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PERMEABILITY DISTRIBUTION IN A HOLOCENE DISTRIBUTARY CHANNEL-FILL NEAR LEERDAM (THE NETHERLANDS)

Permeability measurements and in-situ fluid-flow experiment

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SUMMARY

In order to understand and predict the production performance of a reservoir it may be important to know its permeability distribution in detail. The internal structure of layered sand bodies, such as those that result from the deposition of sands in channels, could for instance cause an overall permeability anisotropy.

We have developed a method of deriving the permeability distribution in such a sand body from measurements on core samples.

This method has been checked by comparing the permeability distribution deduced from measurements on samples from an actual channel-fill with that derived from flow tests in the same sand body.

Our experimental data on unconsolidated distributary channel-fills show that permeability anisotropy is negligible in such sand bodies.

INTRODUCTION

Distributary channel-fills are an important type of oil reservoir, and The Royal Dutch Shell Group produces from such sand bodies in, for example, Venezuela, Nigeria and the USA.

Channel-fill sand bodies are predominantly composed of a rather regular pattern of medium-scale festoon cross-bed sets, which are formed by the common river-bottom type of transverse-migrating sand ripples with curved crests, as a result of a rather strong unidirectional current. The festoons are elongated in the direction of the current and have a "trough" or "spoon"-shaped bottom which is initiated by a so-called bottom-set layer (Jopling, 1967). Compared to a cross-bed set, the latter consists of relatively fine-grained material and has a relatively low permeability. Figure 1 shows how the festoons are enveloped by the surrounding bottom-set layers. The internal structure of the cross-bed sets, together with the systematic nature of their orientation, may cause an overall permeability anisotropy in a channel-fill sand body.

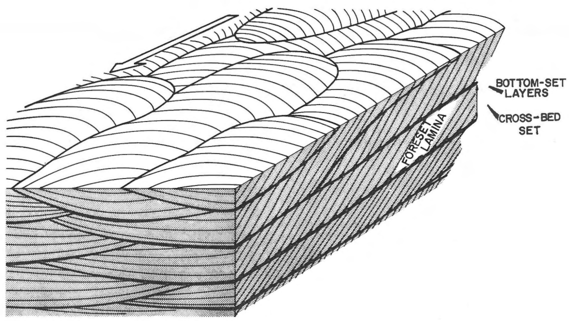

Fig. 1A
Block diagram of a festoon cross-bedded sand body.

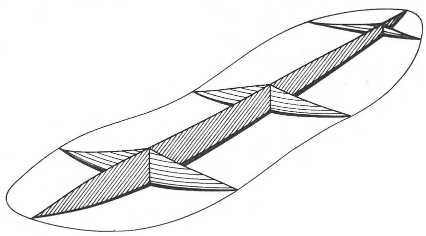

Fig. 1B
Typical geometry of a festoon cross-bed set.

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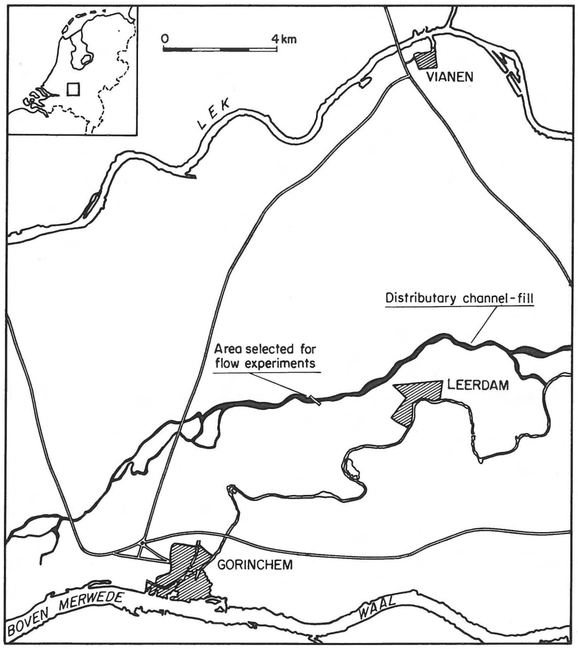

Fig. 2
Fill of holocene non-meandering distributary channel in The Netherlands.

For a good understanding of the production performance of a reservoir, it may be important to have a detailed knowledge of the permeability distribution. For this reason we have studied this distribution in cores taken in a layered sand body, such as results from the deposition of sands in channels.

In the selection of the sand body, we were greatly assisted by the "Geologische Stichting", which has charted a multitude of Holocene distributary channel-fills left behind by the Rhine (V e r b r a e c k, 1970). With their help we succeeded in finding a channel-fill that was clay-based (no connections with the underlying Pleistocene sands) and easily accessible to heavy field trucks (see fig. 2). This allowed us to carry out fluid-flow experiments in the sand body as well, so that we could check our permeability-anisotropy calculations.

PERMEABILITY DISTRIBUTION IN THE CHANNEL-FILL SAND BODY

Description of the sand body

A series of hand-cored holes provided details on the channel's geometry (see fig. 3). In the area studied (375 x 75 m), the channel-fill has a width of 137 m, while the sand thickness varies between 3.00 and 3.75 m over more than half of the width.

