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Minimizing River Training for Flood Control, a Dynamic Concept

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I. INTRODUCTION

This paper presents a generalized approach for minimizing river training works, as elaborated from the design activities for protection works for the Border Meuse Project in the Netherlands. The approach focuses on minimization of the training works which adds to nature restoration and sustainable usage of protection materials, whilst the same time maintaining sufficient scour control during extreme floods (i.e. safety). The new concept is presented, as well as its application in the Border Meuse Project.

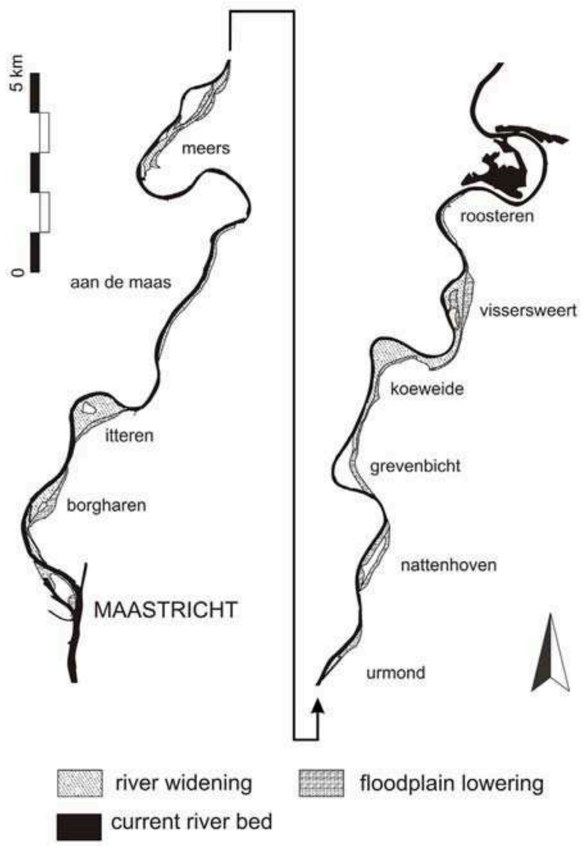

Figure 1. A schematic view of the Border Meuse project

II. BACKGROUND

The new approach was developed within the Border Meuse Project, which is shown in Figure 1. In this project the river will be altered significantly during the coming decade to accommodate higher design discharges, whilst not increasing flood levels, in combination with nature restoration. The alteration will be realized by widening the Border Meuse at gravel mining locations, the revenue of which allows the project to be carried out almost cost-neutral.

The Border Meuse is Netherlands' most natural river, with a (narrow) gravel bed and relatively high flow velocities. Especially in the remaining bottlenecks, in between the widened areas, flow velocities will further increase and erosion will intensify. Hence, the challenge was posed to the design team to minimize the protection works as much as possible and, at the same time, maintaining sufficient scour control to ensure safety.

III. PRINCIPLES OF DYNAMIC RIVER TRAINING

The conventional approach of the problem of ensuring safety against flooding through river widening is illustrated in the diagram below. Generally, the most dynamic locations are known from experience in the past. This knowledge leads to the decision that at those particular locations, regardless of the presence of important infrastructure (i.e. flood banks, bridge piers and other infrastructure of importance), river training works are required. Conservative design of river training works requires a minimum of knowledge of flow velocities and loads on bed and banks, so generally a minimum effort is put into studying these aspects. As a result, extensive river training works are often introduced. This line of thinking is illustrated in Figure 2a.

Because of the extensive river training works, such a conventional ('stable') approach also leads to high initial costs of construction. It is acknowledged that these require little monitoring and maintenance but, on the downside, this approach is not particularly sustainable altogether.

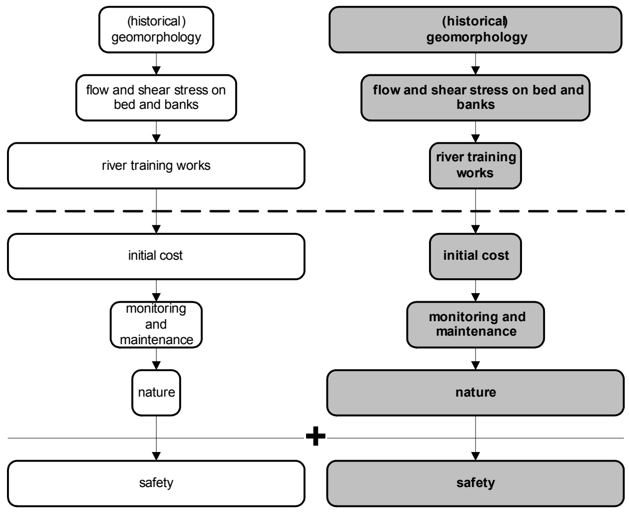

Figure 2. Schematic view on the conventional (a) and dynamic (b) approach in designing river training works to achieve a certain degree of safety.

