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The clogging of coarse gravel river beds by fine sediment

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Key words: clogging, siltation, flushing flows, hydraulic conductivity, infiltration, river bed

Abstract

Laboratory investigations were carried out to examine the clogging process in coarse gravel river beds. Field samples taken from the Langeten river in Switzerland show that the intruded fine particles of the flow are deposited in the top layer of the river bed. For lower discharges the decrease of the hydraulic conductivity depends mainly on the dimensionless shear stress of the flow, the concentration of the suspended load, the hydraulic gradient between river and groundwater and the grain-size distribution of the river bed. However, when the armour layer breaks up during high discharges and the whole river bed is mobilized, the deposited fines are flushed downstream and a new layer with an initial maximum hydraulic conductivity is formed. The relationship between the dimensionless shear stress and the hydraulic conductivity is discussed. Changes in the nature of the catchment area or in the river itself which can accelerate the clogging process in the affected river are also discussed.

Introduction

The river bed forms the boundary between the river and the substrate. On the one hand it is the habitat for invertebrates and enables the reproduction and development of various fish species. On the other hand the river bed is the filter-layer influencing the exchange between river water and groundwater. Depending on the variable characteristics of the flow and the filter layer, the composition of the river bed and thus the hydraulics of seepage change with time.

For a given river bed, the following independent variables can have a dominant influence on the clogging process (compare Geldner, 1982; Beyer & Banscher, 1975):

Physical variables

- the flow conditions in the river, which can be represented by the dimensionless shear stress
- the suspended load
- the grain-size distribution and shape of the suspended particles
- the hydraulic gradient of the seepage flow and its direction

Biological variables

- the variety (of invertebrates, redds, algae) and their commonness
- the extent of eutrophy of the water

Chemical variables

- type and quantity of dissolved matter

In this paper only the influence of the physical variables are examined. The investigation reported considers rivers with high turbulent flow, coarse bed material and water with a comparatively low level of pollution.

The clogging processes in river beds have been described in several publications (Beyer & Banscher, 1975; Beschta & Jackson, 1979; Cunningham *et al.*, 1987; Diplas & Parker, 1991). The flow of each river contains a variable amount of suspended fine particles. In response to interaction between the turbulence of the channel flow, the settling properties of the suspended particles and the seepage rate, a certain amount of the fine particles intrude into the river bed. As a result of different processes these fines are deposited on the river bed or are incorporated into its top layer so that the pore space is reduced, i.e. the river bed is progressively clogged. The characteristics of such clogged river beds are: (a) a dense positioning and a compact texture (low porosity), (b) comparatively high resistance against increasing discharges, and (c) reduced hydraulic conductivity. Under natural conditions this clogged layer can break up during high flood events, so that the deposited fine particles are resuspended and flushed downstream.

The aims of the presented research reported here were: (a) to examine the texture of a river bed by testing different sampling techniques in the field; (b) to observe and measure the clogging and flushing processes in the laboratory; and (c) to describe the function between the hydraulic conductivity and the dominant physical variables using mathematical formulae.

Field investigation

Two different sampling techniques were applied to remove several layers of the river bed. The first used a 0.5 × 0.5 m steel frame which is knocked step by step into the bed at an unsubmerged site. The coarse material of the bed requires that the frame is exposed all the way around, so that big stones immediately underneath the frame can be taken away from the outside. The advantage of this method is the high quality of the samples. On the other hand, if samples have to be taken at a submerged site this can only be achieved with difficulty because the flow winnows the fines as samples are withdrawn. The second method was based on collection of frozen core samples by using liquid nitrogen (modified from Ryan (1970) and Bretschko & Klemens (1986)). One or several connected tubes are knocked about 0.4 m into the bed and filled several times with liquid nitrogen (Fig. 1). After a few minutes the frozen core can be pulled out. With this method, two different points need special attention: (a) the lower part of the tube should be grooved (no holes) so that there is a reliable connection with the surrounding material; (b) according to the roughness of the river bed several attempts may be required before a site is found where the tube can be inserted to the desired depth.

