PAPER No. 231

THEORY AND PHYSICS OF SEEPAGE FLOW FROM CANALS

BY

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Introduction.

Experiments to investigate the seepage losses from canals, both in the saturated and the partially saturated phases, were started in 1936 at R. D. 4,000 of 14 R. Distributary, Upper Jehlum Canal, by the author under the guidance of Mr. E.S. Crump, C. I. E., Results obtained up to 12-9-37 were published in Paper No. 209 of the Punjab Engineering Congress 1938. The quantitative results were given in Plate No. 4 of the said paper, both for the fully-saturated and partially-saturated phases. In Paper No. 209 no detailed comments were made on the pressure observations as insufficient data were available by 12-9-37. The experiments were continued, and the results obtained up to September 1939 are discussed in this paper.

Losses under Saturated Conditions.

From the experiments it was established that under fully saturated conditions of flow (ignoring the effect of staunching) the losses followed a straight line law. The formula for such losses could be written in the form.

$$q = \sigma H$$

where q = Losses in cusecs/million sq. ft. 20°C.

H = Seepage head, *i.e.*, the difference between the free water surface in a canal and the spring level.

σ = Constant depending upon the nature of the soil traversed by seepage flow at 20° C. average temperature.

The value of σ in the case of the soil at 14 R. experimental site was about unity.

In the experiment on 14 R. Distributary, depth of water in the tank was constant at 4·0 ft. Detailed experiments with varying depths were, however, carried out at R. D. 348,000 U. C. C. Lower in a mile long tank. The depth in the tank was varied from 2 to 6 feet. It was found in these experiments that the losses in the saturated conditions were independent of the depth in the tank and followed a straight line law as enunciated above. The losses were found to vary according to the seepage head and the soil constant.

Pressure Observation under Saturated Conditions.

Qualitative conditions in the fully saturated phase, based on the qualitative work done by Wilsdon as described by him in Paper No. 78, P. E. C. 1923 and as shown in Fig. 2 page 11 in Paper No. 209, P. E. C. were accepted. He found that in such conditions the soil pores were fully saturated from the bed of the canal down to the spring level below, and that the moisture content was everywhere more than 23%, that is the region of full saturation.

At the 14 R. site, six pressure pipes were inserted below the bed in order to investigate qualitative conditions. The observations made on these pipes are given in the attached Plate No. 1. Fully saturated conditions were established by 3-8-37 and persisted up to 24-10-38. All the six pipes recorded pressures as shown in Plate No. 1 showing that the soil was fully saturated throughout this period. Pipes Nos. 5 and 6 did not fully respond to the spring level changes, and they were subsequently found to be actually choked. Pressure observations confirmed the qualitative conception of saturated conditions as enunciated by Wilsdon.

It is clear from Plate No. 1 that with a rising spring level fully saturated conditions were established by 3-8-37, when all pipes started recording pressures. The position of spring level (B. S. P.) was then 2·5 ft. below the bed. This means that the soil was saturated by capillarity up to 2·5 ft. above the B. S. P. Level. When the capillary fringe rose to the bed level of the tank, fully saturated conditions were established and the losses attained a maximum value. The losses decreased as the seepage

head declined from 3-8-37 onwards. It may be inferred from this observed behaviour that the saturated capillary fringe in the case of rising water table extends to about 2·5 ft. above the spring level (B. S. P.) under the soil conditions prevailing at the site of the 14 R. Distributary experiments.

It is interesting to note from the losses plotted in Plate No. 1, that they attained a maximum value on 3-8-37, when the full saturation conditions were brought about by a rising spring level, and that they rose to a maximum value on 24-10-37 just before fully saturated conditions were terminated as a result of the spring level falling to 3·4 ft. below the bed. The smaller value of the maximum loss on 24-10-39 as compared with the maximum on 3-8-37 is considered to be due to the staunching of the bed of the tank by fine silt deposited during the interval. It is inferred from this behaviour that the height of capillary fringe above the B. S. P. Level in the case of falling water table was about 3·5 ft.

Losses under Partially Saturated Conditions.

The quantitative results in these conditions, as given in Plate No. 4 of Paper No. 209 P. E. C. and in Plate No. 1 of this paper show that when the fully saturated connection between the bed of the tank and the spring level is broken, the losses drop rapidly and then tend to attain a steady value between 3 and 5 cusecs per million square feet. The lower limit is attained as the staunching of the bed progresses.

Wilsdon's qualitative conception of the problem in partially saturated conditions is given in Fig. 1 page 10 of Paper No. 209. The moisture contours show a reduction in moisture content from the bed of the canal towards the water-table and also from the water-table towards the canal. Thus, there is a region where the moisture-content has a minimum value. Wilsdon regarded the condition as unsaturated when there was a region of moisture-content below 23% between the canal bed and the water-table.

Wilsdon imagined that seepage from canals in the unsaturated phase reached the general water-table under

all conditions even if a region of very low moisture-content intervened between the two sets of equimoisture contours. According to him, the losses from canals increased to some extent with an increase in the distance between the canal bed and the water-table. He imagined that seepage water passed along the thin film of water surrounding each particle of soil and that the soil pores contained imprisoned air under a pressure below the atmospheric as sketched below :—

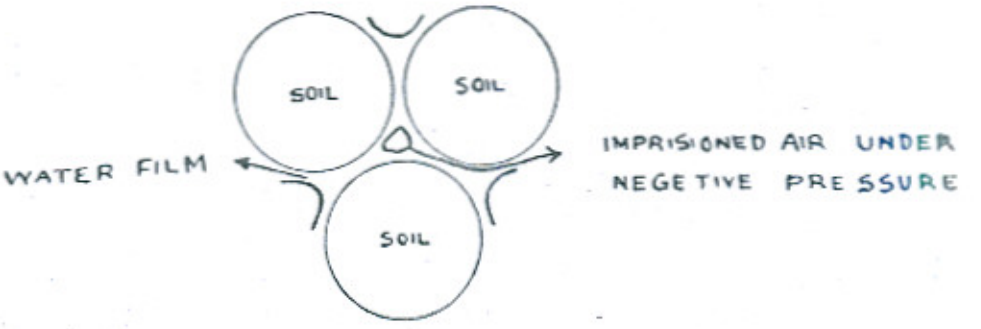


Fig 1

The losses in the unsaturated phase increased as the spring level receded, *i. e.*, as the effect of gravity increased. It is the object of this paper to study from the results of the experiments on 14 R. Distributary to say, if this conception of the losses under unsaturated conditions was correct.

Pressure Observations under Partially Saturated Conditions.

The behaviour of the six pressure pipes is shown in Plate No. I conditions of partial saturation prevailed from 24-10-37 to 4-12-37.

On 24-10-37 Pipe No. 1 having its base 0·5 ft. below bed stopped recording any pressure. Pipe No. 2 having its base 1·0 ft. below bed followed soon after and stopped recording pressure on 29-10-38.

Pipe No. 4 having its base 3 feet below bed stopped recording pressure on 21-11-37. Pipe No. 3 having its base 2 ft. below bed lagged behind and stopped recording any pressure on 30-11-37.

Pressure Pipes Nos. 5 and 6 were found to be choked in this period as a result of clay-slurry sloughing into them. All pipes had open ends and the experience showed that they should be kept clear up to their base levels by dredging in order to keep them responsive. Pipes Nos. 5 and 6 were set right about the end of November 1937. The rapid drop of the water level in them during the closure of December 1937, showed that they had improved in responsiveness. Pipe No. 5 having its base 4 ft. below bed stopped recording any pressure on 8-1-38 when the spring level was 5·83 ft. below bed.

From 28-8-38 to 9-9-38 Pipes Nos. 4, 5 and 6 recorded pressures when the spring level was about 3·5 ft. below bed. On this occasion Pipes Nos. 5 and 6 did not lag behind below the spring level as they did in the previous year. The increase in losses from 28-8-38 indicated that partially saturated conditions were established. Pipe No. 4 stopped recording pressure on 9-9-38 and Pipe No. 5 followed suit on 5-10-38 on 18-10-38. Pipe No. 6 was recording pressure of 0·82 ft. while the spring level was 4·83 ft. below bed. The phreatic water surface in Pipe No. 6 was 0·65 ft. higher than the spring level (B. S. P). Even in the month of August and September the spring levels did not go high enough for saturated conditions to become established and Pipes Nos. 1, 2 and 3 failed to record any pressure. It is concluded that under the partially saturated conditions, pipes with bases 0·5 ft., 1·0 and 2·0 ft. below bed did not record any pressure. This definitely shows that the soil pores were not fully saturated. Darcy's Law as enunciated in the beginning of this note was not applicable under these conditions. However, the zero pressure do not necessarily mean that the soil was dry and that the soil pores were full of air alone. It simply means that the pressure was below the atmospheric. In order to get an idea of what was contained in the soil pores, air was sucked from these pressure pipes and a water manometer was applied to measure the suction head. Tests described, hereafter, were carried out by Mr. Crump and the author on 18-10-38.

Description of the Apparatus.

The apparatus used was an ordinary water manometer as sketched in the attached Plate No. 2. A suction pump was fitted to a metallic cap, which was given an air tight connection to the pressure pipe by means of a rubber band. An air-tight gas cock was provided to cut off the suction instantaneously when desired. Five feet of 3/8″ dia. pressure tubing was used to connect the cap and the U-tube thus ensuring that all joints were air tight. Gauges were pasted on the wooden board below the 5/16″ diameter glass U-tube. Water was put in the U-tube so that it stood 1·6 in both limbs.

In all observations, air was evacuated by means of a pump, so that water in U tube limb was raised to a little over 1·1 ft. The time taken in dropping from 1·1 to 1·0 ft. was noted. This meant change of suction head from 2·2 to 2·0 ft. In all 8 pipes in the tank were tested. There are two pipes which have got their base levels 2·0 ft. and 3 ft. below bed respectively. The results of these tests are tabulated in Appendix I. The spring level was 4·83 ft. below bed, and only one Pipe. No. 6 with base 5 ft. below bed recorded a pressure of 0·82 ft, that is, 0·65 ft. above the spring level and all of the remaining 7 pipes were dry. Results are plotted in Plate No. 2.

Discussoin of Results of Manometric Tests of Pressure Pipes in Partially Saturated Conditions.

Time recorded for suction head variation from 2·2 ft. to 2·0 ft. is plotted in Plate No . 2. It is clear from this plotting that, though seven pipes excepting No. 6 failed to record any pressure, the times recorded were not the same but varied widely. It is concluded that the soil sacs at the base of these pipes contained varying proportions of water and air. All pipes were $1\frac{1}{2}$″ diameter with open ends.

Pipe No. 6 (base 5 ft. below bed) was definitely below spring level and contained 0·82 ft. depth of water. It took only 80 seconds for pressure variation from 2·2 to 2·0 ft. There was no possibility of any air in draught in the case of this pipe. Soil contained free water and it

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was sucked under a suction head of 2·2 ft. Water Level rose by 0·01 ft. in the test.

Pipe No. 5 (base 4 ft. below bed) did not record any pressure and was within the capillary zone above the spring level. It has already been stated that the capillary fringe extended about 2·5 ft. above the phreatic surface. Time taken was 7·0 minutes for a drop of 0·1 in the U-tube limb. This showed that sacs were practically full of water with very little supply of air. No water was drawn into the pipe.

Pipe No. P_{4L} (base 3·0 ft. below bed) did not record any pressure and was within the capillary zone. Time taken was 42 minutes for a drop of 0·1 ft. limb of U-tube. Soil sacs were full of water and with little or no air. It took 42 minutes to arrange air equivalent to 0·1 ft. column of U-tube under a suction head of 2·2 ft. But no free water was available which could be drawn in.

Pipe No. P_{3L} (base 2·0 ft. below bed) did not record any pressure and was above the capillary zone above spring level but it took 1 minute 57 seconds for suction head variation from 2·2 to 2·0 ft. This is not quick enough for free air. It is, therefore, evident that sacs contained a good amount of air and a small quantity of water.

Pipe No. P_2 (base 1·0 ft. below bed) is definitely above the capillary fringe above spring level. It took 6 minutes 16½ seconds for suction head variation from 2·2 to 2·0 ft. Water was drawn in this test and water level in the pipe rose by 1/8th of an inch. This shows that water was available at the base of this pipe. Soil sacs at the base of this pipe contained a large amount of water and very little air.

Pressure Pipe No. P_1 (base 0·5 ft. below bed) did not record any pressure and was, therefore, outside the saturation limit below bed. It took 16 minutes and 27 seconds. Water was sucked in the pipe and water level rose by 0·02 ft. This shows that no free air was available but the sacs contained a large amount of water.

Pipe No. P_{3R} (base 2 ft. below bed) did not record any pressure. It was above the capillary fringe above

spring level. All pipes could be sucked by mouth. Hardest attempt by the writer with mouth failed to create a negative head of 2·2 ft. Suction pump was worked hard to get a head of 2·2 ft. In the first attempt it took only 20 seconds for a drop of 0·1 ft. in the U-tube limb. It meant that free air was available near the base of this pipe. Five observations were taken, which are plotted in diagram No. 4. Time increased at every fresh attempt for the same conditions of the negative head. This shows that the supply of air was exhausted gradually and finally water only was drawn in. At the end of these observations, it was found that water had risen in the pipe. This rise showed not only that in the beginning free air was available, but also, that free water was available at the close of the experiment. Position of its base was both near air and water as shown in Fig. *F*, Plate No. 3.

Pipe No. P_{4R} (base 3 0 ft. below bed) did not record pressure and was within the capillary zone above spring level. Two tests were carried out. In the first test, it took more time than in the second one. Conditions were as sketched in Fig. 2.

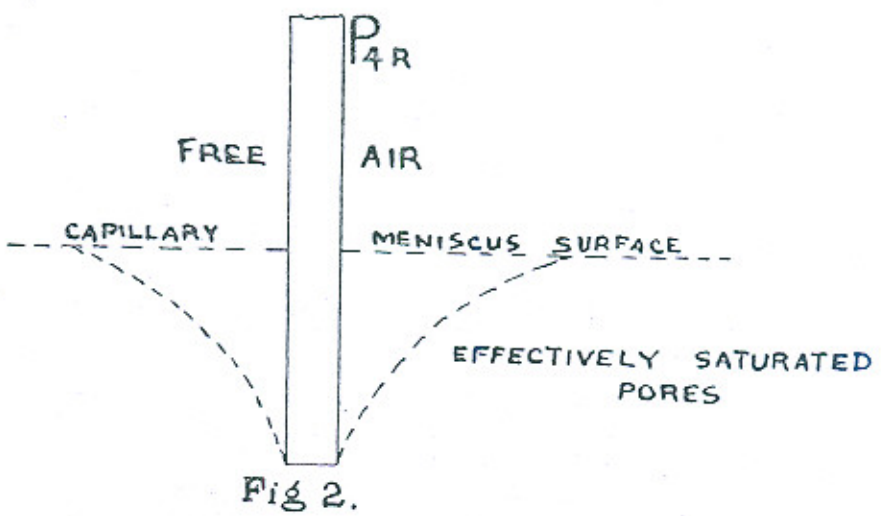


Fig 2.

The capillary fringe was about 0·5′ above the base of pipe with free air above it. In the first attempt, capillary fringe under suction head of 2·2′ was depressed and water was drawn. In the second attempt with depression cone, air was also drawn in. It was, for this reason, that the time taken was less in the second observation. It is

also clear that free water and air were not available in the same quantity as in the case of Pipe No. P_{3R}.

Partially Saturated Conditions.

It is evident from these suction tests that the moisture content in the partially saturated conditions does not vary in the decreasing moisture contours above the phreatic subsoil surface or below the bed of this tank or a canal Pipe No. P_2 (base 2′ below bed) and Pipe No. P_1 base 0·5′ were very slow to yield air. Evidently their bases though above the capillary fringe were in the fully saturated tubes. The moisture content variation under these conditions is very irregular and at random. One may find free water or air in the same plane below the bed.

The picture of the qualitative conditions which one may expect is drawn in Fig. (*F*) Plate No. 4. When these observations were taken, water-table was falling and the phreatic surface was above the B. S. P. Level recorded. A firm saturation line is drawn below the bed of the tank. B. S. P. Level is shown firm and the phreatic surface is shown dotted above it. It was actually 0·65′ above the B. S. P. Capillary miniscus surface is shown firm. The soil is fully saturated in the capillary fringe. There are fully saturated bands or tube connections from the complete saturation below the bed of the tank to that in the Capillary Zone as shown therein. The pressure pipe having their base in these fully saturated tubes even though above the capillary fringe were the slowest to yield air. The partially saturated conditions in the case of rising water-table are sketched in Fig. (*B*) Plate No. 4.

Saturated tube connections in the partially saturated conditions have a special significance. Theory of flow in these tube has already been enunciated and dealt with mathematically in Chapter VIII. Publication No. 12 (Central Board Irrigation) in connection with exit gradients below the weirs. It has been proved there that for soils having a normal pore space of 40%, the exit gradient required is unity so that the soil is not disturbed. In this case, the head due to the depth in the tank or a canal is lost up to the saturation line drawn below the bed. The flow in these saturated tubes is with unity

gradient under the effect of gravity. No pressures were registered by any pipe. The pressure in these tubes is everywhere atmospheric. A foot drop in flow means a loss of head of one foot. As there is no soil movement in these tubes, the gradient cannot be more than unity. If the gradient will be less than unity, the tubes will be cut short and there will be no saturated connection from a canal bed to the water-table below. There is a natural adjustment of the unity gradient in these tubes because of the natural constriction of their sectional area according to the porosity of the soil.

A field verification of these saturated bands is available on the Upper Jhelum Canal. There is a couple of feet of silt above the arches of the syphons at R. D. 229, 530 and R. D. 236, 67C U. J. C. An inspection of the barrel shows that the barrels are dry and wet in bands. These bands give a very vivid indication of the conditions in the partially saturated phase of the losses. It was intended to measure actual pressures in the dry and wet regions by boring holes through the masonry but these tests have been abandoned on account of Mr. Crump leaving India suddenly.

Pressure Observations under Unsaturated Conditions.

Referring to Plate No. 1, clear unsaturated conditions were established from 5-12-37 to 20-8-38. No pipes up to 4·0′ below bed recorded any pressures in this period. It is concluded that it is the characteristic of the unsaturated phase of the losses that the pressures below the bed of a channel are not more than atmospheric. The pressure observations as recorded in this period however do not show the actual pressures below the atmospheric as an open ended pipe could not record a negative pressure. Further tests were carried out as given in Appendix II of this paper and plotted in plate No. 3. The position of the pipes is shown in plate No. 3.

An attempt to record actual pressures with Benzine differential manometer failed on 25-5-39 because of the slow yield from the pressure pipes, and the depression of the capillary fringe with suction. Observations as given in Appendix II were carried out by using a Diaphragm Manometer. These instruments were invented by E. S.

Crump, Esquire, C. I. E, Officer on Special Duty, Water-logging Investigation. Diaphragm Manometer was devised according to the principle of Chattock Micromanometer or the Turtle gauge. It had a rubber diaphragm instead of the liquid one in the Chattock. Electric contact on either side of the Diaphragm was indicated by the Voltameters connected to a Dry Cell Battery. This apparatus needed very little movement of the liquid from the pipes tested.