Gradually, during the design process for the Border Meuse, a dynamic concept was arrived at, in a sense that river training works are only designed at locations where scour of bed and/or banks pose a direct threat to safety. Where no immediate threat is posed, generally the river is allowed maximum freedom [1,2]. Additionally, if scour and bank protection are needed, it is attempted to minimize protection works as much as possible. Nature development will certainly benefit from the increased river dynamics.

Such a dynamic approach requires that the emphasis is laid on different aspects of the design process as well as certain aspects after completion of the stabilization works. This is illustrated in Figure 2b.

Contrary to the stable approach, emphasis is laid on a more thorough assessment of the geomorphology of a river to begin with, rather than focusing on the actual design of river training works too early. After a thorough study of the rivers' geomorphology, the flow and loads on the bed and banks of the rivers bed are investigated in-depth. The combination of these two aspects and knowledge of the location of important infrastructure, such as flood banks and bridge piers, make that it is possible to identify locations where river training works are really a pre-requisite to ensure safety. Hence, the length of river section to be stabilized is minimized, contrary to the conventional approach.

Having minimized the extent and composition of river training works, the initial cost of construction will be much lower as well. However, it is important that more effort be put into future monitoring and maintenance of the river. An important advantage is that a more dynamic river adds significantly to nature development. Most importantly, with the dynamic approach the same degree of safety is achievable as the safety with a conservative protection works at lower (lifecycle) costs. As Figure 2 already suggests, the dynamic approach is much more balanced and sustainable.

In summary, the following three principles of the dynamic concept are:

1) Identification of areas potentially at risk, whilst maximizing river dynamics as much as possible. This is done through assessment of the geomorphologic behavior of the river where relevant for the safety against flooding.

2) Flow field and shear stress data collection and prediction. In order to obtain a detailed prediction of the hydraulic and morphologic structure of the present and – where relevant – the future river configuration at areas potentially at risk.

3) Introduce 'lean' dimensioning of the river training works. This implies using the relevant information of 1) and 2) and state-of-the-art dimensioning tools. Where possible, the principle of dynamic stability is applied.

Hereafter, these principles will be explored in detail.

IV. PRACTICAL APPLICATION OF THE DYNAMIC CONCEPT ON THE BORDER MEUSE

A. Identifying areas potentially at risk

Bed and bank protection works are only introduced where important infrastructure such as bridge piers or flood banks are found within a certain distance from the river bank. The critical range between infrastructure and ultimate river bank position must be chosen on a sound basis of knowledge of (historical) and anticipated geomorphologic behavior of the river.

The amount of outflanking that can occur within the passing of the design flood wave is a good measure. For the Border Meuse, a relatively conservative distance of 50 meters was adopted: Study of the historical erosion of river bends [3] learned that in 15 years, a maximum outflanking of 5 to 10 meters at maximum could be expected. If important infrastructure is found outside the 50 meters zone, its stability will not be affected due to the design flood event. It may, however be necessary to repair damage to the banks afterwards so as to keep the river at a reasonable distance from the infrastructure.

A typical aspect of the Border Meuse as arose from geomorphological analysis, is the fact that generally the inner bends tend to erode much faster than the outer bends. This is due to the hard points in the outer bends and to the flood plains near the inner bends that overflow during flood events and direct the flow towards the inner bank.

B. Flow field and shear stress data collection and analysis

Having identified spatial limitations, flow velocities in the old and new situations are analyzed using a hydraulic model (see also section VI for specific issues regarding the use of hydraulic models). If flow velocities do not increase significantly, bed and bank protection works are not necessary (implicitly assuming the existing bank (protection works) to be in a well maintained condition and stable). If not, the actual flow patterns for design conditions are assessed as a next step.

Assessing the flow velocities in the new situation requires thorough knowledge of the hydraulic and geomorphologic behavior of the river and knowledge of bed and banks (whether protected or not).

