Construction Dewatering by Vacuum Wells

by

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Introduction

IN fine-grained soils, capillary forces hold the water in the voids and atmospheric pressure alone is insufficient to facilitate drainage. Dewatering and stabilization of such soils (where the coefficient of permeability lies in the range of 10^{-3} to 10^{-5} cm/sec) cannot be effectively achieved by the use of conventional methods of pumping. By maintaining a vacuum in the vicinity of wellpoints or wells, the hydraulic gradient is increased under atmospheric pressure, which is about 1 kg/cm^2, and water is gradually squeezed toward the avacuated filters. In certain silty soils, where the effective grain size is less than about 0·05 mm, stabilization by vacuum wellpoints is so successful that pits or trenches can be excavated without the use of sheeting or props.

Operation of Vacuum

The conditions created by the operation of a vacuum system may be explained by Figure 1, where a wellpoint is shown with a screen and riser pipe surrounded with a free-draining sand filter extending to within a metre of the ground surface. The top of the hole is sealed with bentonite or fat clay that prevents aeration. The net vacuum at the wellpoint is the vacuum in the header pipe minus the lift or length of riser pipe. When the vacuum is fully effective, the entrance portion of the wellpoint will be in the capillary fringe, which is a three-phase domain, and a water-air

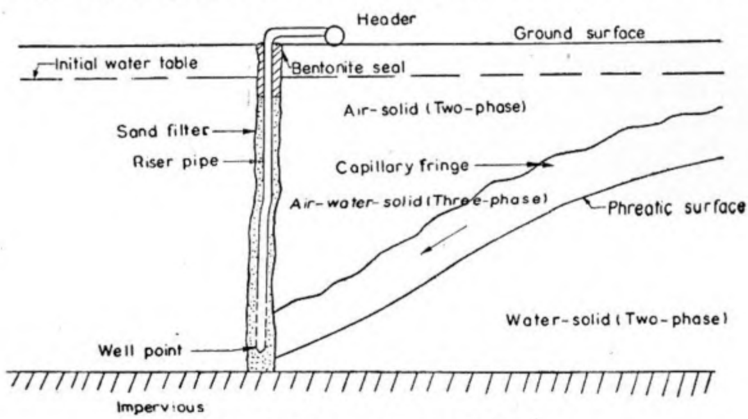

FIGURE 1 : Vacuum system of drainage.

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mixture will enter the wellpoint. The two and three-phase regions are contiguous with an interface (the phreatic surface between them) ; in addition, the upper boundary of the capillary fringe is also unknown. Because of the well sucking mixture of air and water, the discharge will be influenced by air-water ratio. The hydraulic situation around the wellpoint is thus very complicated and is not amenable to rigorous analysis. It is assumed that only water enters the well and this is reasonable as long as the vacuum is not large.

Mathematical Development

There is an important difference between the operation of conventional and vacuum wells. The former are usually operated at constant discharge and the boundary condition at the well is specified in terms of the hydraulic gradient. In the case of vacuum wells (or wellpoints) the objective is to maintain a constant head at the well and the flow discharge will decrease correspondingly ; the boundary condition at the well is, therefore, that of constant head or drawdown. The analogous problem of unsteady heat flow in an infinite solid bounded by a cylinder has been solved by Smith (1937). Jacob and Lohman (1952) adapted the solution to obtain the discharge of a flowing well.

Assuming a homogeneous and isotropic water bearing stratum, radial flow toward a well is governed by the following differential equation :

$$\frac{\partial^2\phi}{\partial r^2}+\frac{1}{r}\frac{\partial\phi}{\partial r}=\frac{1}{a}\frac{\partial\phi}{\partial t} \qquad \text{...(1)}$$

where ϕ is a function of the head, h at time, t and at radial distance, r. For water-table conditions the function, ϕ and the parameter, a, are given by

$$\phi=\tfrac{1}{2}\,(H^2-h^2) \qquad \text{...(2)}$$

$$a=\frac{kH'}{S} \qquad \text{...(3)}$$

where, H is the initial height of piezometric surface and H' is the average height of the water-table during the operation of the well. In the case of vacuum wells, operating with a constant head equal to h_w at the well, H' may be taken as equal to $(2H+h_w)/3$. The coefficients of permeability and storage are k and S respectively. For a stratum of thickness B and subjected to artesian pressure we may write

$$\phi=B(H-h) \qquad \text{...(4)}$$

$$a=\frac{kB}{S} \qquad \text{...(5)}$$

For water-table conditions, the coefficient of storage may be taken equivalent to the specific yield of the material that is dewatered. It may range from 0·01 to 0·30.

