Steady State Drainage Flow in Peat

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•THE drainage of cohesive soils is important in road and agricultural engineering. Information is required for design purposes on problems such as optimum location of longitudinal side-drains, profile of phreatic water surface, change in water content and degree of saturation brought about by drainage, and duration of unsteady phase of groundwater lowering.

This paper describes investigations undertaken on the flow of water to drains in peatland, and is based on the results of full-scale experiments carried out in the field. The vast majority of papers published on this topic are based on experiments involving model studies of flow in sand tanks, electrical analogs, membrane analogies, or analytical methods comprising mathematical or numerical analysis. The most generally used drainage device in the reported work is a well. A well was also used in our experiments, as accurate control of discharge is best effected by this device. The equations governing radial flow to wells are readily adapted for the conditions of parallel flow to trenches (2).

Flow into wells can be divided into two classes: (a) confined flow in which the water is confined under pressure in a stratum sandwiched between two impermeable layers giving rise to artesian conditions; and (b) unconfined or gravity flow in which the water-bearing stratum is not confined by an upper impermeable layer. In this case the groundwater is exposed to the atmosphere, and an imaginary boundary known as the phreatic surface (at all points of which the fluid pressure is atmospheric) constitutes the upper surface of flow, if capillary flow is neglected. All pumped wells are initially in a transient condition. However, flow eventually changes from the nonsteady to the steady state. This can be assumed to have been achieved when no appreciable variation occurs in the water table at a reasonable distance from the pumped well.

The results measured in these experiments are compared with results calculated from formulas proposed by Dupuit (1), Jaeger (2), Babbit and Caldwell (3), Hansen (4), Boulton (5), and Hall (6).

NOTATION

A = cross-sectional area through which flow takes place (Darcy formula)
c = density of fluid
C_x = a coefficient defined by a curve relating drawdown to radius (Babbitt and Caldwell equation)
g = acceleration due to gravity
H = height of undisturbed water surface above the bottom of the well
h_o = depth of water in well during pumping
h_s = height of the free surface above the bottom of the well at the well edge
h_s-h_o = surface of seepage
h_{115} = height of the free surface above the bottom of the well at a distance of 115 r_o from the well center
h = height of phreatic surface above the bottom of the well

Paper sponsored by Committee on Embankments and Earth Slopes and presented at the 46th Annual Meeting.

$\bar{h}$ = height of liquid column (Forchheimer equation)
i = hydraulic gradient
K = a constant depending on the medium and known as the coefficient of permeability
ln = natural logarithm or logarithm to the base e
log = logarithm to base 10
p = penetration expressed as a fraction of the full depth of the water-bearing stratum
Q = volume of water discharged in unit time
R = radius of influence or the radial distance from the well at which the water level is not affected by pumping
r_o = radius of the well
r = radial distance from the well
x, y = coordinates of point h projected on the horizontal plane
μ = coefficient of viscosity
θ = slope of the free water surface at point (r, h)

PREVIOUS INVESTIGATIONS

Hall (7) has reviewed in detail the development of knowledge on the theory of seepage toward wells. Many other workers have carried out extensive analyses on flow through porous media. The results of these investigations in so far as they apply to the case of steady flow to a gravity well will be briefly summarized.

In 1856, Darcy (8) proposed a relationship, now known as Darcy's law, which has become the basic equation for the flow of water through a saturated porous medium. The equation may be written as follows:

$$Q = KAi \tag{1}$$

This basic equation is valid in the case of laminar flows only. The critical value of the Reynolds number, at which the flow through soil changes from laminar to turbulent, lies between 1 and 12. In the present study of flow through peat, the velocity of flow and the effective particle size diameter are so small that the Reynolds number is very much less than one and Darcy's law can be taken as valid.

Dupuit (1) assumed that for small inclinations of the free surface of a gravity-flow system, the streamlines (a) can be taken as horizontal, and (b) are associated with a velocity proportional to the slope of the free surface but are independent of depth. From these assumptions he derived the Dupuit equation for radial flow to a well:

$$Q = \frac{\pi K (H^2 - h_o^2)}{\ln R/r_o} \tag{2}$$

Forchheimer (9) applied the Dupuit assumptions combined with the equations of continuity to the analysis of a fluid in any column of liquid of height $\bar{h}$ above an impermeable base of a layer through which flow is taking place. His treatment yielded the following general equation of the free surface in gravity-flow system,

$$\frac{\delta^2 \bar{h}^2}{\delta x^2} + \frac{\delta^2 \bar{h}^2}{\delta y^2} = 0 \tag{3}$$

This result involving the function $\bar{h}^2$ is analogous to that which is obtained when Darcy's law is combined with the continuity equations, from which operation the function h (total head) is also found to satisfy the Laplace equation

$$\frac{\delta^2 h}{\delta x^2} + \frac{\delta^2 h}{\delta y^2} = 0 \tag{4}$$

Boulton (5) determined the free surface by the relaxation method. He also showed that the discharge given by the Dupuit formula was within 1 percent of the actual discharge as measured on a sand model.

