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Behavior of Soil-Water Pressure Profile in Response to Sudden Unloading-Horizontal Case

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ABSTRACT. The behavior of the pressure profile at early times in an initially saturated porous medium was considered in relation to variation that occur during sudden changes in the position of the water table. In a pumped unconfined aquifer a sudden change of the pressure head is encountered which assimilates with consolidation type experiments. Extensive experiments were carried out to seek an explanation of this phenomenon. The results obtained demonstrate that the pressure dissipation in an initially saturated soil column at the early times will fit quite reasonably a diffusion type equation for both cases with an initially specified uniform and triangular hydrostatic pressure distribution.

1. Introduction

The behavior of pressure profile at an early time in an initially saturated porous media subjected to a sudden drop in the position of the water table is investigated. Two types of initial conditions are considered in relation to variation of sudden changes in the water table position. Firstly, a horizontal column was filled with a saturated soil with one end ($x = 0$) sealed and with the other end ($x = L$) connected to a water reservoir, of which the elevation above the center line of the column could be varied. The reservoir was positioned at the appropriate elevation above the column until a uniform pressure condition along the column were established. At time $t = 0$, the reservoir was then dropped to the center line of the column.

The second set of experiments carried out were for a triangular initial pressure distribution at $t = 0$. Each experiment was established by maintaining a constant hydrostatic pressure at one end of the column ($x = L$) while the other end of the column ($x = 0$) was maintained at zero pressure head. When steady state flow conditions were developed and the pressure head distribution measured, the constant head tank was again lowered at $t = 0$ to the column center line. The results obtained have shown that the relationship between pressure head and distance along the column at any given time has a curvilinear form. The following sections discuss this phenomena in detail and a proposed analytical solution is suggested.

2. Background

Early studies of the mechanisms of early pressure behavior in saturated porous material were carried out by Philip[1] who investigated the transition from rest of steady motion of a fluid in a saturated porous medium during the sudden application of a potential gradient. He found that the time needed to reach a steady state condition generally occurred within a few seconds and sometimes even within a fraction of a second. He also found an error in using Darcy's law which neglects the transient phase. Similar finding was reported by Liakopoulos[2] who stated that Darcy's law does not hold in the initial time increments of infiltration and the drainage processes. Farlow[3] presented a solution of time dependent heat flow equation for a bar where no heat flux is applied. The bar initially was at 100ºC, the both boundaries are cooled instantaneously to 0ºC and 50ºC respectively, and kept at that temperature for all subsequent time levels. The results obtained in this study showed that the diffusion type equation fits quite reasonably the experimental data. Furthermore, Terzaghi and Frohlich[4] showed that there is mathematical analogy between consolidation processes in general and the physical processes of diffusion of substances dissolved in fluids.

3. Details of the Experiment

A horizontal column of 200 cm in length and 5.22 cm in diameter following De Smedt and Wierenga[5] is used. The actual distance between the end screen supporting the porous material was 196 cm. Eleven pressure transducers were positioned in an equal distance along the column. Two types of initial hydrostatic pressure head distribution conditions were considered. These are the uniform pressure and the triangular distribution pressure along the column. A diagrammatic representation of the various components of the measuring system is given in Fig. 1. Experimental set up and measurements were carried out as described by Awadalla[6].

3.1 Uniform Initial Pressure Distribution

An initial uniform pressure distribution was set at 150 cm of water ($x = L$), while the other end ($x = 0$) remained sealed throughout the experiment. At $t = 0$ the constant head tank was lowered to the column center line. Four reasonably uniform materials of decreasing permeability were studied, these being *G*1 sand (K_{sat} = 2.26 cm/min), R8A sand (K_{sat} = 0.83 cm/min), *G*80 and (K_{sat} = 0.266 cm/min) and glass beads (K_{sat} = 0.022 cm/min). In addition, an extreme experiment was attempted with a very course sand known as PF1 sand which exhibited K_{sat} value of approximately 16 cm/min. The dissipation of initial hydrostatic pressure for PF1 sand occurred throughout the entire column in about two seconds. Although it was considered as being a significant upper bound, the experiment was not proceeded further. The experimental results for mentioned materials are given in Fig. 2, 3 and 4 respectively. As expected, the time taken from the full dissipation of the initial pressure head varies with grain size from approximately 50 seconds for G1 to greater than 500 seconds for the glass beads.

