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Decisive Parameters for Backwater Effects Caused by Floating Debris Jams

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Abstract

The dimensional analysis of the backwater effect caused by debris jams results in the Froude number of the approach flow in the initial situation prior to debris jam formation and the debris density as decisive parameters. For the more precise detection of the influence of both parameters the results of different hydraulic model test series at the Laboratory of Hydraulic and Water Resources Engineering of the Technical University of Munich concerning debris jams at spillways as well as at racks for the retention of wooden debris were uniformly evaluated. On the one hand a significant increase of the backwater effect with a rising Froude number of the approach flow could be shown. This is in good correlation to recent test results for debris jams at retention racks at the Laboratory of Hydraulics, Hydrology and Glaciology of the Swiss Federal Institute of Technology Zurich. On the other hand a significant increase of the backwater effect could also be shown for a rising debris density. However, the test results also show that significantly different backwater effects can occur in different test runs with identical test conditions. These differences are a result of the randomness of debris jam development, and therefore, a more exact quantification of the dependence of the backwater effect on the Froude number of the approach flow and on the debris density is not considered useful for the present results.

Keywords

Hydraulic Engineering, Natural Hazards, Floating Debris Jams, Large-Scale Hydraulic Model Tests

1. Introduction

The previous research in the area of floating debris jams focused on the following issues:

- Floating debris jams at natural obstacles in rivers ([1] [2] [3]),
- The influence of different layouts of wooden debris retention racks on the resulting jams ([4] [5] [6] [7]),
- The probability of debris jams at bridges ([8] [9]) and spillways ([10] [11] [12] [13]).

Only little research exists in the area of the consequences of floating debris jams at spillways and wooden debris retention racks, in particular the resulting backwater effect, which is the focus of this paper.

The approach of this study envisaged a dimensional analysis of the backwater effect caused by floating debris jams. For the detected parameters, the Froude number of the approach flow and the debris density, the results of different hydraulic model test series concerning debris jams at spillways as well as at racks for the retention of wooden debris were uniformly evaluated.

2. Dimensional Analysis

The backwater effect caused by floating debris jams directly depends on the development and shape of the jam. The dimensional analysis of the development and shape of debris jams as well as the resulting backwater effect can be performed with only one characteristic parameter ([14] [15]). The characteristic parameter selected in this study is the so-called debris jam compactness. The debris jam compactness is the ratio of height T to length L of the debris jam; *i.e.* compactness is T/L. T and L are illustrated in the example of a debris jam at a spillway bay in **Figure 1** and at a debris retention rack in **Figure 2**.

A number of different variables likely have an influence on the debris jam

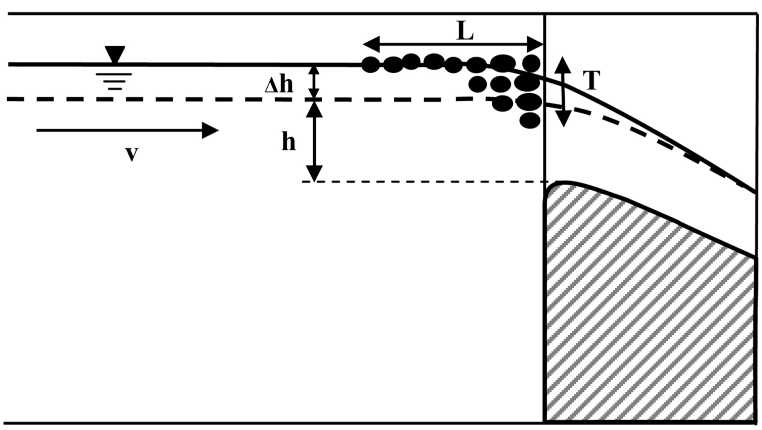

Figure 1. Longitudinal section in flow direction of a spillway bay with a debris jam.

