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MAGNITUDE OF DAMAGE EVENTS ON HYDROTECHNICAL TORRENT CONTROL STRUCTURES

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Abstract

The objectives of this paper address the identification and statistical analysis of the laws underlying the variability of the magnitude of the damages to torrent control structures induced by four of the most well-known events affecting their stability, resistance and durability. The research set consists of 100 torrent control structures that have continuously functioned for almost three decades in a managed torrential watershed in the forested mountainous area of Romania. In the first stage, the criteria and quantitative assessment scales regarding the magnitude of the damage that occurred during this period are set. In the second stage, a statistical analysis is performed aiming at fitting frequency distributions to the magnitude of these events. Quantification of the magnitude is presented by means of two statistical indicators (arithmetic mean and variation coefficient) as well as in the form of a theoretical function that can be used to estimate the frequency of events of various intensities over the entire functional period of the structures. On a 5-degree intensity scale (1=very low; 5=very high), three of the researched events (breakage of the terminal spur, undermining of the body, undermining of the apron) were of medium intensity, and the fourth (erosive damage or abrasion) was of low intensity. The statistical variability of the magnitude of the damage, as well as the nature of the law followed by the frequency distributions of the damage magnitudes, depends on: the nature of the event, the characteristics used for the quantification of the magnitude and the amplitude of the interval used for grouping frequencies into classes. Charlier type A and Beta laws have proved their flexibility in fitting the sequences of experimental frequencies, even if the values of the magnitude variation coefficient ranged, due to the influence of several factors, from 30% to 70%. From a practical point of view, the results can guide future monitoring and maintenance decisions concerning the type, extent and periodicity of the operations ensuring: the required performance of torrent control structures, the reinstatement of the structures affected by stream processes and the reestablishment of systems of which they are part.

Key words: apron undermining event, body structure undermining event, breakage event, erosive damage event

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1. Introduction

In response to the Commission Directive 2007/60/EC on the assessment and management of flood risks and with regard to the requirements imposed by the new generation of programmes and projects in the field of torrential integrated hydrologic watershed management (FAO, 2004, 2005; SAEFL, 2003), the scientific research in this field has recently focused on matters concerning flood risk management (Badaluta-Minda and Cretu, 2010; Bressers and Lulofs, 2010; Grozavu et al., 2013; Heinimann, 2003; Ministry of Environment, 2009), on emphasising the environmental impact and the efficiency of retention dams (Castillo et al., 2007; Conesa-García and García-Lorenzo, 2008; Remaitre et al., 2008; Surian and Rinaldi, 2003; Xiang-zhou et al., 2004) and on an integrated monitoring of the hydrotechnical torrent control structures (Clinciu, 2005; Clinciu and Gaspar, 2005; Davidescu et al., 2012; Giurma-Handley et al. 2010; Lazar and Gaspar, 1994; Mazzorana and Fuchs, 2010; Polyakov et al., 2014; Quiñonero-Rubio et al., 2014). The primary goals are: maintenance of structures within

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the managed torrential network of small, predominantly forested watersheds, reinstatement of those structures affected by stream process, and reestablishment of the systems of which they are part of.

Supporting scientific research regarding statistical analysis of damage patterns can contribute to a better implementation of systematic and permanent monitoring and maintenance of torrent control structures (Clinciu et al., 2010a, 2010b; Giurgiu, 1972; Petrițan and Clinciu, 2009).

By focusing on this goal, this paper continues earlier research initiated to ground the monitoring of torrent control structures on a statistical basis (Clinciu et al., 2010a). This time the purpose is to highlight, on the basis of the developed methodology, the magnitude of the four most dangerous damage patterns: the breakage event, the erosive damage event, the body structure undermining event; and the apron undermining event.

The objectives of this research focus on providing the answers to three scientific questions:

- What is the average magnitude of the events classified as damages?
- How large is the variation of the intensity of damages during the functional period of the structures?
- What are the theoretical laws behind the variation of damage intensity?

Answering these questions is important because predictive knowledge regarding the nature, frequency and average magnitude of damage patterns, allows the central public authority for silviculture to make decisions with respect to the nature, volume and periodicity of operations ensuring: the maintenance of torrent control structures, the reinstatement of those structures affected by stream processes, and the security of systems of which they are part.

On the other hand, it is only after gaining knowledge about the laws underlying statistical variability, that the public decision maker can rely on frequency estimates associated with the intensity of various structural damage patterns in hydrographic watersheds, similar to the one researched, in terms of: surface area and degree of afforestation, pluviometric regime, construction characteristics and functional period of the structures, nature and quality of construction materials, applied execution technologies, etc.

2. Datasets and methods

The datasets are identical to that used in previous research (Clinciu et al., 2010a). The 100 structures built along 21 torrential valleys in the Upper Tărlung Watershed (about 190 km^2), upstream of the Săcele water storage-Braşov county (25^0 48' E, 45^0 30' N) (Fig. 1), were considered. Out of these structures: dams are the most numerous (55, but only 49 of them were taken into account since 6 dams have been totally distroyed by a torrential event), traverses and sills are almost equally represented (23 and 22 respectively), and canals are very poorly represented (only 4).

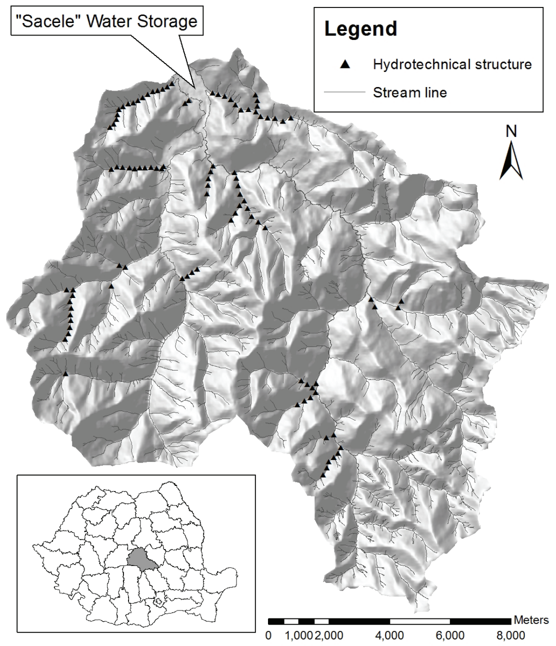


Fig. 1. Location of the hydrotechnical structures on the managed torrentials valleys

The mountaineous area were the 21 managed torrential valleys are located is predominantly grafted on sedimentary rocks (lime and grit stones) and it lies from 730 m to 1875 m. The average annual precipitation is between 800 mm and 1800 mm. The drainage area of watersheds where are located hidrotechnical structures varies from 37 ha to 1393 ha, the afforestation degree from 50% to 96%, and the average slope gradient is 20% … 40%.