Figure 2 shows the result of size analysis of layers collected by the steel frame method. A total of 6 layers were analyzed to a depth of 0.45 m.

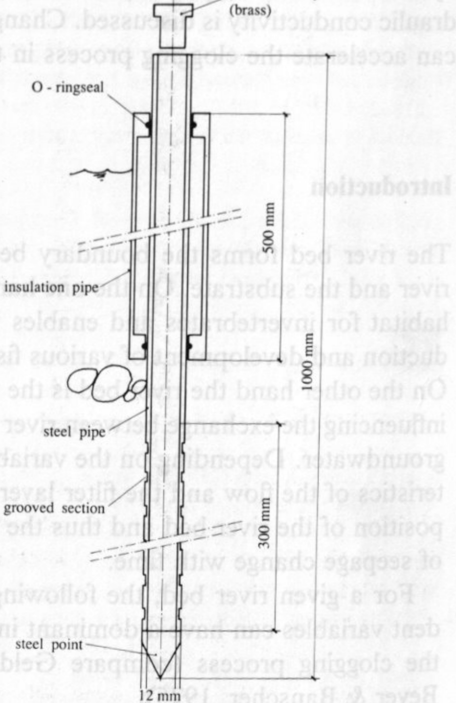

Fig. 1. Single probe freeze core sampler used to collect substrate samples in gravel bed streams.