The solution to the differential equation (Equation 1) may be written as

$$Q=2\pi\, Bks_w\, G(\tau) \qquad \text{...(6)}$$

for an artesian aquifer, and

$$Q=\pi k\,(2H-s_w)\,G(\tau) \qquad \text{...(7)}$$

for a phreatic aquifer, where, Q is the discharge of the well. The function $G(\tau)$ is given by a complicated integral, but, for relatively long times, it may be simplified as

$$G(\tau)=\frac{2}{\log_e (2{\cdot}25\,\tau)} \quad ...(8)$$

where

$$\tau=\frac{at}{r^2_w} \quad ...(9)$$

is the time parameter, r_w, being the radius of the wellpoint.

A related and more important problem in the design of vacuum well systems is that of determining the head at an arbitrary point in the foundation. The problem is similar to that of determining the temperature distribution in the region bounded internally by a circular cylinder. The solution is (Carslaw and Jaeger, 1938)

$$V=V_w\left\{1-\frac{2}{\pi}\int_0^{\infty}\frac{exp(-\tau v^2)\,C_o(v,\bar{r}\,v)}{v[J_o^2\,(v)+Y_o^2\,(v)]}dv\right\} \quad ...(10)$$

where $\bar{r}$ is a dimensionless distance parameter expressed as

$$\bar{r}=\frac{r}{r_w} \quad ...(11)$$

and $$C_o(v,\bar{r}\,v)=J_o(v)\,Y_o(\bar{r}v)-Y_o(v)\,J_o(\bar{r}v) \quad ...(12)$$

J_o and Y_o being the Bessel functions of the zero order and the first and second kinds respectively. In Equation (10), V and V_w are functions of the head h ; they may be expressed as

$$V=H-h \quad ...(13)$$

$$V_w=H-h_w \quad ...(14)$$

for an artesian aquifer, and as

$$V=H^2-h^2 \quad ...(15)$$

$$V_w=H^2-h_w^2 \quad ...(16)$$

for a phreatic aquifer.

Despite the importance of the problem, few numerical results have been reported in the literature for Equation (10), largely because of its rather complicated form. These results are, in general, not suitable for large range of parameters of time and distance associated with dewatering problems. Therefore, integration involved in the equation was carried out numerically. The necessary computations were performed on a digital computer.

Single Wellpoint

The variation in discharge with time and pattern of drawdown around the vacuum well system can best be explained by considering a single vacuum well (or wellpoint). Using Equations (7) and (8) we can obtain the time discharge relationships for a wellpoint operating at a given vacuum in a stratum of known hydraulic characteristics. For a vacuum wellpoint in a phreatic aquifer, this is shown in Figure 2 in terms of dimensionless parameters of time and discharge. The numerical data for the well and the aquifer are shown in the figure.

Figure 3 shows the time—drawdown relationship around a vacuum well. For the purpose of this figure, a dimensionless drawdown parameter, equal to V/V_w is defined, where V and V_w are given by Equations (13) through (16). All values herein are obtained by numerical integration of Equation (10). With the knowledge of the constants of a given well soil system, the time and distance parameters can be computed from Equations (9) and (11) respectively, for a given pumping time at a required location. Generally, the specific values of these two parameters will not be represented by any of the curves in Figure 3, and interpolation will be needed.

Multiple Wellpoints

In practice, the problem of well groups is more important than that of a single well. Ground water is often removed by more than one well. Since Equation (1) is linear in the dependent variable, a linear combination of its solutions (superposition) is also a solution. This principle of superposition can be applied in a limited sense, however, because of the boundary condition which stipulates a constant head at each well. The solutions may be superposed for short periods of pumping during which time the constant drawdown at a given well is not effectively changed due to interference from the neighbouring wells.

Two systems of well groups are considered : single line array and two-line array. In each case, the relationship between drawdown, time, well spacing, and number of wells is shown in terms of dimensionless parameters. Figure 4 is a plot of the drawdown parameter V/V_w, as a function of the time parameter, $kH'\,t/Sr^2_w$. In this Figure 1 is the spacing between the wells and x is the distance between the centre of the system and the point at

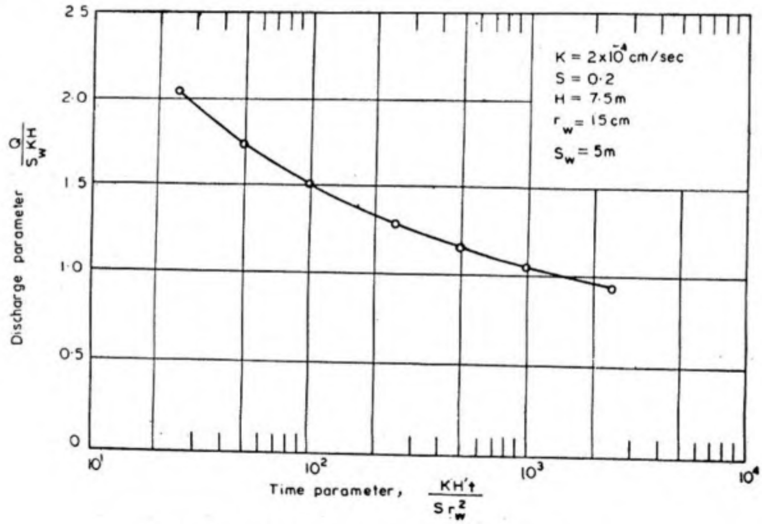

FIGURE 2 : Time-discharge relationship.

