TRANSPORTE DE SEDIMENTOS: DA BACIA HIDROGRÁFICA ATÉ A FOZ
ABRHidro
Associação Brasileira de Recursos Hídricos
XIV Encontro Nacional de Engenharia de Sedimentos
Campinas / SP - Brasil
9 a 13 de novembro de 2020
XIV ENES
CAMPINAS | 2020

Longitudinal training walls on the Waal River (Netherlands) as a River training alternative

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ABSTRACT – Longitudinal training walls are man-made river dividers. They were built in the Netherlands as a replacement of perpendicular groynes as a river training alternative to decrease flood risk and stop the ongoing bed degradation, while still allowing safe navigation. The efficiency of these structures relies on the long-term stability of the two channels on either side of the walls. Sediment and flow distribution are mainly controlled by a sill that behaves as a side weir at the upstream end of the walls. Research conducted to understand the morphodynamic behavior of these sills concludes that three-dimensional flows are present and that their impact on sediment transport still needs to be investigated. This paper presents the historical events that led to the construction of the longitudinal training walls in the Waal River located in the Netherlands, a literature review of previously conducted research and the questions that still need to be addressed in future research to describe the sediment transport over the sill.

Keywords – river training, sediment transport, longitudinal training walls

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1 - INTRODUCTION

Longitudinal training walls are sand-filled structures built in the Waal river. These continuous walls separated by openings (see Figure 1) divide the river into a main channel and an auxiliary channel. At the upstream end, there is an inlet sill. The size and shape of this sill and the openings control the amount of sediment and water that flows towards the auxiliary channel.

During low discharges, the flow can be restricted to the main channel increasing the navigational depth. At high discharges, the water can flow through both channels reducing flood levels and bed degradation. In addition, it also provides mild flow conditions in the side channel that are favorable for the ecology [Collas *et al.* (2018)].

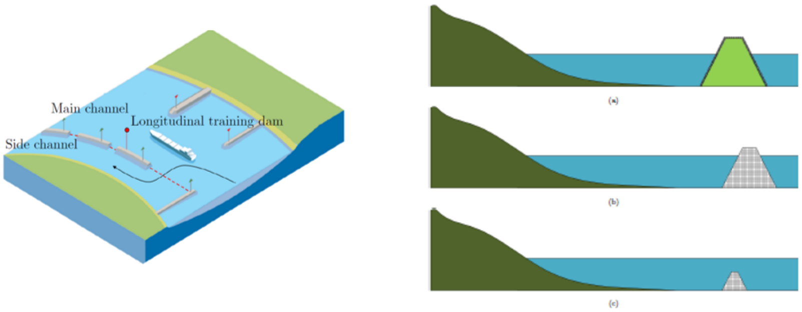

Figure 1 – Sketch of Longitudinal Training Walls (left) and cross sections of the longitudinal training structure (right a) and emerged and submerged sill (b and c) – [Jammers (2017)]

This paper presents the historical events that led to the construction of these structures and what is known about their morphodynamic behavior based on a literature review of previous research. It also provides recommendations for future research based on the identified knowledge gaps.

2 - HISTORICAL EVENTS

The Waal river is one of the most important Rhine River tributaries, consisting of about 2/3 of the Rhine discharge entering the Netherlands from Germany [Havinga *et al.* (2006)] (Figure 2). It has currently a main-channel width of 260 m and a mean depth of 5 m for medium flows (1600 cms). Over time, structural measures were carried out in the river to maintain its functions of safely discharging water, sediment and ice, while allowing use for safe navigation, agriculture, recreation and ecology. One of these measures was the construction of groynes that started during the Roman occupation in the Netherlands. They were built to prevent bank erosion and capture sediments for agricultural use. Further construction of groynes in the Waal occurred in the 18th and 19th century for what was called width normalization. The first normalization prevented the accumulation of sediment and the formation of ice jams during the winter. Although it was not the intended main goal of these measures at the time, the increase in velocity and water depth also improved conditions for navigation. The navigation channel was optimized further in the second and third normalization [Havinga (2020)].