Next, shear stresses acting on the bank and bed are analyzed. In the Border Meuse case, most of the bed consists of the coarse gravel ('toutvenant'), a type of gravel that is very resistant to current attack and has a low mobility at increasing loads. The characteristic flow resistance of the material in terms of critical shear stress is approximately 27 N/m^2. This corresponds roughly to a critical current velocity of 2 m/s. In the initial design it was therefore decided to adopt this critical shear stress for the full length of river.

Knowing the flow field at design conditions from the hydraulic model, it is possible to assess the level of exceedence of critical shear stress in the identified areas at risk. Next, on locations where critical shear stresses are exceeded, the equilibrium scour of the river bed can be determined.

If the above three criteria related to flow and shear stresses are met, it is likely that at the identified location, flow conditions may result in erosion of the river bank to such an extent that important infrastructure can be damaged. It is then necessary that the identified location is considered in greater detail to assess whether bed and/or bank protection works are required to ensure safety. In Fig. 3, the result of the identification of areas potentially at risk and analysis of flow and tractive forces is shown for the location Meers [5]. The black line around the model results represents the distance of 50 meters. It is readily seen that the flood bank lies within the chosen distance.

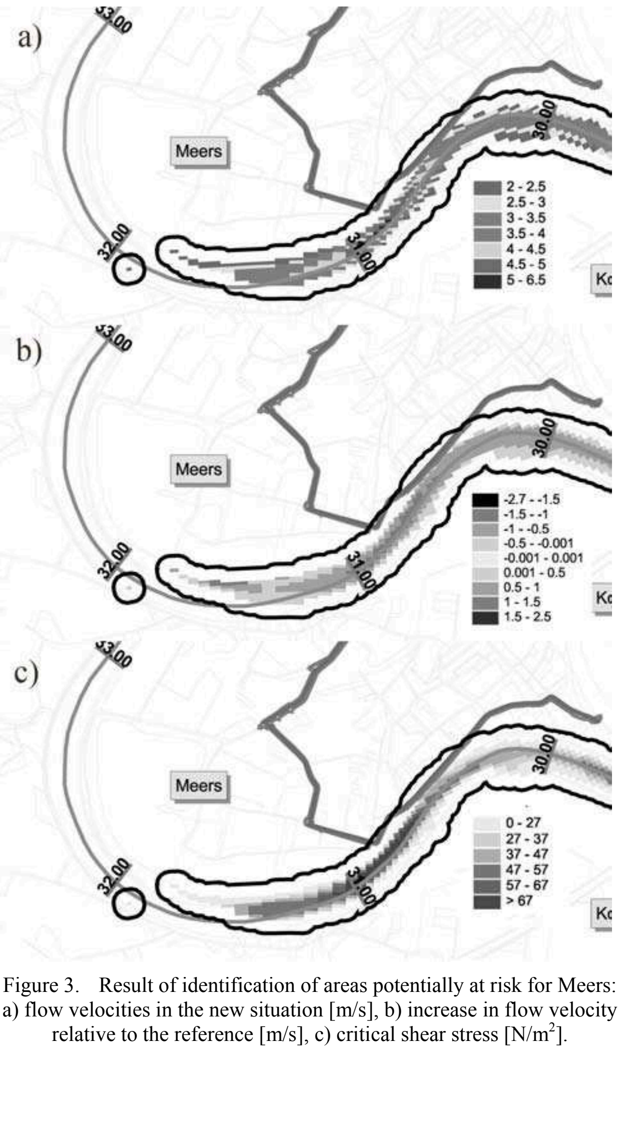

Figure 3. Result of identification of areas potentially at risk for Meers: a) flow velocities in the new situation [m/s], b) increase in flow velocity relative to the reference [m/s], c) critical shear stress [N/m^2].

All areas that do not meet the three criteria simultaneously , principally do not require strengthening of bed and banks. However, it is of great importance that, since the river is still allowed freedom on these locations to alter its flow, monitoring of planform changes after significant floods is carried out. Monitoring is necessary to ensure that safety is maintained not only immediately upon completion of the river works, but also for the medium and long term. Adequate monitoring is a key activity when maintaining scour control in a natural river.

C. *Lean dimensioning of river training works*

If the river banks of the identified area at risk are protected it is required to assess their resistance to the current attack. Dealing with a substantial length of river of which a large part is covered with bank protection works, the exact nature of the construction is often unknown at many locations. Not only is it very unpractical, but also very costly to investigate all banks to such an extent that it is possible to properly determine their resistance to current attack. It has therefore been decided that if the banks in the identified areas at risk are unprotected or if uncertainty had arisen regarding its construction, new protection works are necessary.