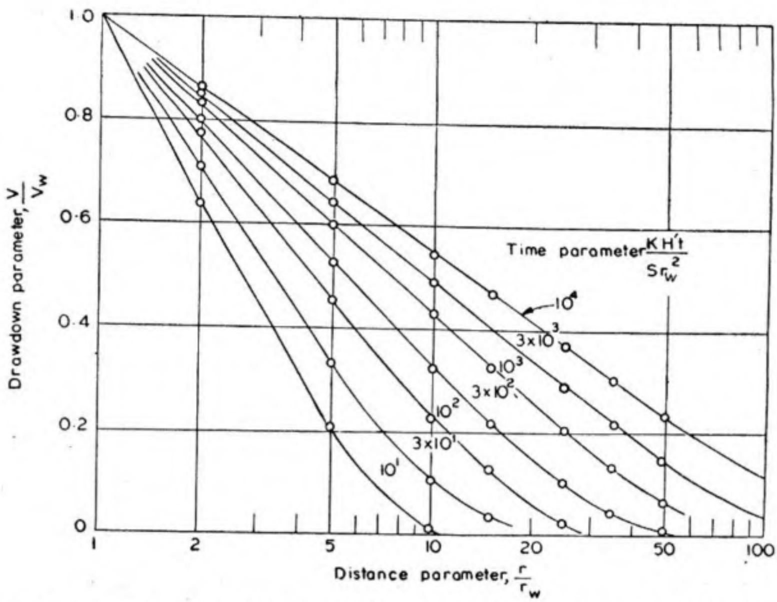

FIGURE 3 : Drawdown parameter as a function of distance and time parameters.

which the drawdown is desired. The broken lines in the figure represent the results obtained by applying the principle of superposition at relatively long times. Since the drawdown parameter corresponding to any broken part of the curves is more than unity, the related value of the drawdown at a given point is, therefore, negative ; this is obviously not correct and, as mentioned before, it is due to the fact that the principle of superposition is not valid in this region.

The relationships for a two-line array are presented in Figure 5. The spacing parameter in this figure is defined as the ratio of d, the spacing of the two lines, and l, the well spacing in each line. The figure is drawn for 41 wells in each line, and similar curves may be prepared for other systems. The region, where the principle of superposition is inapplicable is again shown by broken lines.

Application

Since the engineer is required in many practical problems to balance technical need against economical considerations, the issue becomes one of "how fast" versus "how much". Because the rate of excavation under such conditions is usually governed by the rate at which dewatering is accomplished, it is advantageous to compare several alternatives regarding the pumping time, pump capacity, and spacing requirements. The progress of dewatering may be critical on some jobs, and relatively fast systems may be needed. However, "relatively fast" is a very subjective term, and, in general, few attempts have been made in the past to quantity time considerations, except on intuitive basis. Accordingly, the application of the results obtained above will now be presented.

For the purpose of installing an underground pipe line, an excavation is required in a soil of low permeability ($k=10^{-4}$ cm/sec). The

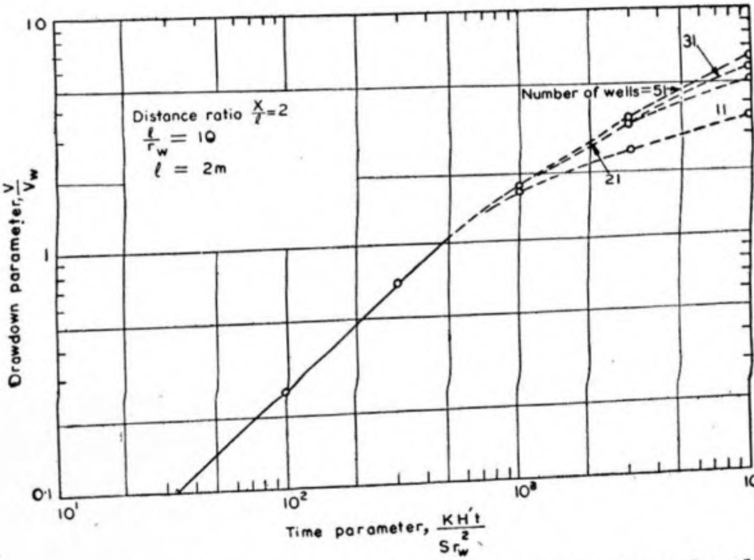

FIGURE 4 : Variation of drawdown parameter with time, and number of wells for a single-line array.

