*Nordic Hydrology,* 25, 1994, 167-182

# Cylindrical Piezometer Responses in a Humified Fen Peat

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Most studies of peat hydrology have concentrated on processes below the watertable where pore water pressures and hydraulic conductivity are measured using piezometers. While piezometer head recovery tests in poorly humified bog peats give responses similar to those expected from rigid soils, a number of studies have suggested that matrix compressibility might be important in affecting head recovery test results in well humified bog peats. Until now no data have been available for humified fen peats. We apply the response time theory of Brand and Premchitt (1982) for compressible soils, and Hvorslev (1951) for rigid soils, to head recovery test data obtained from open cylindrical piezometers installed in a humified fen peat in Somerset, England. To the best of our knowledge this is also the first quantitative application of compressible soil theory for piezometers to any peat. Our results show that compression and swelling of the peat matrix do affect the course of head recovery in the piezometers used in the study. We comment on the significance of this finding for the calculation of hydraulic conductivities and pore water pressures in this peat type.

## Aims of the Study

In recent years there has been an increasing interest in peat hydrology and how it controls and in turn is controlled by mire morphology and ecology (see, for example, Brown and Ingram 1988; Clymo, 1984; Hemond *et al.* 1984, Ingram 1982, 1983). In particular, attention has focused on fen peats. The extensive drainage of this peat type throughout northern and western Europe has led to humification of the peat, and recent attempts at restoration and protection of fen nature reserves have highlighted the need for a clearer understanding of fen peat hydrology.

Most studies of peat hydrology have concentrated on processes below the water table where pore water pressures and hydraulic conductivity are typically measured using piezometers. To assess the reliability of pore water pressure measurements and to obtain values of hydraulic conductivity it is usual to conduct a head recovery test where water is added to (slug injection) or removed from (slug withdrawal) the piezometer and the recovery to the original water level in the instrument recorded. In less- or poorly-humified bog peats these tests give results consistent with the behaviour expected from incompressible or rigid soils (Rycroft *et al.* 1975). In humified bog peats a number of workers have reported apparently anomalous head recovery test results which seem to show that hydraulic conductivity is dependent on the size of the hydraulic head difference between the piezometer and the surrounding peat soil. Some workers have attributed these properties to non-Darcian flow processes within the peat (Rycroft *et al.* 1975; Waine *et al.* 1985), while more recently Brown and Ingram (1988), Hemond *et al.* (1984), and Hemond and Goldman (1985) have suggested that apparent non-Darcian water flow in certain peats can be explained by the effects of matrix compression and swelling which cause variable water storage within the peat. A feature of these studies is that they have concentrated on humified bog peats (Brown and Ingram 1988) and salt marsh peats (Hemond and Goldman 1985). However, it is possible that the hydraulic and storage properties of fen peats are different from bog and salt marsh peats. The hydraulic properties of any peat is, in part, a function of its floristic composition. Fen peats typically contain the remains of higher plants such as *Phragmites australis* (Cav.) Trin. ex Steudel and *Cladium mariscus* (L.) Pohl which are structurally quite different from the *Sphagnum* moss species which make up bog peat. There is laboratory evidence that floristically different peats, even when moderately humified, display different hydraulic and compression properties (see, for example, Boelter 1965; Ivanov 1981 – p. 49; Paivanen 1973). There is an obvious need for further information on the use of piezometers in studying water transmission properties of fen peats. We therefore focus our attention in this paper to study of a fen peat. A second, surprising, feature of the studies of both Brown and Ingram (1988) and Hemond and Goldman (1985) is that they do not attempt to quantify the importance of matrix compressibility during piezometer head recovery in peats. In particular, both studies fail to compare hydraulic conductivity values obtained using compressible and rigid soil theories. We address this deficiency by applying both rigid and compressible soil theories to piezometer head recovery data and comparing the values of hydraulic conductivity obtained using both theories. To the best of our knowledge this study is the first time that such a comparison has been made for any peat soil.

## Piezometer Design

A piezometer is used to measure the pore water pressure in a porous medium. Of the four basic types of piezometer – pneumatic, vibrating wire, closed hydraulic/standpipe, and open hydraulic/standpipe (for a recent review of piezometer systems see Anderson and Kneale 1987, pp. 79-88) – the open standpipe piezometer is the most commonly used where cost and ease of use are limiting factors in the study. Closed hydraulic, pneumatic, and vibrating wire piezometers are essentially closed systems and experience minimal changes in volumetric water content when registering a change in unit pore water pressure in the porous medium. Therefore, the time taken for these instruments to register a change in pore water pressure (the response time) is relatively rapid (see Anderson and Kneale 1987). This is not the case with open standpipe piezometers in which appreciable volume changes are required to register pore water pressure changes. As a result it is important that the time lag of the instrument to changes in pore water pressure is known. The response time of these instruments can be calculated using head recovery test data. Head recovery data from standpipe piezometers also provide a standard means of estimating the hydraulic conductivity of the soil around the piezometer tip. Cylindrical tips are most often used in piezometer systems because of their ease of installation. Because of their widespread use in both pore water pressure and hydraulic conductivity surveys we limit our analysis in this paper to open standpipe piezometers with cylindrical tips.

