The effects of groundwater seepage on stream regimen: a laboratory study

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THE EFFECTS OF GROUNDWATER SEEPAGE ON STREAM REGIMES--A LABORATORY STUDY

by

Samuel S. Harrison

B. S. in Geology, Allegheny College 1963
M. S. in Geology, University of North Dakota 1965

A Dissertation
Submitted to the Faculty
of the
University of North Dakota
in partial fulfillment of the requirements
for the Degree of
Doctor of Philosophy

Grand Forks, North Dakota

March 1968

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Department: GEOLOGY
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ABSTRACT

The effects of groundwater seepage on the competence, bed roughness, and water surface slope of small streams were studied in two laboratory flumes. The larger flume is 20 feet long, 3½ feet wide, and 18 inches deep; the smaller flume is 12 feet long, 6 inches wide, and 10 inches deep. Both flumes are equipped so that groundwater seepage through the stream bed can be controlled and monitored.

In the absence of bedforms, upward (positive) seepage has little effect on stream competence or transport rate, even when quicksand conditions are reached. The decrease in effective grain density brought about by upward seepage might possibly be compensated entirely or in part by a decrease in surface drag and an increase in form drag on individual grains on the stream bed.

In the presence of bedforms such as ripples or dunes, however, seepage appears to have an inverse relationship to steepness of bedform faces (angle of repose), bottom roughness and turbulence, and transport rate. The inverse relationship of seepage to transport rate under these conditions is caused by steepening of bedform faces under conditions of downward seepage which results in greater bottom roughness and turbulence than in runs without seepage. Conversely, upward seepage tends to decrease the steepness of the bedforms, thereby decreasing bottom roughness, turbulence, and transport rate. The angle of repose on bedforms was increased to an average of about
43 degrees under conditions of downward seepage in which a hydraulic seepage gradient of -1.4 was present, as compared to an average angle of repose of about 33 degrees without seepage. A hydraulic seepage gradient of about +0.8 decreased the average angle of repose to about 27 degrees.

With no seepage and with upward seepage, relative roughness of the stream bed in the larger flume ranged from 0.56 to 0.83 (average value of 0.62) whereas with downward seepage it increased to 1.05. This increase in bed roughness, however, did not increase flow resistance sufficiently to cause an increase in the slope of the water surface (measured to within 0.005 ft/ft).

When bedforms are absent, downward (negative) seepage appears to have little effect on competence or transport rate if clear water is present in the channel. If the water is sufficiently turbid, however, the surface of the stream bed becomes clogged by the infiltration of the turbid water. This clogging, or mud-seal effect, decreases the permeability of the stream bed until the sediment underlying the uppermost layer of the bed becomes unsaturated. When this occurs, the weight of the water in the channel must be supported by the grains lying within the mud-seal layer. The effective density of the grains may be increased several hundred times, resulting in a cessation of bedload transport and an increase in compressive strength of the stream bed. Effective grain density under conditions varies inversely with grain diameter and directly with the depth of water in the channel. A mud seal can develop even under conditions of high-regime flow with bedload transport occurring in the form of a moving carpet. If punctured, the seal is self-healing, provided
sufficient suspended sediment is present. It seems likely that natural mud seals may be present on the bed of many irrigation canals and ephemeral streams such as arroyos and alluvial fan streams.
INTRODUCTION

Channel-boundary seepage occurs in nearly all natural channels. This exchange of water through stream-channel boundaries is caused by a state of inequilibrium between the hydrostatic pressure in the channel and in the boundary sediment. Only in unusual cases is the hydrostatic pressure in these two places the same, in which case no seepage can occur. Because of the nearly universal occurrence of channel-boundary seepage in streams, the study of fluvial processes should include the consideration of the effects of this seepage on channel regime and morphology. However, this subject is essentially unstudied.

Recognition of the Problem

The importance of groundwater seepage in streams was brought to the author's attention by Lee Clayton. Clayton and others (1966) studied a seemingly anomalous stream located on the outwash plain of the Sherman Glacier in south-central Alaska. The stream, only a few feet wide, was entirely spring fed and flowed over sandy-cobble gravel. In the middle reaches of the stream, where water was infiltrating out of the channel into the outwash, no sediment transport was taking place. A year-old fault scarp in this area, a few feet in height, was essentially unaltered where it crossed the channel. This provided further evidence of lack of transport.
In the lower reaches of the same stream, however, where groundwater was seeping into the channel, active erosion, transport, and deposition of pebbles and cobbles was taking place. A braided channel pattern also indicated active lateral shifting of this reach of the stream.

The striking difference in competence between the two reaches of the stream could not be explained in terms of known fluvial-regime factors. Measurements of gradient, velocity, and depth of the stream showed that these factors could not account for the observed difference in transport. Interchange of water between the channel and the underlying sediment appeared to be the only possible cause of the seemingly anomalous transport conditions. Infiltration in the upper reaches appeared to decrease the competence whereas upward seepage into the channel further downstream apparently increased the competence.

**Purpose of this Study**

The above observations suggested that seepage into and out of channels is an important factor in fluvial processes. The purpose of this study was to make a detailed laboratory study to determine qualitatively, and if possible, quantitatively, what effect seepage has on stream characteristics such as competence, transport rate, boundary roughness, channel shape, and channel path.

**Previous Studies**

Very little work has been done on the relationship of seepage to stream regimen. A recent book by Leopold, Wolman, and Miller...
(1964), "Fluvial Processes in Geomorphology", has summarized current knowledge of fluvial processes. Only brief mention is made of the possible influence of groundwater seepage on stream regimen. The authors mention the work of Bunting (1961, p. 515), who noted that seepage plays an important role in headward extension of some first-order channels. Leopold, Wolman, and Miller also point out the apparent importance of seepage in promoting the retreat of heads in vertical-walled gullies or arroyos (p. 446). They note, however, that surprisingly little is known about the actual mechanics of the gully erosion process.

In a discussion of flood plains, Leopold and others (1964, p. 453) mention that:

In humid (as opposed to arid) climates, flood plains tend to be absent in most headwater channels but appear at the point where flow in the channel changes from ephemeral to perennial --- that is, where groundwater enters the channel in sufficient quantity to sustain flow through nonstorm periods. The reason for this apparent coincidence of flood plain formation, however rudimentary, and the entrance of groundwater sustaining flow perennially, can only be inferred, for no detailed studies of this matter have, to our knowledge, been made.

The French geomorphologist Dorem (1953, p. 83) pointed out the effects of seepage on bank stability. He suggests that cutbanks are not eroded primarily by the stream current, but by seepage. He noted that the banks are rendered coherent by the infiltration of water from the channel during times of high water. Collapse of the banks takes place, however, during the falling-water stage as a result of the potential gradient toward the falling water surface.

A similar bank erosion phenomena has subsequently been described by Simons and Richardson (1966, p. 16). In addition, they point out that seepage of water through the banks and bed material
of a channel should affect stream competence in the following manner:

If there is inflow, the seepage force acts to reduce the effective weight of the sand and, consequently, the stability of the bed material. If there is outflow, the seepage force acts in the direction of gravity and increases the effective weight of the sand and the stability of the bed material. As a direct result of changing the effective weight, the seepage forces can influence the form of bed roughness, the resistance to flow for a given channel slope, channel shape, bed material, and discharge.

Simons and Richardson gave no evidence, however, that these phenomena had actually been observed or documented.