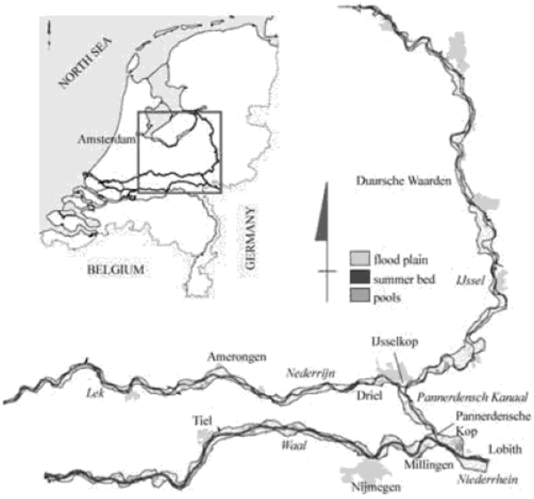

Figure 2 - Rhine River, two bifurcations, three distributaries of which the Waal River is the most important for inland navigation [Havinga *et al.* (2006)]

The construction of groynes at regular distances limited the low water to a channel with constant width. The impact of groyne construction added to the impact of bend cuts, large-scale sand and gravel extraction and reduced sediment supply from Germany. Together these interventions caused bed degradation of almost 4 cm per year [Havinga (2020)].

In 1993 and 1995 major flood events in the Netherlands led the Dutch Government to the development of programs focused on decreasing flood risk by increasing the space available and removing obstacles in the rivers. In 2007, the government started the Room for the river programme [(Dutch Water Sector (2019)]. The programme consisted of over 30 projects that included dike setbacks, river bed lowering and groyne lowering among other intervention.

Interest in navigation resurfaced after the admission of larger tows that would require an increase of the fairway dimensions [Havinga (2020)]. One of the proposed structural measures were the longitudinal training walls built in 2014 and 2015 in a 10 km reach of the Waal river. These structures would still allow the ice conveyance, providing additional benefits to navigation, flood control and the bed degradation condition.

Currently, longitudinal walls are also being considered for their applicability in other systems in the world including the Madeira River in Brazil (DNIT-USACE, 2019). Therefore, developing a deeper understanding of the benefits of these designs and the morphodynamic response of river systems to longitudinal will provide insight to other practitioners considering these design features.

3 - RESEARCH ON MORPHODYNAMICS AND SEDIMENT TRANSPORT

The construction of longitudinal training walls is a human intervention in the natural river system. It will cause short- and long-term impacts on the river morphology. At the upstream end of the longitudinal training walls, water and sediment are distributed between the two channels. This distribution will define the impacts and the stability of the system. For example, in an extreme scenario where half of the water is extracted from the main channel, but all the sediment remains, the main channel will silt up and close.

The ratio between water and sediment extraction from the main channel, along with friction and width reduction, can provide information about the long-term evolution of the channels. Another aspect to be considered is the position of the walls in respect to the crest of the river bars. Steady bars close to bifurcation points can alter the flow pattern and sediment transport direction, affecting the sediment distribution and the stability of the system [Le *et al.* (2018a), Le *et al.* (2018b)].

Le *et al.* (2018a, 2018b) conducted laboratory and numerical investigations on the morphological evolution of a channel divided by a long thin longitudinal training wall. The authors also evaluated the impact of variations of the widths of the channel and sediment characteristics on the results.

According to their research, if the start of the longitudinal training wall is on the upstream side of the crest of a bar in the same side of the auxiliary channel, it silts up, and if the start is on the downstream side than the opposite occurs. This trend does not change for different widths and sediment. However, an analysis of bed elevation data in the field demonstrated that aggradation in the auxiliary channel occurred when degradation was expected for one of the longitudinal training walls [De Ruijsscher *et al.* (2020)].

The difference in the observed aggradation and the laboratory results can be explained by the simplifications of the experimental set-up. Le *et al.* (2018a, 2018b) did not include the sill, nor consider the same general layout of the structures. This demonstrates the importance of the bifurcation geometry and the entrance sill on the control of the long-term stability.

The discharge distribution over the sill is mainly controlled by differences in longitudinal water level slope in both channels [Van Linge (2017)]. The entrance sill behaves as a broad crested side weir in which the amount of discharge is affected by lateral velocity, lateral angle and lateral outflow depth [Hager (1987), De Ruijsscher *et al.* (2020)]. Downstream of the sill, the streamlined flow forms two distinct features: an upstream horizontal secondary circulation cell and a downstream flow separation zone. The second one only appears when water is below the sill crest [De Ruijsscher *et al.* (2019), De Ruijsscher *et al.* (2020), Van Os (2020)]. Increase in flow magnitude and angle in the downstream direction over the sill also occur [De Ruijsscher *et al.* (2019), De Ruijsscher *et al.* (2020), Van Os (2020), Van Linge (2017)].

