The Integrated River Engineering Project on the Danube to the East of Vienna, River Bed Stabilisation by Coarsening of Bed Material – Section Model Tests

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ABSTRACT

The deepening of the river bed of the Danube to the east to Vienna has brought a lowering of the water level, which has negative effects on ecology and water balance. The rehabilitation project comprises several measures. The most significant one is the granulometric bed improvement (GBI) to stabilise the river bed by coarsening the bed material by a gravel layer of grain sizes within the grading curve of the river. Hydraulic model tests were conducted in a 2 m wide and approx. 30 m long channel at a scale of 1:10 in order to investigate the behaviour of the added material. It was verified that the layer of coarse gravel withstands the local bed shear stress at the highest navigable water level. Beyond this discharge level the added layer of coarse gravel mixes with the natural bed load at areas of larger local stress due to locally limited erosion of the added layer and consequent scour building.

1 INTRODUCTION

During the last decades, the deepening of the river bed of the Austrian Danube to the east to Vienna (about 2 to 3 cm per year) has brought about a lowering of the water level and the accompanying groundwater level layers, which has negative effects on the water balance and thus on the floodplains of the "Donau Auen Nationalpark". This national park with an area of about 93 km² is the largest river wetland ecosystem in Central Europe. To solve the existing problems the national waterway operator "ViaDonau - Oesterreichische Wasserstraßen-Gesellschaft mbH" launched the "Integrated River Engineering Project on the Danube to the East of Vienna", which is also targeted at improving navigation related conditions. The respective segment of the Danube has a length of approx. 51 km. At the point in question the river has a width of approx. 300 m, an average discharge of approx. 1,930 m³/s, HQ100 of approx. 10,400 m³/s and a bed load transport capacity of approx. 330,000 m³/a.

The project comprises measures like the regulation of the low water level, renaturation of the artificially constructed river banks and creation of a network of

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waters by connecting ox bow lakes and distributaries of the Danube River to preserve and to improve the ecology of the surrounding national park. But the most significant one is the so called granulometric bed improvement (GBI) by coarsening the bed material in highly stressed areas for the stabilisation of the river bed. The objective of this method is to dynamically stabilise the river bed and to reduce the bed load transport by about 90 %. ViaDonau commissioned the above stated institutes with hydraulic model tests in order to investigate the behaviour of the GBI on stability and mixing since this method has not been applied in this way yet and since there are detailed questions on bed load transport processes and bed morphology.

2 GRANULOMETRIC BED IMPROVEMENT

The GBI was developed by DonauConsult Zottl & Erber ZT-GmbH (engineering consultants).

The basic idea of the GBI method is to apply a 25 cm thick layer of coarse gravel (grainsize 40/70 mm or similar) to the bed of the Danube River in highly stressed areas of the channel. The grading curve of the added material lies within the natural range of the grading curve of the Danube bed load (0 to 120 mm, with a mean diameter dm of about 27 mm calculated according to Meyer-Peter and Mueller 1948). In the course of time the added material should mix with the natural bed load of the Danube due to the stress at high water. The material will presumably mix in a ratio of 1:1 (figure 2, left part). The grading curves of the bed load, of the added material in the model test and of the mixed bed load are shown in figure 1. The right part of figure 2 shows a cross section of the river bed in a model test, immediately after the coarse gravel was added. With 25 cm of added gravel (40/80 mm), about 4 to 5 grains lie on top of each other.

