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Vulnerability assessment of embankments and bridges exposed to flooding hazards

D4.3 Inventory of critical infrastructure assets

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Executive Summary

Based on the developed fragility curves, the vulnerability assessment of selected critical infrastructure in the case study areas in Croatia and the Netherlands has been conducted and the inventory of critical infrastructure assets has been performed.

Keywords: critical infrastructure assets, categorization, vulnerability assessment.

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1 Embankments and riverbanks

As stated in oVERFLOw Deliverable D4.1 (Gavin & Reale, 2022), there is no commonly accepted failure rate in the geotechnical community for slope stability. (Santamarina, 1992) suggested that a failure rate of 0.0001 was acceptable for all slopes, whereas within the same study a failure rate of 0.2 was considered adequate for slopes of negligible consequence, that require substantial investment to improve. There is also significant discrepancies between studies with Santamarina suggesting a failure rate of 0.01 was sufficient for large cuttings on a highway, which would be verging on an unsatisfactory classification from the U.S. Army Corps of Engineers (1999) guideline, see Table 1. (Christian, Ladd and Baecher, 1994) determined 0.001 to be a reasonable design value, assuming normally distributed variable, this aligns well with the target reliability index of 3.0 classified as an above average slope according by the U.S. Army Corps of Engineers. This classification was used in the present study for the classification of embankments and riverbanks.

Table 1 Categorization of embank. and riverbanks based on reliabilities, modified from the USACE

Expected performance	Reliability index (β)	Pf (%)	Probability of failure (P_f)	Colour coding
High	> 5.0	< 0.00003	< 0.0000003	**8**
	5.0 to 4.0	0.00003 - 0.003	0.0000003 - 0.00003	**7**
Good	4.0 to 3.0	0.003 - 0.1	0.00003 - 0.001	**6**
Above average	3.0 to 2.5	0.1 - 0.6	0.001 - 0.006	**5**
Below average	2.5 to 2.0	0.6 - 2.3	0.006 - 0.023	**4**
Poor	2.0 to 1.5	2.3 - 7	0.023 - 0.07	**3**
Unsatisfactory	1.5 to 1.0	7 – 16	0.07 – 0.16	**2**
Hazardous	< 1.0	> 16	> 0.16	**1**

1.1 Croatia: case study- riverbanks of city of Karlovac

Location of selected sections of flood protection riverbank and classification based on their geometry is given on Figure 1.