The results, plotted in plate No. 3 show that the soil pressures from 0·5′ below bed down to 3·8′ below bed was atmospheric. Free air at atmospheric pressure was available in this region in case of all pipes. Absolute pressure at the base of pipes 4·0′ below bed to 5·75′ below bed were below atmospheric. The maximum negative pressure recorded by Pipe F_1 was 2·3′. The capillary fringe was somewhere between 3·0′ and 4·0′ below bed and there was no air in the pores in the capillary region. The pressures recorded by pipes with base 6·5′ to 7·0′ below bed were positive. The B. S. P. Level in these tests was 5·7′ below bed. The phreatic surface was somewhere between 5·75′ and 6·5′ below bed of the tank. These tests clearly show that there was no saturated connections from the tank to the water-table below. Sudden pressure discontinuity below capillary miniscus surface line from ·· atmospheric to 2·3′ below atmospheric is a definite proof of the fact that the soil sacs in the capillary fringe were effectively saturated.

Losses in the Unsaturated Conditions.

The observations in the unsaturated periods are given in Plate No. 1 of this paper and Plate No. 4 of Paper No. 209 P. E. C. 1938. Before a partially saturated connection is made in the case of rising water-table or after the partially saturated connection is broken in the case of falling water-table, the observed losses practically lie on a straight line. In the unsaturated phase, seepage losses tend to be constant.

Referring to Plate No. 1, it will be seen that from 5-12-37 to 8-4-38, the losses were very nearly steady between 4 and 5 cusecs per million square feet in spite of considerable variation in the B. S. P. Levels.

The increase of loss in May 1938 was due to the fresh opening of the tank after stopping observations for over a month on account of closure and the tank dried up in this period. The spring level declined rapidly from 5·7 ft. below bed on 17-5-38 to 7·5 ft. below bed on 8-6-38. The losses were steady in this period. This clearly shows that the losses from the Irrigation Channels in the unsaturated phase are independent of the position of the water-table below. The slight decline in the losses from 8th June 1938 to 15th August 1938 was due to the staunching of the bed in course of time. Ignoring the normal fluctuations in the results, there is no evidence to indicate that the losses increase with an increase in the depth to the water-table under unsaturated conditions. It is, therefore, concluded that constant value of losses in the unsaturated phase (except as influenced by staunching of the bed) is the true characteristic of the unsaturated conditions. This fact has a very important bearing on the problem of waterlogging. The losses are independent of the effect of gravity. They are dependent on the soil conditions only and are a measure of the evaporation which is taking place from the ground adjoining the channel. The seepage water does not directly reach the water-table. The losses are of the low order from 3 to 5 cusecs as observed in these experiments depending on the soil conditions of the bed of the tank (the soil conditions were varied in these experiments by the natural effect of staunching in the observations). The channels having losses in the unsaturated phase do not directly contribute to the water-table but their existence stops the extraction of water from the water-table which would have otherwise been removed by evaporation.

Physics of the Seepage Losses from Channels.

Qualitative and the quantitative experiments on 14 R. Distributary U. J. C. clearly indicate three phases of the losses from channels instead of the two as enunciated by Wilsdon from his qualitative work published in Paper No. 78 P. E. C. 1923. Three phases are described in this paper saturated, partially saturated and unsaturated. The qualitative conditions in these phases are sketched in Plate No. 4, both in the case of the rising and the falling

water-table. The sketches in Plate No.4 are self-explanatory and need no comments.

The swing of the saturated limit where the losses were the maximum from 2·5 ft. below bed (rising water-table) to 3·5 ft. below bed (falling water-table) was explained in Paper No. 209 to be due to flow hysterises. From the sketches in Plate No. 4 of this paper, it is clearly explained by the vertical component of the movement of water-table. The phreatic surface at atmospheric pressure is above the B. S. P. Level (spring level) in the case of falling water-table and it is below in the case of rising water-table. In these sketches a capillary zone is taken to be 2·5 ft. height and is drawn above the phreatic surface in both cases. The saturation below the bed of the tank has been taken to be about 0·5 ft. The sketches clearly show that fully saturated conditions will be established when the B. S. P. is 2·5 ft. below bed in the case of rising water-table and terminated when the B. S. P. is 3·5 ft. below bed in the case of falling water-table.

Conclusions.

The conclusions in the three phases of the losses are summarised below:—

Saturated Phase (Percolation).

1. Losses take place according to the formula

$$Q = \sigma H$$

Where Q = Loss in cusecs in million sq. ft. at 27°C. average temperature.

H = Seepage Head, *i.e.* difference between the free water surface in the canal and B. S. P. Level.

σ = Constant depending on the nature of the soil traversed by the seepage flow.

Various methods have been developed to determine σ in the actual field conditions. Their description is considered beyond the scope of this paper, and will be available from the reports of the Waterlogging Investigation Division, Lahore.

2. The losses are independent of the depth of water in the canal.

3. There is saturated connection from a canal to the water-table and losses are directly added to the water-table.

4. All the pressure pipes inserted below the bed of the canal will record pressures and there will be definite manometric gradient for the base of one pipe to that of another.

5. The head due to the depth of water in the canal was lost within couple of inches below the bed due to deflocculation of the soil particles.

6. There was a definite position of B. S. P. Level below the bed of a canal where losses will be the maximum. Its position varied according to the rising or falling water-table and depended on the height of the capillary zone peculiar to the actual local soil conditions.

7. Major portion of the additions to the water-table from the irrigation channels are in the saturated phase. It has been actually measured that losses in certain reaches of U. C. C., L. C. C. and U. J. C. Main Lines are of the order of 30 to 40 cusecs per million sq. ft. On this account, in the case of such canals, as have seepage losses in the saturated phase lining them is the best remedy as an anti-waterlogging measure.

Partially saturated phase (Percolation).

1. Losses in this phase rapidly decline from the critical position giving the maximum losses in the saturated phase.

2. No mathematical solution has been attempted, though one could be found from the curves given in Plate No. 4, Paper No. 209 P. E. C 1938. This phase is not of much practical importance as it will always be of a limited range (2 to 3 feet) depending on the soil conditions.

3. There are fully saturated tube connections from the canal to the water-table below. Free air at atmospheric pressure in the enclosed spaces between the tubes and free water at atmospheric

pressures in the saturated tubes are available in the same plane between the saturation line below the bed of a canal and the continuous capillary miniscus surface.

4. Major portion of the losses are directly added to the water-table through the saturated tubes and a part of them is contributed by the evaporation from the area adjoining the channel.

Unsaturated Phase (Absorption).

1. The quantitative losses in this phase will be of low order say from 2 to 5 cusecs per million square feet.

2. No formula to determine the losses in the unsaturated phase is needed. The variation of losses in this phase will depend on the following considerations:—

   (*a*) When the clay stratum (commonly found in the Punjab) is more than two feet deep below bed, the loss will be about 2 cusecs. In sandy loam soil bed, the losses will be about 5 cusecs per million sq. ft.

   (*b*) There will be more loss from the sides than through the bed.

   (*c*) The channels in embankment will have relatively higher loss because of the exposure of their sides to evaporation.

   (*d*) The depth in a channel does not directly affect the losses except that it will tend to increase the area of sides and consequently the area exposed to evaporation.

3. There is no saturated connections from a channel to the water-table below it. Free air at atmospheric pressure is everywhere available below the bed of a canal.

4. Losses in this phase are not directly added to the water-table.

5. The losses in the unsaturated phase do indirectly contribute to the waterlogging of a tract be-

cause they cut off the evaporation which would have otherwise taken place.

Irrigation and Rainfall.

The principals of seepage flow from the canals, as enunciated above, equally apply to the rain and the irrigation water put into the fields. In the waterlogged areas where the general water-table is high and where the saturated and the partially saturated conditions are brought about by the capillary action ; that is, when the capillary miniscus surface above the water-table and the saturation line below an irrigated field meet, water from the fields percolates into the general water-table and accentuates the waterlogging trouble. Under these conditions, practically whole of the irrigation and rain water will be added to the general water-table, before there is enough time for the evaporation and the transpiration by the plants to exercise their effect. The evaporation and the transpiration by plants constitute a very slow process especially in rains due to high humidity and they cannot on the average deal with more than quarter inch depth of water on each account in a day whereas, percolation is very effective under a seepage head of the order of 6 or 7 feet (difference between the free water surface in the field and the phreatic surface). In this way, water can easily percolate in waterlogged areas, the surface drains will be of immense value for quick removal of the rain water and the restriction of irrigation is the most suitable anti-waterlogging measure. The usefulness of the surface drains should not be underestimated by fallacious arguments that they carry very low percentage of the total volume of rain water. The usefulness of the surface drains lies in the fact that whatever they carry in floods from the waterlogged areas is the net saving from the subsoil additions and that they carry thousands of tons of salts from the ground surface, which would not have been otherwise disposed off. It is on this account, that nothing can beat the surface drains as a cheap reclamation agent.

In the areas where water-table is low and where capillarity is ineffective to bring about the saturated connection between the free water in a field and the

subsoil water, the rainfall and the irrigation do not contribute to the general water-table. Water is absorbed and is disposed off by the evaporation and the transpiration by the plants. Evaporation alone is strong enough to deal with all rain and irrigation water. Evaporation may be assessed on the safe side as one quarter inch a day. In a year evaporation will dispose off about 90 inches of depth of water. Nowhere in the plains of the Punjab, we have, Irrigation and Rainfall combined more than about 4 feet a year. Effective evaporation from moist soil is about one-half of that from free water surface. Under such conditions, the rainfall and the irrigation do not affect the waterlogging trouble. The general water-table under such areas is influenced only by the underground flow. In such areas, the antiwaterlogging remedies such as lining of channels or restriction of irrigation and the reclamation agents such as surface drains aro not at all needed even as preventive measures.

ABBREVIATIONS.

1. B. S. P. Basic Soil Pressure.
2. P. E. C. Punjab Engineering Congress.
3. L. C. C. Lower Chenab Canal.
4. U. C. C. Upper Chenab Canal.
5. U. J. C. Upper Jhelum Canal.

APPENDIX I.

Pressure Observation at 14 B experiments on 18-10-1938.
Bed Level = 751·54, *Depth* = 3·596

No.	Description of pipe.	Reading from top.	R. L. of M. P.	R. L. of water in pipe.	Length of pipe.	R. L. of base of pipe.	Condition of soil in pipe.	Pressure Level below bed.	REMARKS.
1	B. S. P. spring level	10·44	757·19	746·75	24·71	732·48	Water	4·83	*Note* 1. Strainer length of B. S. P. pipe 3·0 ft.
2	Pressure pipe No. 1.	4·80	756·19	...	5·15	751·04	Dry	...	*Note* 2. Reading of B. S. P. on 17-10-38. = 10·35 Reading of pipe P_6 on ,, = 8·07 Drop in B. S. P. during night = 0·09 Drop in pipe P_6 ,, ,, = 0·06
3	P_2	5·91	756·09	...	6·15	750·54	Moist	...	
4	P_{3L}	7·24	756·80	...	7·26	749·54	Dry	...	
5	P_{3R}	7·00	756·59	...	7·05	749·54	Moist	...	
6	P_{4L}	7·48	756·04	...	7·50	748·54	Moist	...	
7	P_{4R}	8·01	756·59	...	8·05	748·54	Dry	...	
8	P_5	9·23	754·04	...	9·5	747·54	Moist	...	
9	P_6	9·03	756·89	747·86	9·65	746·54	Water	4·19	

Time Observation for suction head 2·2 to 2·0 ft.

No.	Description of pipe.	Base of pipe below bed.	Soil condition before.	Soil condition after.	No. of tests.	Time.	Rise in W. L.
1	B.S.P., pipe spring level.	10·0	Water	Water	1	Unlimited	*Nil*
2	Pressure pipe P_1	·5	Dry	Dry	1	16m. 27sec.	−·02′
3	P_2	1·0	Moist	Moist	1	6m. 10½ ,,	−·01′
4	P_{3L}	2·0	Dry	Dry	2	1m. 57 ,,	...
5	P_{3R}	2·0	Dry	Water	5	20 ,,	·20′
6	P_{4L}	3·0	Moist	Wet	1	49m.	...
7	P_{4R}	3·0	Wet	Water	3	1m. 10sec.	0·15′
8	P_5	4·0	Moist	Moist	1	7m.	...
9	P_6	5·0	Water	Water	2	1m. 20sec.	·01′

Notes :—

1. In case of B. S. P. Pipe no change in water level in U Tube which proved that the apparatus did not leak.
2. All pipes after tests filled with water to top and sinkage was negligibly slow in all pipes except P_{3R} which took 78 seconds to drop from 0·5′ to 1·0′ from top.

Detail of 5 tests of Pipes P_{3R}

Scale reading.	1st Observation time in Sec.	II Observation time	III Observation.	IV Observation.	V Observation.
1·1	0	0	0	0	0
1·0	30	28	85	52	87
·9	48	75	110	165	240
·8		163	225		
·7		372			

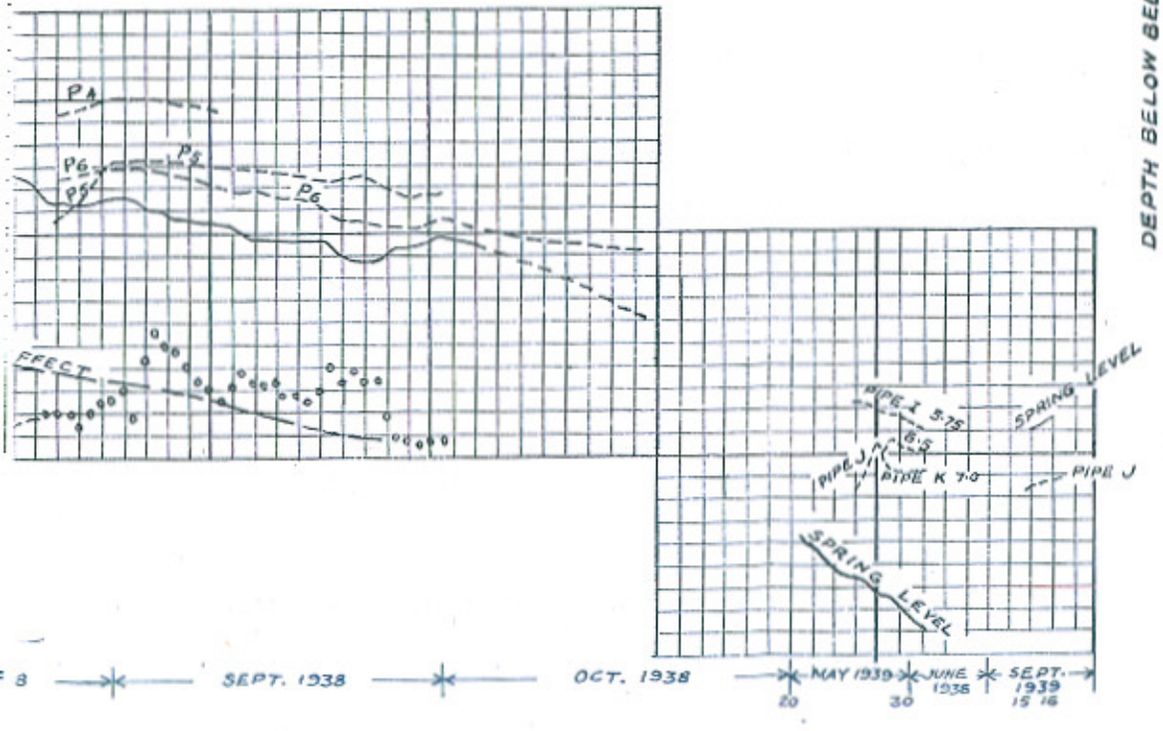
Detail of two tests of P_{4R}

Scale reading.	Time I Observation.	Time II Observation.
1·1	0	0
1·0	70	60
·9	150	132
·8	234	210
·7	322	

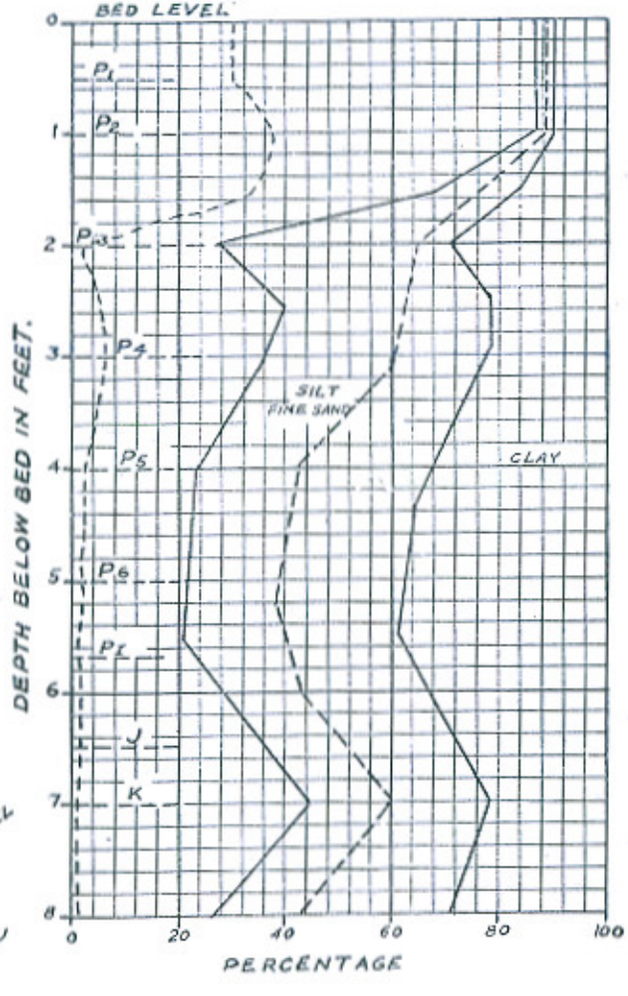
PLATE I
PAPER NO. 231

PERIODS OF UNSATURATED PHASE.