The effects of seepage on the effective density of channel-boundary sediment, and hence on stream competence, was treated in more detail by Clayton and others (1965). They show that the standard transport formula relating threshold drag velocity and grain diameter, \( U_c = \sqrt{\frac{k(\rho - \rho_f) g D \tan \phi}{\rho}} \), can be modified by subtracting the groundwater seepage force, or piezometric gradient (\( i \)), from the gravitational force acting on a grain as follows:

\[
U_c' = \sqrt{\frac{k(\rho - \rho_f) g D \tan \phi}{\rho}} - i
\]

In the above formulae, \( U_c \) is the threshold drag velocity, \( D \) is the diameter of the largest grain transported, \( \rho \) is the mass density of the grains, \( \rho_f \) is the mass density of the fluid, \( \phi \) is the angle of internal friction of the grains, \( k \) is the coefficient of grain shape and packing, and \( g \) is the acceleration of gravity. By squaring both sides of the equation and solving for \( \frac{1}{D} \), the result is

\[
\frac{1}{D} = k \frac{\rho_f - \rho}{\rho} \frac{U_c'^2}{g \tan \phi} - \frac{i}{U_c'^2}
\]

\[
\frac{1}{D} = k \frac{\rho_f - \rho}{\rho} \frac{U_c'^2}{g \tan \phi}.
\]
The angle of internal friction ($\phi$) is slightly decreased by upward
seepage and increased by downward seepage, as will be discussed
later. The part of the equation containing \( (\phi - \phi(1+i)) \) is
equal to 1.65 - 1, if $\phi$ is assumed to be 2.65 grams per cubic
centimeter and $\phi$ is 1.00 gram per cubic centimeter.

\[
\phi - \phi(1+i) = (2.65 - 1.00(1+i)) = 1.65 - 1
\]

Seepage has no effect on $k$, $g$, $\rho$, or $\phi$. Ignoring the effects
of seepage on $\phi$, at any given velocity an increase in the
piezometric gradient (i) will be accompanied by a proportional
decrease in D, the diameter of the largest grain that can be
transported at that velocity. Thus, competence (D) is inversely
proportional to $(1.65 - i)$.

\[
\frac{1}{D} \propto 1.65 - i
\]

If the effects of seepage-induced changes in the angle of repose
were added to the changes in effective grain density, the change
in competence would be even greater.
EQUIPMENT

Controlled-Scouring Fluid-Boundary Flume

During the summer of 1966 a 12-foot-long recirculating flume was constructed (fig. 1A). The flume consists of a fiberglass-covered wooden trough 12 feet long, 6 inches wide, and 10 inches deep, with one side of plexiglass for observation. A settling tank at the outlet end of the flume traps bedload sediment; water and suspended sediment are recirculated. A constant-head overhead tank provides a steady, uniform flow of water to the inlet end of the flume. A stilling tank at the inlet end dampens the turbulence of the water before it enters the flume.

Discharge, depth of flow, slope of the flume bottom, sediment size, seepage, and velocity can be controlled in the flume. Water temperature is kept nearly constant at 68 to 72 degrees Fahrenheit during experiments. Velocity is measured either by timing the movement of floats or dye in the water or with a pitot tube connected to an inclined manometer graduated in one-hundredths of an inch. The pitot tube measurements, though time consuming, enable velocity measurements to be made to about the nearest 0.02 foot per second where necessary.

Inflow or outflow of seepage water through the bottom sediment is controlled over a 2-foot portion of the lower end of the flume, in the section 3½ feet to 5½ feet from the outlet. Water is forced upward or downward through the bottom sediment in this
Figure 1.—Equipment used in the experiments. A. Rigid-boundary controlled-seepage recirculating flume. B. Mobile-boundary controlled-seepage fluvial trough.
area by two hoses with an inside diameter of 5/8 inches. These hoses, perforated with 1/8-inch holes, are connected to two fittings in the bottom of the flume, through which seepage-water flows. Water is fed into the hoses during positive-seepage runs from a constant-head 1-gallon tank which is supplied with water from the large overhead tank. The height of the 1-gallon feed tank above the water surface in the flume determines the pressure under which seepage is fed into the flume sediment (positive seepage). Conversely, water from the flume can be drained downward through the sediment (negative seepage) by lowering the feed tank below the water level in the flume and allowing water from the flume to drain into the feed tank.

In order to facilitate uniform distribution of water through the sediment in the test section, a layer of pea gravel about 2 inches thick was spread on the bottom of the flume. The sediment to be tested in each run was spread over the gravel in a layer about 3 inches thick.

**Controlled-Seepage Mobile-Boundary Trough**

Although the flume is suited for detailed study of the effects of seepage on bedload transport, its closely spaced sides prohibit study of channel morphology and channel pattern and its short length does not permit accurate measurement of surface water slope. Thus, a much larger mobile-boundary controlled-seepage trough was built so that the effects of seepage on channel shape, path, slope, and flow resistance could be investigated.

The trough, 20 feet long, 3½ feet wide, and 16 inches deep,
is constructed of sheet steel with one side of plexiglass (fig. 1(B)). The lower end of the trough can be lowered about 1 foot from the horizontal. A water recirculating system, similar to that used with the flume, provides a maximum discharge of over 100 gallons per minute. Groundwater seepage is controlled by adjusting the hydrostatic head in nine control tanks; each tank is connected to two feeder hoses which in turn are connected to fittings located at 1-foot intervals along the bottom of the trough. Inside the trough, groundwater is distributed into or collected from the overlying sediment by perforated lengths of garden hose placed across the bottom of the trough at 1-foot intervals. Groundwater seepage can either be injected upward through the sediment (positive seepage) or drained downward through the channel bottom (negative seepage) at controlled rates. To monitor the movement of groundwater through the sediment twenty manometers are located at each of nine traverses across the trough. One end of each manometer is fitted up through the bottom of the trough and the other end is attached to a graduated scale on the side of the trough. Manometer readings are probably accurate to within 0.02 feet after precautions have been taken to remove all air bubbles from the tubes. The hydraulic seepage gradient is determined by dividing the height of the manometer fluid above or below the stream surface by the thickness of sediment above the manometer opening. The distribution of manometers at each traverse along the bottom is shown in figure 2.
Figure 2.—Distribution and height of piezometers in the fluvial trough.

Inflow at the head of the trough is controlled by a square-head valve similar to a gas cock. The valve is calibrated for discharges ranging from about 2 to 75 gallons per minute. Base level at the trough outlet is controlled by varying the level of overflow.

Sediment transported from the trough as bedload is collected in a settling tank below the outlet. Dry sediment is fed continuously to the experimental channel by a endless-belt sediment feeder located over the trough inlet.

The slope of the stream surface in the trough is measured with a point gage. Readings are taken at 2-foot intervals along the length of the trough, using the top of the trough as the datum. These readings are subsequently adjusted to compensate for the known slope of the trough. Individual readings are believed to be accurate to within ±0.01 feet.

It should be made clear that the laboratory streams studied in these experiments were not scale models. Modeling of meandering rivers is difficult, if not impossible, to achieve. Olson (1961, p. 154)
considers movable-bed river modeling to be "not only a science but an art".

Because the experiments in this investigation involved seepage, scale modeling would have been even more difficult than in conventional laboratory studies of this nature. Therefore, the streams in these experiments were treated as prototypes or small streams in their own right, not as scale models.

Seepage-stream regime relationships derived from this research will be quantitatively applicable to natural streams of similar size. However, the primary purpose of these experiments was to recognize, under controlled conditions, which stream characteristics are affected by seepage. Any relationships found can then be tested on larger, natural streams.
LABORATORY INVESTIGATION

Theoretical Effects of Seepage on Competence

According to the formula for grain transport proposed by Clayton and others (1966), which was discussed previously, stream competence is inversely proportional to \((1.65 - i)\), where \(i\) is the piezometric gradient. The relationship between seepage and effective grain density as set forth in this formula is shown by the graph in figure 3.

Sediment grains become weightless when the piezometric gradient reaches \(1.65\), a condition commonly known as quick. Under these conditions the sediment grains are buoyed up by the upward-moving water. Theoretically, therefore, if a quick condition exists in the sediment on a stream bed, the stream should be capable of transporting that sediment no matter how low the velocity of the stream. Conditions less than quick, where the piezometric gradient is less than \(1.65\), would have a proportionately lesser effect on stream competence.

The coarser the sediment, however, the greater the velocity and volume of upward-moving water that would be necessary to bring it to a quick condition. It would thus be unlikely that clean gravel would become quick under natural conditions. Upward seepage should be important, however, in finer-grained sediments such as sand and coarse silt.

Conversely, negative seepage (downward moving water) should
Figure 3.--Theoretical relationship of hydraulic seepage gradient to effective grain density and competence.

\[ x = \frac{1}{(1 - 1.65)} \]
increase the effective density of sediment grains, making them more difficult to erode. Whereas the maximum positive piezometric gradient possible in sediment of 2.65 grams per cubic centimeter dry density is +1.65, there is no lower limit of negative piezometric gradient.

