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Numerical Modeling of River Embankment Local Failure under Accidental High-Waters Conditions

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Abstract: *Exploitation in safety condition of flood protection hydraulic structures along watercourses is still an important problem, from economic and social point of view. The complex phenomenon of failure, an event of big importance for riparian areas, must be studied both in terms of genesis and development. In addition to exceeding the filling shear strength, the local failures of the river embankments are most often due to infiltrations through the body of the building, generating suffusions and leaks, respectively discharges over the canopy, generating progressive washing of the downstream facing of the filling. This paper presents a discrete 1D / 2D combined numerical modelling made with the help of the HEC-RAS v.5.07 package that simulates the hydraulic event on the Crasna River in the area of Craidorolț village, Satu Mare county, Romania, under the conditions of forming a breach in the shore defence dam left at the appearance of an accidental flood wave. The configuration of the adopted hydrograph is given by the actual recording during the flood event that took place between 26 and 30 May 2015. The uncertainty parameters at the breach formation through the defence dam were analysed using a probabilistic sampling application of predefined statistical distributions. Specifically, the statistical analysis was performed using the additional McBreach control facility, using the Monte Carlo method. The numerical simulation has as distinct purpose the highlighting of possible breach propagation on the left bank of the flood defence; as well as the estimation of the flood extent and the establishment of the transient (non-permanent) hydraulic parameters. Consequently, some constructive aspects of flood protection of a specific economic objective located nearby are under discussion.*

Keywords: *River engineering, highwaters flow, flood defence structures, crest overtopping, dam breach, hydraulic model.*

1. Introduction

HEC-RAS version 5.07 [4] is a hydrodynamic software which can simulate a structure breach (dam, lateral embankment, flood defence structure or connection type SA/2D structure) with 1D and 2D numerical equations. McBreach © version 5.07 [5] is an external control software application that facilitates the probabilistic modelling of yielding a structure by sampling the yield parameters of predefined statistical distributions and automatic running with HEC-RAS version 5.07 thousand times, using the well-known Monte Carlo method. The probabilistic analysis of a structure failure will thus contribute to the quantification of the uncertainties associated with flood mapping and the associated potential risk attributed to the probabilities of exceeding the peak flood flows.

McBreach © version 5.07 could randomly test predefined statistical distributions for all parameters of yield of frontal (dams) or side hydrotechnical structures, respectively of SA / 2D connections. In addition to the yield parameters, the user may include the flow hydrographs of the numerical model in the probabilistic analysis.

A Monte Carlo simulation with McBreach © version 5.07 produces peak flows with different probability of exceeding flood events, respectively, determines all the parameters of the sampled failure that can be further used to produce flood maps for different annual exceeding probability (A.E.P.) flood events.

McBreach © version 5.07 satisfies the need for hydraulic structures' safety in the modelling of cession as an overly conservative deterministic approach, with the probabilistic approach quantifying the uncertainty in the analysis. McBreach © version 5.07 therefore allows decision-making based on risk and uncertainty and compliments the safety desires of structures, leads to informed about risks and uncertainties in decision-making. Execution in HEC-RAS version 5.07 in an uncertainty exercise in Monte Carlo requires many hundreds or even thousands of simulations to achieve statistical convergence of the mean and standard deviation.

After McBreach © version 5.07 simulation, the user reproduces sets of predefined failure parameters for peak flows, includes them in the fully discretized numerical model, and then maps the flood extension maps. This will usually be done automatically in the eight sets of failure parameters (A.E.P.: 0.2%, 1%, 5%, 10%, 50%, 90%, 95%, 99%).

Fig. 1. Plan view of the private development establishment and a Crasna River reach *–2019*

The numerical modelling is based on a flooding study on Crasna River, in order to establish constructive aspects of flood protection of the technological platform on the left bank of a private development [1]. For the numeric modelling HEC-RAS vers.4.1 [2], 5.07 [5] software package was used, and is based on two discretization numerical systems: one dimensional (1D) system and one-two dimensional (1D-2D) system.

The technological platform of the private development is located at approx. 1 km from the riverbed of river Crasna (approx. distance from the left bank side flood defence embankment).

The natural terrain from the area is agricultural and rural, with an average elevation of 125.50 maSL and covers a total area of 60,000 m^2 (Fig.1).

