Flow Resistance of Vegetated Oblique Weir-like Obstacles during High Water Stages

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Abstract: At high water stages obstacles in the floodplains of a river contribute to the flow resistance. In particular the elevated vegetated parts are expected to play an important role. The objective of this study is to estimate and parameterize the form drag due to vegetated oblique weir-like obstacles. An experimental study has been carried out in the Laboratory of Environmental Fluid Mechanics of Delft University of Technology. Measurements for energy head losses were carried out for a range of discharges and downstream water levels covering submerged and subcritical flow conditions. The Head loss due to submerged vegetated dikes has been modeled by an expansion loss form drag model. Expansion loss form drag model has been derived from one dimensional momentum conservation equation and accounts for the energy loss associated with a deceleration of the flow downstream of a sudden flow expansion. The results have been compared with experimental data.

Keywords: Oblique weir, Vegetated weir, Weir-like obstacles, Flow resistance, Floodplain resistance

1. INTRODUCTION

Water level predictions for extreme events (flood wave) are extremely important for the safer design of the dykes and embankments and the safety of the area behind them. During such extreme discharges, the summer dikes are overflowed and a part of the river discharge flow through the winter bed with several weir-like obstacles (lowland rivers). The winter bed is full of the vegetation and the vegetated weir-like obstacles such as access roads, embankments. These obstacles and vegetation affect the flow levels during floods. River managers are seeking for physical understanding of flow characteristics concerning the summer dikes and such type of obstacles. These Weir-like obstacles are randomly oriented to the flow direction and these could be perpendicular to the flow direction or at an oblique angle and also vegetated. The characteristics and hydraulic behavior of plain weir or standard weirs have been studied for a long time and the understanding on them is rather deep. However, a few studies have been done on weirs placed obliquely in the flow. The most important difference between an oblique weir and plain weir is that the crest of the oblique weir makes an angle with the flow direction in the channel. An extreme example is the side weir, a part of the channel embankment, its crest being parallel to the flow direction in the channel. Aichel (1953) presented new relation for the discharge coefficient of a round crested skewed-weir compared with the plain weir in his report in German language. De Vries (1959) also did many experiments to examine the loss of the flow over dike-form weirs under different oblique angles and flow conditions and published a report in Dutch language (“Scheef aangestroomde overlaten”, April 1959). The main objective of his research was to examine the influence of the obliqueness of the weir to the flow and the experiments were done on trapezoidal weirs (di ke form weirs). Borghei et al. (2003) used experimental results to estimate the discharge coefficient for the oblique rectangular sharp-crested weir. Borghei et al. (2006) improved the formula for discharge coefficient by using the incomplete self similarity (ISS) concept. Wols et al. (2006) published the numerical simulations of oblique weir using non-hydrostatic finite elements model FINLAB, with free surface and k-ε turbulence closure. Tuyen (2006 and 2007) measured the energy head loss and discharge coefficients under different weir configurations and flow conditions. Ali and Uijttewaal (2009&2010) studied the vegetated weir-like structures oriented perpendicular to the flow direction and quantifies the energy head loss caused by such types of obstacles. The objective of this research is to quantitatively determine the energy head loss caused by the oblique vegetated weir-like structures in the floodplain and to describe the structure of the flow over such oblique vegetated weir like structures and other complex phenomenon related to it.
2. MATHEMATICAL FORMULATION

The theoretical analyses on oblique weirs are important for the prediction and interpretation of experimental data. They are the energy conservation, which is applied for the upstream area of the flow; the momentum conservation is applied for the downstream area of the flow, and the continuity (the conservation of the water mass) is valid everywhere. Flow velocity could be decomposed into two components, parallel and perpendicular to the flume axis, it can also be decomposed into two components parallel and perpendicular to the weir axis. Theoretically it is assumed that the crest parallel component does not change its magnitude (although it has effect), when the flow reaches the weir. Accelerating force only acts on the velocity component perpendicular to weir crest and the same holds for the deceleration process. The angle of flow obliqueness is the deviation angle of the stream lines from the normal direction with respect to the weir crest, for plain weir this angle is zero. For an oblique weir value of \( \psi \) can be predicted using energy balance and continuity equation of flow.

\[ \frac{d_0 + \frac{u_0^2}{2g}}{d_1 + \Delta} = \frac{u_1^2}{2g} \]  

\( L \) is length of oblique weir, \( L = \frac{B}{\cos \varphi} \) (B is the channel width). 

