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EFFECT OF CAPILLARITY ON DRAINAGE IN WATER-LOGGED AREAS.

By Dr. V. I. Vaidhianathan and Chanan Singh, Irrigation Research Institute, Lahore.

It is the purpose of this paper to describe laboratory experiments on negative pressure* and capillarity and the application of the results to practical problems on drainage. Other aspects of the problem have been investigated and reported upon in the proceedings of the Indian Academy of Sciences. Reference may be made to that paper for a detailed account of the associated phenomena. This is in the course of publication.

The laboratory experiments which have led to these observations shall now be described.

A cylinder 150 cm. high and about 8 cm. in diameter is packed with sand under water. The cylinder is fitted with four side tubes. The lowest side tube has a long glass tube of small bore attached to it. This tube is as high as the cylinder and the fluctuations of water level in the cylinder are observed in this glass tube. In the preliminary stages of the investigation, in addition to this long side tube, another long tube with a strainer was inserted in the body of the sand in the cylinder and the levels in both the tubes, inside and outside were observed. Since both the tubes always recorded the same level, the tube in the sand was dispensed with.

Before beginning an experiment, water is allowed to pass down the cylinder for two weeks in order to pack the sand and stabilize the conditions. Free water is then allowed to stand on the sand and the level of water in the side tube is noted. The level of water in the cylinder and in the side tube remains the same as in a U tube. One of the side tubes, say, the second from the bottom is now opened so that water begins to drain. As water is being drained the level of water in the cylinder and in the lowest side tube remains the same, as in a U tube, but as soon as the free water surface in the cylinder is brought down by draining and is in contact with the surface of the sand in the cylinder, the level of water in the glass side tube begins to

*The term "negative pressure" here means a pressure less than that at the phreatic surface. The phreatic surface is at atmospheric pressure and the zero of pressure is referred to that at the phreatic surface. There is a term "pressure deficiency" well known in soil literature, but this is associated with unsaturation. The authors had used the latter term before, but it led to confusion and hence this term is avoided in this paper. The negative pressure is not associated with unsaturation, but with the pressure caused by the menisci at the top of the capillary column. This distinction is important.

sink very rapidly. The subsequent depression bears no direct relation to the amount of water drained as it depends on the particle size of the sand in the cylinder. Experiments were carried out with three different grades of sand and the results are given in Figs. 1 to 5.

Fig. 1 shows the results for very coarse sand sieved between 2·5 and 3·5 mm. in diameter. Three curves are shown in the figure. Curve "*a*" shows what the depression should be if there was no sand and if the cylinder was filled with water only and drained. If Q is the volume of water drained and A_1, is the area of cross section, this curve represents Q/A_1. Curve "*b*" shows what the thoretical depression should be if the cylinder is packed with sand under water and the pore space completely drained. Here taking the void space as 40 per cent., the effective area of cross section of the cylinder will be $0{\cdot}4\ A_1$. If we take this effective area as A, then the curve "*b*" will represent $Q/A = Q/0{\cdot}4\ A_1$. If complete drainage and the corresponding fall in level of the water were to take place the curve Q/A will be obtainable. In reality the curve traced is "*c*." This curve may be divided into three parts *viz.* MN, NP and PR. Along the portion of the curve corresponding to MN, a very small quantity of water drained produces a very large depression. In the stage of drainage corresponding to NP the rate of depression is lower than that of MN. After the stage corresponding to P is reached, the curve runs almost parallel to *b*. This shows that after P is reached the amount of water taken out produces a corresponding depression in the level in the pipe, as would be expected according to Q/A relation. But there is a permanent divergence between the curves *b* and *c*. This divergence gives the negative pressure which the soil can develop due to capillarity. If a quantity Q of water was drained from the sand in the cylinder, the corresponding level of water in the cylinder should be expected to be given by curve "*b*" *i.e.* the air-water surface in the sand should theoretically be expected to lie on "*b*". But as stated, what is actually observed is that they appear to be on points on "*c*" as indicated by observations in the pipe. The observed level is thus deeper than the real one by an amount indicated by $X_1\ X_2$ in Fig. 1. This difference in depth indicated by $X_1\ X_2$ is greater for fine sand and increases when the particle size of the sand decreases as could be inferred from Figs. 2 and 4. $X_1\ X_2$ are not marked on these figures.

If we confine our attention to the stage corresponding to MN, it will be seen that this portion of the curve runs almost parallel to the abscissa. A very magnified effect is therefore produced in this stage. In the case of very coarse sand, the bifurcation between *b* and *c* is not very great and the stage corresponding to P is obtainable easily. But the cases with fine and very fine sand are different as will be seen from Figs. 2 and 3.

Fig. 2 shows the results of experiments with fine sand. The curves *a*, *b* and *c* have the same significance here as in Fig. 1. It will be seen from the portion MN of this curve that a small amount of water drained produces a very great depression. Thus in order to produce a depression of 20 cm. 400 c.c. of water are required according to curve *b i.e.* if the Q/A relation were to hold good. But the depression of 20 cm. is observed in the pipe when 5 c.c. of water is drained. This point is of very great practical importance. Qualitatively, the phenomenon with fine sand is similar to that with coarse sand, but the corresponding quantitative values are very different. These can be seen from Fig. 2. The mechanical analysis of this sample is given in Fig. 3.

The results of experiments carried out with very fine sand are shown in Fig. 4. In this case the part MN of the curve was continued up to 150 cm. which was the maximum range of the experimental tube.