Muskat (10) analyzed the flow to wells on a purely theoretical basis and with Wyckoff and Botset carried out a number of sand tank experiments. The sand tank used was equipped with manometers connected to the base. These measured the radial pressure distribution above the bed. The fluid in the tank was kept in continuous circulation so that steady state conditions were easily maintained. They found that the following formula, after correcting for flow in the capillary zone, gave very accurate measurements of discharge:

$$Q = \frac{K\pi\, cg\,(H^2 - h_0^2)}{\mu \ln R/r_0} \tag{5}$$

They also concluded that base piezometric heads rather than heads due to the free surface were given by the Dupuit equation.

Babbitt and Caldwell (3) carried out extensive analyses at the Engineering Experiment Station of the University of Illinois. Their object was to formulate the conditions of flow into gravity wells so that greater precision in the solution of problems could be achieved. They used electric models and sand tanks during the experiments. The Dupuit formula gave accurate results, provided the ratio of well drawdown to the thickness of the groundwater stream penetrated was less than 0.2. On investigation, they noted that the area of influence was circular in very special cases only. It becomes elliptical where the water table is sloping. However, the error involved in assuming the region of influence to be a circle is negligible and the radius of such a circle may be substituted into the Dupuit formula. Kozeny's equation

$$Q = \frac{\pi K (H^2 - h_0^2)}{\ln R/r_0} \left[1 + 7\sqrt{\frac{r_0}{2H}} \cos \frac{\pi P}{2} \right] \tag{6}$$

for calculating the discharge of a partially penetrating well was checked and found to be accurate.

They introduced a new equation for the determination of the free surface

$$Q = \frac{\pi KH (H - h)}{C_x \ln R/0.1H} \tag{7}$$

This equation was based on observations of the free surface in sand tank and electric analog tests, and though empirically derived gave very accurate results.

Hansen (4) carried out experiments using membrane analogy and sand tanks. He verified Muskat's findings that the Dupuit equation gave the piezometric heads above the base rather than the free surface. Having studied the previous work of Babbitt and Caldwell (3), he then proposed another slightly different equation for the free surface by substituting 0.3 log R/r for C_x:

$$\begin{aligned} Q &= \frac{\pi KH (H - h)}{0.3 \log R/r \ln R/0.1H} \\ &= \frac{\pi KH (H - h)}{0.69 \log R/r \log R/0.1H} \end{aligned} \tag{8}$$

Hall (6) conducted a series of large-scale tests with a sand tank and found that the Dupuit equation gave base piezometric rather than free surface heads. He also compared the flow patterns calculated by means of Yang's relaxation technique with the actual flow pattern observed in the tests and found that the maximum discrepancy was

of the order of 6 percent. Finally, he proposed two empirical equations for calculation of the free surface close to the well:

$$\frac{h_s - h_o}{H - h_o} = \frac{1 - (h_o/H)^{2.4}}{\left[1 + \frac{1}{50} \ln R/r_o\right]\left[1 + 5/H/r_o\right]} \tag{9}$$

$$\frac{h - h_s}{H - h_s} = 2.5\left(\frac{r - r_o}{R - r_o}\right) - 1.5\left(\frac{r - r_o}{R - r_o}\right)^{1.5} \tag{10}$$

Many workers had questioned the validity of the Dupuit equation. Its analytical correctness has however been verified by Polubarinova-Kochina (11), Chapman (12, 13, 14) and more recently by Hantush (15). The only limitation imposed by Hantush was that the data analyzed should be from wells at radius $r > 1.5h$ from the pumped well.

Jaeger (2) stated that because of the simplifying assumptions introduced, the Dupuit formula was valid only as an approximation. Furthermore, it should only be used where the value of θ was small. Dupuit's assumption that along any vertical line the streamlines are horizontal in which case the equipotentials are vertical can lead to great errors if used close to the well. He suggested that only a small error was involved in assuming that the equipotentials were circular arcs perpendicular at one end to the impermeable base and at the other end to the water table at any distance from the well. From this hypothesis he developed his equation for flow to a well:

$$Q = 2\pi Krh(1 + h/2r \tan \theta/2)\,\theta \tag{11}$$

An examination shows that this equation cannot be solved by direct integration. The shape of the water table can however be determined from one known point by the method of finite differences. As this is only an approximation, the best results are obtained by taking very small increments of r. This applies, especially, near the well where the value of θ changes rapidly. The amount of work involved in deriving the water table curve in this manner is very great. However, the repetitive nature of the calculations lends itself to analysis by digital computer.

Surface of Seepage

The Dupuit equation is generally used in connection with flow to gravity wells. However, because of the assumptions made by Dupuit that the streamlines are horizontal, the equation will be most accurate at large radial distances from the well where the free surface approaches the horizontal. The greatest inaccuracy in the Dupuit analysis, however, is that the surface given by the equation intersects the well at the level of water in the well. It has been established that this free surface intersects the well face at a point above the water level, giving rise to what is known as the surface of seepage along the well face. When the drawdown is small the surface of seepage is also small but as the drawdown increases, particularly in the case of gravity flow where the ratio of drawdown to total depth can be very large, the water level close to the well will be considerably higher than that given by the Dupuit equation.