As an example of the theoretical effectiveness of seepage according to the relationship set forth by Clayton and others (1966), assume that a stream has a velocity just capable of moving grains 1 mm in diameter. If groundwater seeping up through the stream bed were to create a piezometric gradient of +1.55, the competence would increase 16.5 times, so that the stream could now move grains 16.5 mm in diameter. On the other hand, if downward infiltration through the channel bottom were to produce a piezometric gradient of -14.85, the competence would be decreased by 10 times and the stream would be capable of moving only those grains that are 0.1 mm in diameter or less. Thus, under those conditions, groundwater seepage should change the competence by a factor of 16.5 times.

Procedure and Results of Threshold-Velocity Experiments

To determine the effects of seepage on threshold velocity, several runs were made in the rigid-boundary controlled-seepage flume. Prior to each run, a smooth layer, a few inches thick, of sediment of the selected size was spread over the bed of the flume. The velocity of the water was increased gradually until a few grains began to roll along the bottom of the channel over the test area. The threshold velocity for each sediment size under various conditions of seepage was then measured with a pitot tube. Velocity
readings were made in the center of the channel at about five points along a vertical velocity profile.

In runs using fine sand, medium sand, coarse sand, and pebbly sand, no difference was found for the threshold velocity when the hydraulic seepage gradient was varied from 0 to +1.65. With a gradient approaching +1.65 some areas about 1.5 inch in diameter became quick, yet no noticeable increase in sediment transport could be observed over these areas. The apparent lack of an increase in competence (decrease in threshold velocity) under conditions of positive seepage is not in agreement with the theoretical predictions set forth earlier.

In runs using pebbly sand the velocity was increased under conditions of no seepage until several fine-size to medium-size sand grains were rolling over the test area. After reduction of the hydraulic seepage gradient to -1.0, however, only a few grains continued to move. The resulting difference in threshold velocity was not large enough to be measured with the pilot tube, which could fairly reliably detect velocity differences of 0.02 foot per second. In the fine, medium, and coarse sand no reduction in competence was observed with negative seepage. The reasons for the failure of these results to agree with the theory previously set forth will be discussed in a later section entitled "Summary and Interpretations".

Theoretical Effects of Seepage on Transport Rate

Several formulas have been proposed for calculating the sediment transport of a stream. Some of the more popular formulas
are those derived by DeBoys (1879, in Raudkivi, 1967, p. 39),
Einstein (1942), Kalinske (1947), and Bagnold (1966). All of these
formulas contain a factor to account for the effective density
of the sediment grains. The grains are commonly assumed to have
a dry density of 2.65 grams per cubic centimeter and a submerged
density of 1.65 grams per cubic centimeter. The work that a stream
performs in transporting the sediment load varies directly with
the effective density of the sediment. With a given stream power,
it is logical to conclude that the stream would be capable of
transporting a relatively greater volume of sediment if the effective
density of the bedload were to decrease. As shown earlier, the
effective density of sediment grains on a stream bed can be
decreased by upward seepage and increased by downward seepage.

Another factor to be considered in relation to the sediment
transport equations is the coefficient of solid friction, which is
considered to be equivalent to the angle of repose. According to
laboratory experiments by Van Burkhalow (1945, p. 669), the angle of
repose is dependent on the size, shape, compaction, and density of
sediment grains. She found that for wooden blocks in air, the angle
of repose varied inversely with the density of the blocks. It might
be expected, therefore, that the angle of repose of sediment grains
in water would be increased by upward seepage and decreased by
downward seepage. Others, however, had previously found that grain
density has no effect on the angle of repose (Lehman, 1842, in Van
Burkhalow, 1945) or that the angle of repose varies directly with
grain density (Thoulet, 1887, in Van Burkhalow, 1945). Van Burkhalow
(p. 687) questioned the validity of these earlier findings on the
grounds that other factors besides density were not accounted for.

According to the sediment transport equations, an increase in the angle of repose should decrease the transport rate. Thus, based on the relationship of grain density to angle of repose found by Van Burrello (1945), upward (positive) seepage should decrease the transport rate and downward (negative) seepage should tend to increase the transport rate.

Procedure and Results of Transport-Rate Experiments

Low-Regime Flow—Seventeen runs were made in the rigid-boundary flow to determine the effects of seepage on bedload transport rate under conditions of low-regime flow. With low-regime flow the bedforms present generally are either ripples or dunes; the water surface is either smooth (ripples) or out of phase with the bedforms (dunes). In general, the average velocity during these runs was about 1 foot per second and the flow depth about 8 inches. Medium sand was used throughout the runs. Wet sand was periodically added at the upstream end of the flume to replace sediment which had been transported downstream. The location of the foreset face of the sediment layer was marked on the downstream end of the flume prior to each run. Transport rate was determined by measuring the volume of sand which was transported beyond the initial foreset face during the subsequent run.

Results of these runs are shown in Table 1. In spite of the effect of seepage on effective grain density, bedload transport rate varied inversely with the hydraulic gradient in these runs. Positive seepage caused a decrease in the transport rate whereas
TABLE 1.—Data from low-regime flume runs.

<table>
<thead>
<tr>
<th>Run</th>
<th>Initial Discharge (gpm)</th>
<th>Seepage Rate (gpm)</th>
<th>Seepage Gradient in Test Area</th>
<th>Transport Rate (ft³/hr)</th>
<th>Angle of Repose</th>
<th>Length of Run (hrs)</th>
<th>Sediment Feed Rate (ft³/hr)</th>
<th>Maximum Bed Relief (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-67</td>
<td>100</td>
<td>0.0</td>
<td>0.0</td>
<td>0.015</td>
<td>~30°</td>
<td>4.25</td>
<td>0.028</td>
<td>___</td>
</tr>
<tr>
<td>3-67</td>
<td>100</td>
<td>-3.5</td>
<td>-1.0 to -1.7</td>
<td>0.026</td>
<td>35° to 47°</td>
<td>4.25</td>
<td>0.028</td>
<td>___</td>
</tr>
<tr>
<td>5-67</td>
<td>100</td>
<td>+1.7</td>
<td>+0.7 to +0.9</td>
<td>0.011</td>
<td>19° to 35°</td>
<td>5.50</td>
<td>0.024</td>
<td>~ 0.1</td>
</tr>
<tr>
<td>6-67</td>
<td>100</td>
<td>-1.7</td>
<td>-0.5 to -0.6</td>
<td>0.018</td>
<td>36° to 41°</td>
<td>5.00</td>
<td>0.016</td>
<td>&gt;0.25</td>
</tr>
<tr>
<td>7-67</td>
<td>100</td>
<td>+1.1</td>
<td>+0.4 to +0.5</td>
<td>0.012</td>
<td>27° to 33°</td>
<td>6.75</td>
<td>0.026</td>
<td>0.13</td>
</tr>
<tr>
<td>8-67</td>
<td>100</td>
<td>0.0</td>
<td>0.0</td>
<td>0.013</td>
<td>31° to 36°</td>
<td>7.90</td>
<td>0.027</td>
<td>0.17</td>
</tr>
<tr>
<td>9-67</td>
<td>100</td>
<td>-3.2</td>
<td>-1.1 to -1.7</td>
<td>0.022</td>
<td>39° to 47°</td>
<td>5.50</td>
<td>0.028</td>
<td>0.37</td>
</tr>
</tbody>
</table>
negative seepage caused an increase. More specifically, under conditions of constant discharge (disregarding the discharge added or withdrawn by seepage, which amounted to less than 5 percent) the transport rate was about 40 percent higher when the hydraulic gradient over the test area was -1.0 to -1.7 than when there was no seepage; a positive gradient of 0.7 to 0.9 resulted in a decrease of the transport rate by about 40 percent (fig. 4).

The data in table 1 also show that the angle of repose on the front of the bedforms varied inversely with hydraulic seepage gradient and directly with effective density. The lower the hydraulic gradient, the greater the effective density, and the higher the angle of repose (fig. 4). This change in the angle of repose is in direct contradiction to the predictions made previously on the basis of Van Buren's experiments.

Maximum bed relief also varied inversely with hydraulic seepage gradient (table 1). For the purpose of this paper, maximum bed relief is defined as the maximum vertical distance between the top of a bedform and the trough immediately downstream from the crest.

