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# THE PERMEABILITY OF RIVERBED SEDIMENT SAMPLES

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#### 1 INTRODUCTION

The Canterbury Plain stretches roughly 120 km along the Pacific coast and from the eastern foothills of the Southern Alps, at some 300 m elevation, it stretches roughly 60 km to the coast. A depth of sediment of several hundred metres has been measured near the coast. The sediments consist mainly of gravel and sand mixtures, lenses of gravel-free sand and layers of wind-blown and water-borne glacial silt.

The three major rivers on the plain, the Waimakariri, the Rakaia and the Rangitata remain incised upstream over roughly half their length from the foothills to the coast. According to information collected by the N.Z. Geological Survey of the Department of Scientific and Industrial Research, by the North and South Canterbury Catchment Boards and the Ministry of Works and Development on ground-water contours, supported by field observations on seepage patterns along the river banks, groundwater in this upper section tends to move towards the rivers. Farther downstream the ground-water contours indicate a movement of water from the riverbeds to ground-water. Closer to the coast the levels of riverbeds, ground water and ground surface tend to intersect as evidenced by groundwater-fed streams and drainage problems.

As far as the Waimakariri river is concerned, the river most studied because of its significance for water supply to the city of Christchurch, the contours indicate that the ground-water level dips below the river level a short distance downstream from where river incisement ceases, probably over a distance of 4 km. On the basis of river-flow measurements, recharge of ground water from the riverbed takes place in this section. Using the area-velocity method, a number of measurements have been made on river losses in this sector (summarized by Mandel, 1974), but owing to the difficulty that exists in measuring flow in braided rivers, a certain reservation still persist as to the reliability of the information. Therefore, there remains an interest in obtaining corroboration and further information on the magnitude of the recharge and the factors that govern it. In the present work an attempt has been made to understand some of the basic factors involved in this recharge by studying the hydraulic characteristics of riverbed sediments. In a separate study the movement of fine particles within these sediments is studied and another study aims at improving on the measurement of river flow in braided channels by attempting to refine a dye-dilution method for this purpose.

### 2 CHARACTERISTICS OF THE RIVERBED SEDIMENTS

An infinite variety in manner of deposition occurs; at the one extreme, deposits can be observed in which particle distribution and arrangement seems random (as if they were dumped from a dump truck) and, at the other extreme, one can observe deposits that are clearly sorted and stratified. Sorting refers to the separation and the massing together of particles within a given relatively narrow size range. Stratification refers to the deposition of particles with their longest axis: in a horizontal direction. Often sorting and stratification are combined and one can observe successive layers each with a relatively narrow particle-size distribution.

Dumped deposits, on the other hand, lack, to varying degrees, the separation and massing of particles according to their size and the particle axes in these deposits can be oriented in any direction. However, one can still detect a tendency for more particles to be arranged with their longest axis towards the horizontal than towards the vertical, obviously related to the extent of freedom that existed during deposition for particles to settle in a most stable position. These deposits are supposed to have been laid down during the passage of a flood wave; this type of deposition during flood flows was indeed observed under field conditions. As much of the particle movement down a riverbed takes place during the passing of a flood wave, it is not surprising to observe that dumped deposits of gravel and sand mixtures and of gravel-free sand are of widespread occurrence, as revealed in cross-sections of strata in cliffs or cuttings. Within riverbeds they are most conspicuous immediately after the passage of a flood wave. However, cursory surveys in and near riverbeds give the impression that most deposits are of the stratified and sorted type.

Locally-referred-to silt deposits of varying thickness typically cover coarser deposits along the margins of streams and in pools where flow has been tranquil or where water is or has been stagnant. While observations are still limited, it seems that thicker silt deposits close to the coast are wind-derived; they seem typically subject to changes due to periodic wind action.

Particle-size distributions are shown in figures 1 and 2. With the exception of one sand sample, all samples were collected from the Waimakariri riverbed in the section where ground-water recharge takes place. The channelbed sample was collected below flowing water. It has a content of particles of less than 0.4 cm that is lower than that of the two channelside samples (A and B) collected a few metres away from it. This suggests that finer particles had been sorted out and removed by flowing water. This had typically led to the formation of a so-called "armour-coat" consisting of a layer, a few particle-diameters thick, that is relatively resistant to entrainment. The significance of the armour coat for infiltration is not yet understood.