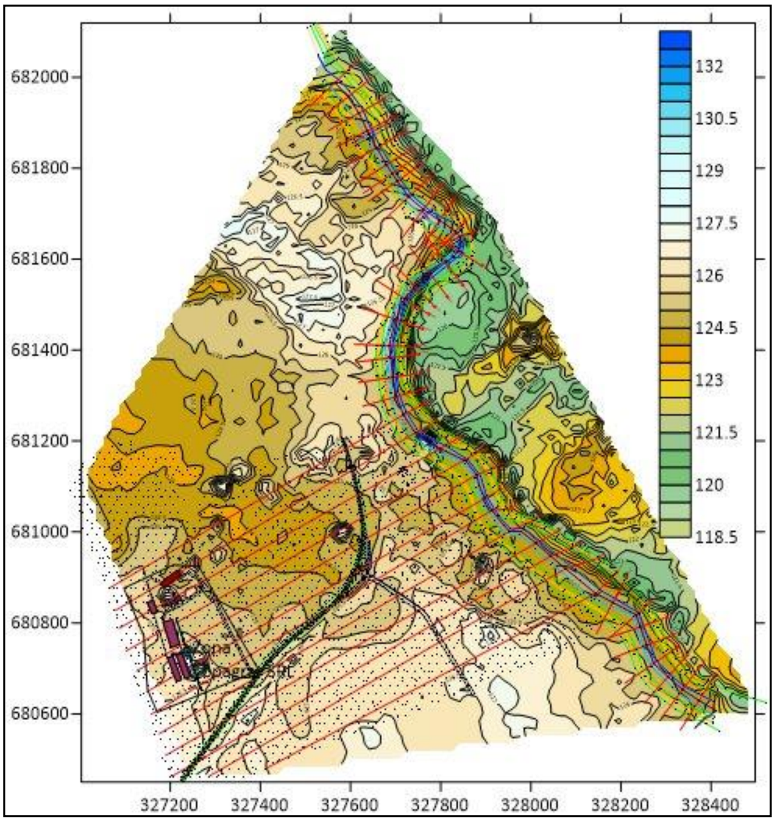

Fig. 2. 3D terrain surface representation

When modelling the geometry of the Crasna riverbed in 1D, a section with a length of approx. 1872 m was considered. On this river reach a database was created with a general plan (topographic survey in Stereo 70), 49 transversal profiles (out of which 37 short profiles framed by the flood defence embankment and respectively, 12 longitudinal profiles that also include the location of the private development, visible in (Fig. 2).

The analysis section of the Crasna River was divided into profiles (49 segments) limited at the ends by 50 cross sections obtained in accordance with the actual topographic surveys, of which a section of automatic linear interpolation (1 segment), respectively, 2 sections upstream and downstream from the road bridge on DJ195B (geometric features are known from the Craidorolț hydrometric station).

Between the two cross-sections was introduced a structure bridge type. The surveyed cross-sections are highlighted in red in the 3D terrain surface representation (Fig. 2). From the current configuration of the natural terrain, originating the spatial points (x, y coordinates, terrain elevation) resulting from the topographic survey - Stereo 70 [1] and the graphic processing of the geometric surface in 3D (analysing different types of procedures in numerical modelling can be seen in detail in the numerical models [7], [8], [10] and [11], respectively, in the technical documentation [13] and [14]), the spatial configuration of the flow range presented in (Fig. 3). The maximum flows for different AEP flood events on the Crasna river, Craidorolț area, at the road crossing bridge location (Craidorolț hydrometric station) are known and have values of: $Q_{5\%}$ = 322 m^3/s and $Q_{1\%}$ = 570 m^3/s.

2. General elements of numerical modelling

2.1 General consideration

The 3D terrain representation is given by satellite graphics of Earth Explorer. This accessible graphic representation is rough, limited to a discrete network of points, most often 30mx30m and at the same time, very difficult to access. A very useful method for graphically processing discrete topographic data known from topographic surveys is presented in documentation [7], [8], [10] and [11]. The method uses a 2D graphical interpolation topographic program, from which a 3D shape surface (shx extension) can then be generated. This surface is then loaded into ArcMAP 9.3 [3], divided by discrete triangular elementary surfaces and resulting in a final 3D spatial shape type TIN (Triangulated Irregular Network).

In order for this spatial form to be recognized by RAS Mapper module (graphics processing or post-processing module in the HEC – RAS 5.07 program [5]), it must be converted into a file with an accessible grid loading form - DTM (Digital Terrain Model).

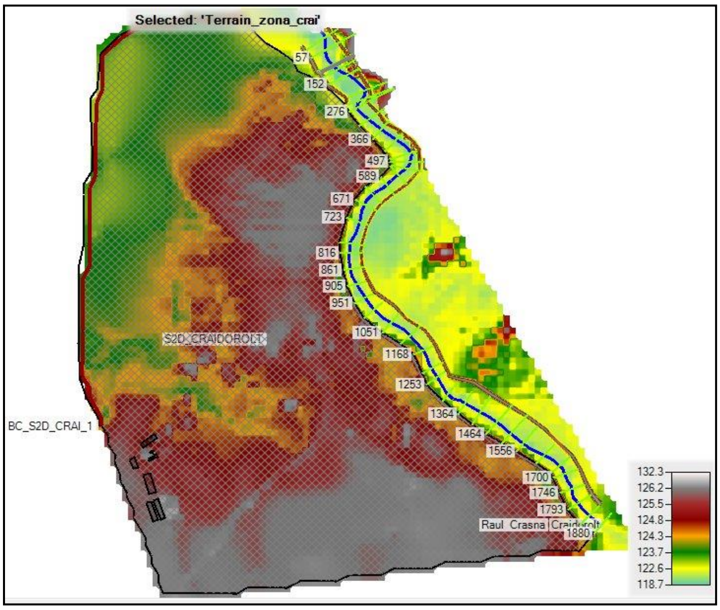

Fig. 3. Numerical model 1D/2D representation: *1D* (*Crasna River*), respectively, *2D* (*2D discretization and lateral structure on left bank* – "*1836*" representation)

A satellite representation example is shown in Fig.3 and was obtained for this paper.

Although these spatial representations are usually based on a small number of points in the topographic survey, they reproduce a real 3D surface quite well.

And yet, this type of model does not faithfully generate the configuration of flood defence embankments, respectively, the configuration of the land below the water level for low return period flood events.

To solve these special issues, within the HEC-RAS program version 5.07, introduced a facility to add a fictitious route through which various corrections can be made to the 3D spatial surface [14]. This route can be a defensive embankment or a watercourse (where successive changes can be introduced on the discrete mode), so that the cross sections below the hydrostatic water level can be updated. In this discrete numerical model these two options were used, and the final discrete surface resulting in the 3D domain has the graphic and visible representation in Fig.3.

