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OPTIMIZATION OF CONCENTRATING STRUCTURES FOR RIVER REGULATION WITH THE USE OF CFD

P. Fošumpaur*

Abstract: *Currently, a project to improve navigation conditions on the Elbe River downstream the Střekov waterwork is preparing. Concentrating structures are important elements in this concept from the 19th century. This paper describes an optimization of newly designed concentrating structures in the frame of the Elbe regulation with the use of computational fluid dynamics (CFD). Analysis is also based on experiences with historical spur dikes. The results were compared with measurement on the physically based model and in situ.*

Keywords: ***concentrating structures, spur dikes, computational fluid dynamics***

1. Introduction

The historical development of modifications of navigable reaches of the Elbe and Vltava rivers shows early stages of such interventions simultaneously with early settlements in the river valleys in medieval times. Modifications of riverbeds reflected the human need for rational utilization of river conditions while reducing harmful effects of water at times of floods and hydrological droughts. The early interventions were effected for various purposes, which included harnessing the power of water for driving mills, sawmills and iron mills by building solid weirs as early as in the 13th century. Another notable purpose for modifying watercourses was to achieve navigability, starting in earnest during the reign of Charles IV in the 14th century.

In technical terms, two basic methods for achieving navigability of watercourses can be discriminated (Novak et al., 2007). The first one is waterway channelisation, when the design width of the waterway and the navigation depth are achieved by regulating interventions and construction of concentrating structures– spur dikes. The other method, canalisation, is concerned with the construction of a cascade of weirs and locks. In the Czech Republic, navigable reaches of the Vltava and Elbe rivers are for the most part made navigable by canalisation, while channelisation was previously implemented only at the lower Elbe from the Střekov barrage to the border between the Czech Republic and Germany. However, at times of low flow rates navigation is suspended. Efforts are being made to ensure undisrupted navigability by developing a project of a Děčín barrage, designed to ensure navigation depths from Děčín to the state border using additional concentrating structures.

This paper focuses on proposals for concentrating structures as well as spur dikes, in the form of longitudinal or transverse dikes within the riverbed designed to ensure sufficient navigation depths even at low flow rates. Requests by environmental organisations resulted in the need to ensure that the space between the spur dikes and the banks are not gradually slogged up with sediments for environmental reasons. The objective is to safeguard the space as a living environment for aquatic organisms and populations living on rocky bottoms. Following a research using a 3D mathematical model, a suitable design of the spur dikes has been devised and optimised, and subsequently verified using a physical model developed by a hydraulic laboratory (Fosumpaur et al., 2010). The first testing spur dikes have been constructed in-situ on the lower Elbe with evaluation of a piloting operation ongoing.

* Doc. Dr. Ing. Pavel Fošumpaur: Czech Technical University, Faculty of Civil Engineering, Department of Hydraulic Structures, Thákurova 7; 166 29, Prague 6; CZ, e-mail: fosumpaur@fsv.cvut.cz

2. Historical overview

The modern history of improving navigability of the Elbe and Vltava rivers begun in the 19th century with systematic modifications of the riverbeds, regular maintenance and construction of docks. These interventions would have been carried out predominantly by the firm of the industrialist and shipbuilder Vojtěch Lanna from České Budějovice. The company has gradually amassed a considerable fleet of dredgers, steam-tugs and barges, as well as other engineering ships, used to carry out majority of channelisation and canalisation measures on Czech rivers. Between the years 1833 and 1862, the company channelled the Vltava, including longitudinal spur dikes to decrease the width of the riverbed, resulting in an increase of the navigation depth and elimination of shallows. The commencement of steam navigation on the Elbe and the subsequent signing of navigation treaties in 1844 obliged the Austrian monarchy to dredge an international stretch of the Elbe to the required depth and to ensure proper maintenance. The legal frame for modern navigability interventions was laid down by the imperial waters act No. 93 passed in 1869 and followed up in 1870 by corresponding acts passed by national assemblies in the individual countries forming the monarchy.

In the next stage of improving navigability, between the years 1880 and 1920, the Elbe was further narrowed through further gradual modifications. Where the watercourse had been particularly broad, channelling was achieved by using concentrating structures, discontinuous in most cases, combined with transverse spur dikes and original bank fortifications. The dikes, as well as the bank reinforcements, were made of quarry stone ripraps, secured at the foot by a levelled quarry stone fill. Some spaces behind the concentrating structures would later be used for storage of material dredged from the river bottom.

Combined continuous structures in particular have been spontaneously covered in sediment, with some also filled in with refuse, such as the top part of the branch “Svádovské rameno”, which had been filled in with fly-ashes from the boiler station of the Setuza plant in Ústí nad Labem between 1945 and 1949 (Zajícová, 2007).