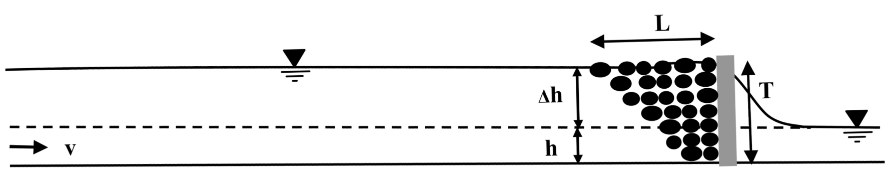

Figure 2. Longitudinal section in flow direction of a retention rack with a debris jam.

compactness T/L. First, a higher approach flow velocity v in the initial situation prior to debris jam formation probably leads to a higher compactness. Different overflow heights or flow depths h should also affect compactness. Gravitational acceleration g together with the densities of the debris ρ_D and water ρ_W can cause some logs to plunge below others floating on the water surface. The compactness T/L of debris jams is thus regarded as a function of v, g, h, ρ_D and ρ_W. Specifically, it will be treated as a product of a proportionality constant $C_{T/L}$ and of v, g, h, ρ_D and ρ_W with the different exponents a, b, c, d and e:

$$T/L = f\left(v, g, h, \rho_D, \rho_W\right) = C_{T/L} \cdot v^a \cdot g^b \cdot h^c \cdot \rho_D^d \cdot \rho_W^e \tag{1}$$

The dimensions matrix $A_{T/L}$ in the mass[m]-length[l]-time[t]-system takes the following form:

$$A_{T/L} = \begin{bmatrix} & v & g & h & \rho_D & \rho_W \\ m & 0 & 0 & 0 & 1 & 1 \\ l & 1 & 1 & 1 & -3 & -3 \\ t & -1 & -2 & 0 & 0 & 0 \end{bmatrix} \tag{2}$$

Because the compactness T/L is dimensionless, solving the dimensions equations of the mass, the length and the time leads to the following:

$$[m]: 0 = d + e \Rightarrow e = -d \tag{3}$$

$$[l]: 0 = a + b + c - 3 \cdot d - 3 \cdot e \Rightarrow c = -a - b = -0.5 \cdot a \tag{4}$$

$$[t]: 0 = -a - 2 \cdot b \Rightarrow b = -0.5 \cdot a \tag{5}$$

$$\begin{aligned} \Rightarrow T/L &= C_{T/L} \cdot v^a \cdot g^b \cdot h^c \cdot \rho_D^d \cdot \rho_W^e = C_{T/L} \cdot v^a \cdot g^{-0.5a} \cdot h^{-0.5a} \cdot \rho_D^d \cdot \rho_W^{-d} \\ &= C_{T/L} \cdot \left[v / (g \cdot h)^{0.5} \right]^a \cdot \left(\rho_D/\rho_W\right)^d = C_{T/L} \cdot F_0{}^a \cdot \left(\rho_D/\rho_W\right)^d \end{aligned} \tag{6}$$

The compactness of the debris jam T/L is a product of the proportionality constant $C_{T/L}$, the Froude number F_0 of the approach flow prior to debris jam formation with the unknown exponent a and of the density ratio of debris and water ρ_D/ρ_W (relative debris density) with the unknown exponent d. This same fundamental dependence is found for the dimensionless parameter relative backwater effect $\Delta h/h$ caused by a debris jam, however with different number values for $C_{T/L}$, a and d.

3. Large-Scale Hydraulic Model Tests

It was the aim to detect the influence of the Froude number F_0 and the relative debris density ρ_D/ρ_W on the backwater effect $\Delta h/h$ caused by debris jams at spillways more precisely. Therefore, the results of a large-scale hydraulic model test series at the Laboratory of Hydraulic and Water Resources Engineering of the Technical University of Munich was evaluated [16]. The model of a spillway intake structure (**Figure 3**) was built in a rectangular canal on the open-air area of the laboratory (canal length: 220 m, width: 2.5 m, depth: 2 m). The scale of the Froude model was 1:20. The intake structure consisted of three identical bays