Harr (16) states that the first approximate method that accounts for the development of the surface of seepage was proposed independently in 1916 by Schaffernak (17) and van Iterson (18). Muskat (10) showed that the surface of seepage must exist as otherwise there would be an infinite velocity at the point of intersection of the water table and well wall. He further stated that since Dupuit had based his conclusions on erroneous assumptions and had neglected to take account of the surface of seepage, his equation should automatically fail. However, results have shown that when the measuring well is far enough removed from the pumped well, the Dupuit equation gave surprisingly accurate results. Muskat therefore concluded that the Dupuit equation, despite the

erroneous assumptions, could be used to give accurate results of the discharge, although he was of the opinion that these results were entirely fortuitous. Babbitt and Caldwell (3), Hall (6) and others recognized the importance of the surface of seepage and proposed empirical equations (7, 9, 10) to measure its height. Hansen (4) was of the opinion that the use of the radius of influence could lead to inaccurate results as it is rather an indefinite and hypothetical measurement. He formulated an expression that used only functions measurable at the well face. By combining these functions in a number of dimensionless parameters he derived the equation:

$$Q/Kr_0^2 = f_1 (h_s/r_0, h_0/r_0) \tag{12}$$

Using the results from the electric analog tests of Babbitt and Caldwell and from his own sand tank measurements, Hansen developed a family of curves based on these dimensionless parameters. These curves can be used to measure the height of the surface of seepage without reference to the radius of influence.

Zee, Peterson and Bock (19) did some further dimensional analysis and introduced another dimensionless parameter and a new equation:

$$Q/K\, r_0^2 = f_2 (h_s/r_0, h_0/r_0, h_{115}/r_0) \tag{13}$$

which can also be used to find the height of the surface of seepage.

Boulton (5) set out specifically to devise a means of measuring the free surface and the surface of seepage. Using relaxation methods, he produced curves by which these could be calculated.

An examination of Jaeger's equation shows that the higher the value of Q, the steeper the water table curve becomes. For small values of Q, the curves intersect the well surface at the level of water in the well. At a particular discharge, the water table curve becomes tangential to the well face. Jaeger postulated that the discharge producing this curve was a critical discharge (Q_c) and that the corresponding depth of water in the well was a critical depth (h_c). Larger discharges produce curves that do not reach the well face and represent imaginary rather than real flows. Lowering the water level in the well below the critical depth therefore would produce a water table appropriate to the critical depth and a surface of seepage would develop between the critical depth and the water level in the well.

In summary, Dupuit completely neglected any consideration of a surface of seepage. Jaeger suggested that a critical depth existed. Where the water level in the well is higher than the critical depth, no surface of seepage occurs. However, if the water level in the well is lower than the critical depth, a surface of seepage develops over this range. Most other workers including Babbitt and Caldwell, Hansen, Boulton, Hall, and Muskat are agreed that a surface of seepage develops immediately after the water level in a well is lowered and that it increases as the water level is further lowered.

FIELD INVESTIGATIONS, FIRST WELL EXPERIMENT

Location

The field work was carried out at the Peatland Experimental Station of the Agricultural Institute, Glenamoy, County Mayo. The Station is situated in an extensive area of blanket peat which varies in depth from 4 ft to 25 ft and averages about 14 ft. The peat is very gelatinous and has a high capacity for water retention. The moisture content is usually around 1400 percent. The water table fluctuates from a few inches below the surface in winter to about 9 in. down in summer.

Experimental

A general view of the experimental site is shown in Figure 1. A 6-in. diameter well made from galvanized wire-mesh gauze was positioned in the center of the experimental area. An area of 60 ft × 60 ft surrounding the well was covered with heavy-duty black polythene sheeting to minimize the effects of rainfall and evapotranspiration in the immediate vicinity of the well.

Three lines of pipes radiating from the central well were installed for the purpose of checking on water table fluctuations. On each line, pipes were driven solidly into the underlying marl at 1-ft, 2-ft, 4-ft, 8-ft, 16-ft, and 32-ft distances from the center of the well. The pipes used were ¾-in. OD 18 SWG conduit 16 ft long. Each pipe was drilled with ⅛-in. diameter holes at 1-in. centers and was closed at its lower end. An effective seal against the ingress of water at the junction of each pipe and polythene was provided. Shallow trenches 8 in. wide × 4 in. deep were excavated across the site 20 ft apart. The polythene was fixed into position in these trenches. In this manner surface water drainage was provided and the danger of wind damage to the polythene obviated. A rubber stopper on top of each pipe prevented rainfall infiltration. The water level in the well was controlled by a float attached to a magnetic type switch which actuated a ⅙ bhp totally enclosed electric motor. This was coupled through a reduction gear to a stainless-steel pump and gave discharges of about 12 gph. It was decided to control the water in the well at a number of predetermined levels. To accomplish this, a tolerance of ½ in. above and below the predetermined water level was allowed. In practice, this meant that the pump cut in when the water level rose ½ in. above the required level and worked until the level dropped to ½ in. below. Under normal conditions approximately 0.2 gallon was pumped at about 1-hour intervals.

