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Fuzzy-random approach to debris model for riverbed scour depth investigation at bridge piers

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ABSTRACT The removal of sediment around bridge abutments and piers due to the erosive action of flowing water (i.e. scouring) is of the greatest concern to society. Currently it has been estimated that scour produced by rivers and streams causes about 60% of the total amount of bridge failures. Underestimating this natural process can seriously threaten the overall safety of the infrastructure. Several factors may affect the scour depth at bridge piers: flow intensity and sediment grading, flow depth, nature and occurrence of floods, side wall effects, sediment size, geometry and inclination of piers, etc. The depth of the scour hole in the sand adjacent to the bridge foundations can be estimated using theoretical models with hydraulic parameters. However, the uncertainty associated with the parameters involved in the evaluation (e.g. flow characteristics, debris, structural and geotechnical factors, etc.) makes it almost impossible to adopt a deterministic approach for the reliability analysis. Therefore, in order to properly assess the structural safety, both aleatory variability (i.e. due to randomness) and epistemic uncertainty (i.e. due to limited data and knowledge) must be considered. A fuzzy-probabilistic approach can take some of those uncertainties into account. This paper proposes an original method for modelling the debris action in river bridges. Based on fuzzy-random theory, both the aleatory variability related to the particle accumulation size and the epistemic uncertainty characterising fluvial hydraulics equations can be successfully modelled.

1 INTRODUCTION

Scouring of streams and rivers is one of the major concerns in bridge engineering and the most common cause of bridge failure worldwide. As reported by Neill in his hydrologic and hydraulic studies in 1973:

> "*A man who overlooks water under bridge will find bridge under water*"

According to Hamill's work (1999), 66 bridges over 143 samples considered between 1847 and 1975, collapsed due to foundation undermining. Several researches on bridges over the Po River in Northern Italy have highlighted the riverbed erosion as the main cause of structural damage and failure (Ballio et al., 1999).

It is well known in structural engineering that design and vulnerability estimation of river bridges must consider scour phenomena around the piers. In the last few decades various numerical (Raikar et al., 2016, Boujia et al., 2017, Zhang et al., 2017) and laboratory (Mohammed et al., 2015, Chen et al., 2017) experiments have been conducted in order to investigate and model the scouring effects.

However, neither the computational models nor the simplified formulas currently available in reports and regulations (Lagasse et al., 2010, Arneson et al., 2012, Zevenbergen, 2012) are free from a high degree of uncertainty which affects the numerous parameters involved in: irregular channel geometry, irregular river flow, contracted velocity, clogging phenomena (Fig. 1).

Amongst the uncertainties above mentioned, few were already analysed and modelled using a fuzzy approach by the authors of the present paper in a previous work (Dordoni et al., 2010). Then, in (Malerba et al., 2011), the authors studied the effects of aleatory uncertainty (due to randomness) and epistemic uncertainty (due to lack of knowledge) on structural response. The research has proved that both the uncertainties can coexist and be modelled in one fuzzy random variable. A Monte Carlo simulation was applied to a case study for the evaluation of drag force and relative undermining.

Figure 1. Clogging phenomenon on a bridge over the Po River, Pieve Porto Morone, Italy (Malerba, et al. 2013).

The current paper is an upgrade of the previous works; it emphasises the needs for a fuzzy random based method to analyse the effects of scour on bridge piers and describes the reasons behind the proposed approach.

In particular, this study shows the importance of considering debris action as a fuzzy-random variable affecting the model.

Variables and equations representing the hydraulic phenomena involved in, data uncertainty, and a fuzzy-random method for debris effect evaluation are described in the following sections.