## Piezometer Head Recovery Theory

The theory describing the response time of open hydraulic piezometers in rigid soils was developed independently by Kirkham (1945) and Hvorslev (1951) and has been extended more recently for cylindrical tip – filter – soil interactions by Brand and Premchitt (1980), Brown and Hodgson (1988) and Kemp *et al.* (1989). For compressible soils, Gibson (1963) studied the relationship between head recovery in piezometers with spherical tips and soil hydraulic conductivity by applying the consolidation theory of Terzaghi (1943, pp. 265-96). Premchitt and Brand (1981) applied the analytical solution of Gibson (1963) to cylindrical piezometers by assuming that a cylindrical piezometer could be replaced by an equivalent spherical one. They later compared their analytical results with a numerical solution of the same problem (Brand and Premchitt 1982).

The assumption of rigidity of the soil structure makes response time theory simple and easy to apply (Vaughan 1974); in other words Hvorslev's theory is simpler than that of Gibson and Brand and Premchitt. However, in clay soils Gibson (1963) and Penman (1961) have demonstrated theoretically and experimentally that the assumption of rigidity may lead to serious errors in the calculation of head recovery and hydraulic conductivity. The degree to which compression and swelling of peat affects head recoveries is less well understood and documented and it is important therefore that both rigid and compressible soil theories are applied to piezometer data from peat soils.

Hvorslev (1951) developed a solution for equalisation during a head recovery test for any shaped piezometer in an incompressible soil by using the basic differential equation that describes saturated flow through a falling head permeameter. The pressure head $u$, at any time $t$, in a piezometer installed in a soil of hydraulic conductivity $k$ was shown to be related to the initial pressure head $u_0$ in the piezometer and the equalisation pressure head $u_\infty$ by

$$\frac{u_\infty - u}{u_\infty - u_0} = \exp\left(\frac{-Fkt}{V\gamma_w}\right) \tag{1}$$

where $\gamma_w$ is the unit weight of the water, $F$ is the shape factor (dimensions of length) which describes the geometry of the flow field around the piezometer (see Hvorslev 1951, p. 9) and $V$ is the volume factor defined as the volume of water required to flow into or out of the piezometer system to equalise a unit pressure difference between the piezometer system and the surrounding soil. In a standpipe piezometer $V$ is numerically equal to the cross-sectional area of the piezometer. When solved for $k$ Eq. (1) becomes the familar solution of Kirkham (1945)

$$k = \frac{V\gamma_w}{-Ft} \log e\left(\frac{u_\infty - u}{u_\infty - u_0}\right)$$

In developing Eq. (1) Hvorslev also assumed that the soil around the piezometer tip was isotropic, fully saturated and infinite in extent.

In compressible soils, the compression and swelling of the soil around the piezometer can play a major part in piezometer response and Eq. (1) may not adequately describe the equalisation process. In a rigid soil the volume occupied by the water per unit volume of saturated soil (the porosity) is independent of the state of stress in the soil. If this condition is satisfied, the quantity of water flowing out of a block of saturated soil is equal to the amount of water which enters the block, regardless of whether or not the state of stress in the soil changes. Terzaghi (1943, pp. 265-266) notes that there is no real soil which satisfies this condition because every change in the state of stress produces a certain change in the volume of the voids per unit volume of the soil. The state of stress in a soil can be described by the effective stress equation

$$\sigma_T = \sigma' + u \tag{2}$$

where $\sigma_T$ is the total stress, and $\sigma'$ the effective stress. Eq. (2) can be used to analyse the effect of compression and swelling on head recovery in a piezometer. Immediately after a slug injection in a piezometer installed in a compressible soil there will be a reduction in the effective stresses around the piezometer tip as the pore water pressure increase while the total vertical stresses remain the same. The soil around the piezometer tip will swell and some of the water flowing from the piezometer will be taken into storage. As the water level in the piezometer recovers, there will be a corresponding increase in the effective stresses around the tip and this will cause water to come out of storage and reduce the rate of head recovery. For cylindrical piezometers installed in a compressible soil the rate of pressure head recovery is given by the consolidation equation in axisymmetrical cylindrical coordinates

$$c\left(\frac{\partial^2 u}{\partial r^2}+\frac{1}{r}\frac{\partial u}{\partial r}+\frac{\partial^2 u}{\partial z^2}\right)=\frac{\partial u}{\partial t} \tag{3}$$

where $r$ is the radial distance from the mid-point of the piezometer tip, $z$ is the vertical distance from the mid-length of the piezometer tip, and $c$ is the coefficient of 'consolidation' (that accounts for both compression and swelling – see below). Using a numerical solution to Eq. (3) Brand and Premchitt (1982) found that the soil-piezometer system during equalisation was quite well represented by a control parameter