1. 26-12-36 TO 28-2-37	DROPPING	W.T.	FROM	5·0	TO	5·7	BELOW BED.
2. 11-6-37 TO 24-7-37	RISING	W.T.	"	6·55	TO	4·13	" "
3. 5-12-37 TO 10-1-38	DROPPING	W.T.	"	5·0	TO	5·85	" "
4. 11-1-38 TO 5-3-38	RISING	W.T.	"	5·85	TO	5·1	" "
5. 6-3-38 TO 7-6-38	DROPPING	W.T.	"	5·1	TO	7·5	" "
6. 7-6-38 TO 20-6-38	RISING	W.T.	"	7·5	TO	3·8	" "
7. 25-5-39	DROPPING	W.T.	B.S.P.	7·5	BELOW	BED	
8. 18-5-39	"	W.T.	B.S.P.	6·6	"	"	



SOIL ANALYSIS



FREE WATER SURFACE R.L. 755·54

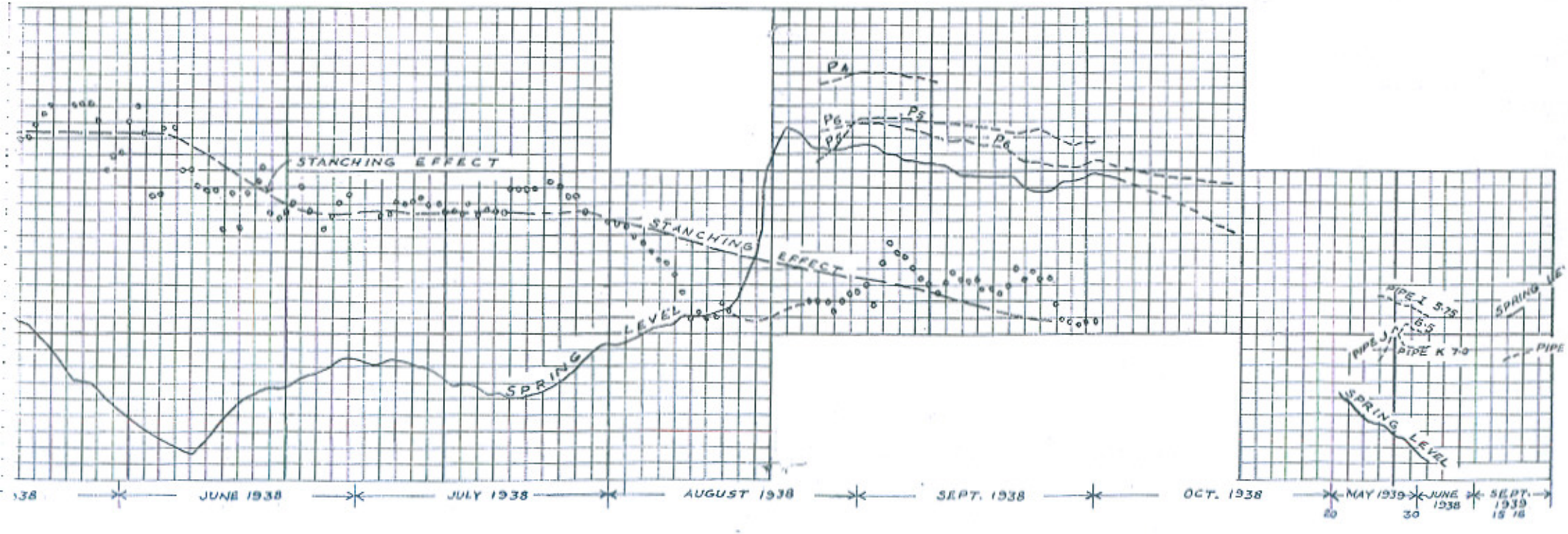
ow BED
"
·3 ABOVE BED
3·2 BELOW BED

PERIODS OF PARTIALLY SATURATED PHASE

1. 4-11-36 TO 25-12-36 W.T. FROM 3·4 TO 5·1 BELOW BED.
2. 24-7-37 TO 2-8-37 RISING W.T. FROM 4·1 TO 2·5 BELOW BED.
3. 24-9-37 TO 4-12-37 DROPPING W.T. " 3·2 TO 5·05 " "
4. 23-8-38 TO 8-9-38 " WATER STEADY 3·4 TO 4·0
5. 18-10-38 " W. T. B.S.P. 4·8 BELOW BED.

PERIODS OF UNSATURATED PHASE.

1. 26-12-36 TO 28-2-37	DROPPING	W.T.	FROM	5·0	TO	5·7	BELOW BED.
2. 11-6-37 TO 24-7-37	RISING	W.T.	"	6·55	TO	4·13	" "
3. 5-12-37 TO 10-1-38	DROPPING	W.T.	"	5·0	TO	5·85	" "
4. 11-1-38 TO 5-3-38	RISING	W.T.	"	5·85	TO	5·1	" "
5. 6-3-38 TO 7-6-38	DROPPING	W.T.	"	5·1	TO	7·5	" "
6. 7-6-38 TO 20-8-38	RISING	W.T.	"	7·5	TO	3·8	" "
7. 25-5-39	DROPPING	W.T.	B.S.P.	7·5	BELOW	BED	
8. 18-5-39	"	W.T.	B.S.P.	6·6	"	"	



EXPERIMENT AT R.D. 40000 OF 14R DISTY:

SEEPAGE LOSSES AND PRESSURES FROM JUNE 1937 TO SEPT. 1939

PERIODS OF SATURATED PHASE.

1. 21-7-36 TO 25-8-36 RISING WATER TABLE 3·52 TO 0·82 BELOW BED
2. 26-8-36 TO 3-11-36 DROPPING " " 0·52 TO 3·4 " "
3. 3-8-37 TO 10-9-37 RISING " " 2·5 BELOW BED TO ·3 ABOVE BED
4. 11-9-37 TO 24-10-37 DROPPING " " ·3 ABOVE BED TO 3·2 BELOW BED

PERIODS OF PARTIALLY

1. 4-11-36 TO 25-12-36 W.T. FR
2. 24-7-37 TO 2-8-37 RISING W
3. 24-9-37 TO 4-12-37 DROPPING
4. 23-8-38 TO 9-9-38 " W
5. 18-10-38 " "

PRESSURE IN PIPE 3.0 FT. BELOW BED ZERO ON 30-11-37

ZERO PRESSURE FROM 1-1-1938 4.0 FT BELOW BED.

PIPE 5.0' BELOW BED ZERO FROM 9-1-38

5·0 FT. PIPE STARTED RECORDING PRESSURE AGAIN FROM 1-2-38

RESTARTED AFTER A BREAK

BED LEVEL = 751·54

CLOSURE

SPRING LEVEL

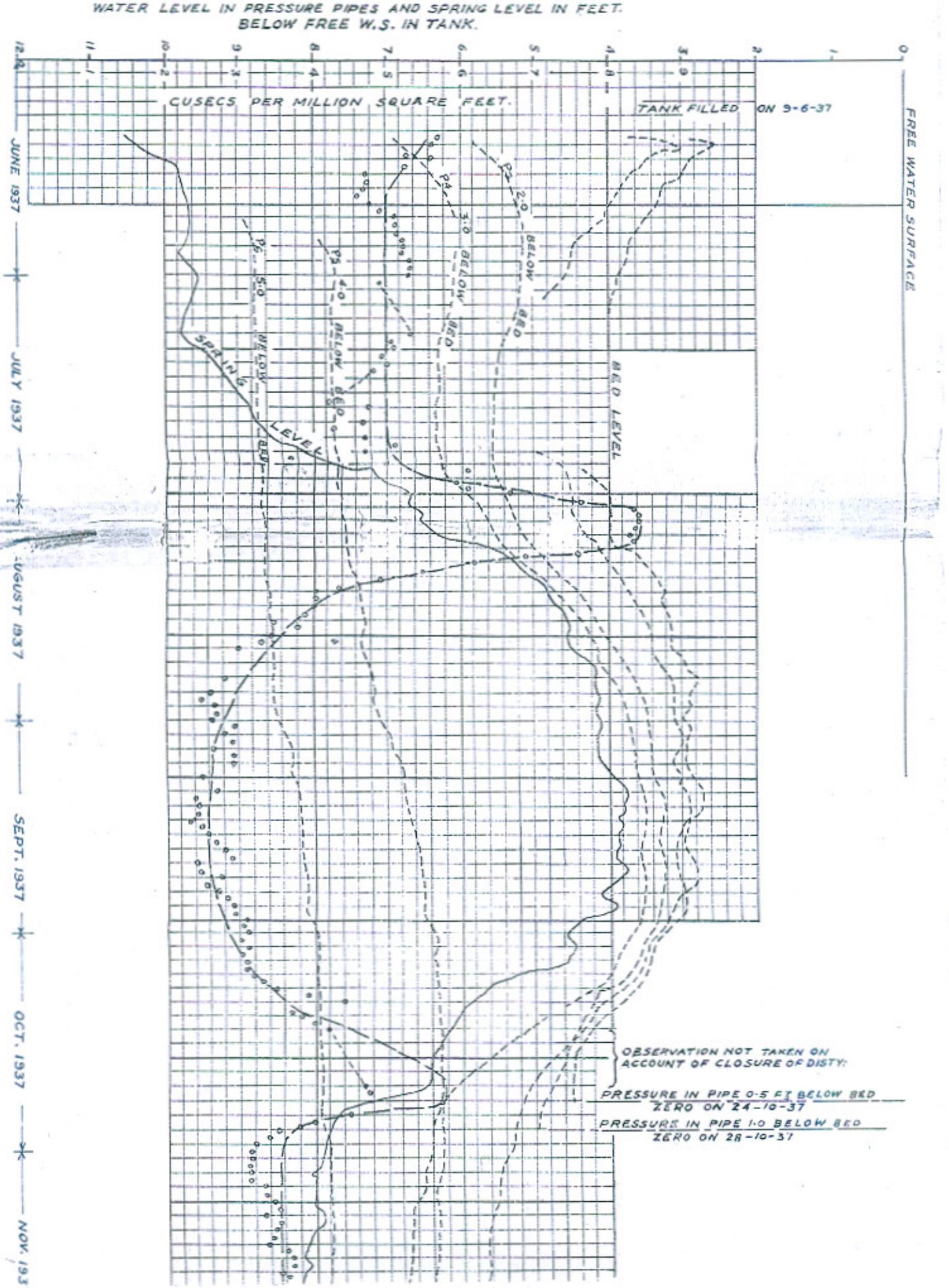
PRESSURE

RAINING

SPRING LEVEL

RESTARTED AFTER A BREAK AND CLOSURE

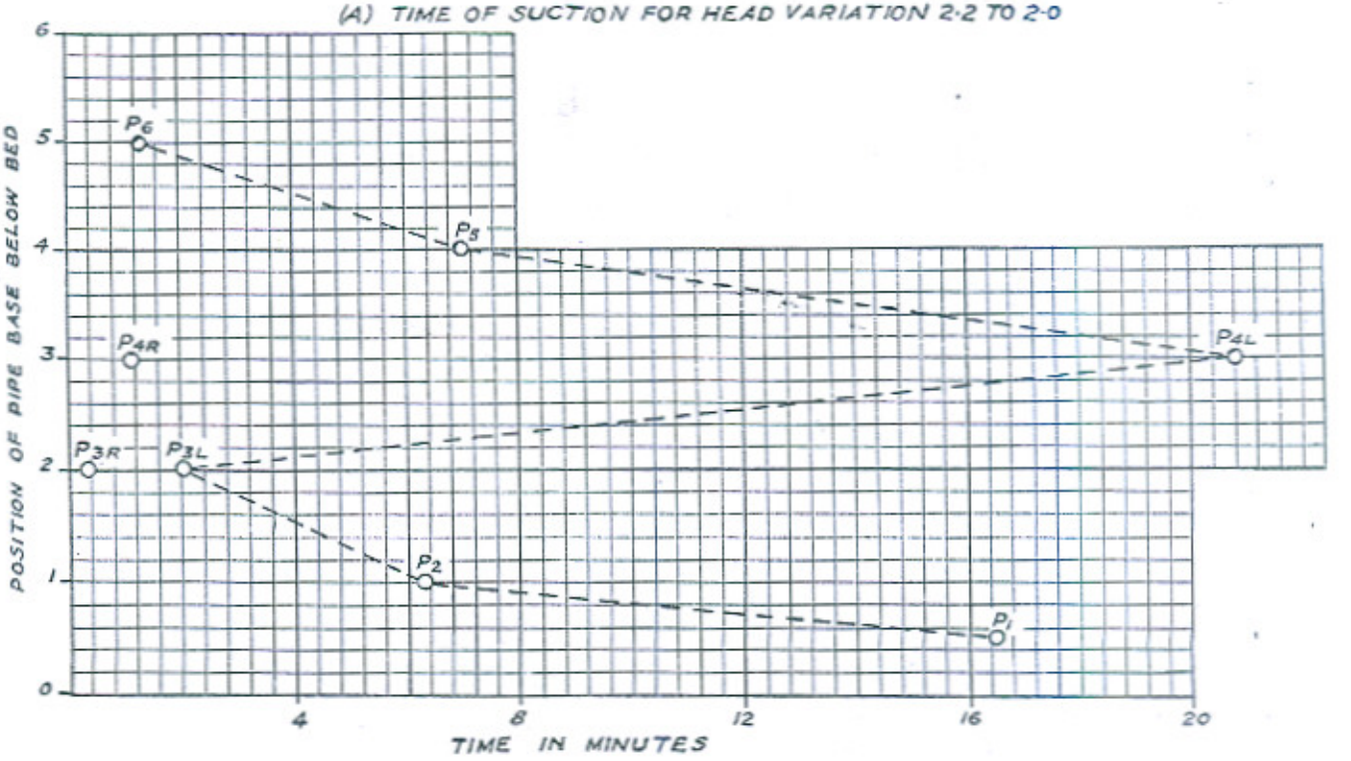
DEC. 1937 — JAN: 1938 — FEB. 1938 — MARCH 1938 — APRIL 38 — MAY 1938 — JUNE 1938


WATER LEVEL IN PRESSURE PIPES AND SPRING LEVEL IN FEET.
BELOW FREE W.S. IN TANK.
CUSECS PER MILLION SQUARE FEET.
TANK FILLED ON 9-6-37
FREE WATER SURFACE
BED LEVEL
P1 5.0 BELOW BED
P2 4.0 BELOW BED
P3 3.0 BELOW BED
P4 2.0 BELOW BED
SPRING LEVEL
JUNE 1937
JULY 1937
AUGUST 1937
SEPT. 1937
OCT. 1937
NOV. 1937
OBSERVATION NOT TAKEN ON ACCOUNT OF CLOSURE OF DISTY:
PRESSURE IN PIPE 0-5 FT BELOW BED ZERO ON 24-10-37
PRESSURE IN PIPE 1-0 BELOW BED ZERO ON 28-10-37

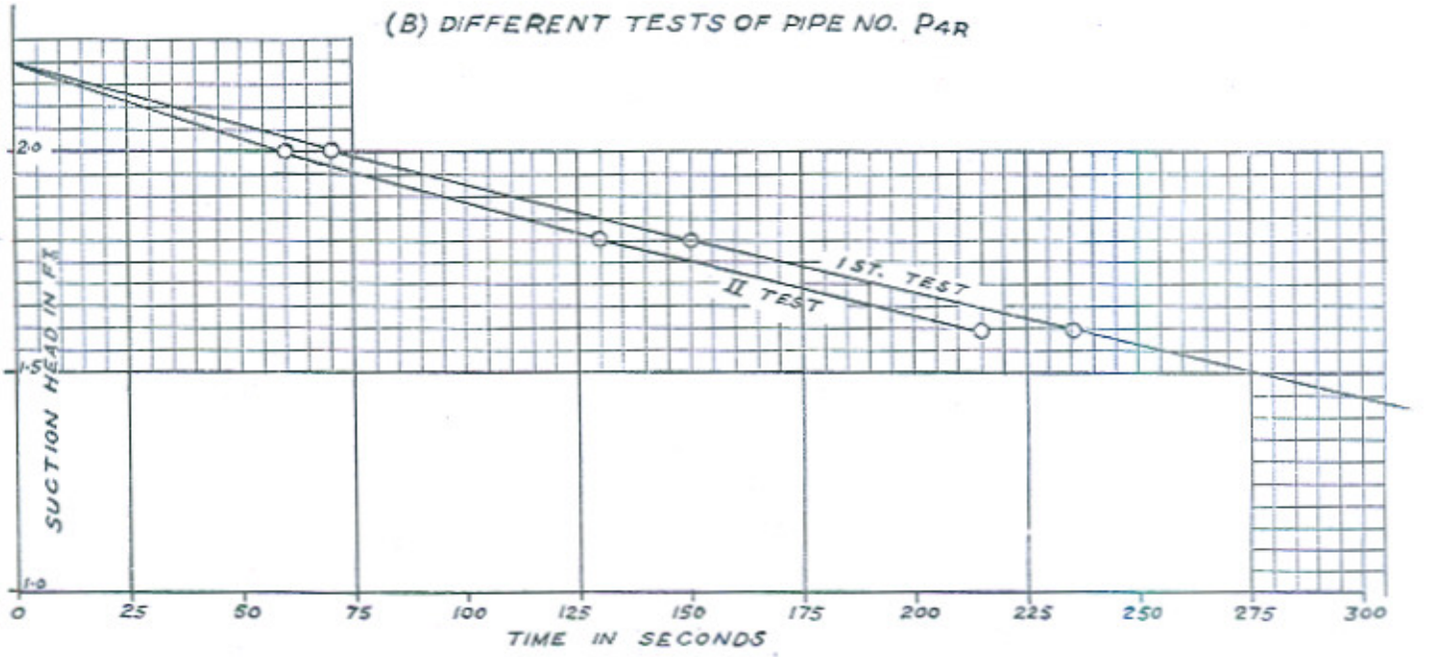
SUCTION TESTS OF PRESSURE PIPES

14 R TANK EXPERIMENTS U.J.C.

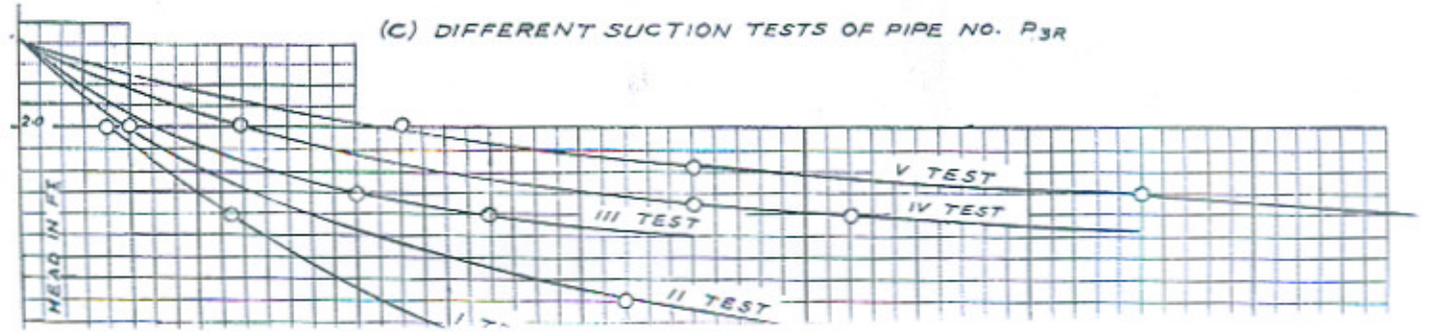
(A) TIME OF SUCTION FOR HEAD VARIATION 2·2 TO 2·0