Obviously, if the nature of the existing bank protection works is adequately known, it is possible to determine threshold levels in terms of a critical velocity that should not be exceeded so as to ensure bank stability. In the Border Meuse case, the banks have historically been protected with rock armour of 10 – 60 kg or 40 – 200 kg. These are resistant to flow velocities of 3.0 m/s and 3.5 m/s respectively. If these threshold levels are exceeded, a new design must be made. If they are not exceeded, monitoring will still be necessary to ensure stability for the future.

In hydraulic bottlenecks, extreme flow velocities on the bed and the lower parts of the banks do generally not exceed 4.0 m/s, except for some locations where velocities up to around 5.0 m/s are found (Fig. 3a). In these more extreme cases other types of bank protection are required in stead of conventional rock. Particularly since it is not desirable to use extremely large sized rock because of the nature restoration objective of the Border Meuse as well as the narrow cross section that is restricted further when applying extremely large rock.

Further up the slope of the river banks, however, velocities decrease rapidly and smaller size of rock suffices to ensure bank stability. In the Border Meuse, toutvenant is abundantly present in the higher layers of soil and thus at the top end of the river bank. This allowed us to use the naturally present material for bed protection,, rather than to introduce rock on the top of the slopes.

The flow resistance of the toutvenant compares to 40/100 mm rock. Since slopes are generally steep along the Border Meuse, it was possible to limit the impact on the natural banks.

An important part of the design of bank protection works is a proper toe construction at the bottom of the slope. Hence, bed stability is also an important issue, since significant scour in the river bed may lead to damage to bank protection works. If scour potential of the bed is considered relatively low, say up to 5 meters, a falling apron may suffice. However, at some locations a much higher scour potential is expected and the river bed must be stabilized across its full width.

Bed stabilization is necessary if the bed material is highly erosive in the new situation, if a positive gradient in the sediment transport occurs and when the equilibrium depth scour depth is large. This is typically the case in the bed section in the hydraulic bottlenecks that are inherently created when widening the river immediately downstream.

If these conditions do not apply, however, it may not be necessary to stabilize the bed. Clearly, adequate monitoring will still be necessary in this case.

V. SOME SPECIFIC DESIGN CONSIDERATIONS

A. Choosing a significant discharge for design of river training works

Along the Border Meuse, flood banks were originally designed for a flood discharge of 1/50 years. After completion of the project, the level of safety should meet the 1/250 standard. This would imply that the bed and bank protection works should meet the same standard. However, applying this standard criterion does not guarantee safety during floods with a lower frequency of occurrence, as followed from hydraulic computations. These computations showed that hydraulic circumstances of less extreme events should be taken into account locally, for instance the 1/50 flood discharge, at which the shear stresses at bed and banks were higher. This causes the design flood event to vary along the river and hence, a longitudinally varying design limit may be necessary.

It was found that the 1/50 flow velocities exceeded the 1/250 flow velocities in 12 of the 18 areas at risk with averagely 0.40 m/s. In extreme cases, flow velocities may exceed the 1/250 circumstance with 1.0 m/s – 1.5 m/s. This results in flow velocities up to 4.5 to 6.0 m/s at normative conditions [3].

In the Border Meuse case, only the 1/250 design flood has been taken into account as a first step in the design. More detailed study is yet to be carried out.

Additional to deciding on the normative discharge for bank protection design, attention should be given to the construction phases of the river adaptation works. Inherently to the scale of these works, a large period of construction with many intermediate situations may exist. In the Border Meuse case, a total of 13 locations are widened in 14 years. The order in which the locations are widened are not hydraulically and morphologically optimized (which would probably mean to start downstream and gradually work in the upstream direction). In fact, since the project is largely funded by the revenue from mining gravel in the process of widening the Border Meuse, the order is governed by other considerations, such as economics.

In terms of river training works, the above implies that during the 14 years of construction, the areas at risk may differ from the areas at risk once the entire project is completed. Still, safety must be guaranteed not only at the end of the project and afterwards, but also during the construction. It is expected that the intermediate hydraulic circumstances that occur during the construction phase, may require the use of temporary bed and bank protection works and / or result in higher design criteria where bed and bank protection works were already expected after completion [3].

Needless to say, the significant discharge for the design of bed and bank protection works after the project has been completed – and which varied for different locations along the river – may well vary from the significant discharge during construction at the same location.

The latter issue of intermediate circumstances is not yet fully addressed and requires further work.

The above shows that deciding on the normative discharge is not an easy issue.

