Ref. Ares(2021)5510669 - 08/09/2021

This project has received funding from the
European Union's Horizon 2020 Framework Programme
Union Civil Protection Mechanism
Grant Agreement Number 874421

Vulnerability assessment of embankments and bridges exposed to flooding hazards

Deliverable 3.2

Report on investigation works and monitoring of bridges

Project Information

Grant Agreement No.	874421
Project Acronym	oVERFLOw
Project Full Title	Vulnerability assessment of embankments and bridges exposed to flooding hazards
Starting Date	1 December 2019
Duration	24 months
Call Identifier	UCPM-2019-PP-AG
Topic	UCPM-2019-PP-PREV-AG: Prevention in civil protection and marine pollution
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ZAVOD ZA GRADBENISTVO SLOVENIJE	Slovenia
Uprava Republike Slovenije za zaščito in reševanje	Slovenia

Document Information

Work Package	3
Deliverable Title	Report on investigation works and monitoring of bridges
Version	2.0
Date of Submission	9/08/2021
Main Editor(s)	Mirko Kosič, Doron Hekič, Jan Kalin, Laurens Oostwegel, Andrej Anžlin
Contributor(s)	-
Reviewer(s)	Irina Stipanović, Sandra Škarić Palić
Citation	M. Kosič, Hekič D., Kalin J., Oostwegel L., Anžlin A. (2021). oVERFLOw Deliverable 3.2: Report on investigation works and monitoring of bridges

Document Classification:									
Draft	**X**	Final		Confidential		Restricted		Public	

History			
Version	**Issue Date**	**Status**	**Distribution**
1	8/30/2021	For consortium review	All partners
2	9/08/2021	Final	For submission

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Executive Summary

This deliverable is a report on the performed investigation works and monitoring of the two case study bridges located in the Croatian city of Karlovac overpassing the Kupa river. It contains a description of the investigated and monitored bridge trial sites, methods used, and collected data from drone and bathymetric surveys, as well as data regarding modal periods and shapes of the case study bridges from in-situ ambient vibration measurements. The results of the deliverable will be used as input for flood fragility analysis of the case study bridges in Work package 4 Vulnerability assessment methodology.

Keywords: investigation works, bridges, drone survey, bathymetric survey, ambient vibration measurements.

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1 Abbreviations and Acronyms

Abbreviation / Acronym	Description
FDD	FREQUENCY DOMAIN DECOMPOSITION
FFT	FAST FOURIER TRANSFORM
GNSS	GLOBAL NAVIGATION SATELLITE SYSTEM
INS	INERTIAL NAVIGATION SYSTEM
LIDAR	LIGHT DETECTION AND RANGING
MEMS	MICRO-ELECTRO-MECHANICAL SYSTEM
RC	REINFORCED CONCRETE
RTK	REAL TIME KINEMATICS
SDOF	SINGLE DEGREE OF FREEDOM
SVD	SINGULAR VALUE DECOMPOSITION
WP	WORK PACKAGE
ZAG	ZAVOD ZA GRADBENIŠTVO SLOVENIJE

2 Background

In accordance with Annex I of Grant Agreement no. 874421, ZAG, as the lead beneficiary of Task 3.2 of WP3, is responsible for preparing Deliverable D3.2, i.e. a report on the performed investigation works and monitoring of the two case study bridges. The deliverable contains a description of the investigated and monitored bridge trial sites, methods used, and collected data from drone and bathymetric surveys, as well as data regarding modal periods and shapes of the case study bridges from in-situ ambient vibration measurements. The results of the deliverable represent the input data for flood fragility analysis of the case study bridges in WP4. This deliverable will be publicly available, and it will be published on the project website.

3 Introduction

This deliverable is a report on the performed investigation works and monitoring of two case study bridges. The examined case studies are two bridges over the Kupa River in Karlovac (Croatia). The first is the Banija Bridge (Figure 1, left), which is a historic steel-riveted girder bridge that leads to the Karlovac city centre. The second bridge is the Karlovac Bridge (Figure 1, right), which is a three-span reinforced concrete (RC) road bridge that carries a heavily trafficked bypass road (Prilaz Većeslava Holjevca) to the city of Karlovac. Both bridges were visually inspected with the help of a drone survey. A bathymetric survey was undertaken to scan the riverbed near the bridges. In addition, in-situ ambient vibration measurements were performed to obtain the modal frequencies and shapes of the two bridges, which will be used for the calibration of numerical models in WP4. The results of the deliverable represent the input data for flood fragility analysis of the case study bridges in WP4.

Both bridges are described in more detail in Chapter 4. Descriptions and condition assessments of bridges were obtained from available documentation (one should note that limited documentation on the concrete bridge was available, to a degree where bottom limits of numerical analysis were reached). The information was complemented with drone and bathymetric survey results, which are presented in Chapter 5. The ambient vibration measurements of the two bridges are described in Chapter 6.

Figure 1: Overview of the case study bridges in city of Karlovac: (left) Banija Bridge, (right) Karlovac Bridge.

4 Description of the case study bridges

4.1 Banija Bridge

4.1.1 Description of the bridge

The Banija Bridge is a steel-riveted girder bridge built between 1945 and 1947 (Figure 2). The bridge was rebuilt after World War II when the older bridge from 1889 was demolished (Figure 3). Construction plans for the new Banija Bridge could not be obtained in the archives of the city of Karlovac neither in Croatian State Archives. However, parts of the construction plans for the old bridge from 1889 were obtained from Croatian State Archives [1] and were used to obtain an idealized geometry of the old bridge (Figure 4). The data regarding the new Banija Bridge was obtained from a retrofitting project from 2017 [2] and related in-situ investigation works [3]. Unfortunately, the retrofitting project did not provide information regarding the grade of the concrete of the middle pier and the foundation, as well as the geometry of the foundations. The missing information regarding the geometry was complemented with results of drone inspection (see Section 5.1) and construction plans of the old bridge. The material properties for the remaining elements were assumed according to available in-situ investigations [3], which include also a condition assessment of all members of the bridge except the foundations. Geotechnical conditions at the location of the bridge were assumed based on geotechnical investigations performed for the purpose of the condition assessment of the case study embankment, documented in Deliverable D3.1 [4].

The Banija Bridge has two main spans with the length of 48.6 m (bearing to bearing distance) and the middle pier founded in the riverbed of the Kupa River (Figure 5). The bridge spans a total length of 97.2 m. The main girders have riveted I-shape cross section with changing flange thickness to follow the bending moment line. The cross section of the bridge is presented in Figure 6. The web of the girders has a constant height of 2400 mm and thickness of 14 mm. Girders flanges have a width of 500 mm, while the thickness varies between 18 mm and 158 mm, which was achieved by riveting additional steel plates to the basic section. The flanges and the web are joined together with steel angles dimension 150x150x15 mm. The total height of the main girders is 2.72 m above the middle pier, and 2.44 m above the abutment. The axial distance between the main girders is 9.5 m. Two traffic lanes are placed between the main girders, whereas the pedestrian zone is constructed on cantilever transverse beams. The total width of the bridge is 12.4 m (Figure 6).

The main girders are connected together every 4.05 m by I-shaped riveted transvers beams of changing height between 820 mm at the main girders and 880 mm in the middle of the span. The flanges of the transverse girders have a width of 210 mm and a changing thickness between 12 and 32 mm, which was achieved by riveting additional steel plates to the basic section. Steel angles dimension 100x100x10 mm were used to join the flanges and the web of the transverse girders. The horizontal in-plane stability of the bridge is provided by double-L steel braces dimension 80x80x8 mm.

Figure 2: Overview of the Banija Bridge.