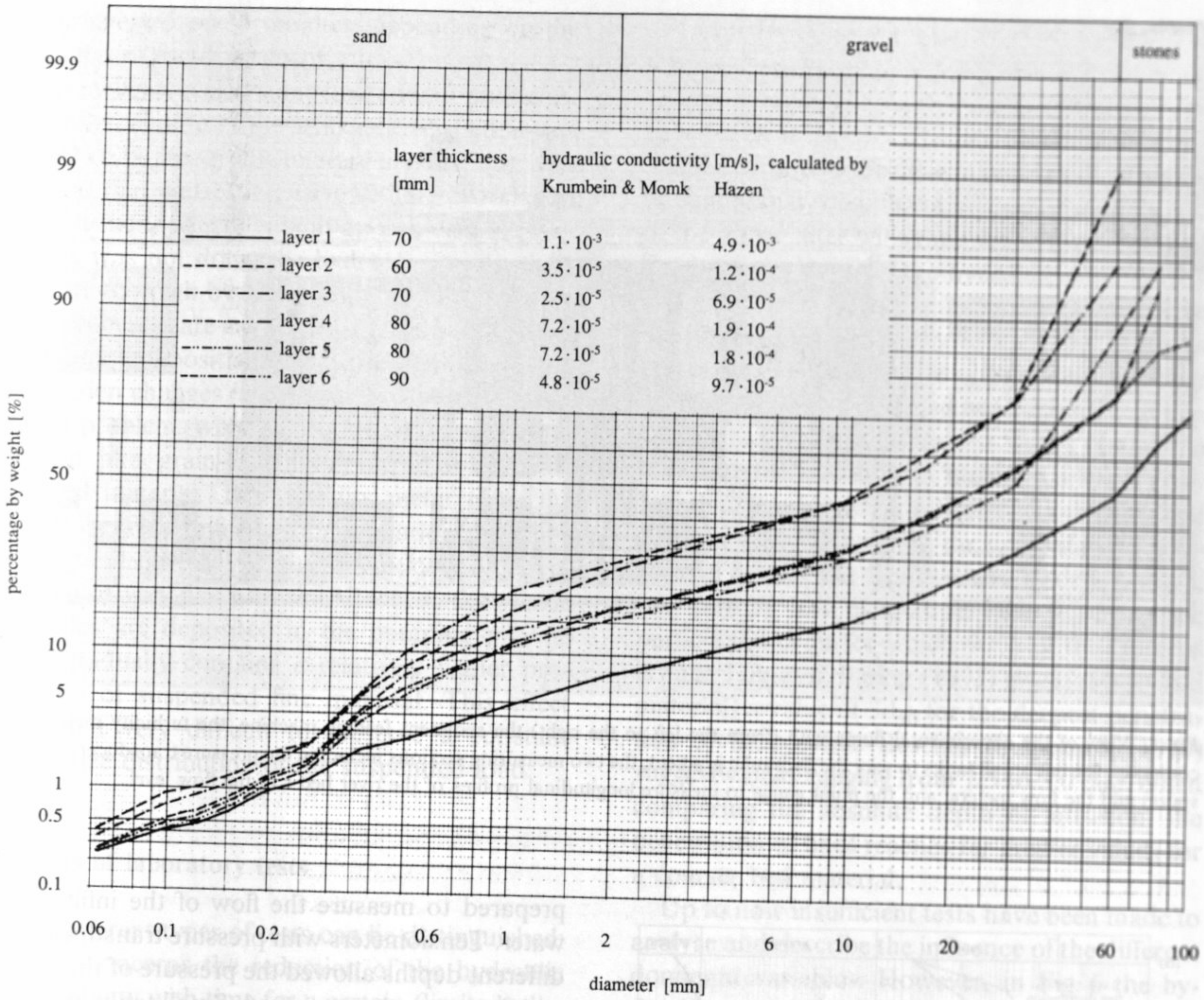

Fig. 2. Grain-size distributions of different layers from samples taken at the Langeten stream. Also given are the corresponding hydraulic conductivities calculated by the methods of two different authors.

The coarse armour overlies two layers with visibly finer material, whereas layers 4 to 6 show a rather constant average grain size distribution. Other samples taken from different sites show almost identical grain size distributions under the armour layer. From this it can be concluded: (a) that in a natural river there are sections where the top layer includes finer particles (i.e. the pore space and the hydraulic conductivity are reduced), and (b) that the intrusion of fine particles does not extend below a certain depth.

Laboratory investigation

Laboratory tests were carried out in a 8 m long and 0.5 m wide flume, to assess the influence of the dominant physical variables on the clogging process (Fig. 3). The river bed material and the suspended matter used in the model were taken directly from the river Rhine upstream of the Bodensee (see grain-size distributions Fig. 4). A reduction in the required flow-depth was achieved by increasing the slope by a factor of 10. Thus the velocity and the shear stresses near the bed are