To obtain permeability data for this sand body, cores had to be taken. The "Laboratorium voor Grondmechanica" cored 10 boreholes for us across the channel, using their newly developed device for taking undisturbed, continuous soil samples (B e g e - m a n n, 1967). Cores of 3 cm diameter were obtained at the locations indicated in figure 3, three of the cores being oriented.

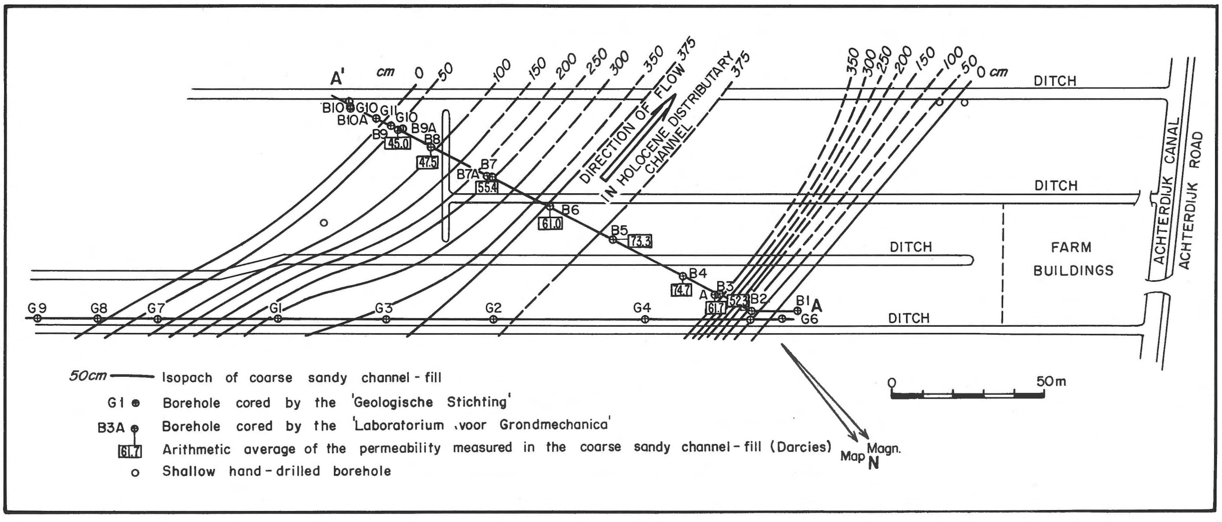

Fig. 3
Map of area selected for low experiments, showing isopachs of coarse sandy channel-fill, locations of cored boreholes and average permeabilities of the coarse sandy channel-fill measured in cores.