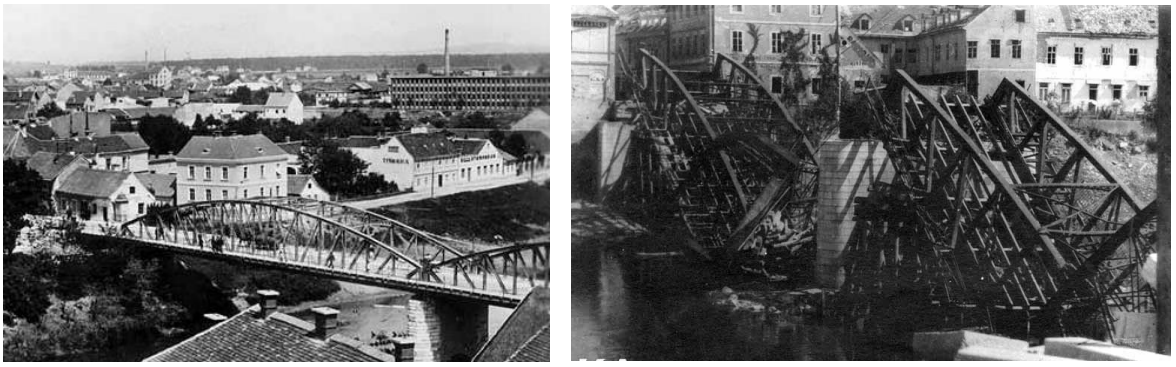


Figure 3: a) Old Banija bridge built in 1889; b) Demolished bridge after WWII in 1945 [5]

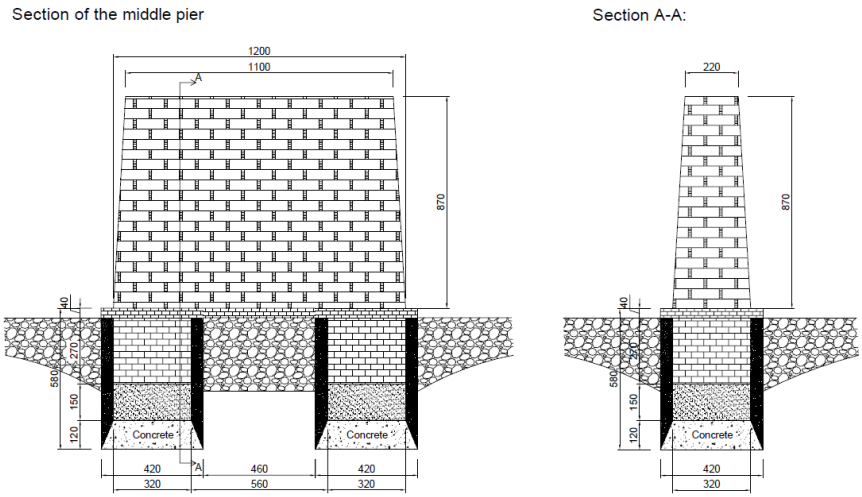


Figure 4: Construction plans of the old Banija Bridge from 1889 as idealized from historic construction plans [1].

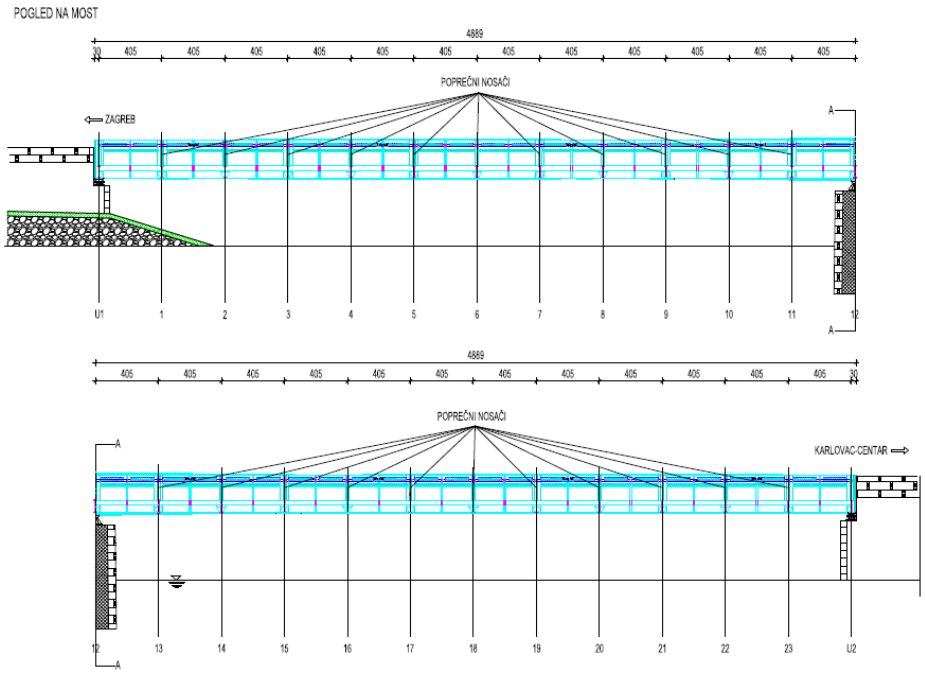


Figure 5: Side-view on the Banija bridge: first span (above), second span (bellow) [2].

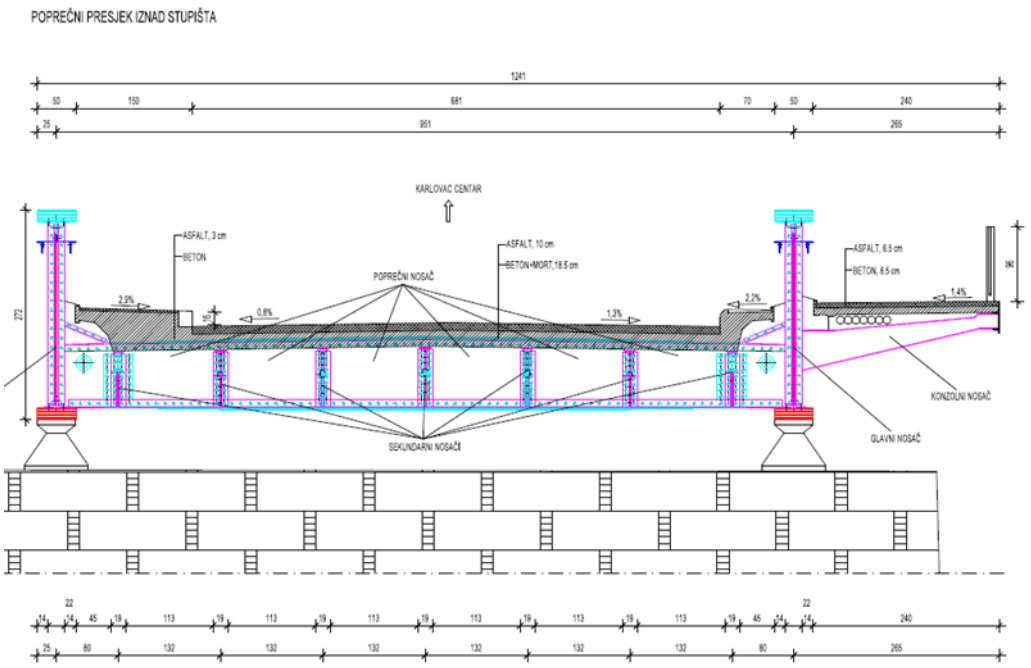


Figure 6: Cross-section of the Banija Bridge deck above the middle pier [2].

The transverse girders are connected with seven longitudinal secondary beams, which support the RC slab of the traffic lanes (Figure 6). The secondary longitudinal beams have a standard hot-rolled section IPN260 at the edges and IPN 320 at intermediated beams. The cantilever beams that support the RC slab of the pedestrian zone have an I-section of changing height and are placed at the same spacing as the transverse girders (Figure 6). The RC slab of the pedestrian zone is supported by C-shaped secondary longitudinal beams.

At the abutments, the bridge is supported by longitudinal roller bearings 20 cm in diameter (Figure 2). Translation in the transverse direction is restrained with shear pins 5 cm in diameter. Translation of the bridge at the middle pier is restrained in all directions by the use of shear pins 5 cm in diameter.

The pier and the abutments are made of RC and are covered with stone cladding. The geometry of the middle pier and foundations was assessed from the idealisation of the bridge model built from the results of drone inspection (see Figure 7). The middle pier has a rectangular section with rounded ends. The outside dimension of the pier is 13.5 x 2.1 m at the bottom and 13.2 x 2.1 m at the top. The height of the pier from the foundation level to the top is 7.5 m. A conservative (lower-bound) assumption regarding the quality of the concrete of the pier and foundation (C25/30 according to [3]) is suggested due to missing more precise data. The pier is founded on two large well foundations 6.5 m in diameter. Due to a lack of the latest construction plans, the depth of the foundations was assumed to be equal to the one used for the old Banija Bridge, i.e. 5.8 m from foundation cap to foundation tip.

According to nearby boring [4], the soil at the foundation level of the bridge is expected to be clayed sand (SC) with a shearing angle of 31°, the cohesion of 5 kPa, SPT number of blows from 32 to 9 and unit weight of 19.8 kN/m^3.

The abutments are not described herein in detail since it is assumed that they will not be explicitly modelled in the flood fragility analysis in WP4.