The angle of repose averaged about 27 degrees and the maximum bed relief was about 0.1 foot when the hydraulic seepage gradient was maintained at about 0.8 (upward seepage). Under conditions of negative seepage (hydraulic seepage gradient about -1.5) the angle of repose increased to an average of 43 degrees with a maximum bed relief of approximately 0.4 foot. Thus, negative seepage caused a steeper angle of repose and greater bed relief, both of which contribute to an increase in bottom roughness and turbulence. The increase in turbulence resulted in more grains being picked up into
Figure 4.—Relationship of hydraulic seepage gradient to transport rate and angle of repose for low-regime flume runs.
the current. These grains were commonly transported 1 foot or more downstream before coming to a temporary rest again on the stream bed. The observed relationship between seepage, bottom roughness, and sediment transport is shown in figure 5.

**Figure 5.**—Relationship of seepage to bottom roughness and turbulence when low-regime bedforms are present on the stream bed.

**High-regime flow.**—Ten runs were made in the rigid-boundary flume to test the effect of seepage on the transport rate under high-regime flow conditions. It was thought that seepage might affect the transport rate differently in these runs than in previous experiments because few or no bedforms were present under the high-regime conditions. Any effects of seepage on bedform roughness were thus eliminated.

Pebbley sand was used in all runs. Sediment transport was in the
form of sheet transport or a "moving carpet" as defined by
Bagnold (1956, p. 7). A layer of grains about 0.02 foot thick
was transported along the stream bed at a velocity approaching
that of the main current. Individual particle movement was by
saltation. Individual grains bounced off the bottom, then followed
a flat trajectory for a foot or more before striking the bottom
again.

Surface velocity, water depth and surface slope, hydraulic seepage
gradient, and transport rate were measured in the test area during
each run (table 2). Discharge into the upper end of the flume
was the same for all runs.

After completing the first nine runs (1.b-671 through 1.b-671),
it appeared that the transport rate was inversely related to the
hydraulic seepage gradient (fig. 6). This was also contradictory
to expectations based on the theory set forth earlier. It was
noticed, however, that over the test area the slope of the water
surface was steeper and the depth was less in runs with negative
seepage than in runs without seepage (table 2). This was presumably
caused by the decrease in discharge over the test area resulting
from the withdrawal of seepage water. To determine the effect of
this increased slope and decreased depth, another run (1.b-671) was
conducted in which all conditions were the same as in previous runs
except that slope and depth of flow over the test area were adjusted
so as to be similar to those in the negative-seepage runs. Under
these conditions, the transport rate was greater than in all
previous runs, indicating that changes in depth and slope of the
water were primarily responsible for the change in transport rate,
TABLE 2.--Data from high-regime transport-rate runs in the flume using well-sorted medium sand.

<table>
<thead>
<tr>
<th>Run</th>
<th>Seepage</th>
<th>Approx. Seepage Gradient</th>
<th>Water Surface Vel. (fps)</th>
<th>Depth $^a$ (ft)</th>
<th>Water Surface Slope (ft/ft)</th>
<th>Length of Run (min.)</th>
<th>Transport Rate (ft$^3$/hr)</th>
<th>Bedforms</th>
</tr>
</thead>
<tbody>
<tr>
<td>14-67A</td>
<td>none</td>
<td>0</td>
<td>2.5</td>
<td>.17</td>
<td>.013</td>
<td>5.5</td>
<td>2.28</td>
<td>none</td>
</tr>
<tr>
<td>14-67B</td>
<td>neg.</td>
<td>-8</td>
<td>2.3</td>
<td>.15</td>
<td>.015</td>
<td>5.5</td>
<td>2.33</td>
<td>standing waves .05' high over test area</td>
</tr>
<tr>
<td>14-67C</td>
<td>pos.</td>
<td>+1</td>
<td>2.1</td>
<td>.17</td>
<td>.007</td>
<td>5.5</td>
<td>1.23</td>
<td>standing waves .03' high over test area</td>
</tr>
<tr>
<td>14-67D</td>
<td>none</td>
<td>0</td>
<td>2.3</td>
<td>.16</td>
<td>.009</td>
<td>5.5</td>
<td>1.70</td>
<td>none</td>
</tr>
<tr>
<td>14-67E</td>
<td>pos.</td>
<td>+1</td>
<td>2.5</td>
<td>.17</td>
<td>.009</td>
<td>5.5</td>
<td>1.33</td>
<td>standing waves .02' high over test area</td>
</tr>
<tr>
<td>14-67F</td>
<td>neg.</td>
<td>-3</td>
<td>2.2</td>
<td>.16</td>
<td>.015</td>
<td>5.5</td>
<td>2.33</td>
<td>standing waves .07' high over test area</td>
</tr>
<tr>
<td>14-67G</td>
<td>none</td>
<td>0</td>
<td>2.1</td>
<td>.16</td>
<td>.009</td>
<td>5.5</td>
<td>1.47</td>
<td>none</td>
</tr>
<tr>
<td>14-67H</td>
<td>none</td>
<td>0</td>
<td>2.0</td>
<td>.17</td>
<td>.009</td>
<td>5.5</td>
<td>1.40</td>
<td>none</td>
</tr>
<tr>
<td>14-67I</td>
<td>neg.</td>
<td>...</td>
<td>2.0</td>
<td>.16</td>
<td>.015</td>
<td>5.5</td>
<td>2.16</td>
<td>standing waves .06' high over test area</td>
</tr>
<tr>
<td>14-67J$^b$</td>
<td>none</td>
<td>0</td>
<td>...</td>
<td>.15</td>
<td>.015</td>
<td>3.0</td>
<td>4.20</td>
<td></td>
</tr>
</tbody>
</table>

$^a$Measurements of depth and water surface slope were made in the test area 4 minutes after the beginning of each run except in run 14-67J, in which they were made after 3 minutes.

$^b$Depth and slope adjusted to coincide with runs having no seepage.
Figure 6.—Data from high-regime transport-rate runs in the flume.
A. Relationship of hydraulic seepage gradient to transport rate.
B. Relationship of seepage conditions to water surface slope.
rather than the direct influence of seepage on grain density (fig. 6).
In the previous negative-seepage runs, the withdrawal of seepage water caused an increase in the velocity over the test area by increasing the slope and decreasing the depth.

On the basis of the above runs it appears that (1) the increase in transport rate with decrease in hydraulic seepage gradient observed here was not caused by any direct effects of seepage on grain density, (2) because the final run (14-67J) resulted in a transport rate even greater than that of the previous negative-seepage runs with similar flow depth and slope, the negative seepage in the earlier runs may have been effective in keeping the transport rate lower than it would have been without seepage, and (3) the effect of seepage on transport rate under conditions of high-regime flow could not be thoroughly tested in these experiments because of the limited water depth and short duration of the runs as dictated by the size of the flume.

Effectiveness of negative seepage with a mud soil.-- In the previous runs, very little suspended sediment was present in the water. It was suspected, however, that if sufficient fine-grained sediment (mud) were present during negative seepage runs, the interstices between the larger grains on the bed might become clogged. This, in turn, might have some effect on the seepage rate and stream competence. To test this hypothesis, additional runs were made in the flume using the pebbly sand from the previous runs, but with a considerable amount of mud added. This finer sediment was carried as suspended load.

Figure 7 shows the results of one of these runs. With a
Figure 7.--Change in unconfined compressive strength of the stream bed, seepage rate, and hydraulic seepage gradient during the development of a mud seal under conditions of low-regime flow and no bedload transport.
surface velocity of about 1.2 feet per second and a flow depth of
0.41 foot over the test area, the velocity was insufficient to cause
bedload transport even under conditions of no seepage. The graph
shows that the hydraulic gradient decreased with time (became more
negative) as the suspended sediment clogged the intergranular pores
on the surface of the bed. This clogging was accompanied by a
decrease in the amount of water seeping downward through the bed.
The clogging effect of the mud will be referred to as a "mud seal"
in the following discussions. Development of the mud seal was
also accompanied by an increase in the compressive strength of the
channel bottom. Measurements made with a Solltest Pocket Penetrometer
range from less than 0.25 tons per square foot without seepage to
more than 0.75 tons per square foot when the mud seal was present.