A ½-in. diameter brass suction pipe was fixed to the well base and had an inlet at 1 ft above the bottom of the well. The float arm was made from narrow bore P. V. C. tubing and could readily be extended or shortened. A 150-watt bulb mounted beside the pump gave sufficient heat to prevent icing during winter.

The pump and switch were mounted on a heavy base which was positioned beside the well. They were protected by an aluminium cover which also covered the well. This accomplished the dual purpose of excluding rain and of allowing the float arm to operate under very stable conditions even in gale-force winds. The pumping unit is shown in Figure 2.

The discharge from the pump was delivered through ½-in. diameter tubing, lagged with glass fiber, to a collecting tank. It was pumped through a perspex float chamber mounted on the roof of the tank (Fig. 3). The float operated a pen on a daily chart and recorded the time of each pumping operation. The water in the collecting tank was

Figure 1. General view of experimental area.

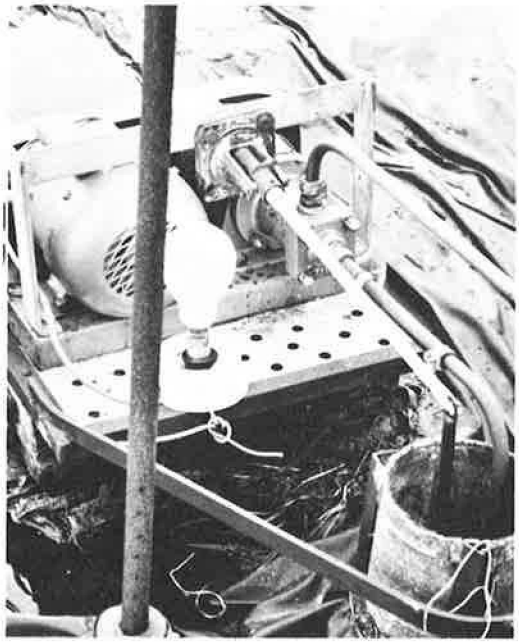

Figure 2. Pumping unit and central well.

Figure 3. Collecting tank and float chamber.

measured and emptied daily. The installation of the float chamber had two objectives: (a) to check on the regular operation of the pump—any miss in the pumping cycle could indicate a sticking float or some other mechanical or electrical breakdown; and (b) to enable the actual daily discharge to be accurately calculated. At a meteorological station beside the site, the usual meteorological data including rainfall, temperature, sunshine hours, wind run and evaporation were recorded daily.

The water table level in each pipe was measured by means of a battery operated probe 6-ft. long (Fig. 4). This was made from ½-in. diameter copper tubing graduated in 0.01-ft intervals attached to an indicating unit consisting of a milliammeter, 1½-volt battery, resistance and switch. The top of each water table pipe was leveled from a temporary bench mark. These levels were checked at intervals throughout the course of the experiment—the variation was negligible in all cases.

Measurements

When all installations were complete, the water table levels in the central well and pipes were measured for a few days until stable conditions were obtained. Then the water level in the central well was lowered approximately 1 ft, and the float was set to control it at this depth. The discharge and water table levels were measured daily. After a period, the water level in the central well was lowered to approximately 3 ft, then to 5 ft and finally to 7 ft. Measurements continued during each well drawdown after which the float was removed and the area allowed to recharge.

The results of each pumping cycle followed roughly the same pattern. A comparatively large daily discharge occurred on first lowering the water level in the central well. However, as the cone of depression extended, the discharge rate fell off and eventually became almost constant. The water levels in the pipes behaved in a somewhat similar fashion. After a few days, large depressions in the water levels were

Figure 4. Water level measurement—close-up of indicating unit.

TABLE 1

MEASURED DRAWDOWNS ALONG THE EAST LINE UNDER STEADY STATE CONDITIONS FOR DIFFERENT WELL LEVELS

Well Drawdown (ft)	Radial Distance (ft)					
	1	2	4	8	16	32
0.97	0.66	0.51	0.38	0.26	0.16	0.07
2.94	1.73	1.25	0.94	0.60	0.34	0.08
5.03	2.03	1.55	1.18	0.79	0.49	0.16
7.03	2.19	1.72	1.31	0.90	0.57	0.27

TABLE 2

DAILY DISCHARGE FIGURES UNDER STEADY STATE CONDITIONS[a]

Well Drawdown (ft)	Measured Discharge (cc per day)	Corrected Discharge (cc per day)	Permeability (cm per day)
0.97	12,816	10,777	0.9816
2.94	24,804	20,857	0.6625
5.03	21,859	18,381	0.3911
7.03	19,911	16,743	0.2937

[a]Corrected for partial penetration of the well, and corresponding permeabilities calculated for the East line by the Dupuit formula.

TABLE 3

AVERAGE TOTAL CONSOLIDATION MEASURED AT THE CONCLUSION OF EACH PUMPING CYCLE

Well Drawdown (ft)	Radial Distance (ft)			
	1-4	8	16	32
0.97	0.04	0.02	–	–
2.94	0.10	0.04	0.02	–
5.03	0.14	0.07	0.03	–
7.03	0.18	0.10	0.05	0.03

observed in the pipes nearest the central well. The rate of fall in these pipes was gradually reduced and the influence of the central well on the water levels in the other pipes became more evident. In time, the water table variations practically ceased and the drawdown curve became stable. Thus, the steady state daily discharge rate and the corresponding phreatic surface were measured and recorded for each pumping cycle. During the course of the experiment the general groundwater table in the area fluctuated due to rainfall and evapotranspiration. These fluctuations gave rise to occasional variations in the measured water table levels. Heavy rainfall caused sudden increases in the water table measuring pipes, but after a few days the levels again dropped to the original.