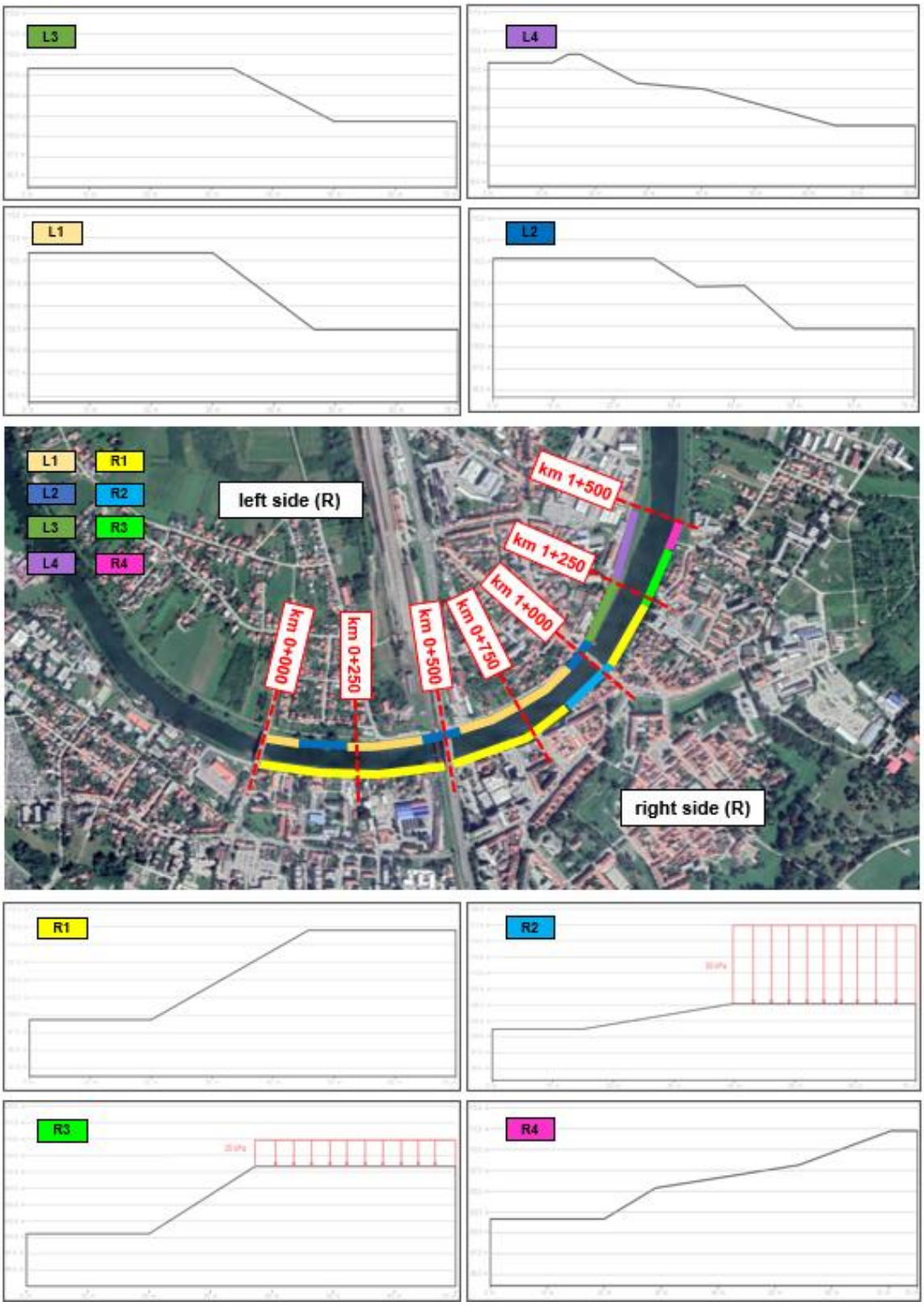

Figure 1 Location of identified riverbank sections in Karlovac based on their geometry

Following tables (2 – 4) show categorization of different sections of riverbanks based on probability of flood occurrence.

Table 2 Low probability of flood occurrence (return period 1000 years)

Left side				Vulnerability class	Total length (m)
Number	**Signage**	**Location (from 0 km designated by Aleksandria bridge)**	**Colour**		
1	L1	0.000 - 0.075		1	955
		0.175 - 0.400		1	
		0.470 - 1.125		1	
2	L2	0.075 - 0.175		7	245
		0.400 - 0.470		7	
		1.125 - 1.200		7	
3	L3	1.200 - 1.375		5	175
4	L4	1.375 - 1.550		5	175
				Total (m)	**1550**

Right side				Vulnerability class	Total length (m)
Number	**Signage**	**Location (from 0 km designated by Aleksandria bridge)**	**Colour**		
1	R1	0.000 - 1.000		3	1175
		1.200 - 1.375		3	
2	R2	1.000 - 1.200		6	200
3	R3	1.375 - 1.525		1	150
4	R4	1.525 - 1.550		3	25
				Total (m)	**1550**

Table 3 Medium probability of flood occurrence (return period 100 years)

Left side				Vulnerability class	Total length (m)
Number	**Signage**	**Location (from 0 km designated by Aleksandria bridge)**	**Colour**		
1	L1	0.000 - 0.075		1	955
		0.175 - 0.400		1	
		0.470 - 1.125		1	
2	L2	0.075 - 0.175		7	245
		0.400 - 0.470		7	
		1.125 - 1.200		7	
3	L3	1.200 - 1.375		5	175
4	L4	1.375 - 1.550		5	175
				Total (m)	**1550**

