investigation and there is also a considerable difference in the time required to carry out experiments on the two portions. The present series of investigations deals with the course of the flow of water under works ; the investigation on the pressures involved is being carried out simultaneously and will form the subject of a further paper.

The first mention of the subject is not direct but in a commentary on a paper by Beresford.[1] Unwin,[2] during the course of his remarks on the paper, states that in the case of floor failures, in many cases the weir floor has been blown up and not destroyed by direct impact of water. Since it is suggested that the floor is blown up, pressures under the floor are involved.

The first experimental work upon water flow and the effect of a sheet pile is that of Clibborn.[3] Clibborn carried out a series of investigations on the passage of water through sand in a tube. From the point of view of the work to be described in this paper, only two of these investigations are of importance :—

(*a*) The pressures capable of blowing sand through orifices,

and (*b*) The useful effect of curtain walls.

From the results he obtained, Clibborn concludes that an effective head of three feet at any point appears capable of blowing sand out with

the water. He remarks that sand is carried through an orifice with water when the water discharged has to pass through an area so limited as to allow of its attaining a certain velocity. Although not stated, Clibborn, therefore, tacitly admits that the blowing of sand is a function of velocity and not necessarily of head. A deduction that may be made from his remark is that any device which increases the velocity of the water at the point of exit tends to the blowing of sand.

In connection with his investigation of the effect of a curtain wall, Clibborn remarks that the value of a curtain wall at the end of a weir is marked by the way in which it prevents sand flowing out with the percolation water. This only deals with the effect of a single curtain wall at the downstream end of the weir. In the experiments to be described the effects of single curtain walls in different positions and various combinations of curtain walls were investigated.

Clibborn is apparently the first to relate a curtain wall with a length of weir. He states that " Each foot (of curtain wall) is equivalent to adding three feet to the length of the weir." Clibborn was dealing with a downstream curtain wall, and in this case his remark is to some extent correct. This conclusion has been applied directly, however, to the effect of an upstream curtain wall by other investigators without experimental confirmation. The experiments which have now been conducted show that Clibborn's conclusion as to the relation between a length of curtain wall and a length of weir cannot be applied to the case of an upstream curtain wall.

Beresford[4] comments on Clibborn's experiments at some length. He does not regard the work as giving useful information on the real action of the percolation of water through sand under a weir. In Plate XVII and in para. 10 of his remarks, Beresford assumes that the flow of water under a weir on a uniform sand is horizontal under the floor. This assumption is shown to be incorrect in our experiments.

In Plate XVI of Beresford's noting, the supposed effect of an impervious layer on the course of the streamlines is shown. This should be compared with Fig. VII in the present paper. The theoretical case of a dam with semi-circular cross section considered by Beresford has been investigated experimentally by us and is described later in the text. Beresford's remarks with regard to this will be discussed in connection with that experiment.

In passing, the work of Slichter and Baldwin Wiseman should be noted. These investigators have confined their attention to the study of the relation of flow of water through a sand to particle size and head. Their work has little application to the present studies, which are concerned only with the course of the water.

Hanbury Brown[5] (quoted by Buckley, Irrigation Pocket Book, pp. 371-372) discussing Clibborn's experiments remarks that, after arguments, " A curtain wall is well placed if upstream of the floor, but

badly placed if downstream." This remark again is not based on experimental evidence and in the light of our experiments appears to be incorrect. A discussion of the remark is postponed until the experiment on the effect of an upstream curtain wall is being described.

Bligh[6] is regarded as the originator of the scientific method of construction. His remarks are therefore of considerable importance. He states,[7] " Up to a quite recent period, the design of such works had not been based on any definite principles, the profiles being merely more or less close copies of older works of similar nature and the sections eventually adjusted by failure and renewal to actual requirements." This dates the application of scientific principles to construction as about 1907. The most important paper of Bligh[8] appeared in 1910.

Bligh[9] makes an important statement which has had a great influence on design. In this statement he introduces the term " creep " for the first time. He states that " The main determining factor in the stability of the sand is the length of percolation or so-called " creep." He devices a formula for determining the enforced length of percolation. This formula involves L, the length of the weir ; H, the head ; and C, a co-efficient depending on the grade of sand. Bligh states that the derivation of the co-efficient ' C ' for the classification of sands will be explained later. Although he gives a number of these co-efficients for different sands, he omits to explain how they were derived.

Bligh[10] proceeds to apply his formula to the consideration of the effect of a curtain wall. He states " If an impervious line of sheet piling be inserted below the floor, the line of creep may be measured down one side of the vertical obstruction and up the other side. The added length of creep will then be twice the length of the curtain." This is a statement which is fundamental to the principles of construction and therefore of considerable importance. It will be seen later that this is a statement which is not based on experimental evidence and is incorrect.

Bligh's[11] deduction from the above statement is that " A curtain wall increases the length of the enforced percolation and immediately reduces pressure at any point of the base." While the total pressure is reduced by a curtain wall, a single curtain wall, as shown in our experiments, results in a concentration of the flow instead of an even distribution as in the absence of a curtain wall. Bligh[12] states also that the position of the drop wall with reference to the floor is immaterial as regards foundation stability. This, again, is a statement that the present experiments appear to disprove.

It may be said here that as a deduction from the experiments to be discussed, the only occasion on which " creep " can occur is when the original work has been badly constructed and that with good construction the line of creep as supposed by Bligh is non-existent.

The first reference throwing doubt on Bligh's statements that we have been able to discover is that of Hutton[13] at the Simla Engineering

Conference 1913. He states that the results at Narora Weir indicate "The path of percolation seemed to follow a line of least resistance instead of the line of creep." Hutton further stated that the percolation would pass direct from the toe of the upstream piling to that of the downstream piling. Our experiments show that this latter statement is incorrect.

Griffith[14] is the first to suppose that the action tending to cause failure results from the concentration of streamlines. The experimental proof of this is given in the present paper. Griffith accepts Bligh's "line of creep" as is shown by his diagram.

Khosla,[15] in dealing with the hydraulic gradient in subsoil water flow in relation to stability of structures resting on saturated soil, states that the design of certain works has been based on the Hydraulic Gradient Theory as set forth by Bligh. These structures failed, and Khosla remarks, "The object of this paper is to show how very materially this theory can be at variance with facts." Khosla mentions that dislocation of subsoil particles is a function of velocity of flow of subsoil water through them. He also deals with the effect of end curtain walls in stopping the blowing out of sand.

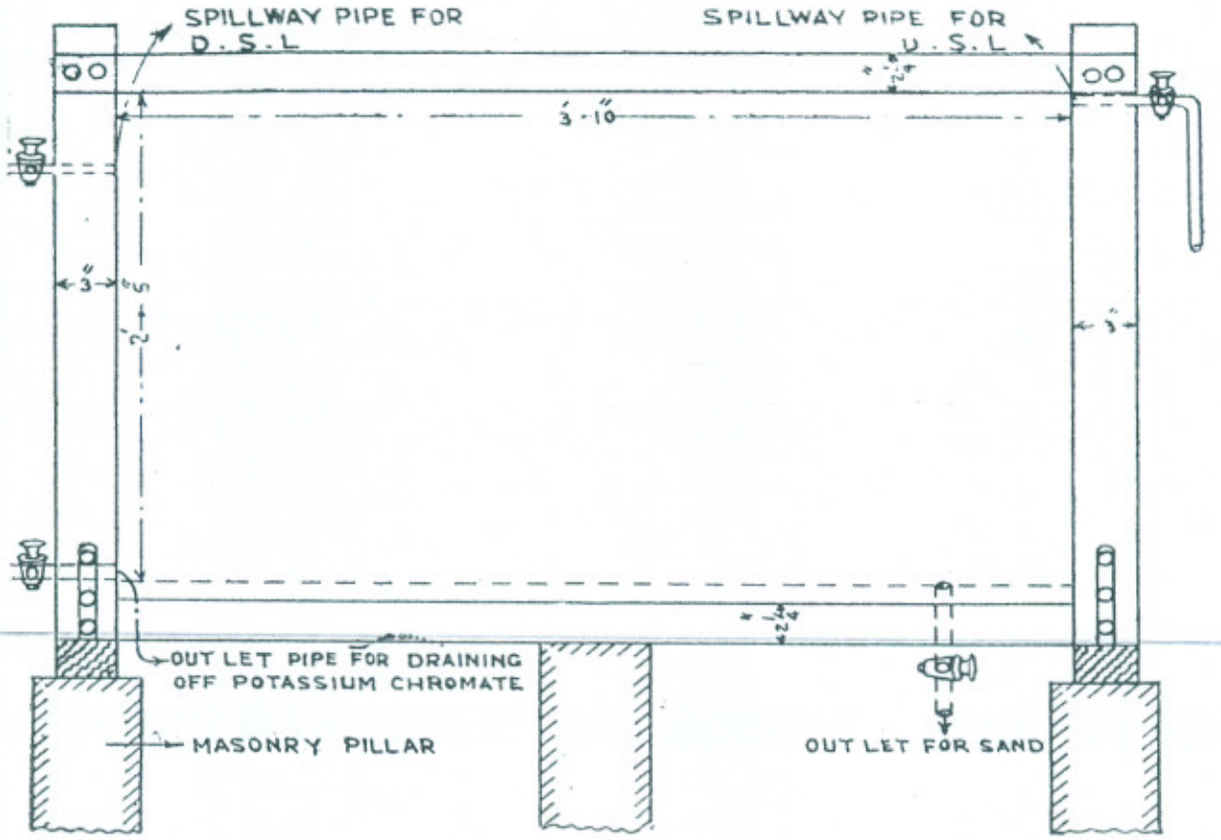
In a later paper Khosla[16] emphasises that the pressure gradient under the floor of a weir differs widely from that supposed by Bligh and that the Hydraulic Gradient Theory of Bligh formed the basis of designs for the structure of weirs, etc. As a result of Khosla's investigation of the literature, he further states that Bligh's theory of Hydraulic Gradient is not founded on experimental evidence. We regard it, therefore, as a hypothesis rather than a theory. Probably the most important investigation up to the present day is that of Khosla.[17] His results as to the course of the streamlines are deduced from the pressure observations made on Panjnad Weir. In a supplement to his paper Khosla publishes photographs of streamlines which were taken by Dr. Rehbock. In these photographs the streamlines are traced by means of dyes. The photographs are of particular interest as they appear to be the first attempt in this direction. No details of the technique are given but from the photographs there appears to be a certain amount of dye diffusion which masks the course of the streamlines at important points.

The foregoing review of the literature on the subject shows that very little experimental work has been done on the subject and that the theories on which conclusions are based are lacking in experimental proof and frequently break down in practice.

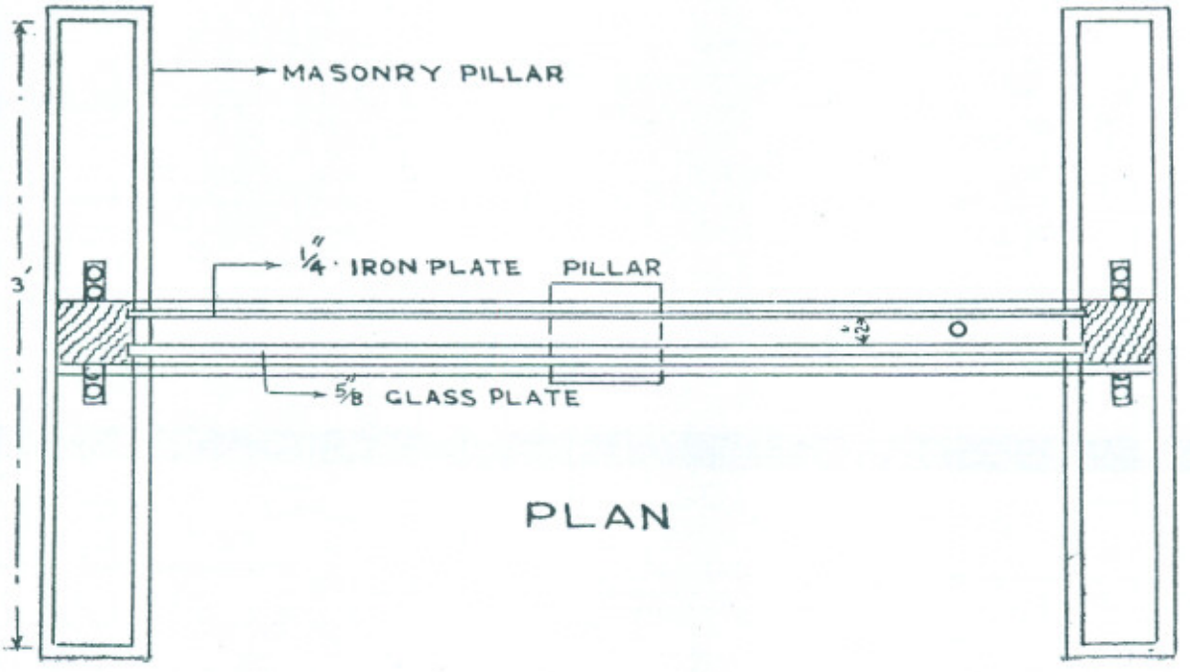
The present series of investigations was started with the object of placing constructional practice on a sounder basis by experimentally determining the conditions of flow under standard forms.

FIG. I

SHOWING THE EXPERIMENTAL TANK



FRONT ELEVATION



PLAN

II.—Method of Investigation.

I. Apparatus :—

(*a*). Experimental Tank :—

The experiments were carried out in a series of tanks which were 3 ft. 10 in. in length, 2 ft. 6 in. in depth and 2 inches wide. Fig. No. 1 is a dimensioned diagram of the tanks used.

The frame of the tank was made of teak. The tank itself consisted, on one side, of a glass plate $\frac{5}{8}$ inch in thickness, and, on the other side, of a steel plate $\frac{1}{4}$ inch thick and similar in size to the glass plate, the ends of the tank being formed by the framework. The frame was grooved near both edges for the insertion of the glass and the steel plates. The tank was mounted on the planks of wood placed at right angles to the bottom of the tank to give it stability.

One difficulty experienced was in connection with making water-tight joints between the glass and steel plates and the frame. After a number of trials the following procedure was adopted to secure water-tight joints. One side of the frame was mounted on the base. Two right-angled steel plates were screwed to the base and the end frame to hold the frame together. The grooves in these two members were then filled with a hot mixture of paraffin wax, bitumen and rosin and the edges of the plates inserted in the grooves. The grooves in the other end of the frame were then filled with the wax-bitumen-rosin mixture and the frame placed in position on the base and slowly forced against the ends of the glass and steel plates by an iron cramp. As a result of the pressure the excess of the cementing mixture was squeezed out of the grooves. The glass and the steel plates were also forced by the press against the grooves in the base. By this method water-tight joints were secured. As a precautionary measure a further quantity of the cementing mixture was applied to joints inside the tank after assembly.

In the bottom of the tank, at the end which was to be upstream of the model, a hole one inch in diameter was bored to provide an outlet for the removal of the sand at the conclusion of the experiment. Towards the bottom of the end frame piece which was to be downstream of the model a glass tube fitted with a strainer was provided for draining off the liquid contents of the tank. The end frame piece which was to be upstream of the tank was fitted with a spill-way pipe provided with a stopcock so that the upstream level of the water could be maintained constant. A similar fitting situated at a lower point was provided on the end frame piece downstream of the model to keep the downstream level also constant. The tank when completed was mounted on cement pillars at a convenient height for observations to be made and photographs taken.

(*b*). Construction and Fitting of the Model.

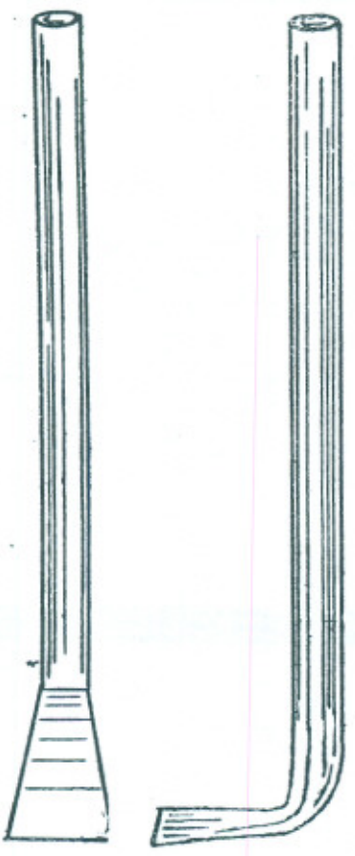
The model of the work to be investigated was made in teak so that it loosely fitted in to the tank. Deep rectangular grooves were cut in

the front and back side of the model, the vertical grooves being temporarily fitted with strips of wood to close them. The distance between the grooves and the edges of the model was $\frac{1}{8}$ of an inch. Before inserting the strips of wood for temporarily closing the grooves, the grooves were greased so that the wood strips could be easily removed after fixing the model.

Before placing the model in position the sand on which the model was to rest was introduced into the tank. The sand used for the purpose was white so that the course of streamlines would show up and would be capable of being photographed. The grade of sand normally used in these experiments was such that it passed a 60 mesh sieve but was retained on the 80 mesh sieve. As is mentioned later, potassium chromate was one of the solutions to be used in tracing the streamlines. In order to secure uniformity of colour, the sand to be used in the experiment was treated with a solution of potassium chromate before being placed in the tank. The tank was filled with sand in the following manner :—

A one per cent. solution of potassium chromate was placed in the tank to a depth of about 4 inches. Sand was then added to the tank in small quantities and the sand-potassium chromate mixture was thoroughly stirred to secure uniform packing. A further quantity of potassium chromate solution was then introduced and the addition of sand repeated. This process was continued until the tank contained sand up to the desired level. When the sand had reached the desired level, the model was placed in position and pressed firmly on to the sand to secure a good joint between the sand and the model. The model was placed in such position in the tank that the upstream and the downstream ends of the model were equi-distant from the upstream and downstream ends of the tank.

Fig. II.



Having fixed the model the solution of potassium chromate was drawn off until the level of the liquid in the sand was below the lowest point of the model. The strips of wood sealing the grooves were now withdrawn and any sand present in the grooves removed by the tools shown in Fig. II. The grooves and the adjacent glass and steel were thoroughly cleaned with methylated spirit and finally dried with acetone.