2 INPUT VARIABLES AND MODEL EQUATIONS

2.1 *Hydraulic force*

Hydraulic force represents the interaction between water stream and a solid corpus. In particular, it expresses the pressure produced by water on a body whenever there is a relative movement. In the case study here explained, the bridge piers are the solid body. If scour is considered, foundations, piers and debris will be the solid body. The hydraulic force can be estimated as (Apelt and Isaacs, 1968, Blevins, 1984):

$$F_D = \frac{1}{2} \cdot \rho \cdot V_2^2 \cdot y_2 \cdot a \cdot C_D \tag{1}$$

where ρ and V_2 represent density and average velocity of river flow, y_2 is the average depth in the contracted section, a is the pier width (direction normal to the flow). The impact surface is represented by y_2 multiplied a. C_D (i.e. drag coefficient) is a dimensionless measure that quantifies the aerodynamic characteristics of a generic object; it consists of two kinds of fluid dynamics resistance: skin frictional drag and pressure or form drag. The coefficient C_D depends on pier shape, distance between two adjacent piers, angle of inflow attack, and *Reynolds* number.

The drag coefficient is experimentally evaluated and several values have been reported in scientific publications. However, according to a research by Blevins (Blevins, 1984), since the drag is highly dependent on the shape of the object considered, the data proposed in literature suffer from high variability (i.e. between 0.2 and 2).

2.2 *Scouring assessment*

The scouring phenomenon around bridge piles consists of three types of scour: contraction scour, local scour and degradation-aggradation of the riverbed (Hamill 1999, Anerson 2012). These erosive processes can be considered separately.

2.2.1 *Degradation and aggradation*

It is the process of fluvial erosion (i.e. degradation) and accumulation (i.e. aggradation) of sediment in a river channel due to the change in the bed gradient. The sediment deposition increases the channel height and changes the river morphology and hydraulic geometry, while the degradation lowers the riverbed and shifts the channel banks. The presence of piers does not influence the phenomenon (Miglio et al., 2009, Goode and Burbank, 2009). This is a long-term erosive process at large scales and it hasn't been considered in the present research.

2.2.2 *Contraction scour*

It is the erosion phenomenon that occurs when a natural contraction or bridge abutments reduce the flow area of a stream. The decrease of section increases the flow velocity and causes the riverbed erosion. The estimation of the contraction scour (d_{sc}) refers to clear-water and live-bed conditions. In the former, the water is clear and does not contain sediment, and the scour happens only at the channel contraction. In the latter, bed material is transported from the upstream into the contracted area, and the erosion happens both upstream and downstream of the bridge. For the purpose of this paper, just the live-bed scour condition has been investigated, based on Laursen's equation (1960):

$$y_2 = y_1 \cdot \left(\frac{Q_2}{Q_1}\right)^{\frac{6}{7}} \cdot \left(\frac{b_1}{b_2}\right)^{k_1} \cdot \left(\frac{n_2}{n_1}\right)^{k_2} \tag{2}$$

$$d_{sc} = y_2 - y_1 \tag{3}$$

where y, Q, b and n represent respectively average flow depth, flow, channel width, and *Manning*'s roughness coefficient. The subscripts refer to upstream channel (1) and contracted section (2). Exponents k_1 and k_2 depend on the way bed material is transported. Table 1 shows the values considered.

As explained in Table 1, k_1 and k_2 depend on the ratio of shear velocity to sediment fall velocity, which describes the current ability to keep sediment particles suspended.

Table 1. Exponents for live-bed contraction scour equation.

u_*/w_f	k_1	k_2	mode of transport
≤ 0.50	0.59	0.066	mostly contact
0.5 to 2.0	0.64	0.210	some suspended
≥ 2.0	0.69	0.370	mostly suspended

2.2.3 *Local scour*

When an obstacle obstructs the water flow, it generates variations in current direction and velocity (i.e. acceleration and deceleration) and produces vortices, causing a process of bed stream erosion limited to the proximity of the obstacle (Zevenbergen et al., 2012).