The point corresponding to P will be attained approximately at about 200 cm. *i.e.* nearly 7 feet. The divergence of the curves *b* and *c* is greater than can be obtained with the present arrangement and so the parallel portions of the curves are not shown in Fig. 4. In other respects the various curves have the same significance as in Figs. 1 and 2. The mechanical analysis of this sample is shown in Fig. 5.

DISCUSSION OF RESULTS

We shall now discuss the bearing of these results on practical problems regarding drains. It is clear from the results that draining water from the subsoil and estimating the fall in water-table are not so simple as have been believed in the past.

Seepage drains in the Punjab generally vary in depth from three to ten feet and are cut in high water table areas. They are meant to deal with both the surface water and the subsoil water. What is the effect of the negative pressure on the drainage of the subsoil ?

When a drain is cut in a waterlogged area the free water standing on the surface of the soil will certainly drain away; no capillary forces exist in the soil at this stage and therefore do not affect this drainage. When this water is drained and the surface of the soil is exposed to air, the soil-air-water interfaces develop a negative pressure depending on the grain size of the soil. If we take for instance a very fine sand, the negative pressure which this can develop is seen to be seven feet. Unless the depth of the drain exceeds this seven feet the pores in the soil must remain full of water.

Suppose for example the results are applied to a drain cut in very fine sand. What amount of water can be removed by such a drain from a saturated soil and what would be the depression in a pipe meant to record the water-table ? It will be seen from curve *b* Fig. 4 that 1800 c.c. of water will have to be drainedfrom the cylinder to produce a depression of water level in the sand corresponding to 90 cm. From curve *c*, Fig. 4, however, it is seen that when 10 c.c. of water is drained, the level in the pipe shows a depression of 90 cm. In this case therefore only 1/180 of the water actually contained in the sand is drained and the water level has apparently fallen by 90 cm. *i.e.* 3 ft. From this it will be seen that such a drain cannot remove the quantity of water from such a soil type that would be expected. Stated briefly, a seepage drain cannot reduce the moisture content of a soil much below its saturation value. There is a minimum depth to which a drain should be cut before its full effect is felt and this depth will depend on the nature of the soil.

What is probably taking place in a field is that when the surface water is drained away, evaporation takes place from the surface of the soil and any subsequent reduction of moisture content of the soil above the water level in the drain will be brought about by evaporation only.

As indicated before, if the drains cannot reduce the moisture content of a soil below saturation and at the same time the water level in a pipe embedded in a soil shows a depression to what does the water level in a pipe actually correspond ? The water level in a pipe corresponds to the phreatic surface, *i.e.* the surface at which the pressure is atmospheric. This surface is a free air-water surface in the pipe, but on a level with the water surface in the pipe there is no corresponding air-water surface within the subsoil. The phreatic surface in the subsoil is not an air-water interface. The pores within the subsoil above this surface are full of water to a certain height and the extent of this height depends on the grain size of the soil. On the top of this saturated fringe, there are innumerable micro-menisci forming the air-water-soil interface. These micro-menisci are analogous to the menisci in capillary tubes and exert the negative pressure which is recorded by the water-level in a pipe. The water level in a pipe is thus a measure of the negative pressure exerted by these micro-menisci at the soil-air-water interface on the top of the capillary column. The movement of the level in a pipe *i.e.* of the phreatic surface is controlled by this pressure. The movement of the phreatic surface therefore does not correspond to the addition or removal of water from the subsoil. It corresponds to conditions associated with change of pressure and these conditions are dependent on the grain size of the soil. To take the phreatic surface as the water-table, as has been done in the past, is thus misleading. The water level which corresponds to the addition or removal of water and is independent of the grain size of the soil is that surface which lies on a level with the plane of the air-water-soil micro-interfaces on the top of the capillary column. This latter water level should be taken as the water-table if it is to be of any practical use to problems associated with water-logging. There may be practical difficulties in observing this water-table, because when a bore is made the soil is removed and only the phreatic surface can be observed in a pipe or well. The process of boring and taking away the soil removes the very cause which is responsible for the water level referred to in the previous sentence, which it is desired to observe. Only laboratory experiments can decide what height should be added to the level of the phreatic surface to obtain the correct water-table level. So far the phreatic surface and its fluctuations have been, unsuspectingly, wrongly interpreted with reference to water-table level.

In a field there are few more points to which attention may be drawn. Firstly the strata may not be uniform. If the field is composed of stratified soil, each stratum differing in grain size, the negative pressure changes as the top of the capillary column passes from one stratum to another and the phreatic surface fluctuates as this happens. If the top of the capillary column leaves a fine stratum and enters a coarser stratum the negative pressure decreases and the phreatic surface moves up. The water level in the pipe also moves up accordingly, though drainage is still taking place. This phenomenon has been observed in the laboratory. It is a further proof that the level of water in a pipe is not an indicator of water-table or the amount of drainage.

A second point is that if there is a source of water near the drain, then the drain may appear to work continuously, but it most probably is removing the water from the source and not reducing the water content of the soil.

It will be noticed that in this paper the terms "capillarity and capillary force" have been employed, but this should not be confused with what is usually known as the "Movement of water on the capillary tube hypothesis." The latter hypothesis depends on the classical Poisuille equation and applies to the volume of water moving. This hypothesis is already discarded in soil science. What we have been considering here is not the movement of water, but the transfer of the negative pressure to the phreatic surface from the menisci at the top of the capillary column and the consequent effects.