In order to make the joints between the model and the tank water tight, paraffin wax was used. A low melting point paraffin wax, 55°C, was melted and just before it became solid, it was run into the grooves and worked into

positions with steel strips. Paraffin wax was also run into the space between the upstream and the downstream ends of the model above the floor so that a solid block of paraffin wax existed between the upstream and downstream levels of water. By the above means it was found that the joints between the model and the tank could readily be made water tight.

II.—Mode of Operation.

The basis for tracing the course of the streamlines was the reaction between potassium chromate and silver nitrate. When solutions of these two substances are brought in contact, a red precipitate of silver chromate is obtained according to the following equation :—

$$2\,Ag.\,NO_3 + K_2\,CrO_4 = Ag_2\,CrO_4 + 2\,K\,NO_3$$

(Colourless) (Yellow) (Red) (Colourless).

The solutions of potassium chromate and silver nitrate used in these experiments were of 1 per cent. strength.

The solution of potassium chromate was contained in an aspirator and placed in such a position that the potassium chromate could be introduced into the top of the tank and maintained at a constant level at the upstream end of the model. Before starting any experiment, the solution of potassium chromate was run through the sand to ensure that the model was water tight, the sand saturated with the solution, and the flow uniform.

The solution of silver nitrate was contained in a series of tap funnels, the points of which were drawn out to give a fine stream. The points of the funnels were introduced into the sand at intervals on the upstream side. The points of the funnels were placed about 1 inch below the sand surface and close up to the glass side of the tank. The head of silver nitrate in the tap funnel was slightly greater than the head of the main bulk of potassium chromate solution to ensure that a stream of silver nitrate was delivered. This additional head was dissipated soon after it left the point of the tap funnel. Arrangements were made to keep the head of silver nitrate constant in the tap funnel. The experiment was commenced by opening the stopcock of the tap funnel at a known time. The silver nitrate reacted with the solution of the potassium chromate and gave a precipitate along the line of flow. After the initial action, as will be seen from the equation, the front of the silver nitrate stream is preceded by a colourless solution of potassium nitrate. This results in an initial colourless development of the streamlines which contrast with the yellow colour of the potassium chromate solution. The precipitate of silver chromate on the course of streamlines develops subsequently. The photographs of the development of the streamlines were taken at intervals, suitable illumination having been provided. It was found necessary to take a series of photographs at intervals as points of interest occur during the experiment which may be obscured by later developments.

III.—Studies of the Flow of Water under various Structural Forms.

A series of investigations was commenced to determine, in the first instance, the lines of flow of water under models designed to show the effect of standard methods of construction. In addition, certain theoretical forms have been investigated since they have been discussed in treatises on the subject, but hitherto without experimental evidence to support the conclusions. The observations made are largely qualitative but have important applications. They have since been supplemented by quantitative studies which will be described in a further paper. The series of investigations commences with the simplest form and leads gradually to the effects of the more complicated structures.

The results are illustrated by photographs taken during the course of the experiments and by diagrams which show intermediate stages.

STUDY No. I.

The Flow of Water under an Impervious Floor.

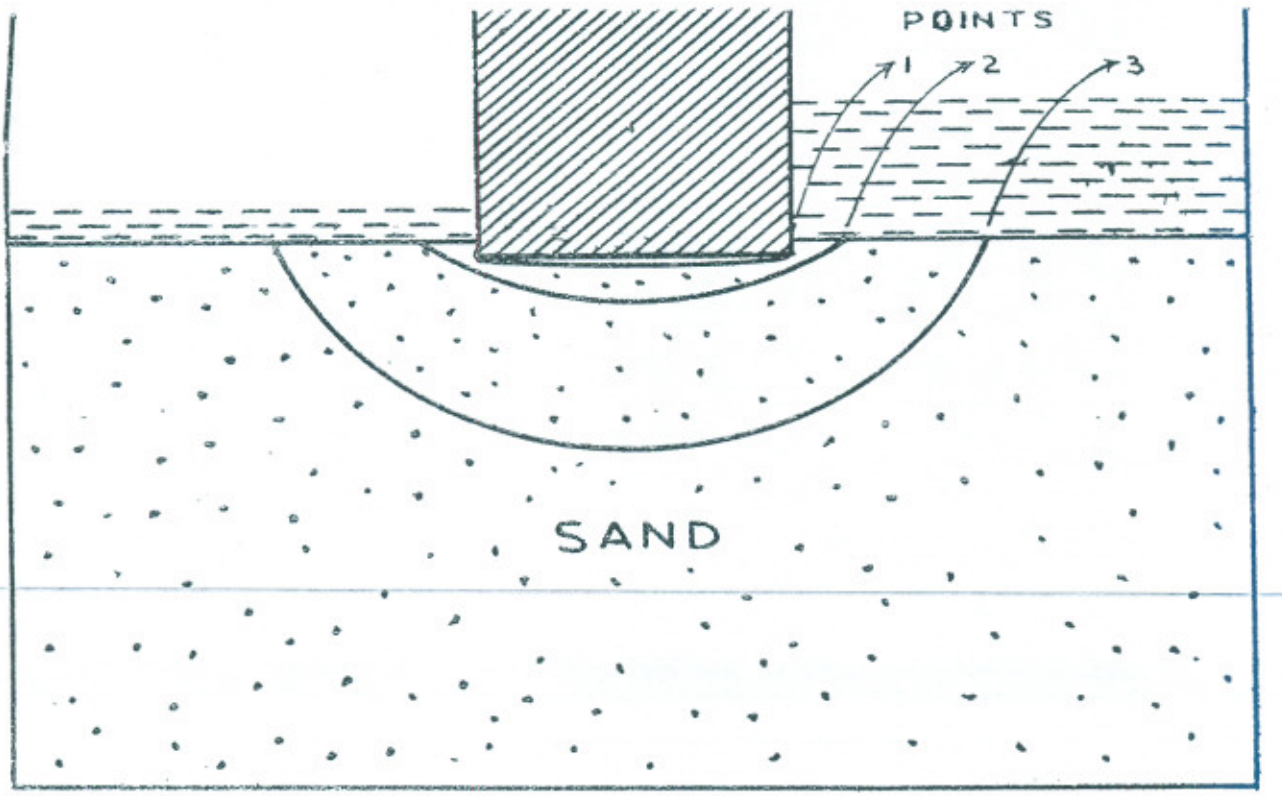
The technique adopted has been described in the previous sections of the paper. The model was constructed and the course of the streamlines photographed at intervals during a period of forty-three hours at the end of which time the development was complete. Fig. III shows the final stage of this development.

The first important conclusion to be derived from this photograph is that the flow of water under a work is streamline. The result of this is that the laws which apply to the study of streamline flow can be applied to subsoil water movement.

The streamline from Point No. 1 emerged downstream of the work approximately four hundred minutes after the commencement of the experiment. It will be seen that the streamlines are symmetrical and take the form of semi-ellipses. The natural course of a streamline under a work without any underground obstruction will be a semi-ellipse. In Fig. III it will be noticed that no line of flow is traced from the upstream end of the floor. The experiment was partially repeated so that such a line could be traced. It was found that the line of flow, when there was good contact between the sand and the model, was a short distance below the floor and the line of flow emerged at the toe of the work. When there was a bad contact between the sand and the floor, the flow took place in contact with the floor. A further important point noted was that the velocity of flow from the upstream end of the floor was lower than that from a point a short distance upstream of the floor. It was also observed that the nearer the point of entrance of flow to the upstream

end of the floor, the greater was the eccentricity of the elliptical streamline. The course of the streamlines near the floor is shown in Fig. IV.

Fig. IV.



Since it has been shown that the course of a streamline is a semi-ellipse, any deviation from this form will be a distortion of the streamline and an unnatural line of flow.

Bligh [18] illustrates the probable course of the flow of water under an impervious floor. In the diagram which he gives he shows that the streamlines take a horizontal course under the floor. The photograph now under discussion shows that this is not the case.

A result of considerable importance arises out of this experiment Bligh [19] uses the expressions "Line of Creep" and "Line of Percolation" synonymously. Griffith[20] states that the line of creep is the streamline directly under the impervious floor and is the only one needing consideration. From the experiment under discussion, it has been shown that the line of percolation, *i.e.*, "creep", nearest the floor has not the highest velocity of flow of the streamlines. It follows, therefore, that the streamline nearest the floor is not a main line of flow. It appears that "creep" as imagined by Bligh does not exist. This will become more evident when dealing with the effect of sheet piling as Bligh makes definite statements regarding the effect of this form of structure.

The results of this study may be summarised as follows :—

1. The flow of water under an impervious floor is streamline.
2. The lines of flow take the form of a series of semi-ellipses. The eccentricity increases as the line of flow approaches the floor.
3. The forms of the flowlines as given by Bligh are incorrect.
4. The streamline entering at the upstream end of the work does not flow in contact with the floor and has a lower velocity than lines of flow some distance from the floor.
5. Since it has been shown that the line of highest velocity of percolation is not in contact with the floor, creep does not exist as imagined by Bligh.

STUDY No. II.

The effect of a Sheet Pile on the Flow of Water in Sand.

This study was made as there is no literature on the subject of the behaviour of a sheet pile towards the flow of water. It is essential to know the effect of simple forms on the flow, if the flow under complicated structures is to be thoroughly understood. Structures are usually combinations of pervious and impervious floors and sheet piles ; a knowledge of the effects of the individual simple forms will therefore be of value.

In this study a sheet pile six inches long was erected in the centre of the tank and the flow of water from the upstream to the downstream side of the sheet pile traced. Fig V shows the form of the streamlines in this case.

As a result of the study of the flow of water under an impervious floor, it was shown that the natural course of the streamlines under the floor was semi-elliptical. A very short sheet pile may be regarded as a very small impervious floor. The lines of flow under this very short sheet pile would be semi-elliptical. Any deviation from this form of flow must be due to the presence of the sheet pile and must be regarded as distortion.

On the upstream side of the sheet pile streamlines from points 1, 2, 3 and 4 can be divided into two parts. The first part shows that the tendency of flow is initially in a semi-elliptical form. The streamlines then come under the influence of the sheet pile and there are definite breaks in the curves. The curvature of the streamlines alters so that they tend to descend more vertically than in their initial stages. This effect of a sheet pile was noticeable in later experiments when other structural

forms were being investigated. The first effect of the sheet pile has been, therefore, to distort, at a certain point of the flow, the streamline from the natural semi-elliptical form.

On the downstream side of the sheet pile, the same two divisions of the curves are noticeable though not quite to the same extent.

It will be noticed that the streamlines become much narrower as they approach and pass under the sheet pile. Further, it will be seen that in addition to becoming narrower the intervals between streamlines passing under the pile are considerably less than the corresponding intervals at the points of entrance and emergence. As the quantity of water flowing under the pile must be the same as that entering the surface of the sand, it follows that there must be a considerable increase in velocity of the water as it flows under the pile. A narrowing of the streamline, therefore, indicates an increase in the velocity of flow of water. Conversely, a broadening of the streamline indicates a reduction in the velocity of flow. After the streamlines have passed under the pile, they again broaden until their width at emergence is very similar to that at entrance. After pasing the sheet pile, therefore, the velocity of the flow of water is again reduced.

The distance from the sheet pile that is affected by the pile is limited. It will be seen in the photograph that streamline from point No. 5 is not affected either in form or velocity by the presence of the pile.

An important point bearing on the " Theory of Creep " is that the streamline from Point No. 1 passed immediately under the pile but left the pile in the downstream side. This streamline having touched the pile, it would be expected that it would take a course on the downstream side of the pile in contact with the pile. Such is not the case. The distance of the point of entrance of the streamline from the pile was measured and also the distance of the point of emergence. It was found that the distance of the streamline from the upstream side of the pile was slightly less than the distance downstream. The tendency is, therefore, for the streamline to leave the pile on the downstream side, an observation contrary to what would be expected if the theory of creep applied. This tendency to leave the downstream side of a sheet pile was confirmed by later observations.

The effect of a sheet pile on the flow of water may be summarised as follows :—

1. The courses of the streamlines are distorted from the semi-elliptical forms, the lines being divisible into two portions both upstream and downstream of the pile.
2. The presence of the sheet pile increases the velocity of flow of the water when it passes under the pile. The velocity of flow is again reduced as the point of emergence is approached.

3. There is a marked tendency for the streamline to leave the downstream side of the sheet pile.
4. The length of the streamline from any particular point in a limited distance upstream is increased by the presence of the pile.

STUDY No. III.

The Flow of Water under an Impervious Floor with a Semi-Circular Foundation.

Having determined the forms of the streamlines as influenced by the two fundamental structures, an impervious floor and a sheet pile, it was decided to investigate a form of purely theoretical interest. The reason for this was that it was the earliest recorded instance of the supposed course of the streamlines having been shown diagrammatically. Beresford [3] in the criticism of Clibborn's paper [4] deals with the flow of water in the theoretical case under consideration. The Beresford Diagram has found its way into test-books and, hence, has become of some importance.

The model consisted of an impervious floor twelve inches long mounted on a semi-circular foundation of six inches radius. The streamlines were traced in the usual manner, their final development being shown in Fig. VI.

In Beresford's Diagram the streamlines are shown as semi-circles concentric with the foundation of the work. An explanation is given as to why they should be semi-circular.

During the initial stages of development of the streamlines in this experiment, they appeared to be semi-circular in form on the upstream side of the model. The photograph of their final development shows, however, that they are definitely not semi-circular but tend to be thrown away from the downstream side of the work. The distances between the upstream and downstream ends of the model and the points of entrance and exit respectively of the streamlines were measured. The results are given in Table I.

TABLE I.

Point No.	1	2	3	4	5
Distance from Upstream end of Model	1·4″	4·8″	8″	10·9″	13·5″
Distance from Downstream end of Model	1·7″	6″	9″	11·6″	13·8″

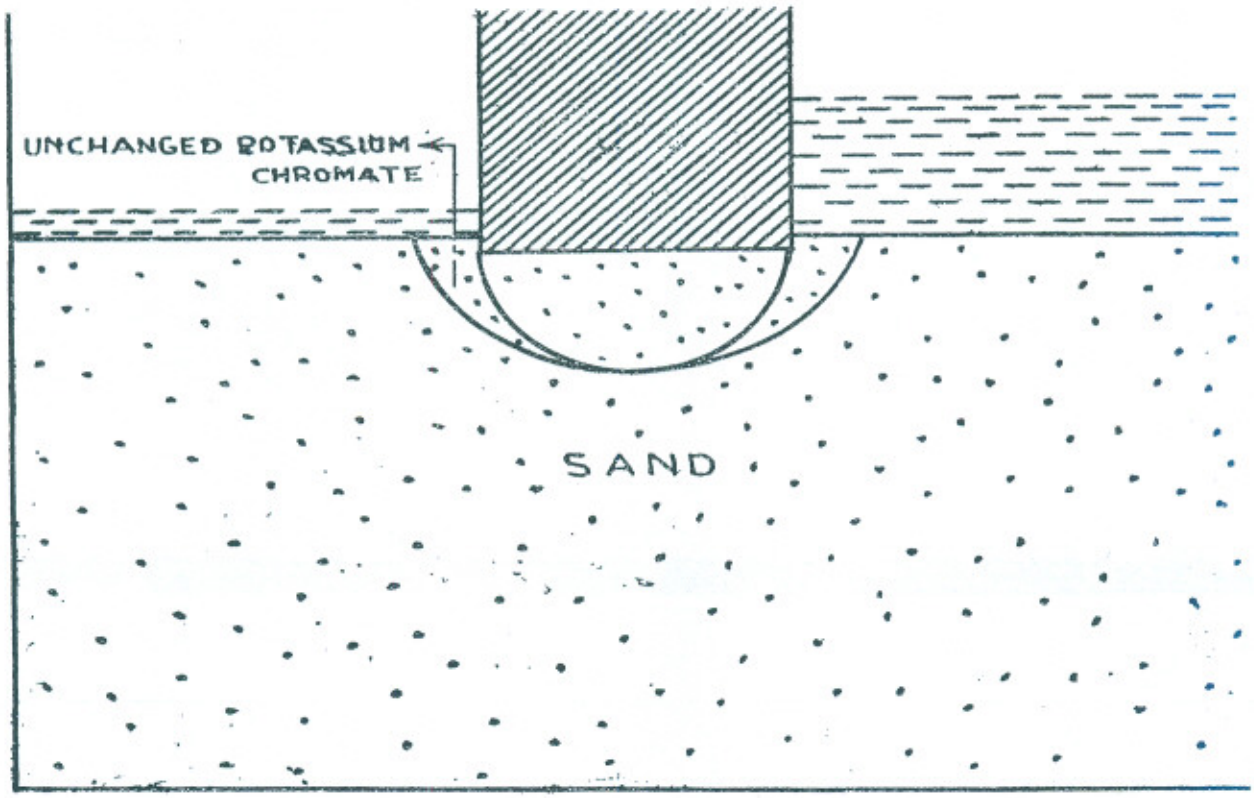
It will be seen that in all cases the distances downstream are greater than those upstream. As the result of the examination of the flow under an impervious floor it was shown that the natural courses of the streamlines were a series of semi-ellipses. The presence of the semi-circular foundation has forced the steamlines out of their natural courses. From the study of the effect of a sheet pile on the flow of water, it was found

that the line of flow tended to leave the pile on the downstream side. It follows from a consideration of the two simple forms that, since there is an obstruction, the streamlines will be distorted and will tend to leave the foundation of the model on the downstream side. It seems probable that there is an area of " dead water " between the first streamline and the downstream side of the model. This suggestion was confirmed in a later study. It will be seen that the diagrammatic representation of the streamlines given by Beresford is not strictly in accordance with the experimental evidence.

Beresford further diagrammatically represented what he considered would be the effect of an underlying impermeable layer on the form of the streamlines under the work. It was decided, therefore, to further extend this study in order to test his conclusions. The impermeable layer was obtained by placing the model in a lower position in the tank. The bottom of the tank thus became an impermeable layer. Fig. VII gives the final development of the streamlines.