It was apparent from the above run that under conditions of
negative seepage with sufficient suspended sediment present, a
mud seal could develop which drastically increases the effective
density of the bottom sediment, and hence causes a decrease in
stream competence. The resulting decrease in competence had not
been measured in the previous run, however, because the flow
velocity was insufficient to transport the bed material even without
the mud seal. Furthermore, it was not known at this point if a
mud seal could form while bedload transport was taking place.

Thus, in the next run the surface velocity was increased to
1.6 feet per second and the flow depth decreased to 0.1 foot or
less. Transport without seepage under these conditions was in the
form of a graded suspension with in-phase standing waves on the bed
and water surface indicating high-reynolds flow conditions.
Figure 6 shows the decrease in transport rate as the negative scourage was initiated. The transport rate during the first 5 minutes of the run, with no negative scourage was 0.28 cubic foot per hour. At the end of the first 5 minutes, the negative scourage was initiated and additional fine sediment was added to the water. During the ensuing 5 minutes the transport rate averaged only 0.15 cubic foot per hour despite a decrease in the flow depth from 0.1 foot to 0.07 foot over the test area. Five minutes after negative scourage was begun all bedload transport had ceased. It was apparent that (1) a mud seal could develop under conditions of rapid bedload transport and (2) the resulting mud seal could drastically decrease, and in some cases eliminate, entainment of channel-bed sediment.

Effects of Scourage on Water Surface Slope, Bedform Roughness, Channel Morphology and Channel Path

The effects of scourage on bedform roughness, water surface slope, channel morphology and path (straight, meandering, or braided) could not be investigated using the flume because the closely spaced sides prohibited development of a natural channel. Furthermore, the flume was too short to permit accurate measurement of the water surface slope during low-regime runs. Therefore, several runs were conducted in the larger mobile-boundary controlled-scarage fluvial trough described earlier.

Although scourage failed to cause striking changes in stream competence in the flume experiments, except where a mud seal was present, it was thought that the effects of scourage on bedform roughness could be more carefully tested by measuring the water surface slope in the 20-foot-long trough. Ideally, an increase in the
Figure 8.-- Effect of a mud seal on transport rate. Sediment was being transported as a moving carpet under conditions of high-regime flow prior to development of the seal.
credibility of the channel sediment or a decrease in channel
roughness brought about by upward seepage should result in a decrease
in the water surface slope because less energy would be required by
the stream to transport its load. Conversely, downward seepage
should require greater energy and result in a relatively steeper
slope for any given discharge.

Runs in pebbly sand.-- In general, the following procedure was
used in these runs. The sediment, pebbly sand, was sloped gently
downward toward the center line of the trough prior to each run.
A selected discharge was begun and the stream formed its own channel
in the sediment within a few minutes. Throughout each run dry
sediment of the same size as that comprising the channel was fed to
the upper end of the stream at a rate of about 0.05 cubic foot per
hour. By adding this sediment, the stream could aggrade or degrade
to adjust its slope and attain an equilibrium condition.

Measurements of the water surface slope were made at 2-foot
intervals along the length of the trough. Once the slope became
essentially constant, the stream was considered to be in equilibrium.
In addition, the width and maximum depth of the channel, approximate
surface velocity, angle of banks, hydraulic gradient, and path of
the equilibrium channel were measured and recorded. High-regime
flow occurred over pebbly sand whenever bedload was transported.
No bedforms were present except occasional short-lived standing sand
and water waves. Individual runs lasted from several hours to a
few days.

Because the discharge varied throughout the length of the
channel during seepage runs, the average discharge for the 0 to 10-foot
reach and for the 10 to 20-foot reach of the channel were calculated. Characteristics of the channel were measured and recorded separately for each reach.

Results of these runs are tabulated in Table 3. The relationship of discharge to water surface slope is shown in Figure 9. As expected, the slope was inversely proportional to the discharge for the runs having no seepage. The slope-discharge relationship does not appear to vary significantly for the seepage runs; points for these runs plot along the line drawn through the points for runs having no seepage. Thus, contrary to expectation, there was no marked effect of seepage on resistance to movement of the channel sediment or to flow resistance under the conditions tested.

Furthermore, there appears to be no consistent relationship of channel path to seepage conditions. Even in runs without seepage, the channel path varied from essentially straight to braided within the 20-foot length of the channel. No insight was gained as to the factors controlling stream path, except that seepage does not appear to be a controlling factor.

Banks in these channels were generally about 0.1 foot high where the stream had cut into the sediment. The slope of the channel banks varied significantly throughout the runs. Channels in runs having no seepage generally had vertical banks. Similarly, channels in the negative seepage run had vertical to slightly overhanging banks. Channels in the positive-seepage runs, however, had bank angles usually less than 45 degrees. In all cases, the sediment making up the banks was moist, either because of upward seepage or capillary forces.
### TABLE 3.—Data from runs in the fluvial trough using pebbly sand.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>ST-6</td>
<td>0</td>
<td>2.3</td>
<td>1.4</td>
<td>.033</td>
<td>0</td>
<td>90°</td>
<td>140</td>
<td>braided</td>
</tr>
<tr>
<td>ST-10</td>
<td>0</td>
<td>6.9</td>
<td>1.1</td>
<td>.025</td>
<td>0</td>
<td>90°</td>
<td>40</td>
<td>braided</td>
</tr>
<tr>
<td>ST-11</td>
<td>+4.7</td>
<td>6.2 inlet</td>
<td>1.6</td>
<td>***</td>
<td>.3 to .7</td>
<td>45°</td>
<td>47</td>
<td>meander</td>
</tr>
<tr>
<td>ST-2</td>
<td>0</td>
<td>11.0</td>
<td>***</td>
<td>.014</td>
<td>0</td>
<td>90°</td>
<td>144</td>
<td>braided</td>
</tr>
<tr>
<td>ST-9B</td>
<td>0</td>
<td>14.5</td>
<td>1.3</td>
<td>.014</td>
<td>0</td>
<td>90°</td>
<td>51</td>
<td>braided</td>
</tr>
<tr>
<td>ST-12</td>
<td>+10.0</td>
<td>11.0 inlet</td>
<td>***</td>
<td>.8 to +1.65</td>
<td>45°</td>
<td>31</td>
<td>straight</td>
<td>straight</td>
</tr>
<tr>
<td>ST-13</td>
<td>-9.0</td>
<td>17.0 inlet</td>
<td>***</td>
<td>-1.0 to -1.5</td>
<td>90°</td>
<td>9</td>
<td>straight</td>
<td>straight</td>
</tr>
<tr>
<td>ST-4</td>
<td>0</td>
<td>27.0</td>
<td>1.7</td>
<td>.008</td>
<td>0</td>
<td>90°</td>
<td>140</td>
<td>straight</td>
</tr>
<tr>
<td>ST-5</td>
<td>0</td>
<td>27.0</td>
<td>1.5</td>
<td>.008</td>
<td>0</td>
<td>90°</td>
<td>122</td>
<td>braided</td>
</tr>
<tr>
<td>ST-9A</td>
<td>0</td>
<td>30.0</td>
<td>1.5</td>
<td>.009</td>
<td>0</td>
<td>90°</td>
<td>30</td>
<td>straight</td>
</tr>
</tbody>
</table>

*Channel impinging on side of trough.*
Figure 9.—Relationship of discharge and seepage to water surface slope in fluvial trough experiments using pebbly sand.
Ruts in well-sorted coarse sand.—In the preceding runs, using pebbly sand, no marked effects of seepage on channel slope could be detected. However, in previous runs no ripples or dunes were present on the channel bed. It was hypothesized that the effects of seepage on bedform morphology, already observed in the flume experiments, might result in a change in the flow resistance and thus in the slope of the water surface. In order for bedforms to develop during subsequent runs, a ½-foot thick layer of clean, well-sorted, coarse sand was put in the stream trough on top of the pebbly sand.