(B) DIFFERENT TESTS OF PIPE NO. P4R

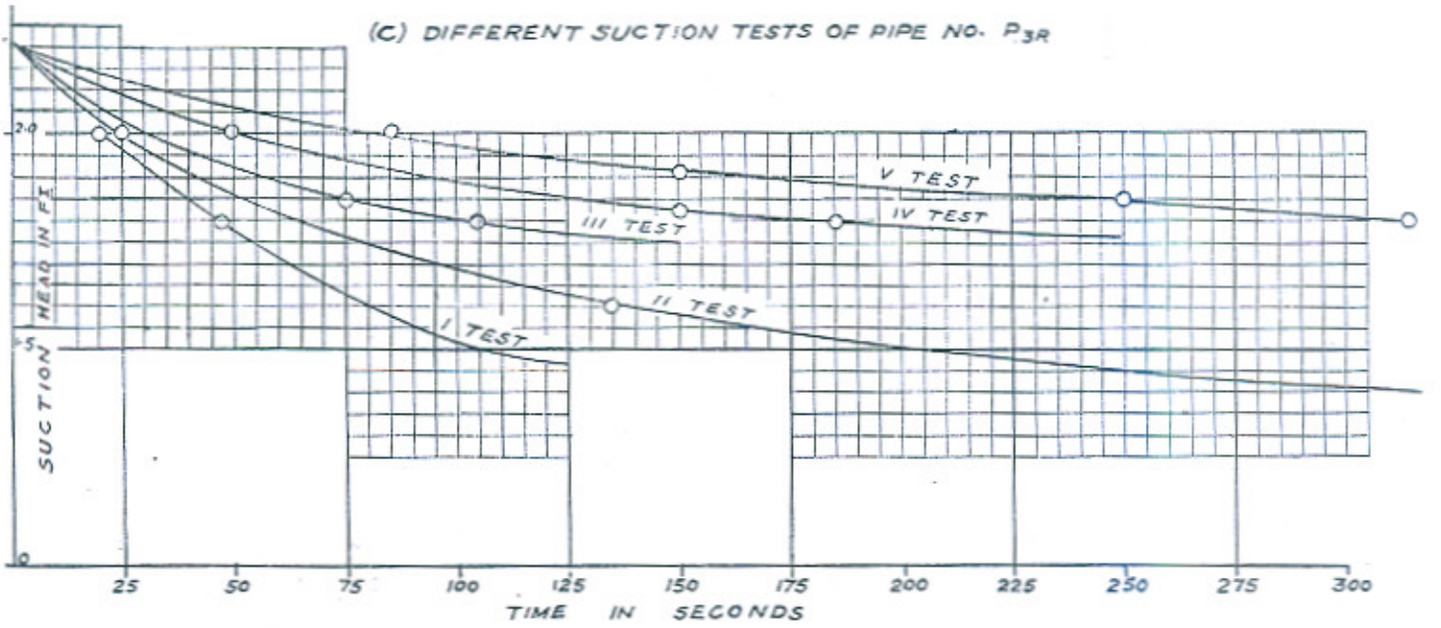


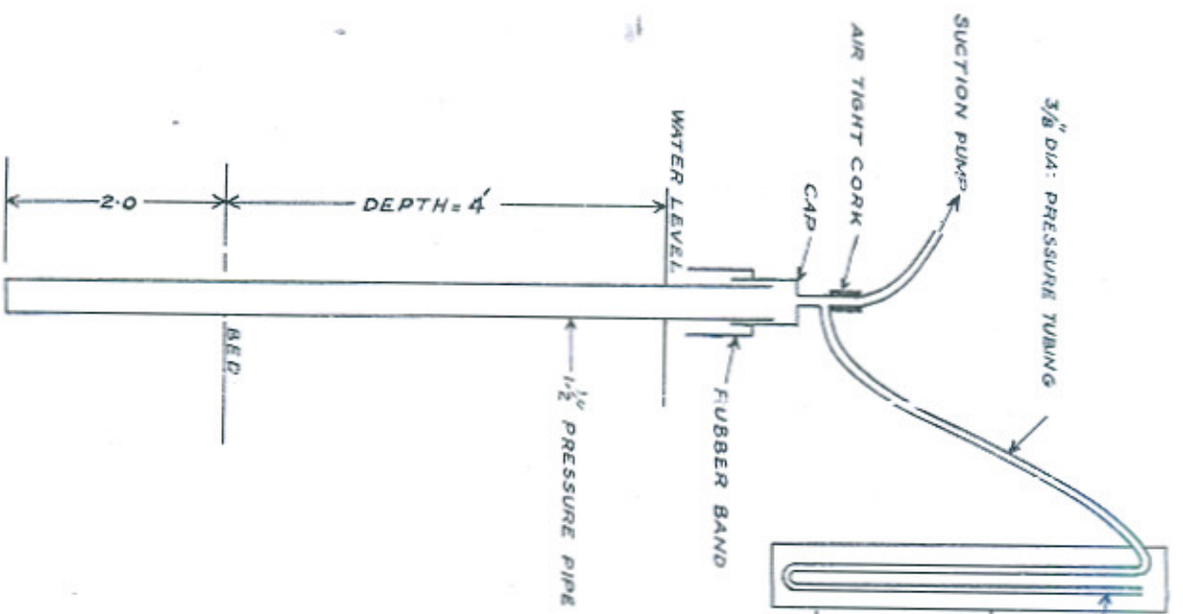
(C) DIFFERENT SUCTION TESTS OF PIPE NO. P3R



TIME IN SECONDS

(C) DIFFERENT SUCTION TESTS OF PIPE NO. P_{3R}





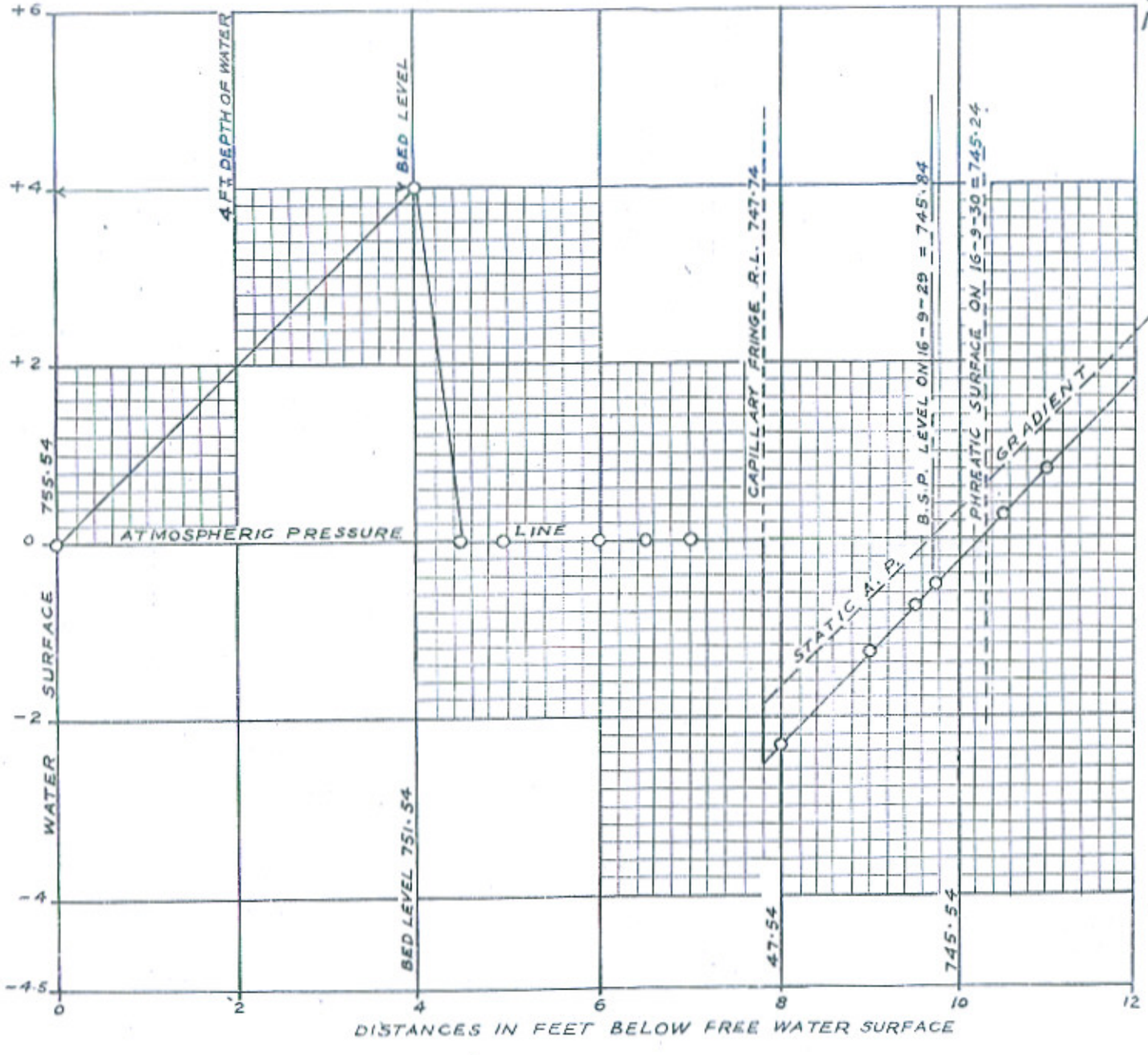
(D) SKETCH OF MANOMETER CONNECTIONS

PLATE 2
PAPER NO. 231

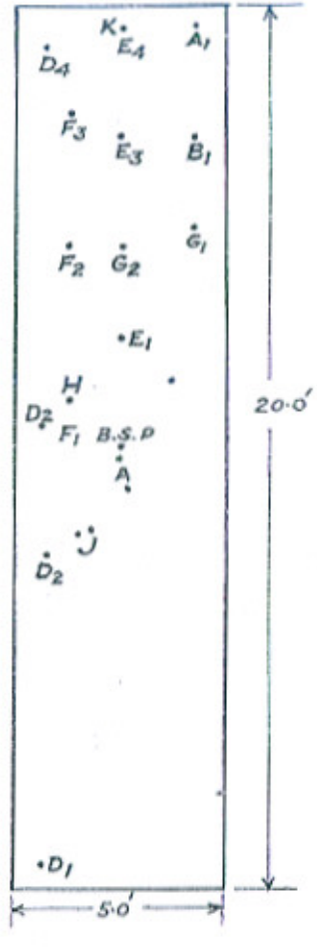
PUNJAB ENGINEERING CONGRESS
1940.

PLATE 3
PAPER NO. 231

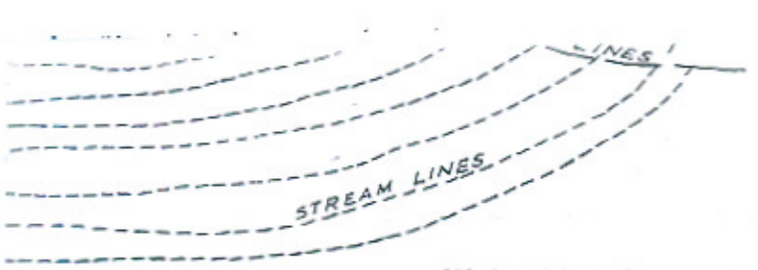
THEORY & PHYSICS OF SEEPAGE LOSSES
14 R TANK EXPERIMENTS U.J.C.
ABSOLUTE PRESSURE DIAGRAM



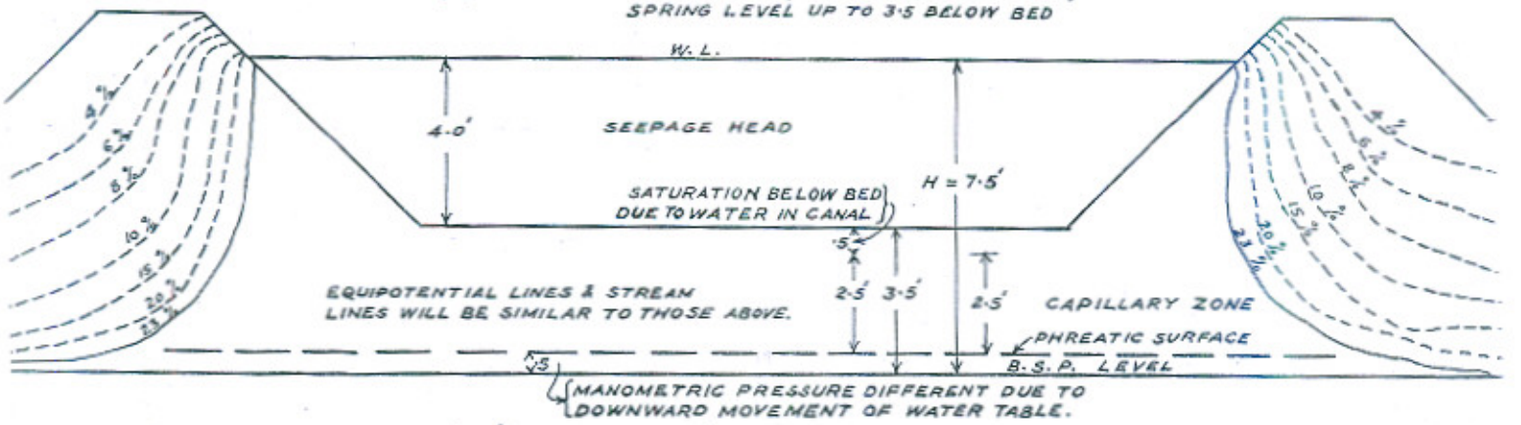
SITE PLAN OF PIPE TESTED
20'x5' TANK



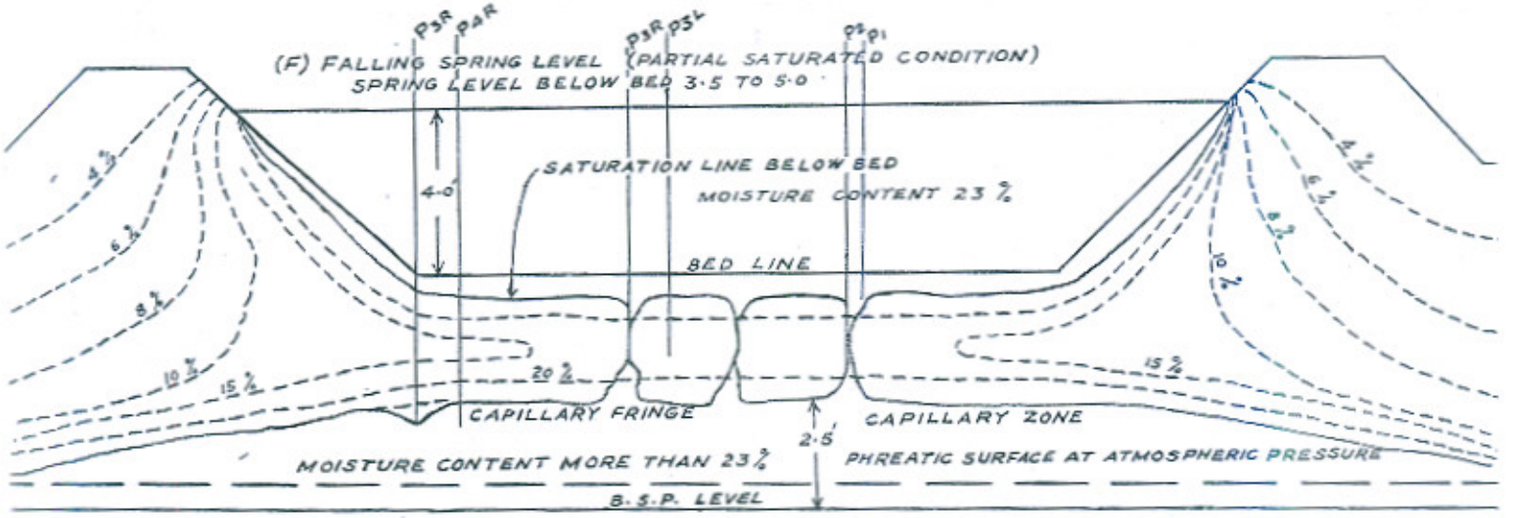
PUNJAB ENGINEERING CONGRESS
1940.



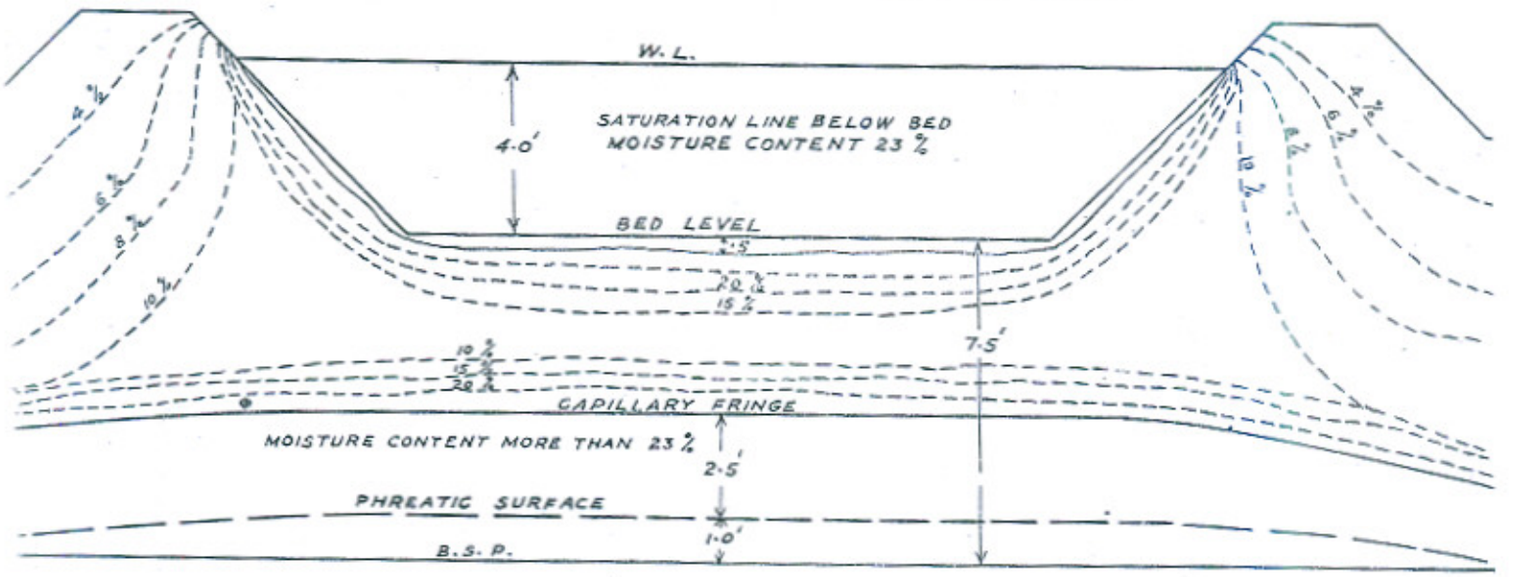
(E) FALLING SPRING LEVELS (SATURATED CONDITION)
SPRING LEVEL UP TO 3·5 BELOW BED