Based on empirical studies and numerical simulations, the methods usually proposed for the estimation of local scour around piers at the bridge site address the definition of a relation between erosion depth, hydraulic variables and geometric characteristics. In particular, at the present, several empirical equations have been formulated to calculate local scour depths. The application of 14 formulas for the evaluation of local scour depth to 56 case studies in the US by Katherine and Holnbeck (2004) resulted in comparable outcomes.

The equation predicting the maximum pier scour depth here proposed is based on HEC-18 document (Richardson and Davis, 2001):

$$F_{r1} = \frac{V_1}{\sqrt{g \cdot y_3}} \tag{4}$$

$$d_{sp} = 2 \cdot y_3 \cdot K_1 \cdot K_2 \cdot K_3 \cdot \left(\frac{a}{y_3}\right)^{0.65} \cdot F_{r1}^{0.43} \tag{5}$$

where a is the pier width (direction normal to the flow), F_{r1} represents the *Froude* number directly upstream of the pier, K_1, K_2, K_3 are correction factors for pier-nose shape, angle of attack of flow and bed condition respectively, and y_3 is the flow depth in the contracted area. The reference values are reported in Richardson and Davis (2001).

3 UNCERTAINTIES IN PHYSICS MODELS

Whenever there is the need for modelling a problem of high complexity and importance, how to properly handle data uncertainty is crucial for achieving significant results.

In the first of their previous works on scouring (Dordoni et al., 2010), the authors highlighted the high degree of uncertainty affecting most of the parameters involved in and decided to apply a fuzzy-based approach to the non-deterministic investigation of the phenomenon. As Regan et al. (2002) did in a biological research, in Malerba et al. (2011), the authors assigned different types of uncertainty (e.g. measurement uncertainty, natural variation, model uncertainty, etc.) to the variables. Each uncertain parameter was described with a specific model (i.e. probabilistic or fuzzy). However, it was clear that the dichotomy fully probabilistic versus fully fuzzy variables sometimes may not properly work. Therefore, random-fuzzy variables were assigned in order to describe parameters affected by both random and epistemic uncertainties.

Figure 2. Clogging phenomenon on a bridge over the Po River, Guastalla, Italy (Malerba, et al. 2013).

Focusing on modelling the debris accumulation at bridge piers, the aim of the present paper is to propose a fuzzy-random approach for the investigation of the scour phenomenon affecting hydraulic infrastructures.

4 DEBRIS INFLUENCE

Debris accumulation (Fig. 2) at bridge piers significantly increases hydraulics force and local scour (Melville 2008).

Experimental tests (Pagliara & Carnacina, 2010, Stolle et al. 2017) and fluid dynamic simulations (Ebrahimi et al. 2017) have been carried out to evaluate the presence of debris. Simplified methods for qualitative verification of bridge scour are available in scientific literature. In particular, Arneson studied the equilibrium between debris size and permeability and introduced the equivalent pier approach. The fuzzy-random method here proposed aims to better investigate the implication of the abovementioned parameters in uncertainty modelling. For this reason, it has been compared with Arneson's procedure.

Report 653 of National Cooperative Highway Research Program extensively describes the effects of particle deposit on bridge stability (Lagasse et al. 2010).

Shape, size and permeability of sediment are the major factors affecting the model of hydraulics phenomena. Basing on the equivalent increment of pier width (i.e. equivalent width, Eq. 6), Arneson et al. (2012) provide a deterministic approach for verifying the influence of debris accumulation on bridge stability to be applied with the previous formulas.

$$a_d^* = \frac{K \cdot (H \cdot W) + (y - K \cdot H) \cdot a}{y} \tag{6}$$

where a and a_d^* are respectively the pier and the equivalent pier widths, W and H represent normal to flow debris width and depth, y is the water depth upstream of the bridge, and K is the debris shape factor. For sediment accumulation with rectangular shape K is equal to 0.79; for triangular shape K is 0.21.

Report 653 gives a mere suggestion on how to model scour phenomenon without any indication for choosing H and W, clarifying that no validation supports the methodology.