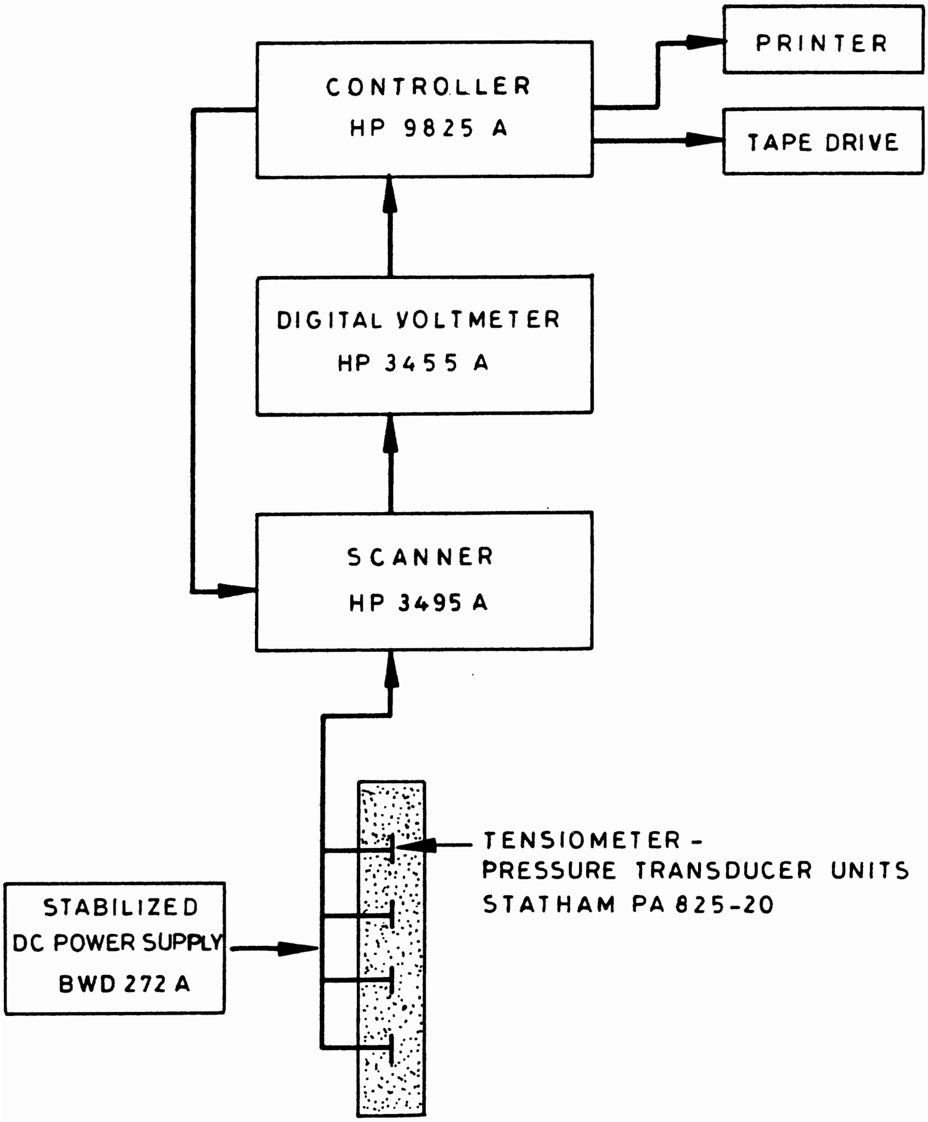

FIG. 1. Diagramatic layout of the data acquisition system.

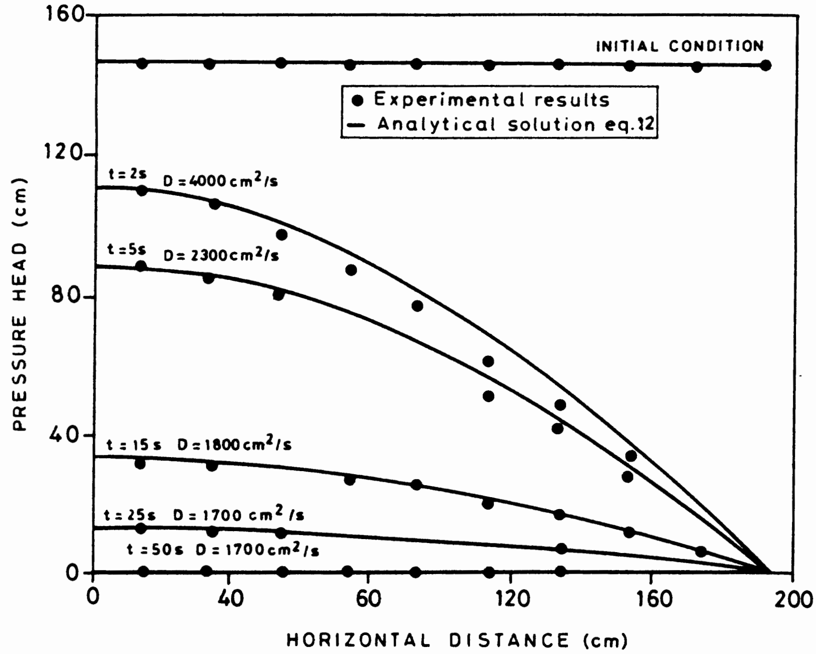

FIG. 2. Pressure head profiles in $G1$ sand showing analytical and experimental data for an initial condition of uniform head.