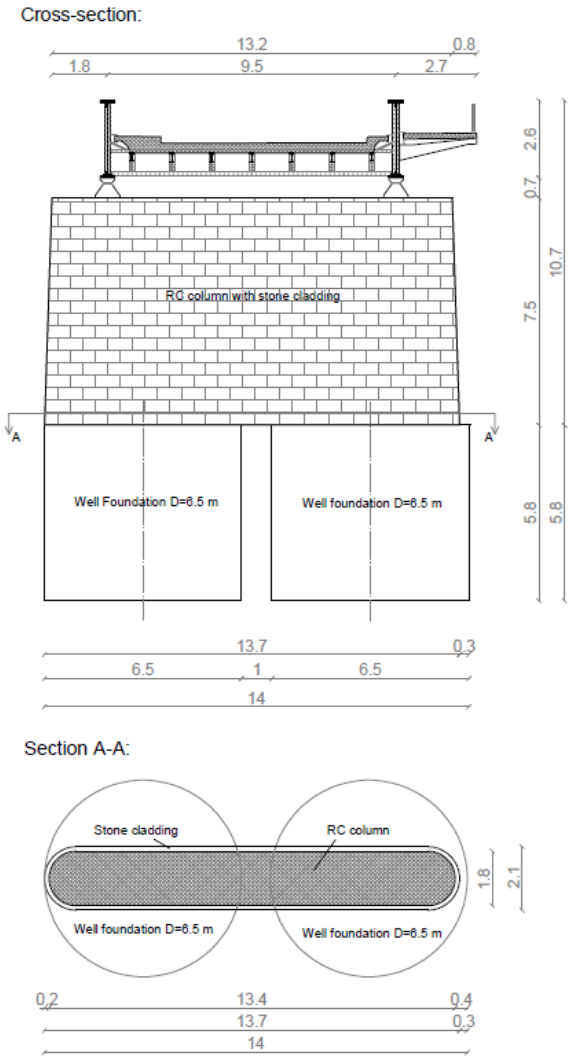


Figure 7: Geometry of the middle pier and foundation of the Banija Bridge as obtained from drone inspection.

4.1.2 Condition assessment

A detailed condition assessment of the Banija Bridge was performed to provide data for theretrofitting design by Ascon institute d.o.o in 2017 [3]. The obtained results were complemented with a visual inspection of the bridge with a drone survey. According to [3], the bridge was first retrofitted in 1997 and secondly in 2011 due to requirements for special cargo transport that often goes over the bridge. On this occasion, the transverse and main girders were strengthened to support the crossing of the special transport. Nevertheless, the results of previous investigation [3] and drone inspection indicated that the condition of the bridge is poor. The inspection indicates cracking in the asphalt layer and damage of construction joints (Figure 8, left), as well as damage of expansion joints due to poor maintenance and traffic wear (expansion joints field with sand, visible deformations) (Figure 8, right). The damage to the roadway led to water leakage on the RC slab and steel elements beneath it. The concrete of the RC slab is degraded with visual signs of corrosion of the reinforcement (Figure 9, left). Anticorrosion protection of the steel members is damaged and some elements are severely corroded. Elements that are most severely damages are secondary longitudinal beam near

malfunctioned water draining pipes (Figure 9; Figure 10, right) and the transverse beams beneath damaged expansion joints (Figure 10, left). Sign of water leakage is also present at the middle pier and abutments (Figure 11), where local mechanical damage of the stone cladding is also visible. The cup of the well foundation (upper edge of the foundation) is in some parts cracked (Figure 12). However, the damage is localised and is not likely to affect the mechanical resistance and stability of the bridge. The foundation of the bridge shows signs of scour related damage, with the stone scour protection being dislodged at the upstream part of the pier (Figure 12).

The conclusion of the bridge condition assessment is that the bridge is in poor condition and requires rehabilitation or retrofitting. The conclusion is in line with the findings of previous works [3]. A retrofitting project was prepared in 2017 [2]. However, up to now, no retrofitting works were performed on the bridge.

Figure 8: (left) Cracked asphalt coating on sidewalk; (right) cracks of the roadway near the expansion joint, damage of the expansion joint, lack of maintenance of the expansion joint (after [3]).

Figure 9: (left) Damaged bottom surface of RC slab due to water leakage, corrosion of reinforcement and steel elements; (right) severe corrosion of secondary longitudinal beam near the main girder, damaged concrete and corrosion of reinforcement in the slab (left figure after [3]).

Figure 10: (left) Corrosion of the transverse girder below the expansion joint at the middle of the bridge; (right) damaged concrete slab with visible corrosion of reinforcement, corrosion of installation pipe and secondary longitudinal beam near the main girder (after [3]).

Figure 11: (left) sign of water leakage at the abutment with visible mechanical damage of the stone cladding; (right) dislodge stone cladding at the middle pier with visible signs of water leakage on the surface (after [3]).

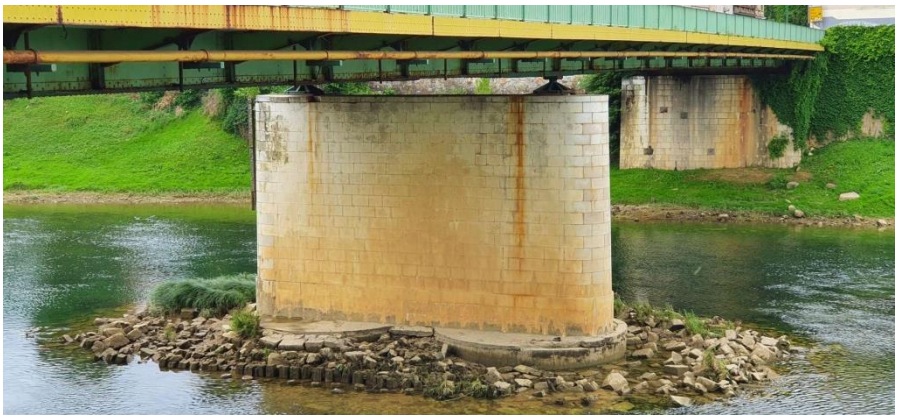


Figure 12: Dislodged foundation stone protection at the upstream part of the pier due to local pier scour, local cracking of the well foundation cup.

4.2 Karlovac Bridge

4.2.1 Description of the bridge

The Karlovac Bridge is a RC three-span road bridge that carries a heavily trafficked bypass road (Prilaz Većeslava Holjevca) over the Kupa River to the city of Karlovac. Search for the design documentation of the bridge was conducted in the archives of the city of Karlovac and the Croatian State Archives. However, the construction plans of the bridge could not be retrieved. It is likely that they have been lost/destroyed during the Croatian War of Independence between 1991-1995. The description of the bridge is thus entirely based on the results of the drone survey.

Considering the type of structural design, it is estimated that the Karlovac Bridge was constructed in the mid-70s or 80s. The bridge is constructed in RC and has three spans with 25.7 m, 71.9 m and 26.4 m length (Figure 13). The total length of the bridge is 124 m. The side spans of the bridge extend continuously over the piers in the middle span with 15.9 m long cantilever segments. At the end of these cantilevers, Gerber hinges are constructed to support the middle 40 m long segment of the bridge.

The deck has a constant longitudinal inclination of 2%. The width of the bridge deck is 22 m. It holds four traffic lanes (2 in each direction) and a pedestrian zone. The traffic lanes are divided by a central reserve and are confined with sidewalks on both sides. The cross-section of the deck is composed of 6 Y-shaped prefabricated girders and a cast-in-place RC slab (Figure 14). The Y-shaped girders have a bottom width of 0.5 m and varying height between 1.75 m at the midspan and 2.5 m above the piers. The depth of the slab is estimated to be 0.5 m at the location of the traffic lines and 0.8 m elsewhere. The total height of the deck varies from 2.5 m to 3.25 m. Transverse stiffening beams are constructed in the perpendicular direction to the main beams to ensure uniform distribution of loading on all main girders.

The deck is supported by two RC piers on each side of the bridge. The piers are 7.5 m high and have a varying thickness of 1.2 m at the top and 0.8 m at the bottom. The length of the piers in the transverse direction is 7.2 m.

The piers are constructed over a continuous foundation beam with a total height of 2.9 m and a bottom width of 5.4 m. The foundation beam is supported by two lines of bored piles. Each line consists of 7 bored piles. The foundation beam is therefore supported by 14 piles. The depth of the foundation piles could not be established based on the performed in-situ investigations.