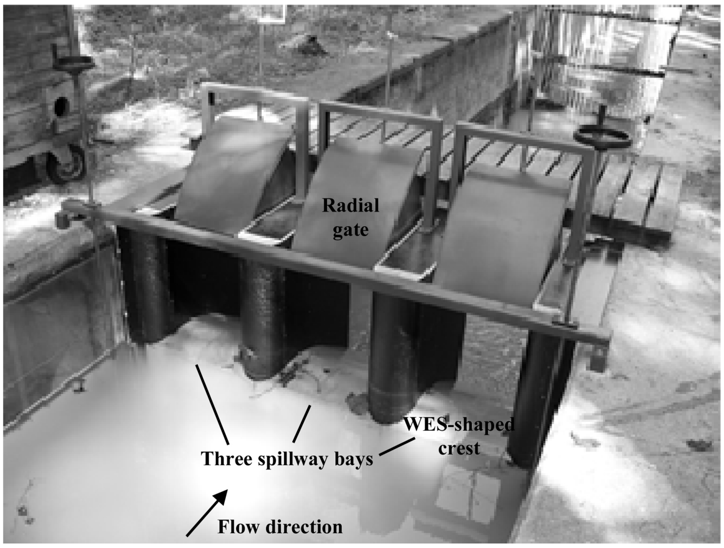

Figure 3. Model of the three-bay spillway intake structure in the rectangular canal.

with a width $W = 50$ cm, WES-shaped crests and radial gates. The gates were fully opened during the described tests and without any influence on the jam process. The standardised dimensions of the model intake structure were representative for many existing structures. With regard to the debris, 100-logs sets with the distribution of the log length l_L shown in Table 1 and model log diameters d_L between 2 cm and 4 cm were used. The logs had no or only a few branches. Describing the procedure of a single test an initial steady-state flow condition without a debris jam was established in the canal first. Then groups of five logs were added to the flow upstream of the spillway intake structure until all three bays were blocked and all remaining logs of the set were added to the flow. The geometric development of the debris jam finally consisting of the total log set was observed. After reaching a new steady-state flow condition, the upstream water level was measured and the relative backwater effect $\Delta h/h$ was derived as the main result.

4. Froude Number F_0 of the Approach Flow

4.1. Debris Jams at Spillways

The test results were evaluated with the focus on the influence of the Froude number F_0 of the approach flow prior to debris jam formation on the relative backwater effect $\Delta h/h$. For this evaluation only the results of tests with natural debris and a mean relative debris density of $\rho_D/\rho_W = 0.8$ were used. For higher Froude numbers $F_0 > 0.30$, multi-layer debris bodies with high compactness T/L (see Figure 4) and high relative backwater effects $\Delta h/h > 12\%$ (see Figure 5) were formed. For lower Froude numbers $F_0 < 0.15$, loose single-layer floating carpets with low compactness T/L and correspondingly low relative backwater effects $\Delta h/h < 6\%$ (see Figure 5) were formed. All values in Figure 5 were

Table 1. Distribution of the log length l_L in the 100-logs sets.

l_L/W	1.0	1.3	1.5	1.7	2.0
Number of logs	15	20	30	20	15

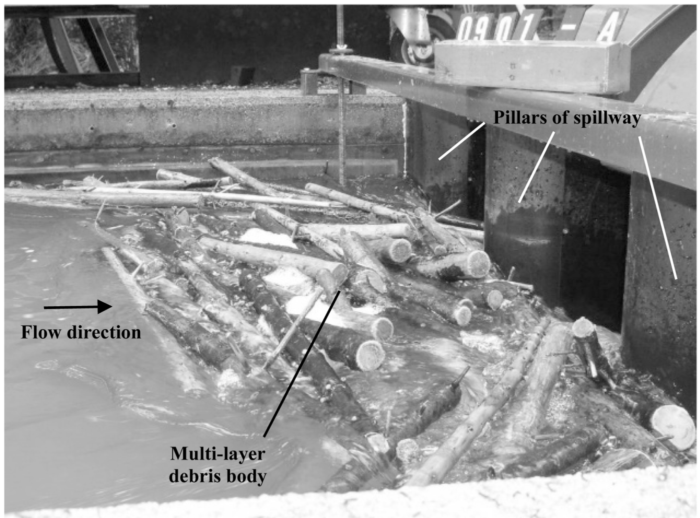

Figure 4. Multi-layer debris body with high compactness for F_0 = 0.35 and $\Delta h/h$ = 15.2%.