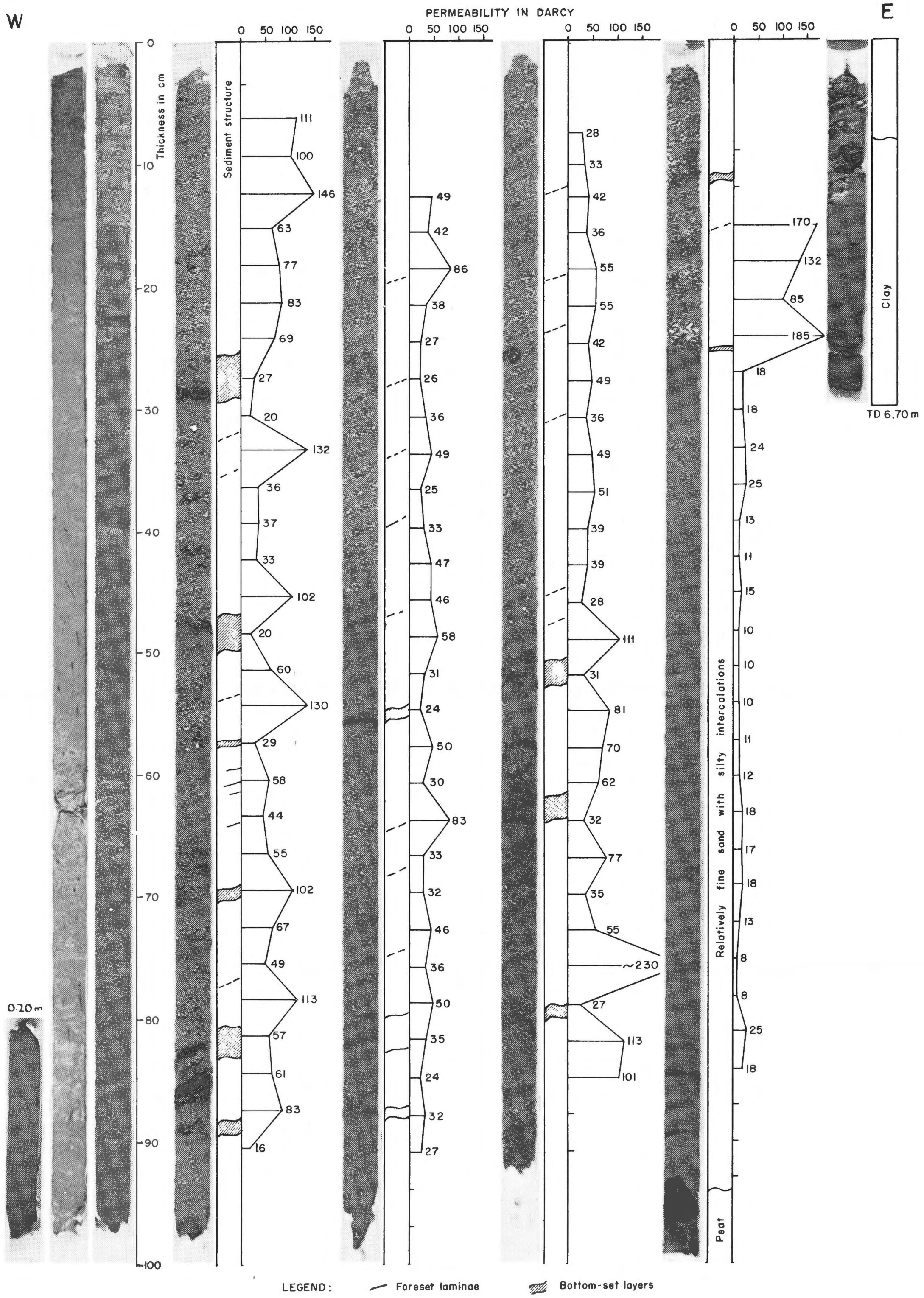

Fig. 4
Sedimentary structures and permeability distribution in the oriented core of borehole B6.

After the cores had been cut in half longitudinally, the sedimentary structures were observed to be quite undisturbed (see fig. 4). In the oriented cores most of the foreset laminae dip to the west, which is in accordance with the local flow direction in the Holocene channel.

The cores were described lithologically. Figure 5 shows a profile through the cored wells (A – A′ in fig. 3). The channel-fill sand body has an asymmetrical cross-section, probably as a result of the sinuous shape of the channel in the area studied (see figs. 2 and 3). Along the outside of the curve (near borehole B2) the channel-bank is much steeper than on the inside.

Permeability analyses of the cores

Because of the small diameter of the cores, a conventional permeability measuring apparatus as produced by Ruska Instrument Corporation could not be used. Instead we used a so-called mini-permeameter which allowed us to measure single-phase air permeabilities every 3 cm along the flat side of the halved cores (E i j p e & W e b e r, in prep.).

The measured permeabilities can almost be regarded as point values, because the volume through which most of the air flows is of the order of 1 cm^3. Thus one will often measure the permeability within only one or two foreset laminae (thickness 0.3-1 cm, see fig. 4). Consequently, the individual measurements are largely independent of the permeability anisotropy in the cross-bed set as a whole.

A number of bottom-set layers can be identified in the cores (see fig. 4). Because of the close vertical spacing of the measurements, the permeabilities of several bottom-set layers have been determined (permeabilities 10-30 D; grain sizes D_{md} 0.1-0.3 mm). However, the sand contains little silt or clay-size material (generally less than 3% < 62 μ), either in the bottom-set layers or in the cross-bed sets. As a result, the observed permeabilities in bottom-set layers and adjacent cross-bed sets in the present channel are high, and permeability contrasts between them are usually less than a factor 4.

Most of the sand is well-sorted and has a medium to coarse grain size. The permeabilities are quite high (10-200 D), and within a single cross-bed set the permeability usually varies by less than a factor 3, except in those places where a few thin, very coarse laminae are present.

In figure 3 the average permeabilities for the eight sand cores are given. We have excluded the intervals of fine sand and interbedded sand and clay along the crest of the channel-fill sand body and an interval of fine sand beneath the coarse channel-fill in borehole 6, which is probably part of a small, older channel-fill. As the realiability of the individual measurements