\( \varphi \cos/BL = \) (B is the channel width).
Velocity could be decomposed into two components:

\[ u_2^2 = u_{2p}^2 + u_{2L}^2, \quad u_1^2 = u_{1p}^2 + u_{1L}^2. \]

Assumption will act here that velocity component parallel to the weir crest remained constant in the area of investigation so \( u_{0L} = u_{1L} \). Using continuity equation and assumption above energy equation (eq. (1)) could be written as eq. (4).

\[
\begin{align*}
&d_0 + \frac{u_{2p}^2}{2g} = (d_1 + \Delta) + \frac{u_{1p}^2}{2g} \\
&d_0 + \frac{u_{2p}^2}{2gd_0^2} = (d_1 + \Delta) + \frac{u_{1p}^2}{2g} \\
&d_0 = (d_1 + \Delta + \frac{u_{1p}^2}{2g})d_0^2 + \frac{u_{1p}^2d_0^2}{2g} = 0
\end{align*}
\]

If the value of \( d_1 \) is known, \( d_0 \) can be found as a root of the Eq. (5), the other parameters can be calculated as follow:

\[ u_0 = \frac{Q}{Bd_0}; \quad u_{0p} = u_0 \cos \phi \]

\( u_i \) can be calculated from above equation. The oblique angle of flow stream lines above weir crest can be calculated as in Eq. (6)

\[ \psi = \arccos \left( \frac{u_{1p}}{u_1} \right) \]

At the downstream side there is a deceleration region. Here the energy is dissipated in the wake region. The depth averaged momentum conservation equation is applied between section 1 and 2 as shown in figure 2.2. The expansion has been considered sudden and the pressure is assumed hydrostatic here also. Momentum conservation equation has the following form eq. (7).

\[
\frac{1}{2}\rho g(d_1 + \Delta)^2 - \frac{1}{2}\rho gd_1^2 = \rho q(u_2 - u_1)
\]

Velocity could be decomposed into two components as above in case of energy balance on upstream of the weir.

\[ u_2^2 = u_{2p}^2 + u_{2L}^2, \quad u_1^2 = u_{1p}^2 + u_{1L}^2 \]

It is assumed that velocity component parallel to the weir crest remained constant in the area of investigation so \( u_{2L} = u_{1L} \). So equation can be written as

\[
\frac{1}{2}\rho g(d_1 + \Delta)^2 - \frac{1}{2}\rho gd_2^2 = \rho q(u_{2p} - u_{1p})
\]

The continuity equation always holds true for flow

\[ Q = u_{1p}d_1L, \quad Q = u_{2p}d_2L \]

\[ u_{1p} = \frac{Q}{d_1L}, \quad u_{2p} = \frac{Q}{d_2L} \]

Putting the value of the \( u_{1p} \) from eq. (9) in eq. (8) (the momentum balance).

\[
\frac{1}{2}Bho g(d_1 + \Delta)^2 - \frac{1}{2}B\rho gd_2^2 = L\rho q(u_{2p} - u_{1p})
\]
If the value of \( d_2 \) is known, \( d_1 \) can be found as a root of the above polynomial eq. (10).

### 2.1 Groyne with Vegetation

For the submerged case, energy head loss is due to the wake of weir, the wake behind the cylinders and also shear layer above the vegetation. There is large difference in flow velocities between the vegetated region and overlying region. There is also an interaction between these different turbulent regions. Here we ignore these interactions and we determined the form drag due to combined effect of weir and vegetation in submerged situation. We are using depth averaged vertical velocity distribution considering the effects of vegetation as a contraction of cross sectional area.