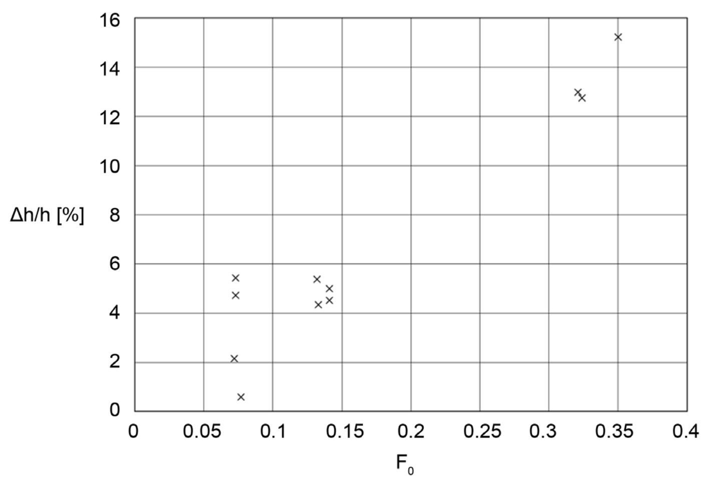

Figure 5. Relative backwater effect $\Delta h/h$ vs. Froude number F_0 of the approach flow in a hydraulic model test series concerning debris jams at a spillway with identical debris mix (natural debris with $\rho_D/\rho_W = 0.8$).

determined for the same 100-logs set of debris. From these results, it can be deduced that the relative backwater effect $\Delta h/h$ increases with rising Froude number F_0 of the approach flow. This means that the exponent a in (6) is positive. But the test results in **Figure 5** also show that significantly different backwater effects can occur in different test runs with identical test conditions. These differences are a result of the randomness of the debris jam development. Therefore, a more exact quantification of the dependence of the backwater effect on the Froude number of the approach flow in the form of the exponent a in (6) is not considered useful for the present results. The randomness of the debris jam development might possibly be eliminated from the test results if the shapes of the debris jams are default in further test series.

4.2. Debris Jams at Retention Racks

Knauss has performed fundamental tests for debris jams at retention racks with different layouts of vertical pillars [4]. A new evaluation of his test results for a V-shaped rack shows a significant increase of the relative backwater effect $\Delta h/h$ with rising initial Froude number F_0 of the approach flow (see **Figure 6**). For the lowest tested Froude number $F_0 = 1.61$ a relative backwater effect $\Delta h/h = 220\%$ was determined. And the highest Froude number $F_0 = 2.45$ caused a relative backwater effect $\Delta h/h = 430\%$. For comparison, the correlations derived from the test results of Weitbrecht and Schmocker [5] as well as of Schmocker and Hager [6] are included in **Figure 6**. These two studies tested retention racks with a layout of the pillars vertical to the flow direction (90˚) and lower Froude numbers of the approach flow. As far as it is verifiable, comparable debris mixes were used in the three different test series.

Two value pairs for F_0 and $\Delta h/h$ can be adopted from Weitbrecht and Schmocker [5]. Based on several test results from Schmocker and Hager [6], there is a linear correlation between the relative backwater effect and the Froude number of the approach flow for $0.5 < F_0 < 1.5$. Schmocker and Hager repeated each test with identical conditions twice and obtained clearly divergent backwater effects due to the randomness of the debris jam development, too. By the calculation of the mean values of the backwater effect for each Froude number

