SEDIMENT TRANSPORT CAPACITY OF PRESSURE FLOW AT BRIDGES

Martin N.R. Jaeggi

Consulting river engineer, Bergholzweg 22, 8123 Ebmatingen, Switzerland
phone +41 44 980 36 26, fax +41 44 980 36 30, e-mail: jaeggi@rivers.ch

ABSTRACT

Pressure flow may occur at bridges, because the bridge cannot be raised above a certain level or because during extreme floods design flood levels are exceeded. A calculation procedure is presented, to assess sediment transport capacity in the bridge section. As in open channel flow, grain friction slope has to be taken as the dominant parameter. A wall drag procedure must be used in the bridge section, in which friction of the ceiling is also considered. By varying the local bed level under the bridge the solution is found by iteration. If pressure flow is considered for a bridge, special attention has to be given to the problem of floating debris.

Keywords: Bridges, sediment transport, pressure flow

1 INTRODUCTION

From a flood protection point of view, the aim is generally to raise the bridges to such a level that the bridge structure will not interfere with flood flow. It is expected that a minimum vertical distance remains between the water level at design flood and the lowest part of the bridge structure. Very often, it is not possible to fulfil this condition, or it would be very inconvenient for the daily use of the bridge. Long ramps would be necessary, which especially for railway tracks is not acceptable or impossible. Noise impact is increased when the position of the road or the railway is high. Finally, when considering higher floods than the design flood, the vertical distance between water level and bridge is reduced and pressure flow may then occur anyway.

If the bridge is not designed for pressure flow, water may in such a case spill over the bridge and the banks. Often, bridges are the weakest points in a flood protection scheme and may trigger inundation. Floating debris gets stuck at the bridge structure and may increase the problem. If part of the flow is leaving the channel by overbank flow, then the sediment transport capacity of the bridge section is reduced. This may end up in a complete blocking of this section (Bezzola et al., 1994).

From a purely hydraulic point of view, pressure flow at a bridge is not a problem in itself. The contraction at the bridge section induces an additional, but not very important energy loss. Just upstream of the bridge, the water level may rise to the level of the energy line. The bridge structure, or eventually an apron at the upstream side, and the banks upstream of the bridge must be high enough to confine the flow. The widely used programme HECRAS includes a procedure to consider pressure flow at bridges.

The question arises how to assess sediment transport capacity of the bridge section in such conditions. In Modane (Savoie, France), after a devastating flood of the Charmaix torrent in 1957, a solution was developed by hydraulic model tests at the SOGREAH Laboratory in Grenoble (Lefebvre, 1993; see fig. 1), where pressure flow under the railway bridge is able to cope with high sediment loads. Generally speaking, mountain rivers and streams carry substantial sediment loads and if a bridge is pressurised, this should not lead to insufficient sediment transport capacity at the bridge section. Numerical models simulating sediment transport and river bed evolution may require a procedure to define sediment transport capacity at a bridge section in case of pressure flow.

Fig. 1: Bridge designed in model tests to allow pressure flow, in order to increase sediment transport capacity (Modane railway station, Savoie, France)

2 PROCESSES

Fig. 2a shows schematically a bridge as it may be introduced in a laboratory flume. The discharge is constant and the tailwater is high, so that pressure flow occurs,. The bridge section is large, thus the local velocity and the energy loss caused by the bridge are small. If now sediment is added at a given rate, deposition will occur and the level of the mobile bed will rise (Fig. 2b). The flow section under the bridge gets smaller and smaller. The velocity increases as well as the friction loss under the bridge. Thus, the water level upstream of the bridge rises. An equilibrium situation is obtained after a significant reduction of the flow section under the bridge, resulting in a high flow velocity which enables the remaining section to stay free (fig. 2c). If the apron is overspilled before equilibrium is obtained, then obviously the sediment load is higher than the sediment transport capacity of the bridge.