$$\lambda=\frac{4\pi a^2 bm}{V} \tag{4}$$

where $a$ is the outside radius, $b$ the half length of the piezometer tip, and $m$ the coefficient of volume compressibility of the soil. The value of $\lambda$ accurately characterises the shape of the head recovery curve for which there is a unique ratio between $t_{90}$ (the time taken for 90 per cent recovery of the initial head difference between the piezometer and the soil) and $t_{50}$. Using $\lambda$ as a control parameter, Brand and Premchitt (1982) were able to derive equalisation nomographs, based on $t_{50}$ and $t_{90}$ that can be used to calculate the hydraulic conductivity and coefficient of 'consolidation' of the soil for any dimension of cylindrical piezometer. Their analysis assumes that the coefficient of 'consolidation' has the same value for both compression and swelling, and that the soil behaves as an elastic medium.

For the field application of head recovery theory, groundwater conditions must be constant. If the water around the piezometer tip is subjected to changes in pore water pressure separate to those induced by the test then the rate at which the pressure in the piezometer recovers will be affected giving inaccurate results. Hvorslev (1951) notes a number of sources of error that can affect the performance and determination of the response time of an open standpipe piezometer. These include:

- Changes in the effective stresses in the soil around the piezometer tip due to removal or displacement of soil during the installation of the piezometer. Hvorslev calls this effect the stress adjustment time lag.
- Sedimentation and clogging of the piezometer tip.

- Gas bubbles in the soil. Gas bubbles in the soil near the piezometer tip will increase the response time by decreasing the conductivity of the soil. The expansion and contraction of gas bubbles as pore water pressure changes in the soil around the tip will also affect response time by altering the hydraulic conductivity and storage capacity of the soil. Evidence for the accumulation of methane gas in humified bog peat has been presented by Reynolds *et al.* (1992), and Mathur and Levesque (1985).
- Gas bubbles in the piezometer. Air or gas bubbles in the open tube may cause the stabilised water level in the piezometer to rise above the groundwater level. To prevent such problems the standpipe diameter should be large enough and the interior smooth enough to permit the rise of gas bubbles. These requirements are satisfied by use of seamless and jointless plastic tubing.

If these errors can be minimised, both Hvorslev's and Brand and Premchitt's theories can be applied to head recovery data, and the effect of compression and swelling on head recovery can be determined. We applied both theories to head recovery data obtained from piezometers installed in a fen peat soil in the Somerset Levels in Southwest England.

Table 1 – Typical profile description of the peat soil found on each site

| Depth: | Comment: | |
|---|---|---|
| 0-40 cm | $O_1$ | Black well humified amorphous peat, moderate fine crumb structure, friable with merging boundary. No visible plant remains. |
| 40-60 cm | $O_2$ | Black well humified amorphous peat, moderate to strong coarse subangular blocky and medium crumb structure. No visible plant remains. |
| 60-80 cm | $O_3$ | Black humified mesofibrous peat, moderate fine crumb structure, with visible plant remains. |
| 80-100 cm | $O_4$ | Black humified fibrous peat with densely packed layers of visible plant remains. |
| 100-120 cm | $O_5$ | Dark reddish brown slightly humified fibrous peat with less densely packed clearly visible plant remains. |
| 120-180 cm | $O_6$ | Light brown slightly humified mesofibrous peat in layers with finer texture. |
| 180-320 cm | $O_7$ | Layers of dark brown slightly humified fibrous peat with visible plant remains and black humified peat with coarse granular subangular structure. |
| 320-360 cm | $O_8$ | Brown to light brown peat with well preserved macrophytes. |
| >360 cm | | Olive grey very fine clay with some well preserved plant remains. |