A statistical approach was developed for the magnitude of behavioural events in the category of damage patterns. In the first research stage, this magnitude was cuantified by two caracteristics in the case of each one of the four researched events, along with definitions of the corresponding scales, subsequently followed by quantification proper (these characteristics are different for each event, see details in Tables 1-3, 5). Depending on the direction of the intensity increase on each scale, the cells resulting from the intersection of the used scale intervals are grouped into five zones each expressing a certain degree of the global magnitude of damage (the same number of cells characterises each of five zones), ranging from very low global magnitude (in the upper left part of the Tables 1, 2, 3 and 5) to very high global magnitude (in the bottom right part of the same table). By weighting these degrees (I_i) by the sum of the frequencies corresponding to each area (n_i), the global average magnitude of each researched event (K_{damage}) is estimated using Eq. (1):

$$K_{damage} = \sum_{i=1}^{5} I_i \cdot n_i \qquad (1)$$

In the second research stage, in order to find the variation of the magnitude of damage patterns and the law underlying this variation, frequency distributions of the damage magnitudes for the affected structures, obtained separately for each individual criterion and for the global criterion resulting from the combination of these individual criteria, are subjected to statistical study both in terms of the main statistical indicators and the possibility of fitting by three of the most well-known theoretical distributions (normal, Charlier type A and Beta).

The data was processed using STATISTICA 8.1. software (Statsoft Inc., 2005) and the results were compiled for each criterion separately, in fields of composed figures each comprising three component parts: the curves of the theoretical and experimental frequencies, the values of the main statistical indicators (m-arithmetic mean, s%-variation coefficient), and the (theoretical and experimental) values of the χ^2 test for the above mentioned theoretical distributions. The χ^2 value was specified for each type of distribution mentioned. This value was computed using Eq. (2):

$$\chi^2 = \sum \frac{\left(n - \hat{n}\right)^2}{\hat{n}} \qquad (2)$$

where n is the experimental frequency, and $\hat{n}$ is the theoretical frequency.

3. Results and discussions

The four damage patterns are analysed referring to frequences and the degree of magnitude. Descriptive and illustrative elements regarding these damage patterns can be found in details in Clinciu et al. (2010 a).

3.1. Breakage event

3.1.1. Introductory elements

During the studied period 34 transverse structures and 47 component parts were affected by a breakage event. Only two of the affected structures are traverses (out of a total of 23), 8 are sills (out of 22), and 24 are dams (out of 49). Thus, the degree of damage is as follows: 8% for traverses, 36% for sills, and 49% for dams.

When compared to the total number of structures (Fig. 2), it has been noted that sills affected by breakage are equally represented (23%), while the degree of damage differs from the degree of representation in the case of dams and traverses: it is much higher for dams (71% as opposed to 51%) and much lower for traverses (6% as opposed to 26%).

The parts most affected by a breakage event are: the apron zone terminal spur, identified in 24 cases (51%), and the energy dissipation teeth, identified in 13 cases (28%). The breakage event rarely occurs in the other 7 component parts; it was recorded only once in 5 parts, twice in one part and three times in another part.

3.1.2. Breakage of the terminal spur

The following two criteria are considered in order to estimate the global magnitude of this event:

- the depth along which breakage occurred, classified by the following degrees: 0.0–0.5 m; 0.5–1.0 m; 1.0–1.5 m; 1.5–2.0 m; 2.0-2.5 m.

- the proportion of the apron length on which breakage occurred, quantified by classes of 10 percent (0–10%, 10–20%, ……, 90–100%).

In order to combine the two criteria in the table of cells, showing the frequencies associated to a breakage event in the intersection areas of the degrees of the two individual criteria (Table 1), five distinct areas (each containing 10 cells) were delimited, each area being characterised by a certain global magnitude of damage, ranging from very low (in the upper left part of the table) to very high (in the bottom right part of Table 1).

The distribution of the identified cases on the intensity scale is as follows:
(1) – very low intensity: 6 cases;
(2) – low intensity: 5 cases;
(3) – medium intensity: 2 cases;
(4) – high intensity: 2 cases;
(5) – very high intensity: 9 cases.

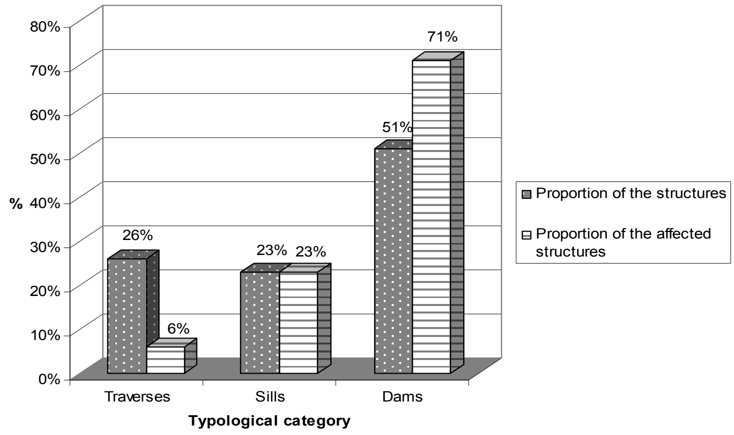


Fig. 2. Comparative percentage frequencies for the researched structures (left) and the structures affected by breakages (right)

Table 1. Frequency zoning for the terminal spur breakage event

Proportion of breakage (%)	***Depth of breakage (m)***					
	0.0…0.5	***0.5…1.0***	***1.0…1.5***	***1.5…2.0***	***2.0…2.5***	**Total**
0 … 10	0	0	0	0	0	**0**
10 … 20	1	1	0	0	0	**2**
20 … 30	0	1	2	0	0	**3**
30 … 40	0	2	1	0	0	**3**
40 … 50	1	1	0	0	0	**2**
50 … 60	0	1	0	0	0	**1**
60 … 70	0	1	1	1	0	**3**
70 … 80	0	1	0	0	0	**1**
80 … 90	0	0	1	0	0	**1**
90… 100	0	0	3	4	1	**8**
Total	**2**	**8**	**8**	**5**	**1**	**24**

The coefficient of the global magnitude of the researched event, having the value as presented in Eq. (3) shows that the breakage of the apron zone terminal spur occurred as a behavioural event of medium magnitude.

$$K_R = \frac{6\cdot 1 + 5\cdot 2 + 2\cdot 3 + 2\cdot 4 + 9\cdot 5}{24} = 3.1 \approx 3 \quad (3)$$

The statistical laws followed by the magnitude of this event were examined based on three frequency distributions:

- the frequency distribution of breakages of the terminal spur (in the apron zone) by categories of depth along which breakage occurred;
- the frequency distribution of the same breakages, by categories of proportion of the apron length on which breakage occurred;
- the frequency distribution of breakages by degrees of the global magnitude of the event, the classification of the magnitude being made on a scale with 5 classes, from 1 (very low intensity) to 5 (very high intensity).