Sediment distribution at the entrance sill depends on how the particles, either in suspension or on the bed, will be affected by the different flow processes. The forces acting on the particle can help determine whether initiation of motion can occur and how far that sediment can be transported. Based on that, Jammers (2017) evaluated the particle trajectories in a conceptual particle model for both one and two-dimensional flow fields. A correction factor was applied to the Shields parameter based on the flow angle and the transverse slope.

Jammers (2017) analyzed combinations of flow angle and sill slope for different flows. The area between the dashed lines and the blue line, indicated in Figure 3, shows the possible combinations of sill slope and flow angles for which sediment particles are transported over the sill based on Jammers's model, assuming that the particle is initially located at the toe of the sill.

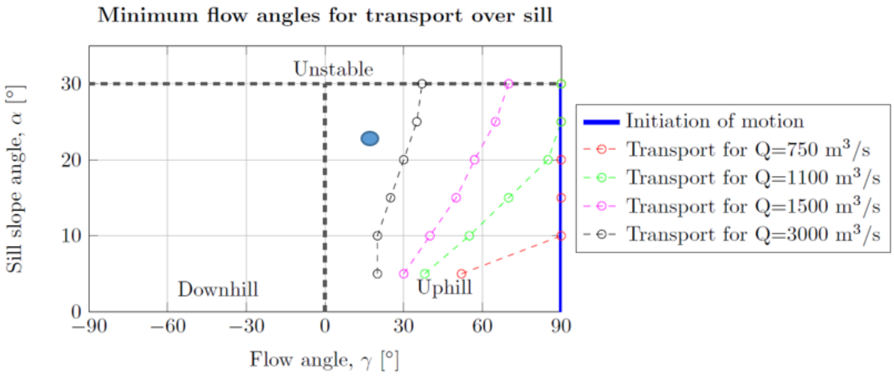

Figure 3 - Minimum flow angles for transport of sediment particle over the sill for different discharges (adapted from [Jammers (2017)]

The blue dot indicates the real field conditions of the sill which has a representative discharge of 1100 cms with a flow angle of 15° and a side slope of 21.8° (1:2.5). According to his model, for these conditions, no particle at the toe would be transported over the sill. This conclusion would not explain the observed aggradation in the side channel. The assumption of a logarithmic velocity profile that does not represent the acceleration at the sill and does not include secondary flow, might explain this divergence.

De Ruijsscher *et al.* (2019) conducted experiments in a scaled physical model of the longitudinal training walls. They investigated the impact of the sill geometry on the local morphology behind the sill. An inner-bend depositional bar and a divergence bar are formed downstream of the sill during low flows. Their shape and location are affected by the different tested geometries. His experiments were validated with field information where similar bars patterns could be observed (Figure 4). No conclusions were drawn on how the sediment from these bars passed over the sill, although their results demonstrated that the design of the entrance sill can impact the sediment being transported to the auxiliary channel.

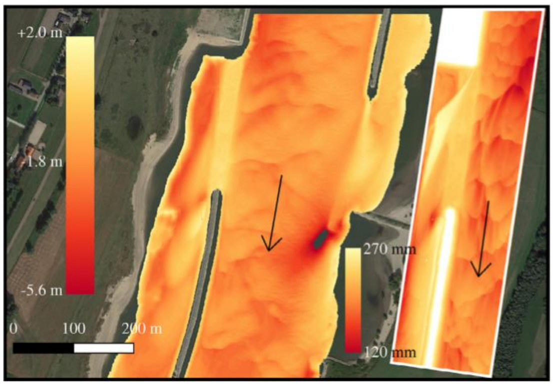

Figure 4 - Qualitative comparison of bed levels from lab and field measurements (Left: Bed level from multi-beam echo soundings Right: Bed level at the end of the experiment). [De Ruijsscher *et al.* (2019)]

Further research based on field measurements of velocity, bed load and suspended sediment load indicated that there is limited bed load sediment being transported over the sill [De Ruijsscher *et al.* (2020)]. The spatial distribution of sediment (Figure 5) shows that coarser sediment is present in the auxiliary channel at the upstream end of the longitudinal training walls, and not present at the downstream end. More data are required to determine whether this holds for all flow conditions.