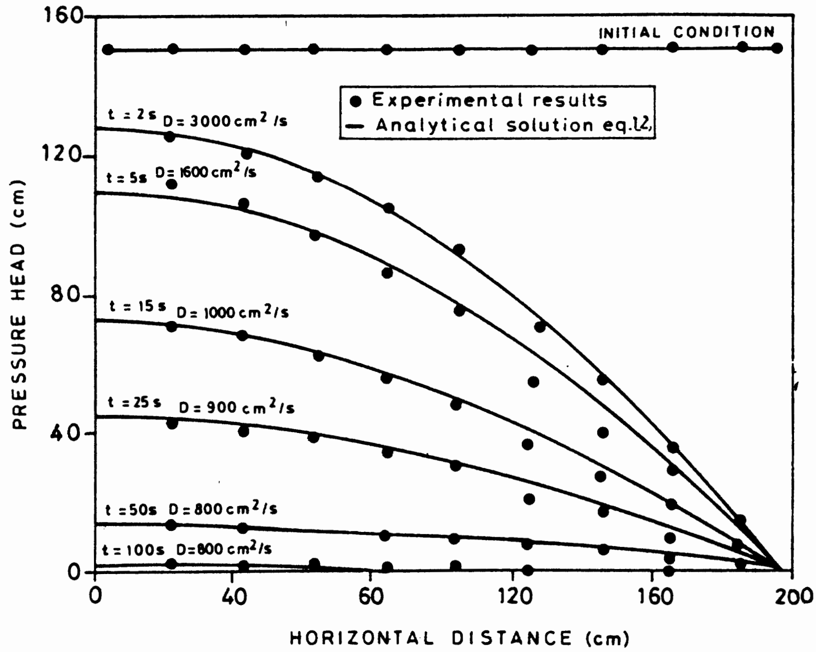

FIG. 3. Pressure head profiles in RBA sand showing analytical experimental data for an initial condition of uniform head.

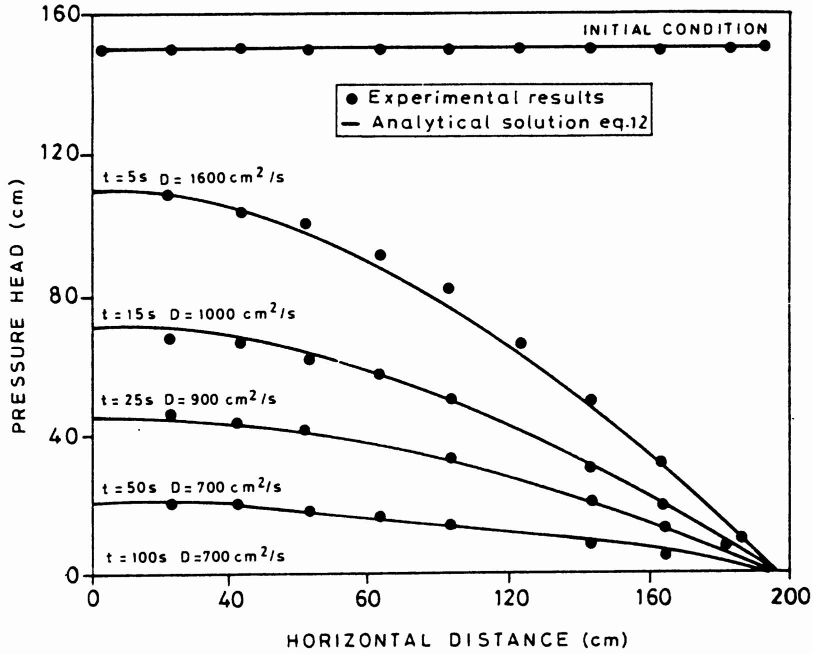

FIG. 4. Pressure head profiles in *G*80 sand showing analytical and experimental data for an initial condition of uniform head.

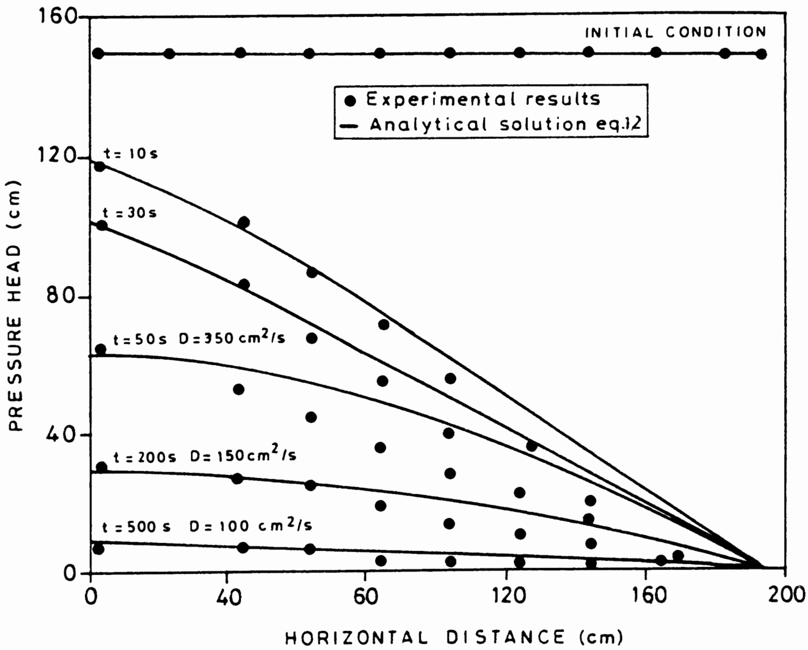

FIG. 5. Pressure head profiles in glass beads sand showing analytical and experimental data for an initial condition of uniform head..