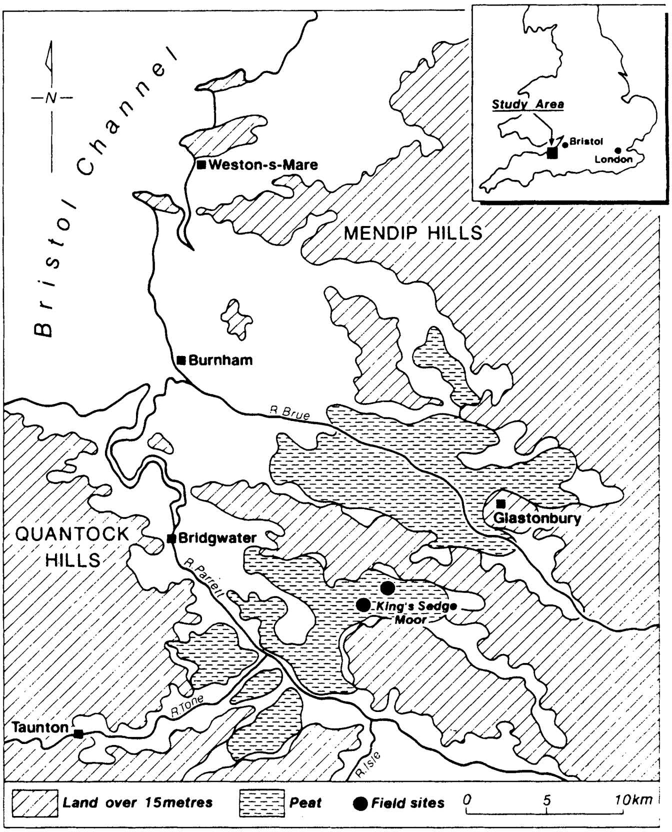

Fig. 1. Location of the field sites.

## Field Investigations

Standpipe piezometers were installed in a humified fen peat on two sites, called for convenience Site 1 and Site 2, on King's Sedgemoor in the Somerset Levels in the Southwest of England (see Fig. 1). Site 1 is located 2°51'00"W 51°05'34"N, while site 2 is located 2°49'17"W 51°06'20"N. The peat soil on each site consits of an upper layer of amorphous, well humified peat underlain by poorly defined layers of peat showing different degrees of humification, and belongs to the Altcar Series of the Altcar 1 Association (Findlay *et al.* 1984). Internationally the soil is classified as a Histosol, suborder Saprist, great group Medisaprist (Soil Survey Staff 1975). From a number of cores it was found that the peat profiles on each site were very similar. The stratigraphy shown in Table 1 is a simplified representation of cores taken from both sites and combines a subjective assessment of the degree of humification using the von Post method with an assessment of the composition of the peat using the technique of Troels-Smith (after Findlay *et al.* 1984). On Site 1 the peat deposit was between 3 and 5 metres in thickness, while on Site 2 it was between 1.2 and 3.5 metres in thickness.

The piezometers were constructed from low air entry Casagrande porous plastic tips with an average pore diameter of $6 \times 10^{-5}$ cm and a hydraulic conductivity of approximately 0.003 cm $s^{-1}$ and smooth walled polyvinyl chloride (PVC) tubes with an inside diameter of 1.4 cm. Anderson and Kneale (1987) note that an open standpipe piezometer should be self de-airing if the standpipe is larger than 1.2 cm in diameter. Each tip had an outside diameter of 2.7 cm and a length of 21 cm. Great care was taken during piezometer installation to prevent damage of the peat in contact with the tip and smearing of the side walls. An auger hole with a diameter of approximately 3 cm was formed with a screw auger. At the depth of the tip a screw auger with a diameter of 2.5 cm, 0.2 cm smaller than the diameter of the piezometer tip, was used. The piezometer was lowered down the hole and the tip was pushed gently into position. The void around the standpipe and immediately above the tip was sealed with a plug of bentonite, while the rest of the void was filled with a peat slurry. No sand filter was used in any of the piezometer installations. The piezometers were installed to depths of 120, 170, and 200 cm below the ground surface. To prevent entrapment of air around the tip each piezometer was installed when the watertable was at least 20 cm above the piezometer tip We had no means of testing for the presence of gas bubbles in the soil around the piezometer tips and in the analysis of the results in the following section it it assumed that gas bubbles were unimportant in the head recovery process.

To ensure stress adjustment time lags caused by the installation were negligible the piezometers were left in position for 6 months before the recovery tests were carried out. On each site the response characteristics of 8 piezometers were measured. Head recovery tests were carried out in which a slug of water was added to the instrument. Initial head differences of between 31.5 and 39 cm were used. At the beginning of each test the head difference was established and measured in a period of up to 10 seconds. Methods of measuring depth to the water level in a piezometer have been reviewed by Anderson and Kneale (1987) and Ingram (1983). A simple and reliable method, and that used in this study, is to blow through a rigid graduated tube as it is lowered into the standpipe. As it approaches the water level a rising pitch followed by bubbling is heard. This method of measurement was tested in laboratory conditions and gave highly reproducible results with an accuracy of 0.2 cm. This level of accuracy is less than that reported by Ingram (1983) but was felt to be sufficient for the tests in this study. In each test head recovery was measured for a period of 10 hours. Longer observation periods were not possible because of fluctuations in the watertable (measured using rapidly responding dipwells). After the head recovery tests the piezometers were excavated and the tips checked for clogging; no top showed evidence of blockage with peat debris.

