MODEL BASED ESTIMATION OF SEDIMENT EROSION IN GROYNE FIELDS ALONG THE RIVER ELBE

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Abstract

Environmental issue of river water quality is still a vital environmental issue, even though ongoing emissions of contaminants are being reduced in several European rivers. The mobility of historically contaminated deposits is key issue in sediment management strategy and remediation planning. Resuspension of contaminated sediments impacts the water quality and thus, it is important for river engineering and ecological rehabilitation. The erodibility of the sediments and associated contaminants is difficult to predict due to complex time depended physical, chemical, and biological processes, as well as due to the lack of information. Therefore, in engineering practice the values for erosion parameters are usually assumed to be constant despite their high spatial and temporal variability, which leads to a large uncertainty of the erosion parameters. The goal of presented study is to compare the conservative approach assuming constant critical erosion shear stress and an innovative approach which takes the critical erosion shear stress as a random variable. Furthermore, quantification of the effective value of the critical erosion shear stress, its applicability in numerical models, and erosion probability will be estimated. The results presented here are based on field measurements and numerical modelling of the groyne fields of the river Elbe.

Keywords: *groyne field, critical erosion shear stress, field data, numerical modelling, River Elbe, sediment*.

1 INTRODUCTION

The prediction of flow, sediment and contaminant transport in natural rivers is very difficult due to river morphology varying in time, complex sediment transport phenomena, and uncertainties related to chemical properties of contaminants. Beside physical factors significant for the bed shear stress, biological characteristics of deposited sediments have also a great influence on resuspension. They have positive effects by the matrix of extracellular polymeric substances (EPS) produced by macrofauna, algae and bacteria (Gerbersdorf et al., 2005, Debnath et al., 2007). All mentioned factors (physical and biological), which influence riverbed flow resistance are represented in numerical modelling by the critical erosion shear stress ($\tau_{cr,E}$). The spatial and temporal variability of the $\tau_{cr,E}$ is not included in the experimental quantitative determination of cohesive erosion (Mehta, 1988). This emphasises the difficulty to determine the effective value of $\tau_{cr,E}$, to be used in transport modelling for engineering practice. Therefore, managing cohesive sediment erosion and resuspension is still a challenging task. In order to avoid inappropriate application of the $\tau_{cr,E}$, natural sediments are sampled and subsequent laboratory measurements are performed to quantify numerical model parameters.

The measuring results presented here are from three different sites of the groyne fields of the River Elbe sampled during different seasons of the year. Based on these measured data and their statistics, various spatial distributions of $\tau_{cr,E}$ were generated and applied in the numerical model. The numerical model used here is 1D multi-strip model, which predicts suspended sediment transport in rivers trained by groynes (Prohaska & Westrich, 2006). The procedure described in this paper compares the traditional deterministic ($\tau_{cr,E} = const$) and statistical ($\tau_{cr,E}$ randomly generated) approach to determine erosion, and estimates the effective value of the critical erosion shear stress and probability of erosion.

Investigated area

The current research is focused on a representative Middle Elbe reach, for which flow and suspended particulate matter (SPM) regime is influenced by two tributaries (Mulde and Saale), see Fig. 1. The groyne structures are built on both river sides. The $\tau_{cr,E}$ was measured for three groyne fields (GF): Coswig (km 235.0), Steakby (km 280.0), and Fahlberg (km 318.0). Coswig is situated on the right river bank in the strong bend of the Elbe (GF width of about 60 m). Steakby is situated on the left river bank with the groyne field width of about 80 m. The biggest investigated groyne field is Fahlberg, situated on the left river bank (GF width of about 90 m).

The simulated domain extends from Wittenberg (km 214.1) to Magdeburg (km 326.6). Cross sections were determined by ultra sonic profiling at each 100 m, together with information on groyne field dimensions.

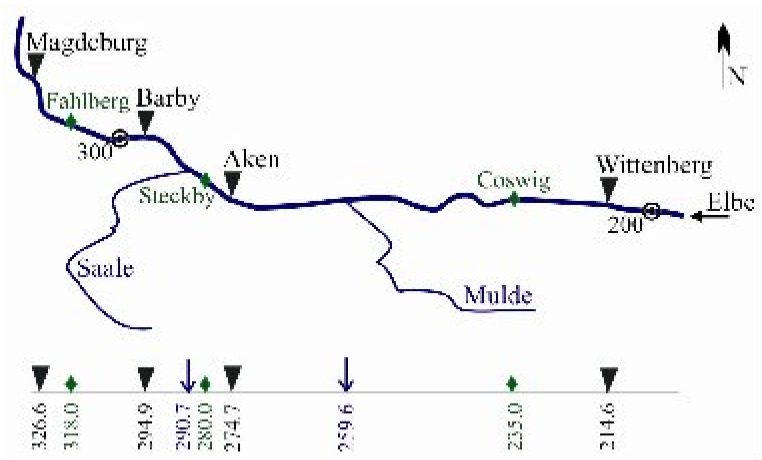

Fig. 1 Middle Elbe: modelled area from Wittenberg to Magdeburg and sampled sites (Coswig, Steckby and Fahlberg).