We have great pleasure in acknowledging our thanks to Dr. E. McKenzie Taylor for his keen interest in the problem.

VERY COARSE SAND

FIG. I
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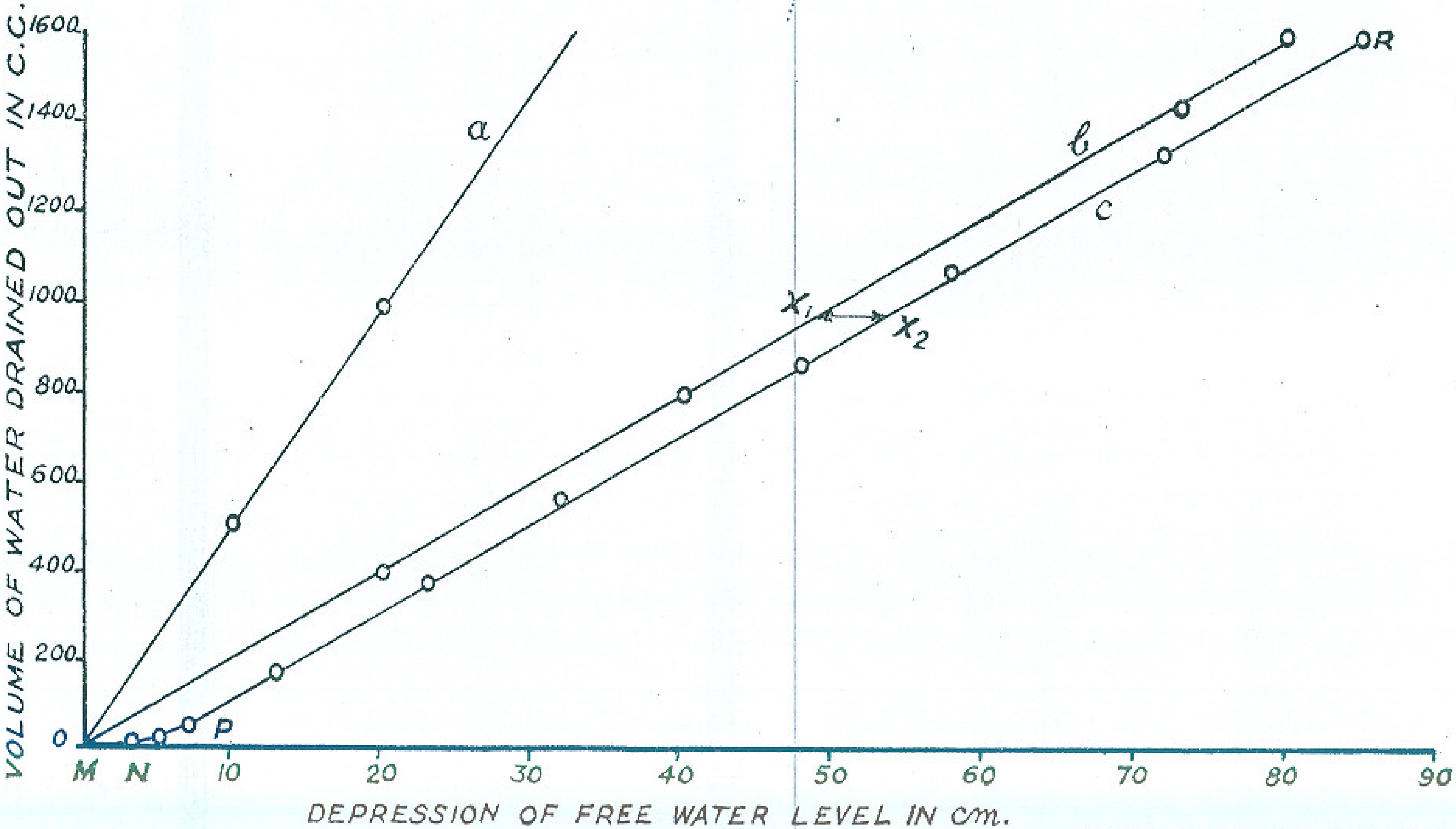

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FIG. 2
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FINE SAND