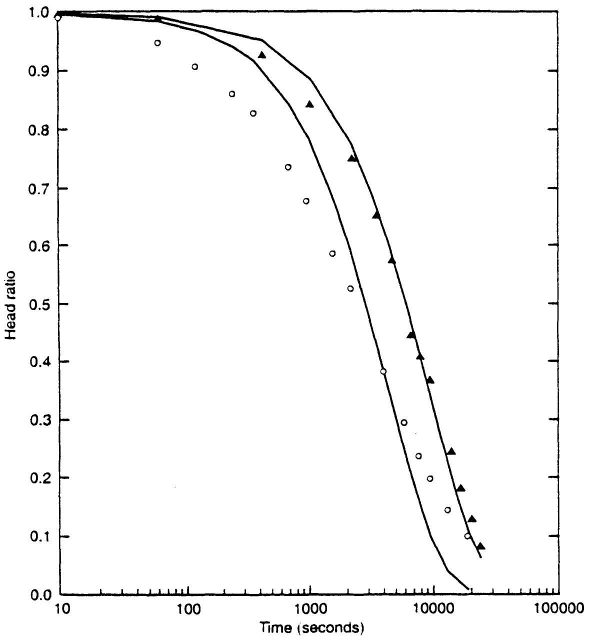

Fig. 2. Example head recoveries. Closed triangles are for piezometer $A_{120}$ on site 1, open circles for piezometer $C_{200}$ on site 2. The solid lines are fitted responses (least differences) according to Eq. (1).

## Results and Discussion

To illustrate the responses of the piezometers, the head recoveries of two of the piezometers are shown in Fig. 2 where the head ratio is plotted as a function of time on a $\log_{10}$ scale. For both of the piezometer responses a fitted response according to Eq. (1) is also shown. It is important to note that if the value of $Fk/V\gamma_w$ in Eq. (1) is changed, the *shape* of the recovery on an arithmetic-$\log_{10}$ plot remains the same. The curve merely translates left or right. As can be seen from Fig. 2, the response of piezometer $A_{120}$ on site 1 corresponds quite closely with the response described by Hvorslev's theory. However, that from the piezometer $C_{200}$ on site 2 shows a pronounced deviation from the curve expected from Hvorslev's theory. It was noted above that immediately after a slug injection there will be a reduction in the effective stresses around the piezometer tip as the pore water pressure increases while the total vertical stresses remain the same. The peat will swell and some of the water flowing from the tube at the start of the head recovery test will be taken into storage. This loss of water to storage is in addition to that flowing from the piezometer due to the head difference between the piezometer

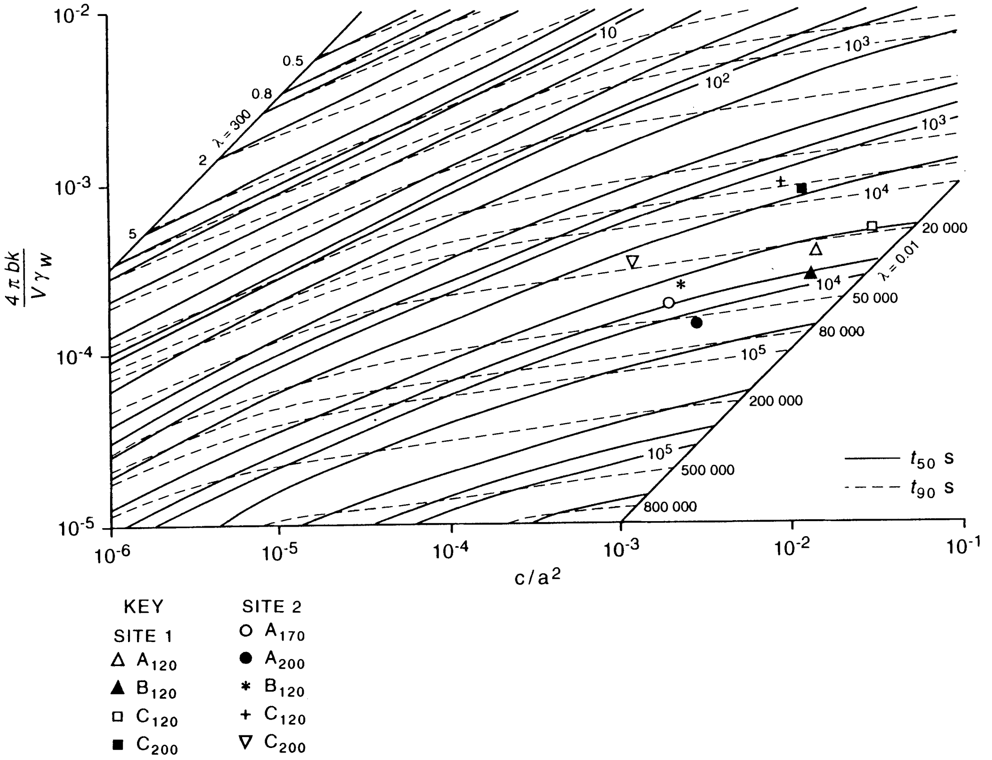

Fig. 3. Interpretation of the head recovery tests by means of the nomograph of Brand and Premchitt (1982).

and the soil. As the pressure head in the piezometer recovers there will be an increase in the effective stress around the piezometer tip causing water to come out of storage reducing the rate of head recovery. The result is that the curve of head ratio against the $\log_{10}$ of time is described by a 'shallower' or less pronounced sigmoid than that given by Eq. (1). *Qualitatively* the plot of $C_{200}$ is very similar in form to the head recovery plots reported by Brown and Ingram (1988) for cylindrical piezometers installed in a humified bog peat and suggests that the peat types show similar response behaviour. Although all of our recoveries showed deviations from rigid soil theory it is not clear how much error the effects of compressibility will introduce into hydraulic conductivity calculations. To do this we calculated values of hydraulic conductivity using Eq. (1) and the nomograph of Brand and Premchitt (1982) (see Fig. 3 and Table 2).