Initial attempts to use a discharge of about 15 gallons per minute resulted in a flat bed covering nearly the full width of the table with flow in an indistinct channel with a depth of less than a couple hundredths of a foot. A small (less than ½-foot wide) channel could not be maintained due to the extremely high channel width-depth ratio in this type of sediment. It was therefore necessary to increase the discharge to 50 to 75 gallons per minute in order to maintain flow over the entire width of the trough at a depth sufficient to allow low-regime bedforms such as ripples or dunes to form. Thus, the sides of the trough acted as the channel banks.

The duration of these runs ranged from 15 to more than 72 hours. Runs were terminated after the slope of the water surface became stable (it was considered to be stable when the water-surface elevation at the 4-foot and 18-foot stations varied by 0.005 foot or less between two consecutive measurements taken a few hours apart).

At the end of each run the approximate surface velocity, average water depth, initial inlet discharge, seepage discharge, hydraulic seepage gradient, and bedform relief were measured. Velocity was determined
by averaging the time required for a float to travel from the 4-foot to the 18-foot station three times. The resulting velocity values are believed to be accurate to only the nearest tenth of a foot per second because of the nonuniform velocity across the width of the trough. Even though the channel covered the entire width of the trough, a meandering thalweg was present.

Depth and bedform relief were determined by measuring the transverse profile at the 4-foot and 18-foot stations. Depth was measured to the nearest one-hundredth of a foot at 15 to 20 points across each traverse. Bedform relief was measured at about 12 points on each traverse.

Discharge for runs having no seepage was determined by measuring the time required to fill a container of known volume at the outlet end of the trough. Three such measurements were made and averaged for each run. The inlet valve at the upstream end of the trough was calibrated using these measurements. For seepage runs, the initial discharge at the inlet was determined from the valve calibrations. Discharge at the outlet end of the trough was measured in the manner described above. The difference between the inlet and outlet discharge was the seepage discharge. The average discharge for the positive seepage runs was calculated as the sum of the initial discharge plus half of the seepage discharge (the seepage rate throughout the length of the trough was assumed to be uniform). Dry sediment, the same size as that comprising the stream bed, was fed continuously during the runs at the rate of 0.05 cubic foot per hour.

Data for these runs are shown in table 4. Because of the small
TABLE 4.—Data from runs in the fluvial trough using well-sorted coarse sand under conditions of low-regime flow.

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>ST-16</td>
<td>54</td>
<td>0</td>
<td>0.0057</td>
<td>0</td>
<td>0.039</td>
<td>0.56</td>
<td>0.77</td>
<td>0.037</td>
<td>0.037</td>
<td>50</td>
</tr>
<tr>
<td>ST-15</td>
<td>76</td>
<td>0</td>
<td>0.0050</td>
<td>0</td>
<td>0.039</td>
<td>0.56</td>
<td>0.77</td>
<td>0.037</td>
<td>0.037</td>
<td>15</td>
</tr>
<tr>
<td>ST-17</td>
<td>70</td>
<td>-12</td>
<td>0.0047</td>
<td>-1.1</td>
<td>0.079</td>
<td>0.082</td>
<td>1.05</td>
<td>0.91</td>
<td>0.034</td>
<td>30</td>
</tr>
<tr>
<td>ST-18</td>
<td>61½</td>
<td>+15</td>
<td>0.0047</td>
<td>+0.5</td>
<td>0.064</td>
<td>0.038</td>
<td>0.59</td>
<td>0.97</td>
<td>0.027</td>
<td>72</td>
</tr>
<tr>
<td>ST-19</td>
<td>76</td>
<td>0</td>
<td>0.0054</td>
<td>0</td>
<td>0.074</td>
<td>0.060</td>
<td>0.83</td>
<td>0.94</td>
<td>0.031</td>
<td>26</td>
</tr>
<tr>
<td>ST-20</td>
<td>66</td>
<td>0</td>
<td>0.0050</td>
<td>0</td>
<td>0.068</td>
<td>0.039</td>
<td>0.58</td>
<td>0.85</td>
<td>0.028</td>
<td>55</td>
</tr>
</tbody>
</table>
range in discharge used to obtain the desired bedforms, only six runs were made.

Values of relative roughness (the ratio of average bedform relief to average depth) are plotted against average discharge on the graph in figure 10(A). For the runs with no seepage, average relief and average depth show a general increase with discharge. The relief appears to increase at a higher rate than the depth, however, resulting in an increase in relative roughness with discharge under the conditions tested. The relative roughness for the positive seepage run appears to be similar to that of a run of equivalent discharge with no seepage. The negative seepage run, however, has a much higher relative roughness value than the other runs.

The value of Manning’s $n$, which is a measure of channel flow resistance, was computed for each run using the basic formula $v = 1.49 R^{2/3} S^{1/2}$, where $v$ is average velocity in fps, $R$ is hydraulic radius in feet (which is equivalent to the average depth in wide, shallow channels), and $S$ is the slope of the water surface in feet per foot. Because the velocity measurements were not believed to be very accurate, discharge ($Q$) divided by cross-sectional area of flow ($A$) was substituted for velocity. The resulting formula is $n = 1.49 R^{2/3} S^{1/2} Q$, where $D$ is the average depth in feet.

Computed values of $n$ are plotted against average discharge on the graph in figure 10(B). No definite relationship between discharge and resistance factor ($n$) can be drawn from these points. It appears, however, that the channel resistance in the negative-seepage runs is somewhat higher than would be expected in a run of the same discharge having no seepage. Similarly, the resistance in the
Figure 10.—Relationship of discharge to water surface slope, relative roughness, and Manning n in low-regime runs in the fluvial trough using coarse sand. A. Relationship of discharge to relative roughness. B. Relationship of discharge to Manning n. C. Relationship of discharge to water surface slope.
positive-seepage run is probably somewhat lower than an equivalent-discharge run without seepage.

A tendency toward a relatively higher resistance to flow under conditions of negative seepage is suggested by the above relative roughness data. A significant increase in flow resistance should require greater stream energy. Under conditions of constant discharge, channel shape, and sediment size, this increase in energy can be brought about only by an increase in the slope of the water surface caused by aggradation at the upstream end of the trough. Measurements of water surface slope made during negative seepage runs, however, fail to reveal a significantly higher value than those obtained from runs of similar discharge without seepage (Fig. 10(b)). Although it can not be concluded from these few data, positive seepage appears to cause a slightly lower slope than would be expected in an equivalent-discharge run without seepage.
SUMMARY AND INTERPRETATIONS

Experiments on Threshold Velocity and Competence

Positive seepage failed to produce noticeable changes in threshold velocity in runs using fine, medium, coarse, and pebbly sand. With the negative seepage present in these experiments, competence theoretically should have been only about 40 percent of what it was without seepage. Positive seepage should have increased competence from 300 percent to infinity. Therefore, negative seepage should not have been expected to produce striking results in these experiments, but positive seepage should have.

It was initially thought that the ineffectiveness of positive seepage might be due to a thickening or upward displacement of the laminar sublayer brought about by the upward moving water. If the laminar sublayer were thickened sufficiently to cover the grains on the stream bed it would protect them from the higher stresses exerted by turbulent flow. Conversely, if negative seepage were to decrease the thickness of the laminar sublayer it might increase the exposure of the grains to turbulent flow. Thus, in this way seepage might tend to counteract the changes in threshold velocity which result from effective density changes.

However, Inman (1949, p. 56) has found that grains larger than silt-size (essentially all sediment transported as bedload) project up through the laminar sublayer at flow velocities less than their
threshold velocity. Therefore the channel bottom in these experiments was hydraulically rough and stress was not uniformly distributed along the bottom. Eddies were shed by the more exposed grains causing a wake to form downstream from each grain (Hamblin, 1967, p. 17). Furthermore, it will be shown later that upward seepage does not increase the thickness of the laminar sublayer but tends to increase turbulence instead.

As opposed to hydraulically smooth flow, in which grains do not project up through the laminar sublayer and only surface drag or viscous skin friction is present, both surface drag and form drag are present in hydraulically rough flow such as occurred in these experiments. Therefore, it is possible that seepage affects both surface drag and form drag in such a manner as to counteract the effects of seepage on effective density of sediment grains.

Form drag is directly proportional to the size of the wake, or eddy, on the downstream side of a grain. Surface drag, however, is inversely proportional to the size of the wake. The relationship of form drag and surface drag to wake size is shown diagramatically in figure 11.