Due to the lack of construction plans, the material characteristics of the RC and reinforcing steel remain unknown. The geotechnical characteristics at the site are also unknown. However, this information could be obtained from geotechnical investigations performed for the purpose of conditionassessment of the case study embankment (see Deliverable D3.1 [4]).

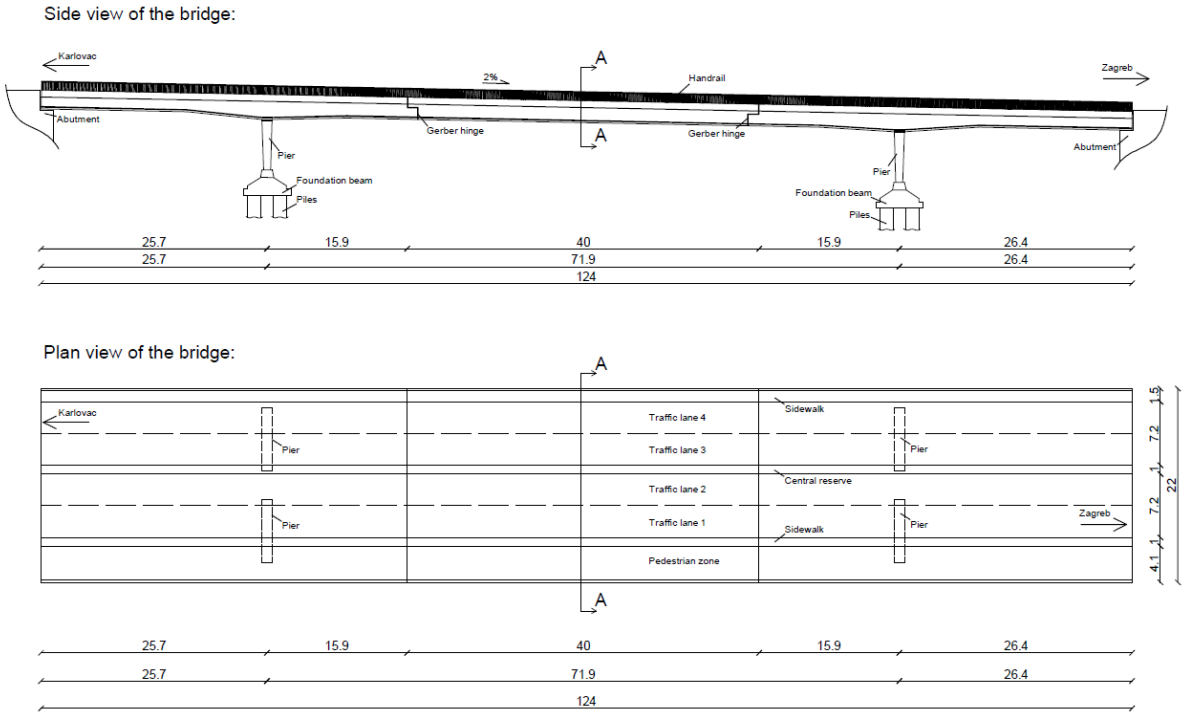


Figure 13: Side and plan view of the Karlovac Bridge

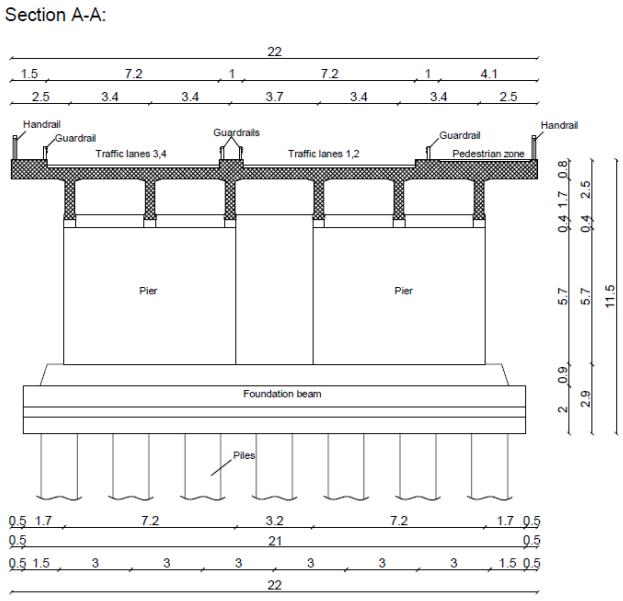


Figure 14: Cross-section A-A at the midspan of the Karlovac Bridge

4.2.2 Condition assessment

The condition assessment of the Karlovac Bridge is based on the results of the drone survey and visual inspection performed without the use of any special vehicles. The condition assessment is thus limited to the parts of the bridge that could be inspected with such a technique. More detailed condition assessment with the use of special vehicles would involve significantly higher

costs and disruption of traffic. Such investigations were thus considered to be out-of-the-scope of this project.

The assessment of the bridge condition indicates a poor condition of the asphalt on the pedestrian zone with severe cracking (Figure 15). The asphalt surface of the roadway is visually in better condition and may have been replaced, although signs of water leakage below the bridge deck indicate that the waterproofing is not functioning (Figure 16). A local intervention is also visible at the expansion joints, which were presumably removed and replaced with an asphalt coating (Figure 15, right). The functionally of such a solution is questionable as vibrations and movements of the bridge usually lead to cracking of the asphalt and, therefore consequently, water leakage on the Gerber hinges. Indeed, visual examination of the Gerber hinge indicated that these critical elements (Ahil's heel of the bridge design) are still subjected to water leakage (Figure 16 and Figure 17). The constant exposure to water resulted in delamination of concrete cover and corrosion of reinforcement (Figure 16 and Figure 17). Visual inspection of these elements could not reveal the whole extent of the damage. Therefore, a more detailed examination is neeeded to ensure the safe usage of the bridge (e.g. inspection with the special vehicle, examination of the state of corrosion, carbonisation of concrete, presence of chlorides etc.). Such detailed investigations, although very crucial, were considered to be out-of-the-scope of this project.

Inspection of the bridge piers indicates local damages and delamination of the bridge cover on the south pier of the bridge (Figure 18, left). Local scour of the bridge foundation was also observed below the foundation beam on the southern part of the bridge. The scour depth amounted to approximately 0.8 m and led to the exposure of all seven piles on the outermost part of the foundation. The observed damage is not expected to affect the safety of the bridge significantly as half of the piles are not affected and since the contribution of the uppermost layer to the pile bearing capacity is negligible. Nevertheless, the observed damage warrants intervention to stop further scour of the foundation.

Figure 15: (left) cracking of asphalt coating on the pedestrian zone; (right) expansion joint at the location of the Gerber hinge

Figure 16: Signs of water leakage on concrete surface below the bridge deck, delamination of concrete cover and corrosion of reinforcement at the location of the Gerber hinge.

Figure 17: Water leakage of concrete at the two Gerber hinges with visible signs of corrosion of reinforcement.

Figure 18: (left) Local damage of the lower part of the bridge pier, scour of the bridge foundation; (right) detail of the exposed pile foundations due to scour.

The conclusion of the bridge condition assessment is that the bridge is in poor condition and would require more in-depth inspection works to assess the structural safety of the bridge adequately. Nevertheless, immediate actions to push the process for the design of the rehabilitation of the bridge are necessary. Especially critical is the degradation of the Gerber hinges, which shows signs of water leakage, delamination of concrete cover and corrosion of reinforcement. Detailed condition assessment would require inspection with a special vehicle and traffic closure, which was out of the scope of this project. Herein, the recommendations for the owner / manager are given. In the first step, a detailed condition assessment is warranted to obtain the exact state of the deterioration of the bridge. The examinations should include assessment of the state of concrete and reinforcement, with the focus on corrosion parametres, carbonation of the concrete, presence of chlorides, permeability properties etc. These should be supplemented with destructive and non-destructive testing to obtain the mechanical characteristics of the materials and dimensions of elements that could not be obtained from visual inspection. A reliability assessment of the bridge should then be performed. Finally, retrofitting measures should be planned based on the results and quidelines of the reliability assessment analysis.

5 Drone and bathymetric survey of the case study bridges

On 17th December 2020, a drone inspection of the case study bridges and a bathymetric survey of the river channel was performed. The goal of the surveys was to obtain detailed geometry of the bridges and the riverbed for the purpose of numerical modelling in WP4. The results of the surveys are point clouds which define the coordinates of the surface areas of the bridges and the riverbed.