In the study here presented, debris geometry is modelled using a fuzzy-random variable and the results are compared with Arneson et al. (2012) method.

5 FUZZY RANDOM VARIABLES

Aleatory variability is usually modelled using random variables, while epistemic uncertainty, vagueness, or more generally non-random uncertainty, are modelled with fuzzy variables (Nguyen, 2015). However, neither the former nor the latter are suited for modelling the uncertainty due to sediment particle accumulation. Debris geometry can be easily represented by a random variable, but it is necessary to consider that sediment particles, as much as they can be compacted, are always subjected to water penetration. As a result, the geometry cannot be considered as a pure random variable. Furthermore, the amount of debris decreases with distance from the pier (Fig. 2). Therefore, the debris influence can be assumed characterised by an unknown decrementing function, with its maximum in the proximity of the pier. The uncertainty related to water infiltration in sediments refers to the incomplete knowledge of model parameters and phenomena involved in (i.e. epistemic uncertainty). Therefore, a fuzzy component is added to the random variables. As a consequence, fuzzy randomness provides the adequate instrument to describe particle accumulation with a fuzzy-random variable (Fig. 3).

Kwakernaak was the first to introduce the idea of fuzzy-random variable as a mean to describe phenomena affected by both aleatory variability and vagueness (Kwakernaak, 1978 and1979). In the last few decades several researches have been developed both in theory (Puri and Ralescu, 1986, Li and Liu, 2006) and in practice (Sickert et al., 2003, Kala, 2007, Holicky, 2010).

The fuzzy probability $\tilde{P}(A_i)$ is the set of all probability $P(\underline{\tilde{X}} \in \underline{A}_i)$ where $\mathrm{A_i}$ represents all the possible solutions, with the corresponding membership values $\mu(P(\underline{\tilde{X}} \in \underline{A}_i))$, which takes into account all states of the (also partial) occurrence of $\underline{\tilde{X}} \in \underline{A}_i$.

$$\tilde{P}(\underline{A}_i)=\{(P_\alpha(\underline{A}_i);\mu(P_\alpha(\underline{A}_i))) \mid P_\alpha(\underline{A}_i)=[P_{\alpha l}(\underline{A}_i);P_{\alpha r}(\underline{A}_i)];\mu(P_\alpha(\underline{A}_i))=\alpha \; \forall\alpha\in(0;1]\} \qquad (7)$$