![Diagram showing relationship of form drag and surface drag to wake size](image)

Figure 11.—Relationship of form drag and surface drag to the size of wake on the downstream side of a sediment grain.
With a given free-stream velocity under conditions of turbulent flow, the size of the wake or the amount of turbulence behind a grain is proportional to the difference in pressure between points 2 and 3 in Figure 12. The pressure at P2 is less than at P3. The

\[ P_1 \quad \rightarrow \quad P_2 \quad \rightarrow \quad P_3 \]

Figure 12.—Theoretical pressure distribution and flow lines over a single sediment grain.

Flow lines converge at P2 in order for the fluid to flow around the grain. This results in an increase in velocity at P2 relative to \( P_1 \) according to the Bernoulli theorem. Conversely, divergent flow between P2 and P3 results in a decrease in velocity and an increase in pressure. Thus, fluid particles traveling along the boundary of the grain accelerate from \( P_1 \) to P2, converting pressure into kinetic energy (Schlichting, 1955, p. 26). In traveling from \( P_1 \) to P2, however, much of the kinetic energy of the fluid particle is consumed in overcoming frictional forces so that the remainder of the kinetic energy is not sufficient to carry the particle through the adverse pressure gradient between P2 and P3. Somewhere between P2 and P3 the particle decelerates to a stop, then reverses its motion to follow the pressure gradient back toward P2. At the point where fluid particles reverse their net motion from downstream to upstream, boundary layer separation takes place. This reverse motion results in increased turbulence, hence increased friction, energy loss, and form drag.
It was shown earlier that form drag is directly proportional to the size of the wake and surface drag is inversely proportional to size of the wake. Thus, any effects of seepage on the size of the wake will cause changes in the ratio of surface drag to form drag. It has been shown that application of suction in areas of adverse pressure gradients which occur in divergent flow will sharply reduce form drag. Figure 13, taken from Schlichting (1955, p. 39) demonstrates this relationship.

![Flow with separation - no suction](image1)

![Flow with boundary layer suction - no separation](image2)

**Figure 13.** The relationship of boundary layer suction to form drag and flow separation in an area of divergent flow (after Schlichting, 1955, p. 39).

The reason for the decrease in form drag when suction is applied is that the suction lowers the pressure in the area of lower velocity and thereby decreases the adverse pressure gradient, permitting fluid particles to enter this zone. The same phenomenon should occur on the downstream side of grains under conditions of negative seepage. By withdrawing water from the high pressure-low velocity cone in the wake, negative seepage should decrease the adverse pressure gradient and thus allow fluid particles to follow the sides of the grain farther before reversing their flow. This would in turn cause the point of boundary layer separation to migrate
farther downstream on the grain and hence decrease the turbulence and form drag behind the grain. However, this shift in the point of boundary layer separation would result in an increase in the area of the grain subjected to surface drag. Theoretically, positive seepage should have the opposite effect—surface drag should be decreased and form drag increased.

The purpose of this discussion was to see if there is some seepage-produced effect that would tend to counteract changes in effective density. According to the above reasoning, positive seepage should decrease effective grain density and surface drag and increase form drag. In order to get the experimental results of this study in closer agreement with theory, some effect of positive seepage is needed to compensate for the decrease in effective grain density. Because form drag is increased at the expense of surface drag by positive seepage, it must be assumed that surface drag exerts proportionately more force on sediment grains than form drag. If this is true, positive seepage, by decreasing surface drag, would tend to decrease the forces acting to set a grain in motion thereby compensating entirely or in part for its decrease in effective density.

However, this possible compensation for a decrease in grain density can not account entirely for the apparent lack of increase in grain transport where a quick condition exists. Theoretically, because grains are effectively weightless in this condition, any downstream vector should result in transport regardless of its magnitude. Noticeable increases in transport over quick areas were not observed in these experiments, however. The reason for this is not known.
Even if transport were more effective over quick areas, however, the resulting increase in transport over the entire stream bed could never be very widespread because of the isolated nature of occurrence of quick areas. Once the hydraulic gradient approaches 1.65, a pipe, or area of concentrated groundwater flow, is initiated in that area of the sediment offering the least flow resistance. A concentrated flow of seepage water escapes through the quick area, resulting in a lowering of the hydraulic gradient in the surrounding area. In addition, quick areas do not tend to migrate. Once initiated, the sediment grains are quickly sorted within the pipe, with the largest grains settling to the bottom of the pipe. This further increases the permeability of the pipe. Lighter, smaller grains are kept in suspension and the lightest grains are flushed out of the pipe. Thus, the localization and self-stabilizing characteristics of quick areas prevent them from affecting relatively large areas of the stream bed.

Hydraulic vs. Transport Rate

Increase in Flow: These runs show that in low-regime flow with ripples or dunes present, the transport rate, angle of repose on the lee face of the bedforms, and bed roughness vary inversely with seepage. According to the theory set forth earlier, the transport rate should have been increased by 90 percent in positive seepage runs with the hydraulic seepage gradient used. Although the downward seepage should have been sufficient to increase the effective grain density to about 3 grams per cubic centimeter, its most striking effect was to increase the angle of repose from about 33 degrees without seepage to about 43 degrees with negative seepage. This
steepening of bedform faces resulted in an increase in turbulence near the bed. Therefore, despite the increase in effective density of grains resting on the bed, the sediment was transported (mostly by saltation) at a greater rate because of the increased turbulence. Positive seepage, on the other hand, decreased the angle of repose, thereby causing a decrease in turbulence and transport rate. Although the flow depth over the test area was about 1-foot, some of the change in transport rate might be attributed to fluctuations in flow depth and water surface slope brought about by withdrawal or addition of seepage water.

**High-seepage flow:** Experiments in the flume to test the effects of seepage on transport rate under conditions of high-seepage flow yielded inconclusive results. In these runs no significant bedforms were present, thus the effects of seepage on bedform roughness were eliminated. What initially appeared to be an increase in transport rate accompanying negative seepage was probably caused by a steeper water surface slope and lesser depth of flow over the test area. These changes in depth and slope were caused by the addition or withdrawal of seepage water into the channel. The effect of seepage-induced changes in effective grain density on transport rate could not be determined in these experiments. Shortcomings in the equipment prevented a more thorough investigation. A flume permitting greater flow depth would diminish the effects of fluctuations in flow depth and surface slope caused by adding or withdrawing seepage water. In addition, a longer flume would enable longer-duration experiments so that transport rate could be more accurately measured. Because of the short length of the present equipment, high-seepage flume runs
had to be restricted to about 5 minutes in length.

Effectiveness of seepage with mud seal.---The initial effect of negative seepage, when suspended mud was present in the stream, was to increase the effective density of the grains as frictional drag was exerted on the grains by downward moving water. Mud particles soon clogged the pores between the sand grains on the bed, thereby reducing the permeability. Growth of the mud seal continued until permeability decreased to the point that the sediment beneath the uppermost bed layer became unsaturated. The resulting mud seal was only a fraction of a millimeter thick. Once the sediment beneath the mud seal became unsaturated, the weight of the water in the channel had to be supported by the uppermost bed layer (fig. 14).

![Diagram of mud seal conditions on a stream bed.](image)

Figure 14---Diagrammatic cross section of mud-seal conditions on a stream bed.

The result of the unsaturated condition beneath the mud-sealed layer is a great increase in the effective density of the grains comprising this layer. Ideally, once the mud seal is developed, only the upper halves of the sand grains on the bed are still submerged in water. Thus the effective density of these grains would increase from 1.65 grams per cubic centimeter to 2.15 grams per cubic centimeter if the water in the channel were just deep enough to cover the grains. The effect of the overlying column of water in the channel, however, is much more important than the slight increase in density just
mentioned. The weight of this water must now be supported by these grains. A column of water 2.15 times as high as the diameter of the grain below it would double the effective density of that grain. Hence, in water about 0.4 foot deep, as was the case in some of these experiments, the effective density of a 0.5 mm sand grain lying within the mud seal would be about 300 grains per cubic centimeter, once the sediment beneath the grain had become unsaturated. In a given depth of water, the increase in effective density of a sediment particle is dependent on its diameter. Calculations in figure 15 show that even through the hydrostatic pressure is essentially uniform on the mud seal surface, the increase in effective density is inversely proportional to grain diameter. The theoretical relationship of water depth to effective grain density for various sizes of sediment within the mud seal is shown in figure 16.