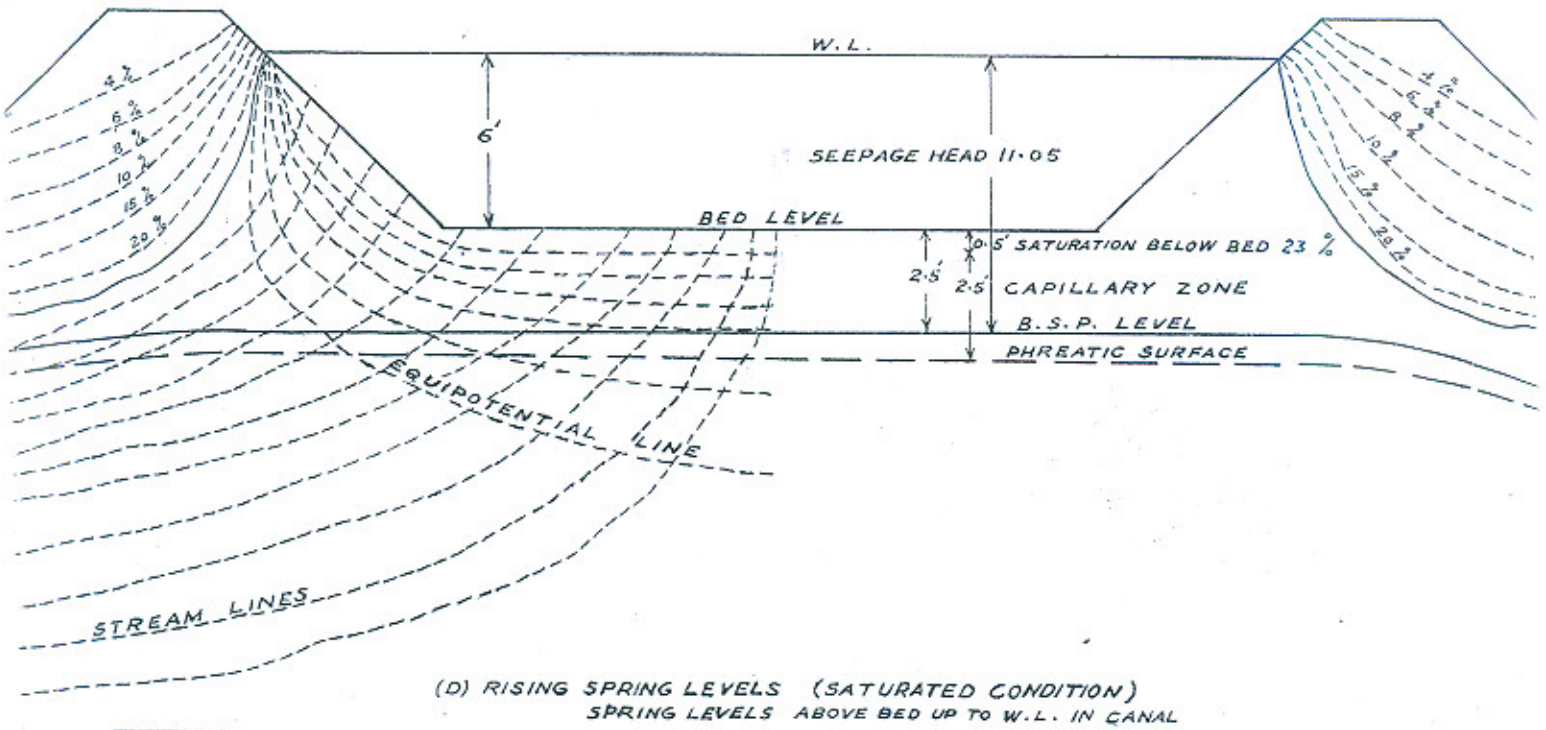
(F) FALLING SPRING LEVEL (PARTIAL SATURATED CONDITION)
SPRING LEVEL BELOW BED 3·5 TO 5·0



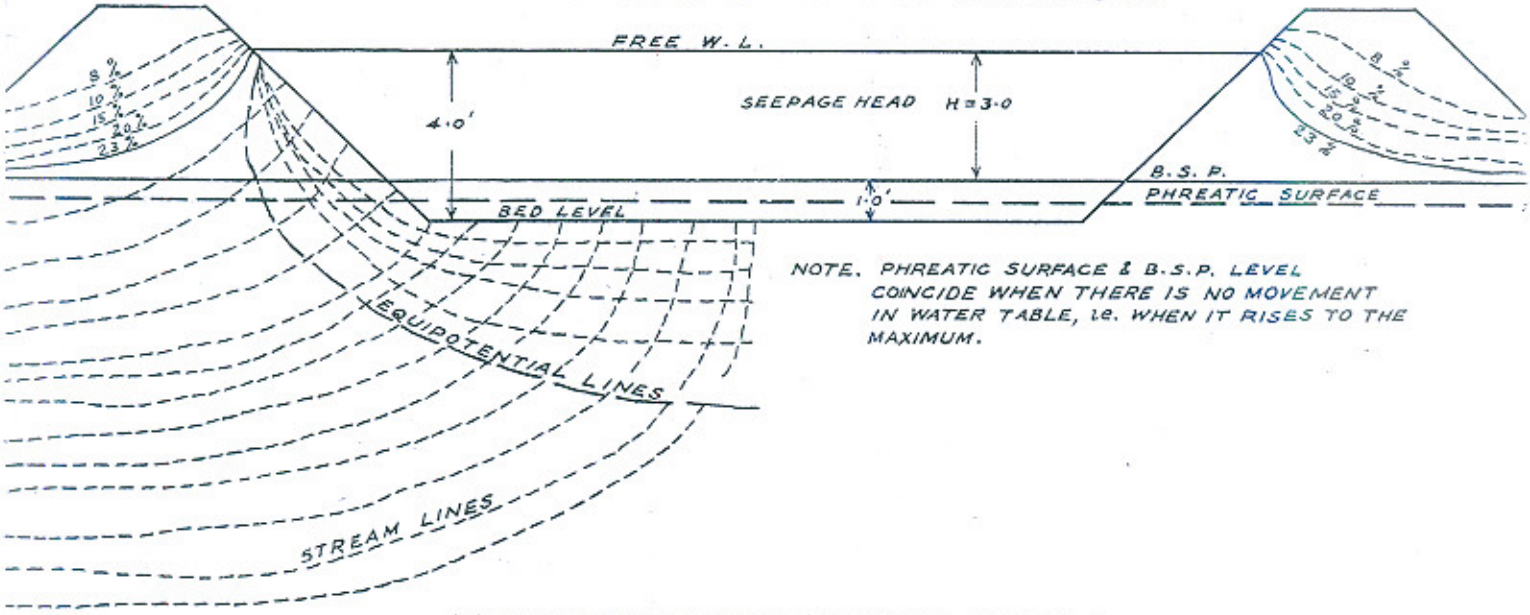
(G) FALLING SPRING LEVELS (UNSATURATED CONDITION)
SPRING LEVEL MORE THAN 5·0 BELOW BED



(C) RISING SPRING LEVELS SATURATED CONDITION
SPRING LEVELS BELOW BED 2·5 TO BED

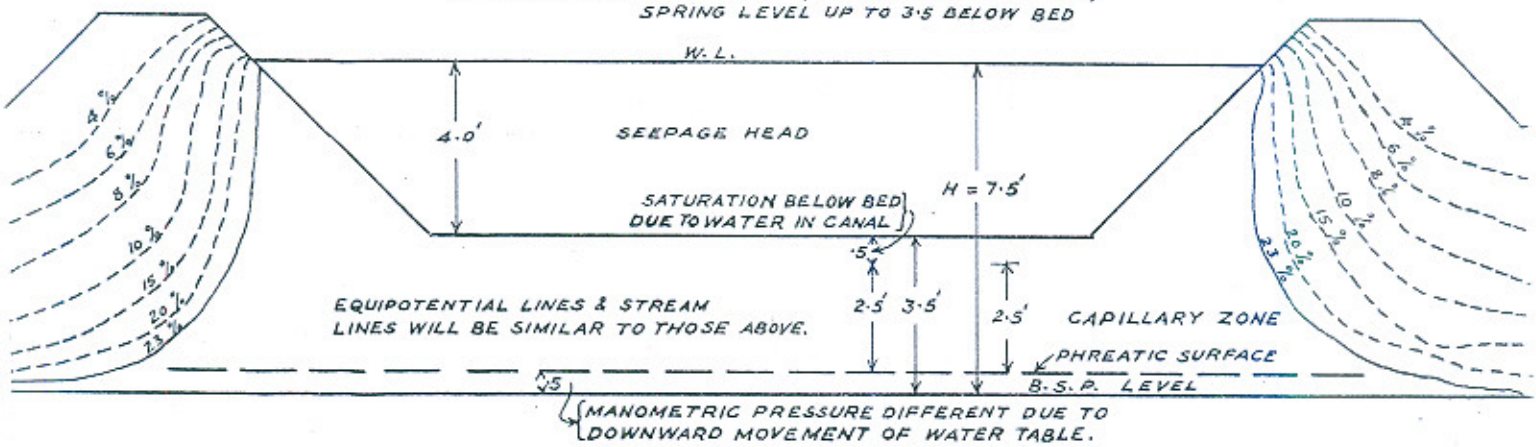


(D) RISING SPRING LEVELS (SATURATED CONDITION)
SPRING LEVELS ABOVE BED UP TO W.L. IN CANAL



NOTE. PHREATIC SURFACE & B.S.P. LEVEL COINCIDE WHEN THERE IS NO MOVEMENT IN WATER TABLE, i.e. WHEN IT RISES TO THE MAXIMUM.

(E) FALLING SPRING LEVELS (SATURATED CONDITION)
SPRING LEVEL UP TO 3·5 BELOW BED



EQUIPOTENTIAL LINES & STREAM LINES WILL BE SIMILAR TO THOSE ABOVE.

(F) FALLING SPRING LEVEL (PARTIAL SATURATED CONDITION)
SPRING LEVEL BELOW BED 3·5 TO 5·0

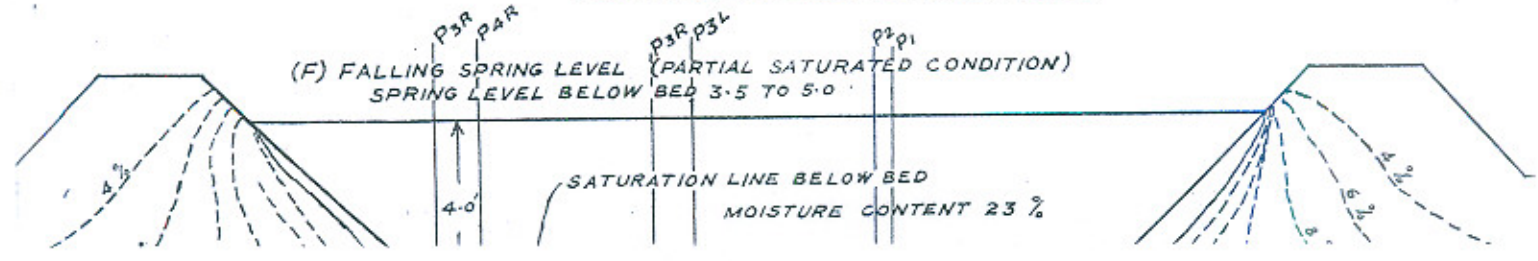


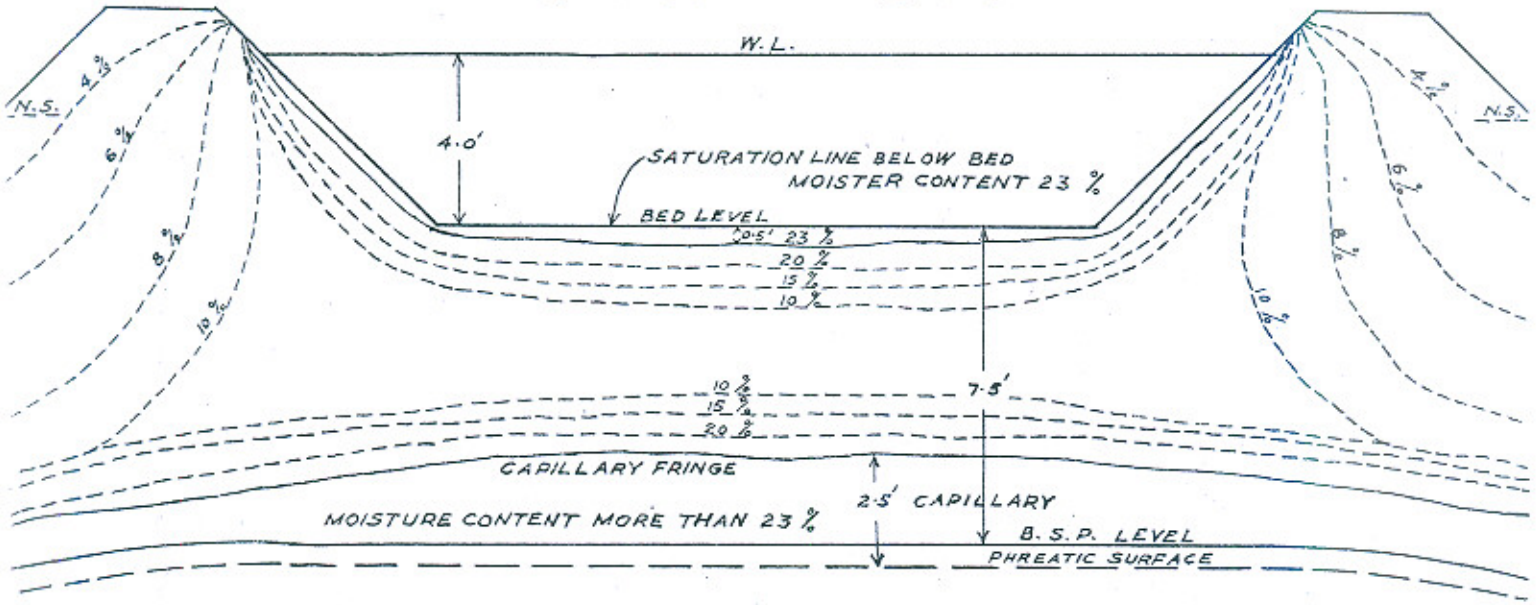
PLATE 4
PAPER NO. 231

14 R TANK EXPERIMENTS U.J.C.

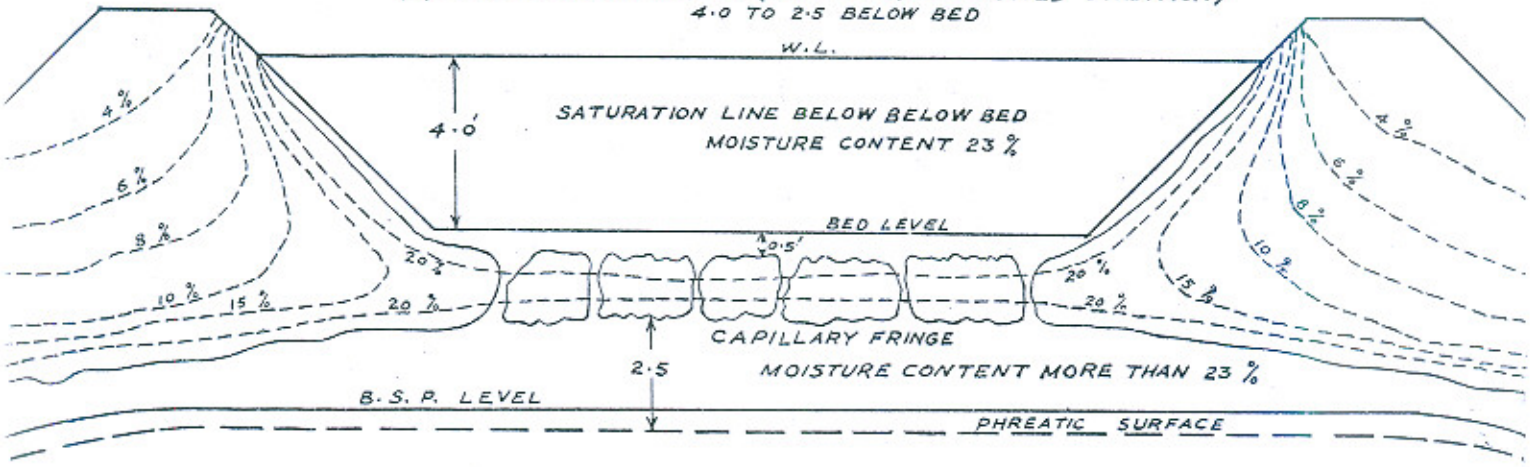
PHYSICS OF SEEPAGE LOSSES IN IRRIGATION CHANNELS

V. SCALE = 1/50

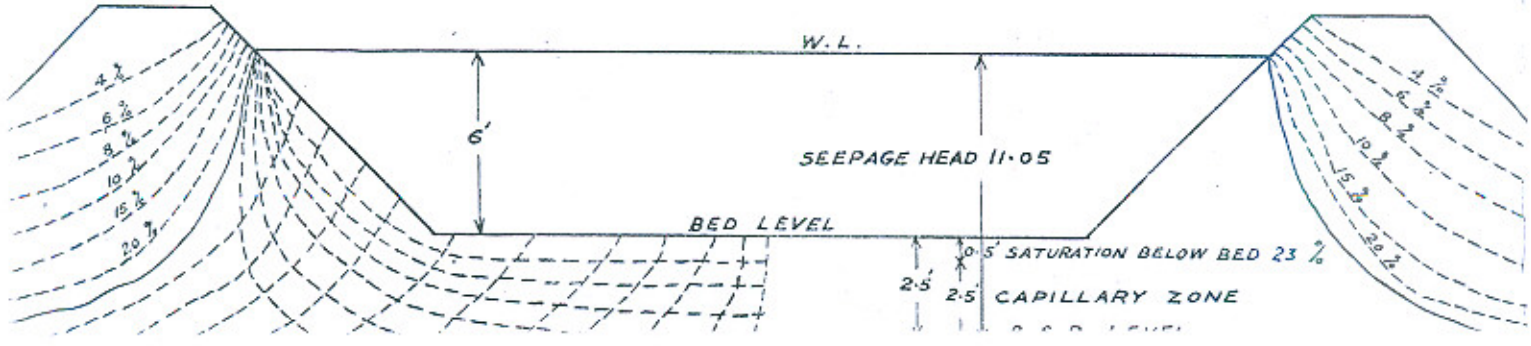
(A) RISING SPRING LEVEL (UNSATURATED CONDITIONS)
SPRING LEVEL BELOW BED 7·5 TO 4·0