Right side				Vulnerability class	Total length (m)
Number	**Signage**	**Location (from 0 km designated by Aleksandria bridge)**	**Colour**		
1	R1	0.000 - 1.000		3	1175
		1.200 - 1.375		3	
2	R2	1.000 - 1.200		6	200
3	R3	1.375 - 1.525		1	150
4	R4	1.525 - 1.550		3	25
				Total (m)	**1550**

Table 4 High probability of flood occurrence (return period 25 years)

Left side				Vulnerability class	Total length (m)
Number	**Signage**	**Location (from 0 km designated by Aleksandria bridge)**	**Colour**		
1	L1	0.000 - 0.075		2	955
		0.175 - 0.400		2	
		0.470 - 1.125		2	
2	L2	0.075 - 0.175		8	245
		0.400 - 0.470		8	
		1.125 - 1.200		8	
3	L3	1.200 - 1.375		5	175
4	L4	1.375 - 1.550		6	175
				Total (m)	**1550**

Right side				Vulnerability class	Total length (m)
Number	**Signage**	**Location (from 0 km designated by Aleksandria bridge)**	**Colour**		
1	R1	0.000 - 1.000		4	1175
		1.200 - 1.375		4	
2	R2	1.000 - 1.200		6	200
3	R3	1.375 - 1.525		1	150
4	R4	1.525 - 1.550		3	25
				Total (m)	**1550**

1.2 The Netherlands: case study - embankment Oostmolendijk

Location of selected sections of Oostomlendijk embankment and classification based on their geometry is given on Figure 2.

Figure 2 Location of identified Oostmolendijk sections based on their geometry

Following table 5 shows categorization of different sections of Oostmolendijk embankment based on probability of flood occurrence.

Table 5 Vulnerability class for Sections 1 to 4 for Oostmolendijk, based on fragility curves and different flood scenarios

	Vulnerability class		
Return Period	100 year	1000 year	100.000 year
Section 1	4	4	3
Section 2	4	4	3
Section 3	5	5	4
Section 4	3	3	3

2 Bridges

As given in oVERFLOw Deliverable D4.2 (Kosič & Anžlin, 2022), categorization of bridges for Serviceability and Ultimate limit states based on the probability of failure is given in Table 6. A colour code is used in the table to ease understanding of the likelihood of exceeding the serviceability limit state: i.e. green colour for low likelihood ($P(SLS|H,V) < 0.33$), orange color for medium likelihood ($0.33 \leq P(SLS|H,V) < 0.66$), and red colour for high likelihood ($P(SLS|H,V) \geq 0.66$).

Table 6 Categorization of bridges based on the probability of failure

Categorization	Probability of failure
Low likelihood	<0.33
Medium likelihood	0.33-0.66
High likelihood	≥0.66

2.1 Case study: Banija Bridge

Figure 3 Banija Bridge in Karlovac

A summary of the probabilities of exceeding the SLS for different flood scenarios and sizes of debris is presented in Table 7.

Table 7 Probabilities of exceeding the serviceability limit state of the Banija Bridge for different flood scenarios and sizes of debris

No debris						
H \ V	0.2 m/s	0.5 m/s	0.8 m/s	1.2 m/s	1.6 m/s	1.8 m/s
2 m	0	0	0	0	0	0
3 m	0	0	0	0	0	0.025
5 m	0	0	0	0	0.025	0.075
7 m	0	0	0	0	0.075	0.15
>7.5 m	1	1	1	1	1	1
Small-size debris, W_d/H_d = 5 m / 2.1 m						
2 m	0	0	0	0	0	0
3 m	0	0	0.05	0.325	0.625	0.725
5 m	0	0	0.025	0.2	0.625	0.6
7 m	0	0	0	0.175	0.625	0.575
>7.5 m	1	1	1	1	1	1
Medium-size debris, W_d/H_d = 10 m / 2.1 m						
2 m	0	0	0	0	0	0
3 m	0	0.275	0.75	0.95	0.975	1
5 m	0	0.05	0.45	0.8	0.925	0.95
7 m	0	0.025	0.275	0.7	0.875	0.925
>7.5 m	1	1	1	1	1	1
Large-size debris, W_d/H_d = 20 m / 2.1 m						
2 m	0	0	0	0	0	0
3 m	0.3	0.95	1	1	1	1
5 m	0.025	0.75	0.95	1	1	1
7 m	0	0.525	0.875	0.975	1	1
>7.5 m	1	1	1	1	1	1

A summary of the probabilities of exceeding the ULS for different flood scenarios and sizes of debris is presented in Table 8.