During the progress of the experiment it was noticed that the streamline from Point No. 1 which started away from the model gradually approached the foundation and finally touched it just before the greatest depth was reached. After passing the point of greatest depth of the model, the streamline left the model and was separated from the model by a layer of sand in which the potassium chromate remained unchanged. This observation is shown diagrammatically in Fig. VII-A and is of considerable importance in connection with the creep theory.

Fig. VII-A.



Since the silver nitrate from Point No. 1 touches the base of the model, it follows that any potassium chromate flowing between this point and the upstream side of the model must react with silver nitrate. Since the streamline develops beyond the lowest point, an excess of silver nitrate must be passing this point and, hence, would be capable of reacting with any potassium chromate on its course of flow. As the potassium chromate in immediate contact with the downstream side of the model is unchanged, it follows that no silver nitrate is flowing in this area. This area must be occupied, therefore, by dead water. Since the streamline touched the base of the model, had creep been a normal process, the streamline should have remained in contact with the model on the downstream side. As the streamline did not follow the supposed theoretical course, it must be concluded that creep is not a normal feature of the flow of water under a work.

In Beresford's Diagram to which reference has already been made, it is shown that the effect of an impermeable layer is to compress the streamlines equally throughout the depth between the work and the impermeable layer. From the photograph under discussion it will be seen that the streamline from Point No. 2 maintains its distance from streamline No. 1 throughout its course. It appears that the streamlines near the work are unaffected by the presence of an underlying impermeable layer.

The intervals between the streamlines as they pass under the model become smaller as the streamlines approach the impermeable layer. The impermeable layer exerts its greatest effect on the streamlines which take their course nearest to it.

In the photograph it will be seen that the nearer the streamline is to the impermeable layer the greater is the reduction in thickness of the streamline as it passes under the model. A further effect of the impermeable layer is, therefore, to increase the velocity of flow along the streamlines in its neighbourhood. This velocity is reduced after passing the lowest point of the work. From investigations of other models uninfluenced by an impermeable layer, it has been found that the greatest increase in velocity of flow occurs on the streamline nearest to the work. The effect of the model on the velocity of flow appears to be counteracted by the impermeable layer.

Summarising the results of this experiment, it may be stated that :—

1. The streamlines under a work on a semi-circular foundation are not semi-circular.
2. There is a zone of dead water between the line of flow nearest the model and the model itself on the downstream side.
3. Although flow may take place in contact with a model, at a certain point, if the continuation of the model from this point is not the natural line of flow, the line of flow leaves the model.

4. Further evidence is afforded of the lack of creep.
5. The effect of an impermeable layer beneath a work is to influence the streamlines, both as regards shape and velocity, nearest the impermeable layer. The streamlines in the neighbourhood of the work are uninfluenced by an impermeable underlying layer.

STUDY No. IV.

The Flow of Water under an Impervious Floor protected by an Upstream Sheet Pile.

This study is the simplest combination of two standard forms. The model consisted of a twelve inch impervious floor and a sheet pile six inches in length. Silver nitrate was introduced at five points, one of which was immediately upstream of the work. A number of interesting points were revealed at intermediate stages of the development of the streamlines. These will be illustrated by a diagram and the photograph of the final development of the streamlines is given in Fig. VIII.

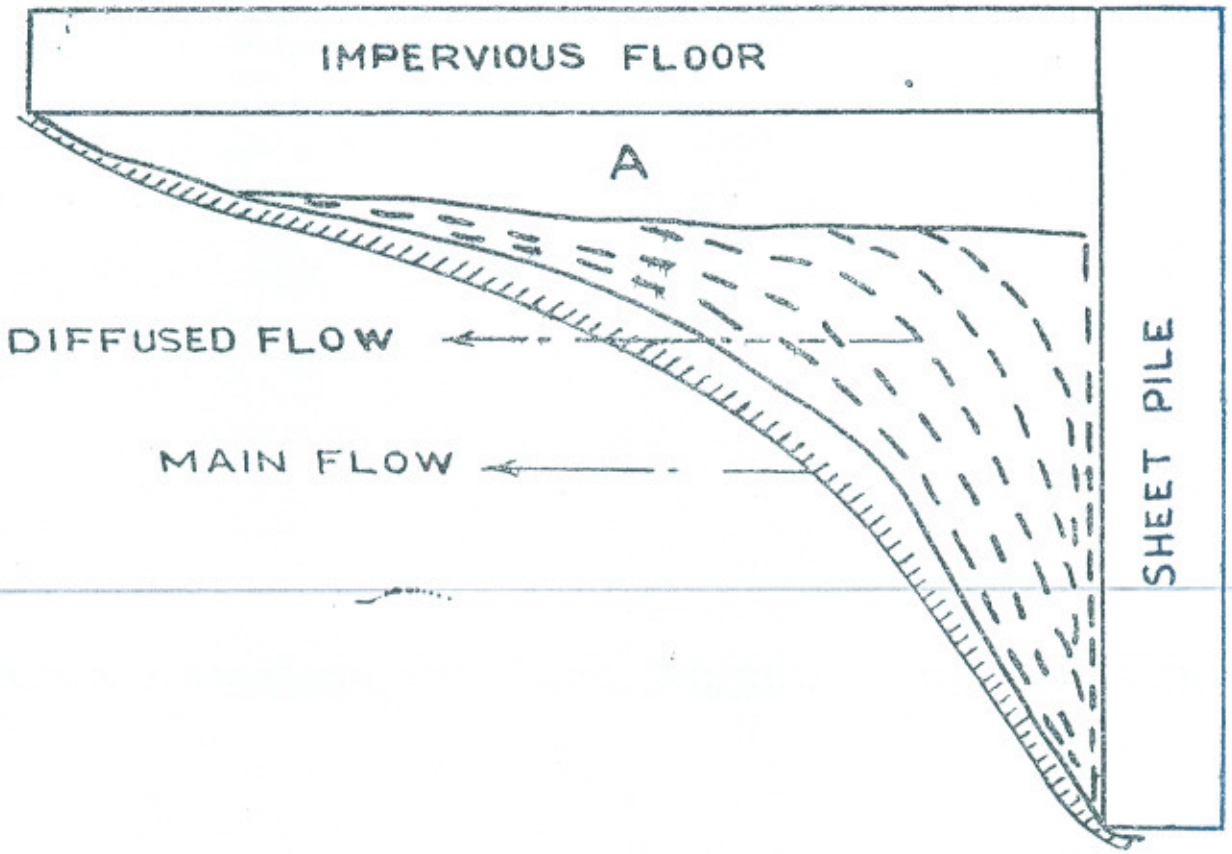
A photograph was taken at the end of one hundred minutes which showed the development of the streamline from Point No. 1. The streamline followed the pile vertically down its upstream face but, after passing under the pile, it left the pile and took a curved course away from it. The main line of flow from Point No. 1 was, therefore, not vertically up the downstream side of the sheet pile. The course of the streamline is shown in Fig. IX.

While the main line of flow of this streamline is in the direction shown, there was a tendency for it to break up after passing the pile and a very slow flow occurred in the space between the main line of flow and the pile. This secondary flow is minute. The main line of flow of streamline No. 1 emerged at the toe of the work 180 minutes after the commencement of the experiment. At this time the condition of flow in the space between the streamline and the work is shown in the Fig. X.

In the unshaded space marked " A " no development of the streamline had taken place. In the final photograph it will be seen that the whole of the space between the main line of flow has become coloured with the precipitate indicating that a slow flow in this region is undoubtedly taking place. The main line of flow is, however, the outside of the curve. Bligh [21] states " the line of creep may be measured down one side of the vertical obstruction and up the other side." The photograph and diagram show that the above statement is not in accordance with the experimental evidence now obtained. The actual length of the major streamline is shorter than that suggested by Bligh and consequently the effect of a sheet pile is not so great as has been considered to be the case in calculation for the design of weirs. It seems that the creep theory as a basis for constructional practice must be abandoned.

A further interesting point is presented by the photograph of the first streamline. Khosla [22] suggests that in the corner between the

Fig. X.



sheet pile and the impervious floor there may be "reverse flow" or "swirls." In this photograph there is no indication that a swirl exists. The flow that has taken place very definitely follows a modified curved line of the main flow from the foot of the sheet pile to the toe of the work.

The photograph shows that streamlines from all the five points are influenced by the sheet pile. Although the streamlines may commence in semi-elliptical forms, there are definite breaks in their courses indicating that they have come under the influence of the pile. In the case of streamlines from Points 1, 2 and 3 there is a reduction in thickness as they come under the influence of the pile indicating an increase in velocity of flow. This increase in velocity of flow is temporary and apparently at exit the velocity is only slightly greater then that of entrance.

The increase in velocity is explained by the concentration of the streamlines that has taken place. Table 2 shows the distances of entrance of the streamlines from the upstream end of the work and the distances of exit from the toe of the work.

TABLE II.

Point No.	1	2	3	4
Distance from Upstream end of Model	3·2″	5·0″	8·0″	11·0″
Distance from Downstream end of Model	1·6″	3·0″	6·0″	9·0″

This concentration of streamlines downstream of the work may be of considerable practical importance. Upstream sheet piles alone have been used to protect a work. If the result of upstream piling is to concentrate the flow at the toe of the work, it follows that the sheet pile may render a work more unstable than it was before the sheet piling was placed in position.

The main conclusions to be drawn from this study are as follows :—

1. The flow of water under an impervious floor protected by an upstream sheet pile does not follow the course postulated by the theory of creep.
2. The application of the theory of creep to constructional practice should be abandoned.
3. The main line of flow after passing a sheet pile is from the foot of the pile on a curved course to the toe of the work.
4. An upstream sheet pile influences the flow from a considerable distance upstream of the work.
5. The presence of an upstream sheet pile leads to the concentration of the flow at the toe of the work. This may be important as regards its stability.
6. No indication of " reverse flow " or " swirls " in the corner between the pile and the floor was obtained.

STUDY No. V.

The Flow of Water under an Impervious Floor protected by Upstream and Downstream Sheet Piles.

The development of these studies consisted of determining the modification in the flow that would be caused by the addition to the previous model of a downstream sheet pile. The dimensions of the floor and upstream sheet pile were maintained the same. The length of the downstream sheet pile was such that the ratio of the lengths of upstream to downstream piles was 25 : 15. Fig. XI shows the final development of the streamlines from six points at the end of twenty-two hours after the beginning of the experiment.

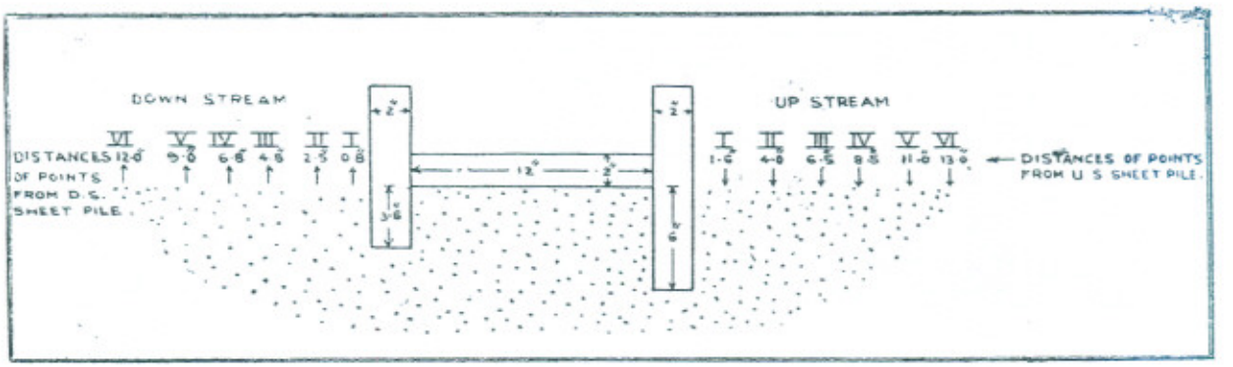
The streamline from Point No. 1 becomes thinner as it passes under the upstream sheet pile indicating the characteristic increase in velocity

noticed in the previous experiments. After passing the pile the streamine takes a curved course away from the pile and again broadens out ndicating a reduction in velocity of flow. Having approached the floor, the streamline then comes under the influence of the downstream sheet pile and it takes a downward course to pass under the pile. There is again an increase in the velocity of flow when passing under the pile. After passing the pile the streamline takes an almost vertical course to the surface of the sand. It is interesting to note that there is no change in the velocity of flow after passing the downstream sheet pile. From later observations, it appears that changes in velocity of flow only take place when the streamlines are forced on to an unnatural curved path. As the path of flow of this streamline after passing the downstream pile is vertical, no alteration in the velocity of flow occurs in this portion.

In the case of other streamlines, there is a characteristic closing together as they pass under the upstream sheet pile. The other features of the streamline from Point No. 1 are repeated in the remaining streamlines though to a modified degree as the influence of the piles becomes diminished.

It has been pointed out that one of the results of the presence of an upstream sheet pile is the concentration of the streamlines at the toe of the work. Concentration has also taken place in the case of two sheet piles. This is brought out in the Fig. XII.

Fig. XII.



There is, however, one important difference between the case of one sheet pile and two sheet piles. In the former case, concentration took place at the toe of the work. The presence of the downstream sheet piles has thrown the streamlines beyond the work and the concentration takes places in an area that is unlikely to affect the stability of the work. Although there has been concentration of the streamlines towards the work, it will be noticed that there is little change in the spacing between the individual streamlines upstream and downstream of the work.

The course of the streamlines again indicates that there is no evidence to support the suggestion that creep is taking place. The first streamline passes close to the sheet pile and shows no tendency to take the

rectilinear course that would be expected were a line of main flow cor guous with the piling and floor.. A photograph confirming this will given in a later study.

The effects of the addition of upstream and downstream sheet pi as protections for an impervious floor have been to lengthen t course of the streamlines and to throw the streamlines from the toe the work to a point downstream and thus secure stability.

The indication is that a single line of sheet piles should not be i serted upstream as a protection as this leads to concentration of strea lines at the toe of the work. The addition of a line of sheet piles at t toe of the work should accompany the piling upstream.

A further indication is that piling intermediate between the u stream and downstream sheet piles will be of little value. If it is sh piling, it will be definitely ineffective as it will not cut a streamline. it is long piling, the increase in length of the streamline that will result bound to be small and can add little to the stability of the work.

STUDY No. VI.

The Flow of Wafer under an Impervious Floor protected by an Upstream Sheet Pile and an Upstream Impervious Apron.

The model consisted of a twelve inch impervious floor protecte by an upstream sheet pile six inches in length and a four inch length c apron upstream of the pile. The model was placed in a central positio in the tank and the steamlines traced. Fig. XIII shows the final develop ment of streamlines from five points.

This photograph should be compared with Fig. VIII showing th streamlines under a floor protected by an upstream sheet pile alone. I will be seen that downstream of the sheet pile the streamlines in the tw cases are similar and, therefore, no further comment on their charac teristics in this region is necessary.

Between the upstream apron and the sheet pile, the streamlines tak a curved course instead of the almost vertical course taken in the absenc of an apron. The first effect of the addition of an upstream apron has been to lengthen the courses of the streamlines.

A further effect has been to cut off the streamlines in the distance upstream now occupied by the apron. To this extent the apron affords protection to the work as it is the flow of water adjacent to the work that is most dangerous.

It will be noticed that when the streamline from Point No. 1 passes under the upstream apron, it is subject to a reduction in velocity of flow. This confirms the suggestion made earlier that change of course is the cause of change in the velocity of flow.

A further point arising out of this investigation concerns the rela- n that is supposed to exist between the length of a pile and its equi- ent in a floor upstream. Colonel Clibborn [23] considered that a eet pile was equivalent to a length of floor. From the experiments it have been described, it will be seen that there is very little similarity tween the effect of a sheet pile and an increase in the length of a floor.

The effect of a sheet pile is to increase the length of the streamlines t at the same time it distorts them and concentrates a certain amount flow at the toe of the work. The sheet pile does not reduce the area stream from which the flow is taking place. It does, however, ngthen the streamlines and keeps the main line of flow away from e work except at the toe. An extension of a floor without a sheet e cuts off the flow in the area occupied by the extension and, hence, concentration downstream is possible. As the effects of the two uctures are entirely different, it is impossible to compare them in ms of each other.

STUDY No. VII.

The Flow of Water under an Impervious Floor protected by Upstream and Downstream Sheet Piles and Upstream and Downstream Impervious Aprons.

The model in this experiment was similar to that in Study III except at aprons were added upstream and downstream of the work. The stream and downstream aprons in the model were three inches and ur inches in length, respectively. The streamlines were traced in the ual manner from four points. Fig. XIV shows their development.

The streamline from Point No. 1 encountered a slight defective ntact between the model and the sand at the end of the upstream apron. s a result in its initial stage it tends to flow along this line. The fect being local, the streamline leaves the model and takes a curved urse to the foot of the upstream sheet pile. If "Creep" had been reality, the streamline having touched the apron should have followed e profile of the work. The course it has taken is further confirmation at "Creep" is non-existent except in defective work.

When the streamline passes under the sheet pile there is a charac- ristic increase in velocity of flow. After passing the upstream sheet le, the streamline takes a curved upward course under the floor and then escends again to pass under the downstream sheet pile. In the space etween the piles there is a reduction in the velocity of flow followed y an increase as it passes under the downstream pile. Variation in elocity again occurred between the foot of the downstream pile and the nd of the apron. The streamline emerges almost vertically at the end f the apron.

It will be seen that the remaining streamlines are all influenced b the form of the model. It was noticed that Streamline No. 2 emerg downstream of the work before Streamline No. 1. This is the on instance noted so far where this has occurred. Streamline No. 2 is long than Streamline No. 1 and consequently it would be expected that i velocity of flow would be slower. An explanation is suggested later.

As this was the most complicated model investigated, it was decid to repeat a portion of the experiment. In the original experiment r streamline was traced from the end of the upstream apron. The repet tion included this streamline. Since the model includes the main con bination of structures used, the course of the streamline from the upstrea end of the model can be taken to represent the general character of streamline from the upstream end of a work.

Fig. XV.