The chart recorder on the discharge line proved most useful in measuring the actual daily discharge from the well. The total discharge was measured and a new chart mounted each morning. However, the measured discharge did not represent a 24-hour figure as the pump scarcely ever cut in at the same time on two successive mornings. By reference to the charts, the actual time over which the measured discharge occurred was computed and the measured quantity adjusted to give a 24-hour discharge figure. This correction was necessary to establish whether or not a steady state condition had been achieved and to measure the actual steady daily discharge.

Results

As the experiment progressed, it became apparent that there was a general groundwater movement across the experimental area. This caused occasional slight fluctuations of the water levels in some observation pipes. Pipes along the East line were least affected by these fluctuations and the discussion is based on measurements made on that line. The drawdown figures under steady state conditions for each well lowering are given in Table 1 and the corresponding measured discharges in Table 2.

Correction for Partial Penetration

The drainage well did not penetrate the full depth of peat to the top of the impermeable layer. The measured discharge was therefore increased by a contributory flow from the peat below the bottom of the well. However, as already stated, Kozeny had postulated and Babbitt and Caldwell had proved that Eq. 6 could be used to calculate the correct discharge from a partially penetrating well. The steady state discharge figures were corrected by this formula and are given in Table 2.

Dupuit Formula

The Dupuit formula (Eq. 2) was used to calculate the permeability of the peat during each pumping cycle. Many workers have verified that this formula can be used to give accurate results, provided the observations are made at a point far enough removed from the central well to lie in the Dupuit zone. Peterson (20) has stated that the observations should be made at a minimum distance of 100 r_0 (25 ft) from the central well while Hantush (15) recommends that at the point of observation r should exceed 1.5h. The 32-ft drawdown figures were used in the calculations.

This radial distance more than satisfied the requirements. The calculated permeabilities (centimeters per day) are given in Table 2. Permeability tests were also run in the laboratory using a modified Bjerrum-Huder apparatus (23). These tests will be described in detail. However, it can be noted here that the permeability figures resulting from the laboratory tests all lay between 0.31 cm per day and 1.52 cm per day. The 0.31 cm per day was achieved while the pore water of the sample was under a suction of -4 psi while the 1.52 cm per day resulted with the pore water under a positive pressure of 12 psi. These measurements check in very well with the field results which run from 0.29 cm per day to 0.98 cm per day.

Permeability and Discharge Variations

Table 2 shows a number of apparent anomalies. One would normally expect that the permeability figures would remain more or less constant throughout the four pumping cycles. An increasing discharge would also be expected as the pumping depth was increased. This discharge might become constant at some stage but would not be expected to decrease. However, reference to the table shows that the maximum permeability was achieved at the 0.97-ft drawdown level. Each succeeding pumping cycle gave a smaller permeability, culminating in the minimum figure at the 7.03-ft well drawdown. The expected increased flow between the first and second pumping cycles occurred. However, this increase was not maintained and the next two cycles produced decreasing flows.

The decrease in permeability, amounting to about 30 percent, that occurred between the first two pumping cycles during which time the discharge rate almost doubled itself is most probably explained by the fact that the top 18 in. of peat is more open and fibrous than the remainder. During the first pumping cycle the water table lay in this zone, but for the other cycles most of the flow was through the gelatinous peat. The further reductions calculated for the 5.03-ft and 7.03-ft well drawdowns are directly related to the decreased discharge rates. These reductions in measured discharge were most unexpected. Normally one expects the discharge to increase with increasing depth or, presupposing the validity of Jaeger's theory, to increase to a maximum and remain constant at that maximum value. However, as an examination of Table 2 shows, the decrease was evident right through each cycle. An explanation was sought.

Ground Level Variation

The consolidation of peat due to the groundwater lowering during each pumping cycle was measured. Fixed points on the surface were checked from a temporary bench mark after each cycle. These points were positioned beside the water table observation pipes so that 18 levels were taken on each occasion. The results of these measurements are given in Table 3. There was a comparatively large amount of traffic in the immediate vicinity of the well. On this account, practically identical consolidation figures

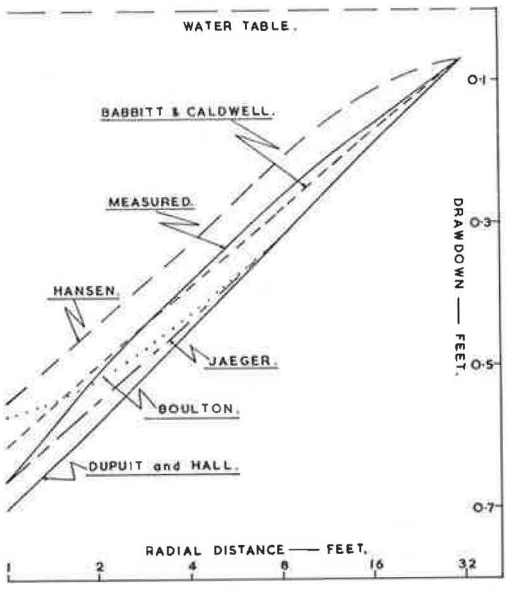

Figure 5. Semilog plot of measured and calculated drawdown curves for 0.97-ft well drawdown.

were achieved at the 1-ft, 2-ft, and 4-ft, distances. For convenience, these figures are bulked in the table under the heading 1 ft to 4 ft.

