Inundated Flood Planes and the Flow over Groynes and Oblique Weirs

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Abstract

At high water stages the flow in groyne fields is highly affected by the water flowing over the groyne. For those conditions the groyne acts as an (im)perfect weir. In a similar way local elevations in the flood planes can be considered as weirs. The arbitrary orientation of those obstacles with respect to the flow prohibits the use of straightforward weir formulations. By considering the generic case of the flow over oblique weirs, a simple analytical approach already gives good insight and acceptable estimates, whereas a 3D numerical model clearly shows the complexities of flow separation and non-hydrostatic effects.

1. Introduction

The winter-bed of many lowland rivers contains a variety of obstacles that affect the flow and its conveyance capacity. Training works such as groynes and summer embankments are build for the purpose of guiding the water at low and moderately high stages. Groynes are constructed in order to stabilize the river banks and to keep the main channel navigable. Summer embankments prevent the flooding of the whole flood plane in the case of incidental high water during summer. During very high discharges both types of obstacles are submerged and will have an effect on the conveyance capacity of the river (stage discharge relation). Despite the fact that the geometry of a trained river has not undergone many changes over the last decades (or even centuries), little is known about the flow details around groynes and other obstacles that induce a sudden change in flow direction, either horizontally or vertically (Bos 1989, Fritz and Hager 1998).

In this paper attention will be paid to groyne field flow patterns as occurring with emerged and submerged conditions. Especially the dynamics of sudden vertical variations will be addressed, as it occurs with submerged summer embankments and groynes.
2. Flow patterns

2.1 Groyne fields

Bank protection by means of groynes is established by keeping the high flow velocities in a river away from the bank. Blocking the flow in the near-bank region confines the cross-sectional area which leads to higher velocities in the centre of the river with a consequent deepening of the main channel. This provides a second purpose for groynes. The equilibrium bed level in the main channel can be ‘tuned’ locally by choosing the proper length for the groynes. The standard flow field in groyne fields with an aspect ratio close to unity consists of a single gyre that fills up the whole groyne field (Fig. 1). The circulation is driven by the momentum exchange through the mixing layer.

Fig. 1. Patterns as observed with dye exchange experiment for two different aspect ratios w/l = 0.7 left, w/l = 0.3 right.

In the corners near the bank small counter rotating gyres are found. With this geometry a stable circulation is obtained which flows rather smoothly at about 30% of the main stream velocity. When the distance between the groynes increases to an aspect ratio of about 3, the circulation cell becomes elongated and separates from the bank (Uijttewaal et al. 2005a). This provides room for a secondary gyre rotating in the opposite direction. The secondary gyre gets its momentum from the primary gyre via an intermediate mixing layer, resulting in a velocity of approximately 30% of the speed of the primary gyre. There appears to be little interaction between the secondary gyre and the main stream. Its flow velocity and the exchange with the main stream are therefore very small. A much stronger interaction is found in the region where the primary gyre is in contact with the main stream. The mixing layer grows to a bigger width than in the square groyne field. This is due to the vortex shedding that occurs downstream of the groyne tip and the velocity gradient sustaining the vortical motion.

2.2 Submerged groynes

When the water level increases, the groynes become submerged and water starts flowing over the groyne crest. The recirculating flow pattern of the emerged case interacts with the unidirectional flow in the top layer. Therefore the momentum balance in the groyne field has two sources that can cause a strongly fluctuating flow field when they are of the same order of magnitude (Uijttewaal 2005b).
Figure 2 shows the contours of the velocity magnitude over a groyne that is 5 cm submerged. It shows that near the bank the water flows uniformly over the crest whereas near the tip the exchange of momentum with the main stream is clearly visible in the much higher velocity there. The larger region with higher velocity downstream of the crest is caused by separation of the flow in the vertical plane. The vertical recirculation provides no room for the surface layer to decelerate.

A further interpretation of the flow dynamics around submerged groynes is sketched in Fig. 3. With high water levels the flow over the groynes is stationary with almost parallel streamlines. The flow will detach in the vertical plane just downstream of the groyne crest. When the groynes are slightly submerged, the dynamics in the flow pattern is caused by the large eddies that move through the groyne field thereby governing the amplitude variations of the flow over the groyne.

Fig. 3. Flow patterns for submerged groynes. Fully submerged; with smooth stationary flow (left), small submergence level causing a dynamic flow field governed by the interfacial vortex (right).
In the idealized configurations, as described above, the mean flow direction is generally perpendicular to the groyne crest. In that case the flow over the groyne shows strong similarities with that over a weir, when the effects of the tip are neglected. The discharge over the groyne crest will be affected by the energy losses due to wall friction and de- and acceleration of the flow. In practice the direction of the groyne crest is not always perpendicular to the flow. Especially for submerged conditions where the flood plane configuration has a great influence on the mean flow direction, it is likely that the flow is oblique with respect to the crest. In order to be able to understand the processes related to the flow over submerged groynes we consider the generic problem of flow over oblique weirs.