2 SEDIMENT SAMPLING CAMPAIGNS

As mentioned in Section 1, the samples were taken from three different sites. At Coswig the undisturbed sediment cores of diameter 13.5 cm were taken in July 2005, at Steakby in July 2005, and at Fahlberg in July, August and November 2005 in zones with approximately highest deposition. Additional sediment sampling at various spots within the groyne field at Fahlberg was performed in October 2006 in order to obtain the spatial variability of the measured parameter. The $\tau_{cr,E}$ was measured in a laboratory channel (SETEG system). SETEG consists of a rectangular channel, where the shear stress is a function of the controlled flow rate based on calibration, see Fig. 2. The sediment cores are inserted from below and sediment is slowly moved upwards. The flow rate is increased until the critical shear stress is reached, i.e., when significant particle erosion can be observed. Using this setup, the critical erosion shear stress can be determined for different sediment layers at every 1 cm down to 50 cm (Kern et al., 1999).

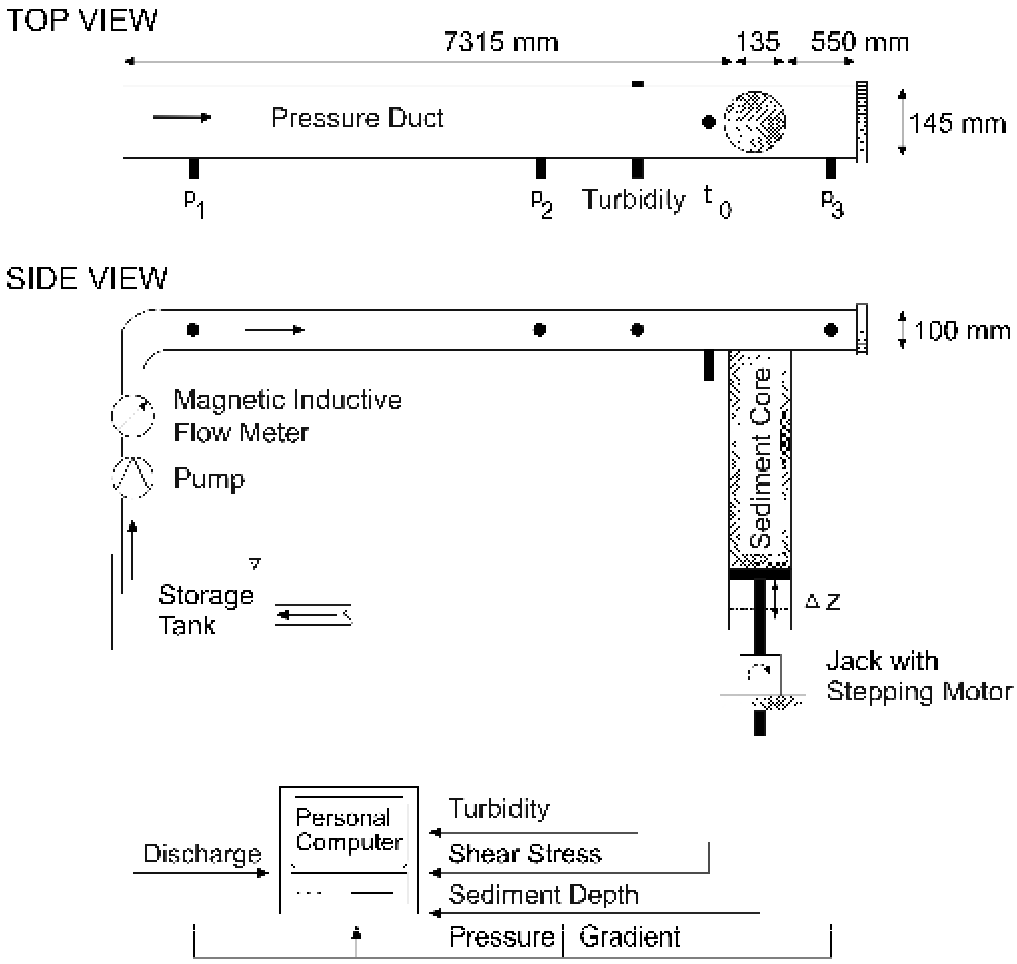

Fig. 2 Schematic configuration of the SETEG-System (Kern et al., 1999). Top and side views are shown.