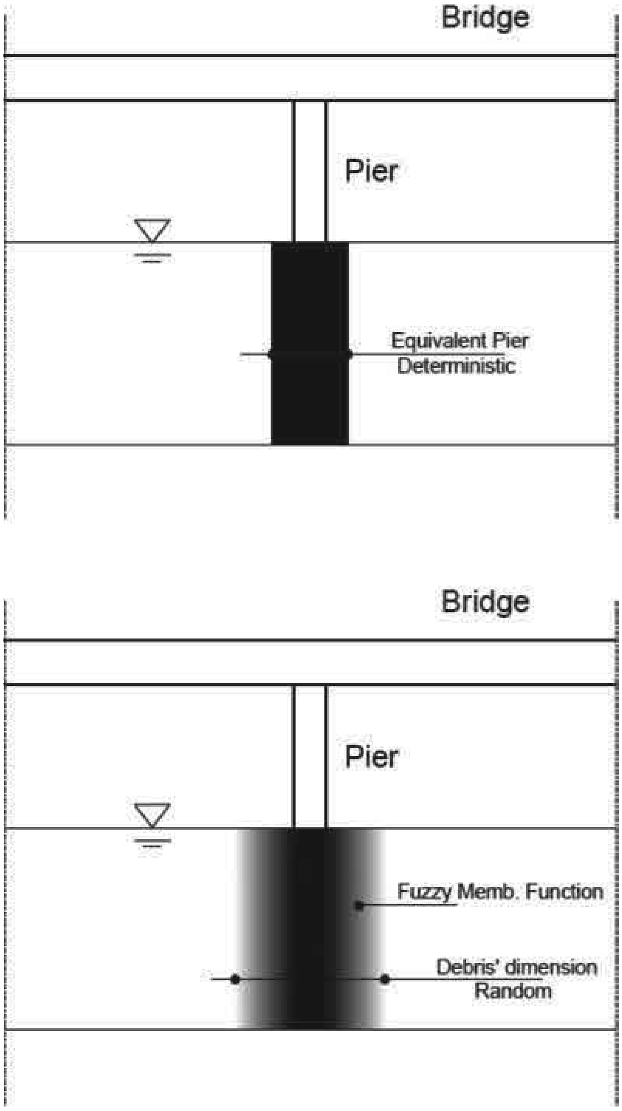

Figure 3. Schematic comparison between equivalent pier method (top) and fuzzy-random approach (bottom).

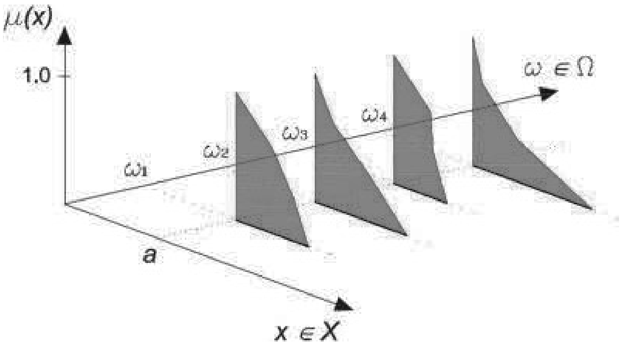

Figure 4. Sampling of one-dimensional fuzzy-random variable.

(more details in Moller, 2002). Figure 4 shows some characteristics of the sampling Ω of the fuzzy-random variable applied in this study for modelling the flowwise debris width.

Variable x is the width of the obstacle hit by water flow. It is described using the shape function $\mu(x)$, which represents the irregularity in the obstacle effects over its entire width (Fig. 3). The adoption of a

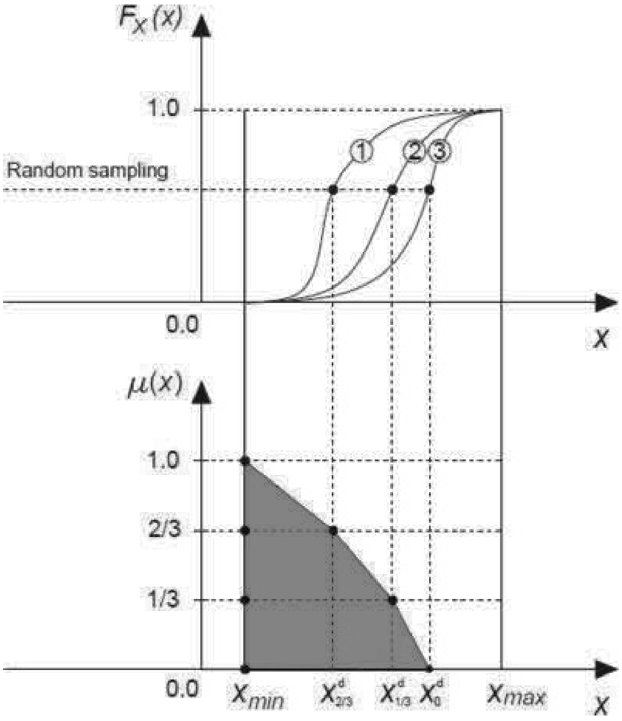

Figure 5. Definition of a fuzzy-random sampling.

tri-linear shape function was preferred over simpler triangular functions in order to makes the model more representative of the real phenomenon.