Figure 1 shows data for two channelside samples. Sample B was collected several months after sample A, because there was no assurance that sample A was sufficiently representative owing to an inadvertent mishap during a first trial experiment with it, when a certain quantity of sand was sucked into the sample, as discussed later. The somewhat higher sand content of sample A than that of sample B is probably due to this mishap. It turned out that sample A had a somewhat higher content in particles below 0.05 cm; the variation shown in particles of one cm and larger is merely one that can be expected in any sample of this type of material.

It is seen from figure 2 that the silt sample falls in the silty sand range, silt being defined by the N.Z. Soil Bureau as "particles between 0.0002 and 0.002 cm". The name silt is, however, adhered to because of its assumed origin as "glacial silt" and to distinguish it from the behaviourally-different sand, characterized by two curves in figure 2.

#### 3 EXPERIMENTAL PROCEDURES

Lateral and vertical coefficients of permeability of gravel and sand mixtures were measured by the apparati shown in figure 3, and those of sand by using a smaller version of these apparati, making use of a cylinder of 15.2 cm diameter for measuring vertical flow. The permeability of silt was measured in two ways: in one case in a cylinder of 4.4 cm diameter and in another case the 15.2 cm diameter cylinder was used. In the latter cylinder a silt layer of 1.2 cm thickness was placed on top of a sand column of 24 cm length. The head loss was measured over the whole length of the 25.2 cm sample and, as the silt dominated the permeability, this loss was applied to the 1.2 cm layer of silt. The relatively small error introduced by doing so has been accounted for by reporting the results as "of the order of".

#### Sample Preparation

Samples were prepared in three ways:

(1) by filling the tank of figure 3 with water and inserting gravel and sand by hand below the water surface. The gravel particles were laid down piece by piece and in such a way that the longest axis became aligned to the horizontal. Sand was released by moving the hand with the fingers partly spread so that particles escaped and descended through water. Insertion of gravel and sand was alternated in such a way that each gravel particle could become embedded in sand. Inspection at the time measurements were completed, both by cutting profiles and by removing the gravel pieces and sand fractions by hand, showed that samples had been prepared that appeared to resemble those occurring under field conditions. Samples prepared in this manner are referred to as stratified samples; (2) by dumping successive quantities of randomized material from a bucket, and shovel or a spoon to simulate dumped deposits laid down by a flood wave.

These samples were saturated from the bottom up, after which water was run through the sample prior to taking measurements, in order to expel any entrapped air and to affect some degree of settlement;

(3) by dumping material in water in the tank in such a way that successive layers of about 5 cm thickness were formed. Before applying a next layer the material was stirred by hand to facilitate an excape of air. This caused the configuration of the sample to become rather similar to that of a stratified sample, but it was felt necessary to do so to obviate a question of air entrainment.

For the measurement of lateral permeabilities the sample surface was covered and sealed by a layer of 10 cm or more of paraffin wax. This allowed variable heads to be applied in compartment A. The discharge pipe (see fig. 3) was set in each case at the level of the upper surface of the sample and any head that formed above it during discharge was taken into account in making calculations. The discharge was measured volumetrically after the system had become stabilised for a particular run. A range of heads were applied (see fig. 5); the interval between each run varied merely because of working hours, daylength, etc, but throughout a series of tests the sample remained either submersed or a small flow was maintained through it to prevent air entrance.

The channelside (B) sample was subjected to three consecutive sets of tests, each set comprising a series of measurements at an initial rising head and a subsequent falling head, in order to simulate a rising and falling river stage. The measurements were continued till in the third set, permeability values for a rising and a falling head virtually coincided.

#### 4 RESULT AND DISCUSSION

Figure 4 shows the permeabilities, in terms of coefficients of permeability or k values, versus hydraulic gradients for both lateral and vertical flow. The calculation of the k values have been based on:

$$Q = k i A, \tag{1}$$

where Q is the measured discharge, i is the hydraulic gradient that applied and A is the cross-sectional area through which the flow took place. If the flow is laminar (Darcian flow), the k values are independent from i and when the permeability is plotted versus i, a straight, horizontal line is formed. If the flow is non-Darcian, the k values do depend on i. Variable k values versus i are indeed shown in figure 4. notably during initial runs. This leads to a consideration of turbulent flow which, when it is similar to that for flow in pipes, is expressed by:

$$Q = K i^{0.5} A,$$
 (2)

where K is a constant depending on the hydraulic characteristics of the sample. From equations (1) and (2) turbulent flow can be characterised by:  $K_{i}^{0,5} \Delta = 0.5$ 