2.2 Numerical model 1D/2D build

Documentation "Flood study" [1] includes in the first phase a discrete 1D numerical model where the floodplain area was discretized as a "Polder" with the real contour, which was obtained using the topographic map of Romania (Craidorolț area, Satu Mare county, scale 1 : 25000), and by planning and processing the surfaces given by the elevation curves. Therefore, the correlation

between the water level in the polder and the possible cumulated water volume was determined (*Table1*).
The flow transition through 1D domain was done in three stages, as follows:
Stage 1 - Model calibration with 26 May 2015 flood event hydrograph, with peak flow Q_{max}= 146 m^3/s
Stage 2 – Flood event for 5% A.E.P., with a peak flow value of $Q_{5\%}$= 322 m^3/s.
Stage 3 – Flood event for 1% A.E.P., with a peak flow value of $Q_{1\%}$= 570 m^3/s.

Table 1

Nr.crt.	Cotă [*mdM*]	Suprafața planimetrată [m^2]	Suprafața mediată [m^2]	Volum acumulat [x10^3 m^3]
0	***122.25***	*1075791.00*	–	***0.000***
1	***123.75***	*9202968.40*	*5139380.00*	***7709.070***
2	***125.00***	*17639613.88*	*13421291.22*	***24485.683***
3	***126.25***	*22759503.43*	*20199558.63*	***42026.062***
4	***127.20***	–	–	–

To monitor the discharged flows over the left bank embankment's crest, respectively on the right bank of Crasna River, two lateral artificial structures were considered. The structures are broad crested weir type structures, with a weir flow coefficient md=0.248. The crest configuration of the two artificial structures was determined by topographic surveyed points.

While monitoring the transition flow water volume over the artificial lateral structure on the left bank, (worst case scenario flow $Q_{1\%}$), and the real polder is marked with "Polder at_ 125.00"; the minimum contour of real representation was chosen to visualize the inner water level contour (at approx. elevation level of 125.00 maSL, for the maximum peak flow of $Q_{1\%}$=570 m^3/s). Therefore, graphical characteristic elements were obtained for the maximum water volume reached.

At an additional analysis of the area at the location of the private development, regarding the natural terrain elevation, it was found the existence of a clogged irrigation canal with an elevation level below 124.50 maSL. For this reason, it was chosen a 1D/2D numerical model to replace the polder from stage 3 with a discrete spatial surface. Thus the floodable area of the natural terrain associated with the lateral artificial structure was replaced with a discrete natural surface limited in 2D and marked as "S2D CRAIDOROLT", in HEC-RAS 5.07, illustrated in graphic representation from Fig.3.

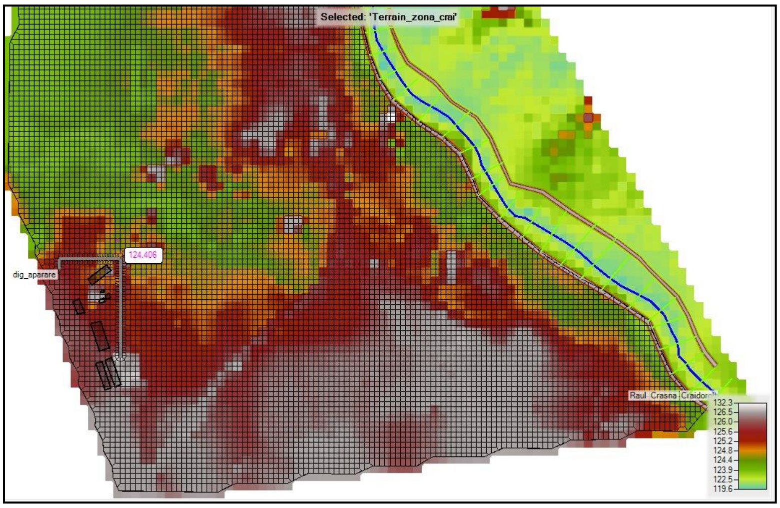

Fig. 4. Detail representation of the additional discretization at the introduced connexion structure (defence embankment) at the northern vicinity of technological platform

Following the actual simulation of this new discrete model and following the graphic processing of the post-processing, the flooding of the platform in the northern area was identified and for protection, additional improvements were made regarding the numerical model described above. Thus, a connection structure was introduced on the northern contour of the technological platform (referred as: dig_aparare) inside the discrete surface" S2D CRAIDOROLT", shown in the graphic representation from Fig.4, as well the development of a breach in the left bank embankment of Crasna River.

The truncated version of the 1D/2D numerical model, required only during McBreach© version 5.07 simulation (used as an external control application), facilitates the probabilistic failure/breach modelling of the embankment through sampling the yield parameters of the predefined statistical distributions and used in the automatic running with HEC-RAS version 5.07 hundreds times using

the Monte Carlo method. Launch of McBreach © version 5.07 [5] mode and automatic coupling with HEC-RAS version 5.07 is illustrated in Fig.5.
The use of probabilistic modelling of the failure of the defense embankment by sampling the parameters of failure of the predefined statistical distributions and associated in automatic running with HEC-RAS version 5.07, can be observed in the representations from the below figures Fig.5 and Fig.6.