When one considers that the total depth of peat at the site of the experiment is about 13.3 ft, it becomes obvious that consolidation alone could not have accounted for the large decreases in permeability and discharge.

Entrapped Air

Another factor which could have had an adverse effect on the permeability was entrapped air. Groundwater holds a quantity of air in solution. This, if released, could occupy a percentage of the pore space and cause a reduction in permeability.

The general water table level close to the well was reduced during pumping. The water in the peat above this reduced level was consequently subjected to tension. Similarly, the water in the peat at all depths below the new water table was under reduced pressures. The general effect, therefore, on the groundwater was one of reduced pressures with tensile forces coming into play above the new water table. This effect was most pronounced at the well face and decreased as the distance from the well increased. These considerations suggested that air could come out of solution and clog pore space, especially at points close to the face of the well. A separate laboratory experiment was undertaken to investigate this. The results showed that as the pore water pressure in the peat was reduced, the measured permeability also dropped. More recently, a paper by Orlob and Radhakrishna (22) has come to hand in which the effects of entrapped gases on permeability are discussed. Their experiments showed that a 10 percent increase in air content could cause a reduction of 35 percent in permeability. This confirmation of a theory that we had independently suggested and proved was most encouraging. It leaves us in no doubt that the decreased discharge rates and the correspondingly reduced permeabilities were caused by entrapped air which was released from solution as the water table was lowered.

Discussion

Babbitt and Caldwell, Hansen, Hall and Boulton all agreed that the Dupuit curve gave base piezometric rather than free surface levels. This, in effect, means that at points sufficiently far removed from the well to lie in the Dupuit zone, the Dupuit formula gives actual drawdown levels. At points inside the Dupuit zone, the actual water level is higher than that given by the Dupuit formula. Their proposed equations were designed to give free surface drawdowns close to the well and to merge with the Dupuit curve in the Dupuit zone. These equations were used to calculate free surface curves for different drawdowns. Jaeger suggested that his own equation could be used to give the drawdown curve at all distances from the well without referring to the Dupuit formula. A computer program (23) was written to solve the Jaeger equation by the method of finite differences. The measured and calculated drawdown curves for each pumping cycle are illustrated (Figs. 5, 6, 7, 8). Examination of Figure 5 (0.97-ft well drawdown) shows that the Dupuit, Hall, Jaeger and Boulton curves lie very close together; in fact, the Dupuit and Hall equations give the same curve. The Jaeger and Boulton curves coincide with this curve to the 8-ft mark and diverge slightly from there. The measured drawdown curve lies between the Hansen and Babbitt and Caldwell curves. It approximates very closely to the Babbitt and Caldwell curve—the divergence being of the order of 0.01 ft from 32- to 2-ft radial distance.

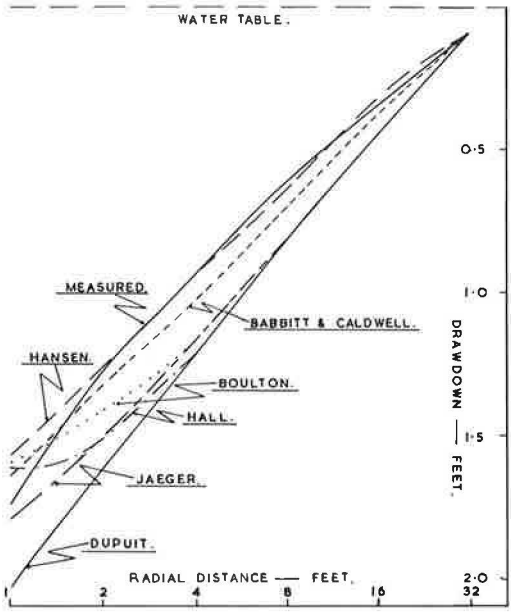

Figure 6. Semilog plot of measured and calculated drawdown curves for 2.94-ft well drawdown.