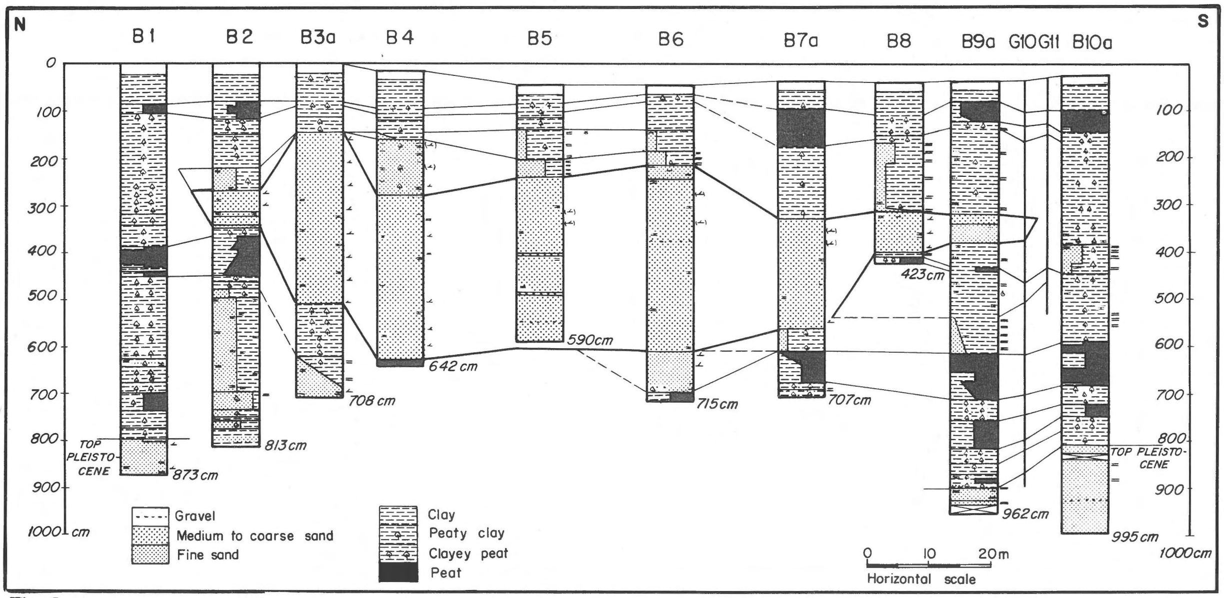

Fig. 5
Cross-section A-A′ (see fig. 3) through a distributary channel-fill near Leerdam (Netherlands).

is probably about ± 10% and the number of measurements is large (~ 500), we expect the average values to be fairly representative. The average permeability is highest in the centre of the channel-fill (~ 74 D) and gradually decreases towards the banks (to 52.3 D close to the north bank and 45.0 D close to the south bank).

HORIZONTAL PERMEABILITY ANISOTROPY IN DISTRIBUTARY CHANNEL-FILL SAND BODIES

Geometry and model representation of festoon cross-bed set

In order to predict the degree of anisotropy, we have worked out a method for calculating the horizontal permeability anisotropy from permeability measurements carried out on a core taken in a sand body.

A study of fluviatile festoon cross-bed sets in a series of recent and ancient outcrops showed their shape to be quite similar in all of these examples.

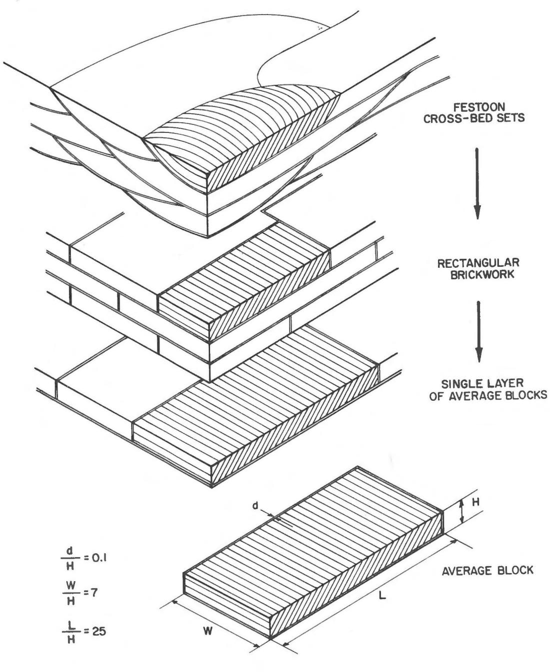

Fig. 6
Derivation of model for calculating permeability anisotropy in fluviatile sand bodies.

The ratio of cross-bed-set width (W) to its average thickness (H) is generally close to 7, with a range of 4-16 for the individual cross-bed sets.

The ratio of cross-bed-set length (L) to H is estimated to be about 25. This is comparable with the ratio of ripple wavelength to ripple height in recent rivers.

The ratio of the bottom-set thickness (d) to H can be measured in cores. In the examples studied, d/H was usually about 0.1.

The consistency of the above ratios justifies representation of a festoon cross-bedded formation by a simplified model. We have chosen a model consisting of a brickwork of rectangular blocks enveloped by bottom-set layers of uniform thickness (see fig. 6). Internally the blocks are composed of parallel planar foreset laminae of varying permeability.

Core analysis with the mini-permeameter and calculation of permeability anisotropy

With the mini-permeameter we can measure the permeability of the individual foreset laminae, k_i, and the thickness, d_i on the core. From these values the average permeability parallel and perpendicular to the laminae, $k_{/\!/}$ and $k_{\perp}$, respectively, can be calculated assuming the laminae to be homogeneous internally (B a s u m a l l i c k, 1966).

Next the permeability k_{α} in a horizontal direction perpendicular to the foreset strike is derived, the streamlines being assumed to coincide with this direction (S c h e i d e g g e r, 1957, p. 63-66). The value of the foreset dip α can also be measured on cross sections of the cores. This procedure and the formulae used are summarised in figure 7.