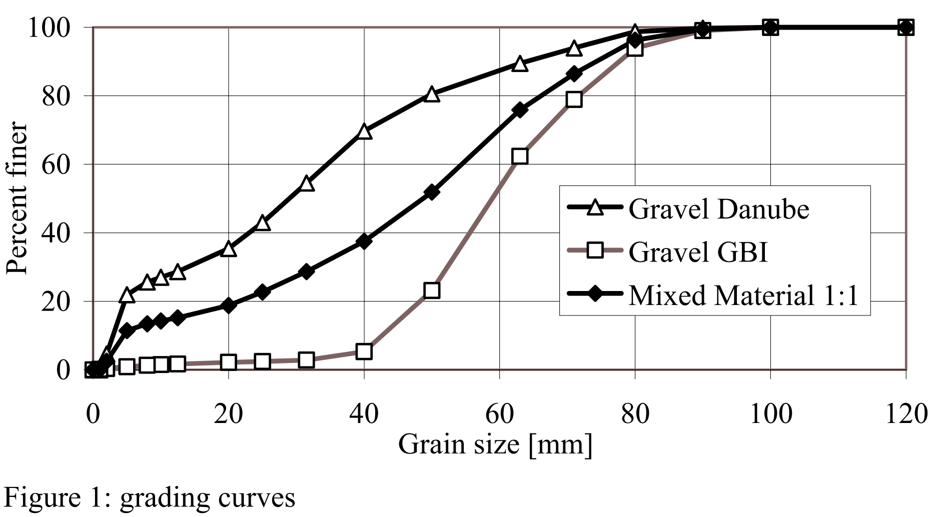

Figure 1: grading curves

The mean grain diameter of the mixed bed load (ratio 1:1) is approx. 47 % bigger than the present bed load. This coarser bed load reduces the calculated transport capacity by 90 %. Since hardly any bed load is naturally added in this segment of the Danube, the remaining 10 % coarse gravel (approx. 33,000 m^3) need to be added every year.

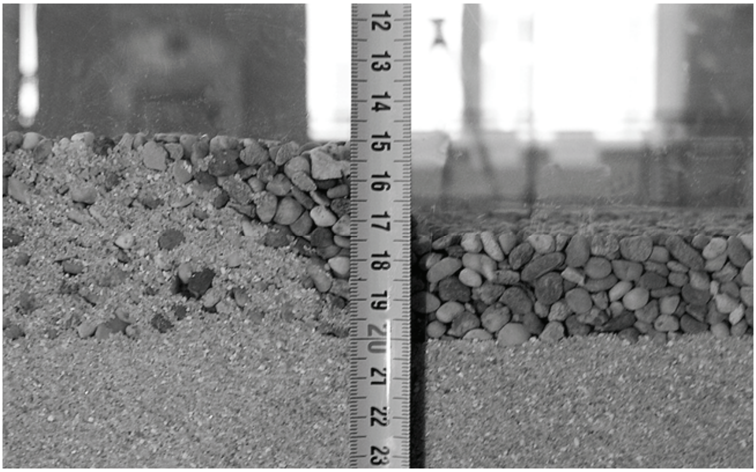

Figure 2: granulometric bed improvement, right: initial condition, left: mixed with Danube gravel 1:1, model scale 1:10

3 EXPERIMENTS

3.1 Scaling and test facility

The length scale of 1:10 of the model was chosen in order to be able to simulate more than 90 % of the grading curve in the model and in order to avoid any non-natural bed forms in the model test. For scaling Froude's model law was used (e.g. Bogardi 1959). The section model was a straight channel, approx. 30 m long, 2 m wide and 1.2 m in height. A constant water flow on the actual test area was produced by an intake canal with a stilling basin. The channel's discharge capacity was 2,500 l/s. At the end of the channel a bed load trap and a flap-gate for controlling the water level in the channel was installed. One side of the channel was made of plexiglass, in order to be able to monitor the flow pattern and morphological processes. The other side was made of very smooth plastic. Due to these smooth vertical walls on both sides of the channel their impact was reduced to a minimum and thus the model could be quite narrow. The minimum ratio of channel width and depth of flow was approx. 2.5, i.e. just sufficient. If the lateral walls were rough, a ratio of at least five would have been necessary in order to eliminate the impact of the sidewalls. Additionally the impact of the sidewalls was taken into account in the planning of the model tests and in the analysis of the measuring results, i.e. they were eliminated numerically.

The length of the channel has an impact on the accuracy of the production of the gradient of the channel bed, as well as on the accuracy of measuring of the gradient of the flow. The gradient of the Danube in the respective section is 0.04 % on average. Froude's model law says that the gradient needs to be the same in nature and in the model, this means that a difference in height of 0.4 mm per meter model length is necessary and 8 mm on a length of 20 m. An inaccuracy in measurement of ±1 mm results in an inaccuracy in measurement of ±0.005 % or 12.5 % based on the channel bed gradient of the Danube on a length of 20 m. The gradient of the section model was doubled in order to reduce (cut in half) the inaccuracies in measurement of the gradient. This increase of gradient is admissible, since in the section model tests only the behaviour of the channel bed in relation to the existing bed shear stress is of interest and not the real water depth as in high water protection projects.