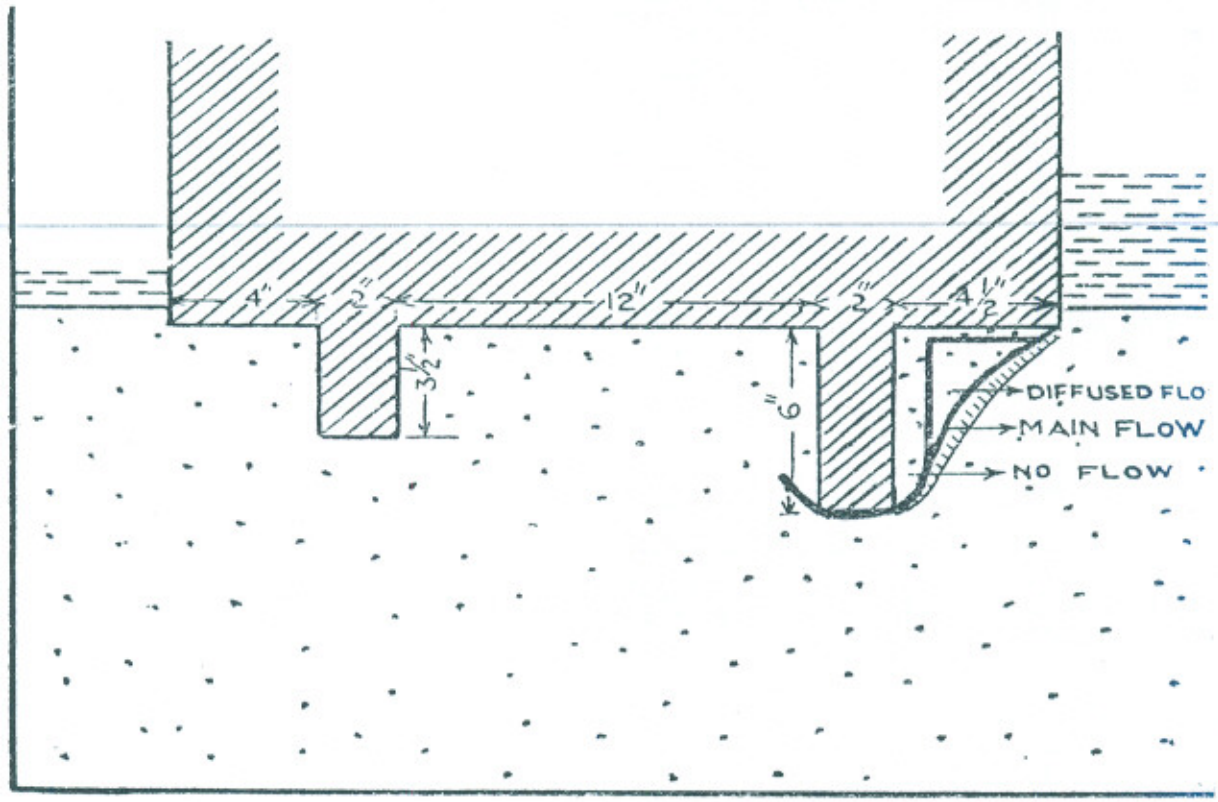


Fig. XV is a diagrammatic representation of the streamline at th end of 75 minutes. Fig. XVI shows the final development.

In Fig. XV the major line of flow is indicated and the beginning o a region of secondary flow between the main line and the work. There is no indication of the major streamline from Point No. 1 following the profile of the model either upstream of the first pile or in the region between the piles.

Fig. XVI shows a later development of the streamlines. It will be seen that the streamline from Point No. 1 has broadened both up-

tream of the pile and in the space between the piles. This indicates hat there is a very slow secondary flow on a much broader course. Even vhen this secondary flow has obtained its maximum dimensions, here was a considerable area between the streamline and the model in vhich the potassium chromate remained unchanged. This experiment ppears to prove conclusively that there is no flow along the profile of the vork as has hitherto been assumed. It is also clear that the reverse flow suggested by Khosla does not occur in the corners between the floor and he piling.

It will be noticed that there is a defective contact between the downstream apron and the sand. The streamlines after passing the downstream sheet pile are drawn towards the apron instead of passing out downstream of the work (*vide* Fig. XIV).

This model indicates that calculations for design should not be based in future on the length of the floor and piling but on the length of the major streamline from the upstream to the downstream end of the work.

In discussing the results of the first model in this study it was stated that the streamline from Point No. 2 emerged downstream of the work before streamline from Point No. 1. In the repetition this was again observed to be the case. It is suggested that the breaking up of the streamline into major and minor portions is the cause of this reduction in velocity of flow. Since this is the only model in which this phenomenon has been observed, it indicates that the combination of forms used in this model will be more effective than any others in controlling the velocity of flow of the water likely to result in damage to a work. It will be extremely interesting to determine the pressures involved in this model. This will be done in due course.

STUDY No. VIII.

The Flow of Water under an Impervious Floor part of which is immediately underlain by a material coarser than the bulk of the material under the work.

This study was suggested by Mr. H. W. Nicholson, Superintending Engineer, Lower Chenab Canal, West Circle. Mr. Nicholson informed the Authors that in some cases weirs had been constructed with concrete blocks directly laid on a coarse material. To simulate this the impervious floor used in other models was laid for two-third of its distance from the downstream end on bajri and for the remainder of the length on the same sand as that filling the remainder of the tank. The streamlines from six points upstream were traced and are shown in Fig. XVII.

Fig. XVII should be compared with Fig. III in order that the induced course of the streamlines may be appreciated. Dealing with the streamline from Point No. 1 it will be seen that, instead of taking a semi-elliptical course as in Study I, after starting on such a course, it takes a

sharp turn and flows towards the bajri through which it passes to the t of the work. This course is taken as it is the line of least resistar although not the natural path of the streamline.

The streamline from Point No. 2 is also deflected from its natu course so that instead of emerging downstream of the impervious flc it is rapidly drawn towards the bajri through which it proceeds to flo The streamline from Point No. 3 also enters the bajri while streamli from Point No. 4 emerges just downstream of the work.

From this study it will be seen that the material immediately bel an impervious floor exerts a considerable influence on the course of t flow of water under the floor. In the present instance the flow fron distance of ten inches upstream of the work is concentrated at the toe the work. There was considerable blowing of sand at the toe indicati that the conditions at this point were unstable.

The present study is of particular interest as it is the first instar so far met with in these experiments in which "Creep," *i.e.*, a ma line of flow in contact with the work has taken place. Creep, it appea should be regarded as a sign of defective work rather than a normal cou of water flow under a work. The actual effect of the bajri has been reduce the effective length of the floor by almost two-thirds.

Since the material immediately underlying a work can determi the course of streamlines under the work, it must be taken into accou when considering the stability of a work. If the material immediat underlying an impervious floor is of a coarser grade than the bulk of t material through which the flow takes place, then the flow will be in cc tact with the floor. If the material immediately underlying an imp vious floor is of a finer grade than the general material upon which t work is constructed, it will offer a greater resistance to flow than t bulk of the material and, consequently, the streamlines will be kept aw from the work. In future construction it may be advisable to lay t floor on a fine grade material to secure increased stability.

STUDY No. IX.

The Flow of Water under an Impervious Floor in Defective Contact Upstream with the Underlying Material.

The model used in the present experiment had been designed f another purpose. By chance a defective contact between the model a the sand at the upstream end of the floor developed which prevent the original experiment being carried out. The results obtained, ho ever, are of considerable interest as they represent a similar condition Study No. VIII, the flow being induced at the upstream end instead at the downstream end of the floor. Fig. XVIII shows the cou of the streamlines at the end of 170 minutes and Fig. XIX at the co pletion of the experiment.

Owing to the defective contact between the model and the sand at the upstream end, an easy course was provided for water flow. The streamline from Point No. 1 after passing the upstream end of the model proceeds to flow directly under the model. The streamline from Point No. 2 is deflected from the normal semi-elliptical course that it should take and is drawn towards the impervious floor. The contact of the model and the sand at the downstream end is good. This results in the holding up of the first streamline which should emerge first. The second streamline encountering the sound joint between the sand and the floor is thrown off the floor and takes a curved course to a point of emergence downstream of the work. The second streamline emerged before the first.

Fig. XIX shows that the streamline from Point No. 1 eventually finds a path along the under side of the floor to emerge downstream of the work. It will also be seen that all the streamlines are affected by the bad contact between the model and the sand. There is a certain amount of concentration of streamlines downstream of the work which was absent in Study No. I.

This study again emphasises the necessity of laying the floor of a work on a material of lower transmitting power than the bulk of the underlying material. It further indicates the importance of securing a good contact between a floor and the sand on which it is being constructed.

A further important point is that a defective contact at the upstream end of a work is not so serious as a defective contact downstream. In Study No. VIII, it was shown that with defective work at the downstream end, the flow of water was concentrated at this point. The present study shows that with sound work at the downstream end, the streamlines are again thrown from the work so as to emerge some distance beyond the end of the impervious floor and that the flow near the work becomes slow.

In this model "Creep" has been taking place. It confirms the statement made previously that creep is the sign of defective work and not a normal course of flow. Had creep been a normal feature, Streamline No. 2 would have continued to flow along the floor, having once reached it, instead of being thrown off again.

The studies that have been described in the paper are the first of a series now being conducted. A considerable number of further investigations suggest themselves and will be taken up in due course. The authors hope that they have demonstrated that models can be of considerable value in design. Studies by the methods which have been developed can test the soundness of a design and will lead to modification where weakness is discovered. It has recently been shown in the Irrigation Research Institute that it is possible to determine the pressures involved in the same model in which the streamlines have been traced. Studies of the pressures involved are now being under-

taken. Combining the streamline and pressure studies will reduce the time required for the investigation of pressures in a cular model but will lead to a considerable saving in expenditur type of work. It is now intended to reconstruct the models wh already been examined and determine the pressures on the work

Probably the most important result obtained in the present studies is the observation that " Creep " is non-existent. Thi have an important bearing on future design. Almost equally i is the result of the study of the flow under a floor protected by and downstream sheet piles and aprons. This appears to be stable form of work possible.

The effect of a line of piles has been generally ascribed to the in length of the line of flow which it causes. While it is impossib a complete explanation of the reason for the reduction in press out examining the actual pressures involved, the present series suggest that the increase in length of the streamline is only a pa tion. It will be noted that in every case so far studied when th obstructed by a pile the streamline nearest the work breaks up portions which may be called the "main" and "diffused" flow to the flow now taking place through a much greater sec velocity of flow near the work is reduced. It seems probable main effect of sheet piles is to break up the flow under a such a manner that what we have called " diffused flow " occ hence, the velocity of flow near the work is low. It seems diffusion of the flow near the work may be dependent upon th of the upstream and downstream piles and the distance betw piles. This indicates a further point to be taken into cons in design and will be further investigated in model form.

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Fig. III.

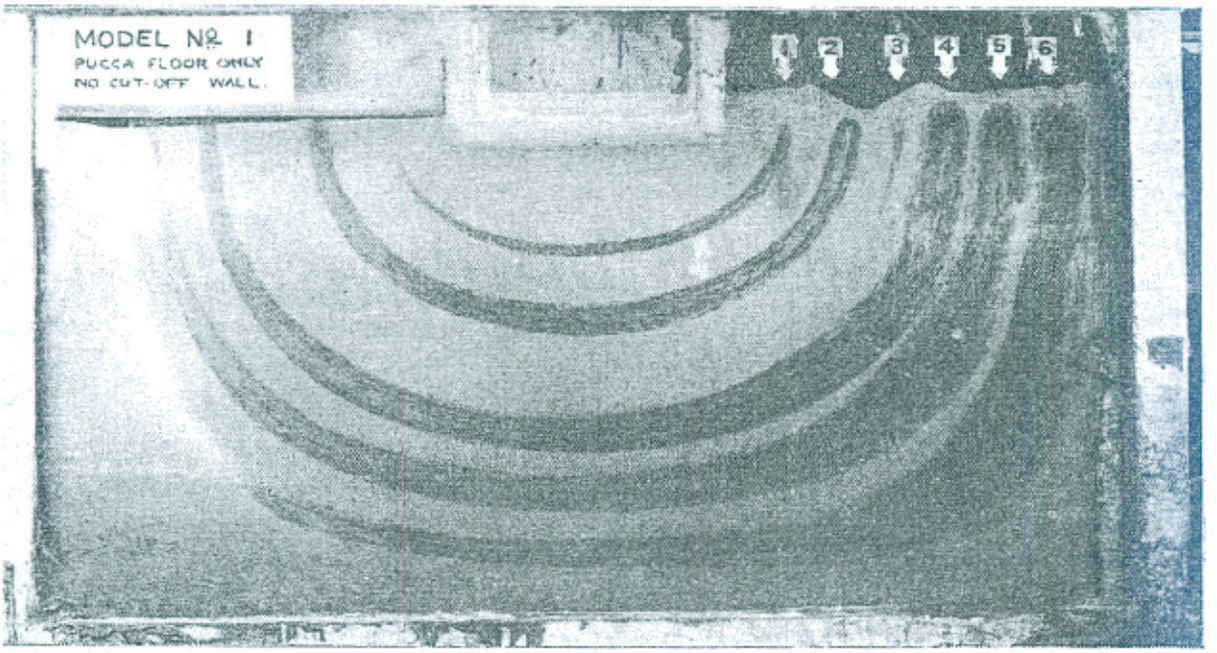

MODEL No. 1
PUCCA FLOOR ONLY
NO CUT-OFF WALL.
1
2
3
4
5
6

Fig. V.

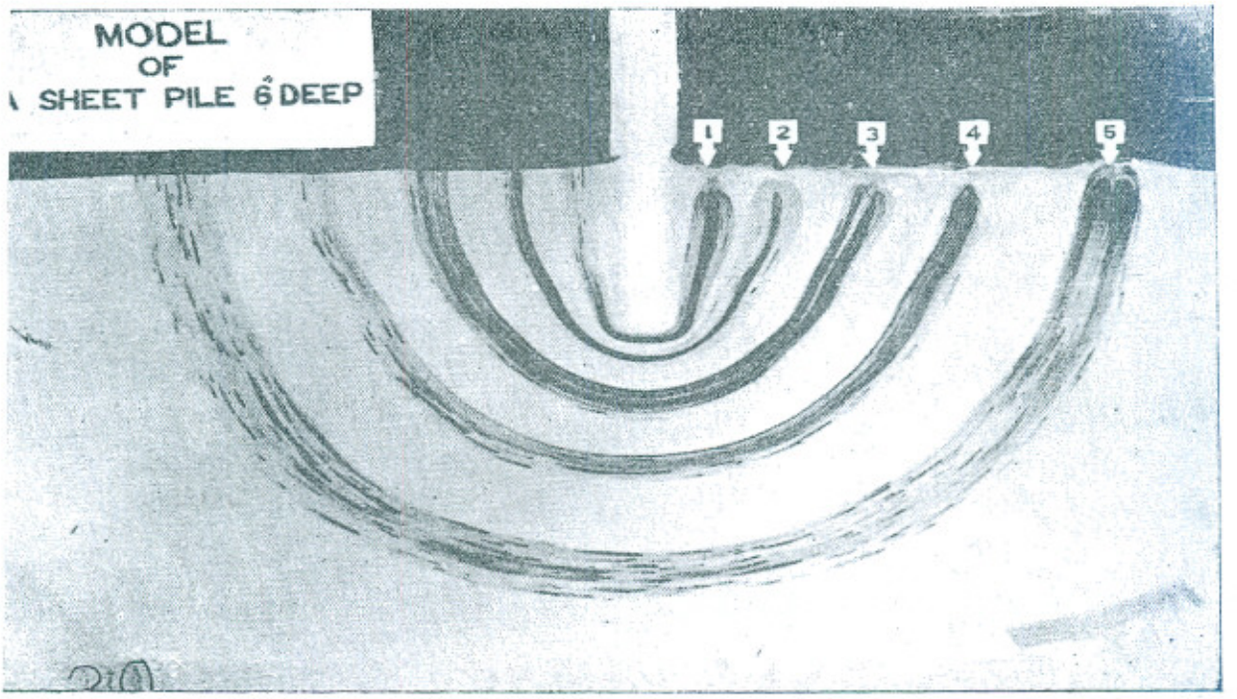

MODEL
OF
SHEET PILE 6 DEEP
1
2
3
4
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Fig. VI.

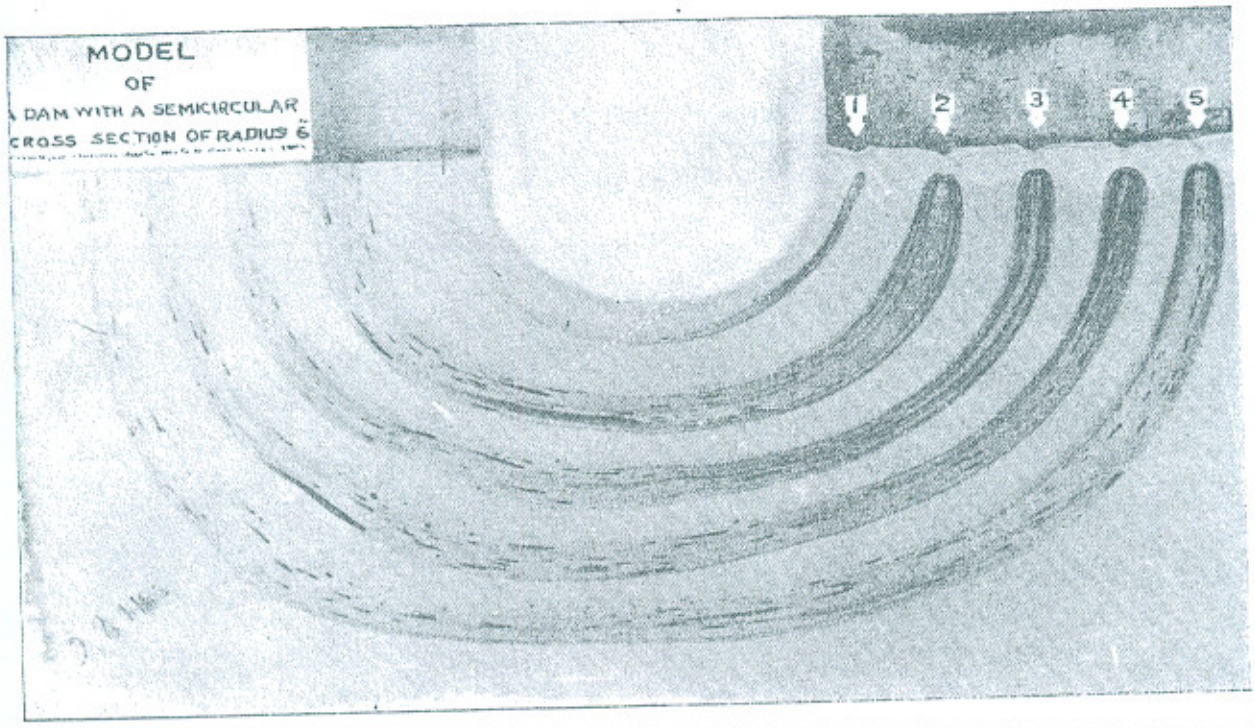


Fig. VII.