$$k = \frac{K i^{0.5} A}{i A} = K i^{-0.5}$$
 (3)

and for flow transitional between laminar and turbulent flow, the equation can be written as:

$$k = K i^{-m}, \qquad (4)$$

where m has a value between zero and 0.5. The value for equation (3) has been drawn in figure 4. This figure shows lateral permeabilities of the order of 1000 to 3000 m/day. At the time these measurements were terminated no further reduction in flow rate could be observed,

that is after a maximum of 960 minutes of continuous water flow through one sample (indicated by "t = ...." near the curves in figure 4.) (The "t" values for vertical permeability represent the time flow was continued or the time the sample had remained saturated between runs to prevent air entrainment).

Vertical permeabilities shown in figure 4 continued to decline over a long period and in a final experiment that spread over 100 hours it was possible to ultimately obtain a stable rate of about 20 m/day (curves A, B and C, fig. 4). Curves A, B and C will be further considered later on. Certain general observations on particle movement are given first.

Work is still being continued and at this stage no conclusions should be drawn on any possible difference in behaviour between permeabilities in dumped and stratified samples.

The differences observed to date, between lateral and vertical permeabilities have, first of all, been ascribed to inherent anisotropy and, additionally, to particle movement that takes place within a newlylaid-down sediment body as a result of continued flow through it.

Any moved particle would tend to become lodged, perhaps only temporarily, in a niche in which it fits. As the gravel particles are smooth-surfaced and have a regular, usually oval shape, these niches are likely to be the passage ways for water between adjacent particles, a phenomenon commonly referred to as "bridging". Owing to the factor of gravity in deposition and considering the (anisotropic) arrangement of the particles, resulting blockage of passage ways should affect vertical permeability more than lateral permeability. The maintenance of high permeability in a lateral direction and the gradual decline and stabilisation of the permeability rate in a vertical direction, shown in figure 4, can be explained on this basis. The flow regime for lateral flow can be different in the upper part from that in the lower part of a sample and turbulent flow may occur in the upper part, while transitional or laminar flow could occur in the lower part of the sample. The surbulent or transitional lateral flow in the upper part of a sample can aid dislocation of particles.

Particles can also move from the outside into a body of sediment. This was illustrated by observations made during a trial experiment with the channelside A sample. In this experiment a layer of gravel-free sand had been placed on the surface of a gravel and sand mixture to prevent any influx of molten wax (see fig. 3). When water was subsequently applied for studying the technique of measuring lateral permeability, much of the sand was sucked into the sample. The relatively high content of sand shown for sample A in figure 1 is accounted for by this event. It became also the reason a second sample, channelside B sample, was collected from the same site. One can consider that 90 percent of the Waimakariri sand sample had a diameter of less than 0.47 mm and particles of this size should readily pass through pores between gravel particles. One can also consider that 50 percent of this sample has a diameter of 0.32 mm or less. Fall velocities for particles of 0.32 mm are of the order of 4 cm/sec (for instance, Richardson, 1971). However, average lateral flow velocities through the samples were of the order of 0.5 to 2.5 cm/sec. Thus, a higher velocity and turbulent flow in the upper part of the sample must account for the sucking-in of the sand.

Consideration should now be given to details of the experiment represented by curves A, B and C in figure 4, representing an attempt to achieve stable and non-reducible vertical permeability in a sample consisting of a gravel and sand mixture. In this experiment the sample was subjected to three series of runs, each series consisting of a rising head (from 5 to 35 cm above the upper surface of the sample) and a subsequent falling head. As shown by figure 5 the heads at which measurements were made were: 5, 10, 15, 20, 25, 30 and 35 cm.

In series A and B the rising and subsequent falling heads gave rise to a hysteresis curve (see fig. 4). The loop formed is characteristic and can be readily reproduced in other experiments. It seems due to a difference in bridging behaviour under the influence of either a rising or a falling head.

Looking at curve A, one detects an initial rather flat section of the curve, that means little particle movement took place at the low heads and permeability remained rather constant. The steepening of the curve at higher heads indicates greater particle movement, increased blockage of passage ways for water and declining permeability. Subsequent changes in permeability were less marked as many finer particles had had an opportunity to move into more stable positions from which many could not be dislodged by a subsequent falling head. In fact, during subsequent low falling or rising heads the curves were nearly horizontal. That means that at these heads the system was more or less in equilibrium in as far as particle arrangement is concerned. Only at the higher heads enough energy was available to further dislodge particles and move them into more stable positions. Thus, a dissipation of the loop formation is induced on continued flow through the sample. When in the third series a nearly horizontal curve was obtained irrelevant whether a rising or a falling head had been applied, the system had obviously reached a degree of equilibrium in particle arrangement that could only be upset and be further affected by an application of heads higher than those applied, that is in excess of 35 cm.