Table 8 Probabilities of exceeding the ultimate limit state of the Banija Bridge for different flood scenarios and sizes of debris

No debris						
H \ V	0.5 m/s	1 m/s	1.2 m/s	1.6 m/s	1.8 m/s	2 m/s
2 m	0	0	0	0	0	0
4 m	0	0	0	0	0	0
6 m	0	0	0	0	0	0
8 m	0	0	0	0	0	0
8.2 m	0	0	0	0	0	0
10 m	0	0	0	0	0.075	0.675
Large debris (W_d/H_d = 20 m / 2.1 m), no amplification of scour						
2 m	0	0	0	0	0	0
4 m	0	0	0	0	0	0
6 m	0	0	0	0	0	0
8 m	0	0	0	0	0	0
8.2 m	0	0	0	0.95	1	1
10 m	0	0	0	0.975	1	1
Large debris W_d/H_d = 20 m / 2.1 m with amplification of scour						
2 m	0	0	0	0	0	0
4 m	0	0.1	0.225	0.525	0.65	0.725
6 m	0	0	0.025	0.2	0.3	0.4
8 m	0	0	0	0.075	0.125	0.2
8.2 m	0	0	0	0.75	0.975	1
10 m	0	0	0	0.725	0.975	1

2.2 Case study: Karlovac Bridge

Figure 4 Karlovac Bridge in Karlovac

A summary of the probabilities of exceeding the SLS for different flood scenarios and sizes of debris is presented in Table 9.

Table 9 Probabilities of exceeding the serviceability limit state of the Karlovac Bridge for different flood scenarios and sizes of debris

No debris						
H \ V	0.2 m/s	0.5 m/s	0.8 m/s	1.2 m/s	1.6 m/s	1.8 m/s
2 m	0	0	0	0	0	0
3 m	0	0	0	0	0	0
5 m	0	0	0	0	0	0
7 m	0	0	0	0	0	0
>7.5 m	1	1	1	1	1	1
Small-size debris, W_d/H_d = 5 m / 2.1 m						
2 m	0	0	0	0	0	0
3 m	0	0	0	0	0	0
5 m	0	0	0.05	0.325	0.625	0.725
7 m	0	0	0	0.075	0.3	0.425
>7.5 m	1	1	1	1	1	1
Medium-size debris, W_d/H_d = 10 m / 2.1 m						
2 m	0	0	0	0	0	0
3 m	0	0	0	0	0	0
5 m	0	0.4	0.825	0.95	1	1
7 m	0	0.05	0.4	0.8	0.925	0.95
>7.5 m	1	1	1	1	1	1
Large-size debris, W_d/H_d = 20 m / 2.1 m						
2 m	0	0	0	0	0	0
3 m	0	0	0	0	0	0
5 m	0.475	0.975	1	1	1	1
7 m	0.05	0.8	0.975	1	1	1
>7.5 m	1	1	1	1	1	1

Table 2 presents a summary of the failure utilization percentages (UP) of the Karlovac Bridge members. The results were obtained considering different water heights, a constant (upper-bound) flow velocity of 1.2 m/s, and the flood-loading scenario with debris and amplification of scour due to debris. A value of 100% indicates that the failure of a particular bridge member is reached.

Table 2: Failure utilization percentages for the Karlovac Bridge members for the different water heights (flow velocity 1.2 m/s) and the scenario with debris and scour

H \ UP [%]	Column bending	Column shear	Deck bending (above pier)	Deck bending (midspan)	Column bearing	Gerber bearing
4 m	0.1	1.9	0.1	0.2	0.5	0.0
8 m	0.1	0.3	0.4	2.0	0.1	3.8
10 m	0.2	0.6	0.4	2.0	0.3	4.5
12 m	0.3	0.8	0.4	2.0	0.5	6.4

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