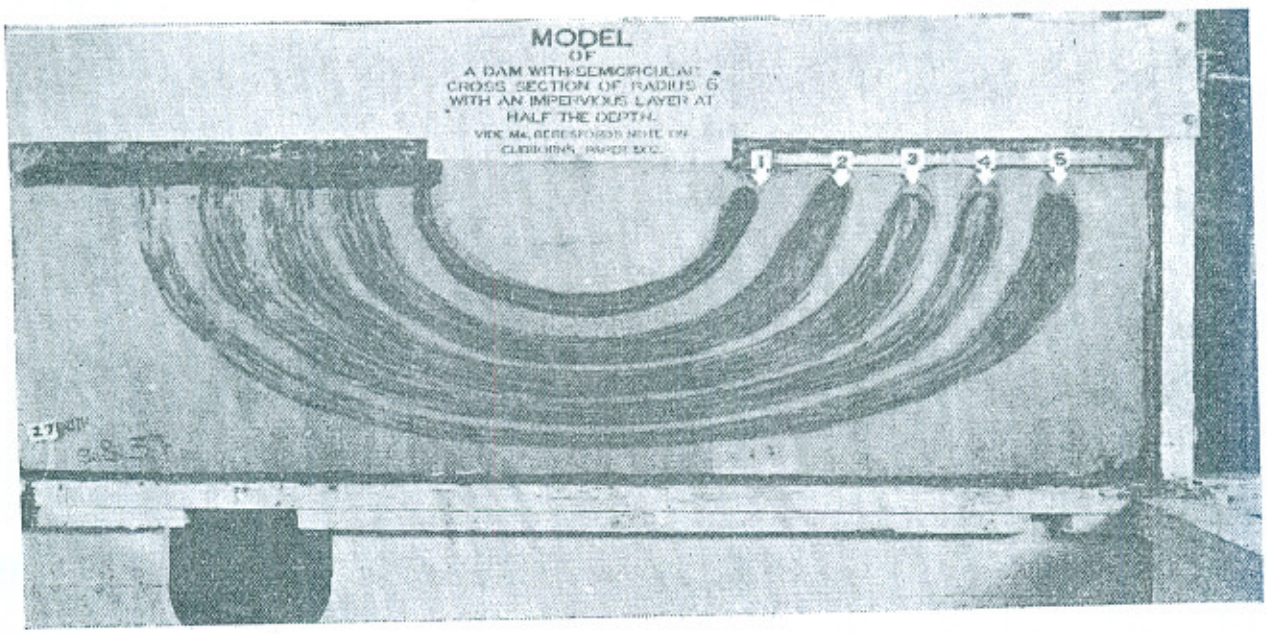


Fig. VIII.

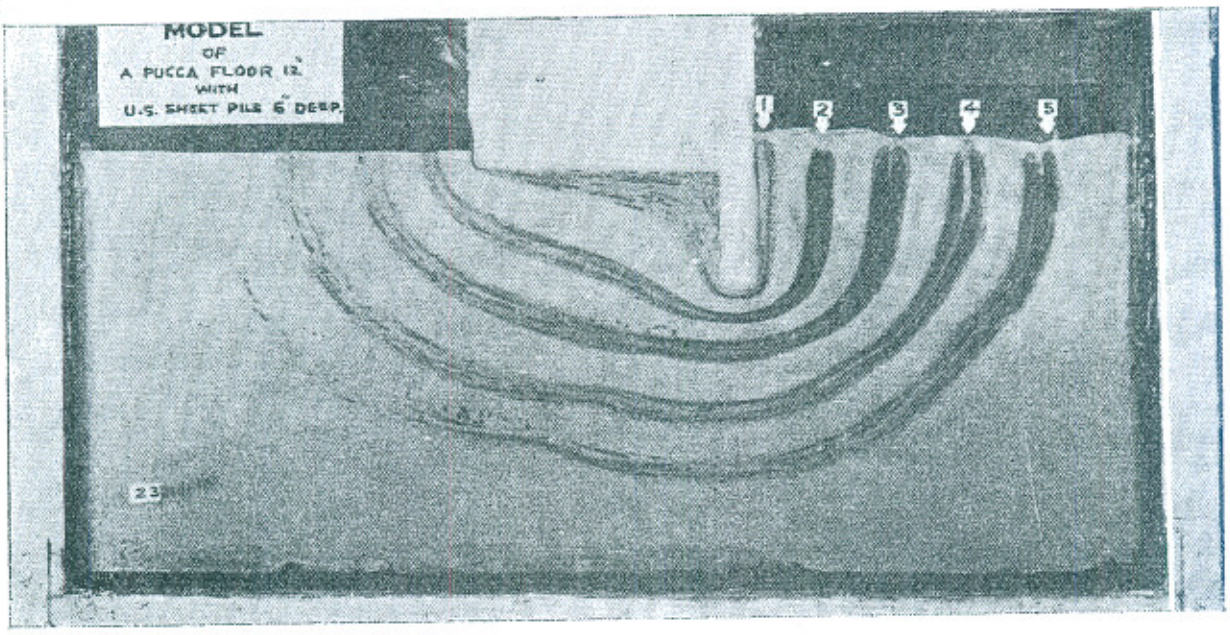


Fig. IX.

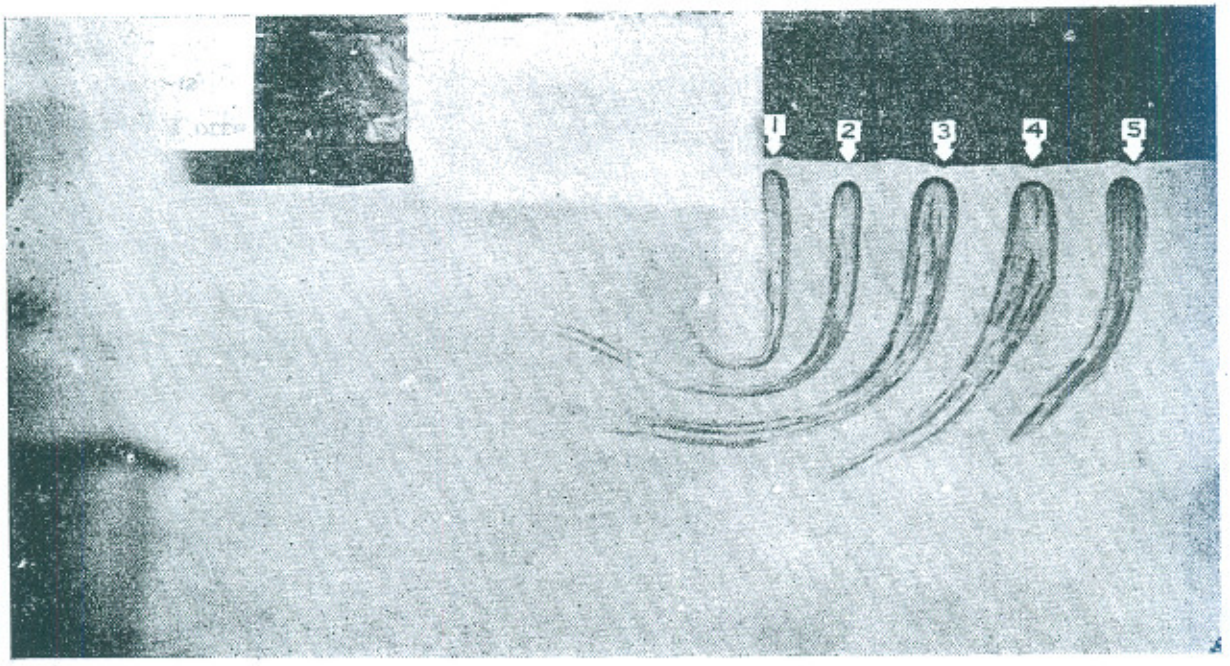


Fig. XI.

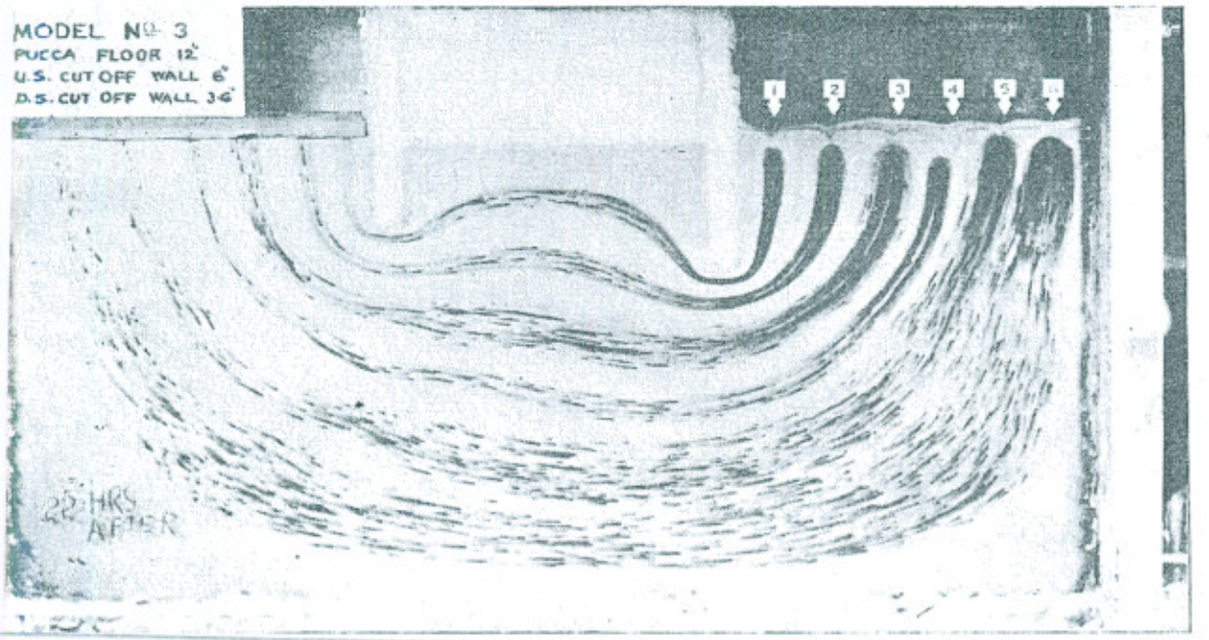


Fig. XIII.

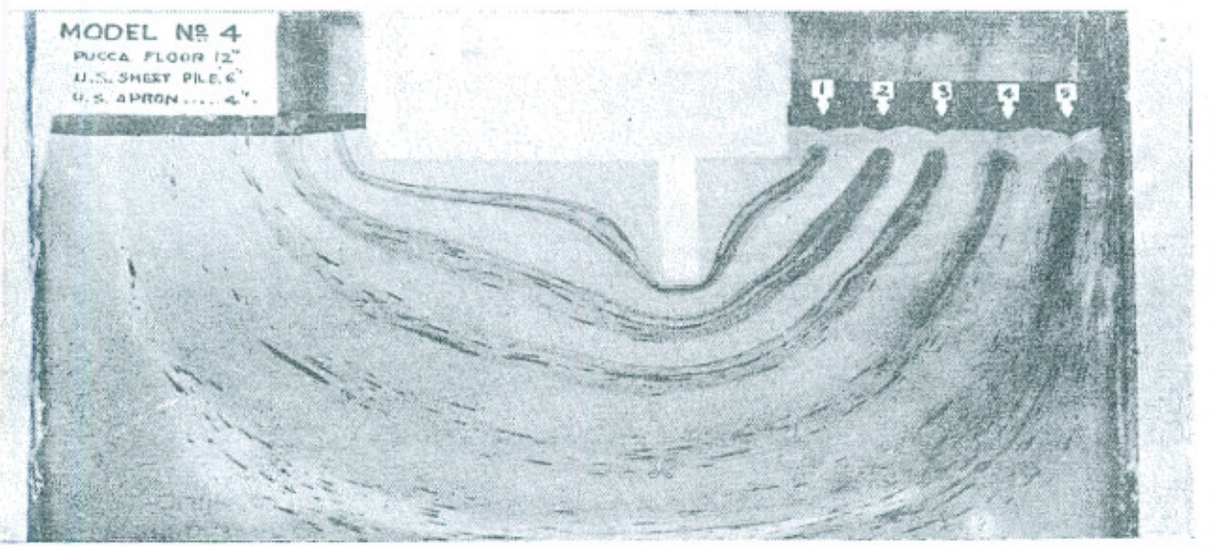


Fig. XIV.

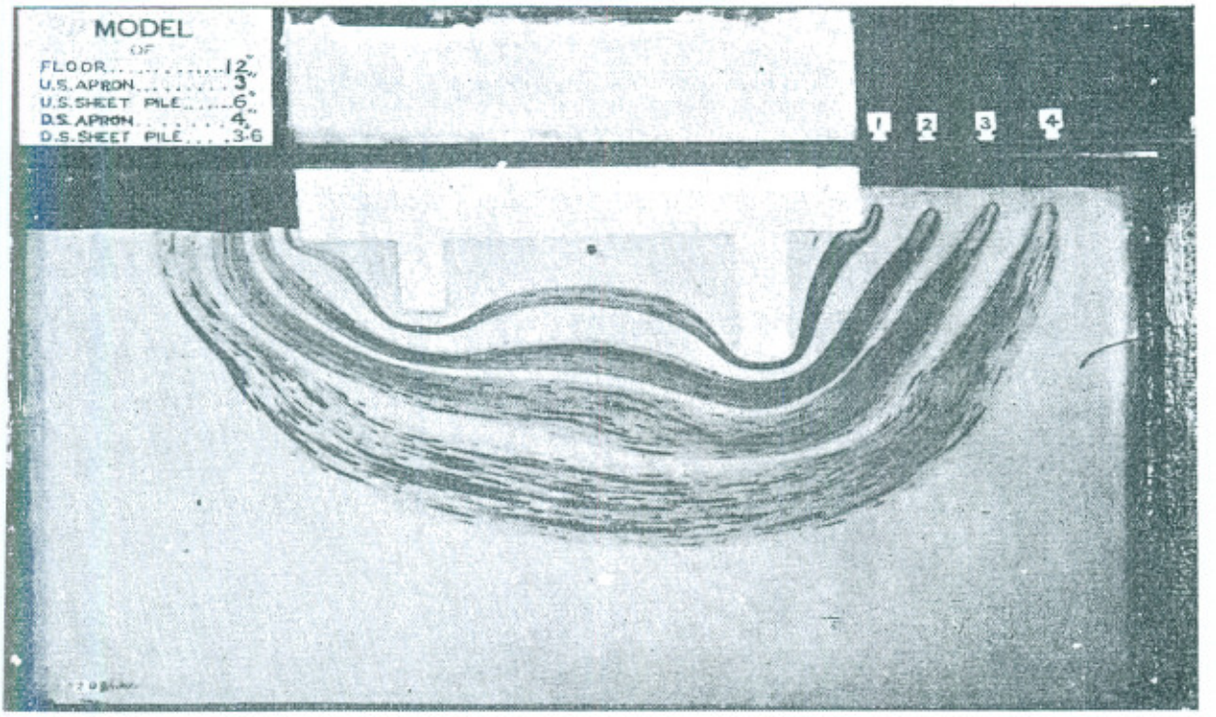


Fig. XVI.

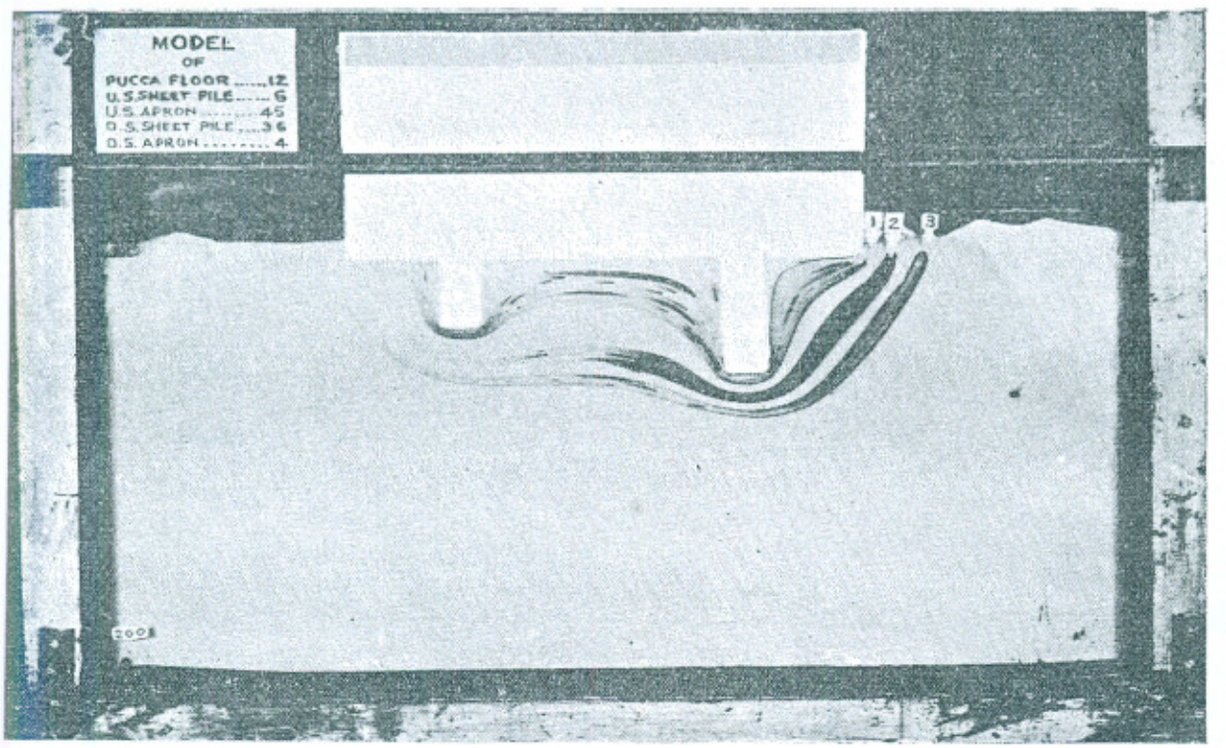


Fig. XVII.