In Fig. 3 measured depth profiles of $\tau_{cr,E}$ are shown for three groyne fields at different time and location. Measurements show strong variation of $\tau_{cr,E}$ depending on the type of the groyne field and the location of the sampling inside, see Fig. 3a. Nevertheless, the values measured at Steckby are considerably higher in the first 12 cm compared to the other locations because of their age and consolidation. The results of the seasonal measurements are shown in Fig. 3b where surprisingly higher values are observed for summer period compared to the autumn one. It is however expected that in summer period biomass and macrofauna are higher and thus, the $\tau_{cr,E}$ to be lower (Gerbersdorf et al., 2005).

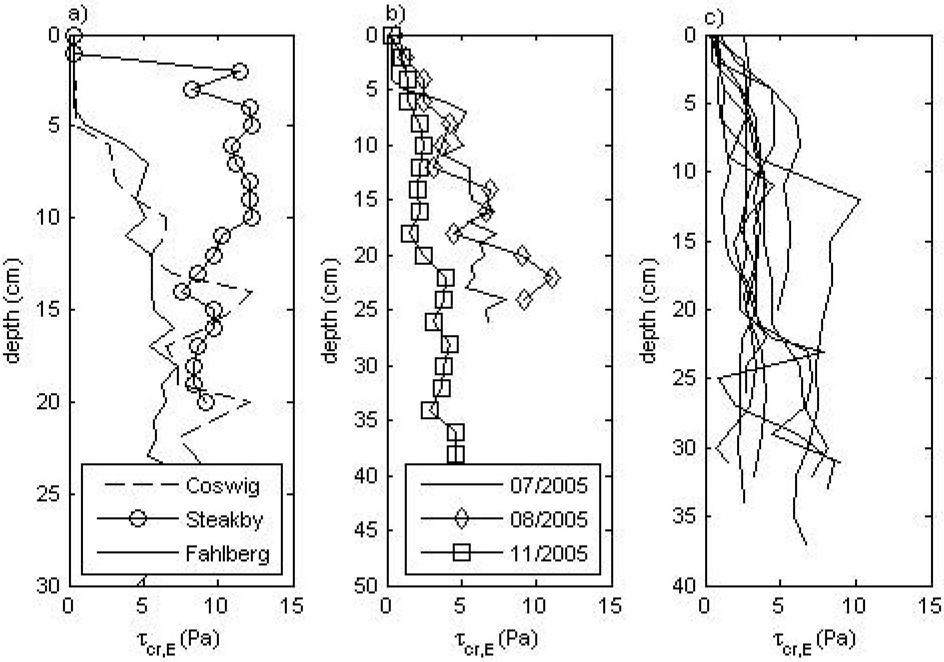

Fig. 3 Measured values of the critical erosion shear stress in depth a) for three groyne fields (July 2002); b) at Fahlberg (July, August, and November 2005); and c) at Fahlberg at different locations within GF (October 2006).

In Fig. 3c a large spatial heterogeneity of the bottom sediments within the groyne field Fahlberg is shown. The sediment stability testes at Fahlberg showed that the $\tau_{cr,E}$ strongly differs depending on the exact location of the sampling point. The difference can be very high, sometimes up to one order of magnitude. Fahlberg groyne field and the exact sampling points are shown in Fig. 4.

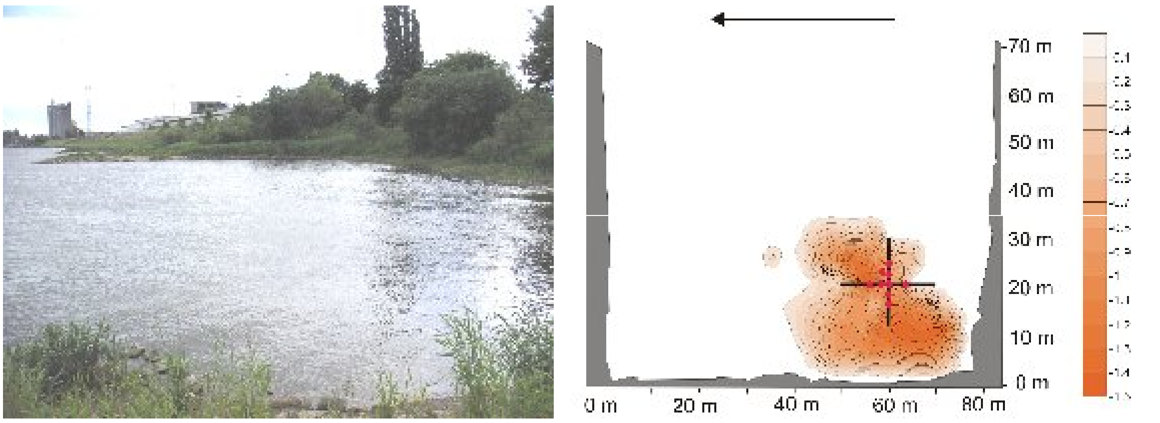

Fig. 4 Left panel: Fahlberg GF. Right panel: exact location of the sampling within the GF (red points).