On this intensity scale (Fig. 3) the global average magnitude of breakage is 3.12, while the variation coefficient for the first two frequency distributions lies from 44% to 49%, and it rises to 55% in the case of the third one. Regarding the concordance between the experimental frequency distributions and the theoretical frequency distributions, the χ^2 test shows the following (Fig. 3):

- for the frequency distribution of the depth of breakage, the law of the behavioural event is well reflected by all three theoretical distributions that were considered, and the goodness-of-fit (estimated by means of the $\chi^2_{exp}/\chi^2_{theor}$ ratio) leads to the following hierarchy of distributions: normal distribution, Charlier type A distribution, and Beta distribution;
- in case of the proportion of the breakage length, Beta and Charlier type A distributions (in this order) show their flexibility, both being a good fit, but normal distribution could be shown;
- finally, the fit is limited only to the theoretical Beta distribution, in the case of the global magnitude of the event.

3.2. Erosive damage event

The detailed analysis upon the damage of the hydrotechnical structures by water and alluvia, regards only the body of the overflowed area, which was identified as having the highest frequency of damage.

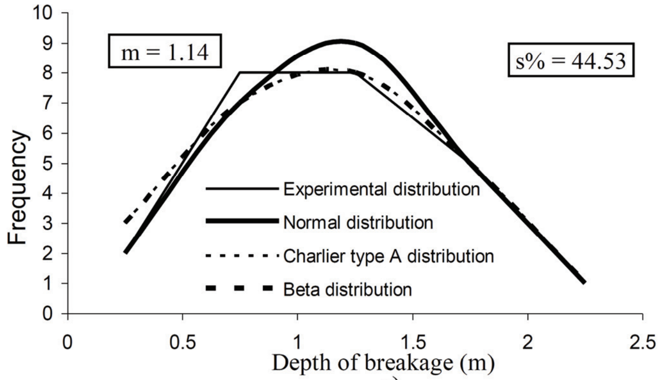
If the depth of the erosive damage is estimated on the scale proposed by Lazăr and Gaspar (1994) (up to 10 cm = superficial erosive damages; over 10 cm = deep erosive damages), the data is distributed as follows: superficial erosive damages - 39 cases (83%), deep erosive damages - 8 cases (17%).

On a more detailed scale, proposed in the present research (1-5 cm = very superficial erosive damages; 5-10 cm = superficial; 10-15 cm = medium deep; 15-20 cm = deep; over 20 cm = very deep), the identified cases of erosive damages are distributed as follows: very superficial - 23 cases (48%), superficial - 17 (35%), medium deep - 2 (4%), deep - 2 (4%), very deep - 4 (9%).

From the point of view of the percentage of damage of the structure part (the body of the overflowed area), the same data reveals the following frequencies:
- very low (up to 20% of the surface): 24 cases (51%);
- low (20-40%): 8 cases (17%);
- medium (40-60%): 10 cases (21%);
- extensive (60-80%): 2 cases (4%);
- highly extensive (80-100%): 3 cases (6%).

Thus, quantifying the intensity by the two individual criteria in turn, the study revealed that only 13% of the cases of erosive damage in the overflowed area are deep or very deep and only 10% of these cases display extensive or highly extensive damaged surfaces.

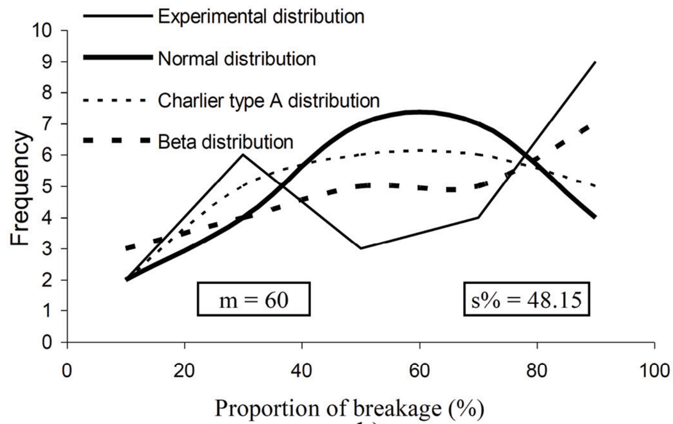
The same method as in the previous case (Table 2) was applied in order to combine the criteria, and the following distribution was discovered with respect to the identified cases by the five degrees of intensity used in this research: (1) very low intensity: 35; (2) low intensity: 7; (3) medium intensity: 3; (4) high intensity: 1; (5) very high intensity: 2.



a)

χ^2 test

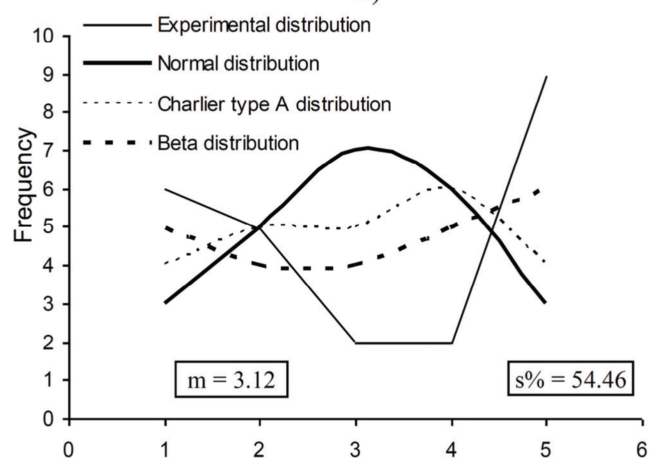
Theoretical distribution	Experimental value	Theoretical value
Normal	0.25	9.48
Charlier, type A	0.47	9.48
Beta	0.47	7.81
Conclusion: All three theoretical distributions fit the experimental distribution.		



b)

χ^2 test

Theoretical distribution	Experimental value	Theoretical value
Normal	10.82	9.48
Charlier, type A	5.56	9.48
Beta	2.91	7.81
Conclusion: Charlier – type A and Beta theoretical distributions fit the experimental distribution		



χ^2 test

Theoretical distribution	Experimental value	Theoretical value
Normal	21.23	9.48
Charlier, type A	11.71	9.48
Beta	4.75	7.81
Conclusion: The experimental distribution follows the law of Beta distribution		

Fig. 3. The experimental frequency polygons, the theoretical frequency curves, the values of the main statistical indicators and the χ^2 test values for the distributions studied in the case of breakages occurring in the terminal spur (apron zone): a) by categories of depth of breakage in the apron zone; b) by categories of proportion of the apron length on which breakage occurred; and c) by degrees of global magnitude of the event

For two out of the three criteria, used in the analysis of the intensity, two frequency distributions, different from the point of view of the amplitude of the class interval, were formed and studied for each one as follows:

- for the *"depth of the erosive damage"* criterion (Fig. 4), the class intervals of 5 and 10 cm were considered respectively;

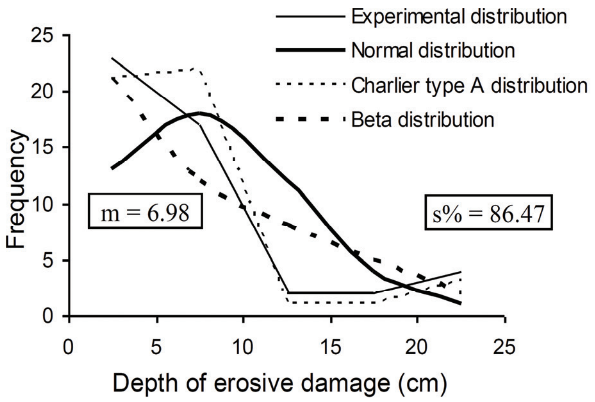
- for the *"proportion of the affected surface"* criterion (Fig. 5), the amplitude of 10% and 20% were considered respectively.