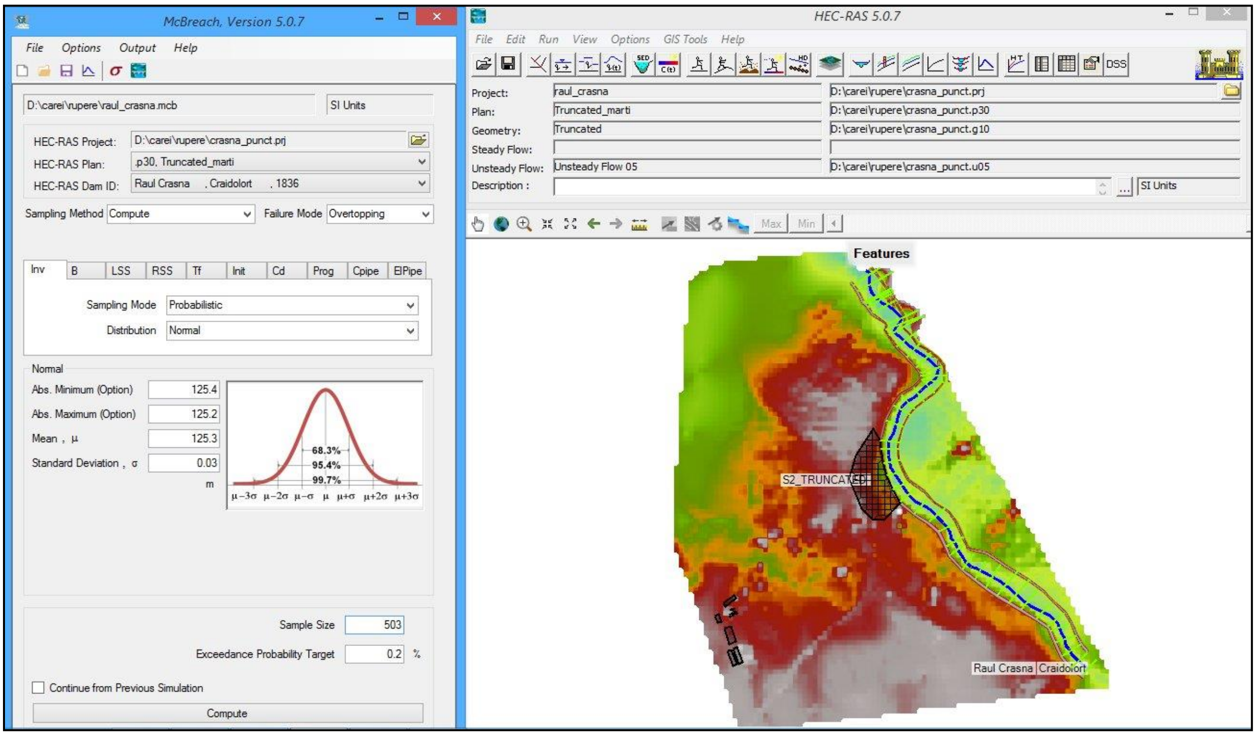

Fig. 5. Numerical model in truncated version of 2D surface and associated with *McBreach © version 5.07*

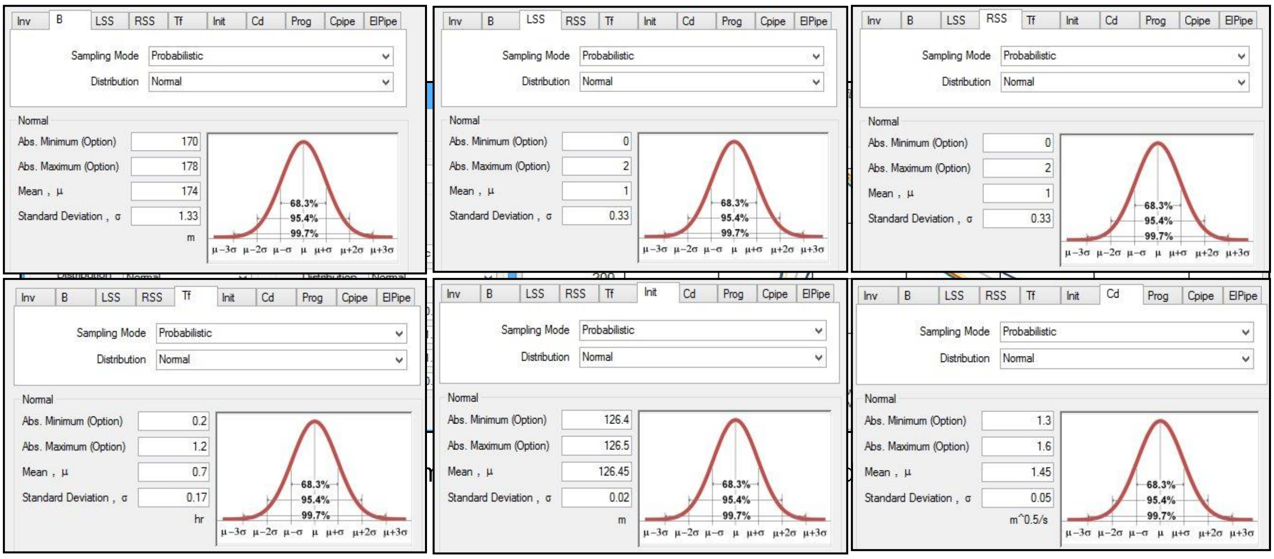

Fig. 6. Sampling elements of predefined statistical distribution failure parameters

In addition to the yield parameters, the user can include the flow hydrograph of the model in the probabilistic analysis by random sampling of the flow hydrograph and scaling factors as seen in the graphical representation shown in Fig.7.

After simulation, the final elements were obtained from sampling the yielding parameters of the statistical distribution (*approx. 11hours*) and are illustrated in the figure below (Fig.8).