Statistics of measured data

In order to analyse the measured values of the $\tau_{cr,E}$, basic statistical parameters were defined and summarised in Table 1. All measured data were taken for the statistical analysis, regardless their spatial and temporal variability. A relatively large data range of 12 Pa and high variance confirm the large spectrum of $\tau_{cr,E}$, even though the measurements were restricted to the top layer of 10 cm of the sampling cores. The measured data were considered as independent random variables.

Tab. 1 Basic statistical parameters of the measured critical erosion shear stress (94 measurements): mean, maximum, arithmetic mean, expected value, standard deviation and variance

$\tau_{cr,E}^{min}$ [Pa]	$\tau_{cr,E}^{max}$ [Pa]	$\bar{\tau}_{cr,E}$ [Pa]	E($\tau_{cr,E}$) [Pa]	σ [Pa]	Var [Pa^2]
0.28	12.27	3.04	3.13	3.20	10.24

The histogram of relative and cumulative frequencies are presented in Fig. 5. The obtained distribution of the measured data is asymmetric with skewness and high variance. Standard deviation is the same order of magnitude as the arithmetic mean value, which means that an effective value of the $\tau_{cr,E}$ can vary highly. The distribution of the measured data is fitted to an exponential function:

$$F(\tau_{cr,E}) = 1 - 1.13 \cdot \exp(-0.38 \cdot \tau_{cr,E}), \quad (1)$$

which is also shown in Fig. 5. This theoretical exponential distribution was further used for generating spatial distribution of $\tau_{cr,E}$.

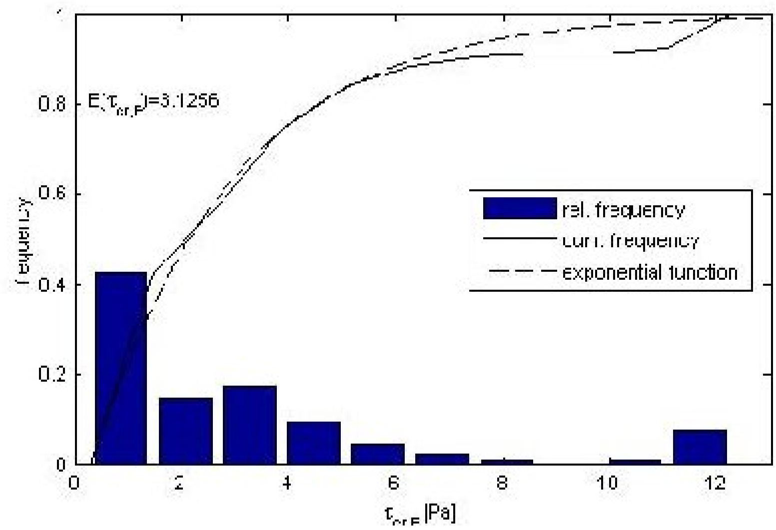

Fig. 5 Relative and cumulative frequency of the measured critical erosion shear stress with fitted exponential distribution function. Expected value E($\tau_{cr,E}$) is shown as well.

After analysing the measured data it can be concluded that high variability of the $\tau_{cr,E}$ was observed depending on: (1) location of a groyne field itself along the river course, (2) the sampling spot within a groyne field, (3) sediment depth, and (4) time, i.e., season when the samples were taken. Additionally, deep layers with high values of $\tau_{cr,E}$ are not likely to be eroded and they protect deeper layers with lower stability from erosion. Therefore, it was very difficult to assign the effective value of the $\tau_{cr,E}$, which represents each groyne field in a river section. In a conservative practice, a constant value of the $\tau_{cr,E}$ is often used irrespective of spatial or temporal variability. The goal of the numerical investigations is to explore the applicability of the traditional approach and to investigate the sensitivity of the $\tau_{cr,E}$ if a different approach is used.