In case of the criterion concerning the global magnitude of damage (Fig. 6), the frequencies were grouped according to 5 degrees of intensity, ranging from 1-very low intensity up to 5-very high intensity.

Consequently, following the functioning of the structures for approximately 25 years, the average depth of erosive damage was approximately 7 cm, and it affected on average approximately 30% of the surface. The global average magnitude obtained was approximately 1.5.

Table 2. Frequency zoning regarding the extent of erosive damages

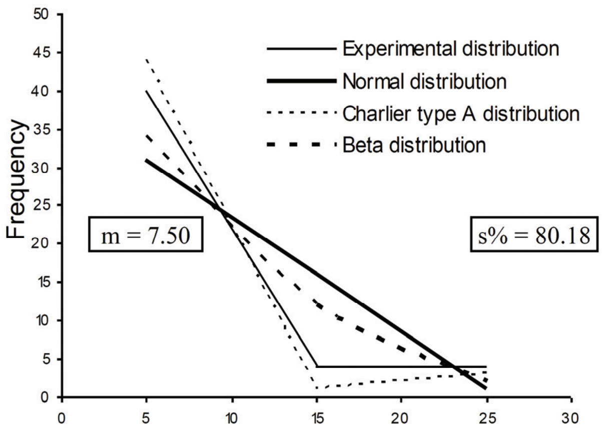
Proportion (%)	***Depth (cm)***					***Total***
	1-5	5-10	10-15	15-20	Over 20	
0 … 10	4	4	1	0	0	**9**
10 … 20	6	6	1	1	1	**15**
20 … 30	3	4	0	0	0	**7**
30 … 40	0	1	0	1	0	**2**
40 … 50	6	1	0	0	1	**8**
50 … 60	1	1	0	0	0	**2**
60 … 70	2	0	0	0	0	**2**
70 … 80	0	0	0	0	0	**0**
80 … 90	0	0	0	0	0	**0**
90… 100	1	0	0	0	2	**3**
Total	**23**	**17**	**2**	**2**	**4**	**48**



a)

χ^2 Test

Theoretical distribution	Experimental value	Theoretical value
Normal	26.08	9.48
Charlier, A type	3.66	9.48
Beta	10.57	7.81
Conclusion: The experimental distribution follows the law of Charlier - type A distribution		



χ^2 Test

Theoretical distribution	Experimental value	Theoretical value
Normal	20.61	5.99
Charlier, A type	9.69	5.99
Beta	8.39	3.84
Conclusion: The experimental distribution does not follow any of the three teoretical distribution		

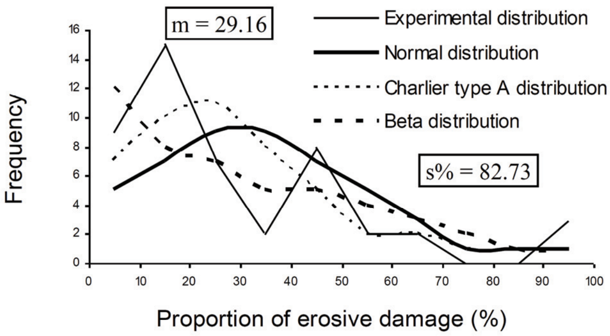
Fig. 4. The frequency distributions regarding the extent of the erosive damage of the structures, formed according to the *"depth of the damage"* criterion: a) classes with an amplitude of 5 cm; b) classes with an amplitude of 10 cm

The high value of the variation coefficient, both for the depth of erosive damage (80-86%) and the extent of the affected surface (81-83%), shows that the event magnitude variation was a significant one. Grouping the frequencies into classes with a different amplitude led to important changes of the variation coefficient only in the case of the global magnitude of damage (67% and 45%), while, for the other criteria, the value of the afore mentioned coefficient showed little variation, both for the depth of erosive damage (86% and 80%) and the extent of the surface affected by erosive damage (83% and 82%).

The application of the χ^2 test, separately for each research variant, proved that the experimental distribution of the depth of erosive damage follows the law of Charlier type A distribution, but only when frequencies are grouped into classes with an amplitude of 5 cm. In the case of the classes with an amplitude of 10 cm, the experimental frequency does not follow any of the three theoretical distribution patterns. In both situations, distributions are very far from normal distribution. In the case of the proportion of the affected surface, the experimental distribution also does not correspond to the normal distribution. Here, the variation of the event magnitude is well rendered either only by the law of Charlier type A distribution, when frequencies are grouped into classes with an amplitude of 10%, or by both the law of Charlier type A distribution and the law of Beta distribution, when frequencies are grouped into classes with an amplitude of 20%. For the global magnitude of damage, the sequence of experimental frequencies follows only the law of Charlier type A distribution; this distribution is also very far from normal distribution.

Consequently, Charlier type A distribution successfully fits the experimental frequencies in four of the six cases, and the Beta distribution only in one case. The normal distribution could not be shown statistically in any of the cases.

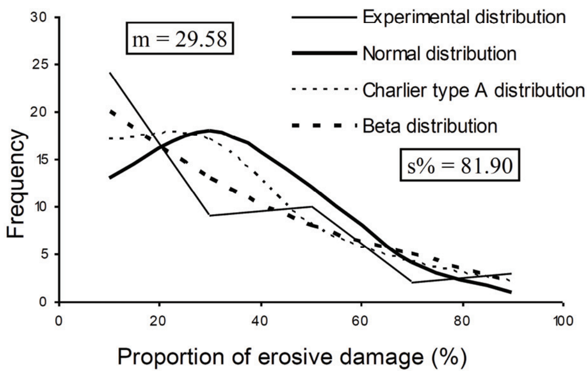
By increasing the amplitude of class interval, the ratio between experimental χ^2 and theoretical χ^2 increases, which confirms that the frequency distribution is even farther from normal distribution.



a)

χ^2 test

Theoretical distribution	Experimental value	Theoretical value
Normal	26.51	16.91
Charlier, type A	16.82	16.91
Beta	18.81	15.51
Conclusion: The experimental distribution follows the law of Charlier type A distribution		

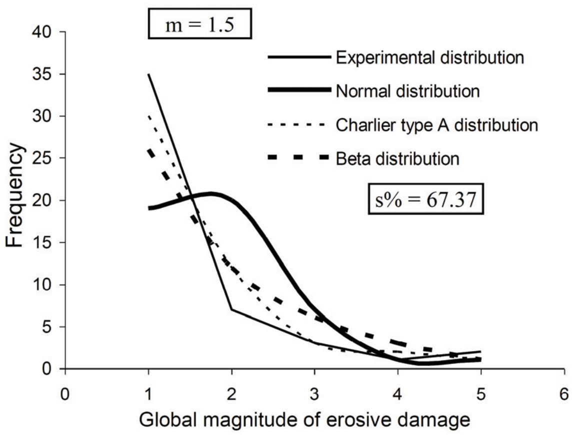


b)