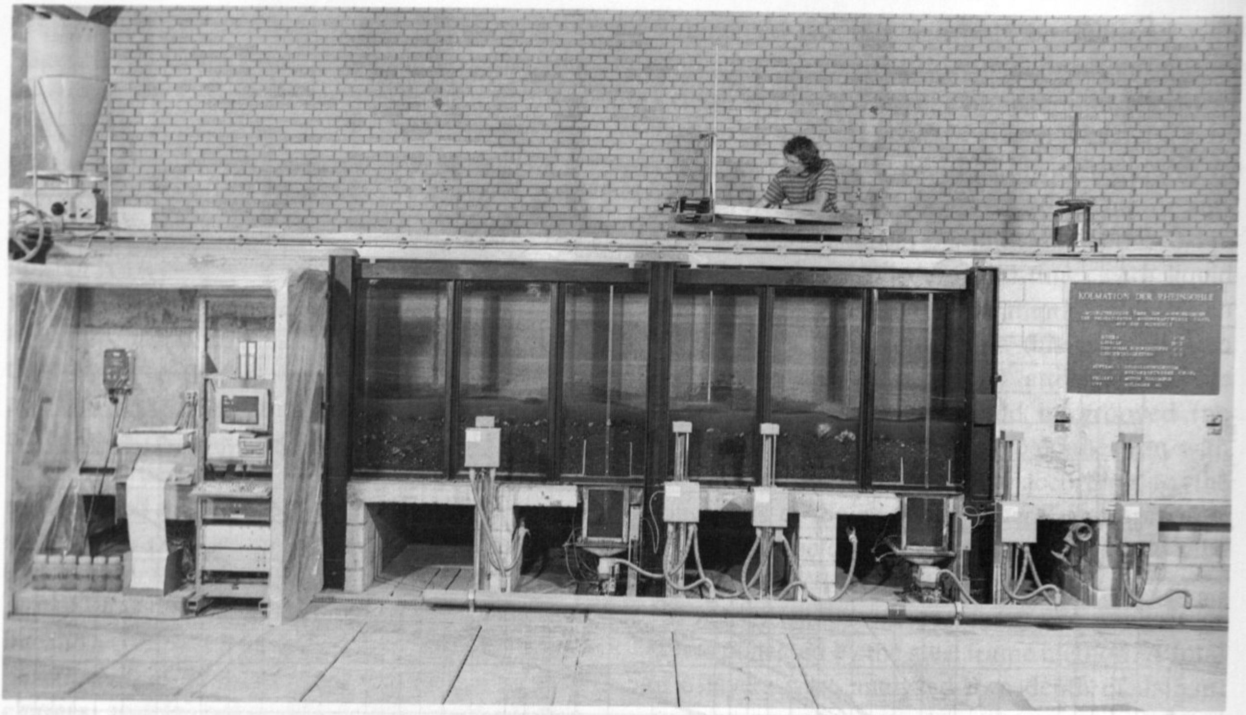

Fig. 3. View of the experimental flume with (from the left to the right) the sediment feeding machine, the turbidity meter, the computer, the fine small tanks to vary the hydraulic gradient, the two measuring sections including the pressure transducers (white spots) and the flow meters, and the point gauge to measure longitudinal profiles of the river bed r of the flow level.

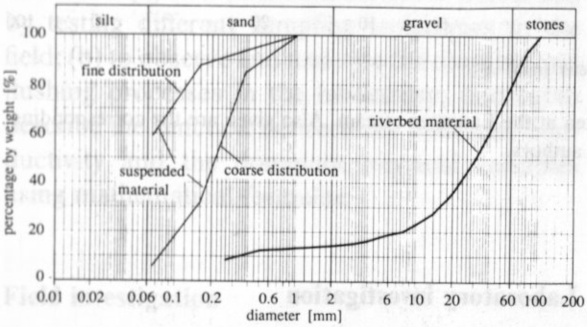

Fig. 4. Grain-size distributions of the river bed and of the suspended load.

about the same as in nature (scale 1:1). The velocity of the infiltrating water is dependent on the hydraulic gradient which could be adjusted to a desired value (see below). The transport of the fines over or into the river bed together with the clogging process are therefore reproduced.

Two sections in the flume (0.3 m × 0.5 m) were prepared to measure the flow of the infiltrating water. Tensiometers with pressure transducers at different depths allowed the pressure of the interstitial water to be measured. Small tanks with an overflow section represent the groundwater level and make it possible to vary the hydraulic gradient. At the upper end of the model a turbidity meter measured the concentration of the suspended load. If the given value was too low, a computer gave the sediment feeding machine a signal to add some more fines to the flow. Additionally from time to time samples of the suspended load were taken by hand (filling a bottle with the flowing water in the model, filtering and drying the ingredients) to determine the proportion of fines smaller than 0.063 mm, i.e. of the cohesive material. Since the deposition and intrusion of the suspended particles and the clogging of the top filter layer are processes which can taken several weeks or even months, all the data were logged on a computer. Measurements were taken every 5 or 30 minutes, depending on the duration of the experiment.

The tests revealed some operational problems. After installation of the artificial river bed, it was found to be important to start the first test with a flood that causes intensive sediment transport so that the top layer is built up in a natural way. If this was not done, the hydraulic conductivity may be too high by a factor of 100 and the clogging processes are not reproduced correctly, since the unnatural positioning of the particles can lead to sudden changes in the texture of the top layer. Other problems were associated with the concentration and grain-size distribution of the suspended material. The turbidity meter gives the same signal for a higher concentration of coarse suspended particles as that for a lower concentration of very fine particles. Because the coarse particles are deposited in the pumping pit, the flow gradually contains a relatively higher proportion of suspended fine material. This effect makes it very difficult to preserve a constant grain-size distribution of the suspended load.