Support size (i.e. point with membership function equal to 0) and shape of each fuzzy variable (i.e. points with membership function equal to 1/3 and 2/3) are sampled randomly from 3 truncated normal distributions between defined minimum X_{min} and maximum X_{max} values (Fig. 5). The minimum value refers to the smallest normal to the flow obstacle width, which cannot be less than the pier width a. According to empirical observations of river and stream bridges, the maximum value is the obstacle largest width, which has to be a fix number, but not infinite, and it is estimated to three times the pier diameter. Debris width and points with membership function equal to 1/3 and 2/3 are estimated by means of a sampling from the three probability distributions before mentioned. When the section degree of certainty is unitary, *Kernel* parameter value remains constant and equal to the pier width (a): this represents the deterministic solution without sediment accumulation.

The graph in Figure 5 shows the sampling process from the three truncated Gaussian distributions for each fuzzy variable. The sampling was performed using a MATLAB function based on the minimax titling method proposed in Botev (2016).

6 CASE STUDY

The methodology has been applied to the Parks Highway Bridge over the Tanana River (Nenana, Alaska, Fig. 6 and 7). Numerical analyses and structural data useful for scour investigation and drag force estimation were collected by U.S. Department of Interior and U.S. Geological Survey and reported in a scientific document in 2006 (Langley 2006).

Figure 6. Aerial view of the Parks Highway Bridge over the Tanana River, Nenana, Alaska, US (Map: Google, DigitalGlobe 2017).

Figure 7. Picture of the bridge structure and the pier in the riverbed (photo credit: Don Moe, http://donmoe.com/blog/2016/01/15/fairbanks-ak-to-denali-highway/).

The Tanana River Bridge, built in 1967, is one of the most important crossing structures along the George Parks Highway, a road that links Alaska South Coast to the Interior.

It consists of a two 150-meter spans K-Parker through truss structure with a total length of 398 m, entrance spans included. The pier supporting the double-span truss is constructed in the riverbed (Fig. 7). The highway deck is 9 meter wide, and the average daily traffic (i.e. ADT) is 1.514 vehicles two-way passing (Bridgehunter.com).

Table 2 shows geometric and hydraulic characteristics from Langley (2006) for 100-year and 500-year return periods. The values of K_1, K_2 e K_3 in Eq. 5 are respectively 1, 1.6 and 1.1 (Langley 2006).

The parameters in Table 2 come from a probabilistic environmental risk analysis (Langley, 2006). For this reason, given the recurrence intervals here investigated, they are considered reliable and assumed as deterministic variables.

As previously reported in section 5, the maximum debris depth is assumed equal to three times the pier diameter, which means 12.8 m. The sediment accumulation is considered triangular-based and distributed over the entire pier height (Fig. 2 and 3). Giving a value of 0.21 to K factor and replacing H with y, Equation 6 provides an equivalent pier depth equal to 6.1 m. Tables 3, 4 and 5 show the scour values deterministically evaluated according to Table 2 variables

Table 2. Variable values in equations 1–5.

	100-year flow	500-year flow
Y_1 [m]	6.77	7.25
Y_2 [m]	7.38	7.99
Y_3 [m]	6.98	7.47
V_2 [m/sec]	2.7	3.12
Q_1 [m^3/sec]	4021	4919
Q_2 [m^3/sec]	4061	5001
a [m]	4.3	4.3
B_1 [m]	242.6	242.6
K_1	0.69	0.69

Table 3. Scour values [m] resulted from equations 1–5 and referred to Table 2 in clear water conditions.

	100-year flow	500-year flow
Contr. scour	0.616	0.707
Local scour	10.8	10.9
Total scour	11.4	11.6

Table 4. Scour values [m] resulted from equations 1–5 and referred to Table 2 data considering maximum debris width.

	100-year flow	500-year flow
Contr. scour	0.826	0.933
Local scour	22.000	22.200
Total scour	22.800	23.100

Table 5. Scour values [m] resulted from equations 1–5 and referred to Table 2 data considering maximum debris width, using the equivalent pier width from Eq. 6.