In this situation, the water level upstream of the bridge tends towards the energy level. It is therefore safe to assume in the design that the water level has reached this level, although in reality, it normally stays somewhat lower.

3 PRINCIPLES FOR CALCULATION

For open channel flow, sediment transport capacity is recognised to be a function of friction slope. In case of presence of bedforms, the bed roughness is generally separated in grain roughness and form roughness. Sediment transport capacity is assumed to be function of grain roughness only (e.g. Yalin, 1977).

In narrow laboratory flumes or rivers a wall drag procedure is normally applied. Einstein (1934, 1950) considered influence zones of the bed and the banks as a function of the velocity distribution. He assumed for the calculation that there is the same mean velocity in the partial sections as well as in the total section, and that friction along the separation lines has not to be considered. Then, he suggested that only the partial discharge flowing through the bed section is related to sediment transport capacity. The hydraulic radius of the bed section replaces the mean flow depth in the transport formula.

Therefore two parameters have to be determined:

- The grain friction slope
- The hydraulic radius of the bed section

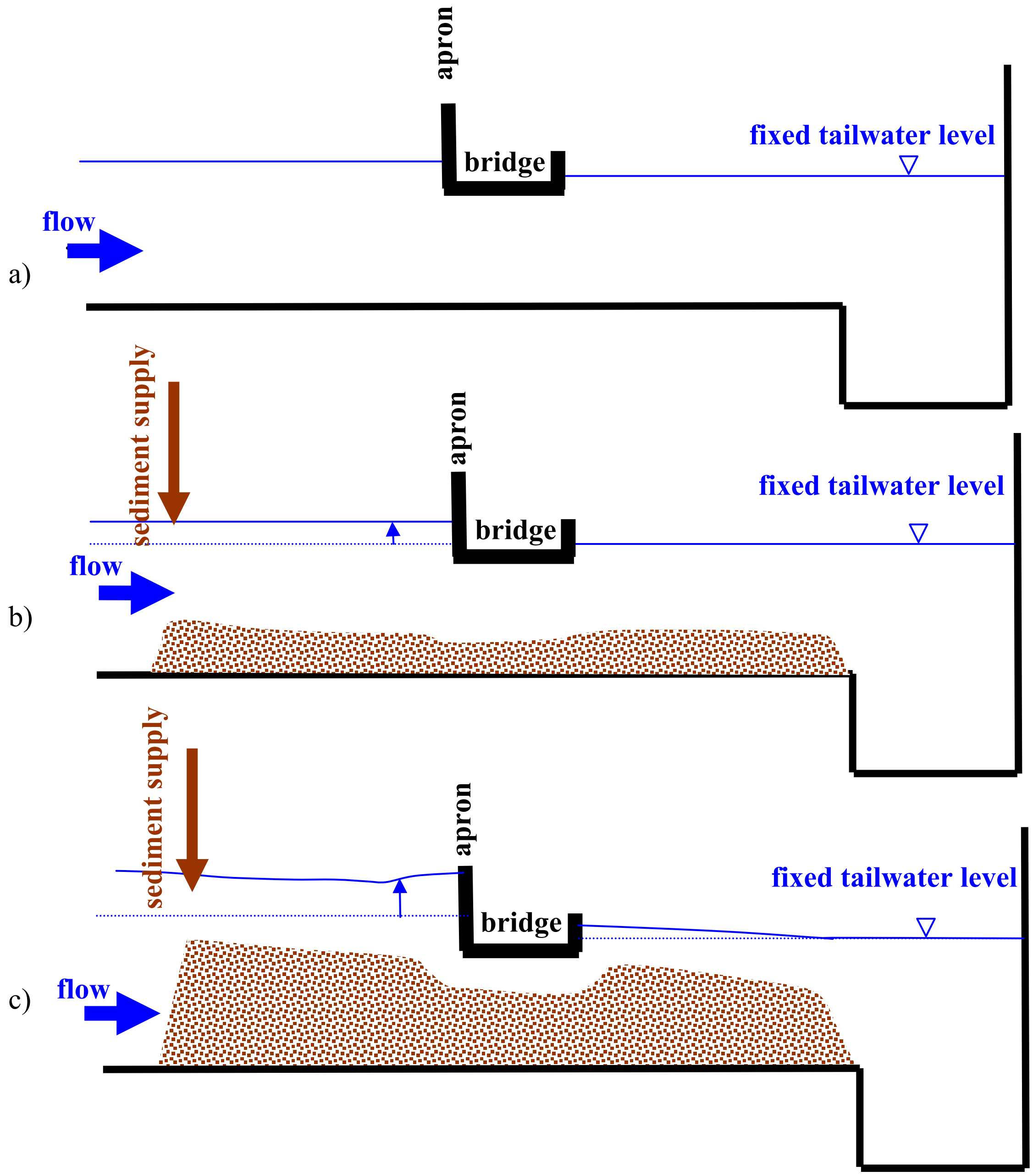

Fig. 2: Schematic representation of a laboratory experiment. The flow is pressurised by a high tailwater level (a). Sediment is added, a sediment bed forms and the headwater level is raised (b). An equilibrium situation is obtained where the headwater is raised furthermore. The flow rate and the sediment transport capacity under the bridge determine the remaining size of the flow section under the bridge (c)

4 CALCULATION PROCEDURE

The variables used in the procedures are defined in fig. 3 and 4. The discharge Q [m^3/s] and the sediment transport rate Q_B [kg/s] are given. In a design case, this rate may be calculated as the sediment transport capacity of the upstream reach. A numerical model would do the same for each time step. The energy slope J_f in the free surface flow reach and the sediment supply rate Q_B are thus interrelated.

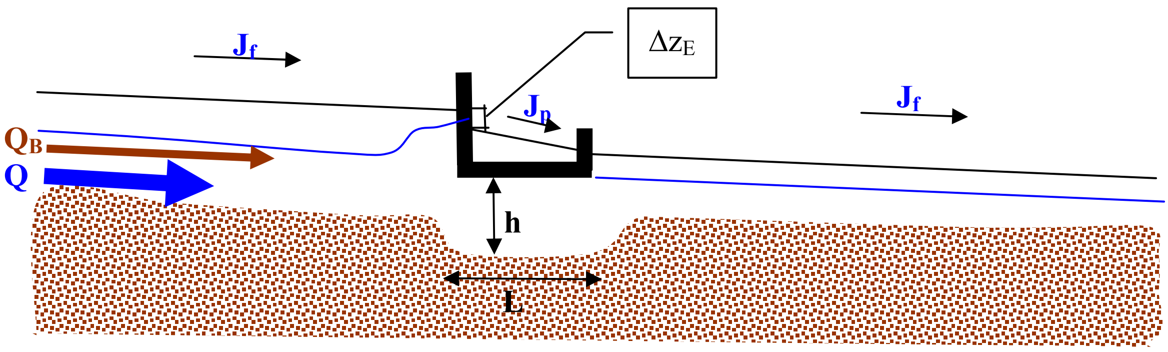

Fig. 3: Longitudinal section of a bridge with pressure flow. Bed profile, water level and energy line. Notations used in the equations