As $k_{/\!/}$ is always higher than k_{α}, we would find a lower permeability in the direction of the channel axis of the cross-bed sets than in a horizontal direction perpendicular to it, if there were no bottom sets. The bottom sets may, however, have an appreciably lower permeability k_B than the sand within the cross-bed sets. Because of the elongated shape of the festoons, the bottom sets alone will therefore give rise to an overall permeability anisotropy with the highest permeability in the direction in which we encounter the fewest bottom-set layers per unit length, i.e. in the direction of the channel axis. This illustrates how the effects of foreset laminae and bottom sets on the overall horizontal permeability anisotropy are opposed to each other.

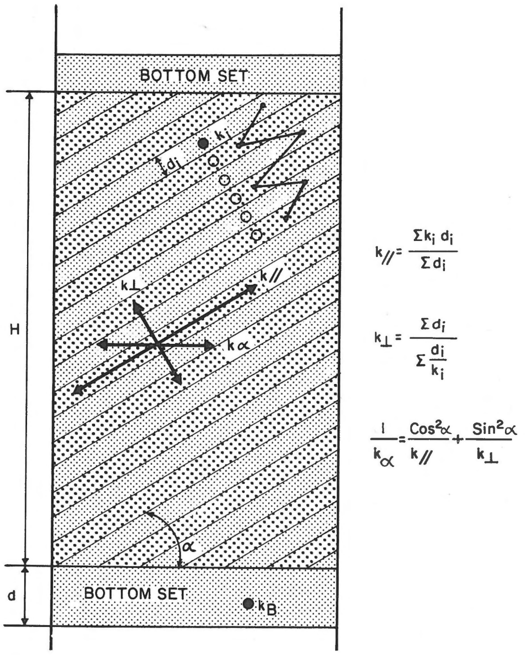

Fig. 7
Scheme of measuring and calculating the permeability distribution in a cored interval of a festoon cross-bed set.

For our simplified model, the horizontal permeabilities parallel to the channel axis (k_x) and perpendicular to the channel axis (k_y) are then given by,

$$k_x = \frac{L}{\frac{d}{k_B} + \frac{L}{k_\alpha}} \quad \text{and} \quad k_y = \frac{W}{\frac{d}{k_B} + \frac{W}{k_{//}}}$$

respectively (fig. 8), as

$$L - d \approx L\ (\frac{L}{d} \approx 250) \text{ and } W - d \approx W\ (\frac{W}{d} \approx 70).$$

To obtain an impression of the effect of the various parameters on the permeability anisotropy, we have calculated this anisotropy $A_h = k_x/k_y$ for a series of parameter values. In figure 9 the graphs are given of A_h versus $k_{/\!/}/k_\perp$ for the most likely values of L/W, L/d and α, i.e. 4, 300 and 30°, respectively, and various values of $k_{/\!/}/k_B$.

For the Leerdam cores the value of $k_{/\!/}/k_B$ was smaller than 4, and $k_{/\!/}/k_\perp$ was about 1.35 or lower, α was about 26° and d/H about 0.04. With the above formula and assuming that L : W : H = 25 : 7 : 1, we have calculated a horizontal permeability anisotropy of 0.96.

IN-SITU FLOW EXPERIMENTS IN THE CHANNEL-FILL SAND BODY

Flow tests are commonly employed to measure the conductivity of aquifers in hydraulic studies. The great advantage of these tests is that the combined effect of all types of sedimentary structures is included in the (permeability) measurements.

A fluid-flow experiment was performed in the channel-fill sand body to check our permeability-anisotropy calculations. A series of steady withdrawal tests was performed in a single well until quasi-equilibrium was reached.

Pumping and observation wells were made in two parts of the channel, the A-field and the α-field, as shown in figure 10. The first 1.75 m of each well was drilled with a motor-driven auger drill. Steel casing or slotted pipe was then driven into the sand body to avoid using drilling mud. Figure 11 shows the experimental set-up in detail.

The pump used was a simple suction pump consisting of an electric motor driving a Teflon propeller at the tip of a 1 m-long axle encased in a suction pipe. Maximum pumping capacity was 2.4 m^3/hr. Pumping rates were measured with a water meter.

Piezometer tubes were installed in the observation wells and the relative heights of the tops of these tubes were determined with the aid of a theodolite. The water levels in the tubes were determined with a hollow-ended dipper attached to a measuring tape. Tapping the dipper on the water surface produces a

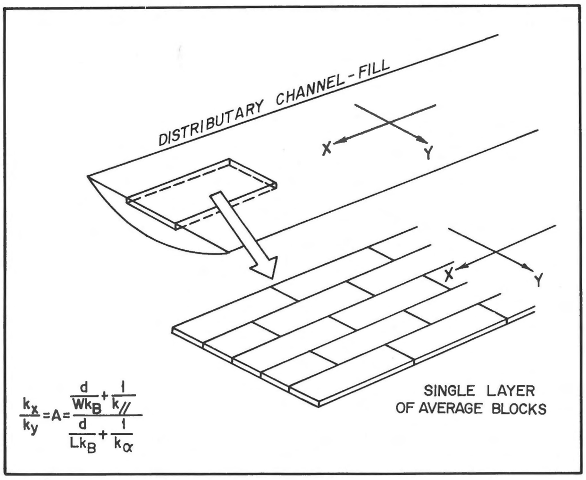

Fig. 8
Model and formula for calculating the permeability anisotropy in a distributary channel-fill.