χ^2 test

Theoretical distribution	Experimental value	Theoretical value
Normal	19.14	9.48
Charlier, type A	8.64	9.48
Beta	4.83	7.81
Conclusion: The experimental distribution follows the law of Charlier type A and Beta distributions		

Fig. 5. The frequency distributions regarding the extent of the erosive damage of the structures, formed according to the *"proportion of the affected surface"* criterion: a) classes with an amplitude of 10%; b) classes with an amplitude of 20%



Theoretical distribution	Experimental value	Theoretical value
Normal	25.20	9.48
Charlier, type A	4.41	9.48
Beta	9.03	7.81
Conclusion: The experimental distribution follows the law of Charlier type A distribution		

Fig. 6. The frequency distributions regarding the extent of the erosive damage of the structures, established by the five degrees of the "*global magnitude of damage*" (very low, low, medium, high and very high)

Finally, comparing Charlier type A and Beta distributions (recognised for their flexibility) in terms of the quality of fitting, Charlier type A distribution was noted to be the best fit, especially if the amplitude of class interval is decreased.

3.3. Body structure undermining event

The cases affected by this event, a total of 7, refer exclusively to traverses (totalling 25) and are distributed in 10 out of the 21 managed torrential valleys. By comparing the proportion of damage and the proportion of typological representation of the structures (Fig. 7), one can notice that, overall, traverses represent only 24%, but they are affected to an extent which is almost three times higher (68%).

In order to estimate the global magnitude of damage, similar criteria to those used in the analysis of the magnitude of the breakage event were taken into consideration:

- the depth of the undermining, by degrees of 0.5 m, and
- the degree of damage to the body of the structure, along its length, by percentage classes with an amplitude of 10%.

Depending on these two criteria, the traverses affected by the undermining of the body are distributed as shown in Table 3. By adding the frequencies found in the cells pertaining to the same area, the following distribution was obtained with respect to the degrees taken into consideration for characterising the global intensity of the event: (1) very low intensity 1 case; (2) low intensity 5 cases; (3) medium intensity 4 cases; (4) high intensity 4 cases; (5) very high intensity 1 case.

By assigning weights to the intensity degrees and by adding the products of these weights and the corresponding frequencies, this coefficient was obtained (Eq. 4):

$$K_{sc} = \frac{1\cdot 1 + 2\cdot 5 + 3\cdot 4 + 4\cdot 4 + 5\cdot 1}{15} = 2.93 \cong 3.00 \quad (4)$$

which shows that the undermining of the body of a traverse was a medium-intensity event.

The statistical analysis of frequency distributions (Fig. 8) proved that the average depth along which the undermining of the body occurred is 0.81 m, and the average proportion of affected body length is 58%.

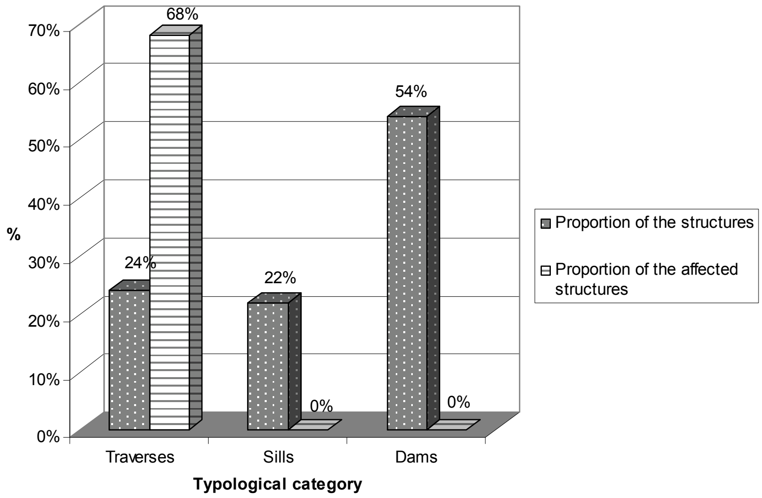
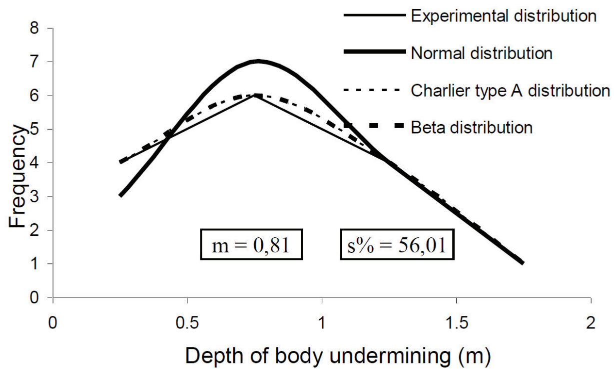


Fig. 7. Comparison between the proportion of damage and the proportion of representation, for the event concerning the undermining of the body of traverses

Table 3. The frequencies of the traverses affected by the body undermining

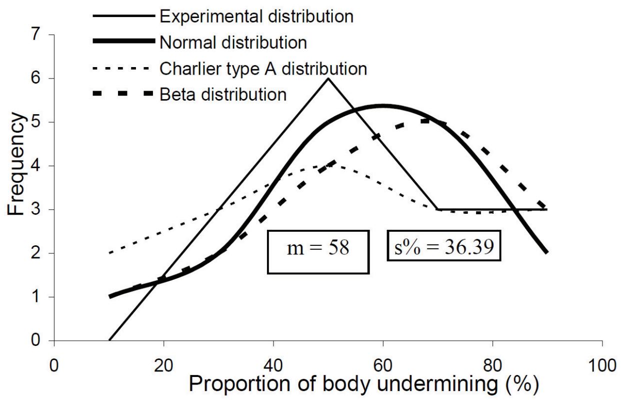
Proportion of body undermining (%)	*Depth of body undermining (m)*				*Total*
	0-0.5	0.5-1.0	1.0-1.5	1.5-2.0	
0-10	0	0	0	0	**0**
10-20	0	0	0	0	**0**
20-30	0	0	0	0	**0**
30-40	1	1	1	0	**3**
40-50	0	3	2	0	**5**
50-60	0	1	0	0	**1**
60-70	1	0	0	1	**2**
70-80	0	0	1	0	**1**
80-90	0	0	0	0	**0**
90-100	2	1	0	0	**3**
Total	**4**	**6**	**4**	**1**	**15**



a)