3.2 Experimental program

Several different possible variations of granulometric bed improvement were tested (table 1), amongst them the initial condition immediately after the adding of coarse gravel (gravel corresponding to a grading curve of 40/80 mm in nature was used in the model), then the initial condition after mixing with the original bed material, intermediate conditions during construction phase and possible faults during production.

Experiment	Description	Content
V01	Initial condition	full-scale layer of coarse gravel 40/80 mm, height 25 cm
V02	Partially uncovered area	50 m long section of the Danube without added layer, remaining segment upstream and downstream with layer of coarse gravel 40/80 mm, height 25 cm
V03	Longitudinal seam	left half of the channel with added layer of coarse gravel 40/80 mm, height 25 cm, right half with Danube gravel
V04	Mixed material	full-scale layer of coarse gravel 40/80 mm and Danube gravel mixed in a ratio of 1:1, height 50 cm
V05	Faults	4 areas each 5x30 m, area 1 without coarse gravel, areas 2, 3, 4 with 10 %, 22 %, 200 % coarse gravel in relation to initial condition, remaining section of the segment complies with initial condition

Table 1: five versions of model tests

Different levels of bed shear stress calculated for the Danube to the east of Vienna were the basis for the precise experimental program. The data for the range of discharge of reference low water levels (RLW) above highest navigable water level

(HNW) up to 100-year flood (HW100) were available. Figure 3 shows the different calculated levels of bed shear stress for one section and the respective amounts of discharge for the whole test section.

We used data of the calculated range of bed shear stress for the model tests, starting with the lowest value (11 N/m² = medium load at low water) and gradually increasing up to the highest value (50 N/m² = peak load at HW100). Thus the behaviour of the river bed at an increasing level of stress could be monitored. Every test series lasted for 268 hours (natural conditions).

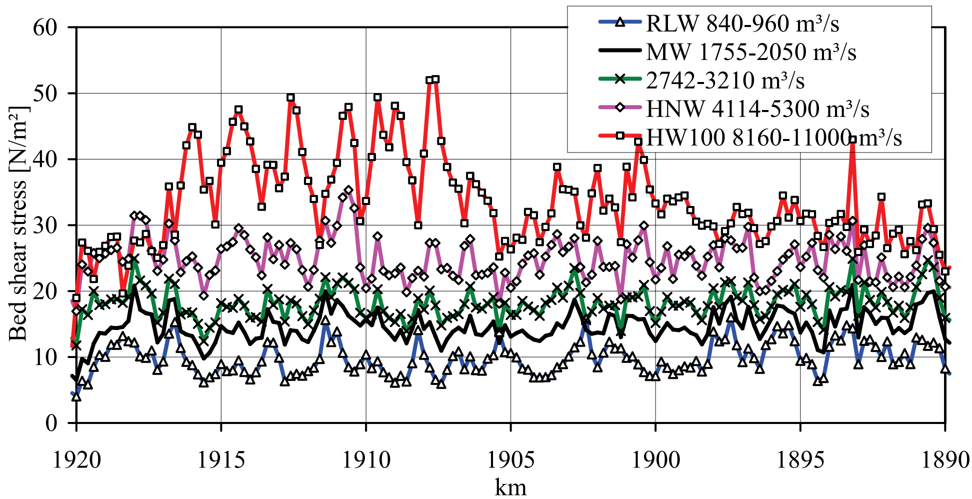

Figure 3: different bed shear stress subject to discharge on a 30 km section of the Danube (Source: 1d calculation DonauConsult)

4 RESULTS

The **results of test series V01** clearly show that granulometric bed improvement is successful in stopping the large-scale deepening process of the river bed of the Danube for the most part or at least in reducing it largely. From shear stress levels of approx. 40 to 45 N/m² onwards bed load transport increases in the model. This complies with a range of Shields-values between 0.031 and 0.070 for a grading curve of 40/80 mm. The added material mixes with the bed load of the Danube in areas with greater local stress – e.g. in some areas at highest navigable water level HNW – as a consequence of local disruptions of the added layer and the development of scours. The added material is transported in the form of bars, wandering over the added layer without damaging it or mixing any further with it. The highest navigable water level complies with the annual discharge of the Danube.