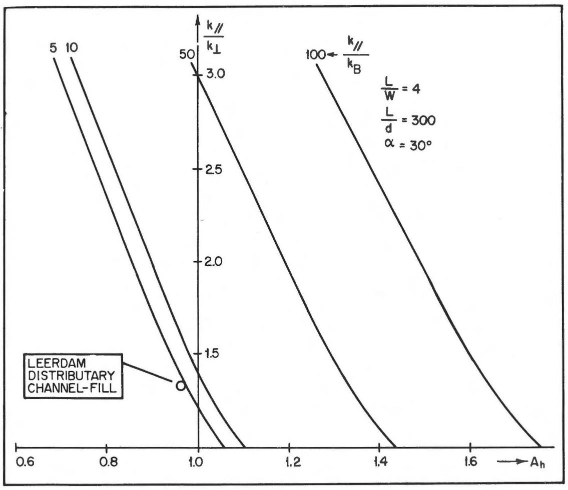

Fig. 9
Relationship between the horizontal permeability anisotropy in a festoon cross-bedded formation and the cross-bed set geometry, bottomset thickness, ratio of foreset laminae permeability over bottomset permeability and permeability distribution within the cross-bed set.

characteristic slapping sound. With some experience the water level can be measured to within an accuracy of about 2 mm.

A series of temperature measurements was carried out which gave an average of 13.5°C. The water

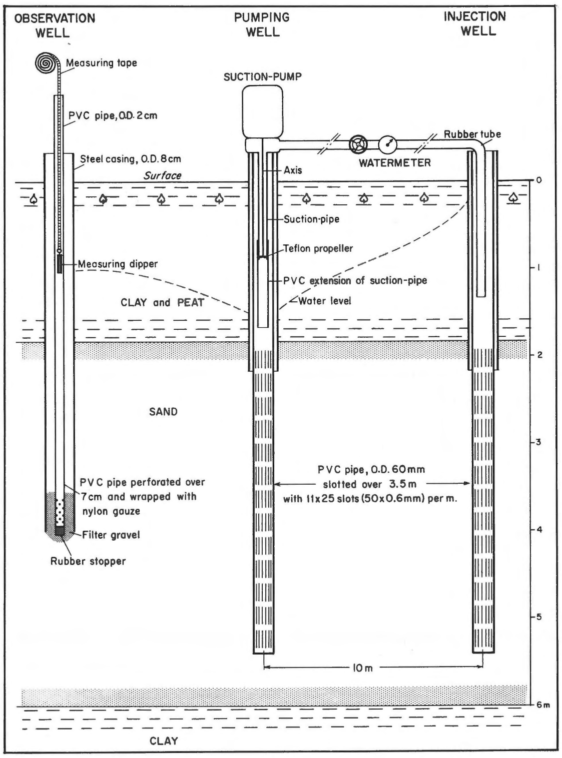

Fig. 11
Set-up of circulation flow test in the A-field.