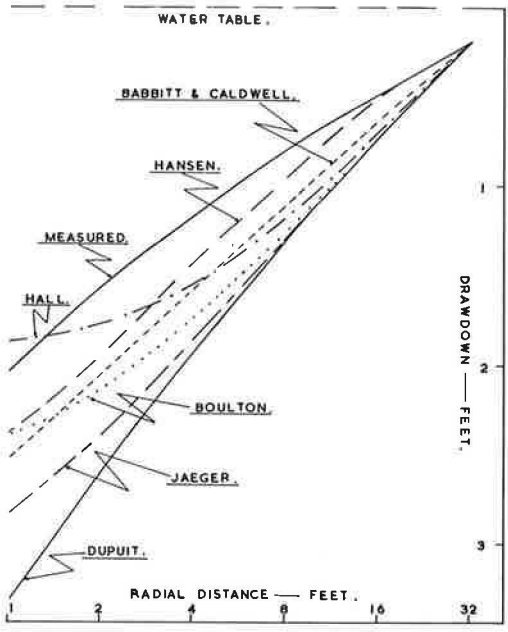

Figure 7. Semilog plot of measured and calculated drawdown curves for 5.03-ft well drawdown.

The 2.94-ft well drawdown (Fig. 6) shows a similar pattern. The Dupuit and Hall curves coincide to the 4-ft mark, from which point they diverge. The Boulton curve also coincides with the Dupuit curve as far as the 8-ft mark. The Jaeger and Dupuit curves coincide to the 16-ft mark. They diverge at this point but the divergence is very gradual. The measured drawdown, Hansen and Babbitt and Caldwell curves again lie very close together. The Hansen curve corresponds most closely to the measured drawdown curve. It coincides with it from 2- to 4-ft radial distance and has a maximum divergence of 0.03 ft from 4- to 32-ft radial distance. The Babbitt and Caldwell curve lies below the measured drawdown, the divergence averaging about 0.06 ft. In the 5.03-ft well drawdown (Fig. 7), the same pattern emerges. The Dupuit and Jaeger curves lie close together. The Boulton curve coincides with the Dupuit curve for a time but then diverges rather rapidly. The Hall curve also follows the Dupuit trend but diverges rapidly inside the 8-ft radial distance. The Babbitt and Caldwell curve lies approximately midway between the measured drawdown and Dupuit curves. The Hansen curve again gives the closest approximation to the measured drawdown. However, in this case the divergence increases from 0.03 ft at 16-ft radial distance to 0.34 ft at 1-ft radial distance.

In the 7.03-ft well drawdown (Fig. 8), the Dupuit and Jaeger curves again lie close together. The measured drawdown corresponds with the Hansen curve to the 16-ft mark but then they diverge rapidly. The Boulton, Hall, and Babbitt and Caldwell curves lie approximately midway between the measured and Dupuit curves. Each curve follows its own course, however, and no two curves, except the Dupuit and Jaeger curves, show a similar trend.

An outstanding feature was the good correlation obtained for all pumping cycles between the Jaeger and Dupuit curves. They diverged slightly as they neared the well face but the divergence, in all cases, was of a comparatively minor nature. The Jaeger curve did not, however, give a good correlation with the measured drawdown curve for any cycle, and our experiments indicated that curves calculated from the Hansen and Babbitt and Caldwell equations approximate much more closely to the measured drawdown curve than does the Jaeger curve. In fact, the correlation between the measured drawdown curve and those calculated from the Hansen and Babbitt and Caldwell equations

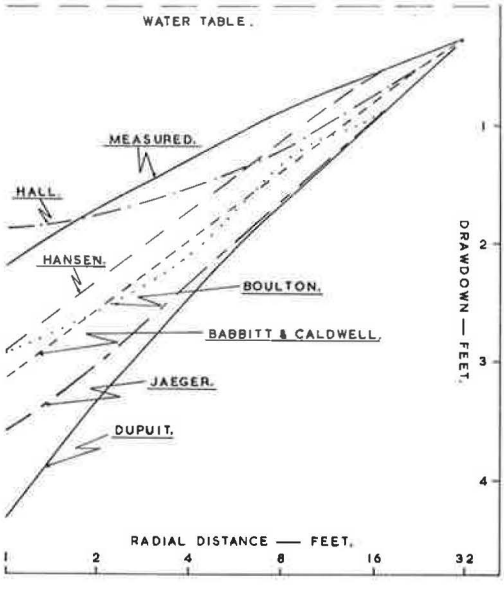

Figure 8. Semilog plot of measured and calculated drawdown curves for 7.03-ft well drawdown.

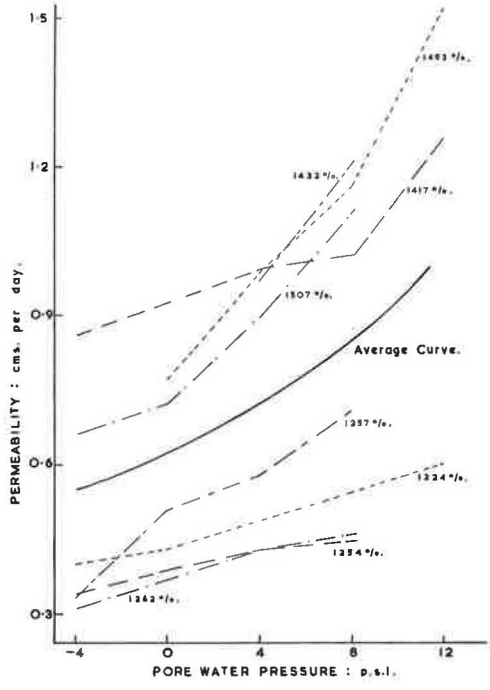

Figure 9. Results of laboratory permeability tests on peat samples showing the variation of permeability at different pore water pressures. Percentage figures quoted are the moisture contents of samples tested.

was excellent for the first two pumping cycles. During the other pumping cycles, however, the measured drawdown curves were affected by air released from solution and trapped within the pore space. This resulted in poor correlation between measured and calculated curves for these cycles.