Exceedance Probability Breach Parameters

	0.2% User	1%	5%	10%	50%	90%	95%	99%
Realization #	503	503	503	503	501	504	504	504
Peak Discharge, m^3/s	503.39	503.39	503.39	503.39	479.47	80.24	80.24	80.24
Invert El., m	125.4	125.4	125.4	125.4	125.4	125.4	125.4	125.4
Bottom Width, m	172.05	172.05	172.05	172.05	174.11	173.13	173.13	173.13
Left Side Slope, m/m	1.08	1.08	1.08	1.08	1.05	1.03	1.03	1.03
Right Side Slope, m/m	0.71	0.71	0.71	0.71	0.49	0.9	0.9	0.9
Formation Time, hr	0.66	0.66	0.66	0.66	0.75	0.75	0.75	0.75
Initiation, m	126.45	126.45	126.45	126.45	126.47	126.43	126.43	126.43
Discharge Coeff.	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Progression	Sine	Sine	Sine	Sine	Sine	Sine	Sine	Sine
Failure Mode	Overtopping	Overtopping	Overtopping	Overtopping	Overtopping	Overtopping	Overtopping	Overtopping
Piping Coeff.	1.49907609616348E+76	1.49907609616348E+76	1.49907609616348E+76	1.49907609616348E+76	-3.01200118148214E+76	1.78020108949793E+77	1.78020108949793E+77	1.78020108949793E+77
Initial Piping El., m	6.57040973605107E+76	6.57040973605107E+76	6.57040973605107E+76	6.57040973605107E+76	1.1417227993801E+77	1.69584024369851E+77	1.69584024369851E+77	1.69584024369851E+77
Flow Multiplier	1.01	1.01	1.01	1.01	1.01	1.02	1.02	1.02
Flow Duration Multiplier	1.07	1.07	1.07	1.07	1.06	1.01	1.01	1.01
Peak Inflow Value, m^3/s	573	573	573	573	578	583	583	583

Fig. 8. The yielding parameters of the statistical distribution

2.3 Initial and boundary conditions

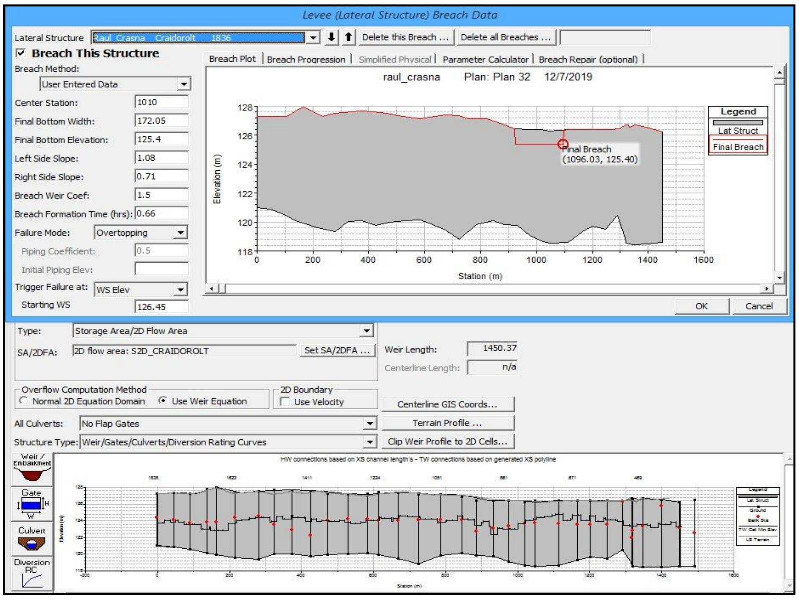

Fig. 9. Uncertainty parameters for left bank breach embankment

From Fig.8 are chosen the parameters with the probability of exceeding of 1 in 100 year (1%), which define the breach from defence embankment on the left bank of the Crasna River, and are then introduced in the discrete numerical model as shown in Fig.9.

Currently, the boundary conditions in the 1D path are given by: the transit flow with a certain probability of exceeding set as an initial flood hydrograph, values that are entered in the upstream section at "1880", hydrodynamic slope (i=0.0695‰) in the last cross section of the numerical model or rating curve in cross section at "21", and for the initial conditions the initial inflow values were set in section "1880" (Q=65.98 m^3/s).

For the initial conditions in 2D, the 2D discrete surface ("S2D_CRAIDOROLT") is associated with the artificial lateral structure from the left bank (1836), respectively setting-up the hydrodynamic slope (i=0.0695‰) as a boundary condition of the 2D discrete surface ("BC_S2D_CRAI_1"). It was chosen the flood flow hydrograph configuration recorded on Crasna River gauge station; and scaled by a numerical coefficient (3.90411) in order to reach the target peak flow value of 570 m^3/s. The numerical simulation of flow transition was set to start from 26th of May 2015 at 6:00 o'clock, and end at 30 of May 2015, hour 18:00. The run simulation has a time step of Δt = 5 seconds, and the output results interval is setup to 5 minutes.

3. Numerical model simulation and results

Following the execution of the actual numerical simulations, all constant or time de-depending parameters were obtained regarding: levels, flow rates and velocities, in all cross sections of the 1D numerical model and on the whole 2D domain (discrete surface referred as "S2D CRAIDOROLT"). Further the 2D domain associated with Crasna river was connected with the artificial lateral structure from the left bank, marked in the new model as "1836"'. The results representation after post-processing in final graphic form on the 1D/2D model in RastMapper, is shown below.