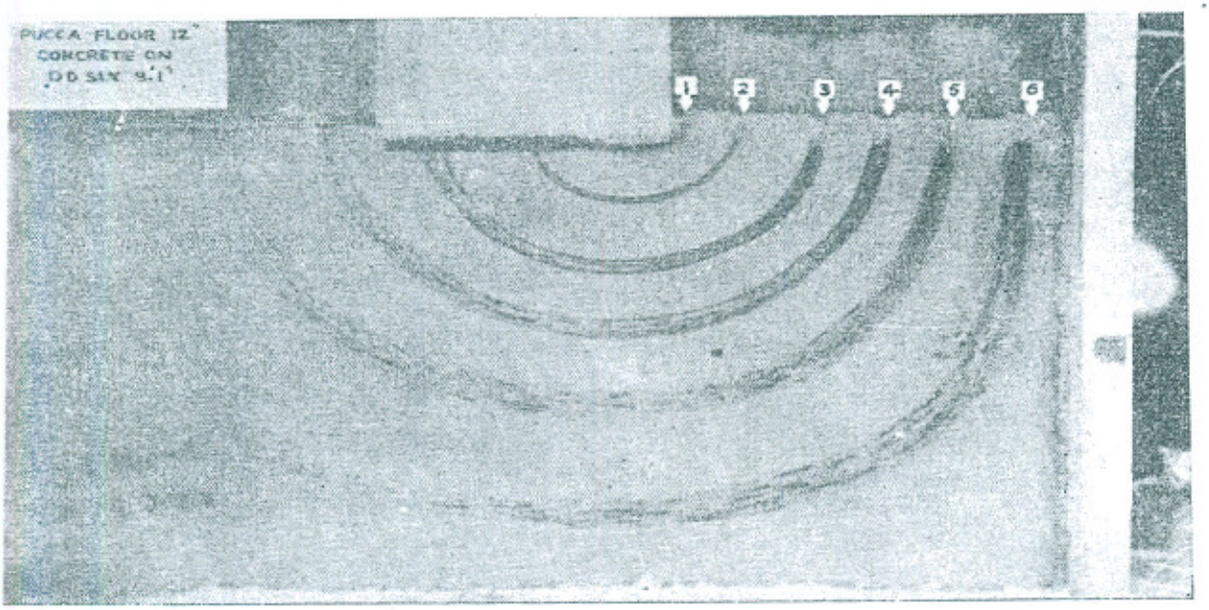


Fig. XVIII.

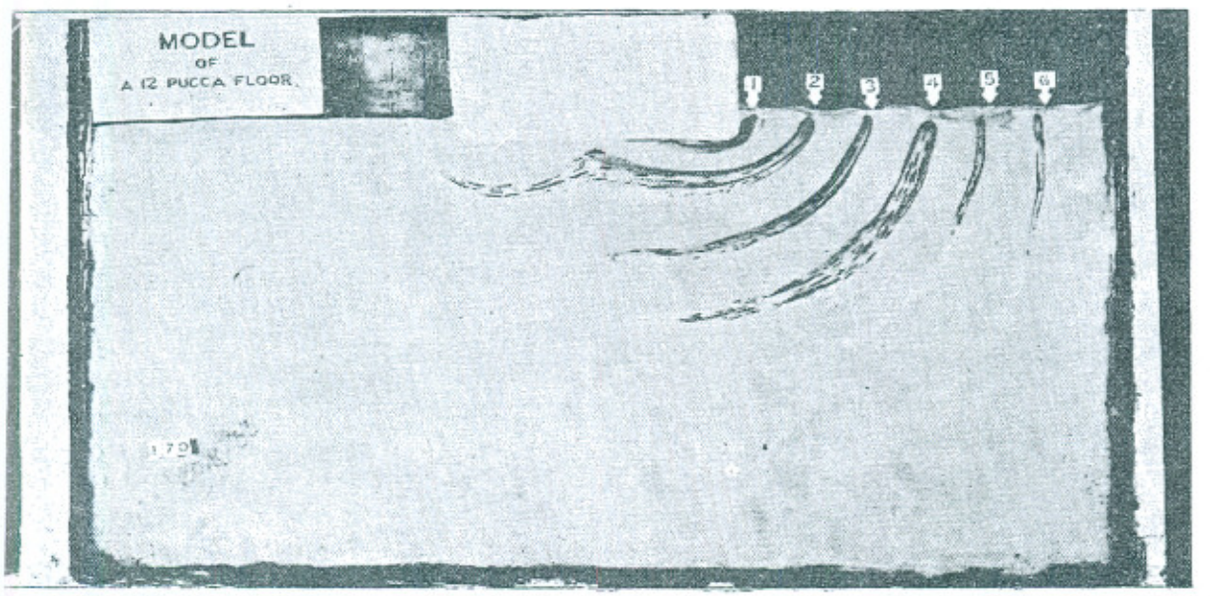
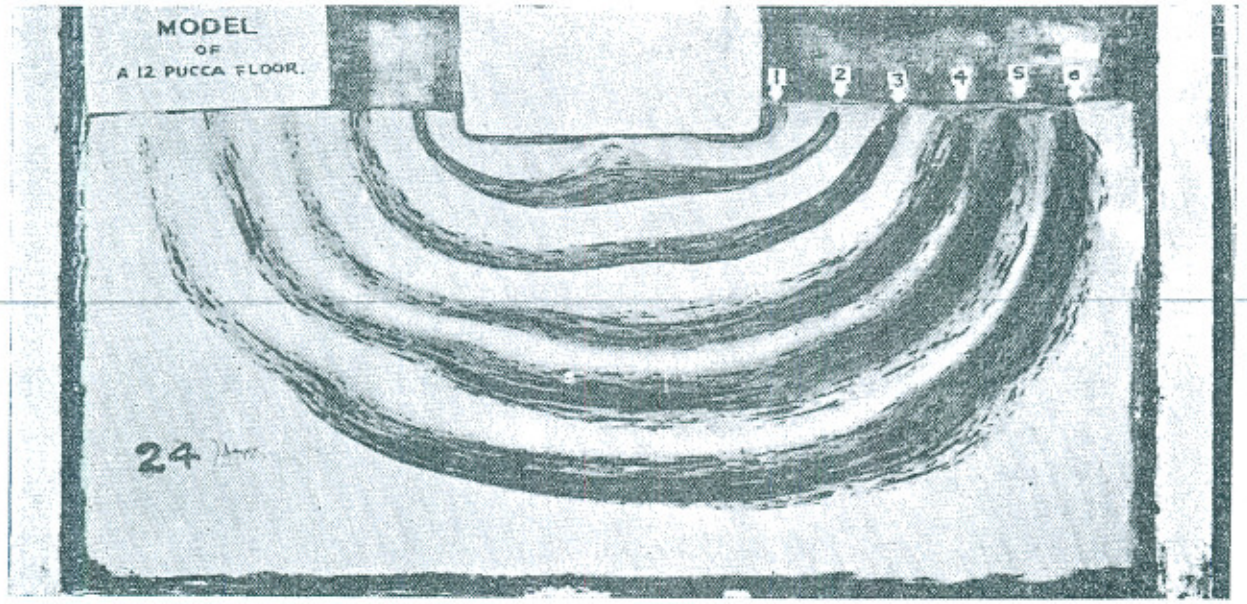


Fig. XIX.



DISCUSSION.

THE AUTHORS in introducing the paper said that the work discussed in the paper had its origin in the repairs which were being undertaken at Khanki during the cold weather of 1932-33. Very little literature on the subject of flow of water under a work was available and the accepted views were not based on any experimental evidence. These views were rather in the nature of hypotheses than theories.

The account of the experiments which has been given relates to work carried out to the end of September 1933. Since this account was written the subject has been considerably developed and, in addition to the study of the actual flow of water, the pressures involved in certain cases have also been determined. The Authors propose to give a brief account of the continuation of this work and certain conclusions that have been reached.

The methods adopted in the paper are new and it has been demonstrated that a profile model, such as has been used, is suitable for the determination of pressures on a work. Some criticisms have been offered as regards the scale on which the work has been undertaken. A small scale experiment has definite advantages over observations on a large work. In the small scale experiment it is possible to secure greater accuracy of observation under carefully standardised conditions. The most convincing proof that the Authors can put forward of the value of model work is that of the Monthly Report to the Chief Engineer for May 1933. It was stated in this report that piling upstream of certain bays in Khanki Weir had rendered these bays unstable. Four days after the submission of the report, the floors of Bays Nos. 3 and 4 were damaged. Engineers may argue as to the cause of the failure of these bays but at least it was possible from model work to forecast the failure.

In the continuation of the experiments, the effect of a downstream sheet pile alone on the flow under the work was examined. The photographs of this and other experiments will be on view in the Hydraulic Laboratory of the Irrigation Research Institute. The main conclusion reached in this investigation was that the flow of water was diverted from the work and thrown off downstream without any concentration at the toe of the work. A downstream sheet pile must be regarded as one of the main factors responsible for the stability of a work.

The effect of pressure relief pipes was also examined in two cases. In the case of a simple impervious floor without any protection it was found that relief pipes resulted in the concentration of flow near the work and the water at the toe had a considerable velocity of exit resulting in the blowing of sand at this point. The second case investigated was the effect of relief pipes in the floor protected by upstream and downstream sheet piles. Again the flow was drawn near the work and resulted finally in the movement of sand which choked the pipes. The pipes were cleared according to the normal method practised on works.

Following the clearing of the pipes, the sand was blown through the relief pipes and cavities formed under the floor. The conclusions reached as a result of these investigations were that relief pipes as at present installed are a source of danger to the work, especially as the damage that might be caused is not open to inspection. In an experiment on the model of Khanki Weir a tube well for the reduction of pressure was introduced. This type of pressure relief pipe although relieving pressure did not interfere with the stability of the work.

The pressures have been investigated on a simple impervious floor. While it is not proposed to discuss the results here, it can be said that the pressures observed do not conform to any accepted theory. The most important point is that the reduction in pressure from upstream to downstream is not symmetrical with reference to the geometrical centre of the model. The results are being examined by the Mathematical Officer in the Irrigation Research Institute with the object of determining the laws governing the flow in this simple case.

The first application of these investigations was to the examination of the alterations which are being made at present to Khanki Weir. The examination of the Khanki Weir showed that cavities existed under the Weir. In the model experiment, these cavities were represented by spaces in between pieces of gravel underneath the floor. An account of this work has been submitted to the Chief Engineer and photographs illustrating it are available for inspection in the Institute. The presence of the cavities under the work results in the flow taking place near the work, even after the introduction of upstream and downstream sheet piles. This flow has a low velocity in contact with the work. So from this point of view the work appears to be stable. The most important results were obtained from the examination of the pressures. It was shown that the presence of the cavities resulted in a steep Hydraulic Gradient at the upstream end of the work. As it is possible for the sand to move into the cavities in this region the upstream portion of the work cannot be regarded as stable. A further important point was that for a considerable length of the floor no reduction in pressure took place. From this it was deduced that the floor must be of the same strength over considerable area to withstand the pressures that are now present.

Demonstrations of the methods that are being used and photographs of investigations that are being made, are available in the Hydraulic Laboratory of the Institute. It is hoped that those Members of the Congress who are interested in the subject will be able to visit the Laboratory to inspect the work in progress.

Mr. J. H. JOHNSTON congratulated the Authors on the excellence of their extremely useful paper and said that it was wonderful how accurately the streamlines were traced. He also congratulated the Authors on their publishing the paper two months before the date of the Congress Session. He stated that the value of the paper was theoretical rather than practical, but he admitted that it would have a certain value in the design of weirs. He added that all engineering designs were based on

ormulae which contained a number of unknown quantities and the paper ;ave information by which such unknown factors could be determined. The Authors stated that pressure investigations were being undertaken nd that the results would, he hoped, be known soon.

Commenting on the paper he said streamlines represented velocities nd velocities in that case were the result of pressures. To discuss he streamlines therefore without discussing the pressures was, in the peaker's opinion, to discuss the cart without the horse. He explained n the blackboard his arguments, and showed that the equations of notion could be put in the form :—

$$\frac{1}{\rho}\frac{\partial p}{\partial x^r} = \kappa U_r + (V_{rs} - V_{sr})V_s + \frac{1}{2}\frac{\partial}{\partial x^r}(V^2) \quad \ldots\ldots\ldots(1)$$

This was a covariant vector equation.

The term on the left represented the gradient of the combined ffects of pressure and gravity. The first term on the right represented ne resistance of the sand assumed for simplicity proportional to the elocity ; the second and third terms were the components of acceleration, ne first causing rotation, the second increase in speed.

Now if one considered a small vector in any direction and took the ner product of this with equation (1), he got the scalar equation :

$$\frac{1}{\rho}dp = \kappa v_r\, dx^r + \frac{1}{2}d(v^2) \quad \ldots\ldots\ldots(2).$$

ssuming that the ' curl ' of the velocity was zero. This corresponded Bernoullis well-known equation. If dx^r was parallel to the streamline, ne second term represented the work done against the resistance of the nd and the equation showed that the increase in velocity along the reamline was wholly due to the gradient of the pressure in that direction exactly the same way as in the case of a venturimeter. It was not ue to what the Authors on page 69 referred to as " unnatural curved ath."

If on the other hand dx^r was taken perpendicular to the streamline ne first term on the right vanished and the equation showed that a fference in velocity between two streamlines was due to the component the pressure gradient at right angles to the streamlines or in other ords, if the pressure contours were orthogonal to the streamlines, the elocities of adjacent streamlines would be the same.

The equation for divergence might be put in the form—

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad \ldots\ldots\ldots\ldots(3).$$

This showed that an increase in velocity along a streamline was invariably ccompanied by a convergence of streamlines in the direction of the crease.

MR. HAIG in a written communication said that Dr. McKenzie Taylor's experiments recorded in the paper under discussion afford a very useful general confirmation of the streamline theory of flow under weirs.

He could not recollect at the moment any reference in which this theory has been clearly defined, but he thought the following description would cover it.

At any point in a submerged permeable material in which the hydraulic pressure varies from static, flow will take place in the direction of the maximum rate of change of excess (over static) pressure and will vary directly with this rate and with the permeability of the material.

The path traced by any particle of water is known as a streamline, and the space covered by any volume of water as a streamtube.

From the above definition it follows that the discharge of any streamtube is given by

$$q = K a \frac{dp}{ds} \quad \ldots\ldots\ldots (1).$$

where " a " is the cross sectional area and " s " is the length of the tube, " p " is the excess pressure, and " k " is a constant known as the " transmission constant " of the material. If the physical characteristics of the soil vary from point to point, k also may vary. If k is constant throughout the material, it is said to be uniform.

The mean velocity of the water through space is given by

$$v = \frac{q}{a} = K \frac{dp}{ds} \quad \ldots\ldots\ldots\ldots (2).$$

This is D'Arcy's theory which is of general application though Dr. Bose in his paper on the Exponential Law of subsoil Flow (No. 140 of the Congress) states that it was originally advanced as applying to surface flow only. The velocity through space must be distinguished from the actual velocity through the interstices of the material. If the interstices occupy 1/n of the volume, the latter velocity will be nv.

The following are general characteristics of streamline flow :—

Surfaces of equal excess pressure cut the streamlines orthogonally.

There must be flow along all boundaries, though in the case of re-entrant angles the flow may be so slight as to be imperceptible by rough methods of detection.

Between fixed boundaries the streamlines between any surfaces of equal pressure are independent of the pressure, and the pressure at any intermediate point is proportional to the total head. This applies to reverse flow.

If the material be uniform the conformation of the streamlines is independent of the value of k.

Although, given the boundaries and k being known, the conformation of the streamlines is unique, its determination, save in very simple cases, is not susceptible to mathematical treatment. In complicated cases the best method appears to be model experiments. Exact models would be necessary in the model experiments. Exact models would be necessary in the case of important works but common forms, in the case of unimportant works, could be estimated from standard forms. To this end, work on the standardisation of forms is in progress in Germany.

It may be mentioned here that given the streamlines or the lines of equal pressure on any section, the other can be readily plotted. The simplest method is to divide the streamtubes, or areas between surfaces of equal pressure, into lengths proportional to their widths. These lengths will represent equal differences of pressure, or discharges, and hence the pressure lines or streamlines can be plotted.

Having outlined the streamline theory, as he understood it, he proceeded to see how far it was confirmed or refuted by the experiments described in the paper.

The references are to the conclusions drawn by Dr. McKenzie Taylor on the various models.

Study No. I.—(2). That the streamlines approximate to ellipses may be granted : That they are mathematically exact ellipses is not proved. Streamline No. 6, which is strongly influenced by the external boundary, is certainly not an ellipse. Similarly, streamlines between No. 1 and the model, assuming the model to have its bottom at a finite depth below the surface of the sand, will be influenced by the model, and will not be a true ellipse.

In the vicinity of the model the eccentricity of the ellipse increases as we approach the floor : but compare Study III, with the impermeable layer below. Here the eccentricity increases as we leave the model and the same result could be obtained in Study I by a suitable arrangement of the outer boundary.