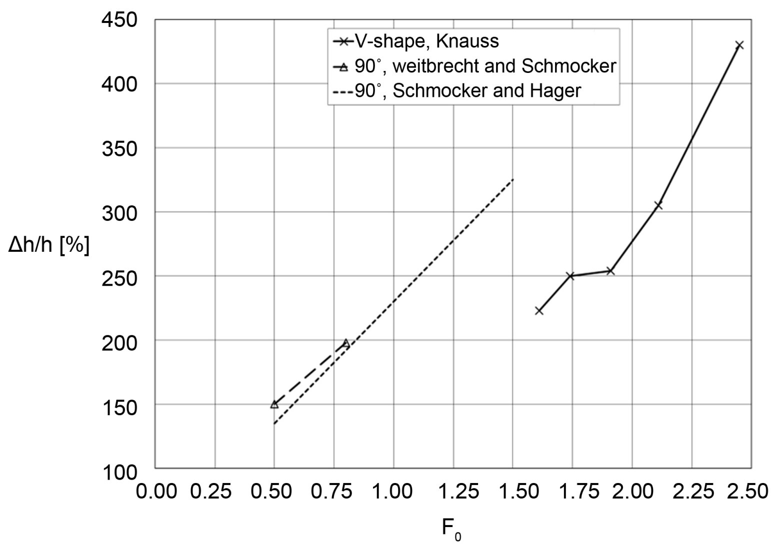

Figure 6. Relative backwater effect $\Delta h/h$ vs. Froude number F_0 of the approach flow in hydraulic model test series concerning debris jams at retention racks by various authors.

they derived the linear correlation. This could rather be seen critically, because the possible strong variation of the backwater effect for identical conditions is lost in the consideration. Using the parameters defined in this paper, the equation of Schmocker and Hager [6] for the dependence of the relative backwater effect $\Delta h/h$ on the Froude number F_0 is:

$$(\Delta h + h)/h = 1.4 + 1.9 \cdot F_0 \quad \text{or} \quad \Delta h/h = 0.4 + 1.9 \cdot F_0 \tag{7}$$

The quantity of the increase of the relative backwater effect $\Delta h/h$ with the rising Froude number F_0 lies in a comparable range in all test series. If the linear correlation of Schmocker und Hager [6] is extrapolated on higher Froude numbers, the relative backwater effect would be significantly larger than for the test series of Knauss [4]. However, this in fact corresponds with the fundamental finding of Knauss [4], debris jams at V-shaped racks cause smaller backwater effects than at 90˚-racks.

5. Relative Debris Density ρ_D/ρ_W

In the hydraulic model tests concerning debris jams at spillways the relative debris density ρ_D/ρ_W was varied for a more precise detection of its influence on the relative backwater effect $\Delta h/h$. To avoid density fluctuations which occur in natural wood due to shrinkage and expansion, artificial 100-logs sets with four different densities (ρ_D/ρ_W = 0.8; 0.9; 0.95 and 0.975) were used. Aside from these density variations, the debris mixes were identical. The quantitative influence of the debris density on the development of the jam and on the backwater effect is comparable to the Froude number of the approach flow. With a rising relative debris density ρ_D/ρ_W the debris jams became more compact and the relative backwater effect $\Delta h/h$ increased. This means that the exponent d in (6) is positive. **Figure 7** shows a loose, single-layer floating carpet for ρ_D/ρ_W = 0.8 (left) and a compact multi-layer debris body for ρ_D/ρ_W = 0.975 (right). In both cases the Froude number was F_0 = 0.08. The steel grid in front of the spillway visible in **Figure 7** was required to prevent some logs of the artificial mix from passing over the spillway.

Figure 8 shows the measured value pairs of the relative debris density ρ_D/ρ_W and the relative backwater effect Δh/h for two different Froude numbers of the approach flow. For F_0 = 0.08, the relative backwater effect increases from $\Delta h/h$ = 5.9% for the smallest relative debris density ρ_D/ρ_W = 0.8 up to $\Delta h/h$ = 45.9% for the largest relative debris density ρ_D/ρ_W = 0.975. For the higher Froude number F_0 = 0.14, the respective values of the relative backwater effect are larger, which corresponds with the findings described in 4.1. In this test series, the relative backwater effect increases from $\Delta h/h$ = 15.7% for ρ_D/ρ_W = 0.8 up to $\Delta h/h$ = 46.4% for ρ_D/ρ_W = 0.975.