• Plotting the trajectories of the overlapping particles over the level surface (in maSL) – graphical representation at different time steps and with corresponding peak flows values: 27 May 2015, time 15.26.00 $\rightarrow$ Q=224.97m^3/s; 27 May 2015, time 15.50.00 $\rightarrow$ Q=258.65m^3/s; 28 May 2015 time 01.57.00 $\rightarrow$ Q=570.00m^3/s and 29 May 2015, time 09.00.00 $\rightarrow$ Q=167.75m^3/s – Fig.10;

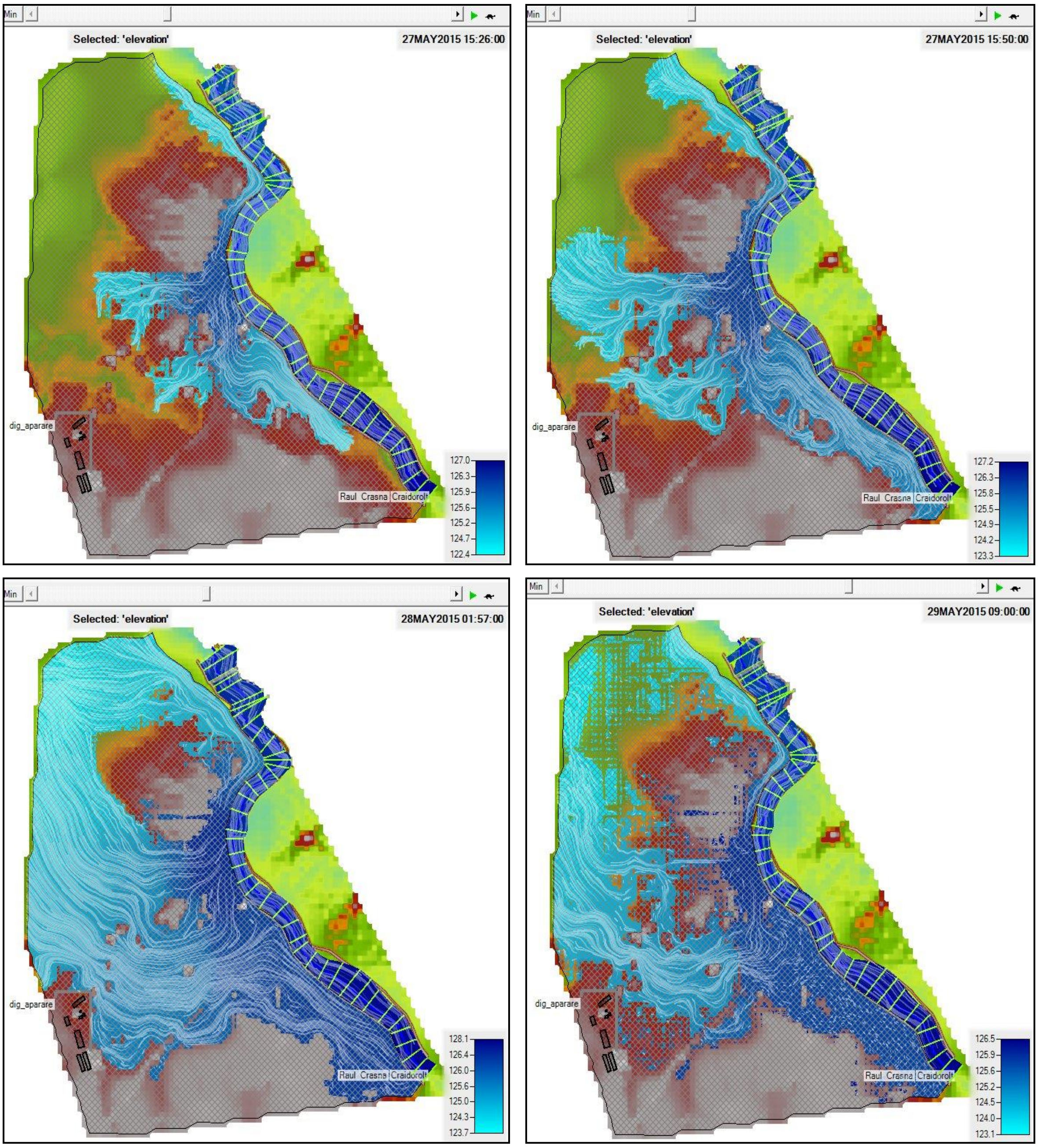

Fig. 10. Surface path draw in 1D/2D model (*maSL*), represented graphic at different time steps 27 of May 2015, time *15.26.00; 27 May 2015 time 15.50.00; 28 May 2015 time 01.57.00 and 29 May 2015 time 09.00.00*

• Water depth variation (m) in 1D/2D model at time step: 28 of May 2015 time 01.00.00, and peak inflow at the entrance Q = 570 m^3/s, respectively, velocity distribution (m/s) from numerical model 1D/2D at time step: 28 May 2015 time 01.01.00 and transitory peak flow at the entrance with a value of Q = 570 m^3/s – Fig.11.