(4). The first part of this conclusion is quite incompatible with the streamline theory, and is not proved by the illustration, since the point of entry of the streamline is not in contact with the model. The correct inference in this respect is that the sections of streamtubes in the vicinity of the floor vary considerably. Take the streamtube between streamline No. 1, and the model, for instance : its minimum section is about 0·4 of its maximum. Obviously too, the disparity increases as we approach the work more closely.

The second part of the conclusion is interesting and confirms the theory. It can be shown that the time of passage of water along a

straight streamtube of uniform section with length " l " under a head " p " is :—

$$t_s = \frac{l^2}{Kp}$$

If the section varies uniformly with length so that its area at one end is n times that at the other, the time required will be

$$t_c = \frac{1}{2} \frac{n+1}{n-1} \log_e n \cdot \frac{l^2}{kp}$$

t_c is always greater than t_s and the arithmetic values of the ratio of the two for n=2, 5 and 10 are 1·04, 1·21 and 1·41. A decrease of velocity might therefore be expected in the vicinity of the floor.

Study No. II—(1). The irregularity of the streamlines of which Dr. McKenzie Taylor makes a feature is inconsistent with the streamline theory. The boundary being regular the streamlines should also be regular at these points. He suggested that the irregularity is due to some unevenness of the sand and that if the experiment be repeated the same result would not be obtained. Similar irregularities do not occur in Studies IV or V where conditions are similar.

(3). The tendency of the streamlines to leave the downstream side of the pile is merely the result of the divergent flow following the contraction under the pile. He imagined that streamline 1 took longer to establish itself than streamline 2. The ratio of the minimum to maximum cross section of the streamtube between streamline 1 and the model is about 0·25. For flow closer to the work, this ratio would be smaller and the time required correspondingly longer.

Study No. III.—He thought Dr. McKenzie Taylor was rather hard on Mr. Beresford. The form of the streamlines revealed by this experiment is sufficiently close to semi-circular to be described by that term for all practical purposes. The fact that the more remote lines are not semi-circular is due to the influence of the external boundary. Had this been semi-circular and concentric with the face of the model, all the streamlines would have been true semi-circles.

The streamline theory affords no explanation of the fact that the streamlines emerged at greater distances from the model than those at which they entered. It is noticeable, however, that in the case of the model shown in Fig. VII this phenomenon is reversed. This would indicate that this feature is due to some accidental cause. It is known that the permeability of sand varies rapidly with the degree of compaction, and, in spite of the care taken to secure uniformity in building up the model, it is possible that sufficient variation may have crept in to cause this discrepancy.

The apparent dead water can be explained as in the previous Study. It is noticeable that this phenomenon does not occur in Fig. VI, where contraction under the model is relatively small. It appears also that the chemical method only indicates the streamlines approximately. This location of a streamline can be estimated by drawing a line through the centre of the area affected by the silver nitrate, but the whole area affected cannot be taken as accurately representing the longitudinal section of a streamtube. For instance the indication of streamline No. 1 in Fig. VII converges after passing the model, while it is perfectly obvious that the streamlines are diverging in this area.

Study No. IV.—This study offers an interesting confirmation of the streamline theory and of the explanation he gave of the delay in the establishing of the streamline indication in the vicinity of the model in Study No. 1. Here obviously the streamtubes in the vicinity of the model vary greatly in cross sectional area and consequently the velocity will be low. Also the length of the streamlines here is great, and we have seen that the time required for establishing them varies as the square of their length. Referring to Fig. 10, there can be no hard and fast distinction between the main flow and the diffused flow. As the streamtubes approach the work, their length and the variation in their section increases, and consequently their velocity is reduced ; there is, however, considerable variation in the section of tubes in the vicinity of streamline No. 2.

I am of opinion that conclusion No. 5 that the existence of the pile leads to concentration of flow at the toe of the work is wrongly expressed. It would be better to say that the pile forced the upstream ends of the streamlines away from the work. Comparing Figs. III and VIII the form of the streamlines at the downstream end are similar. It is true that flow from points at given distances from the upstream end of the model emerge at points relatively closer to the downstream toe, but at the same time, owing to the relatively greater length of the streamlines in Fig. VIII, the discharge must be relatively reduced. When the pressure distribution of these models is completed I anticipate that that of the model shown in Fig. VIII will be more favourable than that of Fig. III. By more favourable, I mean that the pressure gradient will be flatter in the vicinity of the toe. The form of Fig. VIII, while not good, is an improvement on that of Fig. III by reason of the greater average length of the streamlines. If we imagine Fig. VIII reversed we have a much better form from the point of view of resisting blow out.

These very interesting experiments go a long way towards confirming the streamline theory. The points on which discrepancies occur are generally of minor importance and the evidence of the models in these instances is not well substantiated.

From the point of view of the practical application of the theory, the pressure distribution is of paramount importance and consequently the second paper promised by Dr. McKenzie Taylor will be awaited with great interest.

R. B. LALA AJUDHIA NATH KHOSLA said that Dr. McKenzie Taylo and Mr. Harbans Lal Uppal, in their studies of the flow of water unde works resting on porous soils, had, in the course of a few months, pro duced results of considerable importance and value and had thus earnec the gratitude of the Engineering profession. They deserved to be con gratulated for this most valuable contribution, which was one of the bes so far made to this Congress.

The Paper deals, and that partially, with one aspect only of the flow of the subsoil water under hydraulic structures, that is, its distributior and direction, under the different formations of the floor and vertica cut-offs. The second and the more important aspect was the distributior of pressures under the work, for it was this latter which governed the general design of such works.

The present study, though still in the course of being completed, had led to the enunciation of some general principles which were of fundamental importance in the design of the hydraulic structures. The bulk of the conclusions arrived at in the investigations were in such close agreement with observed facts that they could be readily accepted, at least qualitatively.

The paper clearly demonstrated the great value of model experiments in design. By this means, the designs could be tested and suitably modified to give maximum economy and safety, with little cost in time and money.

The fact that the flow of water in the subsoil through embankments, from canals or under hydraulic works, was in streamlines, had already been demonstrated by Professors Forchheimer and Rhebock who used aniline dyes to trace the course of these streamlines. These investigations were, however, restricted in their scope so far as hydraulic structures were concerned. Dr. McKenzie Taylor's work marked a real advance on distinctly original lines, both in technique and in scope. The enunciation of the first principles of designs of works resting on soils had their origin in India and it was in the fitness of things that the Punjab, the premier irrigation province in the World, should give a lead in the final develpment of these principles on scientific lines and thus give to the profession something definite to form the basis of truly safe and economic designs.

Exception has been taken in some quarters to the tracing of streamlines by means of a precipitate formed by the reaction of silver nitrate with potassium chromate. This precipitate it is suggested might alter the physical properties of the subsoil by the insertion of the beds of this precipitate along the planes of streamlines. If this be so, the pressures in a given test before the insertion of the silver nitrate should materially vary from those obtained after the deposition of such precipitate along the streamlines. According to the Authors no such difference was apparent and therefore the precipitate was not introducing new

conditions of stratification. The Authors would perhaps throw more light on this aspect and it might be worth while to carry out further and conclusive tests to put this controversy to rest.

Until recently the profession was wedded to the theory of creep with all its implications. There were stray voices of dissent, but tradition always proved too strong for them. The experiments at the Dugri and the Jaurian syphons of the Upper Chenab Canal—described in Papers Nos. 138—140 of this Congress—gave the first decisive blow to this traditional theory of creep. The results of the observations at Panjnad confirmed that this theory was a myth. The experiments of Dr. McKenzie Taylor and Mr. Harbans Lal Uppal might be said to have sealed its doom and it was hoped that this theory would soon receive its official funeral.

The conclusions of this paper were generally sound and in keeping with the observed facts. They were necessarily qualitative so far, as the investigations regarding the pressure distribution were yet incomplete. The main conclusions which might be accepted as correct independent of pressure data, were :—

1. The flow of water under the impervious floor was in streamlines.

2. There was no such thing as creep as commonly understood. The only cases where creep could occur, were found where the work was defective.

3. A line of sheet piles at the upstream end of a floor accompanied by a similar one at the downstream end appeared to be the most stable form of work possible.

4. The piling intermediate between the downstream and upstream sheet piles would be of little value.

The Authors had also stated that the streamlines were semi-ellipses. No definite proof had, however, been offered to substantiate this statement but it appeared to be reasonably correct. Perhaps some mathematicians would comment on this. On page 68 of this paper they stated that if the results of the upstream sheet piling was to concentrate the flow at the toe of the work, it followed that the sheet piling might render a work more unstable than it was before the sheet piling was placed in position, in the absence of data of pressure distribution this statement appeared premature. The concentration of streamlines was certainly an indication of danger but if the upstream piles so reduced the pressures that the discharge at the exit was, in spite of the concentration of streamlines, small, compared to what it would be if there were no such sheet piles, the statement would not hold. Apart from the above, there was, however, no doubt that a downstream pile line was as essential as an upstream one, for while the former reduced the pressures at the start, thus enabling the floor downstream to be built with less thickness, the latter protected the subsoil from getting undermined. Thus though it

was not possible to agree with the statement as made, the conclusion, that the two lines of piles at the two ends of a floor gave the most stable form of design, was incontestible.

The conclusion No. 6 on page 68 of the paper ruled out the possibility of a reverse flow as indicated in the Panjnad results. The conclusion might be correct, but the arguments were not conclusive. The reverse flow, if it did exist, would be in the region of what might be called dead flow and this region would be outside the reach of silver nitrate which followed the streamlines. The only way to determine whether the reverse flow did or did not occur was to insert silver nitrate independently in this region of dead flow.

The Studies Nos. VIII and IX were of special significance as they indicated the danger of a practice which was advocated in certain quarters.

It was essential for the development of rational principles of designs that the results obtained on models should be in keeping with those on actual works, and conversely that the latter should be reproducible on models. Unless this was done, it would not be possible to inspire confidence in results obtained from models. To establish the reliability of models both quantitatively and qualitatively, it was essential to have a scale model of the Panjnad Weir and to compare the results obtained therefrom with those recorded at Panjnad during the last two years. This scale model, it was understood, had been sanctioned and would be shortly set up.

A similar set of pressure pipes were now being installed at Khanki, the results of which, when available, were likely to be of considerable interest and value, due to the existence of a substratum of clay some depth below the floor in one part of the weir and an absence of that substratum in the rest of the weir.

At the Panjand Weir the temperature appeared to be an important factor in determining the pressures under the weir. It was for consideration whether this factor could be studied in the laboratory on models.

It was hoped that this most valuable work would be carried to its completion, and that money would be forthcoming to enable the investigation to be as comprehensive and complete as possible. The small sums spent on this work would be repaid a thousand times over in the economies consequently rendered possible in design and in the elimination of the risk of failures.

It was further hoped that the excellent lead given by this paper would stimulate research in other countries of the world.

LALA KANWAR SAIN said that the Authors were to be congratulated for bringing the laboratory to the aid of the Engineer in the field. The subject was of special importance to the design of weirs and dams in sandy river beds. Crores of rupees were spent on the construction of such weirs and any money spent on the investigation of the behaviour

of water in connection with such works would be fully justified. Results of laboratory experiments made on small models, must, however, be applied with caution, as behaviour under actual works conditions might be somewhat different from the laboratory model. If the pressure pipe observations of the model—these, the writers stated, were still to be done—corresponded to the pressure pipe observations on the existing weirs, it would be a convincing circumstance in favour of the laboratory results. It was important that observations should be made under the direction of the Research Department on the existing weirs to correlate the results with those obtained from the laboratory.

The flow according to the experiments varied according to the coarseness of the underlying materials as well as the nature of the contact.

Bligh's formula might be supposed to allow for the worst construction and bad workmanship and give a safe rule for design, even though it might not represent the actual existing conditions. To be in a position to replace Bligh, it is suggested that the Authors should carry out the experiments with sands taken from various weirs and correlate such results as are obtained from models with observations made on the actual weirs.

MR. R. T. WYNNE GOODMAN said that in the experiments carried out by Dr. McKenzie Taylor and L. Harbans Lal Uppal, there appeared to him the possibility of distortion as the ink traces photographed could only be those between the glass and the sand ; but, he hoped the Authors might be able to say whether the proximity of the glass to the traces would be likely to upset the results in any way. He added that a model somewhat of the nature under discussion was projected to be made in Ferozepore about 1925 but so far as he knew was not ultimately made as it was felt the glass, providing as it must a plane for creep and so short-circuiting the effects of the sand below the model to be analysed, would vitiate the results.

K. B. MIAN IQBAL HUSSAIN said that these experiments were carried out in a well packed heavy selected sand, which had also been saturated before the dyes were introduced. Physical behaviour of sand was that it contracted when wet. Again its contraction was proportional to its moisture content. Such sand ordinarily required 23 per cent. of its volume for complete saturation. When such saturation took place the media became perfectly compact and flow through it could only be gravitational, otherwise capillarity came into play. The compactness which could be got in an experimental box could not be had in actual practice nor was it possible to maintain it. Again if gravitational flow was not permitted then the direction of forced flow was simply controlled by circumstances. If the depth of the box would have been double the size of the model and the sand not fully saturated, the dye tubes would follow quite different lines than those adopted by them in the present photographs. For instance Dr. Rhebock's lines of flow were quite different to those obtained by the Authors.

There appears to be the following defects in these model experiments :—

(i) Such selected materials were used in these experiments as are not found existing in our subsoils.

(ii) No regard was paid to stratigraphy.

(iii) The direction of flow was controlled from all sides and from the bottom.

(iv) Very much lower pressures were applied than are found in actual practice. Heavy sand might require about 2·0 feet of head to blow off, while light sands required just a few inches, and in these experiments the hydrostatic head was insignificant.

Under the circumstances the speaker thought that he would rather be cautious in accepting deductions as arrived at by the Authors.

As regards creep, the Authors' photographs showed as in Figs. V, VIII, XI, XIII and XIV that water in the case of tubes 1 and 2, moved very much slower on the upstream side than it did on the downstream one, while the reverse was the behaviour in the case of tubes 3, 4 and 5.

This was a clear indication that this higher velocity in the immediate vicinity of the work on the downstream side might cause a creep one day and the versions of the denounced authorities, Bligh, Beresford and Clibborn, might prove to be more correct or more true than those mentioned in this paper.

How much had we learnt from the failure of the Islam Weir? Had it not received the same sheet-piling protection or the same supervision that other heads did? He fancied it did but still it failed.

Truth was that each case demanded independent consideration and examination and therefore it would be safe to follow the true and practical scientific method as advised by Bligh and as mentioned by the Authors on page 53, *viz.*, combine theories with common sense and apply them diligently.

Mr. A. N. Wilson remarked that it was part of his duty to help the Authors in the matter of overcoming practical difficulties of construction of tanks and models. He pointed out that the principal difficulty was to make both the tank and the model absolutely watertight, as the slightest leakage in either entirely upset the course of streamlines ; but these difficulties had been overcome in spite of the fact that it took nearly three months to produce the first satisfactory model.

The paper did not deal with pressures, but a previous speaker had attempted to explain the course of streamlines by pressures and an equation of motion. Although the investigation of pressures was incomplete there were sufficient results available to show that no ordinary equation of motion applies to subsoil flow. This was illustrated by the

fact that under a simple floor without piles, and where there was no appreciable change of velocity along any streamline, 40 per cent. of the total pressure was lost in a short distance at entry, a further 40 per cent. lost under the comparatively very long distance under the floor and the remaining 20 per cent. lost in a short distance at exit.

He concluded his remarks by stating that the paper illustrated the extremely valuable use of models in the design of works and by expressing the hope that in the future models would form an essential part of the work of design of all engineering structures.

DR. N. K. BOSE said that at the outset he should like to say a few words about Mr. Johnston's remarks. Mr. Johnston had done all the mathematics for him and he would add only one word to it, that these equations of Mr. Johnston do not apply to the case under discussion where we had flow of water in a porous medium such as sand. His equations apply to open flow in rivers and canals.

Before proceeding to discuss the paper of Dr. McKenzie Taylor Dr. N. K. Bose said that he would like to say a few words about the present position of subsoil hydraulics, *i.e.*, the science of flow of water in the subsoil such as below a weir or a dam or seepage from canals and reservoirs. At Vienna, Forchheimer had standardised the whole line of attack from the theoretical standpoint, though it was Darcy who first experimented on such flow and obtained the empirical relation $V=K\frac{h}{l}$ which he established only for horizontal flow, Forchheimer as early as 1904 extended this relation and give it a differential form

$$V = K\frac{dh}{dl}$$

and assuming that the flow in the pore space was similar to the flow in capillaries, deduced his well-known "Potential Law of Flow" which was the same as what was usually called the "Law of Streamline Flow." This law, Forchheimer admitted, had not been rigorously proved up till now and though it might hold in certain cases, it required more thorough and extensive investigations before it could be used generally and he was sure with the present series of experiments and the pressure observations that were to follow we should be in a position to test this theory. The standpoint of Professor Schaffernak and Dr. Dachler in Vienna was more correct and practical. They based all their experiments on the assumption that the flow of water in a porous medium such as sand was essentially laminar and, if the pressure gradient be the same in the model as in the prototype, then the lines of flow in the model should be strictly reproducible in the field. Now, model experiments were nothing if they were not reproducible. He would have occasion later on to refer to this point in the discussion of the paper.

In transferring all these model results to the field, great care had to be exercised. Generally the following points should be considered :—

(i) The porosity of the soil below the works in the field being different from that in the model, the effect of this fact on the seepage was to be carefully taken into consideration.

(ii) Generally the soil below the works in the field is stratified, this was specially the case in river construction. The effects of this stratification on the model results have to be calculated beforehand.

(iii) In the field there is generally a subsoil flow more or less horizontal. The effect of this horizontal flow has to be taken into consideration while building the model.

(iv) Sometimes in the field an impervious layer is struck not very deep below the work. This had to be carefully considered while the dimensions of the model were being settled.

He would now examine a few statements from the paper.