Results of laboratory tests

Two different types of tests can be distinguished: Type 1 concerns the reduction of the hydraulic conductivity with time for a certain (limited) discharge, suspended load and hydraulic gradient, whereas Type 2 concerns the changes of hydraulic conductivity for an initially clogged river bed with increasing discharges (flood flows).

The hydraulic conductivity K was calculated using Darcy's law

$$K = v/i \tag{1}$$

which is valid for laminar flow conditions and a saturated river bed. For Eqn. 1 the seepage rate v is calculated from the measured seepage flow divided by the area of the infiltration section. The hydraulic gradient i_j of a specific layer j is calculated from the (measured) pressures of the interstitial water at consecutive depths h_j and h_{j+1}, and the thickness of the layer z_j:

$$i_j = [h_j + z_j - h_{j+1}]/z_j$$

Type 1 tests

Figure 5 shows the development of the hydraulic conductivity of different consecutive layers and of the entire filter with time for a Type 1 test. It can be seen that only the hydraulic conductivity of the top layer (thickness 0.15 m) decreases while the hydraulic conductivity of the other layers is more or less constant. The hydraulic conductivity of the entire filter, obtained by combining all layers, decreases slowly. This test shows that all the fines that intruded into the river bed are held back and deposited in the top layer. The thickness of this top layer depends on the grain-size distributions of the river bed and the suspended material, but may be less than 2d$_{90}$, with d$_{90}$ being the particle diameter for which 90% of the material is finer. Diplas & Parker (1991) give (for finer bed material) a value of 3d$_{90}$ for the deepest penetration of fines, while Beschta & Jackson (1979) suggest values ranging from 2.5 to 5.0 d$_{90}$. When comparing the absolute depth of intrusion, the penetration of fines reaches far greater values for a coarser bed material.

Up to now insufficient tests have been made to analyse and describe the influence of the different dominant variables. However, in Fig. 6 the hydraulic conductivity of the top layers of 5 differ-

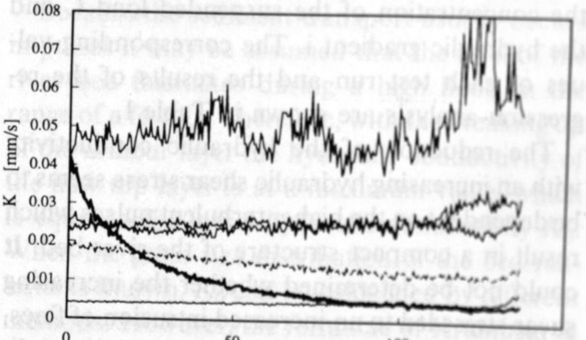

Fig. 5. Example of the changing hydraulic conductivity (K) of the top layer, of the 4 sub-layers and of the entire filter (river bed) with time (t).

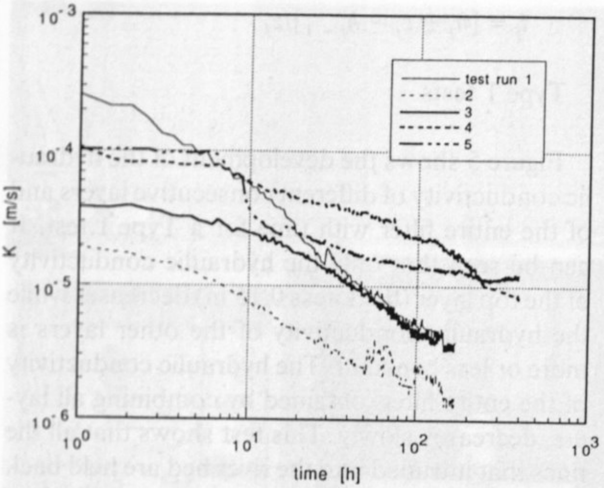

Fig. 6. Relationship between the hydraulic conductivity (K) and time (t) for five different type 1 tests.