3.2 Triangular Initial Pressure Distribution

The triangular initial pressure distribution can only be achieved by commencing with a steady state flow condition. The length of the column used was 196 cm and the head at one end providing the energy input for the flow was 150 cm. Figures 6, 7 and 8 shows relevant pressure response data for sands, *G*1, R8A and *G*80 and are shown as solid circle.

4. An Analysis of Early Time Pressure Distribution

It is believed that there are at least four possible reasons of observed early pressure behavior which require some analysis. These are:

1) Compressibility of the porous matrix.
2) Compressibility of fluid.
3) Non-Darcy effects under the local extreme pressure gradient.
4) Diffusion type equation.

The following sections discuss in some detail the early time pressure head behavior.

4.1 Compressibility of Porous Matrix

The porous media in each experiment was thoroughly packed into the column under saturated condition using distilled water. The experiments were repeatedly carried out and the results were reliable as they indicated that the packing of the column was con

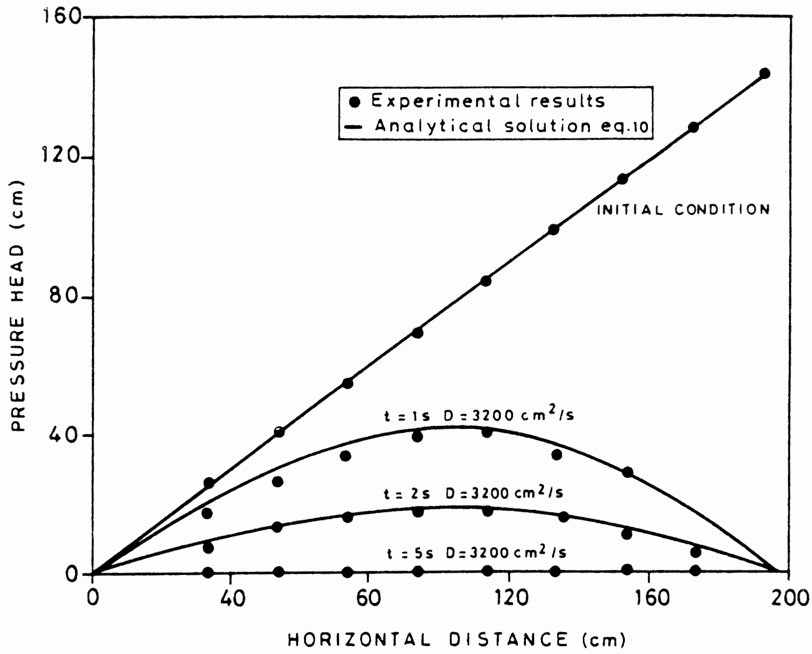

FIG. 6. Pressure head profiles in *G*1 sand showing analytical and experimental data for an initial head condition of triangular form.

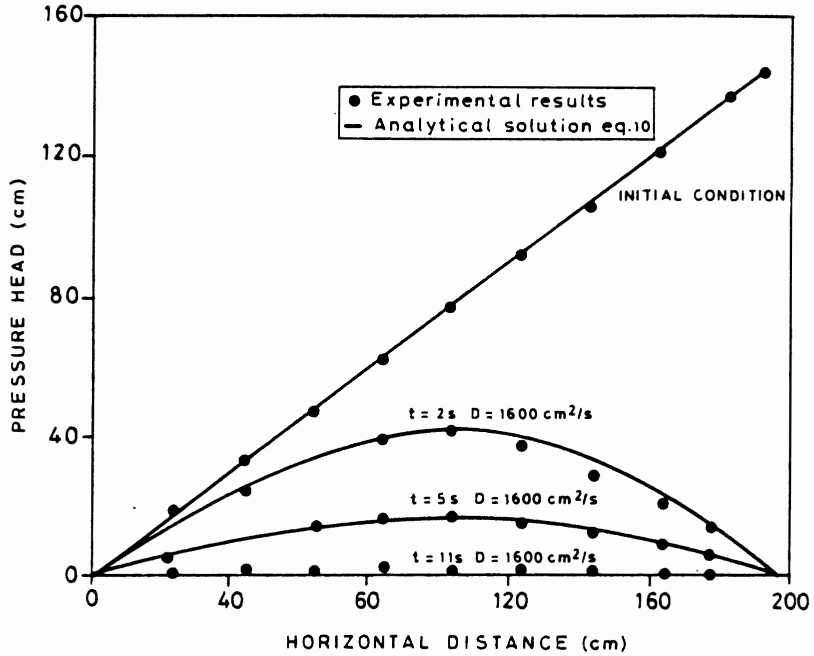

FIG. 7. Pressure head profiles in RBA sand showing analytical and experimental data for an initial head condition of triangular form.