χ^2 test

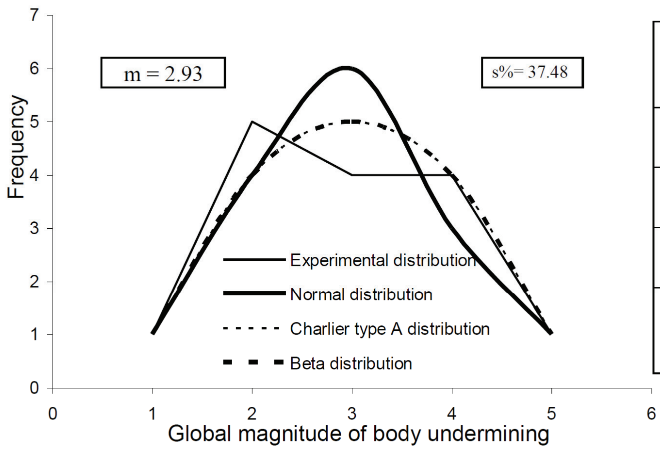
Theoretical distribution	Experimental value	Theoretical value
Normal	0.47	7.81
Charlier, type A	0.00	7.81
Beta	0.00	5.99
Conclusion: All three theoretical distributions fit the experimental distribution		



b)

χ^2 test

Theoretical distribution	Experimental value	Theoretical value
Normal	3.00	9.48
Charlier, type A	5.50	9.48
Beta	3.30	7.81
Conclusion: All three theoretical distributions fit the experimental distribution		



c)

χ^2 test

Theoretical distribution	Experimental value	Theoretical value
Normal	1.25	9.48
Charlier, type A	0.45	9.48
Beta	0.45	7.81
Conclusion: All three theoretical distributions fit the experimental distribution		

Fig. 8. The experimental frequency polygons, the theoretical frequency curves, the values of the main statistical indicators and the χ^2 test values for the distributions regarding body undermining: a) by degrees of depth of body undermining; b) by categories of proportion of damage to the length of the body; c) by degrees of global magnitude of damage

The distribution obtained for the criterion regarding the depth of the undermining of the body registers the highest variation coefficient (56%). Lower than this (approximately 37%) is the variation coefficient which resulted for the other two criteria.

The χ^2 test, applied separately to each case, proved that the three theoretical distributions used in this analysis fit the experimental distributions, for all the three characteristics that were considered (depth of body undermining, proportion of damage to the length of the body and global magnitude of event occurrence).

The quality of fitting (estimated by means of the $\chi^2_{exp}/\chi^2_{theor}$ ratio) gives the following hierarchy of the theoretical distributions: for the first characteristic, Beta distribution, Charlier type A distribution and normal distribution; for the second characteristic, normal distribution, Beta distribution and Charlier type A distribution; and for the third characteristic, Charlier type A distribution, Beta distribution and normal distribution.

Consequently, for the magnitude of the behavioural event concerning the undermining of the body of traverses, the normality of the frequency distribution could be statistically shown for all the three characteristics taken into consideration when forming the distributions.

3.4. Apron undermining event

This event was identified in 42 out of 78 transverse structures endowed with apron, 59% (13 cases) of the sills and 53% (29 cases) of the dams were affected.

By comparing the proportion of damage and the proportion of representation (Fig. 9), one can easily note that the highest difference is displayed by the category of sills. Apparently, the result contradicts expectations, since for the category of dams, the degree of damage (53%) is placed below the level of typological representation of the structures in this category (71%).

A possible explanation could be that, in the category of sills, the energy dissipation teeth were included only in 50% of the structures constructed, while the implementation of this dissipation system was carried out to a much larger extent (76%), in the case of dams. Indeed, the re-centralisation of the data revealed that only 6 sills are provided with energy dissipation teeth (46%) out of the 13 affected by apron undermining.

In other words, was slightly higher the proportion of apron undermining in the case of sills of which the apron was not provided with energy dissipation teeth.

On the other hand, as the name "*apron undermining*" encompasses an event localised downstream of the terminal spur of the structure, both in the apron segment and in the two lateral segments (left and right of the apron), the frequency of occurrence of the event was also analysed depending on the positioning of these two component parts of the structures.

The most affected part was the right apron zone spur, identified in 41 cases, while the next on the list, namely the left terminal spur, was identified only in 3 cases and the right terminal spur in only one case (Fig. 10).

The fact that undermining represents one of the causal factors of breakages is suggested by the data shown comparatively in the same figure, where it can be noted that, whereas for the right and the left terminal spur the frequency is similar, for the apron zone terminal spur the frequency is considerably different. It is assumed that this difference is due to the sequence of events because once undermining occurs at the base of the apron favourable conditions for breakage, in the terminal spur on this section of the structure, (also) develop.

In order to prove the formulated hypothesis, rank correlation was applied in order to study the correlative dependence between the number of structures affected by apron undermining, and the number of structures affected by breakage of the terminal spur in the apron zone (Table 4).

The result obtained (a very significant correlation coefficient – Table 4) confirms the assumption that the analysed behavioural events are strongly correlated. Consequently, one can state that apron undermining is the event which determines terminal spur breakage on this section of the structure.

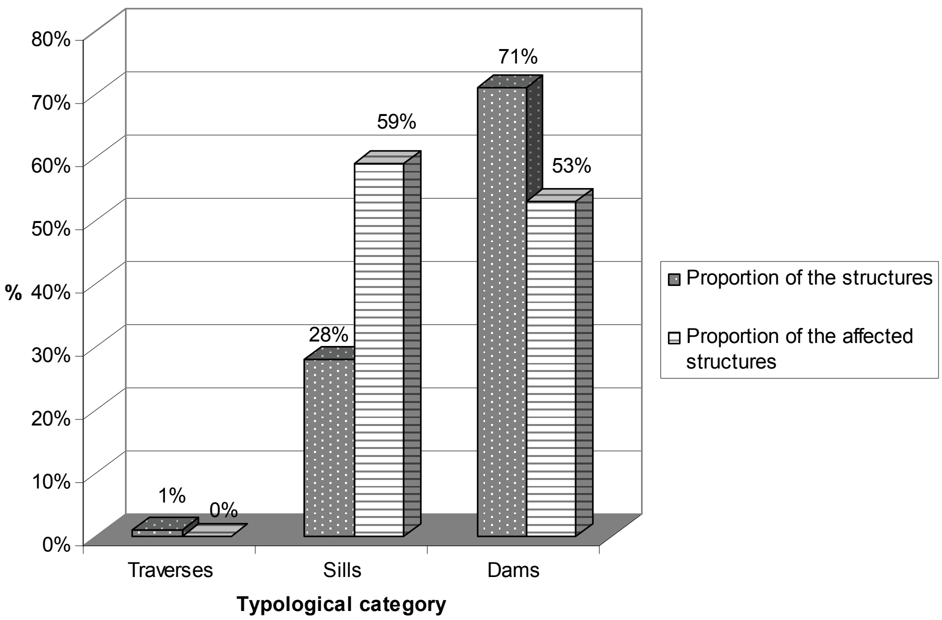


Fig. 9. Comparison between the proportion of damage and the proportion of representation, for the event concerning the apron undermining