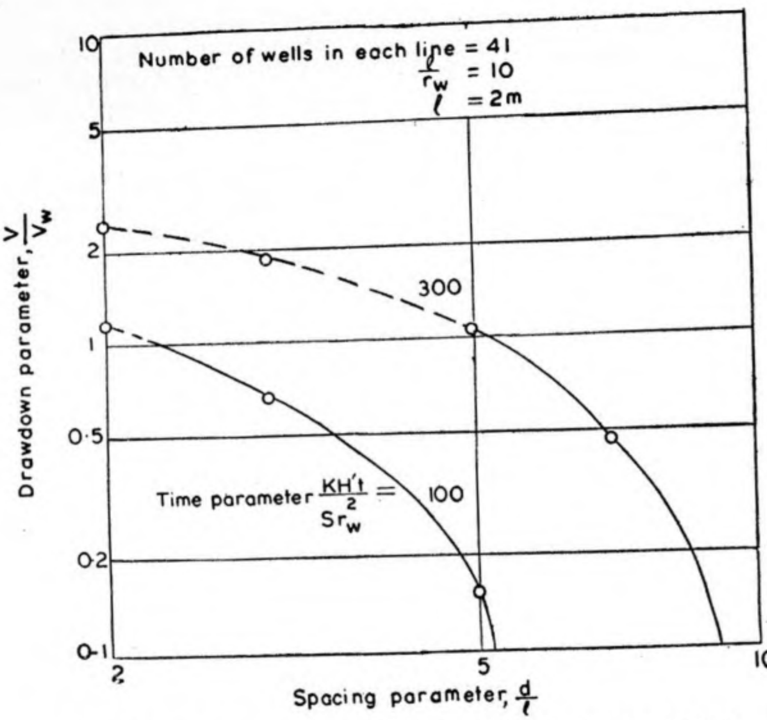

FIGURE 5 : Drawdown parameter as a function of spacing and time parameters for a two-line array.

conventional methods of gravity drainage do not effectively drain the site and vacuum wellpoints are needed. The initial height of the water-table is 7·5 m, and the coefficient of storage, S, of the water-bearing stratum is 0·2. It is proposed to use two lines of vacuum wellpoints on each side of excavation. The number of wellpoints in each line is 40 and they are spaced at 1·5 m along the line. The spacing between the lines is about 5 m. The effective radius of the wellpoint r_w, may be assumed as 15 cm. The net vacuum available at the wellpoint is such that the constant head h_w is about 2 m. Preliminary estimate is needed as to the depth to which water-table can be lowered at the midpoint of the group after about a day of pumping.

For the above data, the average height of the water-table may be computed as $(2H+h_w)/3=(2\times7{\cdot}5+2)/3$ or $\bar{H}=5{\cdot}7$ m. The related time parameter is $kH't/Sr^2_w=109$ for a pumping period of 1 day. The distance parameter, l/r_w, is $1{\cdot}5/0{\cdot}15=10$ and the spacing parameter, d/l, is 3.3. From Figure 5, the drawdown parameter may be read as 0·66. Thus, the head at the midpoint of the group after a day of pumping is 4·7 m, which means that the water-table is lowered by 2·8 m. Similar computations may be made for other requirements and alternatives.

Summary

This study is concerned with ground water control in foundations by use of vacuum wellpoints. Since sufficient theoretical analysis regarding the application of vacuum in drainage projects is not available at the present time, the discharge and drawdown patterns around vacuum systems are examined in detail. Charts are presented to enable the engineer to deduce more objective estimates which are required in the design of such systems. Finally, a representative dewatering problem has been included to demonstrate an application of the procedures developed.

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Notations

The following symbols are used in this paper :

a = parameter $=Bk/S$;

B = thickness of aquifer;

d = spacing between well lines;

G = function of time;

h = head;

h_w = head at the well;

H = initial height of water-table;

H' = average height of water-table;

J_0 = Bessel function of zero order and first kind;

k = coefficient of permeability;

l = well spacing in each line;

Q = discharge rate;

r = radial distance;

r_w = radius of well;

$\bar{r}$ = distance parameter;

s_w = drawdown at the well;

S = coefficient of storage;

t = time;

v = variable;

V, V_w = function of head;

x = distance;

Y_o = Bessel function of zero order and second kind;

τ = time parameter;

ϕ = function of head.

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