2.3 **Oblique weirs**

From a standard analysis using energy conservation the specific discharge over a perfect weir (i.e. critical flow over the weir crest) is readily obtained:

\[ q_{w} = C_{d} \frac{1}{2} H_{0} \sqrt{\frac{1}{2} g H_{0}} \]

where \( H_{0} \) is the upstream energy height above the crest and \( C_{d} \) the discharge coefficient. The imperfect (sub-critical) condition can straightforwardly be analysed using momentum conservation for the downstream part. Though this approach leads to exact solution, the downstream energy loss is quite often described multiplying with an extra loss coefficient \( C_{e} = \sqrt{1 - \left( \frac{H_{2}}{H_{0}} \right)^{p}} \) where \( H_{2} \) is the downstream energy height and \( p \) an adjustable parameter (Villemonte 1947).

When a weir is situated under an angle with the main flow direction the length of the weir, denoted \( B_{k} \), is larger than the width of the stream \( B_{s} \) resulting in a decreased discharge per unit weir length. This geometrical effect is often used to increase the discharge capacity of perfect weirs used for regulation of the water level. Also, from the viewpoint of inundating floodplains, we are mainly interested in the specific discharge for the weir \( q = Q / B_{k} \) rather than \( Q / B_{s} \) (see also Fig. 4).

![Fig. 4. Flow configuration with definitions of weir dimensions and flow properties. The dash-dotted line represents the energy height while the upper solid line is the free surface.](image)
The approaches for the oblique weirs as found in literature are not very attractive mainly because of their highly empirical character. Aichel (1953) suggested that the specific discharge $q$ for an oblique weir relates to the specific discharge $q_\perp$ of a perpendicular weir in accordance with:

$$\frac{q}{q_\perp} = 1 - \beta \frac{h_0 - a}{a}$$  \hspace{1cm} (1)

All effects of the obliqueness are captured in a single coefficient $\beta$. This method was extended by Borghei et al. (2003) using a large number of coefficients and calibrating them for small values of $(h_0 - a)/a$ only. It was found that for free flow the discharge coefficient increases with upstream water level for inclinations $\varphi < 45^\circ$ whereas $C_d$ decreases for $\varphi > 45^\circ$. For submerged conditions the inclination gave slight increases of the discharge. Since Borghei et al. did not account for the effects of the upstream velocity it is difficult to read their results in terms of energy loss.

In order to better understand the physics, we look for a very simple approach and see how well this explains reality. For an inclination of the weir with respect to the approaching streamlines the flow is decomposed in a component perpendicular to the weir and a component parallel to the weir (see Fig. 5). The component parallel to the weir is assumed not to be affected by the weir because away from the wall significant pressure gradients in that direction are absent. The effects of bed friction are neglected for the smooth-bed cases while short downstream distances are considered. The above described weir behaviour can now be applied to the perpendicular velocity component straightforwardly.

![Fig. 5. Decomposition of velocities parallel and perpendicular with respect to the oblique weir.](image)

The increased velocity above the weir results in a change in flow direction towards the crest-normal direction. For perfect weir conditions and small values of $(h_0 - a)/a$, the upstream velocity is small and the flow will be directed almost perpendicular to the weir (see Fig. 5). For increasing water levels the relative increase of the velocity above the weir is smaller resulting in a large angle with respect to the weir crest. In the
limit of very high water levels the flow is hardly sensing the weir and keeps its direction: $\beta \approx \varphi$.

3. Experiments and numerical simulations

The data that we use to validate the above assumptions in combination with the model computations are obtained from an experiment performed long ago by DeVries (1959). It concerns a 1:25 scaled physical model as depicted in Fig. 3. The typical weir height was 0.12 m whereas the width of the flume $B$ was equal to 4 m. Unfortunately the available information is limited to upstream energy height and downstream water level $(h_2 - a)/H_0$. For a number of discharges the properties are determined with weirs of various inclinations $\varphi = 0^\circ, 30^\circ, 45^\circ, \text{and } 60^\circ$. Despite its limitations this data set contains at least a number of cases with submerged weirs and is thus very useful in view of application to inundated flood planes at high water stages. In order to supplement the limited data set and to obtain a more detailed insight into the structure of the flow, 3D numerical simulations were performed using the FINLAB-model with non-hydrostatic pressure formulation and a moving free-surface. For more details see Wols (2006).

The numerical model captures the distinct flow regimes ranging from fully submerged to critical flows quite well, with a proper representation of the undular and breaking hydraulic jump. Figure 6 shows the result of a simulated undular hydraulic jump with a strong deformation of the free surface and associated deviation of the mean pressure from the hydrostatic pressure. It is only a small part of the domain where the strong deviations occur, clearly related to the surface curvature.

![Fig. 6. Example of a simulation showing the surface deformation and deviations of the mean pressure from the hydrostatic pressure for an undular jump.](image)

The energy loss associated with the flow over the weir can straightforwardly be determined from the numerical data by determining velocities and water levels. In this way, the numerical simulations may be used to analyze the cause of the increased losses in case of obliqueness of the weirs. With sufficiently accurate simulations, to be confirmed by direct comparison of the model results with the experimental data, the numerical results may be used to further analyze the energy losses in the flow field, including the 3D flow structure in the wake of the weir.