5.1 Description of the drone survey

The drone inspection of the riverbanks and both bridges was performed with the commercial drone platform DJI Matrice 300 RTK [6] (Figure 19, left). The drone offers 55 min flight time, a 15 km transmission range, advanced AI technology, and 6-directional sensing and positioning. Exact detection of position of the drone in space was achieved by the use of Real Time Kinematics (RTK) positioning. For this purpose, a reference station with known coordinates was used. The drone was equipped with DJI ZEN MUSE X5S [7] classic camera and DJI ZEN MUSE XT2 [8] thermal camera. The results of the thermal camera can be used for the detection of delaminated concrete or leakage hot spots.

The survey consists of flying the drone near the surveyed objects and scanning them with the installed camera and ultrasound sensor (Figure 19, right). The latter is used to measure the distances to the recorded points. During the scanning, the position of the drone is constantly tracked with the use of 6-directional sensing and positioning. This allows for each of the surveyed points to obtain its global coordinates. A 3D point cloud model of the survey objects can thus be constructed.

The drone survey comprised the scanning of the two bridges and a high-altitude scanning of the riverbanks between the two bridges. In total, 1192 georeferenced figures were made during the survey.

Figure 19: (left) DJI Matrice 300 RTK drone platform; (right) scanning of bridges in the Karlovac case study area

5.2 Description of the bathymetric survey

The bathymetric survey of the riverbed covered the area between the two case study bridges and about 50 m on both sides (Figure 20). The total length of the performed bathymetric survey was thus about 600 m. The survey was conducted using a 4m-length boat. The equipment on the boat comprised of:

- a multi-beam sonar placed in the axis of the boat (KONGSBERG GEOACOUSTICS GEOSWATH PLUS 500 kHz)
- a tilt sensor (SMC IMU 108);
- a Global Navigation Satellite System (GNSS) receiver with a primary and secondary antenna (Hemisphere VECTOR VS330)
- a sound velocity sensor (VALEPORT Mini SVS)
- a sound velocity profiler (VALEPORT SVP)
- Digital acquisition and navigation system
- Dual GNSS + Inertial Navigation System (INS) receiver (Honeywell a580)
- Mobile LIDAR scanner (Velodyne HDL32E)

The multi-beam sonar helped us obtain a profile of the river channel. The acquisition width of the multi-beam sonar was roughly 8-times the depth of the water, whereas the single-beam sonar measured the depth of the water directly underneath the boat. Due to relatively low water levels, several passages were required to scan the entire river bed. The installed mobile LIDAR scanner helped to obtain a better prediction of the water level near the river banks. In total, 4 hours were required to complete the bathymetric survey. Selected pictures from the investigation campaign are presented in Figure 22.

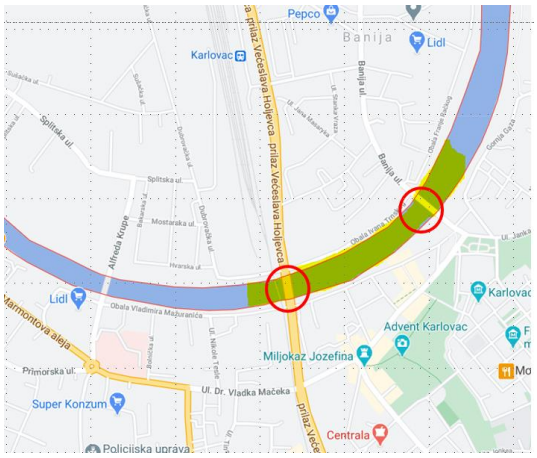


Figure 20: Extent of the bathymetric survey

Figure 21: (left) Boat used for the bathymetric survey; (right) Multi-beam sonar used for riverbed scanning

Figure 22: Bathymetric survey of the riverbed in the Karlovac case study area

5.3 Results of the surveys

Using photogrammetry, a point cloud was created from the drone survey. As both the drone survey and the bathymetric survey were georeferenced using GNSS, they could be merged into a combined 3D point cloud model of the two bridges and the riverbed. This process was achieved using the Agisoft Metashape software [9] . Finally, the point cloud was converted to a tessellated surface model, that made analysing, processing and viewing the model more effortless.

The 3D point cloud models were used to obtain and verify the geometry of the two case study bridges. In the case of the Banija Bridge, detailed geometry of the middle pier and foundations could not be retrieved from available documentation [2]. Therefore, the geometry of the middle pier and the foundation was obtained from the point cloud model. A comparison of the actual photo and the 3D point cloud point model of the Banija Bridge is presented in Figure 23.

Figure 23: Actual photo and the 3D point cloud render model of the Banija Bridge

In the case of the Karlovac Bridge, construction plans could not be retrieved in the archives of the city of Karlovac neither in Croatian State Archives. Thus, the geometry of the bridge was based entirely on the results of the drone inspection. The comparison of the actual photo and the 3D point cloud model of the Karlovac Bridge is presented in Figure 24.

Figure 24: Actual photo and the 3D point cloud render model of the Karlovac Bridge

The point cloud models were also used to obtain the riverbed cross-sections beneath both bridges. This will be used for numerical modelling of the flooding loading in WP4. The 3D models of the bridges and riverbed cross-sections beneath the bridges are presented in Figure 25 and Figure 26.

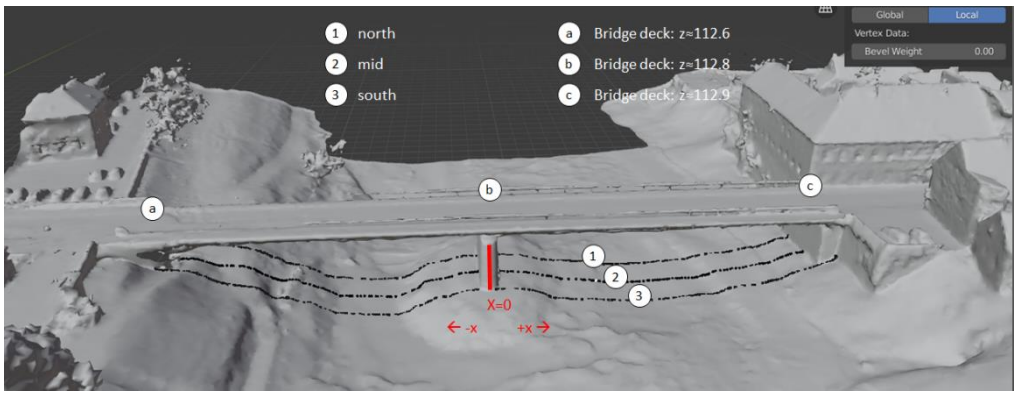


Figure 25: 3D model of the Banija Bridge and riverbed cross-sections beneath the bridge

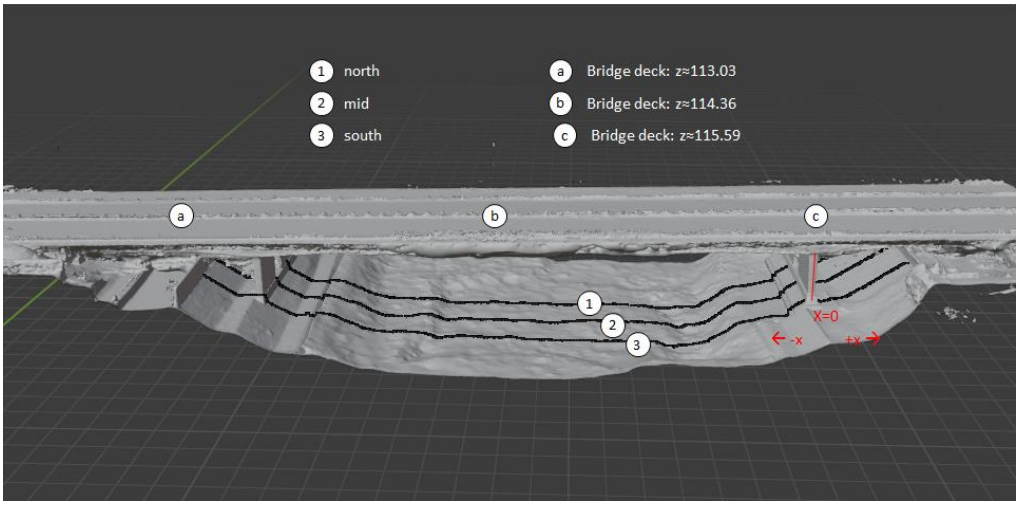


Figure 26: 3D model of the Karlovac Bridge and riverbed cross-sections beneath the bridge

6 Ambient vibration measurements

The ambient vibration measurements of the two case study bridges were conducted on 9th March 2021. The measurements consist of recording the acceleration response of the bridge to random vibrations from the environment (e.g. wind, traffic, etc.). For this purpose, accelerometers were placed on the two bridges at different locations. Operational modal analysis was then performed to estimate the bridge modal frequencies and shapes (modal parameters) from the measured signals. The obtained modal parameters represent important information for calibration of the numerical models to be used for flood fragility analysis in WP4.