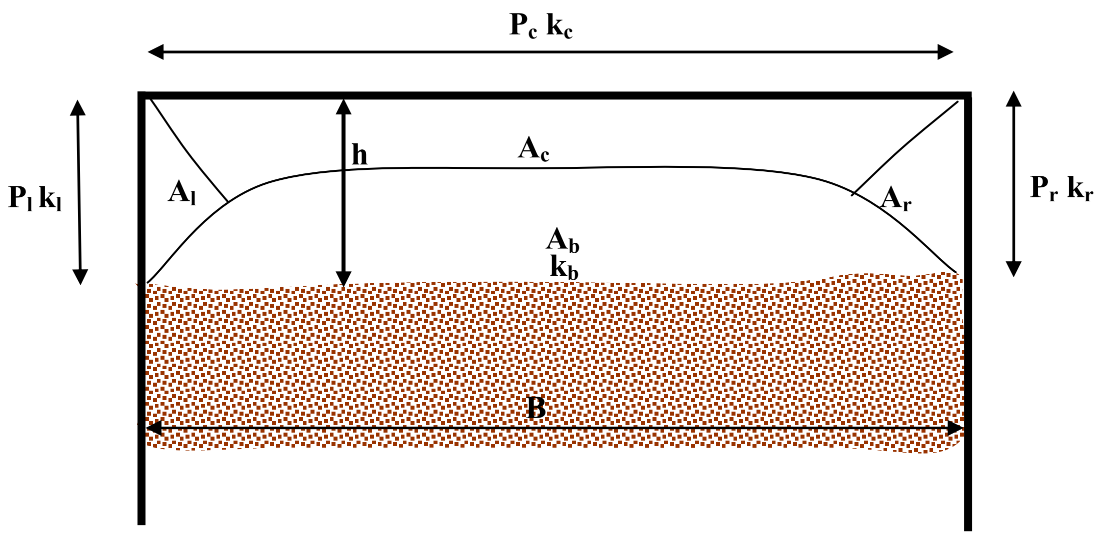

Fig. 4: Cross section of a bridge with pressure flow. Partial flow sections, according to Einstein's procedure. Notations used in the equations. A are section areas, P wetted perimeters, and k roughness coefficients according to Strickler (inverse values of Mannins n). The index b refers to the bed or bed section, the index c to the ceiling or the ceiling influence section. Similarly, the indices l and r refer to the left and the right wall

First, a bed level elevation below the bridge must be assumed. A mean bridge section with a height h and a width B is thus defined (fig. 4). Mean flow velocity v_m is then determined by dividing the discharge Q by the section area A. Roughness parameters for the boundaries must be defined. Applying Einstein's original procedure using the Manning Strickler law allows to calculate directly a mean roughness coefficient:

$$k_m = \frac{P^{2/3}}{\left[\frac{B}{k_b^{1.5}} + \frac{P_l}{k_l^{1.5}} + \frac{P_r}{k_r^{1.5}} + \frac{P_c}{k_c^{1.5}}\right]^{2/3}}$$

The grain friction slope J_p in the pressure zone under the bridge and the entry loss can now be calculated (the exit loss is neglected):

$$J_p = \frac{v_m^2}{k_m^2 R^{4/3}}$$, where $R = \frac{A_{tot}}{P_{tot}}$ is the hydraulic radius of the total section

The entry loss $\Delta z_E = \xi_E \frac{v_m^2}{2g}$ can be calculated from the mean velocity. The entry coefficient ξ_E can be taken as $0.1<\xi_E<0.15$

The total energy loss of the bridge is

$$\Delta H_E = \Delta z_E + LJ_P$$

The hydraulic radius of the bed section is, according to Einstein's procedure:

$$R_b = \left(\frac{v_m}{k_b \sqrt{J_p}} \right)^{1.5}$$

The sediment transport capacity can now be computed, using an appropriate formula. The grain friction slope J_p and the reduced flow Q_r (or the parameter R_b) must be used. Q_r and R_b are interrelated: $Q_r = R_b\, B\, v_m$.

Since the flow depth under the bridge h has been chosen arbitrarily, the transport rates computed from either the upstream slope J_f or the grain friction slope under the bridge J_p will not be the same. By iteration, h has to be varied until the two transport rates are identical.