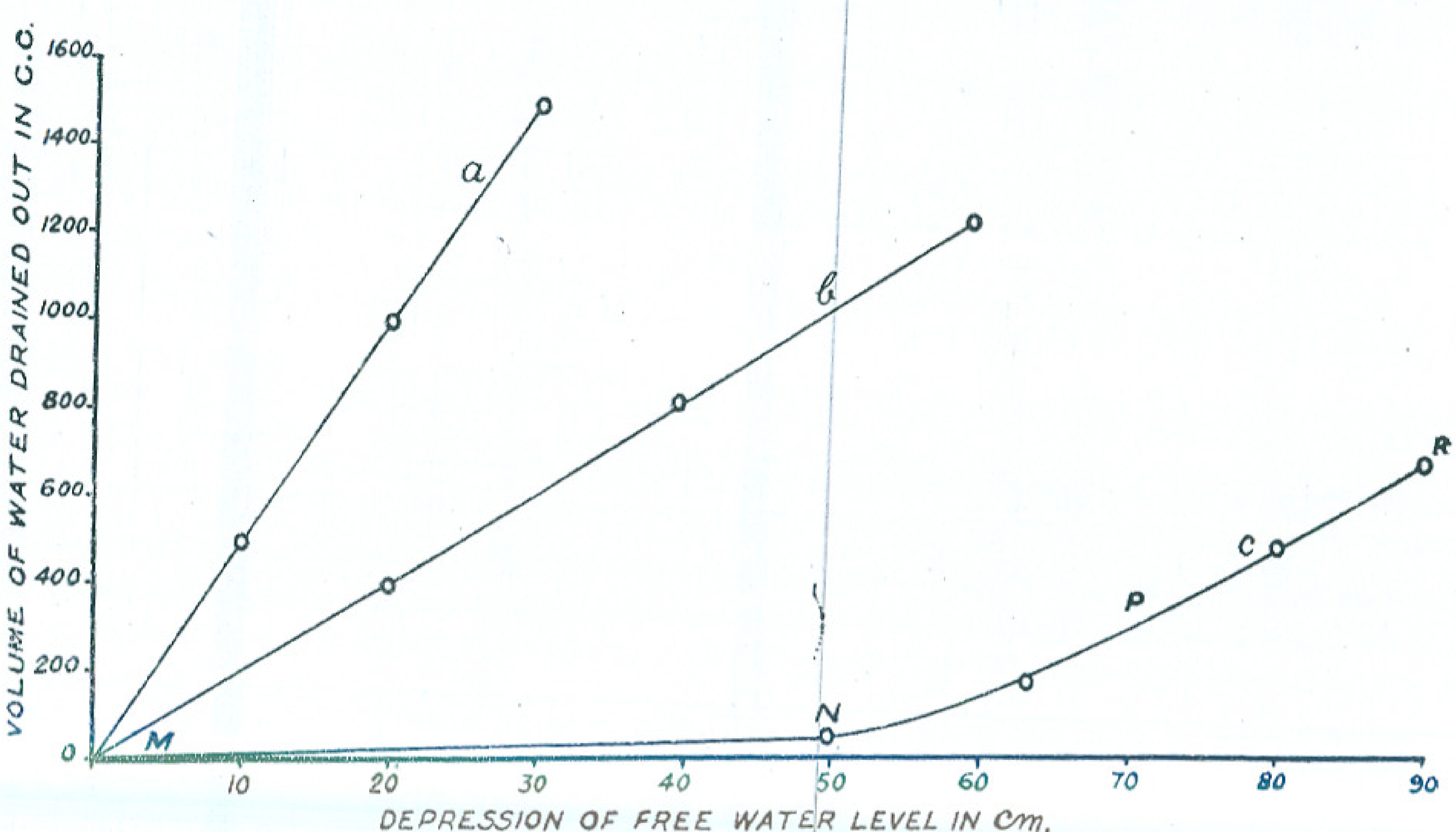

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FIG. 3
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SIZE DISTRIBUTION CURVE
(FINE SAND)