The close correspondence between the Jaeger and Dupuit curves is as expected when one considers that Jaeger set about correcting what he assumed were errors in the basic Dupuit assumptions but did not take the surface of seepage into account. The experimental results show that a surface of seepage does exist. They also vindicate the accuracy of the Hansen and Babbitt and Caldwell equations and indicate, that for this gelatinous blanket peat, shallow drains (3- to 3½-ft deep) give much better drainage results than deeper drains.

LABORATORY INVESTIGATIONS, PERMEABILITY

When the third and fourth pumping cycles gave reduced steady state discharges, the theory of entrapped air resulting in reduced permeability suggested itself. A comprehensive permeability analysis was then carried out.

The Bjerrum-Huder permeability apparatus (21) consists essentially of a closed system of which the sample is part. This system can be pressurized to any required value by means of a pressure pump, while at the same time a hydraulic head can be generated within the system by raising a mercury column over a system of pulleys. A series of tests was run on a modified Bjerrum-Huder apparatus (23). The peat samples were taken in thin-wall tubes close to the site of the experiment and each sample was tested with its pore water pressure controlled at 0, 4, 8, 12, and -4 psi.

Results

The test results are shown in Figure 9. They fall into two distinct groups. The permeabilities of the first group run from 0.31 cm per day to 0.71 cm per day. The

final moisture content of the samples in this group is about 1250 percent. The permeabilities of the second group run from 0.66 cm per day to 1.52 cm per day at final moisture contents of about 1450 percent. All these samples were taken from the same site and at the same depth. We noted however that the final ovendry weights of samples in the lower range were greater than those of the high-range samples. This accounted for the variation in moisture content as a difference of less than 1 grm. dry weight was sufficient to give a moisture content difference of 200 percent. It also suggested that the low-range samples contained more fibrous material than the other samples, and furnished further evidence of the variability of peat and the difficulty of obtaining representative samples.

Discussion

An average permeability curve is shown in Figure 9. This curve represents the average of all laboratory permeability tests carried out and has been weighted to allow for missing values. It shows a permeability range from 0.55 cm per day at -4 psi to 1 cm per day at 12 psi. This corresponds very well with the field values which range from 0.29 cm per day to 0.98 cm per day. The average laboratory result at 0 psi of 0.63 cm per day compares very favorably with the field result of 0.66 cm per day measured during the 2.94-ft well drawdown.

It is very difficult to represent the result of a lowered water table with its consequent reduced positive pressures and induced suction in a laboratory test. However, our tests do show a very positive reduction in permeability as the pore water pressure is reduced. They also give excellent correlation with field measurements, and we are quite satisfied that entrapped air, released from solution as the water table is lowered, is responsible for the observed reductions in permeability and discharge.

FIELD INVESTIGATIONS, SECOND WELL EXPERIMENT

The pump was stopped and the float removed from the well on completion of the first four pumping cycles. The well was then allowed to recharge. The recharging took about 200 days. One further pumping cycle was then carried out, the float being regulated to give a well drawdown of 2.30 ft.

Results

The usual trend of increasing drawdowns and decreasing discharge rates was observed. The drawdowns increased quickly at first and then more slowly to maximum figures. The relatively high initial discharge figure fell off quickly in the early stages, the rate of fall-off decreasing gradually. The measured steady state discharge of 11,685 cc per day was divided by 1.1955 (correction factor for partial penetration of the well) to give a corrected daily discharge rate of 9,774 cc. This figure was then used in the Dupuit formula and gave a permeability value of 0.2867 cm per day.

Discussion

The outstanding result of this experiment is the low permeability figure. The calculated value of 0.2867 cm per day is approximately the same as that calculated for the 7.03-ft well drawdown (0.2937 cm per day). This shows that even after a 200-day recharging period, the permeability did not improve and the entrapped air was not dislodged or dissolved by the rising water table. Another notable feature is the short radius of influence. This reached a maximum value of approximately 10 ft after 79 days but reduced again to about 7 ft at a later stage. The results indicate that the installation of deep drains in blanket peat can cause a permeanent or semipermanent reduction of permeability. The position was not remedied in our experiment by a 7-month recharging operation. Whether or not a longer recharging period would result in increased permeability will have to be verified by long-term experiments. We can, however, say that the installation of drains at depths greater than $3\frac{1}{2}$ ft offers no advantages and may result in a permanent reduction in permeability.

ACKNOWLEDGMENTS

We wish to thank the Director of the Agricultural Institute for his interest in the project and for the facilities granted in its execution; the staffs of the Soil Physics Department, the Peatland Experimental Station and the Statistics Department of the Agricultural Institute; the staff of the Soil Mechanics Department, University College, Dublin; and Michael Sheeran, Technician in charge of the field work at Glenamoy.

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