3 MODEL SIMULATION AND RESULTS

Setup of the Elbe model

Numerical simulations were performed with the 1D multi-strip model for a river reach from Wittenberg to Magdeburg as shown in Fig. 1. The multi-strip model was developed aiming to describe the erosion, dispersion and deposition dynamics of fine suspended sediments for regulated rivers with typical training works such as near bank groyne fields. The total river cross section is subdivided into three compartments: main channel, adjacent groyne fields and flood plains on the left and right bank, respectively (Prohaska & Westrich, 2006). The set of 1D transport equations for the strips are coupled by dispersive and advective exchange terms.
For all simulations boundary conditions and model parameters were fixed, except the critical erosion shear stress. Simulations were performed for steady state flow and transport with constant inflow conditions for a time period of one day. As the goal was to investigate the influence of $\tau_{cr,E}$ on erosion, flood discharge conditions were used. The simulated Elbe discharge of 1790 m^3/s corresponds to a flood with a five years return period. The Mulde and Saale discharges were 144 m^3/s and 503 m^3/s, respectively. Inflow of suspended sediments from the Elbe, Mulde and Saale was 58 g/l, 43 g/l, and 43 g/l, respectively.

Basic ideas of the innovative approach

The innovative approach to determine the spatial distribution of the parameter needed for numerical models was obtained by means of stochastic analysis. The spatial distribution of $\tau_{cr,E}$ was generated based on a theoretical distribution of the measured data. Adjustment of the measured data to a theoretical distribution was one of the key factors indicating the quality of obtained results. Therefore, it was indispensable to have a large number of measurements in order to do statistical analysis and determine their distribution, which is used as distribution for generating the spatial distribution of $\tau_{cr,E}$.

Spatial distribution of critical erosion shear stress

In order to generate random numbers according to the known exponential distribution (Eq. 1), the following procedure was used: (1) random numbers ($u[0,1]$) were generated using the MATLAB generator (Hahn & Valentine, 2002); (2) generated random numbers were sorted in increasing order saving the original order; (3) for each generated random number corresponding value of $\tau_{cr,E}$ was calculated as inverse value of the exponential distribution, see Eq. 1 (i.e., $F(\tau_{cr,E}) = u[0,1]$); and (4) the obtained values were returned in the saved original order.
Generated values of the $\tau_{cr,E}$ were determined for each groyne field in the simulated domain of the Elbe. In Fig. 6 generated values for the whole simulated domain are shown, where the circles and dots represent the left and right side groyne fields, respectively.

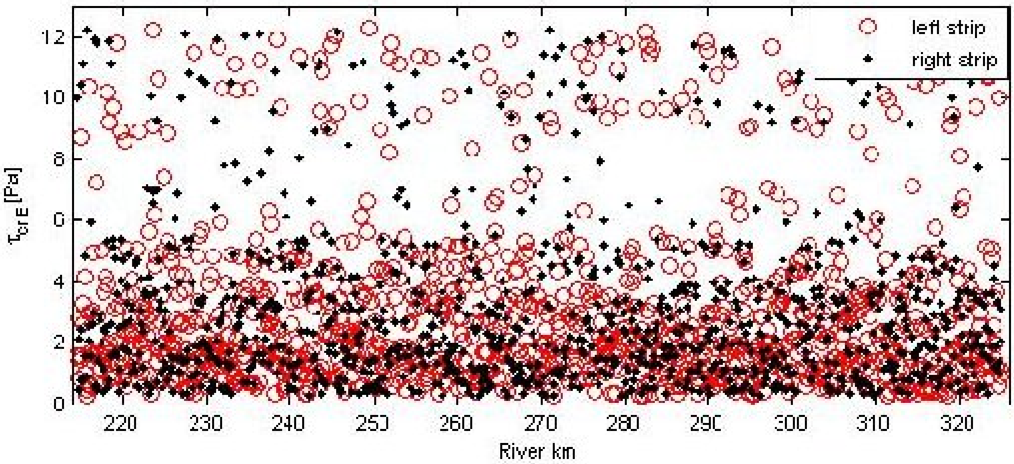

Fig. 6 One realisation of randomly distributed values of the $\tau_{cr,E}$ for each GF in the domain. Left strip stands for GFs on the left river bank and right strip stands for GFs on the right river bank.

Comparison between conservative and statistical approach

In order to compare the deterministic conservative (cases 1, 2, and 3) and statistical (case 4) approaches, different values of $\tau_{cr,E}$ were used:

1. constant mean measured value ($\tau_{cr,E} = 3.04$ Pa),
2. constant mean value plus standard deviation ($\tau_{cr,E} = 6.24$ Pa),
3. constant minimum measured value ($\tau_{cr,E} = 0.28$ Pa), and
4. randomly spatially distributed values comprising the whole data range.