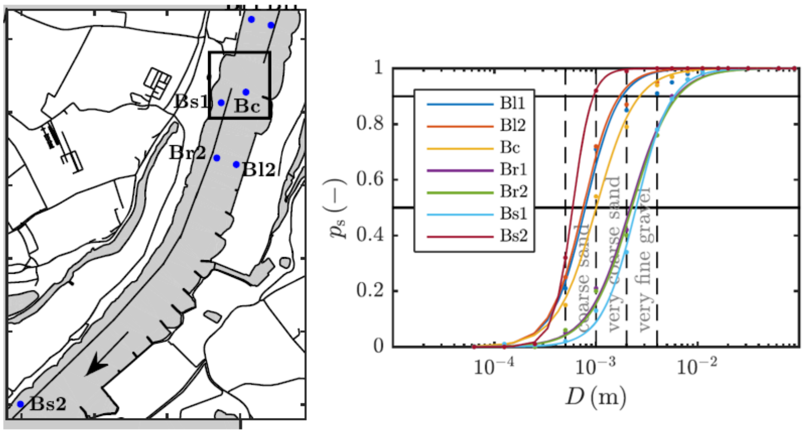

Figure 5 – Bed sample locations (left) and gradation of the samples (right) [De Ruijsscher *et al.* (2020)]

Van Os (2020) investigated the three-dimensional flow structures at the entrance sill based on a laboratory experiment. Flow velocities at the surface, mid depth and bottom were measured for different discharge distributions and degrees of submergence. Recirculation zones observed in her experiment match the observation by De Ruijsscher *et al.* (2018) (Figure 6). Her results also indicated the presence of helical flow due to blocking effects and curvature of the streamlines.

However, the impact of these flow structures on sediment transport remains to be investigated.

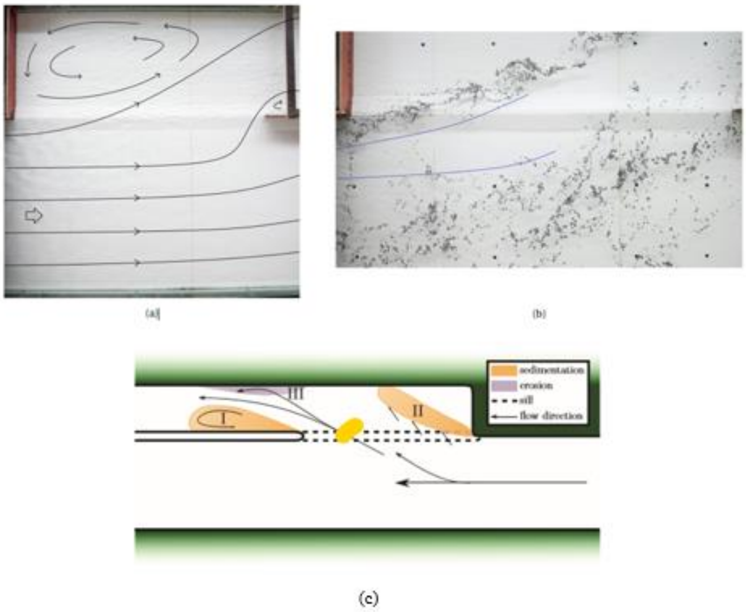

Figure 6 – Top view of the flume with hand-drawn flow lines (a) and during particle tracing measurements (b) [Van Os, (2020)] Schematic Overview of bed morphology at the bifurcations (c) [De Ruijsscher *et al.* (2018)]

4 - CONCLUSIONS AND RECOMMENDATIONS

Longitudinal training walls are structures built in the river as a replacement of perpendicular groynes. They were built to lower water level at high flows, a larger navigation depth at low flows, improved riverine habitats, and reduction of the ongoing bed degradation. The effectiveness of the training walls relies on the stability of the channels on either side of the walls. The amounts of sediment and flow passing through them need to be in balance to avoid uncontrolled deposition and erosion that can cause one of the channels to close. Quantifying the amount of flow going into each channel does not pose great problems but quantifying the amount of sediment presents a major gap in our knowledge. This knowledge is fundamental for evaluating the long-term stability and effectiveness of these structures. Therefore, based on the presented literature review some questions still need to be addressed to fully describe the sediment transport over the sill such as: What are the relevant three-dimensional flow processes that affect the sediment transport towards the auxiliary channel? How can sediment transport be estimated based on these processes? How can it be simplified for representation in two-dimensional depth-averaged models routinely used for evaluating the effects of river interventions? How could the design of the sill regulate the sediment transport through the auxiliary channel?

These questions can be answered by analyzing previous experiments to learn about the 3D hydrodynamic conditions at the entrance, collecting and analyzing field data, carrying out 3D hydrodynamic simulations, proposing suitable parameterizations, and implementing and testing the parameterizations in a 2D depth-averaged modelling environment. This is the challenge for a recently started PhD research project by the first author.

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