Fig. 1: Svádov following the construction of concentrating structures and before the 2002 floods (Zajicova, 2007).

At other sites, the space between the spur dikes and the riverbank has not aggraded in more than 150 years in operation. This finding has lead us to study the design differences between individual historical spur dikes and to devise ways of further optimisation based on modern computing approaches. An example of such a spur dike is the setting at Nebočady, where the spur dikes were built in latter 19th century and lie directly adjacent to the natural monument of Nebočady alluvial plain with a dead end branch and a peninsula in between the branch and the main riverbed. The structure of the spur dikes at Nebočady is supplemented with a feeding shallow ditch featuring a slightly decreased crest at the transition between the transverse and oblique segments. The function of the shallow ditch is quite apparent from the images in Fig. 2, made under conditions of volumetric flow rate of approximately Q_{180d}. The photos clearly demonstrate the feeding function of the shallow ditch, affecting desirably the current behind the spur dikes at water levels mildly exceeding overflow edge of the ditch. The area behind the dikes is subject to a continuous flow, preventing sedimentation.


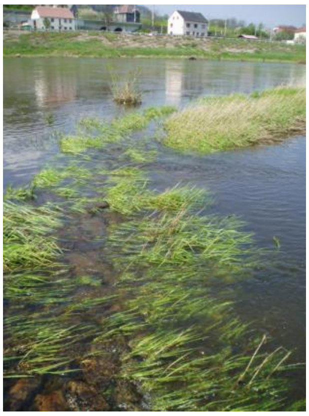

Fig. 2: Spur dikes near Nebočady and a detail of the feeding area.

3. Methods

To simulate flow conditions for different types of spur dikes a turbulent k-ε model was used. Reynolds equation for the turbulent flow of a real liquid is given by the formula:

$$\rho\frac{\partial\overline{\mathbf{u}}}{\partial t}-\mu\nabla.\nabla\,\overline{\mathbf{u}}+\rho\,\overline{\mathbf{u}}.\nabla\,\overline{\mathbf{u}}+\nabla\overline{p}+\nabla\left(\rho\,\overline{\mathbf{u}'\otimes\mathbf{u}'}\right)=\mathbf{F} \tag{1}$$

where **F** is the unit body force. In our case $F_x = F_y = 0$ and $F_z = -g$. The turbulent component is approximated by means of what is called turbulent stress and individual turbulent models differ mutually just by the manner of their description (Wilcox, 1998). In practical applications, k-ε turbulent model is used that belongs to the most favourite at the present time due to its relative simplicity and sufficient reliability of the solution for the majority of engineering tasks. The turbulent momentum transport in the k-ε model is given by the relation:

$$\begin{aligned}&\left(\overline{\mathbf{u}'\otimes\mathbf{u}'}\right)=-\nu_T\left(\nabla\overline{\mathbf{u}}+(\nabla\overline{\mathbf{u}})^T\right)\\&\nu_T=C_\mu\frac{k^2}{\varepsilon}\end{aligned} \tag{2}$$

where ν_T is the turbulent viscosity and C_μ is the model constant (see below). This assumption leads to the following form of the momentum equation and the continuity equation:

$$\begin{aligned}&\rho\frac{\partial\overline{\mathbf{u}}}{\partial t}-\nabla.\left[\left(\mu+\rho C_\mu\frac{k^2}{\varepsilon}\right).\left(\nabla\,\overline{\mathbf{u}}+(\nabla\,\overline{\mathbf{u}})^T\right)\right]+\rho\,\overline{\mathbf{u}}.\nabla\,\overline{\mathbf{u}}+\nabla\overline{p}=\mathbf{F}\\&\nabla.\overline{\mathbf{u}}=0\end{aligned} \tag{3}$$

The transport equation of the turbulent kinetic energy k is given by the equation:

$$\begin{aligned}&\rho\frac{\partial k}{\partial t}-\nabla.\left[\left(\mu+\rho\frac{C_\mu}{\sigma_k}\frac{k^2}{\varepsilon}\right)\nabla k\right]+\rho\,\overline{\mathbf{u}}.\nabla k=\\&=\rho\,C_\mu\frac{k^2}{\varepsilon}\left(\nabla\,\overline{\mathbf{u}}\right)^2-\rho\varepsilon\end{aligned} \tag{4}$$

and the equation of the dissipation of turbulent energy ε:

$$\begin{aligned}&\rho\frac{\partial\varepsilon}{\partial t}-\nabla.\left[\left(\mu+\rho\frac{C_\mu}{\sigma_\varepsilon}\frac{k^2}{\varepsilon}\right)\nabla\varepsilon\right]+\rho\,\overline{\mathbf{u}}.\nabla\varepsilon=\\&=\rho\,C_{\varepsilon1}C_\mu k\left(\nabla\,\overline{\mathbf{u}}\right)^2-\rho C_{\varepsilon2}\frac{\varepsilon^2}{k}\end{aligned} \tag{5}$$

The *k-ε* model contains following constants that were deduced by experimental research according to Table 1:

Tab. 1: Parameters of k-ε turbulent model.