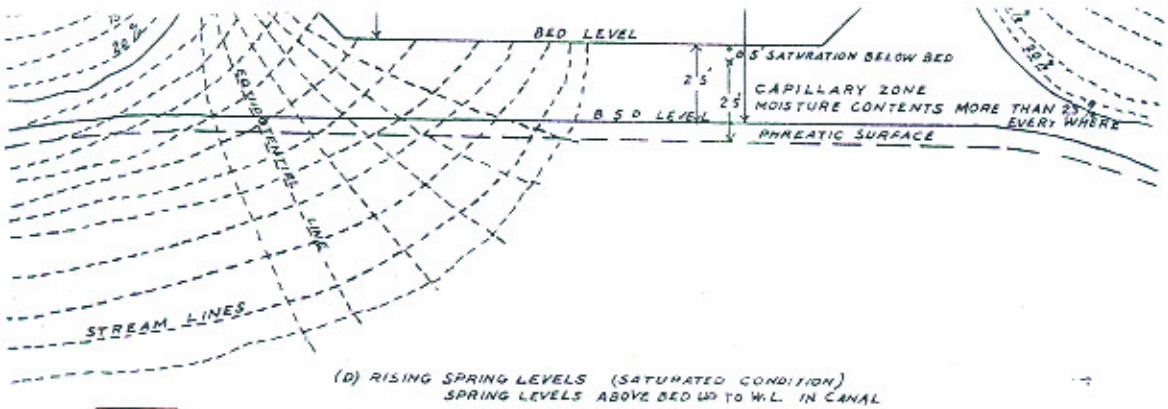


(B) RISING SPRING LEVEL (PARTIALLY SATURATED CONDITION)
4·0 TO 2·5 BELOW BED

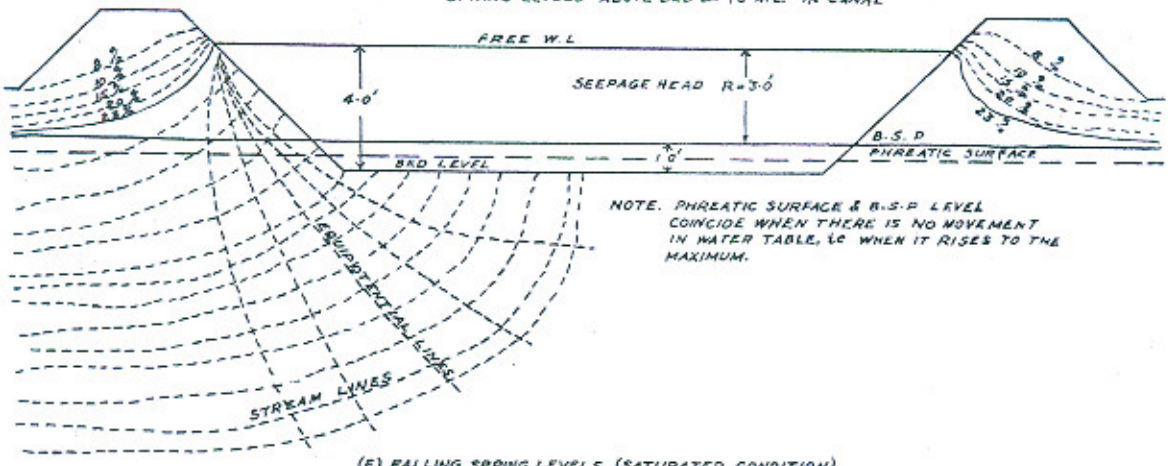


(C) RISING SPRING LEVELS SATURATED CONDITION
SPRING LEVELS BELOW BED 2·5 TO BED



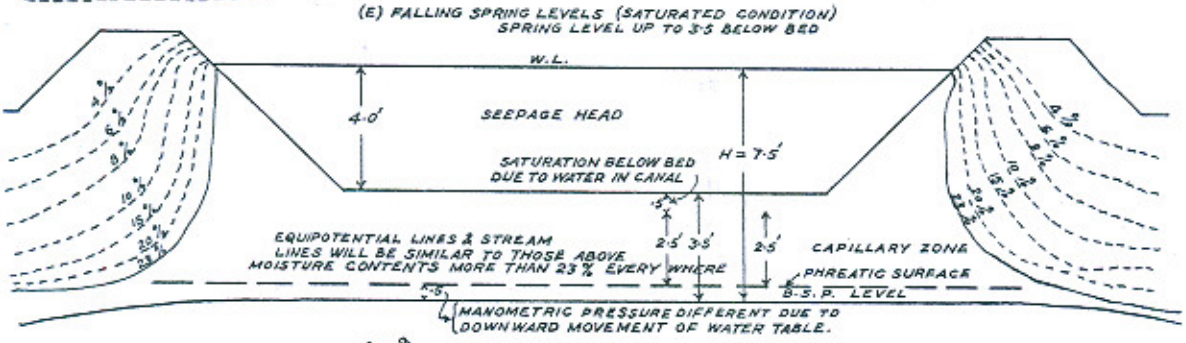


(D) RISING SPRING LEVELS (SATURATED CONDITION)
SPRING LEVELS ABOVE BED UP TO W.L. IN CANAL

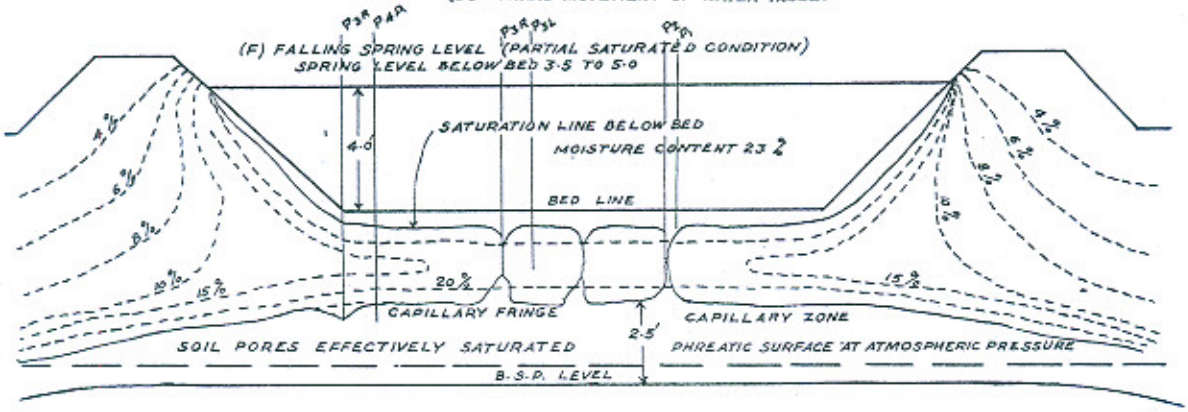


NOTE. PHREATIC SURFACE & B.S.P. LEVEL COINCIDE WHEN THERE IS NO MOVEMENT IN WATER TABLE, IE WHEN IT RISES TO THE MAXIMUM.

(E) FALLING SPRING LEVELS (SATURATED CONDITION)
SPRING LEVEL UP TO 3·5 BELOW BED



(F) FALLING SPRING LEVEL (PARTIAL SATURATED CONDITION)
SPRING LEVEL BELOW BED 3·5 TO 5·0



(G) FALLING SPRING LEVELS (UNSATURATED CONDITION)
SPRING LEVEL MORE THAN 5·0' BELOW BED

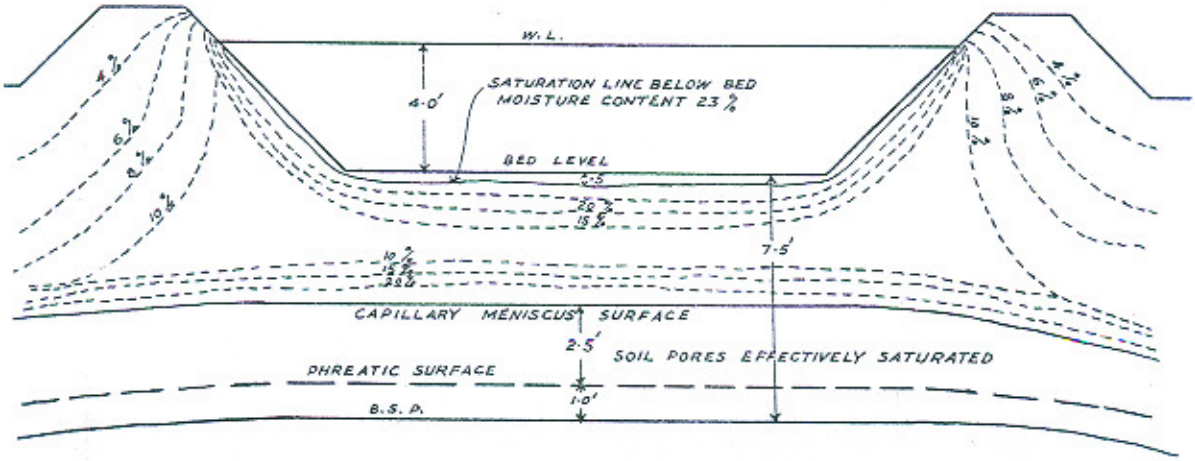


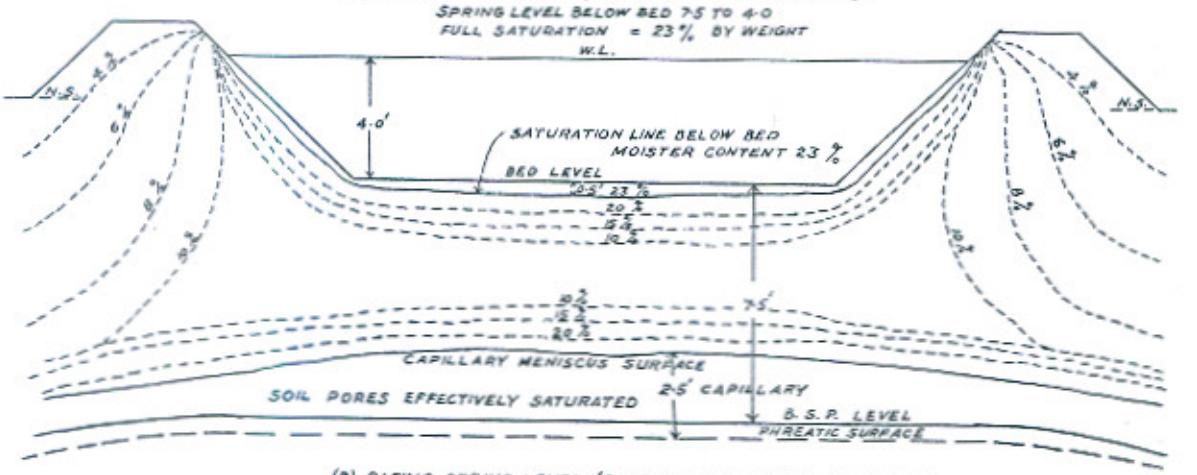
PLATE 4
PAPER NO. 231

14 R TANK EXPERIMENTS U.J.C.

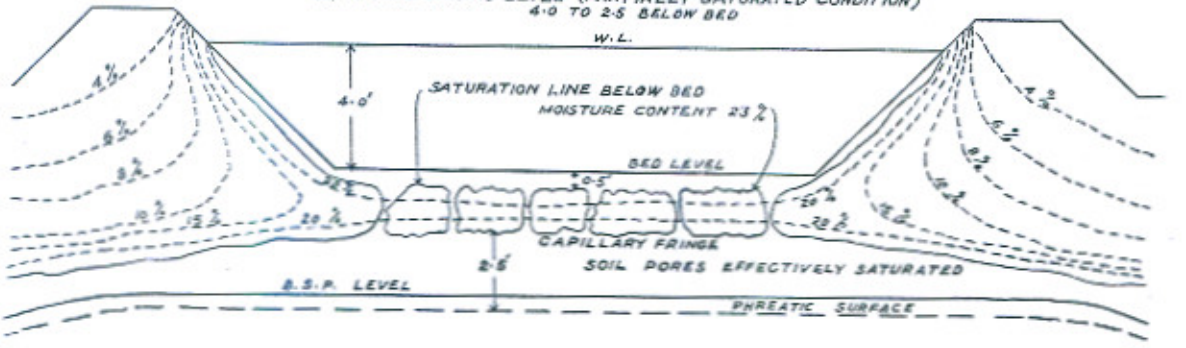
PHYSICS OF SEEPAGE LOSSES IN IRRIGATION CHANNELS

V. SCALE = 1/50

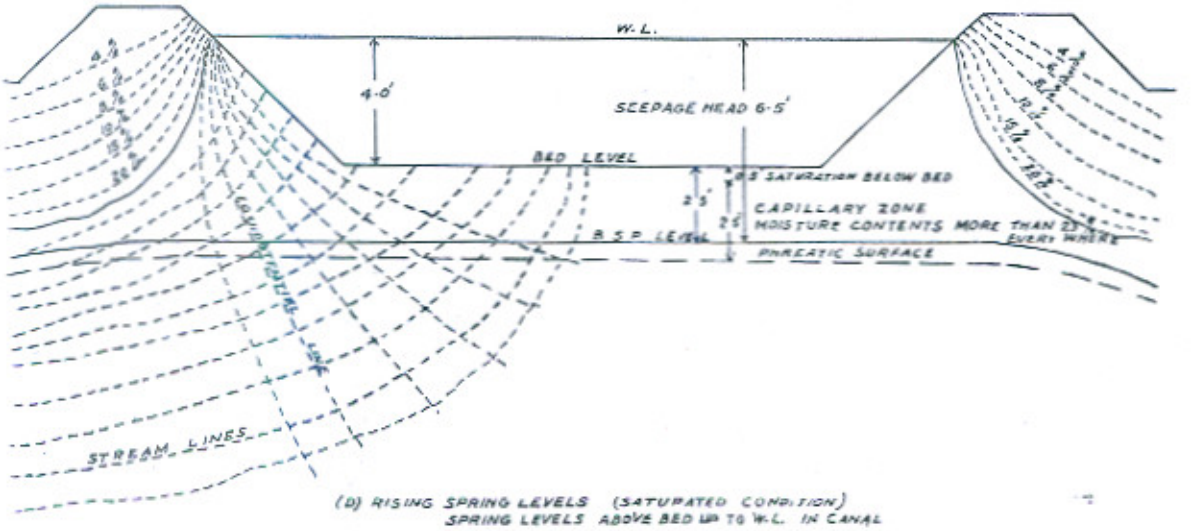
(A) RISING SPRING LEVEL (UNSATURATED CONDITIONS)
SPRING LEVEL BELOW BED 7·5 TO 4·0
FULL SATURATION = 23% BY WEIGHT



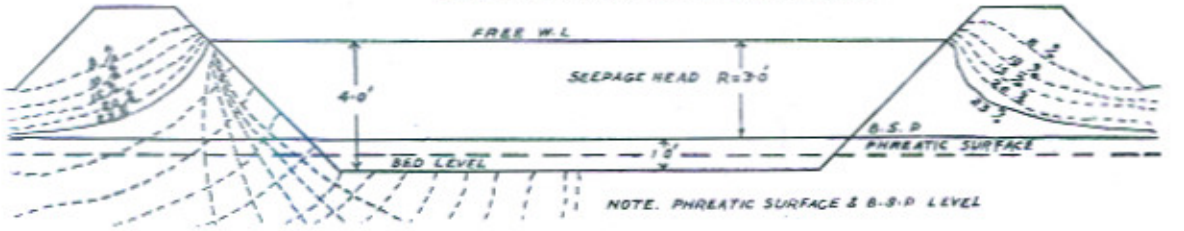
(B) RISING SPRING LEVEL (PARTIALLY SATURATED CONDITION)
4·0 TO 2·5 BELOW BED



(C) RISING SPRING LEVELS SATURATED CONDITION
SPRING LEVELS BELOW BED 2·5 TO BED



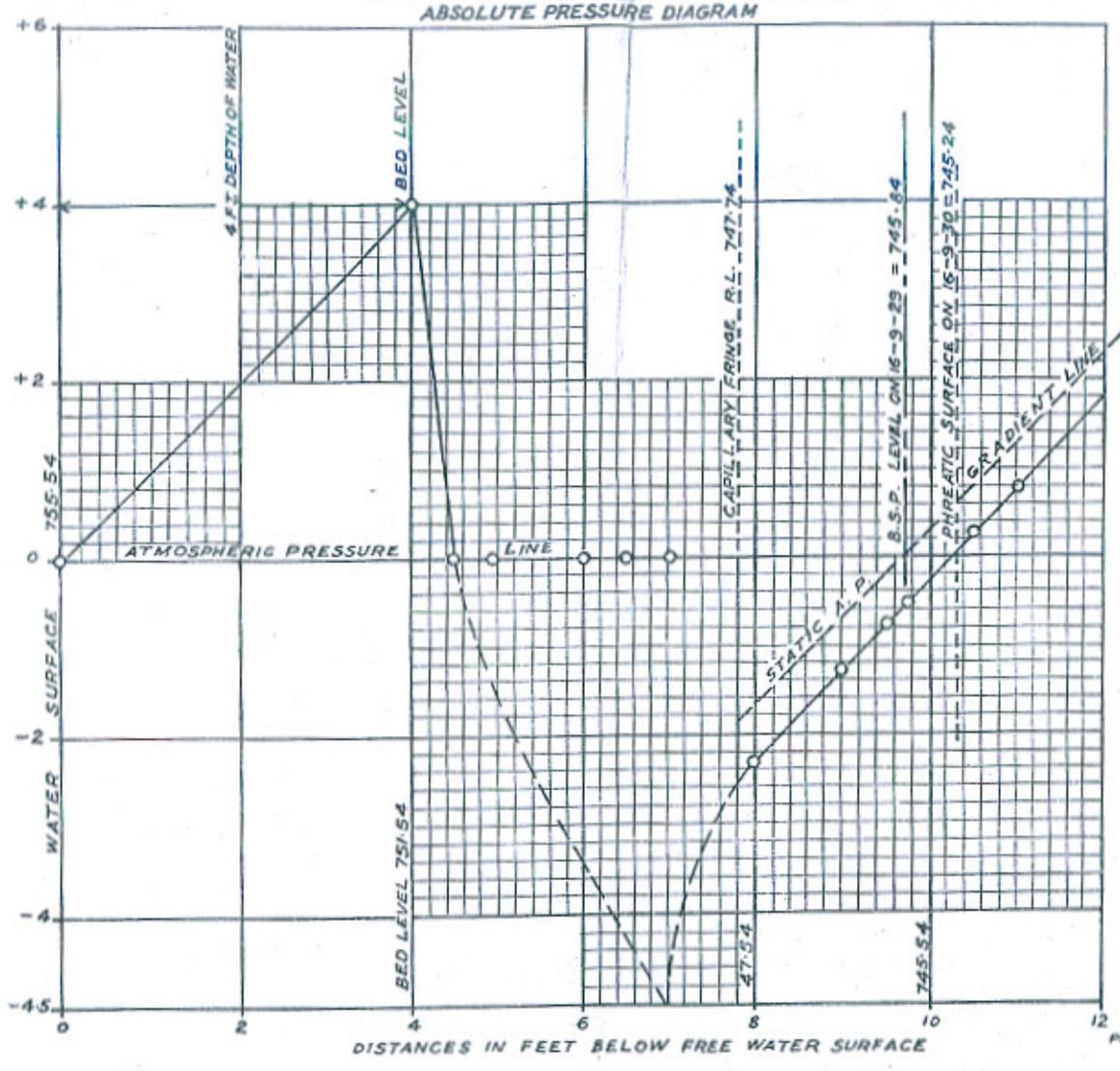
(D) RISING SPRING LEVELS (SATURATED CONDITION)
SPRING LEVELS ABOVE BED UP TO W.L. IN CANAL



NOTE. PHREATIC SURFACE & B.S.P. LEVEL

PLATE 5
PAPER NO. 231

THEORY & PHYSICS OF SEEPAGE LOSSES
14R TANK EXPERIMENTS U.J.C.
ABSOLUTE PRESSURE DIAGRAM



PUNJAB ENGINEERING CONGRESS
1940.

INTRODUCTION BY THE AUTHOR.