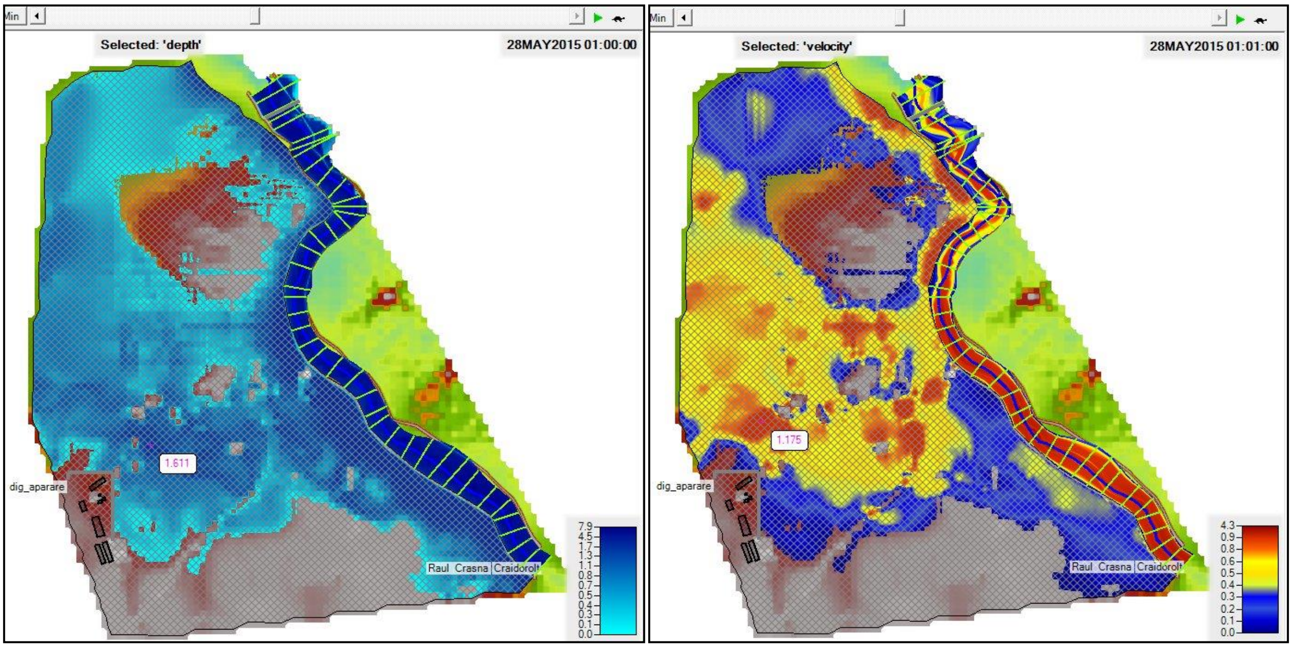

Fig. 11. Water depth variation (*m*), respectively, velocities (*m/s*) – graphic representation in 1D/2D model at time step: *28 Mat 2015 time 01.00.00* and peak flow of *Q = 570 m^3/s*

• Plotting the trajectories of overlapping particles over the level surface (maSL), respectively, the variation of water level in the longitudinal profile by the discrete model 1D and 2D, referred as: "*profil_longitudinal 1D_2D*" (maSL) – graphical representation at time step: *28 of May 2015 at time 1.00 – Fig.12*.

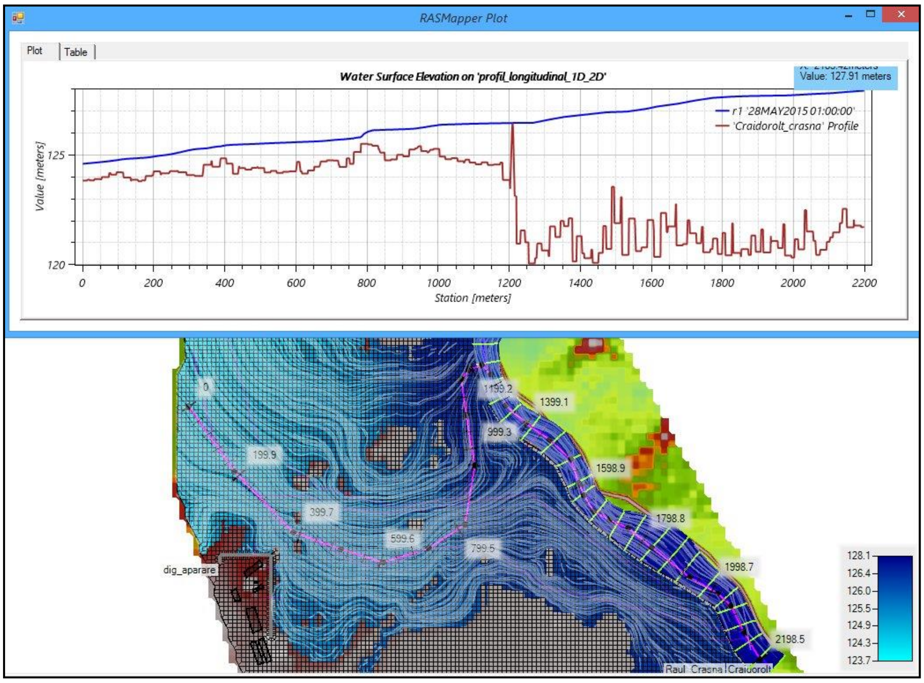

Fig. 12. Surface trajectories draw over the level surface (maSL) and longitudinal section through 1D/2D model – graphic representation at time step: *28 of May 2015 time 01.00.00* and inflow *Q = 570 m^3/s*

• Piezometric line variation (maSL) in longitudinal profile in 1D at time step: 28 May 2015 hour 01.00 and at peak flow value at the entrance section of Q = 570 m^3/s, respectively, the location of the beach in the left bank defence embankment, obtained from sampling the yielding parameters of the statistical distribution (Fig. 13).