An important step in the identification of the modal parameters of the bridges is the selection of appropriate sensor locations. This is especially important for the identification of modal shapes as the bridge response is only predicted at discrete points (sensor locations). Poor selection of the sensor locations can inhibit the detection of some modal shapes. Therefore, preliminary numerical analyses are advisable to assess the most efficient sensor distributions. Engineering judgement can also be used in cases when preliminary numerical results are not available.

In this deliverable, operational modal analysis was performed to estimate the modal parameters of the two bridges. The inputs for the operational modal analysis are the measured acceleration time series from ambient vibration measurements.

The employed equipment for in-situ ambient vibration measurements is presented in Section 6.1. Description of the in-situ measurements and results is presented separately for the Banija Bridge and the Karlovac Bridge in Sections 6.2 and 6.3, respectively.

6.1 Employed equipment

The MonoDAQ wired structural health monitoring solution [10] was used for ambient vibrations measurements. The system is based on the industrial EtherCAT communication protocol, which allows the sensors to be daisy-chained with a single inexpensive CAT6 cable providing power, data transfer and synchronisation (down to 1 ms) up to 100m device to device distances. This allows the sensors to be placed in a series connection with node-to-node distances between sensors of up to 100 m. The sensors used for ambient vibration measurements were three-axial Micro-Electro-Mechanical System (MEMS) accelerometers.

The setup employed for ambient vibration comprised:

- Portable 220V power
- Portable industrial computer with MonoDAQ digital acquisition software [10]
- EtherCAT switch with up to 8 channels
- 12 three-axial MEMS accelerometers – MonoDAQ-E-gMeter [10].
- EtherCAT cables are used to connect the sensors

A portable solution for 220V power supply was achieved employing a 12V to 220V car power inverter, which delivered power to the sensors and the portable computer. The accelerometers

were daisy-chained together in EtherCAT cable to the desired location. The EtherCAT switch allows further branching of the chains of sensors, which facilitates the placing of sensors at different parts of the bridge. The accelerometers were screwed on steel plates and were attached to the steel parts of the bridges with the use of magnets. Digital acquisition software allows the synchronised recordings from different accelerometers and offers the possibility to monitor the results of the measurements in real-time (e.g. the display of acceleration response, Fast Fourier Transform (FFT) spectra etc.).

6.2 Banija Bridge

6.2.1 Description of the measurements

The measurements were first performed for the Banija Bridge. In total, 12 accelerometers were placed on the bridge to measure its response to ambient vibrations. The employed distribution of sensors is presented in Figure 27. The sensors were placed on the two main steel girders. Steel plates and magnets were used to attach the sensor to the web of the main girder (Figure 28). Two branches of sensors were created by the use of the EtherCAT switch. On each side of the main girders, the daisy chain of sensors comprised 6 accelerometers. The accelerometers were placed at an equidistant spacing of approximately 12 m. The measuring system was connected together with a standard EtherCAT cable (Figure 28). The power supply to the system was delivered by a 12V to 220V car power inverter. The ambient vibrations were recorded in ten 10-minute time windows. The sampling frequency of the measurements was 500 Hz. Selected pictures from the investigation campaign of the Banija Bridge are presented in Figure 28.

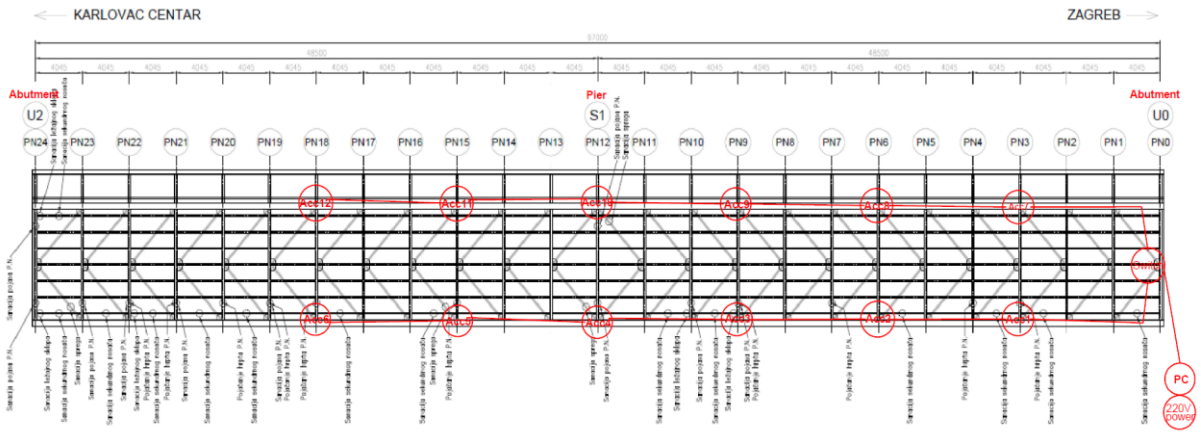


Figure 27: Distribution of sensors for ambient vibration measurements of the Banija Bridge

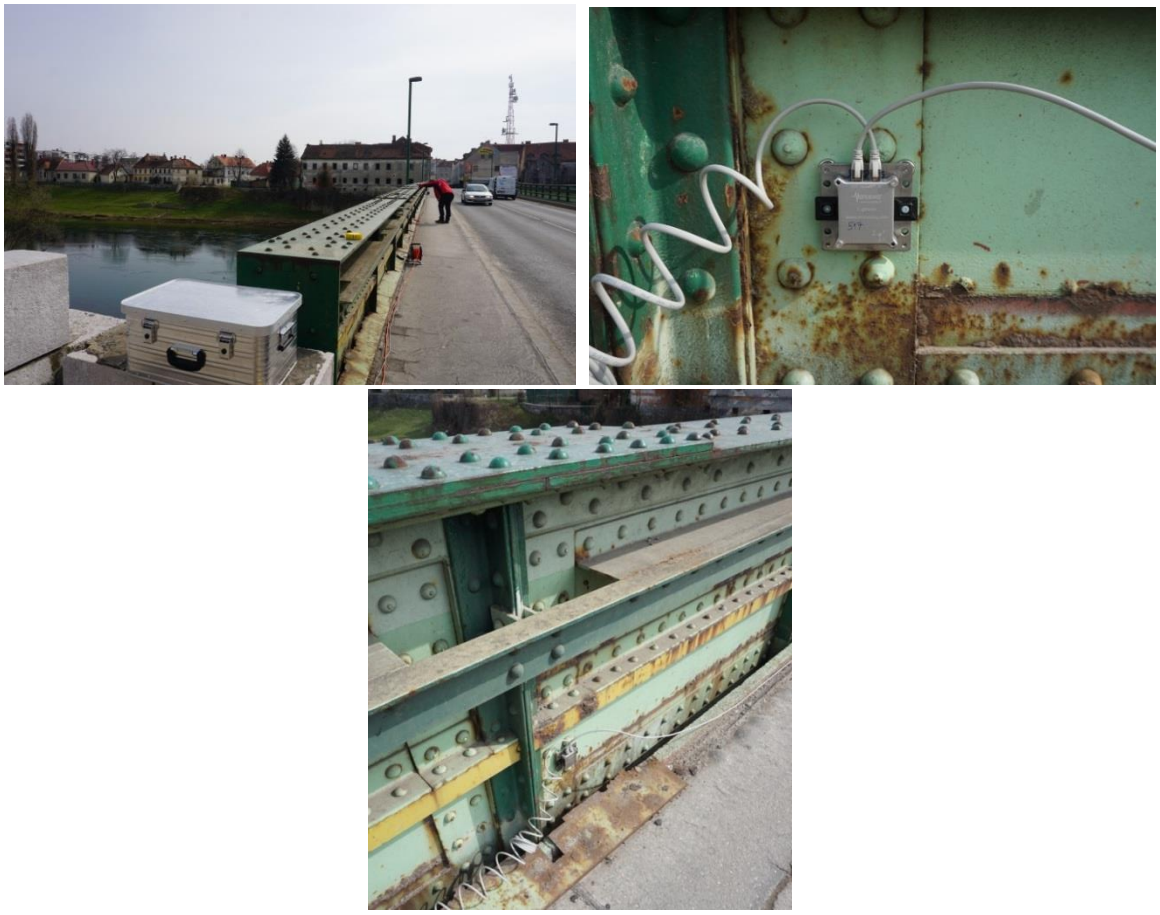


Figure 28: Selected pictures from ambient vibration measurements of the Banija Bridge

6.2.2 Measured modal characteristics

Before performing the operational modal analysis, the measured signals were post-processed. The post-processing of the signals involved zero-mean normalisation, linear detrending, down-sampling of the frequency range 0-250 Hz, and low-pass filtering with a 40 Hz cut-off frequency. The signal was then analysed with the Frequency Domain Decomposition (FDD) [11], where the Singular Value Decomposition (SVD) is used to decompose the power spectral density function matrix. This effectively decomposes the spectral response into a set of single degree of freedom (SDOF) systems, each corresponding to one individual mode. The results of the procedure are exact in the case where the loading is white noise, the structure is lightly damped and when the mode shapes of close modes are geometrically orthogonal. If these assumptions are not satisfied, the decomposition to SDOF is approximate but can still often lead to practically useful results. The obtained modal frequencies and periods of the Banija Bridge are presented in Table 1. Graphic representation of the corresponding mode shapes is presented in **Error! Reference source not found.**.