If one considers the hydraulic gradients that relate to the measurements represented by the curves A, B and C in figure 4 (which are shown in fig. 5) further information shows up. Firstly, a steep hydraulic gradient is apparent in the bottom part of the sample, between 0 and 15 cm from the base, right from the beginning of experimentation. This means that during the puddling preparation of the sample (by method 3). a certain quantity of finer material settled towards the bottom.

Secondly, if one follows the change in hydraulic gradients upon passing from a rising head (represented by curve A, fig. 4) to a falling head (curve B, fig. 4), one will notice: (1) that the gradient became steeper in the bottom part of the sample and (2) that the gradient became flatter in the upper part of the sample, except at the 5 cm head. This means that the pore space in the upper part of the sample was increasing and that in the lower part it was decreasing which suggests a downward movement of particles within the sample. The reason the piezometric pressure at 5 cm head was less for a falling head than for a rising head is not clear yet.

Thirdly, continuing flow through the sample ultimately produced the same permeabilities at either a rising or a falling head at the same hydraulic gradients as shown by figure 5 and curve C, figure 4.

If the postulation is correct that the decline and ultimate stabilisation of vertical permeability is due to the movement of particles within the sediment sample this should show in the mechanical composition of the sample at various levels above its base after completion of the measurements. The particle-size distribution shown in figure 7, indeed supports the postulation.

If the data are indicative of what happens in nature, one would be inclined to conclude that a sediment body consisting of gravel and sand in composition similar to that of the sample (fig. 6 and 7), a stable vertical permeability (k value) of around 20 m/day would be attained at heads up to 35 cm. However, it is doubtful if such a bold conclusion could be drawn at this stage.

The permeabilities (k values) measured in sand and silt samples were as follows:

Lateral permeability	m/day
Dumped sand	33
Stratified sand	21
Vertical permeability	
Dumped sand	14 to 20
Stratified sand	4 to 5
Stratified silt (of the order of)	0.12 to 0.8

#### CONCLUSIONS

1. Riverbed deposits in the field vary from those that are clearly sorted and stratified to those that lack clear visible signs of sorting and stratification. The latter are laid down by flood flows and have been referred to as dumped deposits. The former are widespread at riverbed surfaces as armour coats, usually of a few particles thick. Below them flooddumped deposits are common.



Figure 7.

 Particle-size distribution in relation to depth below sample surface after completion of permeability measurements in a gravel and sand mixture (represented by curves A, B and C, Figure 4).

- 2. The permeabilities in channelside samples were higher than in channelbed samples because of a lower content of particles of less than 0.4 cm in the latter. However, if the armour coat were eliminated from the channelbed samples, permeabilities of the underlying material is likely to approach those of channelside samples.
- 3. In as far as available data indicate, lateral permeabilities are substantially greater than vertical ones due to inherent anisotropy and the movement of fine particles under the influence of water movement through the samples.
- 4. Transitional to turbulent flow tended to persist in lateral flows, but, while transitional or turbulent flow seemed to occur during initial vertical flows, continued water applications caused vertical flow to become laminar.
- 5. Because of the manner in which particle movement in sediment bodies takes place, the maintenance of high lateral permeabilities can be explained. On the other hand, the pattern of particle movement can also explain the observation on a gradual decline in vertical permeabilities till ultimately a stable rate is reached.
- 6. A curious difference in behaviour was observed depending on whether a rising or a falling head was applied giving rise to a loop or hysteresis curve. The looped nature of the curves become less as flow through a sample is continued and ultimately disappears as stable permeability rates are attained.
- 7. No clear evidence has been obtained yet on differences in hydraulic behaviour in stratified and dumped deposits, a subject that is still further pursued.

#### REFERENCES

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Figure 1. Particle-size distribution of riverbed gravel and sand mixtures



# Figure 2. Particle-size distribution of riverbed sand and silt samples.







(b) Apparatus used for vertical seepage.

Figure 3. Apparati for measuring permeability

note: all measurements in centimetres.