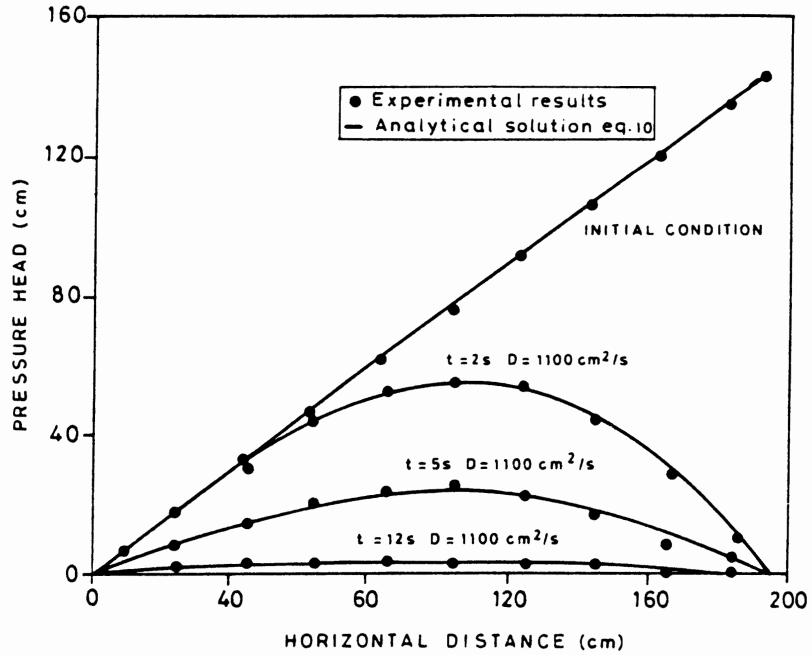

FIG. 8. *Pressure head* profiles in *G*80 sand showing analytical and experimental data for an initial head condition of triangular form.

sistent and highly efficient. In each experiment the column was packed onto a filter, which was fixed in place by a brass cap at the lower end of the column. The top of the column was over packed by the use of an extension column, which was cut back to working length with a sharp-edged scraper. The brass cap at this top end (while packing) was then fixed in place and the column gently swung into the horizontal position. Deformation of the medium under suddenly applied pressure distribution changes may have caused both longitudinal (along the column axis) and lateral stress on the body of the column. It might be expected that if deformation occurs under the applied pressure change in these cases most changes would occur laterally since longitudinally the ends were constrained by the brass caps. An analysis of effective stress and potential deformation or reformation loads was carried out. For the horizontal column under the rest, the total stress at time $t = 0$ on a horizontal plane at depth z is equal to the weight of the material (solid + water) per unit area above that depth (Fig. 9).

$$\sigma = z\gamma_{sat} + \gamma_w (h_w - z) \quad (1)$$
$$= 2.61 \times 2.65 + (152.61 - 2.61)(1)$$

where γ_{sat} saturated weight per unit volume.
z the depth of soil to the center line of the column,
h_w the water table height above the center line of the column.

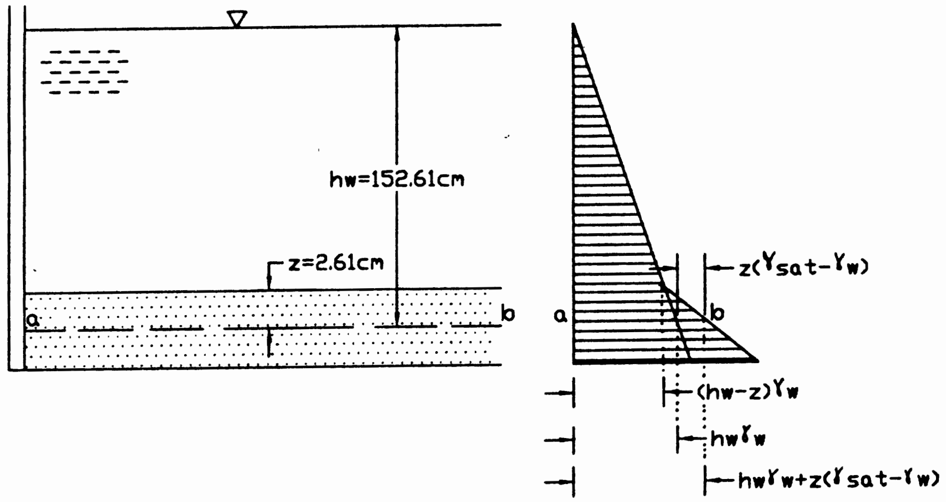

FIG. 9. Effective and total stress in a saturated sand.