	100-year flow	500-year flow
Contr. scour	0.661	0.749
Local scour	13.500	13.600
Total scour	14.200	14.300

respectively in clear water conditions, with maximum debris width, and using the equivalent pier width.

According to section 5, the debris have been modelled with a fuzzy-random variable. Then a Monte Carlo simulation with a sampling of that variable as input data, gives the opportunity to compare and evaluate Equations 1–5. The random set Ω here utilized consists in 1000 fuzzy variables with the membership function in Figure 5. The basis geometry of the membership function is a right triangle with minimum value equal to the pier width and maximum three times the support width. The sampling of values with $\mu = 2/3$, $\mu = 1/3$, $\mu = 0$ from truncated normal distributions with a mean same as the value in the basis curve and a variance of 30% the sampled values (Fig. 5) allowed the shape variation of the membership function. The validity of this procedure hasn't been proved yet and the method still remain subjective. However, experimental analysis can highlight the relation between scour, debris shape and permeability and provide the opportune validation and data to review and improve the methodology.

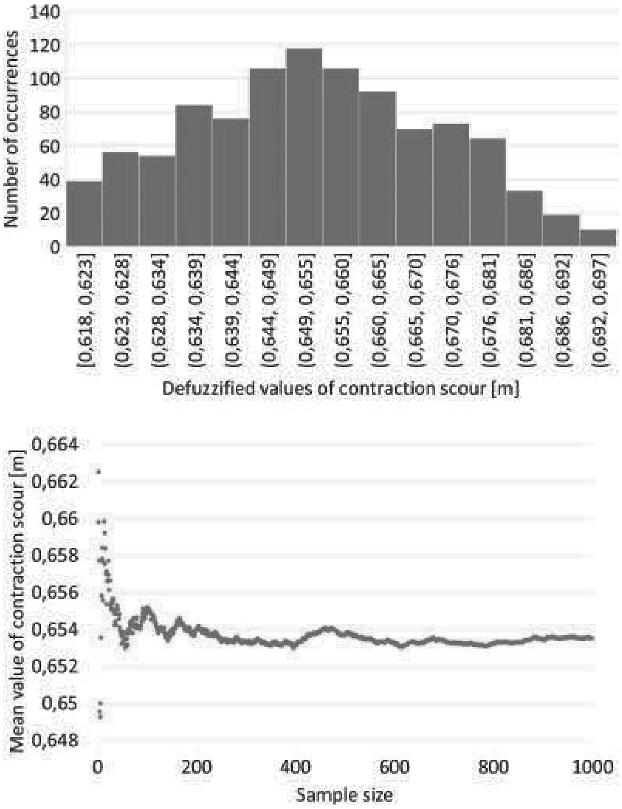

Figure 8. Bar chart of defuzzified values of contraction scour (top) and convergence curve of the related mean value (bottom).

Figures 8, 9 and 10 show the fuzzy-random Monte Carlo simulation results. Since the results related to 100-year flow and the ones referred to 500-year flow are very close, only the former outcomes are listed.

Bar charts in Figure 8 and 9 (contraction scour and local scour) are followed by the convergence curve of mean values as a proof that with a sample size of 1000 the simulation is converged.

Compared to the bar chart in Figure 9, the one in Figure 8 is more symmetrical. The reason could be that debris effect and uncertainty are more pronounced in the local scour than in the contraction scour.

The values related to the equivalent pier depth method are included in the relative bar charts, more precisely they are at the 65th fractile in contraction scour and 72th fractile in local scour.

The curve in Figure 10 show the bar chart for the total scour, which is the sum of the previous ones, is very close to the local scour histogram.