In Table 2 values of $t_{90}/t_{50}$ are given in the first column. In a rigid soil or a soil that behaves as if it were rigid this value will be 3.322 regardless of the value of $Fk/V\gamma_w$ whereas in a compressible soil the ratio will vary but will always be greater than 3.322 and will increase with the value of the volume compressibility of the soil

Table 2 – Values of hydraulic conductivity calculated using rigid and compressible soil theories. $k_{50}$ and $k_{90}$ calculated using the 50 and 90 per cent equalisation time respectively. $k^*$ calculated using the response time charts derived numerically by Brand and Premchitt. IR denotes insufficient response during the measurement period (10 hours) to make a calculation

| | | Hvorslev (1951) 'rigid soil' | | Brand and Premchitt (1982) 'compressible soil' | |
|---|---|---|---|---|---|
| Piezometer code | $t_{90}/t_{50}$ | $k_{50}$ ($\times 10^{-6}$ cms$^{-1}$) | $k_{90}$ ($\times 10^{-6}$ cms$^{-1}$) | $k^*$ ($\times 10^{-6}$ cms$^{-1}$) | $c$ ($\times 10^{-3}$ cm$^2$s$^{-1}$) |
| Site 1 | | | | | |
| $A_{120}$ | 3.958 | 3.482 | 2.921 | 4.317 | 6.86 |
| $A_{170}$ | IR | 0.790 | IR | – | – |
| $A_{200}$ | IR | 0.817 | IR | – | – |
| $B_{120}$ | 3.895 | 2.310 | 1.970 | 3.033 | 6.37 |
| $B_{170}$ | IR | 0.982 | IR | – | – |
| $B_{200}$ | IR | 0.691 | IR | – | – |
| $C_{120}$ | 4.043 | 4.654 | 3.739 | 5.833 | 13.23 |
| $C_{200}$ | 4.871 | 10.695 | 7.315 | 9.800 | 6.37 |
| Site 2 | | | | | |
| $A_{170}$ | 4.798 | 2.489 | 1.724 | 2.217 | 0.88 |
| $A_{200}$ | 4.439 | 1.692 | 1.266 | 1.750 | 1.32 |
| $B_{120}$ | 5.319 | 3.876 | 2.415 | 2.800 | 1.08 |
| $B_{170}$ | IR | IR | IR | – | – |
| $B_{200}$ | IR | IR | IR | – | – |
| $C_{120}$ | 5.602 | 15.421 | 9.145 | 10.500 | 4.02 |
| $C_{170}$ | IR | IR | IR | – | – |
| $C_{200}$ | 7.575 | 7.999 | 3.508 | 3.617 | 0.56 |

(see Premchitt and Brand 1981; Brand and Premchitt 1982). In essence the ratio $t_{90}/t_{50}$ is a measure of the effect of compressibility on the head recovery; as it increases it describes the increasing 'shallowness' of the head recovery sigmoid. All of the piezometers show values of this ratio greater than 3.322 with values ranging from 3.895 ($B_{120}$ on site 1) to 7.575 ($C_{200}$ on site 2). Generally the piezometers on site 1 had lower values of $t_{90}/t_{50}$ than the piezometers on site 2. Values of hydraulic conductivity for $t_{50}$ and $t_{90}$ were calculated using Eq. (1). The shape factor of the tips was obtained using the equation of Brand and Premchitt (1980)

$$F = 7d + 1.65l \tag{5}$$

where $d$ is the tip diameter and $l$ the tip length, giving a value of $F$ of 53.55. In all of the piezometers the 'hydraulic conductivity' calculated using $t_{50}$ was greater than the value calculated using $t_{90}$. As noted above, when applying rigid soil theory to a compressible soil this is to be expected since some of the flow out the piezometer in early time in a slug injection test is water going into storage. Because Eq. (1) does not account for variable storage the effect is to give an increase in the apparent hydraulic conductivity in early time. This effect is quite small in those piezometers with a value of $t_{90}/t_{50}$ less than or equal to about 4. For piezometer $B_{120}$ on site 1, for example, the ratio between $k_{50}$ and $k_{90}$ is 1.173 while for piezometer $C_{120}$ on site 1 the ratio is 1.245. However, strictly, Hvorslev's theory is invalid for all of the piezometers.