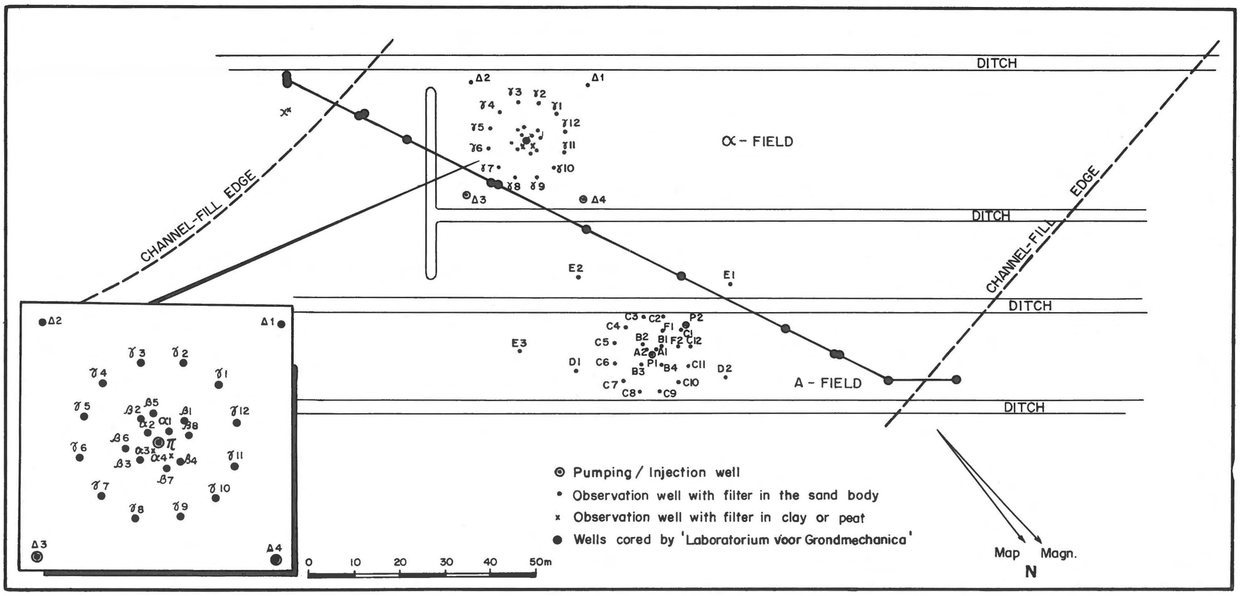

Fig. 10
Patterns of pumping/injection and observation wells in the test area.

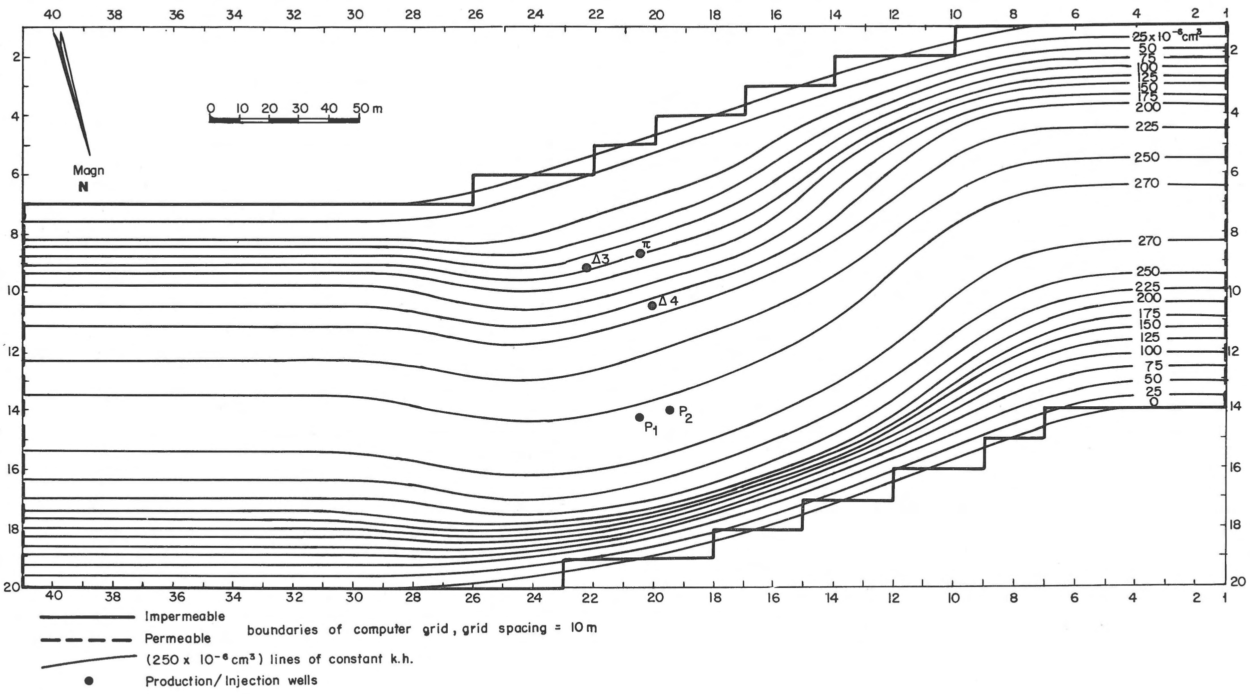

Fig. 12
Lines of constant kh values and grid used in the computer calculations for the various flow experiments.

viscosity at this temperature was used in our calculation.

The results of the flow experiment were compared with calculations based on the sand body's geometry and the permeability distribution derived from cores.

We have assumed that no seepage occurs from adjacent beds as the sand body under study is nearly completely surrounded by clay layers. Furthermore, at the chosen measuring level the anisotropy in the vertical plane appears to have negligible influence on the horizontal pressure distribution. This has been demonstrated during a separate computer study on a hypothetical sand body.

The steady-state equation for the flow potential ϕ in a heterogeneous layer at the measuring level can then be written as

$$\frac{\partial}{\partial x}\left(kh\frac{\partial \phi}{\partial x}\right) + \frac{\partial}{\partial y}\left(kh\frac{\partial \phi}{\partial y}\right) = 0$$

This equation can be solved, provided the values of kh are known throughout the sand body. The kh-values used in the calculations are shown in figure 12. They are based on measurements made on cores of the medium to coarse grained sand of the channel-fill.

The results of the withdrawal test are shown in figures 13 and 14. The correlation between the measured and computed data appears to be remarkably good.