The **results of test series V02 (partially uncovered area)** simulating uncovered ford zones or areas across to the direction of the flow without the layer of added material show that up to the mean bed shear stress at HNW there is no significant dispersion of material out of the uncovered areas. An increase of discharge, however, favours the development of scours, from which original bed material, partially mixed with newly added material from the downstream edge of the uncovered area is transported in the form of a bar over the added layer without destructing it. This bar was approx. 1 m in height after exposure of stress of 30 N/m² (medium bed shear stress at HW100). At τ = 45 N/m² the added material started to move, similar to test series V01.

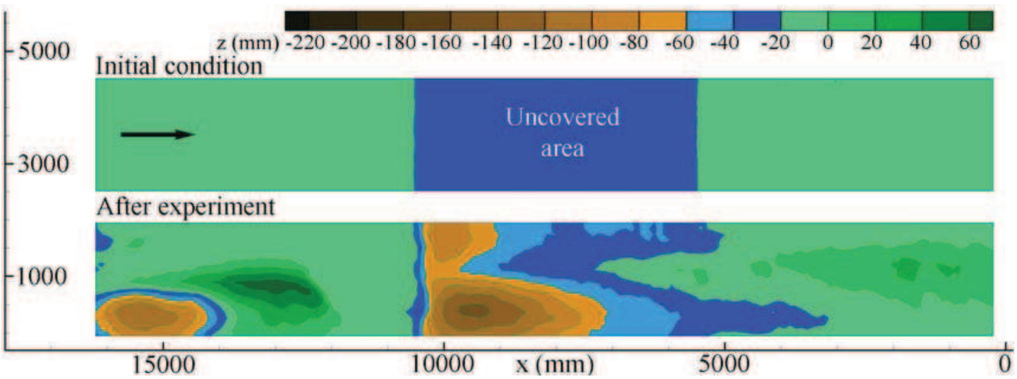

Figure 4: heights of bed before and after test V02 (uncovered area) – model dimensions

The upstream edge of the uncovered area remains stable even under highest stress with the exception of some few stones. The downstream edge erodes with increasing boundary shear at some exposed areas. There is no risk, however, that the downstream layer of added material will erode on a large-scale basis.

Test series V03 examined how the transition in lengthwise direction from areas with the added layer of coarse gravel to uncovered areas would effect the development of the bed and the added layer.

The test series which was conducted in the same way as the aforementioned series up to a bed shear stress of τ = 50 N/m² shows that the added coarse gravel layer is not destructed in any way in the transition area as long as no deep scours extending into the transition area develop into the half of the Danube gravel. With bed load beyond medium bed shear stress at HW100 secondary flows develop sediment loads in the area of GBI, moving over the added layer without destructing it. The model showed a slight lateral inclination of the water level from the covered to the uncovered part. In the uncovered area a ravine developed concentrating the discharge. The reason for this is that the bed load transport of the Danube gravel starts much earlier than the transport of the coarse gravel, the bed shear stress was equally distributed across the width of the channel in the beginning and consequently the load is shifted to those areas which are easier to erode. Measurements of current velocities near the bed show that in the uncovered areas of the channel the currents are significantly faster than in areas with the added layer of coarse gravel.

Test series V04 with the 1:1 mixed material showed that up to stress of $\tau = 30$ N/m² bed load is only partially transported. Beyond bed shear stress of between $\tau = 34$ and 39 N/m² bed load transport is increased. This complies with Shields-values between 0.048 and 0.055 for the mixed material (dm = 44 mm). After peak stress of $\tau =$ 49 N/m² (Shields-value 0.069) several scours develop in the bed, from which the bed load is transported downstream.

The **test series V05** examined the consequences of possible technical faults during the production of the coarse gravel layer. Focus of this test series are areas which are not correctly covered by the added layer of coarse gravel, i.e. too much or not enough material. It was meant as an analysis of a range of possible faults rather than as an examination of every possible fault and gives a qualitatively rather good overview. It is to be presumed that the consequences of actually occurring construction faults can be created by combining the single tested faults.