A comparison of hydraulic conductivity values calculated using both theories shows that in six of the tests in which 90 per cent recovery occurred within the 10 hour measurement period the value of $k^*$ was nearer to $k_{50}$ than $k_{90}$. In the case of piezometers $A_{120}$, $B_{120}$, and $C_{120}$ on site 1, and $A_{200}$ on site 2 $k^*$ was actually greater than $k_{50}$. This result is somewhat surprising since a number of workers have suggested that in compressible soils the use of Hvorslev's theory only results in accurate estimations of hydraulic conductivity when calculated using $t_{99}$ or greater; that is we would expect $k^*$ to be less than $k_{90}$. Penman (1961), for example, compared hydraulic conductivities in a highly compressible clay soil calculated using a triaxial cell apparatus set up as a constant head permeameter and using piezometer head recovery data applied to Eq. (1) and found that the two values were only in close agreement when $t_{99.99}$ was used in Eq. (1). Hvorslev (1951) similarly suggests that reliable estimates of hydraulic conductivity in compressible soils can only be calculated using Eq. (1) when exchanges to and from storage are nearly complete at the end of the head recovery process. In those piezometers which showed the highest values $t_{90}/t_{50}$ ($B_{120}$, $C_{120}$, and $C_{200}$ on site 2) the method of Brand and Premchitt (1982) did give values of hydraulic conductivity closer to $k_{90}$ than $k_{50}$. Brand and Premchitt (1982) acknowledge that their method is only approximate, and the rather high values of hydraulic conductivity obtained using their method is probably a reflection of this approximation. An advantage of the method of Brand and Premchitt (1982) is that, as well as hydraulic conductivity, a value of the coefficient of 'consolidation' for the peat soil can also be obtained. Values from the tests are given for information in the last column of Table 2. Values of $c$ could be important in modelling water flow in peats subject to rapid changes in pore water pressures, for example during pump drainage, which would in turn cause changes in the effective stresses in the soil and its storage.

## Concluding Remarks

In the comparison of $k^*$, $k_{50}$ and $k_{90}$ it is important to note that both rigid and compressible soil theories give values of hydraulic conductivity for each piezometer installation within a factor of two of each other. For a parameter that is known to vary by several orders of magnitude at the field scale these differences might be regarded as insignificant when only a general estimate of hydraulic conductivity is required. However, the comparison of the two methods does show the problem of accurately estimating hydraulic conductivities of peat using piezometer tests. Due to the effects of compressibility, Hvorslev's (1951) theory gives values of hydraulic conductivity that are too high and depend on the length of time over which observations are made, while, due to approximations in the treatment of compressibility and in the numerical analysis, the method of Brand and Premchitt (1982) also appears to give values of hydraulic conductivity that are too high. Laboratory testing of hydraulic conductivity is unlikely to provide a satisfactory solution to this problem because of the damage caused to samples during destructive field sampling. Rapid stress changes caused by destructive sampling, especially at depth, will alter the peat structure, and therefore its hydraulic and storage properties. If such damage was irreversible, recompression in the laboratory could not be used to simulate stress conditions in the field. A further problem is the oxidation and humification of the sample. Recording the pore water pressure in the piezometer until $t_{99}$ and then applying rigid soil theory is also unrealistic since pore water pressures in the field are rarely stable over the time period necessary to achieve such recovery.

The clear deviation of most of the head recoveries from rigid soil theory also means that Hvorslev's analysis cannot be used to calculate the error in piezometer pore water pressure measurements when pore water pressures in the soil are changing. Either the application of numerical models using consolidation theory or the use of stiffer piezometer designs, such as the vibrating wire piezometer, would be needed to calculate or minimise errors in measurement.

To the best of our knowledge this study is the first application of Brand and Premchitt's (1982) head recovery theory to data from any peat soil and is the first evidence of compressible behaviour during head recovery in a humified fen peat. We note above (see Results and Discussion) that qualitatively our piezometer responses are similar to those recorded in a bog fen peat by Brown and Ingram (1988). However, since Brown and Ingram do not analyse their data using compressible soil theory a comparison of hydraulic conductivies in the different peat types is not possible. Despite giving values of hydraulic conductivity that appear to be too high the theory of Brand and Premchitt does allow a standard comparison of hydraulic and storage properties between different peat types and we would recommend its use for such comparisons.

## References

Anderson, M. G., and Kneale, P. E. (1987) Instrumentation of pore pressures and soil water suctions. In Anderson, M. G. and Richards, K. S. (eds) *Slope stability: geotechnical engineering and geomorphology,* John Wiley, Chichester, pp. 77-112.

Boelter, D. H. (1965) Hydraulic conductivity of peats, *Soil Science, Vol. 100(4),* pp. 227-231.

Brand, E. W., and Premchitt, J. (1980) Shape factors of cylindrical piezometers, *Geotechnique, Vol. 30(4),* pp. 369-384.