C_μ	$C_{\varepsilon 1}$	$C_{\varepsilon 2}$	σ_k	σ_ε
0,09	0,1256	1,92	1,0	1,3

To assess the risk of sedimentation of particles in the space behind the spur dikes the fall velocity has to be calculated. Falling particle achieves its fall velocity when the resultant of gravity force and buoyancy force equals the drag force. Resultant of gravity force and buoyancy force is:

$$G_v = V\mathrm{g}(\rho_p - \rho) = \frac{1}{6}\pi d^3 \mathrm{g}(\rho_p - \rho), \tag{6}$$

where V is the volume of the particle with diameter d, g is the gravity acceleration, ρ_p is the density of the particle (~2700 kg.m^{-3}) and ρ is the density of the fluid (1000 kg.m^{-3} for water). The drag force is given according the formula:

$$F = \frac{C_D}{8}\pi d^2 w^2 \rho\,, \tag{7}$$

where C_D is the drag coefficient and w is the fall velocity. The value of the fall velocity is according to formulas (6) and (7):

$$w = \sqrt{\frac{4}{3}\frac{d(\rho_p - \rho)g}{C_D \rho}}\,. \tag{8}$$

The value of the drag coefficient C_D depends on the Reynolds number. Final values of the fall velocity for different hydraulic conditions according the Reynolds number and particle diameter describe following equations (Miedema, Vlasblom, 1996). For the laminar regime for particles with diameter $d \leq 0{,}1$ mm the reduced Stokes equation was used:

$$w = 424\frac{(\rho_p - \rho)}{\rho}d^2\,. \tag{9}$$

For the particles with diameter 0,1 mm < d < 1 mm a Budryck equation is valid:

$$w = \frac{8{,}925}{d}\sqrt{1 + 95\frac{(\rho_p - \rho)}{\rho}d^3} - 1\,, \tag{10}$$

and in the turbulent regime for particles with diameter d > 1 mm the Rittinger equation was used:

$$w = 87\sqrt{\frac{(\rho_p - \rho)}{\rho}d}\,. \tag{11}$$

In equations (9) to (11) the particle diameter is in [mm] and the fall velocity is in [mm.s^{-1}]. Following Table 2 summarizes fall velocities according to equations (9) to (11) for particles of different diameter.

Tab. 2: Fall velocity for different particles

D [mm]	0.004	0.01	0.02	0.05	0.063	0.1	0.25	0.5	1
w [mm.s^{-1}]	0.01	0.07	0.29	1.80	2.86	7.21	66	81	113

4. Results

The final design for the flow-through spur dikes was optimised in accordance with simulations of flow-rate fields between the Elbe riverbank and the spur dike. The objective was to determine the shape of spur dikes that would prevent sedimentation of clay and suspended silt particles behind the spur dikes. The resulting spur dike design is shown in Fig. 3. Individual spur dikes feature a longitudinal section 70 to 100 meters long and an oblique part forming an angle with the riverbank of 45°, at a length of approximately 50 metres. The crest of the longitudinal spur dike section is at the water achieved at volumetric flow rate of Q_{180d}. The area behind the spur dikes is washed by water fed by a localised drop in the crest height at the transverse segment, achieved by means of a shallow ditch across the crest. The shallow ditch slopes at a rate of 1:5 from the level of Q_{180d} to Q_{345d}, the width of the overflow edge of the shallow ditch is 10 m. The cross-section of the rock-formed spur dikes is of a trapezoid shape with a width at the crest of 1 m and slopes of 1:5 towards the riverbank and 1:3 towards the watercourse axis. The crest is intended to widen at the termination of the longitudinal section to as much as 10 m. Fig. 4 shows the velocity field around the spur dike modeled by a 3D mathematical model at a flow rate of Q_{180d}. The results confirmed the suitability of the design, which was appreciated as the optimal and subsequently verified using a hydraulic model.

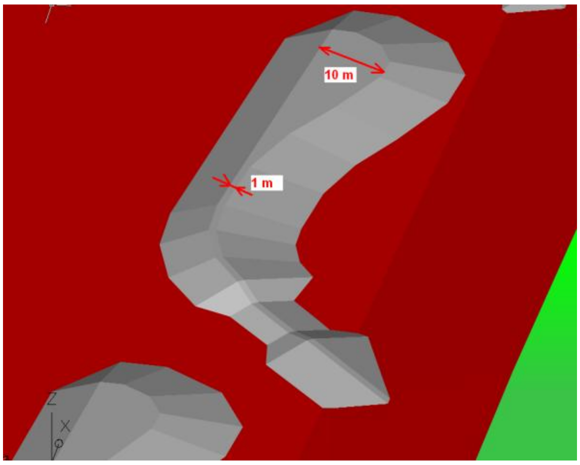

Fig. 3: Optimized spur dike.