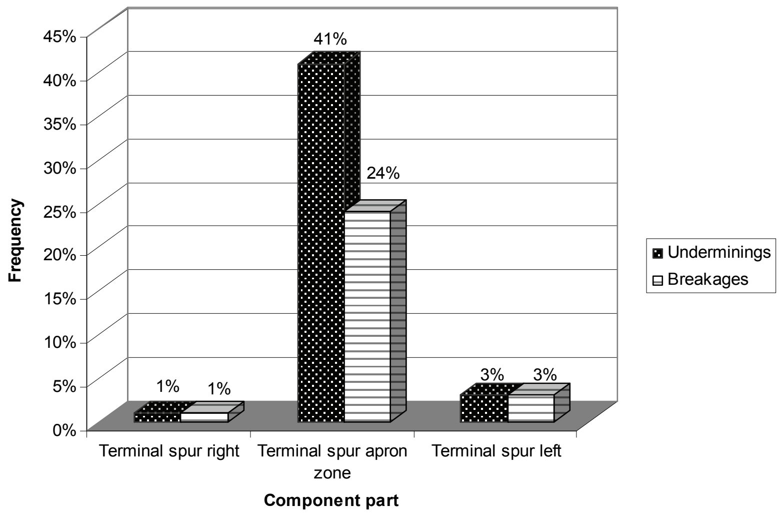


Fig. 10. Comparative presentation of the frequencies of events concerning apron undermining and breakage of the terminal spur in the apron zone

Table 4. Rank correlation between the number of structures with undermining and the number of structures with breakage

Number of:		***The rank by:***		***Difference:***	
Underminings	***Breakages***	***Underminings***	***Breakages***	***d***	***d^2***
1	0	7.5	9	1.5	2.25
8	4	2	3	1	1
4	2	5.5	6	0.5	0.25
7	4	3	3	0	0
4	3	5.5	5	0.5	0.25
5	5	4	1	3	9
0	0	9.5	9	0.5	0.25
9	4	1	3	2	4
0	0	9.5	9	0.5	0.25
1	1	7.5	7	0.5	0.25
Σ					17.50
$r_s = 1 - \frac{6\Sigma d^2}{n(n^2-1)} = 1 - \frac{6 \cdot 17.5}{10(100-1)} = 0.894^{***}$					
To f = n – 2 = 10 – 2 = 8 degrees of liberty: $r_{0,001} = 0.872 < 0.894$					

Table 5. The frequencies for each of the 5 areas of the same apron undermining

Proportion of apron undermining (%)	***Depth of apron undermining (m)***				***Total***
	0-0.5	0.5-1.0	1.0-1.5	1.5-2.0	
0-10	2	0	0	0	**2**
10-20	1	1	0	0	**2**
20-30	0	2	4	0	**6**
30-40	0	2	1	0	**3**
40-50	4	1	0	1	**6**
50-60	2	1	0	0	**3**
60-70	0	2	1	1	**4**
70-80	0	1	0	0	**1**
80-90	0	0	1	0	**1**
90-100	0	1	4	4	**9**
Total	**9**	**11**	**11**	**6**	**37**

Only the right apron zone spur (the most affected) was subjected to the statistical analysis of the magnitude of the apron undermining event, taking into consideration the following criteria:

- the depth of the undermining in the apron zone by degrees of 0.5 m;

- the proportion of damage to the apron, estimated along its width, by intervals with an amplitude of 10%.

In order to combine the two criteria with a view to characterising the global magnitude of damage, each of the frequencies identified for apron undermining was placed in the corresponding cell in Table 5, and by successively adding the frequencies for each of the 5 areas of the same damage magnitude, the following case distribution was found:

(1) - very low intensity 10 cases (27 %);
(2) - low intensity 9 cases (24 %);
(3) - medium intensity 4 cases (11 %);
(4) - high intensity 4 cases (11 %);
(5) - very high intensity 10 cases (27 %).

The coefficient resulting by assigning weights to the five degrees of intensity is according to Eq. (5):

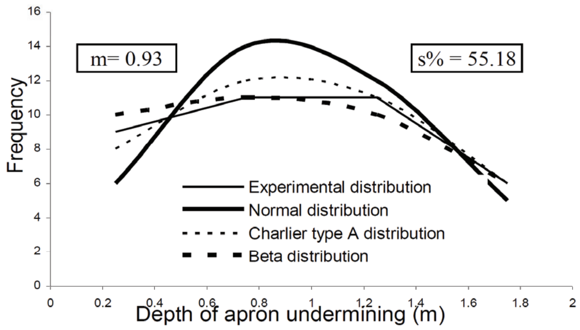
$$K_{Sr} = \frac{1 \cdot 10 + 2 \cdot 9 + 3 \cdot 4 + 4 \cdot 4 + 5 \cdot 10}{37} = 2.86 \approx 3 \quad (5)$$

which shows that apron undermining was a medium-intensity event during the functional period of the structures.

A detailed statistical analysis of the three distributions (Fig. 11) showed that the average depth along which the apron undermining occurred is 0.93 m, and the average proportion of the apron width affected by undermining is 54%.

Both in the case of individual use of analysis criteria and in the case of combined use of these criteria, the values that resulted in the variation coefficient of the event magnitude were close (between 51% and 56%).

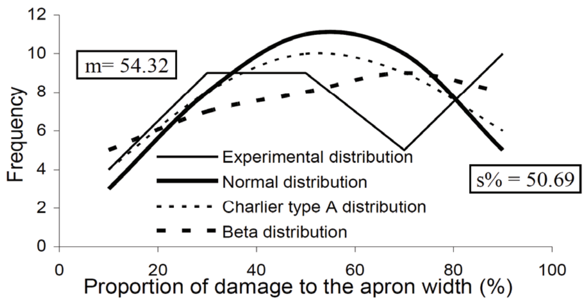
The χ^2 test, applied separately for each sequence of frequencies, showed that the experimental distributions are in concordance with the theoretical distributions only for the first two research characteristics of the magnitude (i.e. depth of apron undermining and proportion of damage to the apron width). Concerning the global magnitude of the event, the experimental distribution follows only the laws of Charlier type A and Beta distributions.



a)

χ^2 test

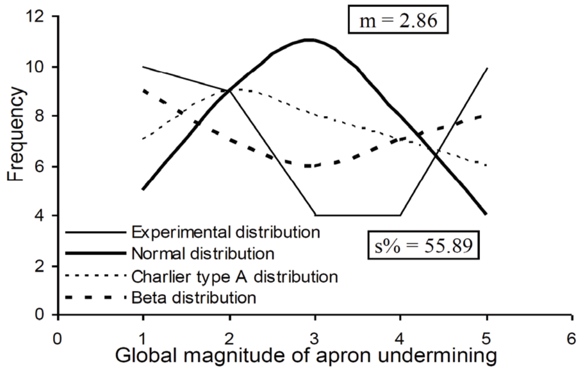
Theoretical distribution	Experimental value	Theoretical value
Normal	2.42	7.81
Charlier, type A	0.90	7.81
Beta	0.20	0.55
Conclusion: All three theoretical distributions fit the experimental distribution		



b)

χ^2 test

Theoretical distribution	Experimental value	Theoretical value
Normal	8.32	9.48
Charlier, type A	4.66	9.48
Beta	3.17	7.81
Conclusion: All three theoretical distributions fit the experimental distribution		



c)

χ^2 test

Theoretical distribution	Experimental value	Theoretical value
Normal	20.45	9.48
Charlier, type A	7.23	9.48
Beta	3.13	7.81
Conclusion: the experimental distribution follows the laws of Charlier type A and Beta distributions		