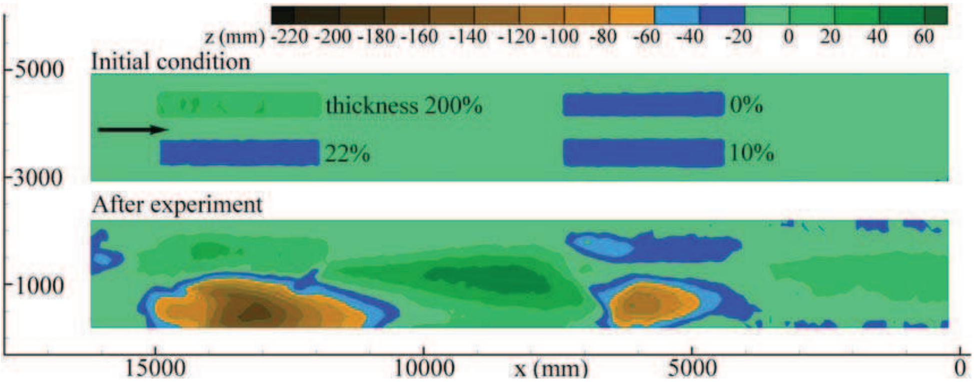

Figure 5: heights of bed before and after test series V05 – model dimensions

The results of test series V05 largely verified the results of previous test series. Additionally local bed shear stress peaks were observed, produced by the rough river bed, which caused locally varying bed morphological deformations.

Even with low stress fine material was dispersed and scours developed in the uncovered area. The scours did not become very deep and the edges largely remained stable up to $\tau =$ approx. 40 N/m². As a consequence of a shift of the main current to the other edge of the channel the bed remained more stable in this area than expected.

Up to $\tau = 20$ N/m² the development of the bed in this area with 10 % cover was similar to the uncovered area. The bed largely remained stable up to medium bed shear stress at HW100. Beyond $\tau = 40$ N/m² scours developed significantly faster compared to uncovered areas due to the shifting of the current to the above mentioned side of the channel and thus higher bed shear stress.

The one-layer cover (22 %) started to decrease as soon as the bed shear stress complied with the highest navigable water level (HNW). A small scour developed at the end of the test with HW100. At a bed shear stress of 40 N/m² scours developed quickly in this area, probably due to higher local stress at the beginning of the channel. The material from the scour moved downstream in the shape of a bar towards the centre of the channel and caused the aforementioned shift of the current to the side of the channel.

In the area with double-layer cover there was no levelling during the whole testing period although the edges of the layer protruded the surrounding bed. Additionally there was no evidence that local changes in flow ratios cause higher stress in the close environment.

5 CONCLUSIONS

The experiments verified that the layer of coarse gravel withstands the local bed shear stress of the highest most possible navigable water level. Beyond this discharge level the added layer of coarse gravel mixes with the bed load at areas of larger local stress due to locally limited erosion of the added layer and consequent scour building. In case of the River Danube the planned GBI is suitable for bed shear stresses up to 40 N/m² (local and temporary up to 45 N/m²). This stress complies with Shields-values from 0.056 to 0.063 for the mixture of Danube gravel and added coarse gravel 40/80 mm (1:1 ratio). Tests at the edges of the GBI (transitional zone of the added layer of coarse gravel and natural bed load of the Danube) showed that even with minor bed shear stress a further type of mixing of material takes place. The more the stress increases the more mixing takes place comprising material of the river bed from non-stabilised areas and parts of the coarse gravel of the transitional zone. Tests on the consequences of areas with a thinner layer of added material showed that even with smaller discharges scours develop due to local currents and higher local stress, which does not mean, however, that these thinner layers of added material, if these areas are limited in size, are expected to cause the bed stabilisation measure to fail in general.

After these section model tests the very promising method of granulometric bed improvement should be tested in a larger full scale model to study the behaviour under fully three dimensional currents where higher turbulence is expected. Furthermore different bed stress levels occur lengthwise and lateral to the flow direction due to geometry and variable local currents.

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