B. The use of hydraulic models

In order to properly assess scour potential and design criteria for bed and bank protection works, reliable flow information is required. In the Border Meuse case, the flow patterns were derived from a curvi-linear WAQUA model. This state-of-the-art model provides sufficiently reliable results where the river bed is relatively level in cross-section. Due to the relatively steep slopes of the river of the Border Meuse, results are less reliable near the banks. The diagram below shows a typical cross-section of the Border Meuse [5]. It is readily seen that the flow velocity from the bed towards the bank drops dramatically according to the WAQUA model. This could lead to underestimating flow velocities on the bank.

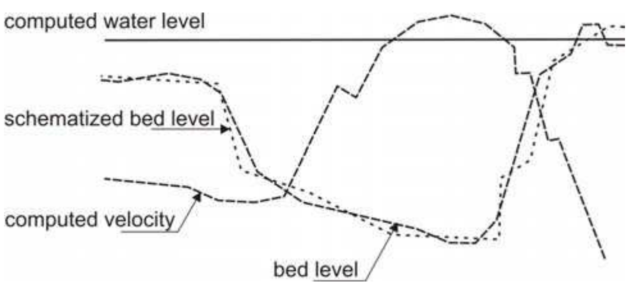

Figure 4. Cross-section with water levels and flow velocities

This problem was solved using the last reliable result near the toe of the bank as a reference. The flow velocity may then be computed assuming the water level gradient at the slope (i_{bank}) to be equal to the water level gradient in the channel (i_{bed}). This requires that a slope roughness be assumed also. Here, a Nikuradse roughness of k_s = 0,2 m was assumed. As the slope roughness depends on the applied grade of rock in the bank protection works, flow velocities on the river bank need to be solved via iteration.

Another important aspect which is not represented in steady-state flow computations is the Jones' effect [7]. The Jones' effect is the effect that during the rising stage of a flood wave, flow velocities are higher than the flow velocities with a corresponding water level after the passing of a flood wave. However, using a hydrodynamic model to incorporate this effect is generally not practical and cost-effective due to the required high resolution (on average 10 x 40 meters in the river bed) and the large number of simulations to must be run for different normative discharges and construction stages.

From theoretical analysis it was found that in the case of the Border Meuse, actual flow velocities can be some 5 percent higher than computed with the steady-state hydraulic model for the 1/250 design flood. In the case of less extreme events, the Jones' effect will be stronger and actual flow velocities may even be 10 percent higher than computed. .

C. Maintenance & unpredictability

Having minimized bed and bank protection works through the above methodology, verification is still required. The bed and bank protections need to be included in the hydraulic model, so as to see whether the influence of these works lead to a significant change in potential areas at risk, flow velocities and so forth. In the Border Meuse case, it has been found that the flow pattern is influenced significantly and may lead to more protection works in order to establish the required safety. Rough estimates for the Border Meuse have lead to several kilometers of additional bed and bank protection works [6].

VI. CONCLUSIONS

Using the dynamic concept and methodology, it is very well possible to maintain a natural and (relatively) free flowing river after the alterations. This means: minimum bed and bank protection works whilst maintaining safety. Such a dynamic design concept adds value to nature development in the flood plains.

Normative (design) discharges need to be chosen carefully. Extreme events in terms of flooding do not necessarily result in the most extreme loads on bed and banks of rivers. It may be necessary to use different normative discharge on different stretches of the river. Moreover, when dealing with a large scale river alteration project, many intermediate hydraulic circumstances should be considered during the construction phase, during which design loads may vary. This could also lead to the need for temporary bed and bank protection works or alteration of the final works.

Hydraulic models are of the utmost importance for identification of areas at risk and for delivering boundary conditions for the design of bed and bank protection works. The results, however require careful consideration and use as well as engineering sense, especially where sudden discontinuities exist in the cross-sectional geometry. Verification of computations with an initial design of bed and bank protection works is always necessary. The influence of bed and bank protection works on the flow patterns is thus that greater lengths of bed and bank protection works may be required (using the methodology developed) because current attack increases in new areas.

In all of the above problems that face the design engineer, thorough knowledge of the geomorphology is key to minimizing protection works. Inherently attached to minimization of the protection works, monitoring of morphodynamic behavior is an important aspect of river maintenance. Rather than focusing on the upkeep of massive bed and bank protection works, focus should be put on monitoring hydraulic and morphologic changes – preferably combined with an updated hydraulic model to assess changes in (the location of) areas at risk – to support maintenance. This will add to a sustainable river development where its freedom is only limited when safety is threatened.

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