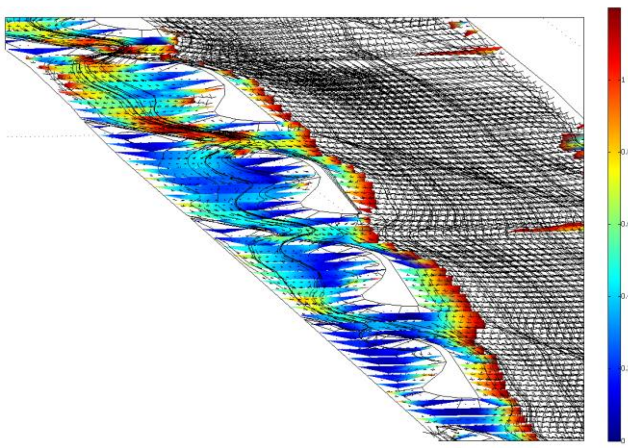

Fig. 4: 3D simulation – velocity field [m.s^{-1}].

The risk of sedimentation was assessed in a simplified form using a comparison between the sedimentation and dragging velocities as per Fig. 5. If the resultant for the sedimentation velocity *w* and the flow velocity *u* for the water current intersects the bed behind a spur dike between two feeding shallow ditches sedimentation will occur, and vice versa. The drag velocity was estimated as the current velocity according to the simulation using the 3D mathematical model.

Analysis of the sedimentation issue is further based on the presumption that the maximum distance L between adjacent spur dikes is up to 100 m, and the depth of water behind spur dikes at Q_{180d} is approximately H = 1.0 m.

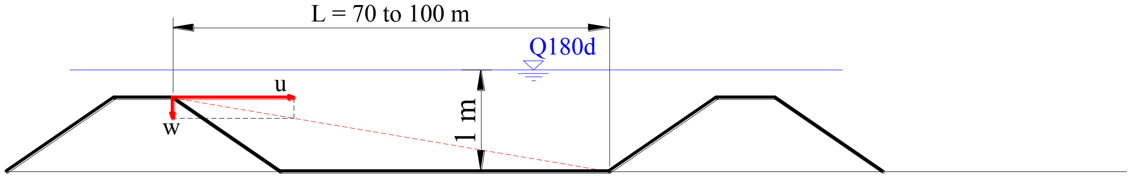

Fig. 5: Sedimentation assessment scheme.

The results obtained demonstrated that sedimentation of clay particles d < 4μm was not possible, and the sedimentation of suspended silt particles of 4 μm < d < 63 μm was not possible for all practical purposes. On the other hand, sedimentation of fine sand particles of 63 μm < d < 250 μm cannot be ruled out, in particular in areas of no current during low flow rates. During periods of increased flow rates, re-transportation of settled sand particles can be expected due to turbulence. Medium-size sand particles of 250 μm < d < 1000 μm are rare in suspended sediment in the lower Elbe (up to 4% ratio) according to Rudis et al. (1999).

A follow-up investigation using a hydraulic model verified the stability of directing spur dikes under flood conditions. The investigation was conducted in the water management laboratory of the Faculty of Civil Engineering of the Czech Technical University in Prague. Stability of the spur dike design was confirmed up to and including the investigated volumetric flow rate of Q_{100}.

5. Conclusions

The research focused on designing a suitable shape of concentrating spur dikes with a view of improving navigability at the lower Elbe below the planned Děčín barrage to the state border between the Czech Republic and Germany. The key purpose of spur dikes is to ensure sufficient navigation depth even under conditions of low volumetric flow rates on the Elbe. An important requirement in the research was the reduction of sedimentation of suspended clay and silt particles in the area between the spur dikes and the riverbank. Historical spur dikes at the lower Elbe had been designed for the most part to lead to complete targeted aggradation. The initial inspiration for the research was therefore taken from spur dikes near Nebočady where partial washing of the riverbed behind the spur dikes is ensured at flow rates exceeding Q_{180d}. The shape of the spur dikes was further optimised using a 3D mathematical modeling. The optimisation aimed to determine the spur dike design that would best prevent sedimentation of suspended clay and silt particles. The results obtained from the 3D modeling were subsequently verified on a physical model, focusing particularly on stability under flood flow rates, with positive results. Initial pilot spur dike projects were constructed in the target area of the lower Elbe in 2010, with a currently ongoing evaluation of their function in terms of river navigation and sedimentation of small suspended particles. The initial results of the measurements fully support the proposed solution.

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