In this case we consider the vegetation on the weir crest as submerged. Energy and momentum balance upstream and downstream of the weir can be written respectively as,

\[
\frac{1}{2} Bgd_1^3 + gB\Delta d_1^2 + \left( \frac{1}{2} Bg\Delta^2 - \frac{1}{2} Bgd_2^3 - Qu_{2p} \right) d_1 + \frac{Q^2}{L} = 0 \tag{10}
\]

\[
\frac{d_1}{d_1 - L/4} = \frac{Q}{2g} \tag{11}
\]

\[
d_0 + \frac{\beta u_{2p}^2}{2g} = (d_1 + \Delta) + \frac{\beta u_{1p}^2}{2g} \tag{12}
\]

\[
\frac{1}{2} \rho g (d_1 + \Delta)^2 - \frac{1}{2} \rho g d_2^2 = \rho q (\beta_{2u_{2p}} - \beta_{1u_{1p}}) \tag{13}
\]

\[
\alpha = \int \frac{V^3}{V_m^2} dA \quad \text{Kinetic energy correction coefficient.}
\]

\[
\beta = \int \frac{V^2}{V_m^2} dA \quad \text{Momentum correction coefficient. Here } V_m \text{ is mean velocity over cross-section}
\]

### 3. EXPERIMENTAL SETUP

#### 3.1 Experimental flume

The experiments were conducted in the a rectangular horizontal glass flume, 19.2 m long 2m wide and 0.22 m deep. In the middle area of the flume, the research object, which is an oblique weir is situated the weir in the experiments had a general height of 8 cm. The flume bed as well as the weir has been made hydraulically rough by gluing 5mm to 8mm diameter gravel to the bed to represent the actual field conditions as in the floodplain. The angle of obliqueness of the weir is 45\(^\circ\).The water for experiments was taken from and returned to the main circulation system in the laboratory. The flow from a 250mm conduit was discharged into a buffer basin and then into the experimental flume. Discharge of water to flume was measured by an electromagnetic flow meter.
3.1 Prototype dike
For the study a trapezoidal embankment dike is used. It has a height of 6m, crest width of 3m and a side slope of 1V:4H on the upstream side and 1V:4H downstream (Figure 3.2).

3.1.2 Model weir
The model is made of composite, wood and concrete material. The side slopes of the model weir were the same as with the prototype. The oblique Model weir has a height of 8cm (crest width 4 cm, scale 1/75) because of the flume depth limitations, with the upstream and downstream slopes of 1:4(Figure 3.2).

3.1.3 Pseudo vegetation
For this principal study, the vegetation on the weir crest is modeled by using circular cylinders. The relative blockage on the top of the weir due to the model vegetation is 25 %. The height of the model plants is 4cm (Figure 3.2).

3.2 Measuring equipments

3.2.1 Point gauges
Point gauges are used to measure the flow depth for energy loss and discharge calculations. These are also used to draw the free surface profile of the flow. To measure the water depths first the elevation of the water surface and then the elevation of the bed at that point was measured. To get the value of flow depth, the later was subtracted from the first. There were two point gauges mounted on a moveable beam in such a way that the measurement can be made across the flume. The beam itself is mounted on the flume on two side rails. Point gauges were used to measure the height of the free surface and the bed level to ±0.1mm.

In the supercritical flows, the water surface became highly unstable behind the weir, and sometimes there was air entrainment, these aspects together decreased the accuracy to ±1mm. Far downstream, the flow surface calmed down and the accuracy of the depth measurement can be insured as normal (±0.1mm).

Figure 3.1. Schematized plane view of the flume and measuring apparatus.