Brand, E. W., and Premchitt, J. (1982) Response times of cylindrical piezometers, *Geotechnique, Vol. 32(3),* pp. 203-216.

Brown, J. M. B., and Hodgson, M. P. (1988) Finite element computation of shape factors for Kirkham's piezometer tube method for hydraulic conductivity of saturated soil, *Hydrological Processes, Vol. 2,* pp. 219-255.

Brown, J. M. B., and Ingram, H. A. P. (1988) Changing storage beneath a stationary watertable – an anomaly of certain humified peats, *Quaterly Journal of Engineering Geology, Vol. 21,* pp. 177-182.

Clymo, R. S. (1984) The limits to peat bog growth, *Philosophical Transactions of the Royal Society London, Vol. B303,* pp. 605-654.

Findlay, D. C., Colborne, G. J. N., Cope, D. W., Harrod, T. R., Hogin, D. V., and Staines, S. J. (1984) *Soils and their use in South West England.* Soil Survey of England and Wales, Harpenden.

Gibson, R. G. (1963) An analysis of sytem flexibility and its effects on time lags in pore pressure measurements, *Geotechnique, Vol. 13,* pp. 1-19.

Hemond, H. F., and Goldman, C. (1985) On non-Darcian water flow in peat, *Journal of Ecology, Vol. 73,* pp. 579-584.

Hemond, H. F., Nuttle, W. K., Burke, R. W., and Stolzenbach, K. D. (1984) Surface infiltration in salt marshes: theory, measurement, and biogeochemical implications, *Water Resources Research, Vol. 20(5),* pp. 591-600.

Hvorslev, M. J. (1951) Time lag and soil permeability in groundwater observations, Bulletin number 36, Waterways Experimental Station. Corps of Engineers, United States Army, Vicksburg, Mississippi.

Ingram, H. A. P. (1982) Size and shape in raised mire ecosystems: a geophysical model, *Nature, Vol. 297,* pp. 300-303.

Ingram, H. A. P. (1983) Hydrology. In A. J. P. Gore (ed.) *Mires: swamp, bog, fen and moor,* Elsevier, Amsterdam, pp. 67-158.

Ivanov, K. E. (1981) *Water movement in mirelands,* English language edition translated by A. Thompson and H. A. P. Ingram, Academic Press, London.

Kemp, M. J., Nash, D. F. T., and Anderson, M. G. (1989) Modelling installation designs for soil water instrumentation, with particular reference to Casagrande type piezometer systems, *Earth Surface Processes and Landforms, Vol. 14,* pp. 375-382.

Kirkham, D. (1945) Proposed method for field measurement of permeability of soil below the watertable, *Proceedings of the Soil Science Society of America, Vol. 10,* pp. 58-68.

Mathur, S. P., and Levesque, M. (1985) Negative effects of depth on saturated hydraulic conductivity of histosols, *Soil Science, Vol. 140(6),* pp. 462-466.

Paivanen, J. (1973) Hydraulic conductivity and water retention in peat soils, *Acta Forestalia*

*Fennica, Vol. 129,* pp. 1-70.

Penman, A. D. M. (1961) A study of the response time of various piezometers. In *Pore pressure and suction in soils,* Butterworths, London, pp. 53-8. Proceedings of a conference organised by the British National Society of the International Society of Soil Mechanics and Foundation Engineering at the Institution of Civil Engineers held on March 30th and 31st 1960.

Premchitt, J., and Brand, E. W. (1981) Pore pressure equalisation of piezometers in compressible soils, *Geotechnique, Vol. 31(1),* pp. 105-123.

Reynolds, W. D., Brown, D. A., Mathur, S. P., and Overend, R. P. (1992) Effect of *in-situ* gas accumulation on the hydraulic conductivity of peat, *Soil Science, Vol. 153(5),* pp. 397-408.

Rycroft, D. W., Williams, D. J. A., and Ingram, H. A. P. (1975) The transmission of water through peat. 2: Field experiments, *Journal of Ecology, Vol. 63,* pp. 557-567.

Soil Survey Staff (1975) *Soil taxonomy – a basic system of soil classification for making and interpreting soil surveys,* United States Department of Agriculture Agricultural Handbook number 436. United States Government Printing Office, Washington D.C.

Terzaghi, K. (1943) *Theoretical soil mechanics,* John Wiley, New York.

Vaughan, P. R. (1974) The measurement of pore pressures with piezometers. In *Proceedings of the British Geotechnical Society symposium on field instrumentation in geotechnical engineering,* Butterworths, London, pp. 411-422.

Waine, J., Brown, J. M. B., and Ingram, H. A. P. (1985) Non-Darcian transmission of water in certain humified peats, *Journal of Hydrology, Vol. 82,* pp. 327-339.

First received: 9 August, 1993
Revised version received: 14 October, 1993
Accepted: 8 December, 1993

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