Table 1. Gradient G, concentration of the suspended load C, dimensionless shear stress Θ and D_{10} representing the diameter where 10% by weight are smaller or equal than this value. The last three lines give the results of the regression analysis where $-\alpha$ represents the slope of the regression line, K_i the point of intersection with the K-axis and R^2 the correlation.

Variable		Test run				
		1	2	3	4	5
G	[-]	0.43	0.57	0.41	0.22	0.26
C	[mg/l]	354	354	840	120	120
Θ	[-]	0.075	0.017	0.033	0.014	0.010
D_{10}	[mm]	0.34	0.34			
α	[-]	0.935	0.605	0.797	0.566	0.328
K_i	[mm/s]	0.393	0.028	0.187	0.269	0.070
R^2	[-]	0.989	0.962	0.985	0.923	0.830

ent tests are shown in log K – log t diagram. Ten hours after starting the experiment the different tests can each be represented by a straight line. This means that the relationship between the time t and the hydraulic conductivity K follows the power-function of the form:

$$K = K_0\, t^{-\alpha}$$

where K_0 is the initial (maximum) hydraulic conductivity and α is the clogging exponent. This relationship corresponds with the observations of Banscher (1976). α depends on certain parameters of the test run, especially the dimensionless shear stress Θ (identical with the Shields factor), the concentration of the suspended load C and the hydraulic gradient i. The corresponding values of each test run and the results of the regression-analysis are shown in Table 1.

The reduction of the hydraulic conductivity with an increasing hydraulic shear stress seems to be dependent on the higher turbulent pulses which result in a compact structure of the river bed. It could not be determined whether the increasing shear stress led to an increased intrusion of fines. Beschta & Jackson (1979) found for higher sediment inputs an increasing intrusion of sand, whereas Carling (1984) found no significant relationship between the shear stress and the deposition of fines. However, the boundary conditions of the experiments were different and this makes a comparison of the results difficult.

Type 2 tests

The changes in the hydraulic conductivity during a flood event are shown in Fig. 7 (Type 2 test). The bold and thin line represent the hydraulic conductivity of the top layer and the entire filter respectively, whereas the dotted line shows the dimensionless shear stress Θ. Above the diagram the levels of the bed and the flow surface are shown. It can be seen that for Θ less than or equal to 0.060 the hydraulic conductivity of the top layer does not change significantly. When Θ increases to 0.076, due to slight erosion of the bed, the hydraulic conductivity of the top layer increases suddenly. This erosion-process continues until Θ reaches 0.086 and the hydraulic conductivity still increases by at least a factor of 100. This increase in hydraulic conductivity is based on the breaking up and the erosion of the clogged armour layer. The intruded and deposited fine particles are resuspended and flushed downstream.

The results of 10 tests with high floods are shown in a logK/Θ diagram in Fig. 8. Again it can be seen that for small dimensionless shear stresses less than 0.060, the K values decrease or remain constant (clogging phase).