Fig. 11. The experimental frequency polygons, the theoretical frequency curves, the values of the main statistical indicators and the χ^2 test values for the distributions concerning the apron undermining: a) by degrees of depth of apron undermining; b) by categories of proportion of damage to the apron width; c) by degrees of global magnitude of damage

Table 6. The main results obtained with respect to the magnitude of the four researched events

Running no.	***Name of damage***	***Characteristic studied in order to estimate the magnitude of damage***	***Unit of measurement***	***Class amplitude***	***Arithmetic mean***	***Variation coefficient (%)***	***Normal***	***Charlier-type A***	***Beta***
1	Breakage of apron zone terminal spur	Depth of breakage	m	0.5	1.14	44.53			
		Proportion of breakage	%	20	60.00	48.15	-		
		Global magnitude of breakage	-	1	3.12	54.46	-	-	
2	Erosive damage	Depth of erosive damage	cm	5	6.98	86.47	-		-
				10	7.50	80.18	-	-	-
		Proportion of erosive damage	%	10	29.16	82.73	-		-
				20	29.58	81.90	-		
		Global magnitude of erosive damage	-	1	1.50	67.37	-		-
3	Body undermining	Depth of body undermining	m	0.5	0.81	56.01			
		Proportion of body undermining	%	20	58.00	36.39			
		Global magnitude of body undermining	-	1	2.93	37.48			
4	Apron undermining	Depth of apron undermining	m	0.5	0.93	55.18			
		Proportion of damage to the apron width	%	20	54.32	50.69			
		Global magnitude of apron undermining	-	1	2.86	55.89	-		

Note: The cells in the table rendered in grey tones represent the research characteristics of the magnitude of damages for which the concordance between the experimental and theoretical frequency was shown.

The quality of fitting (estimated by means of the value of $\chi^2_{exp}/\chi^2_{theor}$ ratio) ranks the theoretical distributions in the order: for the first characteristic, Charlier type A distribution, normal distribution and Beta distribution; for the second characteristic, Beta distribution, Charlier type A distribution and normal distribution; for the third characteristic, Beta distribution, Charlier type A distribution and normal distribution.

Consequently, regarding the magnitude of the apron undermining event, a normal frequency distribution was shown for two of the three studied characteristics.

3.5. Synthesis of the main results. Discussion

The results of the statistical approach developed from this research, represented synthetically in the Table 6, represent answers to the three scientific questions formulated in the introductory part of this paper.

The frequency distributions formed and studied in order to find these answers show that the values of the main statistical indicators and the experimental values of the χ^2 concordance test depend on: the nature of the damage, the nature of the criterion used for characterising damage magnitude, and the amplitude of the interval used for grouping frequencies into classes.

The limits of the variation coefficient vary as follows:

- between 30% and 40%, in the case of body undermining, when the studied characteristics are the proportion of body undermining and the global magnitude of body undermining;
- between 40% and 50%, in the case of the breakage of terminal spur, when the studied characteristics are depth of breakage and proportion of breakage;
- between 50% and 60%, for breakage of terminal spur when the researched characteristic is the global magnitude of breakage, for body undermining when the researched characteristic is depth of body undermining, and for apron undermining, irrespective of the nature of the studied characteristic (depth of undermining, proportion of damage to the apron width, or global magnitude of undermining);
- between 80% and 90%, for the event of erosive damage, when the researched characteristics are depth and proportion of the erosive damage (irrespective of the amplitude of class interval).

If comparative analysis is limited only to the global magnitude of events, the four types of studied damage are ranked on a scale of the variation coefficient as follows:

- body undermining, between 30% and 40%;
- breakage of terminal spur and apron undermining, between 50% and 60%;
- erosive damage, between 60% and 70%.

Consequently, in all the studied cases, the variation coefficient of the magnitude of the event exceeds the threshold of 30%, considered the limit to move from homogeneous distributions to non-homogeneous distributions (Giurgiu, 1972). Hence, it is recommended that future developments of scientific research should also take into consideration the homogenisation of the watershed statistical population, through the stratification of the structures affected by various behavioural events according to the most important factors causing the variability of the magnitude of these events.

According to the average recorded by the global magnitude of damage during the period spanning from the structures construction, three events (breakage of terminal spur, body undermining and apron undermining) were of medium intensity, and the fourth (erosive damage) was of low intensity.

For damage caused by body undermining and apron undermining, the normal frequency distribution was statistically shown for all three characteristics used in order to discover the variation laws of magnitude. For the damage concerning the breakage of the terminal spur, normal distribution was highlighted only for one of the three research characteristics that were considered whereas, for the erosive damage of structures, normal distribution could not be shown statistically for any of the three research characteristics that were used.

Charlier type A and Beta theoretical distributions showed their flexibility (also) in the case of fitting the experimental frequencies that were formed and studied, for the first time, in this paper. Indeed, the magnitude of the four events under analysis generated sequences of experimental frequencies that, in most cases, proved to be consistant with the sequences of theoretical distributions corresponding to the two afore mentioned distributions. In conclusion, for the group of the four events classified as damages, normal, Charlier type A and Beta theoretical distributions can provide solutions of fitting the sequences of experimental frequencies for any of the characteristics defined with a view to estimating the magnitude of damages.

Finally, in case of performing a classification of theoretical distributions according to the number of experimental distributions that the first fit, it can be noted that Charlier type A distribution holds the first position with 12 fitted distributions (out of a total of 15), while Beta distribution, with 10 fitted experimental distributions, holds the second place. In this classification, the normal distribution occupies the third place, providing solutions for 6 out of the 15 studied experimental distributions.

4. Conclusions

This paper's findings are most applicable to future scientific research; nevertheless, they also have practical significance.

The magnitude of damage patterns – as a random variable the knowledge of which is essential in order to conceive and to apply a programme of systematic and permanent monitoring of the hydrotechnical torrent control structures – has to be quantified, for each event separately, both by means of two statistical indicators (arithmetic mean and variation coefficient) and in the form of a theoretical function, that can be used to predict the frequency of behavioural events, by different degrees of intensity, over the entire functional period of the structures.

Knowing frequency distributions does not have only a theoretical value, but also has a practical value. Indeed in managed torrential watersheds, similar to those taken in study, where detailed research can be done, there are possible estimations of the number of structures that can be affected with a certain intensity of events. In this way an anticipated planning of funds is possible for a rehabilitation programme.

As well as this, for organising the research regarding damage patterns, the variation coefficient provides an important practical factor. This coefficient can be useful in research for establishing the number of structures taken into consideration for a certain degree of precision.

The practical value of the results emerges from the fact that the intensity of each event taken into consideration is reflected, with a certain weight, in the physical status of the structure. If this weight is established (using a multicriterial analysis) and if summing the products between intensity and weight of events during the functioning period of the structures then a so called "structure condition index" can be defined.

Taking this index into consideration, the structures can be classified (such as having a very bad, bad, medium, good or very good structural condition) and prioritised for accomplishing necessary rehabilitation operations.

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