Figure 3.2. Prototype dyke and model weir (scaled 1:75)
3.2.2 Laser displacement Sensors

Laser displacement sensors (ILD1300) are used to measure the water depth 2m (from centre of the weir) upstream and 3m down stream of the weir. It is an optical sensor for measurements with micrometer accuracy. These sensors use the principle of optical triangulation, i.e. a visible, modulated point of light is projected onto the target surface. Depending on the distance the diffuse fraction of the reflection of this point of light is then focused onto a position sensitive element (CCD-array) the controller calculates the measured value from the CCD-array. An internal close-loop control enables the sensor to measure against different surfaces. The laser beam is directed perpendicular onto the surface of the target. Point gauge is used to measure the water depth on the crest of the weir with an accuracy of ±0.1mm.

3.3 Head loss measurements

Tests have been carried out (for an oblique weir) for several flow conditions by varying the discharge and downstream water level. The inflow has been provided with the discharges of 20, 25,30,35,40 l/sec. For each discharge the down stream water level was adjusted to give the 15 different flow states, from completely submerged to the free flow regime. The downstream water level was gradually varied from one experiment to other to get different flow regimes and states. After adjustment, almost 10 minutes are required to stabilize the flow and then the water depth measurements can be performed. The Different cases for an oblique weir with a down stream slope of 1:4 are

- Model Weir with out vegetation
- Model Weir with cylinders (25% blockage area).

Here the height of the cylinders is 4 cm.

4. RESULTS AND DISCUSSION

Following figure 4.1 presents the head loss variation with the downstream water depth for different discharges and for vegetated and non-vegetated weirs.

As can be seen from the measurement data the influences of some main hydraulic parameters to the energy head loss can be summarized as follow:

1. With the same discharges, the head loss decreases with the increase of the downstream water head (increase the submergence).
2. With the same down stream water depth, the higher the discharge, more the head loss.
3. At the free flow state, the relationship between downstream water depth and the energy head loss is linear.

![Figure 4.1. Energy head loss versus downstream water depth for different discharges.](image-url)
Figure 4.2 Comparison of energy head loss of vegetated and non-vegetated oblique weir.

Figure 4.2 presents the comparison of the energy head loss of vegetated and non-vegetated weir for different discharges. It can be seen from the measured data that the energy head loss increased due to the extra blockage (vegetation blockage) on the weir crest. Pseudo vegetation on weir crest also enhances the turbulence in the flow which increases the energy head loss. At high submergence it is difficult to see the effect of enhanced energy head loss due to vegetation. In case of the low energy head loss, the measurement accuracy is low also.

4.1 Analysis of the energy head loss measurements

The results from the theoretical analyses based on the energy and momentum balance has been compared with the measured ones in figure 4.3 and 4.4. There is reasonable agreement of results in case of the weir without vegetation and there is deviation for the measured results in case of low energy head loss and may be it is the inaccuracy of measurement due to the limitation of instrument accuracy. In case of vegetated oblique weirs the predicted results are lower than the measured ones. In this simple theoretical model we ignored the velocity component parallel to the oblique weir but this
component does sense the vegetated elements on the weir crest, that’s why the model under-estimates the energy head loss here. For higher energy head loss the deviation from the predicted results is due to the surface undulations. This model can predict energy head loss in submerged flow conditions only.

5. CONCLUSIONS

Some main conclusions could be drawn from this study;
Changing the downstream water level will lead to changes in the flow regime and the behavior of the flow over the oblique weir with low down stream water level, there is usually a classical hydraulic jump. The hydraulic jump is dominated at the right side of the flume, to the left; the flow has a smoother pattern. Increasing the downstream water level further, the hydraulic jump will change into an undular jump.

- The energy dissipation has its maximum value for the case of a hydraulic jump behind weir, and minimum value for the case of completely submerged flow.
- Flow always turns its direction when it reaches and passes the weir, towards a perpendicular orientation.
- The velocity decomposition proves to be an important step in studying the flow over an oblique weir without vegetation. The velocity component perpendicular to the weir accounts for most of the change in the total velocity, whereas the parallel component stays almost unchanged.
- The turbulent flow behind the weir accounts for the bulk of the energy dissipation.
- The energy head loss increased due to the extra blockage (vegetation blockage) on the weir crest. Pseudo vegetation on weir crest also enhances the turbulence in flow which increases the energy head loss.

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