On page 59, the Authors stated that " the first important conclusion to be derived from these photographs is that the flow of water under a work is streamline." This conclusion had very important bearings. He had shown in his Congress Paper No. 140 that with this assumption, combined with the fact that movement of water in the sand medium was very slow, certain definite conclusions could be arrived at that were in very good agreement with Darcy's experimental results. We knew that the criterion of turbulent flow was the magnitude of Reynold's Number. In the present case, as the movement was very slow and viscosity of the medium very large, the corresponding Reynold's Number would be very small, even as small as 0·2. It was well-known that with such a small velocity and Reynold's Number, motion was essentially laminar and no abrupt discontinuity in motion could take place anywhere in the medium. This was very well illustrated by the flow of water against a cylindrical obstacle. We knew that when the flow was very slow the streamlines as they approached the obstacle divided, went round it and closed up again at the back of the cylinder. As the velocity of flow is increased these streamlines did not close up but left the surface of the cylinder, the point where they left the surface depending on the velocity. So for extremely small velocities, we do not expect streamline flow to develop discontinuity and an area of dead water. If there were a region of dead water in the midst of water flowing with such a small velocity " streamline theory of flow " could not explain it.

There was another observation on page 76 that demanded very careful consideration. The Authors stated that the most important result obtained in the present series of studies was the observation that creep was non-existent. It was not very clear from the statement whether by creep the Authors meant the flow near the fixed boundary or at the fixed boundary. We know in fluids of small viscosity there is a layer of liquid between the fixed boundary and the flowing fluid in which there

was an abrupt change of velocity. But this boundary layer, whose thickness varies inversely as the square root of the viscosity of the medium, was appreciable only in fluids of small viscosity and almost non-existent in very viscous flow. All the photographs showed these boundary layers very distinctly ; so it would be seen that these photographs did not support two of the most important deductions from the theory of streamline flow.

From the above it appears that the streamline theory of flow is inadequate to explain two of the most outstanding deductions from these experiments. In view of these contradictions between streamline theory of flow and these photographs, he thought that it was essential that very careful pressure observation on the same models should be taken and analysed. This would show if these discrepancies between the streamline flow theory and the present series of experimental observations were real or not. He had examined only one set of pressure observations that had been made. They referred to Study No. 1. This is shown in the figure. It would be seen that if the pressure line representing 44 per cent. residual head is taken as the central line, the system of equi-pressure lines is symmetrically distributed about this central line. This means that the pressure line No. 88 on the upstream side corresponded to the pressure line No. 0 on the downstream side. It follows that 12 per cent. of the pressure is lost at the upstream end of the tank, and the remaining 88 per cent. is lost symmetrically about the obstacle. From the streamline flow theory this symmetrical distribution is to be expected and the curves of equi-pressure should belong to a system of confocal hyperbolas. Further pressure observations were necessary to find out how this 12 per cent. drop at the upstream end varied since the streamline theory of flow was incapable of explaining it.

As regards the reproducibility of these model experiments in the actual field, besides the above practical considerations, the most important point to investigate is whether the movement of water in the porous medium such as the sand is laminar or not. If the movement is laminar and takes place in streamlines it can be shown that under similar pressure gradients similar streamlines will develop in the model as well as in the prototype. This means that if the Streamline Theory of Flow does not hold in the sand medium, then the results derived from small scale model experiments will have very limited application in the field. This is exactly the same difficulty that is experienced in open flow hydraulic experiments. Two open flow hydraulic experiments are not dynamically similar if they are not carried out in the turbulent region above a certain Reynold's Number.

Before he concluded, the speaker pointed out that for establishing a theory of subsoil flow, a theory that would make all model experiments unnecessary and our hydraulic structures safe, very careful pressure observations were necessary. For accuracy of observation, models on a bigger scale than the existing ones were required. He thought the money spent on such a big model would be more than repaid by the

saving on future model experiments and by the added safety and confidence with which our weirs and dams could be built.

DR. AHMAD said that the construction of the model does not fulfil the natural conditions obtainable in practice. In practice, there were no up and downstream boundary limits and, therefore, it was necessary that a model should also be free from such limitations. In that model there was no outlet and the outward flow was forced to rise up after leaving the foundation of the work which was quite contrary to the actual seepage flow in a river. Naturally this action turned the streamlines upwards and they found them making the semi-ellipses shown in the Authors' diagram No. 3.

MR. NAND GOPAL said that a study of the paper would convince any Irrigation Engineer how vast was the importance and usefulness of the contribution to science made by this paper. He did not wish to dilate on this point but would confine himself to one or two enquiries and suggestions.

Bligh's theory of creep had been almost fully and perhaps finally exploded. It was, however, stated by the Authors that it held in cases of defects in construction where contact between the work and strata below was poor but for sound work it over-estimated the effect of piles and curtain walls. It was recommended that the best form of construction was that given in Study No. VII with two lines of piles and aprons both upstream and downstream.

Another point he would like to mention was that some of our weirs had under the upstream impervious floor a layer of clay puddle. It would be interesting to know if that was of use. The flow being there, perhaps the smallest velocity would shift clay particles and in course of time create a cavity thereby endangering the work.

It was stated by the Authors that, in the line of flow, velocity changed ; the extent of this was not known yet and we were promised quantitative analysis later on. When this was worked out, it would be of interest to know what would happen if the increased velocity exceeded the limit that would just shift the sand, while the normal velocity did not. He mentioned this point to be kept in view when further experiments were undertaken.

PANDIT K. R. SHARMA congratulated the Authors on inventing a method by which the flow of water below the hydraulic structures could be visually examined but he felt that in all practical problems, creep existed as imagined by Bligh. He gave instances of works apart from weirs where creep played its part in practice.

Twigs left in closing breaches, even in well puddled banks, caused failures in practice by virtue of creep. Outlets were outflanked if creep action along the sides were neglected. Wooden shoots in practice required a longer length of creep than the masonry orifices. A scientist

might use a glass tube as his outlet for efficiency but even 30 feet length of good puddled earth joint would fail against creep for a couple of feet of head, while 4 or 5 feet of earth would retain it against percolation. Similarly creep existed in other works such as syphons, aqueducts and falls.

LALA ISHAR DAS congratulated the Authors on the production of this important paper and gave an instance of practical utilization of the Authors' results. At present the problem of seepage drains was requiring increasing attention and the works built thereon already required to be remodelled.

In Shahpur Division, Lower Jhelum Canal, there was an escape channel which was also an outfall of an existing drain now being remodelled. Two road bridges were built to pass about 800 cusecs maximum with certain floor levels. With changing conditions the floor level of the bridges had to be lowered by about 4 feet as greater waterway was required to pass a greater discharge of 2,000 cusecs.

The design for remodelling these two bridges was under consideration when this paper was received. On reading this he suggested that much deeper curtain walls should be provided in addition to the protection of the piers.

Replying to Mr. Johnston, the AUTHORS agreed that the work was incomplete without the pressure investigations. Time had not permitted the pressure determinations to be made before the submission of the paper. The results even in their incomplete form had proved of interest to a number of engineers and it was thought that they might form the matter of a communication suitable for the Engineering Congress.

Mr. Johnston discussed the theory of flow without any data. The Authors could have done likewise, but as pressure determinations indicated complications that had not been taken into account in the theoretical consideration of the subject, they decided that it was better to develop a theory based on actual observations than to attempt to make observations fit a pre-conceived theory. Experimental work is in progress from which it is hoped to evolve a theory giving the flow under any form of work.

Replying to Mr. Haigh, the AUTHORS said that Mr. Haigh in his comments states that the experiments afford a general confirmation of the streamline theory of flow under weirs. The Authors would like to emphasise the distinction that must be drawn between a hypothesis and a theory. A theory is based on data : a hypothesis is an opinion from which an investigation can be started. Prior to the results set out in the paper, no data were available. A hypothesis had been put forward by Forchheimer as to the form of the flow under an impervious floor. The data now presented and those subsequently obtained show that Forchheimer's hypothesis is only partially correct. Forchheimer omitted to take into consideration the unequal distribution of the equi-pressure lines on either side of the geometrical centre of the model. It is hoped, when the data now available have been completely analysed, that it will be possible to put forward a theory of flow under weirs.

Mr. Haigh gives in some detail his conception of the "theory" of streamline flow. The hypothesis of Forchheimer which covers this has already been tested and found to be incomplete.

With regard to the specific criticisms made by Mr. Haigh, it has now been proved that the streamlines under a simple impervious floor are a series of confocal ellipses of varying eccentricity. They are not symmetrical with reference to the floor but to the equi-pressure line of 44 per cent. loss in head. It is admitted that Streamline No. 6, Study I, is influenced by the model. As this was the first experiment conducted, it was not to be expected that the whole of the limiting conditions could be foreseen.

The model in Study III, to which reference has been made, is in reality a complex structure situated under a different set of conditions to that of Study I. The model is really that of an impervious floor with an infinite number of sheet piles of varying length underneath it. The model itself distorts the streamlines, though as Streamline No. 2 resembles more closely Streamline No. 1 than Streamline No. 3, there appears to be a limit to the influence of the model under these conditions. Streamlines 3, 4 and 5 are influenced more by the boundary conditions imposed by the impermeable layer than by the model. It was impossible, therefore, to refer the streamlines in this case to the model alone.

No theory of streamline flow under a weir has been put forward. To say that the conclusion either agrees or disagrees with a theory is impossible. It may not be in accordance with Mr. Haigh's conception of what the theory of streamline flow should be. As the photograph of the experiment was difficult to reproduce to bring out the points which it was wished to illustrate, a line drawing of the photograph was made. So far as possible the illustration shows the course of the streamline as it was actually found.

The feature of the streamlines in Study II with which disagreement is expressed is reproducible. No further comments appear to be necessary. Streamline No. 1 emerged downstream before Streamline No. 2. The argument put forward is, therefore, untenable.

I had no wish to be hard on the views held by Mr. Beresford. Mr. Haigh states that my views as to the streamlines being semi-ellipses may not be mathematically accurate and yet he says that the streamlines in Study III are "semi-circular.....for all practical purposes." The difference between these two statements amounts to inconsistency. Accuracy has been aimed at in the experiments and it is justifiable, therefore, to point out inaccuracies in accepted views. The fact remains that the streamlines in this case are not "mathematically exact" circles.

The streamline theory of flow as enunciated by Mr. Haigh may not explain certain points, nor may any theory without limitations be applicable to all the possible combination of forms. That certain points are not capable of explanation at present is admitted; that apparent inconsistencies are due to errors is not admitted.

The non-occurrence of the " dead water " in Fig. VI is possibly due to the fact that no streamline was traced in contact with the model. Its presence is indicated by the throw-off of Streamline No. 1 downstream. It will be noticed, especially in the later models when improved technique had been developed, that the boundaries of the streamlines are strongly defined. As the method is based on chemical precipitation due to the contact of two solutions, I can see no reason why the streamlines as traced should not trace accurately the lines of flow. Mr. Haigh might have given evidence to substantiate his statement.

Fig. X to which reference is made, accurately represents the conditions observed. There is one main line of *strongly* defined flow of relatively high velocity, and a secondary tube of flow of extremely low velocity. The facts are as stated.

In reply to L. Ajudhia Nath Khosla, the Authors said that in connection with points raised by him regarding the alteration that might be caused in the pressures by the formation of the precipitate, the precipitate only formed in contact with glass, and the bulk of the sand under the model remained unchanged. However, to overcome any possible objection on this ground, pressure determinations were now being made before the streamlines were traced.

It is undoubted that the sheet piling upstream of the work will reduce the pressure at the toe of the work. From this point of view the presence of an upstream sheet pile must increase stability. When, however, the flow is concentrated at the toe instability of the sand in this region may follow, and from this point of view the work is less stable than it would be without an upstream sheet pile. The Authors are endeavouring to intensively investigate the area in which Mr. Khosla suggests reverse flow takes place. There are, however, many experimental difficulties to be overcome.

Replying to Mr. Goodman, the Authors pointed out that the course of the streamlines was independent of head. Pressure determinations had shown that the percentage loss of pressure at any point under the model was also constant and independent of the head. It seems reasonable to conclude, therefore, that the streamlines as traced are very definitely the lines of flow. It was further pointed out by the Authors that the form of the model determined the shape of the streamlines. Had there been any distortion due to the proximity of the sand and glass, this distortion would have persisted throughout the series of experiments and masked the effect of the form of the model.

Replying to K. B. Mian Iqbal Hussain, the Authors stated that his conception of the physical behaviour of sand when wet was incorrect. Sand is inert and no change in volume occurs due to wetting. His remarks, therefore, on this point did not hold.

As far as the Authors were aware, the sand under any work is saturated when a head is maintained upstream of the work. The theoretical

case put forward by K. B. Mian Iqbal Hussain with the sand not fully saturated does not appear to have any practical application. With regard to the defects mentioned, sand of the grade used is found under weirs in the Punjab. In a model of Khanki Weir which has been investigated, the type of strata has been taken into consideration and the results agree with those forecasted. It is true that the flow is to some extent controlled, but the shape of the streamlines in the neighbourhood of the work is controlled by the form of the model. The streamlines adjacent to the work are the most important.

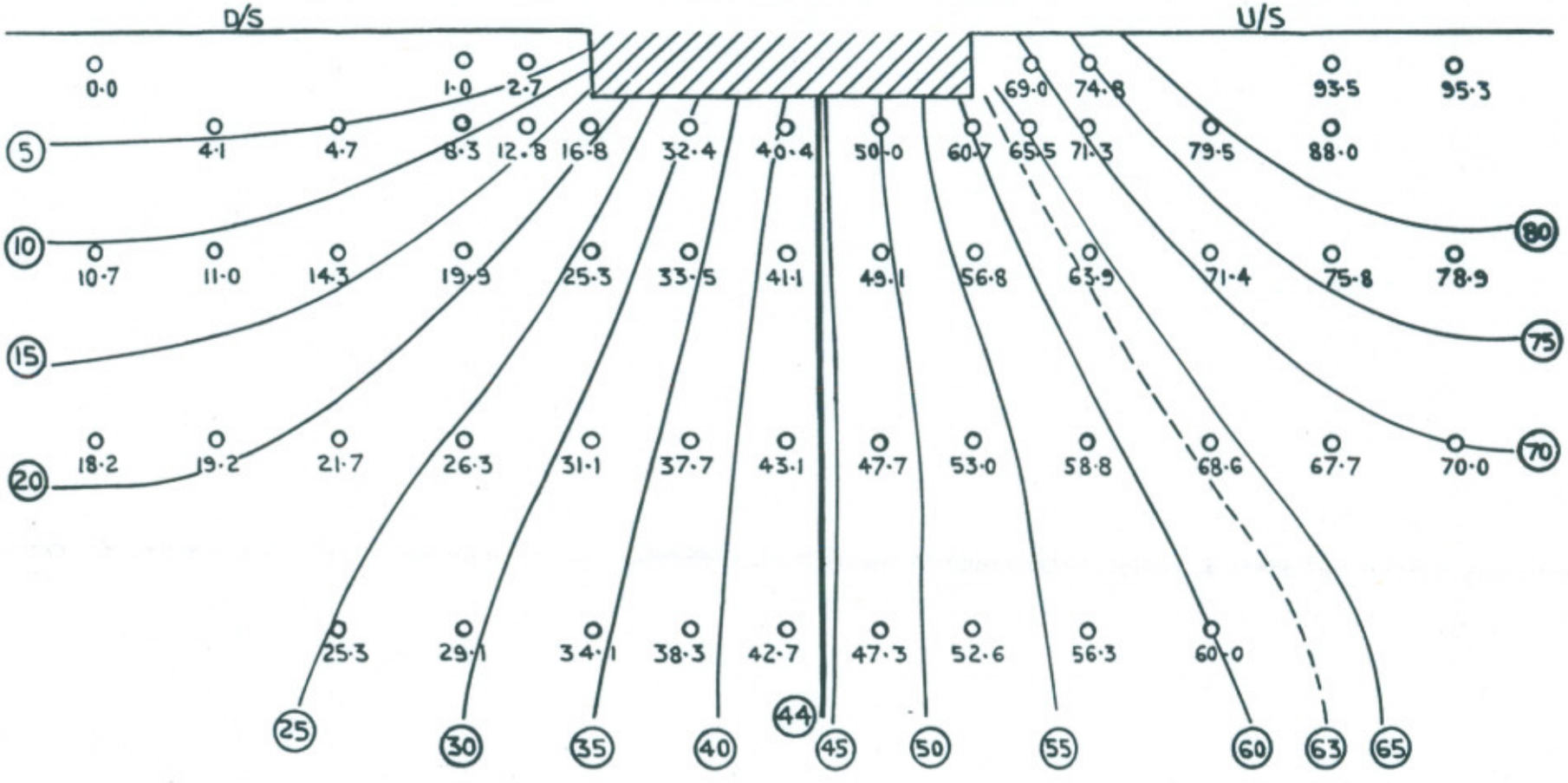
In reply to Dr. Bose, the Authors stated that he would have the opportunity of examining the pressure under the works when the results were obtained. The Authors agreed with Dr. Bose that there were difficulties in accepting the streamline theory of flow as a result of the pressure observations which had so far been made. Further results would probably enable an explanation to be given.

In reply to Dr. Ahmad, the Authors pointed out that in practice there might be no up and downstream boundary limits, but it was the flow near the work that was of the greatest importance. Since it had been shown in these model experiments that the shape of a streamline near the work was determined by the form of the work, the models were reproducing the conditions actually found in practice. In a number of works in Punjab, springs occur and a pool downstream of the work usually exists which shows that the seepage flow under the model reproduces that of the river. The Authors referred Dr. Ahmad to the paper on Panjnad Weir by R. B. Ajudia Nath Khosla (Punjab Engineering Congress, Paper No. 162 of 1933). The flow lines under Panjnad Weir were derived from the pressures. The flow lines emerge downstream in a similar manner to those in the model studies.

In reply to Mr. Nand Gopal, the Authors pointed out that clay had cohesion, it is therefore unlikely that fine particles will be removed from the clay.

Replying to Mr. Sharma, the Authors agreed that if the work is defective, undoubtedly creep might occur. This they had already stated. A sound contact between the work and the underlying material should be aimed at.

The President in winding up the discussion remarked that he hoped that the way in which the replies to discussion on Paper No. 173 were given by L. Harbans Lal Uppal would be appreciated by all. He was greatly impressed by the careful manner in which these replies were given and congratulated the Authors on producing such a paper.



STUDY Nº 1
PRESSURE CONTOURS

(PAGE 780 OF THE DISCUSSION BY Dr. BOSE.)