The changes in bed elevation for all four cases for the left strip (groyne fields on the left river side) are shown in Fig. 7. For the case 2, lower erosion and deposition occurred in comparison to the case 1. Case 3 gave the extreme case of very high erosion that would rarely occur in nature. Case 4 resulted in higher erosion and deposition in comparison to the case 1.
Using a constant value of the $\tau_{cr,E}$ (cases 1 to 3), the bed elevation differences occurred only due to varying the parameter, whereas it was independent on the size of a groyne field. This means that larger groyne fields contribute more to the total mass balance than smaller ones. Therefore, the erosion/deposition patterns remained the same for the cases 1, 2, and 3, see Fig. 7. In contrary, this was not the case for randomly distributed $\tau_{cr,E}$ (case 4), for which the differences in bed elevation occurred depending on both the varying value of $\tau_{cr,E}$ and the groyne field size. It might happen in a large groyne field that the random value of $\tau_{cr,E}$ was smaller than the mean, which would result in increased erosion. To the small size groyne field this would result in almost no change in erosion, due to small area that can be eroded.
Nevertheless, randomly distributed $\tau_{cr,E}$, due to mass balance dependency on groyne field size as well as on the parameter value, requires further detail statistical investigation by performing a large enough number of numerical simulations.

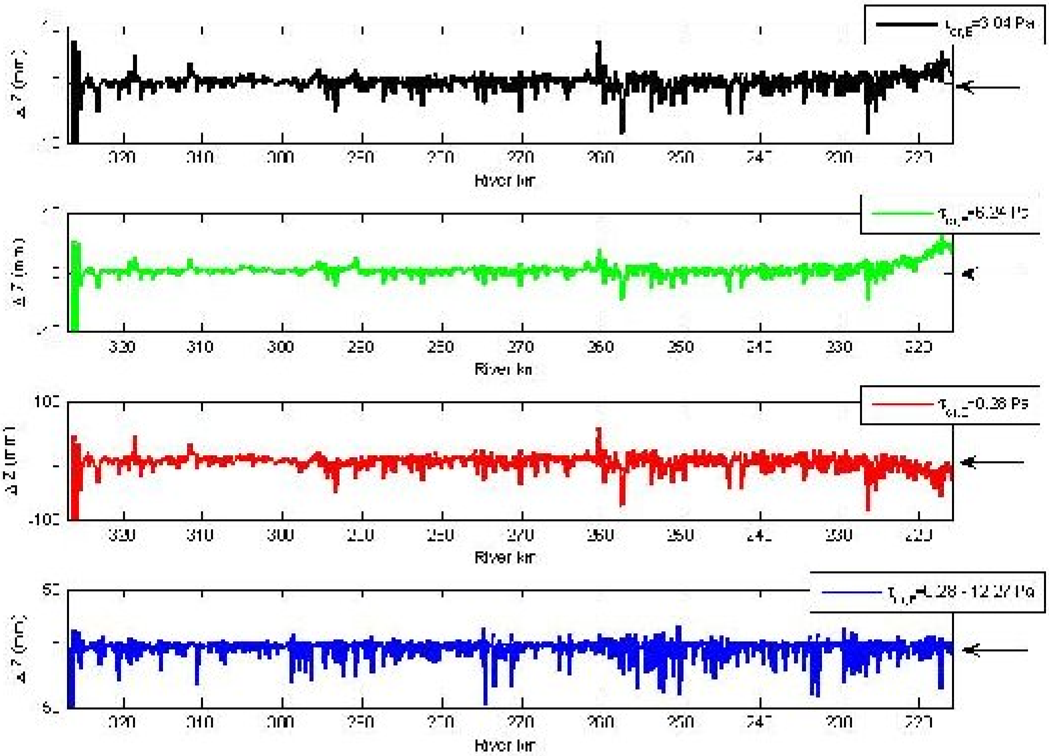

Fig. 7 Longitudinal change in bottom elevation of groyne fields on the left side (note different scales).

Estimating the effective value of the critical erosion shear stress by Monte Carlo method

As this study aims at estimating the effective value of $\tau_{cr,E}$ and probability that a certain amount of groyne field sediments will erode, a Monte Carlo procedure was applied (Montgomery & Runger, 2003). Many randomly distributed values of $\tau_{cr,E}$ were generated and for each realisation total net erosion was calcualted by the multi-strip model. As the result of each numerical simulation was different, they are analysed statistically. The number of realisations was gradually increased, from 50, 200, 1000, to 5000.