The pore water pressure at that depth z will be hydrostatic since the void space between the solids is continuous. Therefore at depth z, the pore water pressure (u) may be written

$$u = \gamma_w h_w \quad (2)$$

Where h_w the unit weight of water, $z = 2.61$ cm and $h_w = 152.61$ cm. The effective stress relationship is given by,

$$\sigma' = \sigma - u \quad (3)$$

Where the effective stress σ' on the plane *a-b* represents the stress transmitted through the soil skeleton only. It is necessary to investigate the effective stress response to a sudden change in total stress. The case studied was a fully saturated soil subjected to a sudden change in the total vertical stress and the longitudinal strain was zero, where the column is bounded from both sides by brass caps. Any volume change due to the deformation of the soil would most likely occur entirely in the vertical direction. It is assumed initially that the pore water pressure is constant at a value governed by the position of the water table. The initial value is called static pore water pressure and when the total vertical stress is suddenly changed the soil particle should immediately take up a new positions. However, the head of water placed in the soil column was 152.61 cm, the soil is longitudinally confined by the column caps, laterally sand is contained by the perspex column, and it is unlikely that there is significant particle rearrangement. Thus, it is unlikely that there is a significant increase in the inter-particle forces. Therefore the change in effective stress will be very small with reference to the sudden change in the total stress. The total stress at z is calculated as the weight per unit area of all solids and liquids occurring above that point and is estimated to be 0.157 kg/cm^2. The pore water pressure at that depth is 0.153 kg/cm^2. The effective stress as a result of applying that pressure is 0.004 kg/cm^2.

4.2 Compressibility of Fluid

If stress is imparted to a fluid through the fluid pressure *P*, an increase in pressure head *P* leads to a decrease in volume *v* of the given mass of water. The compressibility of water may be defined as,

$$\beta = \frac{\partial v_w / v_w}{\partial p} \tag{4}$$

A change in the pressure will result in a change Δv_w in the volume. The size of Δv_w will depend on the nature of the process involved, a process where the temperature remains constant. The value for β can be taken as 4.4×10^{-7} m^2/kN. As a result of the step pressure change from 152.61 cm to zero pressure head, the volume of water will increase due to decompression. Thus

$$\frac{\partial v_w}{v_w} = \beta \partial p \tag{5}$$

where dP = 14.97 kN/m^2, thus

$$\frac{\partial v_w}{v_w} = 4.4 \times 10^{-7} \times 14.97 \tag{6}$$

For the soil column of R8A sand with 30% porosity, then

$$dv_m = 0.3 \times (5.2)^2 / 4 \times 196 \times 6.6 \times 10^{-6} = 8.242 \times 10^{-3}\ \text{cm}^3$$

Under the loads encountered in these experiments the assumption of fluid incompressibility is very difficult to be noticed or measured.

4.3 Non-Darcy Effects under the Local Extreme Pressure Gradient

The boundary condition of uniform pressure and triangular pressure distribution provide the basis for the third assumption which is the non-Darcy effects. Assuming that the transient pressure gradient is nonlinear, the outflow calculation were carried out using Darcy equation for the two materials $G1$ and $G80$ respectively. This is to give an estimate of the volume of water which might be expected to outflow from the column. A water volume 5.83 cc was estimated for $G1$ sand and 2.5 cc for $G80$ sand. The effort was made to discover any escape of water from the column during the course of the experiment. However, no visual evidence of this magnitude is found to have escaped from the column. If water was to flow from the column under the influence of nonlinear pressure gradients decaying with time, that water must be replaced with either more water or air. Since there was no water supply to replenish the amounts which could be lost, replacement by air remains the only alternative for this to happen. Also, no air flow was noticed during the experiment's course. However, for the initial uniform pressure distribution case, the imposition of a sealed end with impermeable circumferential boundaries of the column provide the assumption that pressure dissipation in the column may occur under highly damped wave process. The pressure dissipation results, shown in Fig. 2,3,4 and 5, for the horizontal column were investigated initially from the stand point of a highly damped wave process but no success was achieved with fitting such relationships. The propagation time is far too rapid compared with the experimental results and the transient pressure curve shapes did not agree with those obtained experimentally. The comparison indicated that a slower process was responsible for the dissipation of pressure in the medium and it was decided to attempt to fit a diffusion type equation to the process. A thorough review of published literature did not provide any conclusive basis for the validity of the assumption that the pressure could by itself dissipate by diffusion. However, the results obtained from the experiments indicate a possibility that a diffusion-type process can be applied.

5. Pressure Diffusion Type Equation

The diffusion type processes include the saturated and unsaturated porous media flow and consolidation of soils. For saturated porous media the flow equation applies to both confined and unconfined aquifer systems of groundwater, Bear[7]. In unsaturated flow, problems are frequently encountered in the soil water studies which involves for instance, infiltration or simultaneous transfer of heat and moisture. The governing differential equations can be used to simulate evaporation of soil water and gravity drainage, Hillel[8]. It involves the transport through diffusion and convection of chemical pollutants, contaminants, and dissolved salts in water under saturated and unsaturated soils. El-Damak[9] used Galerkin's one dimensional finite element models to solve simultaneously the moisture, heat and solute transport in porous media. Terzaghi and Pek[10] showed that there is a mathematical analogy between consolidation processes in general and physical processes of diffusion of substance dissolved in liquids. Biot[11-14] presented a theory of elasticity of a porous material saturated with an elastic fluid for a three dimensional case with an arbitrary and variable load. This theory was developed and extended by Brutsaert[15] and Bratsaert & Luthin[16] to describe the elasticity of an unconsolidated granular material containing two fluid in its interstices. Later Verruijt[17] showed that Biot's theory for a saturated material can be simplified to describe groundwater movement in most cases of practical interest. In developing the mathematical solution the fundamental physical concepts of diffusion theory, as introduced by Fick's law[18] were applied. The mathematical solution for the pressure dissipation in saturated porous media is presented for a case of uniform initial pressure distribution and the diffusion coefficient D is a function of time but is independent of other variables such as saturated hydraulic conductivity. In the case of the triangular initial pressure distribution, D is constant with time.