As it can be seen from Table 1 and **Error! Reference source not found.**, the employed algorithm allowed the identification of 7 mode shapes and corresponding mode frequencies. The mode shapes include both bending and torsional modes of the bridge deck in the vertical direction. As expected, it was not possible to identify the horizontal mode shape of the bridge as the excitation on the bridge resulted mostly from traffic, which induces most vertical

excitations. Horizontal excitations seem to have been below the level of the noise of the sensors. Nevertheless, the obtained results provide valuable data for model calibration in WP4.

Table 1: Measured modal frequencies and periods of the Banija Bridge

Mode No.	Frequency [Hz]	Period [s]	Description
1	1.46	0.68	Bending mode
2	2.2	0.45	Torsional mode
3	2.32	0.43	Bending mode
4	3.05	0.33	Torsional mode
5	4.76	0.21	Bending mode
6	5.13	0.19	Bending mode
7	6.96	0.14	Torsional mode

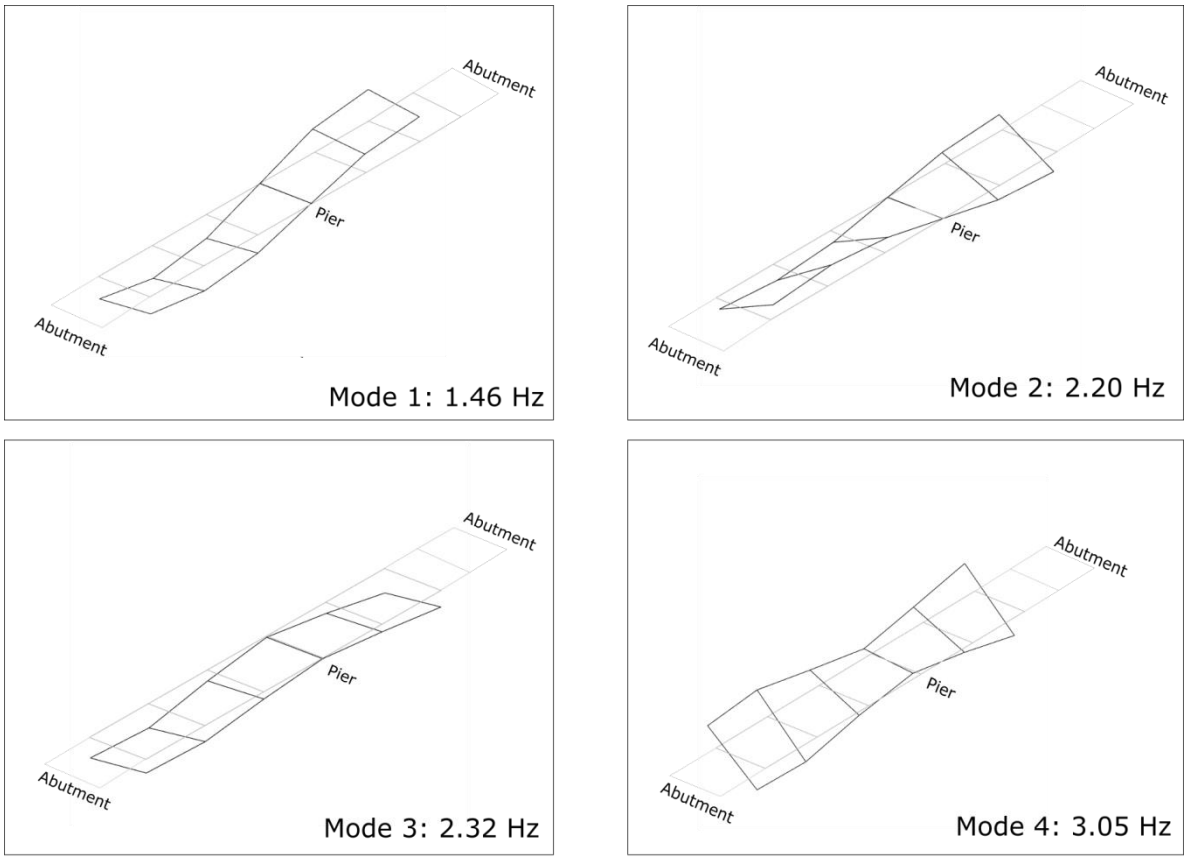
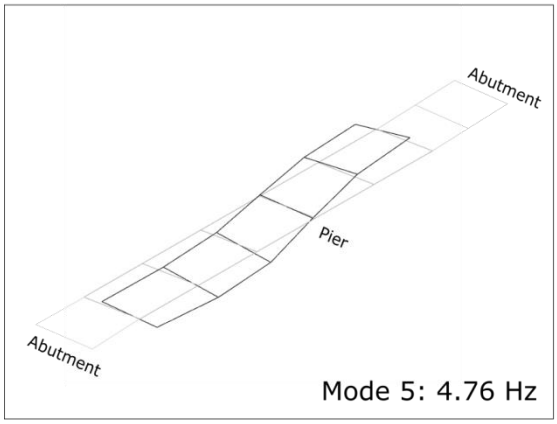
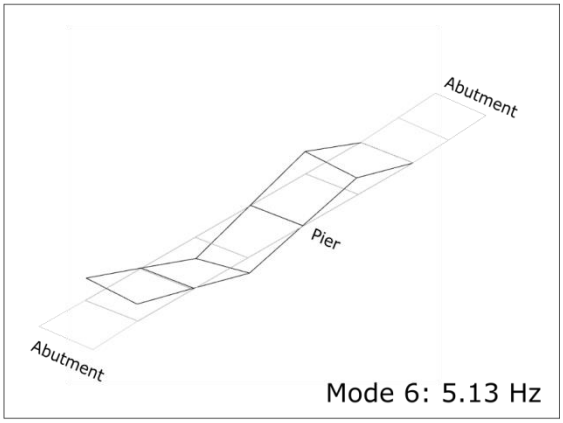


Figure 29: Measured mode shapes of the Banija Bridge





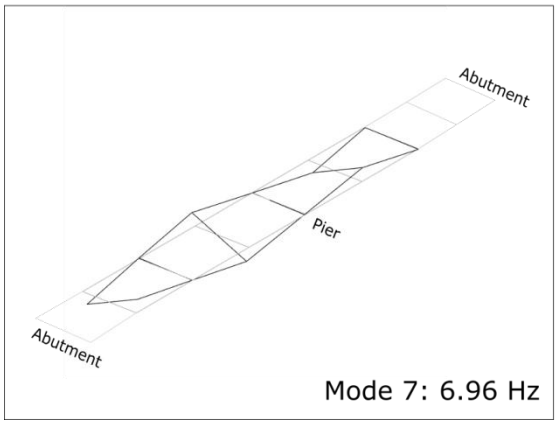


Figure 30: Measured mode shapes of the Banija Bridge (continued)

6.3 Karlovac Bridge

6.3.1 Description of the measurements

Ambient vibration measurements were also performed for the Karlovac Bridge. The employed distribution of sensors is presented in Figure 31. In this case, a single daisy chain of 6 sensors was placed on a pedestrian zone on the downstream side of the bridge due to difficulties in accessing the other side of the bridge with running traffic. The employed distribution of sensors is not optimal for the identification of the modal shape of the bridge due to difficulties in distinguishing between the vertical and torsional mode shapes. Nevertheless, it can still provide a benchmark for calibration of the numerical model in WP4.