Figure 7 shows a comparison of the experimental analytical and numerical weir discharge coefficients $C_d = C \cdot C_{d\text{v}}$ for the various conditions of the experiment. Despite the scatter in the measured data, the agreement between the three approaches is rather
good. There is only a clear deviation for the 60°-case where the analytical model over-
estimates the discharge whereas the numerical model properly accounts for the addi-
tional energy losses.

### 3.1 Velocity direction

With the simple analysis sketched in Fig. 5, the assumption was made that the velocity
in the direction parallel to the weir was not affected by the weir. In order to demon-
strate the validity of this assumption, the magnitudes of the decomposed velocity
components obtained from the numerical simulations are shown in Fig. 8.

![Fig. 7. Discharge coefficients for different weir inclination compared.](image)

The upper panel reveals that over almost the full length of the weir the perpendicu-
lar velocity component is uniform and that only small effects of the side walls are
visible. Further downstream the deflected flow interacts with the side walls and this
uniformity is gradually lost. The deflected flow might also give rise to flow separation
in the horizontal plane. At the location \((x, y) = (3.5 \, \text{m}, 2 \, \text{m})\), the velocity becomes very
small and might even change sign. This interesting phenomenon lies outside the scope
of this study but will receive further attention in the program of experiments that will
be undertaken.

In a similar way, the parallel velocity component is mostly affected near the side
walls. For the larger part of the domain this velocity is roughly constant and only a
small and gradual change is observed in the vicinity of the weir. At the downstream
side of the weir the non-uniformity is the largest. Nevertheless, the results show that the assumption of a constant weir-parallel velocity is valid for the locations not too close to the wall.

Fig. 8. Contour plots of decomposed velocities for a 45° weir. The flow is from left to right and the weir crest is located between \((x, y) = (-2 \text{ m}, -2 \text{ m})\) and \((x, y) = (2 \text{ m}, 2 \text{ m})\).

3.2 Flow separation

It turns out that for the imperfect flow over an oblique weir, the detailed flow field downstream of the weir is highly affected by the angle of the weir with respect to the approach flow. Even if the submergence is relatively large, the weir causes a strong deflection of the flow. The inclination, in combination with the separation zone at the downstream side, gives rise to helical streamlines transporting mass and momentum along the weir. Figure 9 shows that through this effect material can be advected over large distances across the flow. Near the bed, high velocities can occur that can give rise to bed scour.

The simulated shape of the recirculation zone is highly affected by the inclination of the weir. In Fig. 10, the flow separates in the area of strong deceleration. For the perpendicular case (left) the downward directed momentum leaves little room for a separation bubble. There seems to be an almost stagnant region but it is not very convincing. It should be noted that the limited resolution puts restrictions on the flow details that can be reproduced. Keeping the total discharge constant while changing
the inclination of the weir to 60° results in a more pronounced separation bubble. With
the same total discharge the greater length of the weir leads to a smaller velocity per-
pendicular to the weir and a smaller associated momentum transport.

Fig. 9. Free surface (light grey) and streamlines (black) around an oblique weir (dark grey).

Fig. 10. Flow pattern downstream of the weir in the plane perpendicular to the weir crest (left)
perpendicular weir, (middle) oblique 60°, with the same total discharge, (right) oblique 60°
weir with same specific discharge as the perpendicular weir left.

This might enhance the separation and give a larger recirculation zone. For a fair
comparison also the flow pattern around the inclined weir is shown where the specific
discharge and velocities perpendicular to the weir are kept the same (right). In this
case a clear separation bubble is found. Since the total velocity over the inclined weir
is much bigger, wall friction will play a bigger role. It is also seen that the depression
in the free surface is not as deep as in the case of a perpendicular weir. These details
show that the velocity component parallel to the weir crest affects the flow separation
and results in a slightly smaller energy loss reflected in a higher downstream water
level. It must be noted here that the details that are resolved by the numerical model
are not compared with experimental data because these were not available. Clearly,
detailed data are necessary in order to find out whether the modeling details including
the turbulence model, resolution and boundary conditions are correct.
4. Conclusions
Groynes have a profound effect on the flow in rivers and give rise to a large variety of flow phenomena. The momentum exchange driving the circulations is governed by separation. Depending on the relative submergence, the mixing layer at the groyne field interface is capable to sustain a gyre pattern including a return flow near the bank. With increasing water level, the flow over the groyne crest dominates resulting in a unidirectional flow through the groyne field. Depending on the direction of the approach flow in relation to the groyne crest, the flow will be deflected in the acceleration phase.

Separation in the vertical plane is governing the discharge over the groyne. A numerical model used for estimating discharge capacity and dispersion should therefore account for the observed complex flow phenomena. This requires a non-hydrostatic model with a moving free surface and advanced turbulence modeling. The latter is important for the vertical separation of the flow downstream of the groyne crest but also for the large-scale horizontal separation near the groyne tip.

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