5.1 Constant Diffusion Coefficient

The solution presented is obtained by using a separation of variables.The diffusion equation, Fick's law[12] given by,

$$\frac{\partial h}{\partial t} = D\frac{\partial^2 h}{\partial x^2} \tag{7}$$

where D is constant. The initial condition is,

$$h(x, 0) = H \tag{8}$$

where H is the elevation of the free water surface in the movable reservoir above the center line of the column. If the length of the column is defined as L in the analysis, for the sake of convenience, was carried out over $2L$ with each end being assumed open. The symmetry of the system indicates a zero flux at the mid point thus meeting the boundary condition requirement of the sealed end. The boundary condition may be written as

$$h(0, t) = 0, \quad t > 0 \tag{9}$$

$$h(2L, t) = 0, \quad t > 0$$

where L is the length of the column, cm. The final solution may be written as:

$$h(x,t) = \frac{2H}{\Pi}\sum_{n-0}^{n=\infty}\frac{1}{(2n+1)}\left[e^{-Dt(\frac{2n+1)\Pi}{2L})^2}\right]\sin\frac{(2n+1)\Pi x}{2L} \tag{10}$$

5.2 Diffusion Coefficient Varies with Time

The fundamental differential equation of diffusion in an isotropic medium may be written, Farlow[11]

$$\frac{\partial h}{\partial t} = D(t)\frac{\partial^2 h}{\partial x^2} \tag{11}$$

The same initial and boundary condition described for the case of D constant are used in this case. It has been found that the diffusion type equation fits the experimental results reasonably well for both cases of uniform and triangular pressure. The final solution for this case is

$$h(x,t) = \frac{2H}{\Pi}\sum_{n=0}^{n=\infty}\frac{1}{(2n+1)}[e^{(\frac{-(2n+1)\Pi}{2L})^2(w(t)-w(o))}]\sin\frac{(2n+1)\Pi x}{2L} \tag{12}$$

Detailed solution of Equation 12 and sample calculation can be seen in Appendix 1.

6. Discussion

The results of the analytical solutions for both initial conditions were compared with experimental results in order to find a value of D (for the time in question) which gave the best fit with the experimental data. The analytical solutions for the selected D values are shown as the continuous lines Fig. 2 to 5 inclusive. These figures show that good correspondence with the experimental data can be obtained using the analytical solution when an appropriate value of D is chosen. It can be seen from the figures that the range of D values for $G1$ sand were 4000 cm^2/s, 2300 cm^2/s and 1700 cm^2/s at 2, 5 and 25 seconds respectively from the initial condition. The other porous materials, namely R8A sand and $G80$ sand, lay between these sets of values. For the triangular initial condition the value of D although different for each material studied, did not vary with time as shown in Fig. 6, 7 and 8. In addition, the steady state flow case allowed equilibrium conditions to be reached far more quickly to zero pressure head in a shorter time. A significant part of this rapid response is due to drainage path, where dissipation rate is related to the square of the drainage path length. The values of D were 3200 cm^2/s, 1600 cm^2/s and 1100 cm^2/s respectively for $G1$, R8A and $G80$ sand.

7. Conclusion

The main objective of this study is to analyze the results obtained for the pressure dissipation in porous media for horizontal column as a result of step function pressure change. The effect of fluid compressibility was found to have minor influence on the behavior of pressure distribution. The solid matrix material and pore water are relatively incompressible, and it is unlikely that they undergo any appreciable volume change. Possible result of decompression is an escape of water from the voids. Applying Darcy's law to calculate amount of outflow, the calculation revealed that those amounts of outflow are relatively large in volume and have not been observed during the course of the experiments. The damping wave criteria has been tried as a possible explanation for the obtained experimental results but no agreement has been achieved between the experimental values and the theoretical approach. The diffusion like process is supported by work carried out on a closely related situation, Farlow[3]. The physical arguments presented here indicate that the pressure dissipation is saturated porous media as found in the experimental horizontal column is a diffusion type process. From the foregoing discussion it is concluded that the diffusion type equation gives reasonably practical fit to the experimental results for both cases of uniform and triangular pressure distribution. However, further work is needed to study early delays in pressure dissipation for a vertical column with gravity force and air entry value included.