In introducing his Paper the **AUTHOR** said that the quantitative results of seepage losses from canals were published in Plate No. 4, Paper No. 209 of the Punjab Engineering Congress, 1938. These results were confirmed to be correct by experimental evidence at the Poona Central Research Institute as pointed out by Mr. Inglis in the discussion of the said Paper. The results are graphically shown in the sketch below :—

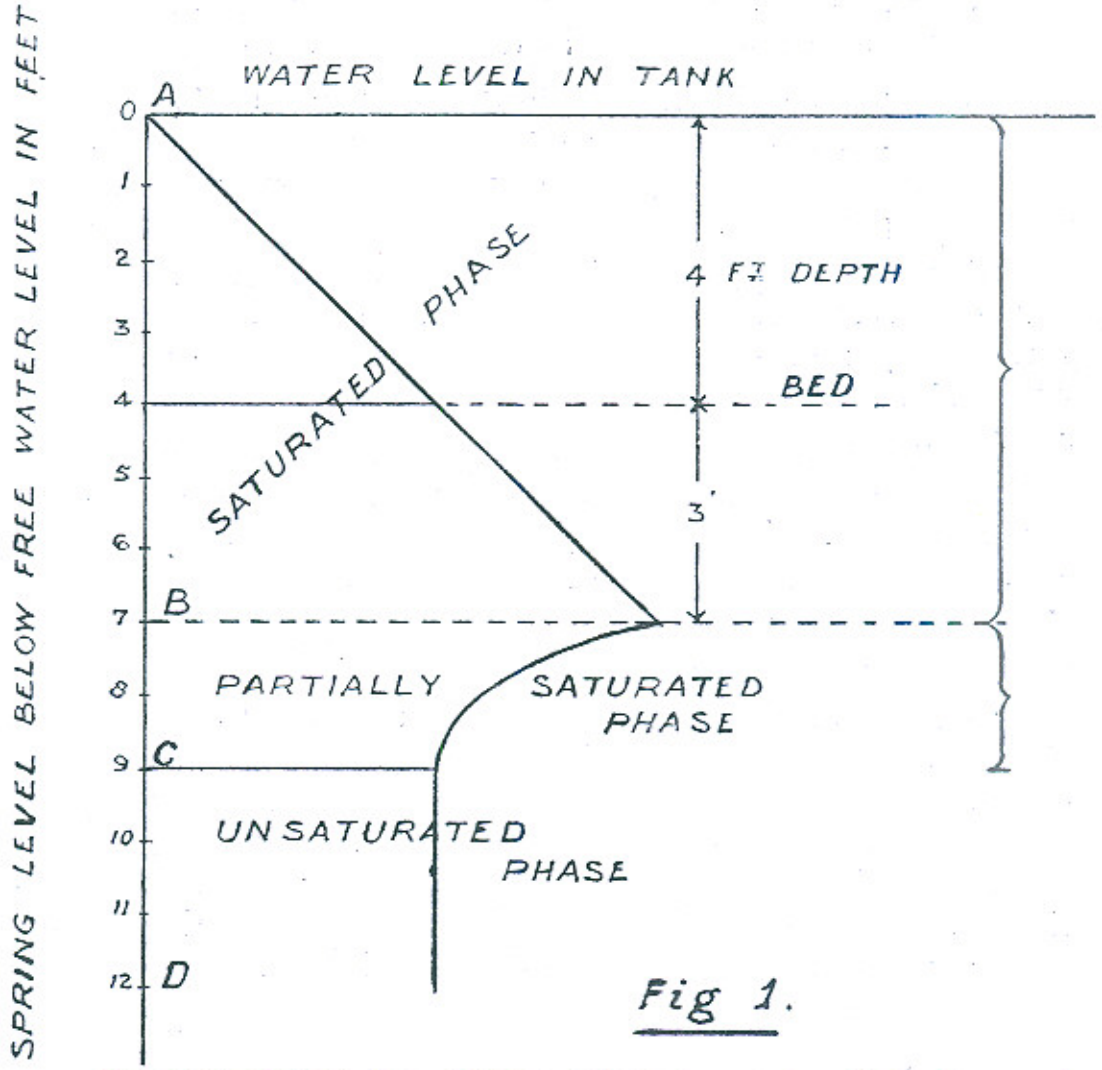


Fig 1.

Quantitatively the three phases were clear beyond doubt. In the saturated phase, the loss $q = \sigma$ H. P. It is a straight line function of the effective seepage head, H, that is, gravity. In the partially saturated conditions, it is varying and is a function of wetted perimeter and the

soil conditions but is independent of gravity. In the unsaturated phase, loss is constant and depends on the wetted perimeter and the soil conditions but is independent of gravity.

Qualitatively, the problem was not clear when the Paper No. 209 was written under the joint authorship of Mr. Nand Gopal and the Author. Further investigations were carried out and are described in this Paper elucidating the points :—

1. The soil conditions under the tank as shown by the suction tests in the three phases.
2. The seepage flow below bed of the tank, that is, the addition of seepage water from the canals to the sub-soil as shown by the observed pressure gradients.

The pressure observations were carried out by using water manometers without any addition of water to the soil. They relate only to those regions where soil pores were effectively saturated. The observed pressures are hydrostalic pressure whether positive or negative.

Where the soil pores were not effectively saturated, the water menisci pressures (Pressure Deficiency—negative) could not be measured. Under these conditions, the tests showed that free air was available which was at atmospheric pressure.

It was not thought necessary to go into the detail of soil physics in the partially saturated regions, where the soil pores were not effectively saturated. The reducing moisture contours as pointed out by Mr. Wilsdon were shown in Plate No. 4 in the regions of the partial saturation above the capillary meniscus surface of the ground water and below the saturation line below the bed of tank.

Capillary fringe is defined to be the pressure transmitting zone above the phreatic surface. At any point in this zone, the absolute pressure is negative, that is, below atmospheric and is equal for the static conditions to the height of the point above the phreatic surface. The soil pores in the fringe are effectively saturated.

Meniscus surface is defined to be the upper boundary

of the capillary fringe. Immediately above it there is no pressure transmitting water. Above it are air at atmospheric pressure and Funicular or Pendular water, held by the menisci round the points of contact of the soil particles.

The determination of capillary height in soils has been the cause of lot of trouble and controversy among the soil physists. Various theories are enumerated below in the historical order as one was superseded by the other.

1. Capillary theory of Hall and verified by Green and Ampt.
2. Heat and electricity conductivity theory of Buckingham and Gardener.
3. pF Theory of Joffe and Maclean which failed because of errors introduced by the presence of pores in the porcelain pot itself.
4. Cellular pore space theory of Briggs developed by Hains and Keen.
5. Vapour pressure theory of Fisher and Puri.

All of these theories based on the experiments in laboratories failed to determine correctly the capillary height in the actual field conditions, because it was impossible to reproduce a soil crust in a laboratory. All tried to carry out experiments in sands or ideal sands in laboratories and propounded theories which were not applicable to the soil conditions in the fields. When a soil physist says that capillarity is a wash out, he simply means that the capillary theory has been superseded and that he had no means of ascertaining capillary height in a soil crust, though he could definitely say that capillarity in sands was negligibly small.

A practical definition of capillarity has, therefore, been given as used in this Paper and practical observations have been specified to determine its height in the actual field conditions in every case. This is a practical Engineer's definition, how so much unpalatable to a soil physist.

The qualitative conception of the problem has been summarised in the conclusions in this Paper in the three phases of the losses. There is one conclusion which needs special mention and elucidation. It is the Author's conclusion that the seepage loss (absorption) in the unsaturated phase does not reach the water table and, therefore, does not affect the water-logging. This is a very important point and its full realization will cut short the cost of anti-waterlogging measures by about 75 per cent. There will then be no need to waste money on lining water courses and channels and no adverse effect could be expected from rainfall or irrigation *in areas where the losses are in the unsaturated phases.* Fortunately such channels and such areas are about 75 per cent. in the Punjab.

There are three arguments produced in the Paper which lead to this important conclusion.

(1) The absorption loss is constant, quantitatively. The constant value shows that the position of water table or gravity, has no influence when the unsaturated phase is established. This simply means that there was some other constant factor such as soil evaporation which accounted for the loss, and that no addition was being made to the water table, which would increase with distance of the source from the water table.

(2) The reducing moisture contours as observed by Mr. Wilsdon and shown in Plate No. 4 below a canal and above the water table mean equilibrium but no liquid flow because of—

(*a*) Resistance to flow being stronger than gravity.

(*b*) Pendular water being definitely disconnected.

(*c*) Flow being possible in Funicular water only if the gradient of flow is positive and more than the equilibrium gradient.

(3) The pressure observations as given in Plate No. 3 clearly showed that even taking gravity into account there was no manometeric pressure gradient (positive) connoting downward flow. The pressure diagram was completed in the

partial saturated regions in Plate No. 3 accepting Wilsdon's observations that saturation varied as log of the distance from the full saturation line. The results are tabulated below :—

Manometric gradient below bed 14 R experiments—unsaturated phase on 16-9-39.

No.	Region below bed.	Pressure change.	Pressure drop.	Gravity.	Total drop.	Distance.	Gradient loss in ft. per foot.
1	2	3	4	5	6	7	8
1	0 to ·5	+4·0 to 0	+4·0	+ ·5	+4·5	·5	+9·0
2	·5 to 1·0	0 to −1·6	+1·6	+ ·5	+2·1	·5	+4·2
3	1 to 2·0	−1·6 to −3·5	+1·9	+1·0	+2·9	1·0	+2·9
4	2 to 3·0	−3·5 to −4·5	+1·0	+1·0	+2·0	1·0	+2·0
5	3 to 4·0	−4·5 to −2·3	−1·2	+1·0	− ·2	1·0	− ·2
6	4 to 5	−2·3 to −1·25	−1·05	+1·0	− ·05	1·0	− ·05
7	5 to 6	−1·25 to − ·2	−1·05	+1·0	− ·05	1·0	− ·05

Column No. 8 should be positive everywhere if there was any percolation or any addition to the water table.

The essential condition to establish percolation or addition to the water was that the pressure gradient was throughout positive from the bed of a source down to the water table. This essential condition was also laid down by Mr. Wilsdon on page '22-*a*,' Punjab Engineering Congress 1923. "Water movement would be determined by the factors governing absorption when the moisture content was below saturation, while percolation was *only* met with when the soil was saturated or the hydrostatic pressures positive, establishing positive gradient,"

Two more arguments in favour of this conclusion came to light while analysing a year's observations of the daily B. S. P. stations in the Rechna Doab. They are stated as below: —.

(1) Daily B. S. P. stations in the unwaterlogged areas, where the losses were in the unsaturated phase (West of Sangla and Buchiana) were not affected by the immediate sources, such as canals, distributaries, irrigation and rainfall. The closures of even branch canals had no effect.

(2) In the yearly cycle of the B. S. P. levels of the stations in the un-waterlogged areas, the highest peak did not occur in the month of August or September (synchronising with rainfall and rice cultivation) in all cases but varied according to the distance from the water-logged areas (where the additions were in the saturated phase) as given below :—

Month	*Daily B. S. P. Sites.*
August	Khanki, Hinduana, Khai (River effect).
September	Chuharkana, Sagar, Buchiana, Pacca Dalla.
October	Kot Khudayar.
November	Lyallpur and Tarkhani.
December	Tawan, Lakhlana, Muridwala, Bachherianwala.
January	Magneja.

These observations clearly showed that there was no addition to the water table in the unsaturated phase and that the B. S. P. levels in such areas were influenced only by the underground flow.

Lastly the Author pointed out that the observations and the conclusions discussed in this Paper pertained to the natural soil crust conditions. In sands, the unsaturated phase could not exist even if the water table was hundred feet below the bed of a channel, because gravity was stronger than the resistance to flow in sands. The additions to the water table in sandy soils would always be in the form of percolation (saturated or partially saturated).

Mr. Nand Gopal said that the Author deserved admiration for the patience and perseverance he had shown in pursuing this intricate subject of seepage flow. From his investigations, it appeared that the work had become an end in itself rather than a means to an end, namely seepage losses from canals. He had given the Engineer the how and why of water lost by seepage which could not but be of academic interest which scientists might fight over. To a practical Engineer he did not appear to give much help. According to him to determine losses it had first to be determined for every bit of a canal what phase of seepage existed, that is, percolation, absorption or intermediate. Then, nature of strata must be known and this was known to change in Punjab soil very frequently along the length of a canal. Then head of water pressure was to be observed. When all that had been done, results might yet be approximate only, as the co-efficients were not easily and accurately determinable. This was for existing canals. For projected canals, one might well be in a maze to get any figures to go on. For practical purposes, therefore, the statistical method of finding losses in existing canals was much to be preferred. The old figure of 8 cusecs per million sq. ft. of wetted surface had not been found to be much wrong. A nearer approximation had been found to be 8 cusecs in the dry and hot part of the year and half of it, *i.e.*, 4 cusecs per million sq. ft. in the wet and cold season. For intermediate conditions, intermediate figures might be adopted.

He added that pipes had been stuck by the Author along main canals at every mile and observations made of seepage discharge and Head, thus deducing average values of σ which he applied to reversed conditions of flow. Complicated, difficult and expensive as this method was scientists doubted its applicability. For Distributaries, such methods were even more impracticable. Therefore unless the Author could give some practical method of determining σ and H, his Paper must remain only of theoretical interest and of little practical utility.

In the last para. of his Paper "Irrigation and Rainfall" the Author had laid down many axioms of rate

of absorption and evaporation in rather a dogmatic manner. It would be interesting to know if he had made any experiments on these points. From these he had arrived at the conclusion that surface drains were of immense value as Reclamation agents. This was true in a limited sense. But when he called the low percentages of run-off a fallacious agrument, he was on slippery ground. He questioned the Author's statement that the value of drains was immense, a drain or system of drains in a catchment removed 2 or 3% of the water poured in as most drains seemed to do, and the bulk of the balance was adding to the water table. The fact was that the value of a drain was immense in its vicinity only and hardly a few hundred feet from it. If the value (and it was a big 'if') was to be immense for the whole catchment, branch drains and field drain must be made every few hundred feet apart and connected up into a net work. The cost of such a system would run into crores of rupees for a single catchment of a few hundred square miles. Thus the value of drains would be immense only if the expense was much more immense and not commensurate with the value. It was here that, as anti-waterlogging measures, tube wells and the lining of canals scored over drains as financially more sound propostitions when water saved (unlike drains) had also a value. Drains must always have only a very limited value when efficiency was compared with the cost of reclamation of any area.

Mr. Blench stated that, as the Author had been working under him on Waterlogging Investigation and performing some experiments related to those described, he felt himself compelled to make some comments. He understood that the original idea of the Paper was to deal with the experiments only, and omit all reference to waterlogging. He did not see the Paper till it was published, and regretted that the last section "Irrigation and Rainfall" dealt with waterlogging matters that could only be judged in terms of hard facts, and whose final analysis was not yet ready. He had to say that the findings of that section were quite different from his own view based on those facts, and on theory also.

The experiments themselves were of value as a check on actual soil-water pressures found between a tank bed and the water-table when the capillary fringes of both had coalesced. To his mind the work was a vindication of Wilsdon's theory. He thought the Author had got into considerable difficulties in explaining a highly complex subject, and had based his opinions on not understanding how pressure could be negative above the water-table in spite of water moving towards that water-table. The Author had got over the difficulty by concluding that the water could not be moving to the water-table at all under these circumstances, and he had produced a new phase of water movement to explain this.

Actually there was nothing remarkable about water moving against pressure—in fact it did so in the downstream half of a Ventuni Meter. In the soil-water case, however, the peculiarity was not due to acceleration ; but due to the fact that the water was in the funicular stage, *i.e*, the flow was bounded by soil particles and by capillary films. The capillary films also bounded continuous air passages as could be appreciated by visualising the three-dimensional case of Fig. 1. The films caused the water to be at less pressure than the "atmosphere" outside—just as in the simpler case of the mensiscus at the top of water in a glass capillary tube. The existence of negative pressure was thus a proof that the flow was incompletely saturated. So much for the cause of negative pressure. That fluid could move against pressure was due to the fact that it was moving downwards and its own weight was a motive force in that direction. The negative pressure gradient was, therefore, possible for downward flow so long as it did not numerically exceed the positive gravity gradient. Wilsdon's differential equations showed this clearly.

The Author in his Plate No. 4, had tacitly defined the capillary fringe from below as being fully saturated. There were ample observations from the U. S. A. and the Punjab to show that a capillary fringe formed from below was not fully saturated. In fact, a moisture gradient was required to produce the pressure gradient that counteracted

gravity and enabled it to form at all. More popularly stated, capillary movement was from moist to dry. He also showed his flow lines not at right angles to his equipotential lines—an error.

What was interesting was the difference between B. S. P. level and phreatic surface. B. S. P. level meant the level of water in a deep tapping pipe. Phreatic surface meant the true water-table, *i. e.*, the surface of atmospheric pressure in the soil water. If water were moving upwards to replace evaporatian, or in the growth of a new fringe, than the upward pressure gradient associated with moisture gradient, acted against gravity, and the lower pipe gave the higher reading. If water was moving down as in seepage, the reverse held. There could not be movement without pressure drop to cause it. This fact had not always been fully appreciated, and its non-appreciation seemed to be at the root of the statement. "There can be no water-table in a clay soil". When the water-table got into a Punjab clay crust, there was normally upward movement to evaporation or transpiration, and therefore the water-table was not in the position indicated by borings through the crust into sand. Observations in the crust, merely by borings, were further complicated by the tremendous resistance of the crust. As a result of this resistance the crust water would take weeks to follow the pressure changes of the water just below the crust—as calculations from transmission constants showed. The phenomenon could be understood best by a heat conduction analogue. Thus, imagine an asbestos slab (the crust) subjected to a cyclic temperature variation on the lower face. The temperature at a point in the slab would remain almost unaltered because the wave of temperature would only be partly on its way by the time the wave below the slab had changed direction. Only actual pressure observations could show what was really happening, and the Author's own observations had confirmed simple theory.

There was no doubt that the Author had tackled a theoretical problem of considerable complexity.

Dr. Bose said that in this Paper which was a continuation of Paper No. 209 of P. E. C. 1938, the

Author had introduced the idea of Basic Subsoil Pressure (B. S. P.) of Mr. Crump. This was the pressure recorded by a pipe whose strainer point was 19ft. below the bed of the tank. The Author thought that his B. S. P. pipe recorded the undisturbed spring level below the tank. The following table of data collected from his observations would show if his assumption was correct :—

Table I.

Date.	Pipe No.	Base of pipe below bed.	B. S. P. level below bed when pipe stopped recordin .	B.S.P. rising or falling.	Higher B.S.P. level.	% clay.	Remarks.
24 10 37	P_1	0 5'	3·4′	F	0·25' above bed.	10%	
29 10 37	P_2	1·0'	3·8′	F		10%	
21 11 37	P_4	3·0'	4·3′	F		22%	
30 11 37	P_3	2 0'	4·8′	F		28%	
8 1 38	P_5	4·0'	5·83′	Closure		32%	Starts recording.
30 1 38	P_5	4·0'	5·3'	Steady rising after closure.	Lowest level 5·87'		
28 8 38	P_4	3·0′	3·7′				
28 8 38	P_5	4·0′	3·7′	,,	3·5′ below bed.		Starts recording.
28 8 38	P_6	5 0′	3·7′				
9 9 38	P_4	3·0′	3·9′	F			
5 10 38	P_5	4·0′	4·05′	F	3·5′ below bed.		
18 10 38	P_6	5·0′	4·83	F			

Of these pipes, pipe No. 5. (base of pipe 4·0′ below bed) recorded pressure continuously from June, 1937, onwards till B. S. P. level went down to 5·83′ below bed during closure on 8-1-38. The B. S. P. level crossed 4·0 ft. level below bed on 3-11-37. So that even two months after the B. S. P. level had crossed the base level of P_5, the pipe was still recording pressure.

On re-opening P_5 started recording pressure on 30-1-38 when B. S. P. was 5·3 below bed. It went on recording pressure off and on when B. S. P. was more than 5·3′ level below bed.

B. S. P. level then went down and remained under 6·0 ft. below bed till 317·38 and then started rising. P_5 did not start recording till B. S. P. level was 3·7′ below bed and stopped recording as soon as B. S. P. level went lower than 4.05 ft. below bed. The B. S. P. level had crossed 4·0′ level below bed about 8 or 9 days previously.

From this it would be seen that in one case on 8-1-38 P_5 was still recording pressure though B. S. P. level had gone 5·83′ below bed ; whereas on another occasion on 5-10-38 P_5 stopped recording even when B.S.P. level had scarcely gone 4·05 ft. below bed. So that there was no apparent correlation between the B. S. P. level and the appearance of water in P_5. He added that the Author would require much more experimental evidence to verify his B. S. P. conception.

Another new idea introduced by the Author was that there were three phases of losses from channels instead of the usually accepted idea of two phases. They were, according to him, "saturated," "partially saturated" and unsaturated". "Saturated" phase was that when all the pore spaces were completely filled with water which was readily available in any pipe. "Partially saturated" phase denoted that stage when some parts of the medium was completely saturated while others were not. "Unsaturated" phase was that stage when there was no saturated zone. This classification was based on a series of suction experiments carried out by the Author on 18-10-38 when B.S.P. level was 4·83′ below bed of the tank.

Table II.