Considering only one chosen groyne field, in Figs. 8a and b it can be seen that generated random numbers have the same distribution as measured data. Calculated erosion rates for each generated $\tau_{cr,E}$ at the chosen groyne field give also the same distribution with the expected value of erosion of $1.04e^{-4}$ kg/m^{2}s, see Fig. 8c. Summarising the erosion for the whole river reach (i.e., summarising independent and identical distributions shown in Fig. 8c), the mean total net erosion rate of 0.22 kg/m^{2}s is obtained. Furthermore, with increasing the number of realisations the exponential distribution tends to Gaussian distribution according to the central limit theorem (Montgomery & Runger, 2003), see Fig. 9. This implies that an effective value of $\tau_{cr,E}$ (constant for the whole domain) which would give the erosion rate of 0.22 kg/m^{2}s is 1.42 Pa. It can be seen that the calculated effective value is smaller than the mean measured value. This underlines the importance of statistical analysis in determining the effective value of the parameter due to considering the whole range of measured values, not only one constant value. The suggested statistical method applies, in an indirect way, the depth profiles of the critical erosion shear stress, which is important for long lasting floods where deeper layers with different values of $\tau_{cr,E}$ can erode as well.

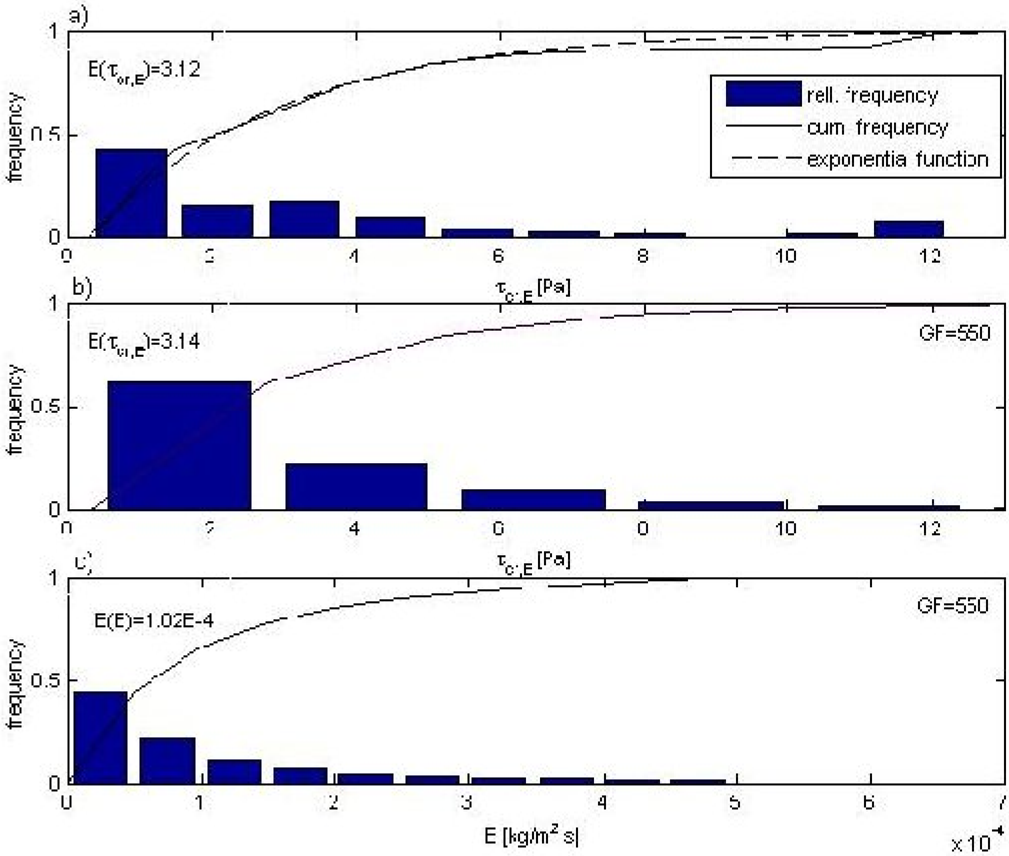

Fig. 8 Statistics of a) the measured data; b) generated values at chosen GF; and c) the calculated erosion. Expected values are shown as well.

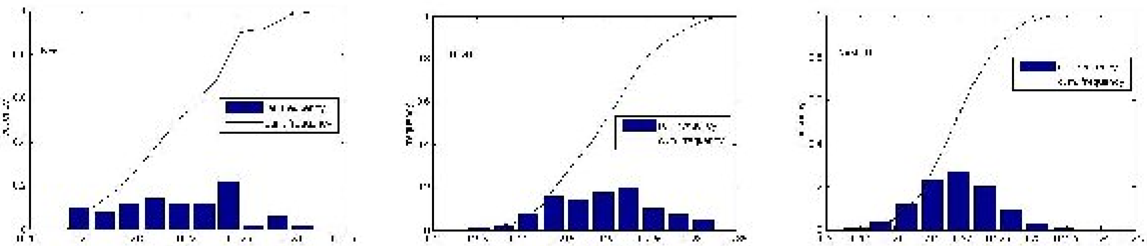

Fig. 9 Histograms of relative frequencies of eroded volumes for different number of realisations.