Over a certain range of discharges it was ob-

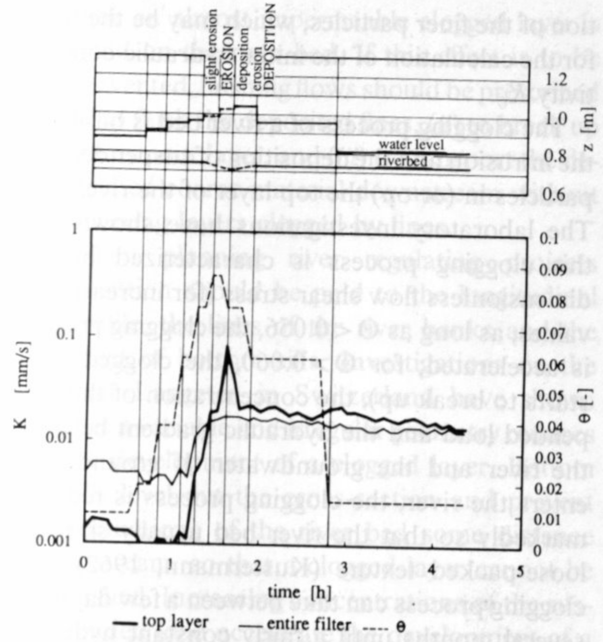

Fig. 7. Example of the changes of the hydraulic conductivity (K) of the top layer and the entire filter with increasing dimensionless shear stress (Θ).

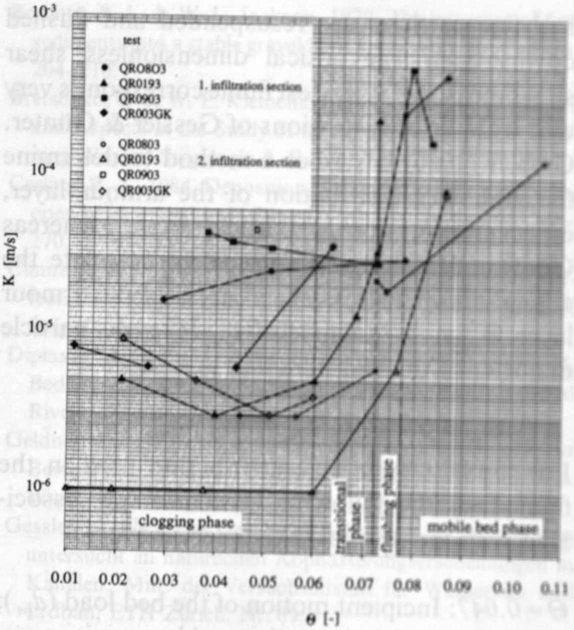

Fig. 8. Relationship between the hydraulic conductivity (K) and the increasing dimensionless shear stresses Θ for several type 2 tests.

served that depending on the local flow conditions (turbulence), three different processes are the main cause of an increase of the hydraulic conductivity of the top layer. These are:

(a) gravel transport can affect the clogged surface of turbulence-protected areas. Once this surface is broken the deposited fine particles at this spot are flushed away rapidly.
(b) because of the increasing shear stress the deposited fine particles in openings and gaps between the larger components of the armour layer are flushed away.
(c) the base of the stabilizing larger components of the bed is partly washed away while the armour layer is still stable. Due to this, the clogged layer erodes beside and underneath these stones.

These processes occur between the clogging phase and the flushing phase and thus can be called the transitional phase; they occur in a range $0.060 < \Theta < 0.072$. The observed increase in the hydraulic conductivity is dependent on the initial hydraulic conductivity at the beginning of the test run (Fig. 8). For lower initial K values these transitional processes have a greater influence than for higher initial K values.

When the discharge reaches the critical value of stability of the river bed, the armour layer breaks up and the intruded fines are flushed downstream (flushing phase). For even higher discharges the whole bed is mobilized (mobile bed phase).

Because the sediment transport usually occurs in pulses it may be assumed that the level of the river bed fluctuates during a high flood in the range of a few d_m. Therefore, with the breaking up of the armour layer the hydraulic conductivity of the new top layer is at a maximum value, which is equal to the initial hydraulic conductivity K_0. When the grain-size distribution of the bed material is known, K_0 can be calculated by different methods. However, the formulae of Krumbein & Momk (Krumbein & Sloss, 1951) and Hazen (1892) respectively give values that are too low. Further investigations should lead to better predictive equations.