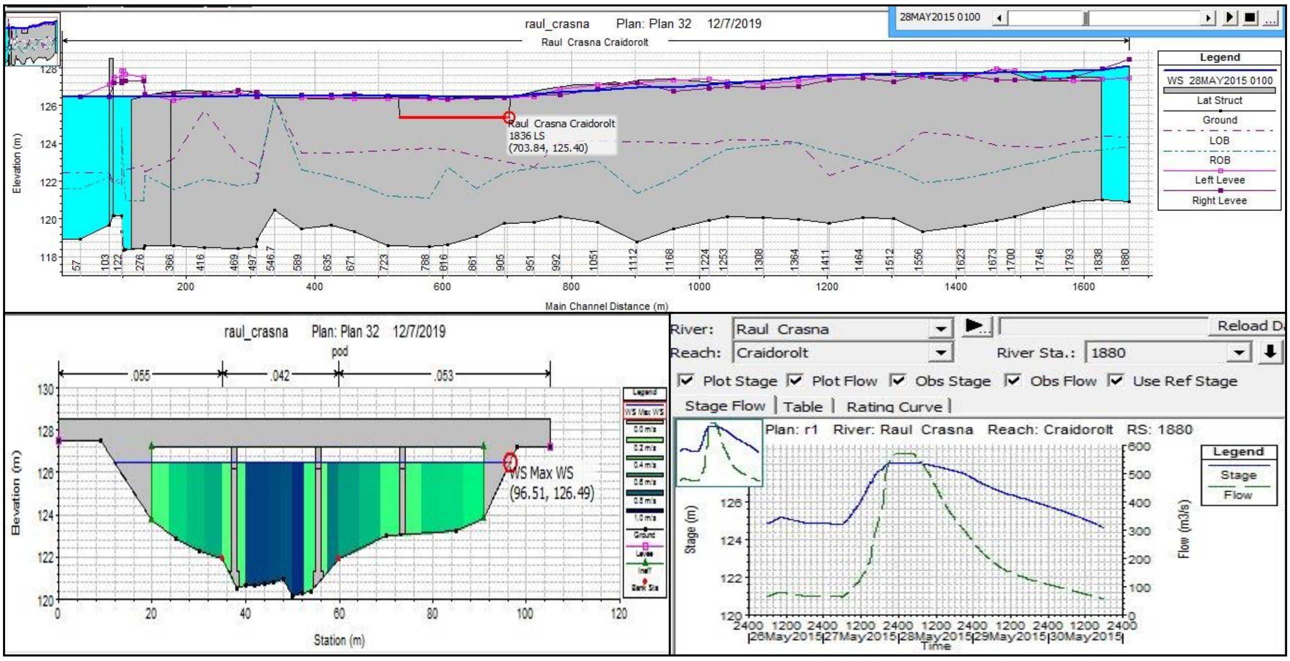

Fig. 13. Piezometric line (maSL) in 1D longitudinal profile – at time: *28 May 2015 hour 01.00*, and graphical breach location in the defence embankment; Maximum water level in section "106.50"; Level and flow hydrographs in the entrance section

Fig.14 illustrates geometric characteristic of the contour flood defence embankment, and the maximum water level reached in the accidental flow transit scenario (125.50 maSL), for the worst case scenario, 1% A.E.P on Crasna River with a peak flow value of $Q_{1\%}$ =570 m^3/s (safety embankment level at 125.60 maSL).

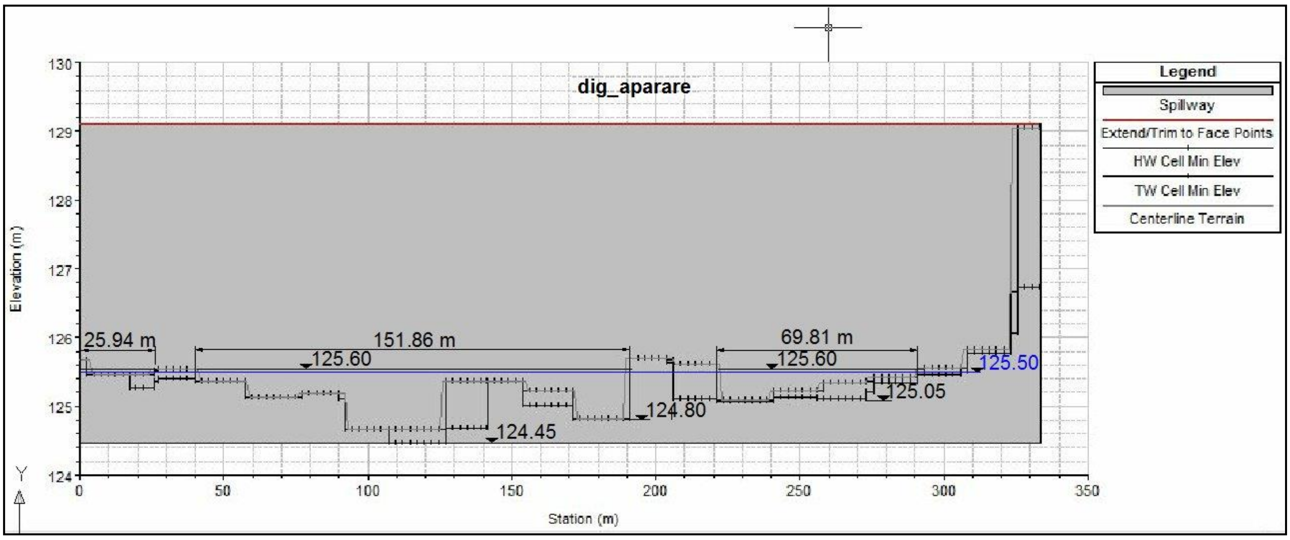

Fig. 14. Contour defence embankment - Longitudinal profile

4. Conclusions

It is observed in this discrete numerical modelling that the water transits through the minor floodplain, the major floodplain and over the defence embankments on the two banks of Crasna river, as well as through the breach developed at the left bank defence embankment. The flow transition starts when the possible transit flow reaches the maximum value for the verification flow with the probability of exceeding 1% (ex. the value $Q_{1\%}$ = 570 m^3/s), on the other hand flooding is not occurring in the private development establishment, at this accidental transition.
In conclusion, in the case in which the embankment on the left bank fails and a breach occurs with a base length of approx. 172.05 m, and in the floodplain a flood protection of the technological enclosure is made by placing a contour defence embankment, it can be said that the platform chosen for the private development is not at risk of flooding when the accidental flood flow transits.
Therefore, the variation of water levels reached in the floodplain area, highlighted and obtained by non-permanent hydraulic calculations (with the HEC-RAS software package version 5.07 in dynamic flow regime, respectively, with the McBreach © version 5.07 program, used as an external control system application that quantifies the uncertainty), reflects the existing situation at the terrain's ground level at the moment of the topographic surveys.

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