Furthermore, large number of realisations allows erosion probability estimation. The probability that a certain volume of sediments will erode from groyne fields is shown for 5000 realisations in Fig. 10. A significant part of the uncertainty inherent to groyne field erosion is due to the randomness of the critical erosion shear stress and therefore, a probabilistic approach can provide a valuable framework for assessing erosion.

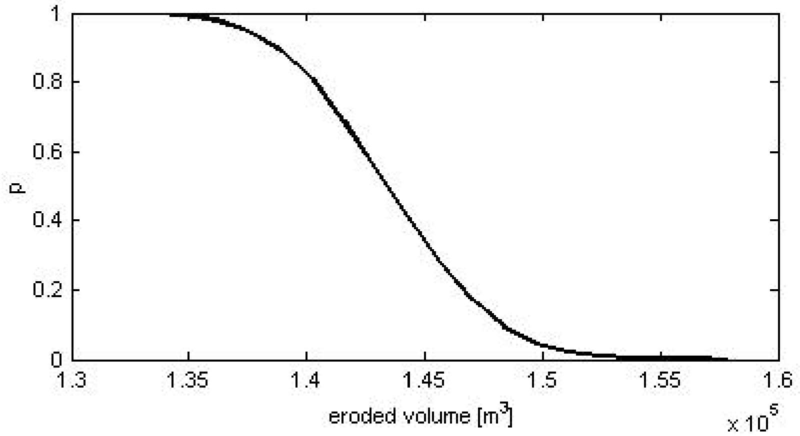

Fig. 10 Probability of groyne field erosion.

4 CONCLUSIONS

The new methodology was implemented in the study of a critical erosion shear stress and its application in numerical modelling. Stochastic methods, which are widely used in geostatistics and prediction of pier scour (Kitanidis, 1997; Brandimarte et al., 2006), were coupled with a numerical modelling of suspended sediment transport. In order to estimate an effective value of the parameter and erosion probability a spatial distribution of the critical erosion shear stress was generated and a large number of realisations were calculated by the multi-strip model.
The results of stochastic analysis, suggested in this paper by treating critical erosion shear stress values as random variables, were compared with a traditional approach, which evaluates erosion by referring to a mean constant value of the parameter applied to the whole river reach. This approach assumes that erosion can be estimated by using a single value of the critical erosion shear stress, ignoring the fact that with on going erosion deeper layers with different value of the parameter will be exposed to flow. The analysis gave the effective value of the critical erosion shear stress to be smaller compared to the mean measured value. The results showed that the conservative method for determining erosion lead to underestimates of groyne field erosion.

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References

Brandimarte, L., Montanari, A., Braud, J.L. & D'Odorico, P. 2006: Stochastic Flow Analysis for Predicting River Scour of Cohesive Soils. Journal of Hydraulic Engineering, Vol. 132; 493-500.
Debnath, K., Nikora, V., Aberle, J., Westrich, B. & Muste, M. 2007: Erosion of Cohesive Sediments: Resuspension, Bed Load, and Erosion Patterns from Field Experiments. Journal of hydraulic engineering, Vol. 133 (5); 508-520.
Gerbersdorf, S.U., Jancke, T. & Westrich, B. 2005: Physico-chemical and biological sediment properties determining erosion resistance of contaminated riverine sediments – Temporal and vertical pattern at the Lauffen reservoir/River Neckar, Germany. Limnologica, Vol. 35; 132-144.

Hahn, B. & Valentine D. 2002: Essential MATLAB for Engineers and Scientists. Elsevier Ltd. Oxford, United Kingdom.
Kern, U., Schuerlein, V., Holzwarth, M., Haag, I. & Westrich, B. 1999: Ein Strömungskanal zur Ermittlung der tiefenabhängigen Erosionsstabilität von Gewässersedimenten: das SETEG-System. Wasserwirtschaft, Vol. 89; 72-77.
Kitanidis, R.K. 1997: Introduction to goestatistics, application in hydrogeology. Cambridge University Press, United Kingdom.
Mehta, A.J. 1988: Laboratory studies on cohesive sediment deposition and erosion. In: J. Dronkers and W. van Leussen (Eds.), Physical Processes in Estuaries, Springer-Verlag, Berlin Heidelberg; 427-445.
Montgomery, D.C. & Runger, G.C. 2003: Applied statistics and probability for engineers, John Willey & Sons, USA.
Prohaska, S. & Westrich, B. 2006: One-dimensional multi-strip transport model for long distance sediment transport in navigation channels, case study the River Elbe, paper presented at 23. Conference of the Danubian Countries on the Hydrological Forecasting and Hydrological Bases of Water Management, Belgrade, Serbia.