If the transport rate in the upstream reach has been determined from the free surface slope J_f, the grain roughness slope J_p under the bridge, which is necessary to transport that given rate, can also be derived using a transport formula. If, for instance, the Meyer-Peter/Mueller equation in the form modified by Hunziker (1995) is used, then

$$J_p = \frac{0.05(s-1)d_m + \left[\frac{Q_B (s-1)}{5B\rho_s \sqrt{g}} \right]^{0.667}}{R_b}$$

d_m is the mean grain size of the sediment mixture, ρ_s the density of the sediment, s the relative density of sediment to water and g the gravitational constant. Again, for the first iteration step different values will be obtained for this grain roughness slope, from the hydraulic calculation on one side and the transport calculation on the other side. Varying the elevation of the bed level under the bridge or the parameter h is again necessary to accomplish the calculation procedure.

5 DISCUSSION

Because of higher boundary friction than in open channel flow, the ratio Q_r/Q will be noticeably smaller for pressure flow. This will be compensated by a value of J_p higher than the energy slope in the river reach upstream of the bridge. Typical values of Q_r/Q_B will be in the order of 0.15 to 0.4 and J_p/J_f may take values of 2 – 2.5.The apron of the bridge must be in any case high enough, in order to cope with the total loss.

Einstein's procedure is based on the assumption that the same mean velocity exists in the partial section and in the full section. If a more refined velocity distribution model would be applied, the reduced flow of the bed section may be somewhat higher. The calculation is therefore on the safe side.

The same procedure may also be applied to galleries, for instance in case of flood bypasses.

6 FLOATING DEBRIS

Floating debris is usually considered to be a major hazard at bridge crossings. It is therefore very important, that for these pressurised bridges a solution must also be found with respect to floating debris. Smooth and rounded surfaces have to be chosen for the apron and generally speaking for the entry section. Tree trunks and other debris can then not be tangled into the bridge structure. As soon as part of the debris protrudes into the flow section under the bridge, the hydrodynamic force on the element will be extremely important. When this element is not stuck in the bridge structure, then it will be sucked through the bridge section by the flow. If it gets stuck in the mobile bed, this can lead to a temporary partial obstruction of the flow section. This will lead to higher local velocities and thus to an increase of the pressure head. Scouring will then occur, which will liberate the stuck element. Again, this needs a sufficiently high apron.

There is no 100% guarantee that those processes will work in any case. Safety can be improved if engines are placed on the bridge in case of flood events, which will then dump the floating debris and help them to cross the bridge section. Eventually, special detention structures have to be planned upstream, to hold back the floating debris and so to reduce the risk at the bridge.

7 THE GAMSA CROSSING

Figures 5 and 6 show the crossing of the Gamsa river by the Simplon railway near Brig (Canton of Valais, Switzerland), for which the presented calculation procedure has been applied. Just downstream of the bridge the Gamsa flows into the Rhone river. High flood levels have to be expected there, compared to the elevation of the railway track. To design the bridge for pressure flow was the only solution. The apron is about 1.5 m higher than the level of the railway track, which gives a sufficient head. If a hundred year flood occurs in both rivers, there is still a 40 cm margin at the top of the apron. The grain roughness slope is then about double the slope of the upstream reach and the entry loss is estimated to be about 50 cm.

Figure 6 illustrates the good performance of the bridge during the first floods. A high flood level in the Rhone has caused a bar to form at the confluence. During receding flow in the Rhone the tributary has cut a channel through the bar.

8 CONCLUSIONS

In case of pressure flow under bridges, sediment transport capacity in the bridge section depends on the drag exerted by the walls and the ceiling and the local grain roughness slope, which depends on the local bed elevation. Designing the entry section with a sufficiently high apron allows compensating for the loss in sediment transport capacity resulting from higher wall drag in the bridge section compared to the open channel flow reaches. A smooth and rounded entry section with also reduce the risk of clogging by floating debris.

Fig. 5: Bridge with apron allowing pressure flow to cope with high tailwater levels. Crossing of the Simplon railway line over the Gamsa river, near Brig (upstream view)

Fig. 6: Bridge of fig. 5, downstream view. The bar and the incised channel document the tailwater variations and the response of the bed level

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