As already described, the intruded and deposited fine particles are resuspended and flushed downstream. The critical dimensionless shear stress measured in the test flume corresponds very well with the investigations of Gessler & Günter. Gessler (1965) describes a method to determine the grain-size distribution of the armour layer, especially of its average particle size d_{A_m}, whereas Günter (1971) gives a formula to calculate the critical dimensionless shear stress of the armour layer Θ_A as a function of d_m (average particle diameter of the bed material) and d_{A_m}:

$$\Theta_A = 0.047(d_m/d_{A_m})^{2/3}$$

For the first grain-size distribution used in the flume-tests the following Q-values were associated with the processes outlined above:

$\Theta = 0.047$: Incipient motion of the bed load (d_m); the armour layer remains stable.

$\Theta < 0.056$: Clogging phase: Further reduction of the hydraulic conductivity.

$0.060 < \Theta < 0.072$: Transitional phase: The hydraulic conductivity of the top layer increases by a factor of 10.

$0.072 < \Theta_A < 0.078$: Flushing phase: Break-up of the armour layer. Increase of the hydraulic conductivity to maximum value K_0. The method of Gessler & Günter gives a value of $\Theta_A = 0.074$.

$\Theta > 0.0775$: Mobile bed phase: The whole river bed is mobilized. Dependant on fluctuations of the river bed, the hydraulic conductivity remains at the maximal value (further slow erosion) or starts to decrease (stable bed level or deposits).

Conclusions

The investigations so far have focussed on the natural phenomena concerning the clogging process of the river bed and the effect of large floods. By taking samples of the river bed, the clogging layer could be identified; it was observed that this layer with a higher proportion of fines is limited to a relatively thin zone. Samples of the river bed are important for an accurate determination of the grain-size distribution, especially of the portion of the finer particles, which may be the basis for the calculation of the initial hydraulic conductivity K_0.

The clogging process of a river bed is based on the intrusion and the deposition of suspended fine particles in (or on) the top layer of the river bed. The laboratory investigations have shown that this clogging process is characterized by the dimensionless flow shear stress (for increasing Θ values, as long as $\Theta < 0.056$, the clogging process is accelerated; for $\Theta > 0.060$, the clogged layer starts to break up), the concentration of the suspended load and the hydraulic gradient between the river and the groundwater. If groundwater enters the river, the clogging process is reduced markedly so that the river bed usually shows a loose-packed texture (Kustermann, 1962). The clogging process can take between a few days and several months until a fairly constant hydraulic conductivity is reached. Only during a sufficiently large flood, when the dimensionless shear stress exceeds the critical value for the stability of the armour layer, is the clogged filter layer destroyed and a new filter with an initial hydraulic conductivity K_0 formed.

In regions where there is great economic interest in the groundwater table, river water often plays a dominant role in groundwater recharge. Artificial changes in the nature of the catchment area or in the river itself may affect the characteristics of the flow or sediment transport and thus the texture and the hydraulic conductivity of the river bed. This happens in particular in river-storage basins or downstream of a water diversion structure:

(a) When water is diverted, the existence of flushing flows should still be guaranteed (Reiser *et al.*, 1985). The minimum peak discharge of these flushing flows can be determined by calculating the critical dimensionless shear stress by Gessler & Günter. Additionally, the clogging process should not be accelerated by increasing the concentration of the suspended load.

(b) In river storage basins the flow velocity is markedly reduced so that the suspended particles are deposited in a graded manner. With time an almost impermeable clogged layer is build on the river bed. If this effect is to be prevented, flushing flows should be prescribed (*i*) to flush the deposited fines, (*ii*) to break up the armour layer, and (*iii*) to transport the deposited coarse material downstream without covering layers clogged by fines.

(c) When planning river regulating projects attention should be paid to the longitudinal profile, the lines of the river banks and the effect of bottom sills. Investigations on the river Langeten in Switzerland have shown that a variable and irregular geometry reduces the development of a clogged layer. Bottom sills level out the cross-section and prevent fluctuations of the river bed some distance upstream, so that a clogged layer cannot be flushed. Increasing concentrations of the suspended load accelerate the development of a clogged layer.

Further tests in the laboratory with different grain-size distributions of bed material and suspended fines should help in understanding the functional relationship between the independent variables, the texture and the hydraulic conductivity of the river bed.

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