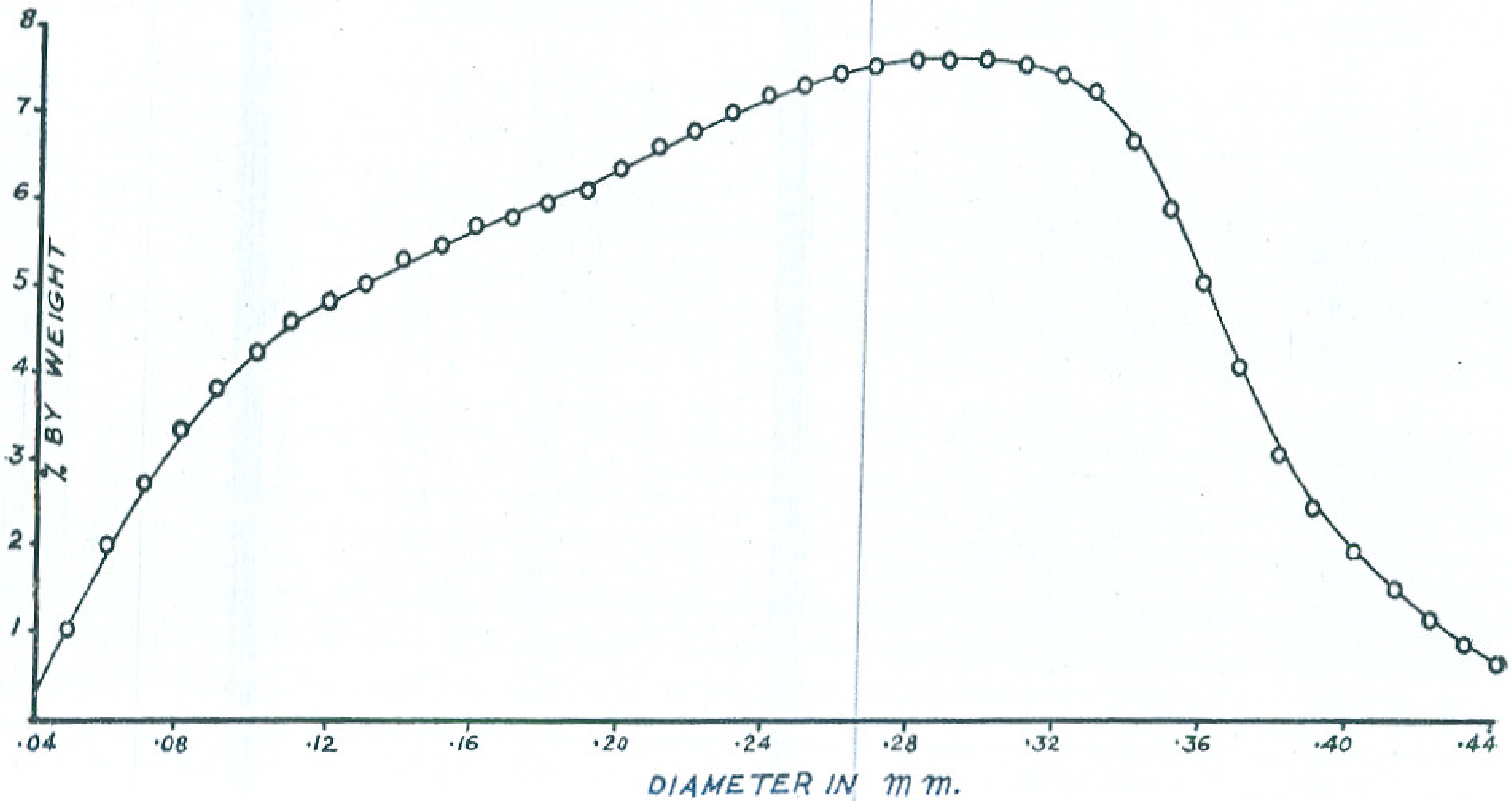

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FIG. 4
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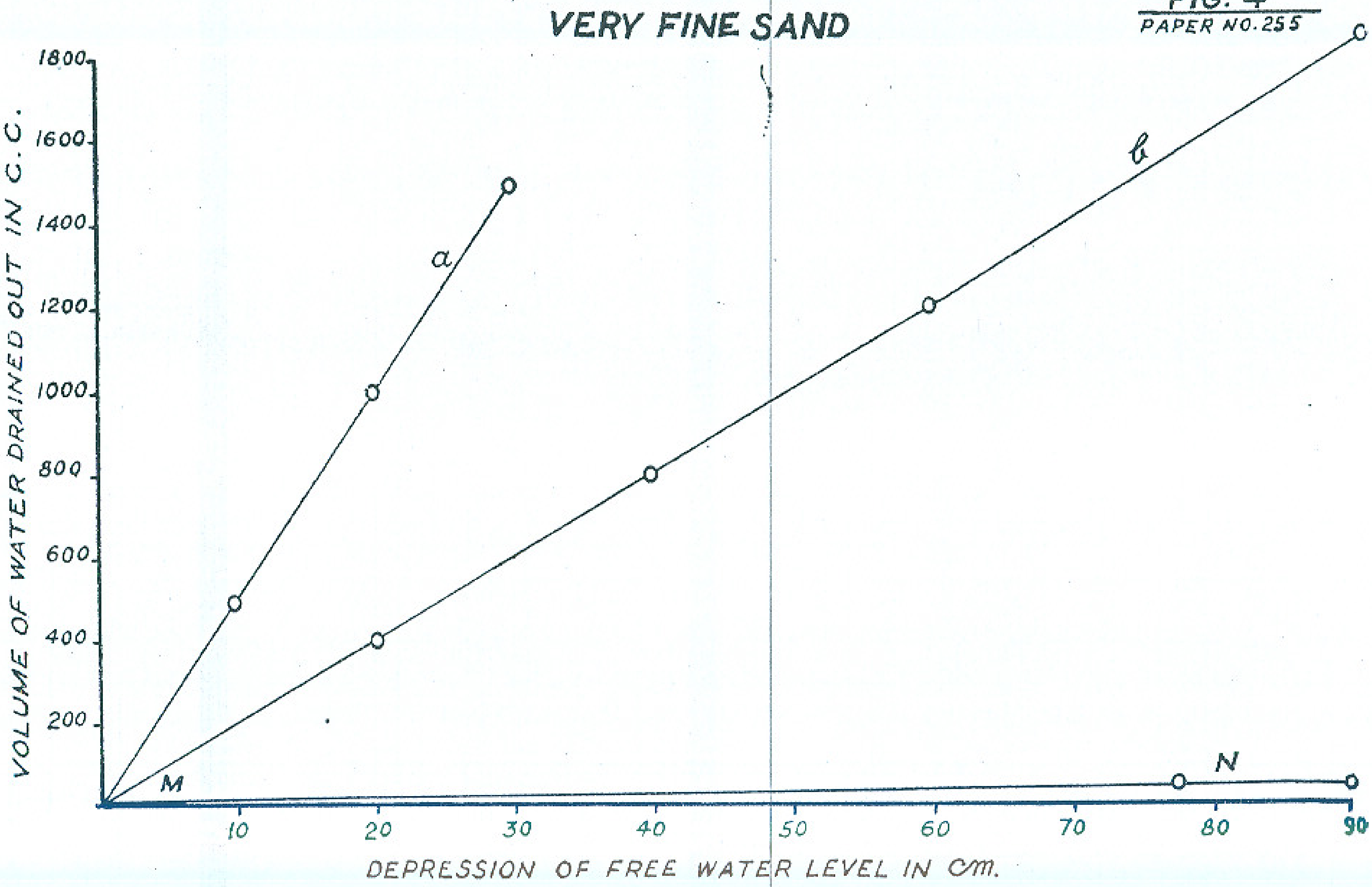