For a constant (horizontal) permeability anisotropy, systematic differences should be observed between calculated and measured data with respect to the principal directions. Therefore, to give the order of magnitude of these differences we have calculated the effect of a constant ratio between k_x and k_y of 1.1. This came down to plus or minus 2 mm for the two principal directions, respectively, irrespective of the distance from the pumping well. As figures 13 and 14 do not show these symmetric differences, we conclude that horizontal permeability anisotropy in the Leerdam channel-fill is certainly less than 1.1, for both A and α-fields.

In the α-field, there are systematic deviations (fig. 14). They indicate that the gradient of kh towards the southern boundary is somewhat less than follows from figure 12. Finally, a check on the absolute value of kh, as shown in figure 12, was made. In order to obtain the best correlation between the measured and computed drawdowns using the least-

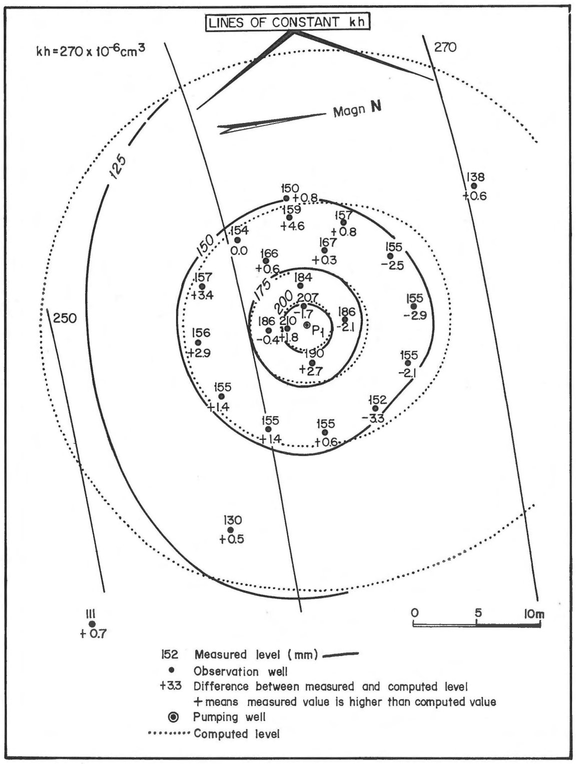

Fig. 13
Level changes as a result of pumping test in A-field equilibrium reached after withdrawal of water from well P_1 at a rate of 159 m^3/h for 750 min.

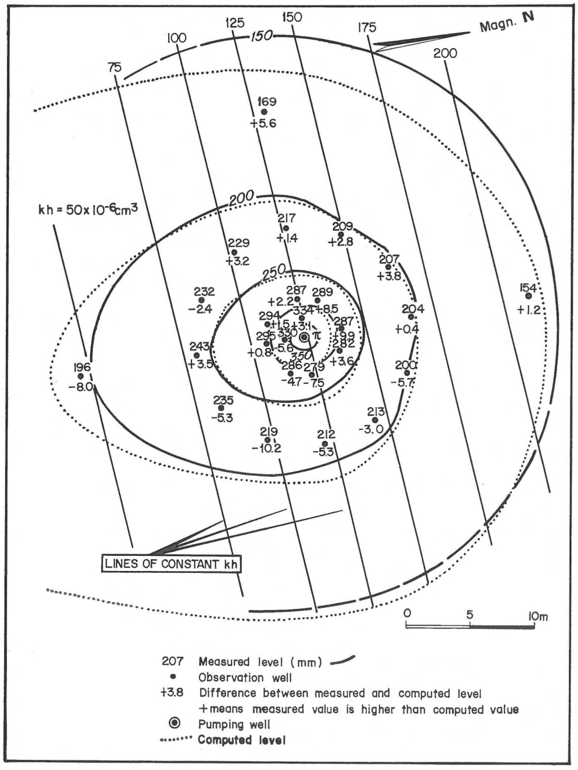

Fig. 14
Level changes as result of pumping test in α-field equilibrium reached after withdrawal of water from well π at a rate of 161 m^3/h for 1400 min.

squares method, we had to multiply all kh-values given in figure 12 by 1.15. Consequently, a slightly higher value of kh has been found. This may be because, in the derivation of the kh-values shown in figure 12, the relatively low-permeability beds adjacent to the sand body had not been taken into account.

The results of the flow experiment are in very good agreement with the above calculations of the permeability anisotropy based on the model representation.

CONCLUSIONS

In unconsolidated river sands $\frac{k_{\parallel}}{k_{\perp}}$ is unlikely to be much higher than 3. Furthermore, $\frac{k_{\parallel}}{k_B}$ will rarely be larger than 100. Thus values of A_h either higher than about 1.6 or lower than 0.7 can hardly be expected (fig. 9). Moreover, these values can only be reached in the rather unlikely case where a low $\frac{k_{\parallel}}{k_{\perp}}$ is coupled with a high $\frac{k_{\parallel}}{k_B}$, , or vice versa.

We conclude that the horizontal permeability anisotropy in unconsolidated festoon cross-bed formations will generally be small.

In consolidated sands, however, the ratio $\frac{k_{\parallel}}{k_B}$ can be very large (R o a c h & T h o m s o n, 1959) and anisotropy may be much more important.

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