Date.—18-10-38. B. S. L. below bed = 4·83'

Pipe No.	Base of pipe below bed.	Time of suction bed variation. 2·2' U. 2·0'	Free water before pumping.	Free water after pumping.	Water level rise in U-tubes.	Remarks of the Author.
P_6	5·0′	80 sc.	Yes	Yes	$\frac{1}{8}''$	In water table.
P_5	4 0′	420 sc.	No	No	Nil	In C. 2 Sacs full of water with very little supply of air.
P_4l	3·0′	2520 sc.	No	No	Nil	In C.2 Sacs full of water with little or no air.
P_4r	3·0′	72 sc.	No	Yes	,,	In C.2.
P_3l	2·0′	117 sc.	No	,,	,,	Above C.2 Sacs contained great amount of air and small amount of water.
P_3r	2·0′	20 sc.	No	Yes	Yes	Above C.2. It meant that full air was available near the base of the pipe. This shows that supply of air was exhausted gradually and finally water was down in. *At the end of these experiments it was found that water had risen in the pipe.*
P_2	1·0′	376·5 sc.	No	Yes	L″ 8	Above C.2. This showed that water was available at the base of the pipe. Soil Sacs at the base contained a large amount of water and very little air.
P_1	0·5′	987 sc.	No	Yes	L″ 16	Outside saturation zone below bed of the tank. No free air was available but the Sacs contained a large amount of water.

From this it would be seen that P_5 which according to the Author was in capillary zone did not yield water even after suction while P_{3R} and P_2 both of which were above the capillary zone according to him yielded water readily when suction was applied. In the remarks column it would be seen that soil Sacs round P_5 were full of water while they did not yield water while suction was applied but the soil Sacs round P_2 and P_{3R} were full of air though suction drew out water readily.

Another device was adopted by him to find out if the soil Sacs at the base of the pipes contained different proportion of water and air. This was shown in column 3 of the above Table. According to the Author P_6 was in water-table, time of suction for this pipe was 80 sc. while P_{3R}, time for which was 20 sc., was outside the water-table and P_2, time for which was 376·5 sc., was also outside the water-table.

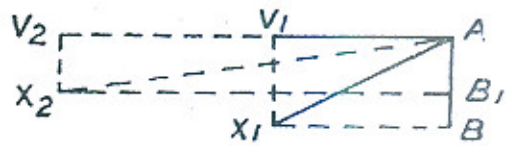
Dr. Bose added that it was difficult to see on what principles the Author had based his conclusions.

Analysis of the data in Table II showed that these pipes were not recording pressure faithfully ; one cause for this might be the fact that they were not provided with strainer points. Another reason might be that the Author had started his experiments in a medium which was well-known for heterogeneity. Dr. Bose asked the Author to take out these pipes, fit them with strainer ends and then repeat these experiments. He added that he was sure the Author would find his experiments conform with the generally accepted ideas on saturated and unsaturated flow if the medium was fairly uniform.

He said in the conclusion that the Author had made a number of statements for which he had not produced any experimental evidence and others which went directly against common experience.

Mr. S. L. Malhotra said that the experiments on which the conclusions drawn by the Author were based were performed in tanks with still water. These conclusions and laws enumerated by him had not been tested on flowing channels, and would not apply to them.

Absorption and seepage losses from a flowing stream to its sides and bed must be different from those in tanks and the formula $q = \sigma H$. did not take into consideration the horizontal velocity of the stream. The losses should depend on the resultant of the velocity created by the vertical pressure and the horizontal velocity. Suppose vertical pressure or H of the Author was AB and the mean velocity of the channel AV, the seepage should be of the magnitude and direction of AX. If the horizontal velocity increased to AV_2 and the depth decreased to AB_1 the losses should be much less. This was only a diagramatic representation, but should explain the point clearly, and should prove that the horizontal velocity could be neglected in any formula for seepage losses. *K. B.* Mian Iqbal Hussain, Superintending Engineer, Haveli Canals, had been studying this subject from this aspect, and held that absorption and seepage losses in a channel were inversely proportional to the square of the mean velocity of the channel. He had evolved the following formula :—



$$q = \frac{W}{C\left(\frac{\cdot 0225}{N}\ Vm\right)^2}$$

where q = Absorption per million sq.ft. of wetted perimeter
N = Kutter's
Vm = Mean Velocity
W = Wetted perimeter.
and C = A constant varying with nature of soil.

The co-efficient had been found to be 1.85 for most soils, but might have to be slightly varied after some more observations.

This formula had been actually tested on some of the Haveli channels and found to be fitting wonderfully accurately. On Vinoi Distributary in the reach 41800 to 80800, with N = ·021, actually observed absorption losses were found to be 5·2 Cs. against 50 Cs. per million sq. ft. worked out from this formula. On Hithar Distributary

with N = ·02438 the actual observed absorption was found to be 2·99 Cs. against 3·06 calculated from this formula.

Such observations could be made easily on all Punjab channels which had got properly caliberated flumes throughout their lengths. He asked the Author if he had tested his formula with actual observations on running channels. If not, it was necessary to do so before bringing it out before the profession. He should not neglect the horizontal velocity which was an important factor. Some experiments were in progress in the Haveli Circle under the guidance of the Superintending Engineer which clearly showed the accuracy of the above formula. A wooden channel with bed consisting of copper gauze covered with sand or other material under test was used and the velocity was changed by increasing its incline. The absorption losses had been found to vary inversely as the square of velocity. He asked the Author if he had ever tried to find the relation of seepage with the velocity of the stream.

Mr. Jesson referred to the question of losses on the Lower Chenab Canal at different periods of the year. He pointed out that, although the losses on most distributaries did not increase during the summer, as evidenced by the fact that the head indent of these channels, which was based on a meter flume gauge, did not increase, yet the supply at the head of the Lower Gugera Branch had to be increased during the summer in order to meet the indents of the offtaking channels.

He had discussed the matter with Mr. Blench, and had compared his own results with those obtained by Mr. Blench by quite different methods, and the comparison had shown exactly the same results.

Mr. Blench had promised to examine conditions on some of the Lower Chenab Canal Distributaries, in order to ascertain why there was no increase in the losses during the summer.

CORRESPONDENCE.

Mr. Thomas wrote that he was interested in the experiments described in the Paper because a parallel series of experiments, to observe seepage flow under controlled laboratory conditions, was in progress at the Central Irrigation and Hydrodynamic Research Station, Poona.

In the latter series, as described by Mr. C. C. Inglis in his discussion on Paper No. 209 (1938), fine sand was packed uniformly in pipes, 1·5 ft. diameter, standing vertically, thus forming columns of various heights. A constant level of water, representing a canal, was maintained on top of the column and the downstream water level was also maintained constant, representing the sub-soil water table, and the rate of seepage was observed.

The characteristics of the seepage curve, shown in figure 76 of the Annual Report of the station for the year 1938-39 (now in the Press), were very similar to those of the Author's experiments as shown in Plate No. 4 of Paper No. 209.

In the Poona experiments no lateral movement of water was permitted, being prevented by the impervious pipe. Under these conditions seepage was found to occur in unsaturated sand, the rate being independent of the depth down to sub-soil water level, as in the Author's experiments, but was dependent on the size of sand or soil particles. These results did not support the Author's theory, given on page 56, that under these conditions "the losses are independent of the effect of gravity.....and are a measure of the evaporation which is taking place from the ground adjoining the channel. The seepage water does not directly reach the water table."

That the seepage water did reach the water table in the Poona experiments had been shown by direct observation, the rate of addition to the water table having actually measured.

These experiments also showed that the peculiar characteristic of the seepage curve in reaching a maximum when the water table was about 3 ft. below canal bed

level and reducing to a lower constant value with lower water table, was not due to a stratum of clay—as suggested by Dr. Bose—or to any non-uniformity of soil profile, because in the Poona experiments the sand was uniform throughout the column. The characteristic mentioned clearly depended on the properties of the soil and water, and on gravity.

He added that the results of the Author's pressure observations were most interesting and he hoped that the Author would continue them.

Replying to the remarks of Mr. Nand Gopal, the **AUTHOR** wrote that Mr. Nand Gopal, had stated that the Subject had become too difficult to be understood.

The Author could not suggest short cuts to the already simple laws of seepage losses enunciated in this Paper. Evidently Mr. Nand Gopal had lagged behind time, whereas the subject had progressed.

The utility of the formula $q = \sigma$ H. had been proved beyond doubt by comparing the results with the statistical methods and the actual discharge measurements on the Lower Chenab Canal, Upper Chenab Canal and Upper Jhelum Canal. He requested Mr. Nand Gopal to refer to the reports of the Water-logging Investigation Division on the subject.

He (the Author) had not tried to be dogmatic in the last paragraph. His remarks in question were a natural corollary to the conclusions given in the Paper. Mr. Nand Gopal was confusing the surface drains with the seepage drains. The Author agreed with him in toto, that the seepage drains were useless in waterlogged areas, because they could not be maintained in the soil conditions of the Punjab ; but the surface drains were of immense utility because they served to quickly remove the rain water, which would become ground water on account of the possibility of saturated flow of this water to the water table in waterlogged areas. Whatever the

surface drains could carry was a net saving from the additions of rain water to the water table.

He was aware of the fact, that Mr. Nand Gopal had worked out a low percentage of discharge run-off for the Budhinala of Upper Jhelum Canal to prove that the surface drains were useless. This was not the correct way of looking at this important point. The Author was in charge of the drainage system for four years. The waterlogged area was served only by the P. R. K. and Machiana Drain which were tributaries of the Budhinala upstream R. D. 40,000. When the Machiana Drain brought 200 to 300 cusecs, and the P. R. K. 1,000 to 1,800 cusecs, the maximum discharge at the measuring point in Budhinala near the was only 350 cusecs. Water spread below R. D. 000 in Budhinala which was an old wide river creek. m R. D. 40,000 to tail R. D. 2, 10,000 Budhinala sed in unwaterlogged areas. The drainage system of Upper Jhelum was doing immense good by quickly moving about 2,000 cusecs from the waterlogged areas, which if allowed to stagnate in that tract would percolate and become ground water. This discharge could not do any mischief in the tail reaches of the Budhinala, even if it spread and moved out slowly into the river, because the phase of the losses in the tail reach was unsaturated. It was, therefore, that low percentage run-off figures were fallacious.

Replying to the remarks of Mr. Blench, the Author wrote that he had supplied a copy of the final Paper to Mr. Blench in October 1939 before sending the Paper to the Press. Mr. Blench had remained so busy throughout the winter that he could not read through it; the original draft also had previously been sent through Mr. Blench to Mr. Crump who edited this Paper.

Mr. Blench was not justified to suppose that the Author's findings were in accord with the theory of Mr. Wilsdon. The experiments described in this Paper corroborated the experimental findings of Mr. Wilsdon but they definitely disproved the conjectures of Mr. Wilsdon based on theory.

Mr. Wilsdon worked out a differential equation of seepage flow (absorption cum percolation) on page 13 P. E. C. 1923.

$$\sigma = k_{11} \int \frac{dh}{h} - \frac{k_1}{k} \int \frac{\text{Sin}\,\theta}{(\text{D}-\rho\ \text{Sin}\theta)^2}\, d\rho + k_2 \int h.\ \text{F}\theta.d$$

The first was the absorption term, the second the ground water correction term and the third the percolation or gravity term. No solution of the equation was found by Mr. Wilsdon except by neglecting the middle term. His calculated absorption in his experimental channel at Lyallpur was 11·5 cusecs per million sq. ft. He had not made any observations to check-measure. The Engineers working in that locality knew this full wel that his figure was out by four times. Notations in th formula are as below :—

(*a*) δ = unnamed term but $-\frac{\alpha\ \sigma}{\alpha x} = hv$ and $-\phi\, w =$

(*b*) h = moisture content

(*c*) $\text{F}\theta = \frac{\alpha(\sigma\rho\ \sin^2\vartheta)}{\alpha\theta}$ when ρ and θ are polar co-ordinat

(*d*) D = depth to spring level

(*e*) ϕ = Hydrostatic pressure

(*f*) $-\propto \phi = \frac{\text{A}}{h} - \text{B}$ (Emperical formula of Wilsdon connecting moisture content and hydrostatic pressure)

The following assumptions were made by Mr. Wilsdon to work out his formula :—

1. Constant velocity V. (Page 8 and 18).
2. Conductivity was independent of the moisture content and varied with the average radius of the soil particle and viscosity. (Page 8).
3. Slichter's transmission constant of the saturated flow applied to the unsaturated flow. (Page 8).
4. Stoke's Law :—Limiting velocity of a sphere moving relatively to a liquid was proportional to the impelling force and inversely as the viscosity and radius (Page 8).

5. Form of moisture contours was assumed as eliptic, confocal to the centre of the channel. (Page 22-*a*).
   Further assumptions based on his experiments were :—

6. The moisture content varied as log of distance from the saturation line below bed. (Page 22-P).

7. Emperical relation between hydrostatic pressure and moisture content ((*f*) above.— Page 2).

His own findings did lend material support to Mr. Wilsdon's points No. 6 and 7 but no modern soil physist would look at such an equation based on the first five simple and pure assumptions, which were apparently wrong specially No. 2 and 3.

Mr. Wilsdon had imagined that ten per cent. of the absorption in deep channels was percolation (page 17) but Mr. Inglis had explained in the discussion that the effect of depth was only to increase the loss, that is, the area of the saturation line below bed (page 22-*k*). Mr. Wilsdon had not proved that absorption reached the water table but imagined that the negative term was small (page 22-*w* reply to discussion).

It was here that his own pressure observations, which Mr. Blench had the occasion to check many a times ; proved beyond doubt that the observed negative gradient was stronger than gravity and that Mr. Wilsdon's imagination was not justified. Mr. Blench accepted the accuracy of the observations in his remarks.

Mr. Blench's example of a venturi flume was not to the point. The Author had not stated anywhere in the Paper that because the pressure reading was negative, there could be no flow. Negative hydrostatic pressure reading was no barrier to flow but all that was required was a positive manometric gradient from the bed of a source down to the water table. In a venturi flume, if

one drew the total energy line, there was a definite positive drop per unit length throughout the length of the venturi flume.

Mr. Wilsdon's differential equations did not show that the flow was possible with negative gradient, but the definition of percolation given by Mr. Wilsdon quoted verbatum in the introduction by the Author, definitely enjointed the necessity of positive gradient for percolation.

The Author thanked Mr. Blench for the elucidation of other points such as B. S. P.

Replying to Dr. Bose, the Author wrote that Dr. Bose was not right in imagining that B. S. P. recorded the undisturbed spring level. He had not said that anywhere in the Paper. Mr. Blench had explained in his comments what was meant by B. S. P. The Author gave a standard definition of B. S. P. as below which is the same as originally used by Mr. Crump :—

B. S. P. is defined in practice to be the manometric pressure registered by a strainer tipped pipe which has been sunk along side a very deep standard pipe in the same or directly connected stratum, till it records a reading not appreciably different from that in the standard. The level, thus recorded, is almost uninfluenced by the effect of the distortion of stream lines caused by the presence of a source or a sink. In rectilinear flow with no upward and downward movement the B. S. P. level and phreatic surface are the same. A B. S. P. Pipe responds to the water table changes unaffected by the vertical component of flow.

Dr. Bose had said that he could not understand B. S. P. because he found no co-relation between the B. S. P. level and the levels recorded by various pressure pipes. The science of statistics had failed. Dr. Bose was trying to find a relation between two things which had no relation whatsoever with each other.

He added that statistics was nothing but a science of digits without attributes. It was the duty of the statistician to work out the co-relations and leave them for the professional men to supply the attributes.

Mr. Blench or the Author could guide Dr. Bose straightaway to the facts that he was toiling for nothing and that there was no relation between the levels recorded by the various pipes, though the pressure differences and the variation of the B. S. P. were definitely co-related.

He added that Dr. Bose would find more than enough experimental evidence from the reports of the waterlogging investigation of B. S. P. Dr. Bose was unable to understand the suction tests. The principles were quite simple. When time taken was great, the soil pore contained water but not free. When the time taken for a suction tests was small, the soil pore contained either free water or free air, but in the case of free water, water rose in the pipe. The suggestion of Dr. Bose to fit the pipes with strainers in a soil crust was of no use. The Author had tried it and the pipe had become completely choked. It was the free area which made the pipe responsive in the soils. It was no doubt admitted that the responsiveness of the pipes could be increased by fitting strainers in sands. The pressures recorded by the various pipes were absolutely genuine.

Replying to the remarks of Mr. Malhotra, the Author wrote that Mr. Malhotra had not apparently cared to understand the Paper before making his remarks. He was confusing the Author's formula $Q = \rho$ H. P., meant for the saturated phase, with his formulæ which was apparantly meant for Distributaries mostly in the unsaturated phase. In the unsaturated phase the losses did not depend on H but were absolutely independent of gravity as proved in his Paper. Surely they were dependent only on the soil conditions and wetted perimeter as brought out by experiments in this Paper, but they have nothing to do with the forward velocity of a channel. Supposing the resultant velocity was taken, what would happen ? The downward velocity of seepage had been measured to seldom exceed 0·00001 ft. per second. In a channel with 3 ft. per second forward velocity the resultant would be hardly 3·00001 ft. per second but its direction of flow would be along the bed. This meant that the resultant

would never meet the water table below. This line of argument would show that there would be no losses from a channel, if its forward velocity had anything to do as suggested by Mr. Malhotra.

Replying to the remarks of Mr. Jesson, the Author wrote that the seepage losses increased with temperature in all cases according to the formula and diagrams published in Author's Paper No. 209, Punjab Engineering Congress, 1938. In the case of Branch Canals Mr. Jesson admitted that greater supplies had to be run in summer but in the case of the Distributaries, the indents were kept the same. On Distributaries water allowance for losses was generally liberal. The result was that there was excess at the tails in winter and very nearly authorised supply in summer.

Replying to the remarks of Mr. Thomas, the Author wrote that he was glad to learn that the Poona experiments corroborated quantitatively the results of these experiments as published in Plate No. 4, Paper No. 209 and thereby proved beyond doubt the three phases of the losses from the channels.

However the disagreement of Mr. Thomas with the Author's conclusion that in the unsaturated phase the losses did not reach the water table, was not justified from what he had stated. The essential difference between the Author's and Mr. Thomas' work was that Mr. Thomas' experiments were made with artificially packed sand but the Author's experiments were in the natural soil. In clean sand, the unsaturated phase could not occur whatever was the position of the water table below. Gravity was stronger than the possible resistance to flow in sands. Even if Mr. Thomas's experiments showed that the loss was independent of gravity it was also true in the case of percolation in the saturated tubes with unity gradient, when the remaining mass of sand would be unsaturated. It was suggested that pressure observations should be added by Mr. Thomas to clearly differentiate the different phases and it would then be apparent that the unsaturated phase was not at all possible in sands.

Concluding the discussion, the Author wrote that the five arguments, based on the experimental evidence produced in support of the conclusion that there were no additions to the water table in the unsaturated phase in soils, were valid and unshaken by the criticism. This was a bit of original research work of fundamental importance to the Punjab Province likely to result in the savings of crores of rupees in the cost of the anti-water-logging measures.

He added that the conclusions outlined in this Paper clearly brought out the fact that the resort to leaching as a reclamation remedy would be criminal in waterlogged areas where water used would become ground water. In unwaterlogged areas it would be successful without any adverse effect on the waterlogging problem but the remedy would have to be repeated say every five years. As a practical Engineer with the interest of the Province at heart the Author recommended the reclamation of lands by following Nature's method in washing salts into the surface drains.