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FIG. 5
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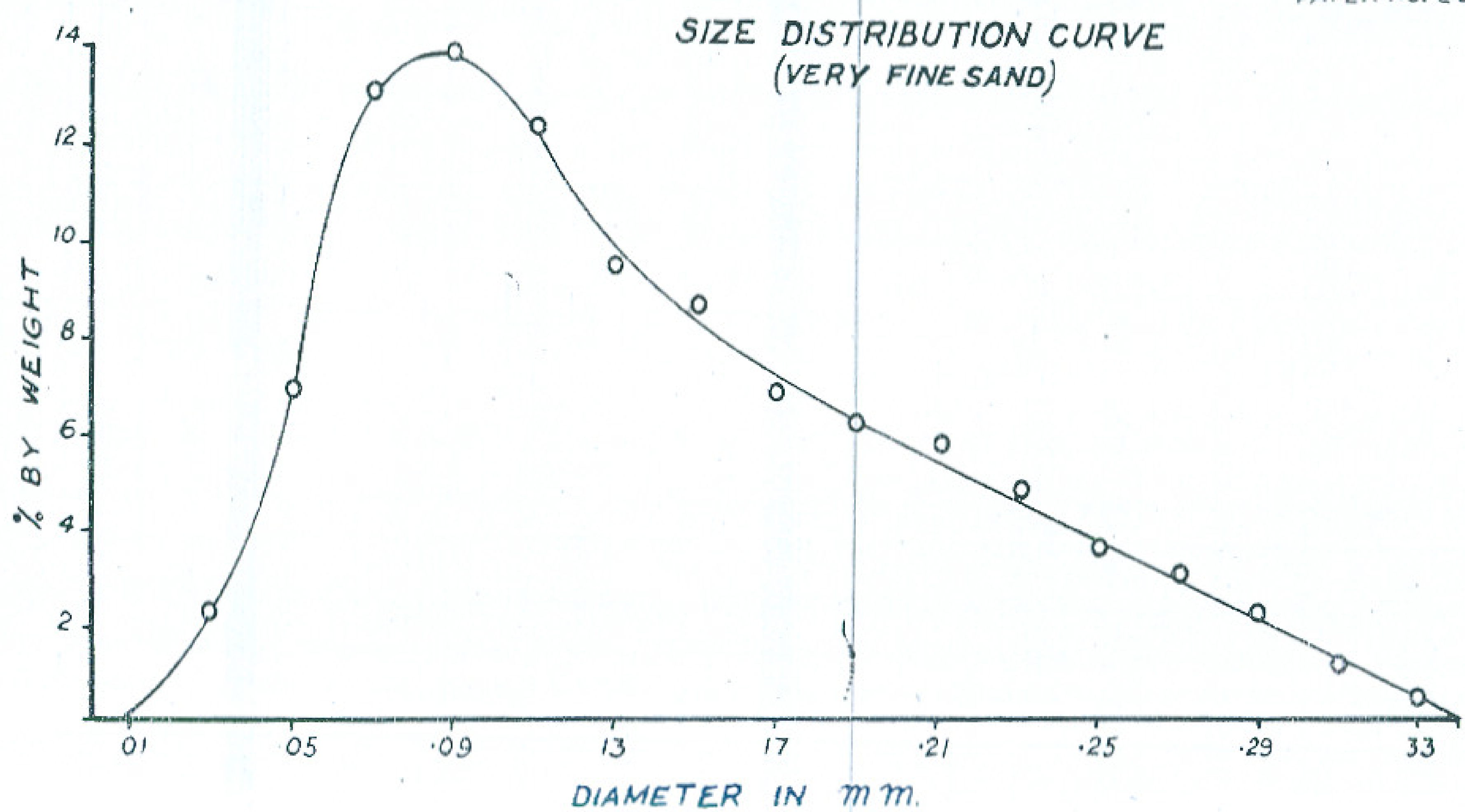

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DISCUSSION

The AUTHOR in introducing the paper said that this new phenomenon which has been observed will require a revision of our ideas of water-table as distinct from the water-level in a pipe. He then showed graphs indicating that when a small quantity of water is drained from a saturated sand, the water-level in the pipes falls many times that which can be accounted for by the amount of water drained. This fall depended on the grade of sand, being larger for finer sands. The change of level of water in a pipe, therefore, does not indicate quantitatively the amount of water drained and water cannot be drained unless a certain negative pressure characteristic of the soil has been developed. The past attempts to correlate fall of water-level and drainage were, therefore, incorrect. He then demonstrated the experiments in tubes by draining the subsoil and showing the abnormal fall in the tubes. In one of the tubes where there was a stratification, the bottom being filled with sand coarser than that at the top, the level of water began to fall at first when the tube was drained, but most surprisingly it then began to rise, in spite of the fact that water was still being drained. The author explained this as due to the change in the capillary force at the interface of the coarse and fine particles of sand.

MR. NAND GOPAL said that the behaviour of S. S. Water flow into constructed drains and the indications of W. L.s in observation pipes had puzzled Drainage Engineers since many years. While the Irrigation Department in the Punjab had gone on making observations of pipes ever since the construction of Seepage Drains had been undertaken since about 1925, they had come across discrepancies which had been put down roughly to behaviour or misbehaviour of soil or pipes being wrongly driven. Such discrepancies had been even put down to wrong observations by subordinates. An attempt had been made as early as 1929 in connection with observations of S. S. Water on the Chakanwali Reclamation Farm in the form of a note by the speaker. The factors causing disturbances had been found to be so numerous that it had become practically impossible to eliminate them or even to observe effect of each factor. Some of these factors were known to be :

(*i*) W. L. in Canal when near enough.
(*ii*) Temperature at time of observation.
(*iii*) Rainfall.
(*iv*) Depth and nature of filter-point.
(*v*) Nature of subsoil, wherein the filter-point lies.