Similar to the dependence on the Froude number of the approach flow, a more exact quantification of the dependence of the backwater effect on the relative debris density in the form of the exponent d in (6) is not considered useful

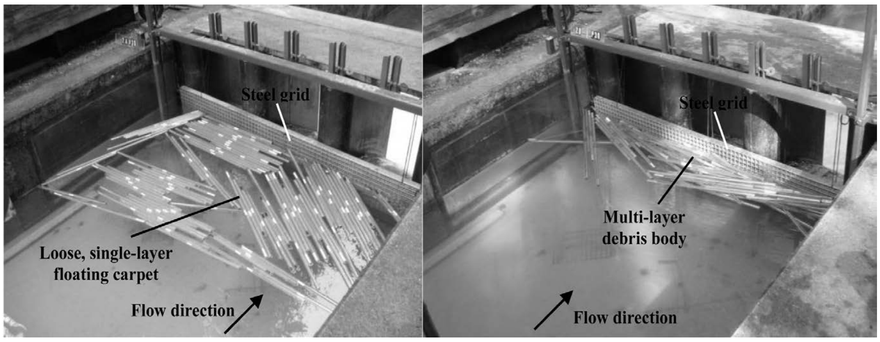

Figure 7. Loose, single-layer floating carpet with low compactness for $\rho_D/\rho_W = 0.8$ and $\Delta h/h = 5.9\%$ (left) and multi-layer debris body with high compactness for $\rho_D/\rho_W = 0.975$ and $\Delta h/h = 45.9\%$ (right).

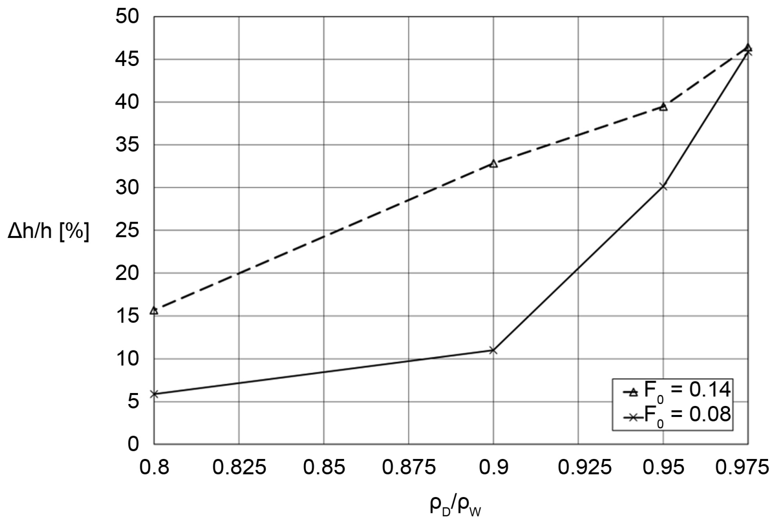

Figure 8. Relative backwater effect $\Delta h/h$ vs. relative debris density ρ_D/ρ_W in systematic hydraulic model test series concerning debris jams at spillways.

for the present test results. The reason is the randomness of the debris jam development which might possibly be eliminated from the test results if the shapes of the debris jams are default in further test series.

6. Conclusion

Current and previous hydraulic model tests at the Laboratory of Hydraulic and Water Resources Engineering of the Technical University of Munich concerning debris jams at spillways as well as at racks for the retention of wooden debris were uniformly evaluated. The evaluation resulted in the Froude number of the approach flow and the debris density as the decisive parameters. The higher the Froude number of the approach flow and the larger the debris density, the more compact is the debris jam and the higher is its backwater effect. Due to the randomness of the debris jam development a more exact quantification of the dependence of the backwater effect on the Froude number of the approach flow and on the debris density is not considered useful for the present results.

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Notation

The following symbols are used in this paper:

a = exponent

$A_{T/L}$ = dimensions matrix

b = exponent

c = exponent

$C_{T/L}$ = proportionality constant

d = exponent

d_L = log diameter

e = exponent

F_0 = Froude number of the approach flow prior to debris jam formation

g = gravitational acceleration

h = flow height or flow depth

l = length

l_L = log length

L = length of the debris jam

m = mass

t = time

T = height of the debris jam

T/L = debris jam compactness

v = approach flow velocity prior to debris jam formation

W = width of spillway bay

$\Delta h/h$ = relative backwater effect

ρ_D = density of the debris

ρ_D/ρ_W = relative debris density

ρ_W = density of water