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Appendix 1. Analytical Solution for Horizontal System

The results obtained from the experiments have been studied in an attempt to find a physical explanation for the phenomenon observed and an appropriate analytical solution. The diffusion equation with D function of time may be written;

$$\frac{\partial h}{\partial t} = D(t)\frac{\partial^2 h}{\partial x^2} \tag{1.1}$$

Assuming that h is a product of some function of x and some function of t, giving;

$$h(x, t) = f(x)\, g(t) \tag{1.2}$$

Equation (1.1) may be written

$$f(x)g'(x) = D(t)f''(x)g(t) \tag{1.3}$$

$$\frac{f''(x)}{f(x)} = \frac{g'(t)}{D(t)g(t)} = \text{constant} = -\mu^2 \tag{1.4}$$

$$f''(x) + \mu^2 f(x) = 0 \tag{1.5}$$

$$g'(t) = -\mu D(t)g(t) \tag{1.6}$$

$$g(t) = Ee^{-\mu^2 D(t)dt} \tag{1.7}$$

$$g(t) = Ee^{-\mu^2(w(t)-w(0))} \tag{1.8}$$

and $f(x) = F\sin x + R\cos x$

where E, F and R are arbitrary constants. Applying the boundary condition

$$h(0, t) = 0 = f(0)g(t) \tag{1.9}$$

then $f(0) = 0$ and $R = 0$, therefore,

$$0 = f\sin \mu 2L \tag{1.10}$$

then

$$2\mu L = n\pi \;;\; n = 1, 2, \dots \tag{1.11}$$

$$h(x,0) = \sum_{n=0}^{n=\infty} e^{\left[-(\frac{n\pi}{2L})^2(w(t)-w(0))\right]} \sin\frac{n\pi x}{2L} \tag{1.12}$$

applying the initial condition Equation (1.12) becomes.

$$h(x,0)=\sum_{n=0}^{n=\infty} b_n \sin\frac{n\pi x}{2L} \tag{1.13}$$

but, $h(x,0)=H$

Using Fourier method

$$b_n=\frac{2}{L}\sin\frac{n\pi x}{2L} \tag{1.14}$$

$$b_n=\frac{2H}{n\pi}(\cos\pi+\cos 0) \tag{1.15}$$

$$h(x,t)=\frac{2H}{\pi}\sum_{n=0}^{n=\infty}\frac{1}{(2n+1)}\left[e^{\left(\frac{-(2n+1)}{2L}\right)^2(w(t)-u(o))}\right]\sin\frac{(2n+1)\pi x}{2L} \tag{1.16}$$

Sample for Calculating h(x, t) Using Equation (12)

```
  data t/1.,2.,4.,8.,16.,30.,35.,40.,50.,60./
  data x/0.,2.,8.,14.,22.,28.,34.,40.,46.,52.,62.,68.,76.,86.
  1,98.,108.,118.,128.,138.,148.,162./
   Dimenion t(10),x(21),h(21)
   pi=3.14159265
    read*,L,n
5  continue
   read*,D
  if(D.eq.0) stop
  do 90 it=1,10
  print*,'time',t(it)
  print*,'head  depth'
  do 70 iz=1,21
  s=0
  do 50 i=1,n
```

```
  term=exp((-(i*pi/L)**2)D*t(it)*sin(i*pi*x(iz)/L)
  s=s+term/i*(1.-(-1.)**i)
50  continue
  h(iz)=s*2*L/pi
  print*,h(iz),x(iz)
  70  continue
  90  continue
     go to 5
     end
 ? 162  20
 ? 100
 time 1
 head    depth
 0        0.
 18.21    2.
 69.39    8.
 109.80   14.
 142.59   22.
 154.27   28.
 159.37   34.
 161.24   40.
 161.81   46.
```

161.96	52.
161.99	62.
161.99	68.
161.99	76.
161.99	86.
161.99	98.
161.97	108.
161.69	118.
159.37	128.
147.47	138.
109.80	148.
0.	162.

سـلوك ضغـط المـاء بالتربـة نتيجـة التغـير المفـاجيء للأحمـال (حالـة أفقيـة)

صلاح الدين عوض الله

قسم علوم وإدارة موارد المياه ، كلية الأرصاد والبيئة وزراعة المناطق الجافة

جامعة الملك عبد العزيز ، جـدة - المملكة العربية السعودية

المستخلص . أجريت دراسة على سلوك عمود ضغط الماء بالتربة لقطاع مشبع بالماء ، وعلاقته بالتغير المفاجيء لوضع الماء الأرضي . تشاهد هذه الظاهرة في الآبار غير المحددة ، وذلك للهبوط المفاجيء للماء الأرضي ، نتيجة لعمليات الضخ التي تشابه ظاهرة التصلد .

لقد تم إجراء تجارب مكثفة لدراسة هذه الظاهرة وإيجاد التفسير العلمي لها . أوضحت الدراسة أن ظاهرة انتشارية الضغط في القطاع المشبع تتلائم مع معادلة الانتشار لكلا الحالتين ، الضغط الموحد والضغط الهيدروستاتي الموزع مع العمق .