He then stated that the writer of the paper had done a signal service to the profession in general and to the problem of waterlogging in particular by devising a simple apparatus to determine the effect of one factor at least. He suggested taking up of other factors and similarly determining their effect.

2. He added that while reading the paper, one wished for a sketch of the apparatus having been attached. According to him the following points were not quite clear :

(*i*) It was stated that four side-tubes had been fitted to the cylinder. Where had those been fitted, *viz.* at what level and what had been the function of those ? Only one was stated to have been used for draining.

(*ii*) The depth of soil packed in the tube and the depth of water on top thereof was not stated. These might have an effect on the resultant flow and may be considered.

(*iii*) The graphs in Figures 1, 2 and 4 were stated to be for Q/A, *viz.* volume of water drained per unit of area. The time factor might also have an effect. If the flow were allowed for a longer time, a lower level in the side-tube might be attained.

3. The problem dealt with in the paper was of everyday application on drainage works. While deep drains were flowing within a few feet, pools and collections of water were seen to be standing for long periods, until perhaps dried by evaporation or slow infiltration depending on the degree of permeability of the soil beneath. This phenomenon had been responsible for the Speaker's observations in articles on "Waterlogging in the Land of Five Rivers," which had appeared in June to September issues of *Indian Engineering* in 1938. It had been contended that seepage drains, as such, did not drain the subsoil water for a very long distance away from the drain. The S. S. Water slope observed by pressure pipes, in cross-section lines indicated a slope of about 1 in 40 in average loam soil. Thus if a drain were dug 3.0 ft. below S.S. W.L., it might drain a width of about 100 ft. only on either side. The authors of the paper had experimented with very coarse, fine and very fine sand only. The speaker suggested that it would be of more practical use if tests were made with loam, containing varying percentages of sand and clay, as was met with in construction of drains. He stated that Dr. Vaidyanathan had written a paper on Transmission Coefficients of Soils. He asked Dr. Vaidyanathan if he could not give us a formula connecting negative pressures of this paper with resultant flow through soils having different Transmission Coefficients, so that we could by observing pressures in profiles, determine discharge of a seepage drain before construction. That would be something very helpful for designs of seepage drains, which were now mainly dependent on guess work.

Mr. N. D. Gulhati said that in the paper under discussion the authors had described certain laboratory experiments on negative pressure and capillarity, and that the results obtained had been applied to practical problems regarding drainage. The laboratory experiments described by the authors had been carried out with soil represented by different grades of sand held in a pipe of about 3 in. diameter, containing a fixed amount of moisture. In nature the soil affected by a drain could not be isolated as in the experiment. Also the moisture-charge varied, and apart from subsoil flow there was always some inflow from above into the soil. He pointed out that the authors had not allowed for these natural conditions and, therefore, the results of their experiments could only be applied to natural conditions with caution. No error was more frequent in hydraulic discussion than that of applying an otherwise good result to cases where it did not hold. He stated that a law in hydraulics was limited in its application to a definite set of conditions, and when one or more of these conditions were altered, the law might not be applicable.

He opined that the principles enunciated by the authors would be correctly applicable in their qualitative aspect to conditions in nature, but that quantitatively the results obtained in the laboratory would require to be considerably modified before they could be used in practical problems ; that the authors had, however, established clearly that the rise and fall of the water-table as determined by the observations of the phreatic surface gave no indication whatever of the volume of water added or removed from the subsoil ; that in that respect the results of their experiments were of far-reaching importance that above the phreatic surface, which had been our conception so far of the water-table, the strata might be saturated with water up to a height depending on the nature of the soil , and, lastly, that there was, however, no free water and the moisture held was in a state of equilibrium by virtue of capillarity action.

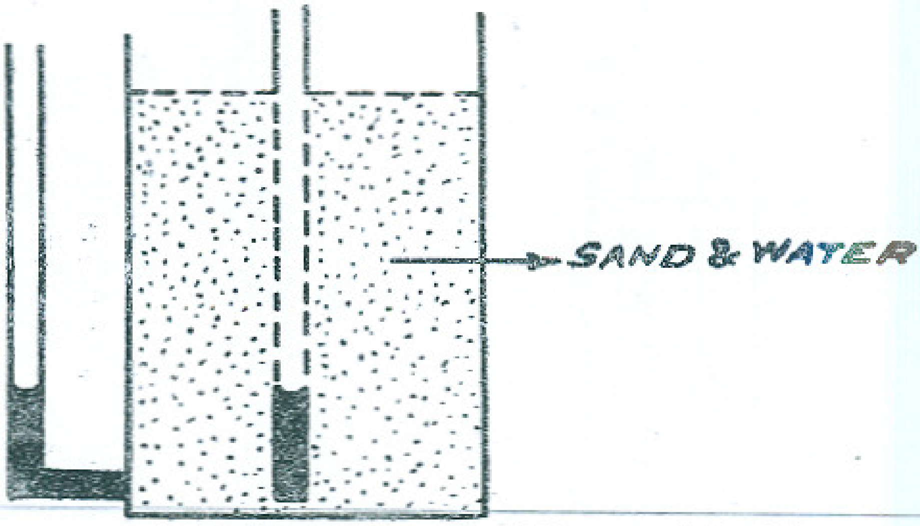
He, then, said that the authors went on to show that seepage drains, unless very deep, could not reduce the moisture-content of a soil much below its saturation value. This according to him fitted in with the statement so often made that drains were a failure inasmuch as the quantity of water removed by them from the subsoil was only a small fraction of the water that went into the soil. While the truth of this last statement was not denied by anyone, it was by now well-known that drains did a definite and substantial good to the area served by them. An explanation of this apparent inconsistency had now been made available in the paper under discussion. When a drain was constructed in an area which was more or less a swamp with water standing on the surface, or almost at it, the free water in the soil for some depth below the surface was drained away. The removal of this stagnant free water appeared to change the physical properties of the soil in so far as its fitness for cultivation was concerned. In this matter the evaporation that was continuously taking place from the soil was of considerable help. The top layers of the soil got practically dry and the soil would become firm. It was, thus, clear that to reclaim a swamp all that was necessary was to remove the stagnant or free water from the surface and for some distance below it, and to establish a definite flow in the subsoil water-level, no matter how small it was. The speaker believed that small quantity of water which was removed by the drains made a great difference to the conditions of the soil.