Figure 8, 9 e 10 show the uncertainty affecting the scour depth due to exclusively sediment accumulation. Bar charts risult purely from the fuzzy-random

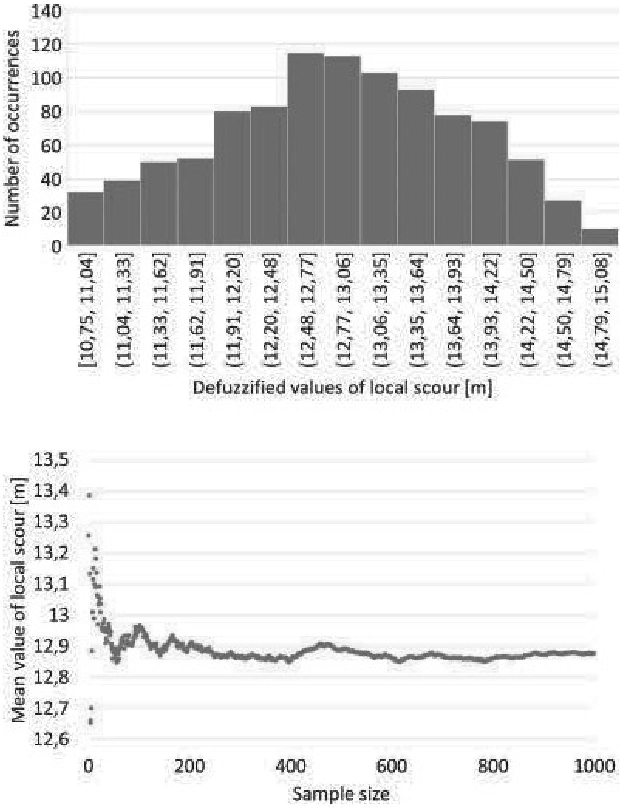

Figure 9. Bar chart of defuzzified values of local scour (top) and convergence curve of the related mean value (bottom).

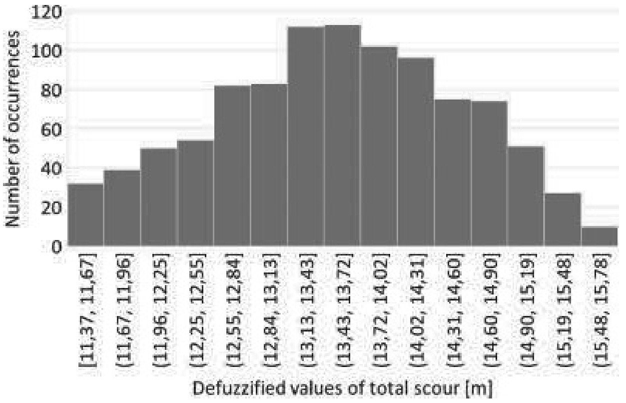

Figure 10. Bar chart of defuzzified values of total scour.

modelling of the debris geometry, and prove the fuzzy-random approach to be valid in aleatory and epistemic uncertainty evaluation related to pier cross section increment.

Further developments of this study will provide a wider uncertainty analysis, assuming also the remaining model parameters influenced by debris deposition and a fuzzy-random assessment of bridge security.

7 CONCLUSION

This paper propose an original method for modelling the debris action in river bridges. Based on fuzzy-random theory, both the aleatory variability related to the particle accumulation size and the epistemic uncertainty characterizing fluvial hydraulics equations can be successfully modelled. As a consequence, the method here presented can describe in a more general, proper way the uncertainty of scour phenomenon.

The approach is applied to a case study (Parks Highway Bridge over the Tanana River, Alaska) in order to compare its results with the ones achieved by the U.S. Department of Transportation using a different procedure (equivalent pier depth method) and prove its efficacy, thanks to the proximity of the values obtained.

As well as for the equivalent pier depth method, at the present, there are no data in scientific literature that can validate the results achieved with this original approach. Therefore, this work can be considered as a methodology paper. However, when more experimental data are available, the aleatory variables will be easily identified.

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