The net effect of the mud seal in these experiments was to increase the compressive strength of the channel bottom and to eliminate erosion of bottom sediment. The fact that the seal can form while bedload transport is taking place is important in that it allows the seal to heal itself if it is broken by overriding sediment or debris. The possible importance of the mud seal in natural streams will be discussed later.

**Fluvial Trench Experiments**

Seepage failed to cause measurable changes in the water surface slope of channels up to 2-feet wide in the fluvial trough. The slope of the water surface was inversely proportional to discharge in all runs, as was expected. No bedforms except occasional, short-lived
volume of water column = 98 cm \times 2 \text{ cm} \times 2 \text{ cm} = 392 \text{ cc}

volume of water column = 99 \text{ cm} \times 1 \text{ cm} \times 1 \text{ cm} = 99 \text{ cc}

\[ \rho = 1 \text{ g/cc} \]

\[ \rho = 2 \text{ g/cc} \]

\[ \text{cube 1} \]

Total effective weight of cube 1

\[
\begin{align*}
392 \text{ g} & \quad \text{water column} \\
16 \text{ g} & \quad \text{cube} \\
408 \text{ g} & \quad \text{total}
\end{align*}
\]

Effective density of cube 1

\[
\frac{408 \text{ g}}{8 \text{ cc}} = 51 \text{ g/cc}
\]

\[ \rho = 2 \text{ g/cc} \]

\[ \text{cube 2} \]

Total effective weight of cube 2

\[
\begin{align*}
99 \text{ g} & \quad \text{water column} \\
2 \text{ g} & \quad \text{cube} \\
101 \text{ g} & \quad \text{total}
\end{align*}
\]

Effective density of cube 2

\[
\frac{101 \text{ g}}{1 \text{ cc}} = 101 \text{ g/cc}
\]

Figure 15.--Relationship of grain size to effective density of grains within a mud seal.
Figure 16.--Relationship of water depth to effective grain density of various sizes of grains in a mud seal.
standing waves were present during these runs due to the coarseness and poor sorting of the pearly sand. Any changes in resistance of the channel bed which were caused by seepage should have been reflected in a change in slope of the water surface. If there was any effect of seepage on the channel resistance, it was too slight to be observed or measured with the point gage used in these experiments. The smallest increment of slope that could be measured with the point gage is equivalent to about 1 1/2 feet per mile.

With the negative seepage used in these experiments (hydraulic seepage gradient as low as about -1.5), spectacular effects could not be expected. With the positive seepage, however, (hydraulic seepage gradient up to +4.65) the credibility of the sediment should have been greatly increased. This should have been accompanied by a corresponding decrease in flow resistance and water surface slope. Such was not the case, however. At this time, the only explanation for the lack of noticeable effects of positive seepage is the possible decrease in surface drag on the individual sediment grains as a result of upward seepage. This was discussed in detail earlier, with regard to the flume experiments.

Experiments using pearly sand yielded no definite relationship between channel path and seepage. Even in the runs without seepage, all three types of channel path occurred. The factors controlling channel path are still not known.

The slope of the channel banks in these small experimental streams varied inversely with seepage. Denou (1958, p. 83) and Simons and Richardson (1966, p. 16) described the effects of seepage on bank stability, but no mention was made of its effect on the
inclination of the banks. Although it seems logical that upward
seepage should decrease bank stability and steepness, as was found
in these experiments, extension of these finds to such larger
channels is probably not justifiable because the relative importance
of surface tension would change drastically with increase in bank
height.

Runs in the fluvial trough in which well-sorted coarse sand
was used resulted in the development of low-regime bedforms such as
ripples and dunes. The sides of the trough acted as rigid channel
boundaries so that the channel in these runs was 3½ feet wide.

Negative seepage increased the stability of the sand grains,
which resulted in an increase in the angle of repose on the lee face
of the bedforms. The steepening of the angle of repose resulted
in increased turbulence, greater bedform relief, and greater bed
roughness. Despite the increase in flow resistance, as indicated
by an increase in the values of relative roughness and Manning n
with negative seepage, the slope of the water surface did not appear
to differ significantly from that of equivalent-discharge runs having
no seepage or positive seepage. Thus, either the changes in water
surface slope caused by seepage (−1.1 to +0.5) were too small to be
detected with the point gage used in these experiments, or the
changes in flow resistance brought about by bedform roughness were
compensated for by other unrecognized factors.
CONCLUSIONS

Even though upward seepage is capable of reducing the effective density of sediment grains on a stream bed, it appears to have little effect on stream competence or threshold velocity. The fact that effectively lighter grains do not appear to be moved more readily than effectively heavier grains suggests that the decrease in effective density is in part compensated for by a decrease in surface drag and an increase in form drag on individual grains as a result of upward seepage. In order for this compensation to be effective, it is necessary to assume that surface drag is relatively more important than form drag in resisting stress on the sediment grains under the flow conditions found in these experiments.

At its maximum limit (quick condition), upward seepage also appears to be ineffective in promoting bedload transport. However, it was difficult to measure transport associated with a quick condition because of the localized, non-migrating nature of the quick areas. The fact that quick areas in natural streams are also localized would tend to minimize any effects they might have on natural channels.

Downward seepage under conditions where the sediment beneath the stream bed is saturated produces little change in stream characteristics other than to increase the angle of repose on bedforms and slightly increase bottom roughness. These changes do not appear to cause significant changes in the slope or overall regime of stream channels, however.
Downward seepage in the presence of sufficient suspended sediment leads to development of a mud seal on the bottom of the channel and unsaturated conditions in the underlying sediment. This can lead to an increase in the effective density of grains on the channel bottom by several hundred times. A sharp decrease in erodibility and an increase in compressive strength of the channel bottom results. In the case of the spring-fed stream studied by Clayton and others (1966), which was discussed earlier, the anomalous transport conditions observed there were undoubtedly caused by the presence of a mud seal in the nontransporting reach of the stream rather than the effect of upward seepage in the transporting part of the stream as was originally suggested.

Seepage, along with the type of sediment, probably control bank failure in natural channels. In relatively cohesive sediment, positive seepage during drawdown is the primary cause of bank collapse after floods. Similarly, positive seepage is probably also important in preventing sloughing of blocks of cohesive sediment at the base of the headcuts in ephemeral streams such as arroyos (Leopold, 1965, p. 446 and Hamilton, 1967, p. 70).

The loss of water due to negative seepage in non-turbid streams is sometimes sufficient in quantity to cause deposition of all or part of the sediment. This has recently been recognized in streams on alluvial fans in California and is called sieve-lobes deposition (Heege, 1967, p. 441). Individual sieve lobes commonly have a slope of 20 degrees or greater and are frequently misidentified as midflow levees. The deposition in the sieve lobes, however, is due primarily to the loss of water from the channel rather than to the direct effects
of negative seepage on the effective density of the sediment.

Negative seepage in fine-grained cohesive sediment may result in a mud seal in the channel area above the headcuts in conveyors and thus inhibit erosion there. Mud-seal conditions might also be expected in streams on alluvial fans, in oxbow streams, and in irrigation canals. The only prerequisite for negative seepage through the channel bottom and sufficient suspended sediment to form the seal.

However, the lower limit of permeability required in order for a mud seal to develop is not known. On the basis of this study it can not be concluded for certain that a mud seal can develop on fine-grained sediments typical of some ephemeral stream channels in semiarid areas. It has been reported (Ball, 1965, p. 106) that the water in conveyors on some fine-grained alluvial fans does not penetrate below the root zone. Whether or not this lack of penetration is caused by a mud seal on the surface of the sediment or by the low permeability of the sediment as a whole is not presently known. Field investigations of the possible occurrence of mud seals in natural stream channels might shed considerable light on stream erosion processes and erosion cycles, especially in semiarid regions.

The influence of seepage on bank stability and floodplain formation could not be thoroughly investigated in this study because this aspect of seepage does not readily lend itself to small-scale laboratory investigations. Future field studies of bank erosion and floodplain formation should consider the possibility that seepage may be an important factor in these processes.
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