Referring to page 137 where the authors had stated that if there was a source of water near the drain then the drain might appear to work continuously, but that it most probably was removing the water from the source and not reducing the water-content of the soil, the speaker opined that that statement was somewhat misleading and could be made to imply that if there was no drain there would be no drawing of water from the source, and the drain as such was redundant. He stated that a little more than a year ago some experiments had been made on the Rechna Seepage Drain which runs for a length of 16 miles along the Upper Gugera Branch, at a distance of 1,000 ft. from it. As a result of observations carried over a period of two years it had been established that before the construction of the Upper Gugera Branch there had been a natural flow of subsoil water from the left towards the Upper Gugera Branch. With the construction of the Upper Gugera Branch, seepage from it had been superimposed and a sort of pond had been produced in the subsoil immediately close to the branch on its left. The experiments had showed fairly conclusively that the Rechna Seepage Drain situated as it was at a distance of 1,000 feet from the Upper Gugera Branch had not been inducing any additional seepage from the Branch, but that it had removed the water which had otherwise been accumulating in the pond formed by the seepage flow from two opposite directions.

Mr. G. R. Sawhney was the next speaker. At the outset he congratulated the author on writing this rather interesting and valuable thesis. He said that the author was a master in the art of drawing sufficient conclusions from insufficient premises. According to him the author had made rather astounding observations by which he proved that it was not what a man knew that made him wise but what his friends did not know.

He pointed out that the author carried out a very elaborate set of experiments with different grades of sand with a view to apply his conclusions, arrived therefrom, to drains which invariably passed through soils having quite a different grain-size, but as his own result varied so much with fine sand what would happen in the case of other soils, left one guessing. He compared this to trying the balancing trick on a tight rope over an abyss. He said that the author had plainly told us that we were working on wrong basis and recording false pressures in pipes, but had not taken the trouble to offer any suitable advice. He requested the author to try some early experiments with various soil grains that we had to deal with in the case of our drains, and then tell us what to do and thus help us to avoid our spending more money on cutting drains to wrong depths or collecting incorrect data and compiling wrong statistics. He concluded with the aphorism that knowledge like timber should not be used till it is well seasoned.

Dr. N. K. Bose, M.Sc., of the Irrigation Research Institute, commenting on the paper said that he wanted to make one point clear which had been missed by Dr. Viadhianathan. He said that when these experiments were being carried out in the Research Institute, he had the opportunity of being in touch and that he had asked Dr. Viadhianathan to put in a strainer pipe in the body of the sand—the whole length of the pipe being strainer. Dr. Viadhianathan found that even in this strainer (see attached figure) the water-level was the same as was recorded by the side-tube. This showed that though the actual water-level had been very much higher, the pull of the sand had been so high as to stop any water trickling into the strainer tube through the pores. This would give an idea about the magnitude of the pull which kept the water surface in the sand high up. This point, the speaker said, would be of particular interest to the agriculturists.



Dr. V. I. Viadhianathan, the author, before replying to the various criticisms on his paper, thanked his critics for their congratulations on his discovery of that new phenomenon which, as he had mentioned in the introduction, would lead to a revision of many of our ideas about water-table.

Regarding the criticism by Mr. Nand Gopal, he agreed that the factors which he had mentioned would affect the level of water, but that these effects were very small compared to the effect of capillarity which had been observed.

According to him the number of side-tubes were immaterial and a depth of water above the surface of sand did not also matter. He explained that the phenomenon would be observable as soon as the top-surface water was removed. He stated that attempts were being made to experiment with fine soil. He hoped that in course of time the design of drains would be put on a scientific basis and not on guess work as Mr. Nand Gopal stated was done at present.

Commenting on the statement of Mr. Gulhati that the results obtained in the laboratory could be applied in the field only with caution, he explained that a physical phenomenon was applicable anywhere but that in the field there might be other conditions which had also to be taken into account. He agreed with Mr. Gulhati in his statement that the water removed by the drains was only a small fraction of that which went into the soil. He admitted that evaporation came into play and made a difference to the property of the soil, as he found from his experience. He expressed his inability to say more about it without further experiments.

He, then, thanked Mr. Sawhney for his interesting criticism. In the end, he said that the point which Dr. Bose had raised had been investigated in the laboratory and that he was thankful to bim for drawing the attention of agriculturists to those results.