The sensors were attached to the steel railing of the bridge with the use of steel plates and magnets (Figure 32). The first two accelerometers in the daisy chain were placed in the first span of the bridge at approximately 1/3 and 2/3 of the span length. The third accelerometer was placed above the pier, and the remaining three accelerometers were placed in the main span of the bridge. One of the accelerometers was placed in the middle of the span and two at the location of the Gerber bearings. The ambient vibrations were recorded in four 10-minute time windows. The sampling frequency of the measurements was 500 Hz. Selected pictures from the investigation campaign of the Karlovac Bridge are presented in Figure 32.

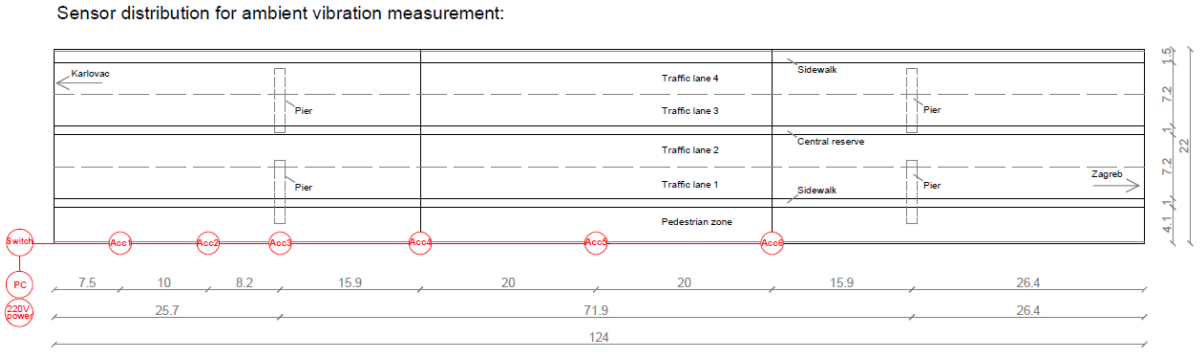


Figure 31: Sensors distribution for ambient vibration measurement of the Karlovac Bridge

Figure 32: Selected pictures from ambient vibration measurements of the Karlovac Bridge.

6.3.2 Measured modal characteristics

In line with the procedure used for the Banija Bridge, the modal characteristic of the bridge were estimated with the Frequency Domain Decomposition (FDD) [11] . Before the analysis, the signal were processed applying zero-mean normalisation, linear detrending, down-sampling of the frequency range 0-250 Hz, and low-pass filtering with a 40 Hz cut-off frequency. The obtained modal frequencies and periods of the Karlovac Bridge are presented in Table 2. Graphic representation of the corresponding mode shapes is presented in Figure 33.

As it can be seen from Table 2 and Figure 33, the employed algorithm allowed the identification of 4 mode shapes. All identified modes act in the vertical direction of the bridge. The distinction between bending and torsional modes was complicated by the employed distribution of sensors, based on which it is not possible to detect if the two sides of the bridge moves in the same or opposite directions. Engineering judgement had thus to be employed in the interpretation of results. The first mode was identified to be the first bending mode of the bridge. The second and third modes have very similar vibration frequencies. Based on the comparison of the mode shape, it was identified that the third mode has a more pronounced displacement component in the transverse direction. It was thus deduced that this mode shape is likely the first torsional mode. Such a transverse component was not observed for the second mode, which was thus characterised as the second bending mode. Similarly, the fourth mode shape had no significant transverse displacement component. Therefore, it was characterised as the 3rd bending mode. A more precise interpretation of the obtained results will be made with the support of data from numerical models.

Very similar to the case of the Banija Bridge, the performed measurements didn't allow for the identification of horizontal modes. This is likely a consequences of the excitations on the bridge resulted mainly from the traffic. Horizontal excitations seem to have been below the level of the noise of the sensors. Nevertheless, the obtained results provide valuable data for model calibration in WP4.

Table 2: Measured modal frequencies and periods of the Karlovac Bridge

Mode No.	Frequency [Hz]	Period [s]	Description
1	1.65	0.61	Bending mode
2	2.50	0.40	Bending mode
3	2.53	0.40	Torsional mode
4	4.27	0.23	Bending mode

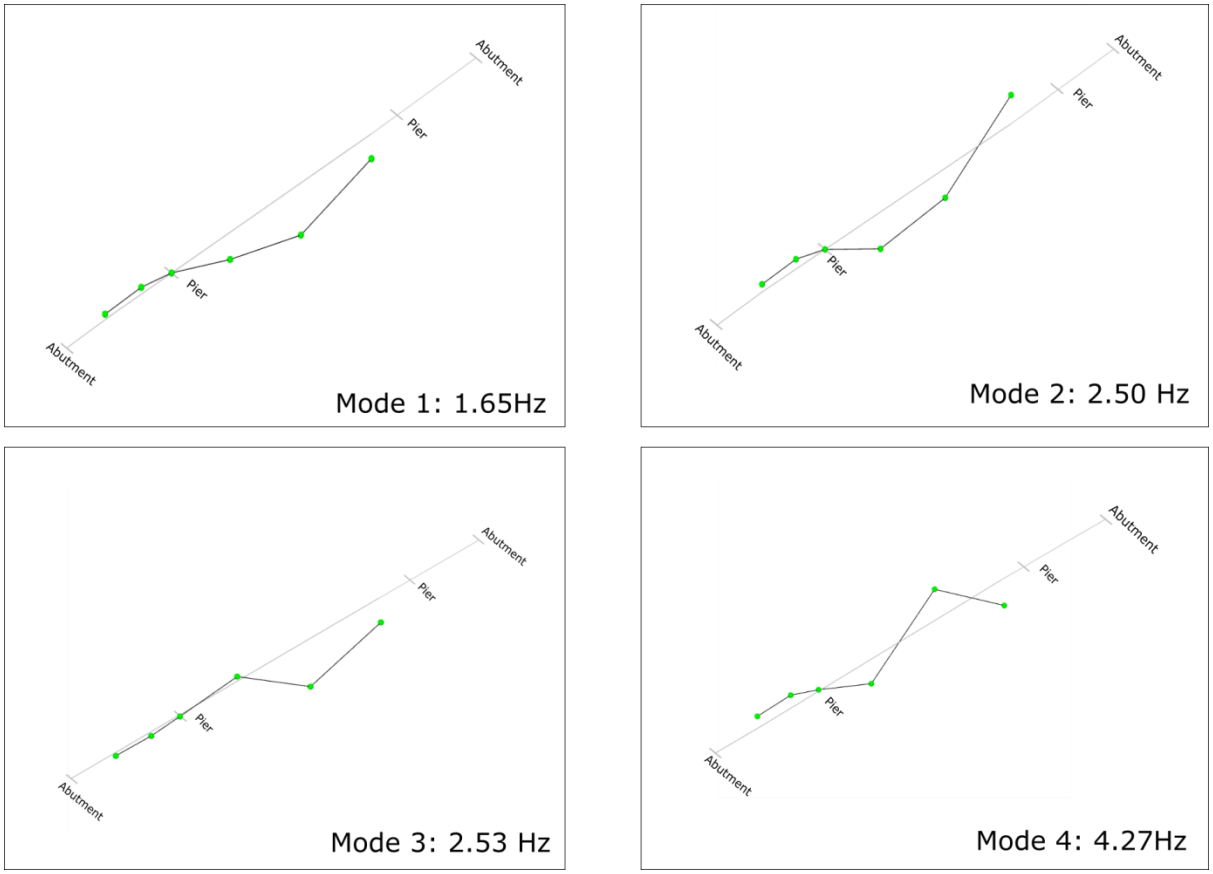


Figure 33: Measured mode shapes of the Karlovac Bridge

7 Conclusions

This deliverable is a report on the performed investigation works and monitoring of the two case study bridges overpassing the Kupa river in the city of Karlovac in Croatia. The performed investigations comprised a drone survey of the two bridges, a bathymetric survey of the river channel between the bridges, and measurements of ambient vibration of the two bridges. The results of the drone survey were used to record and verify the geometry of the case study bridges. The river profiles near the bridges were obtained from the results of the performed bathymetric survey. The results of both surveys were merged together to obtain 3D point cloud models for both bridges and the riverbed. The performed ambient vibration measurements allow the identification of the modal frequencies and shape of the case study bridges, which can be used for the calibration of numerical models to be used for flood fragility analysis in WP4.

In case of the Banija Bridge, the obtained 3D point cloud model help us identify the geometry of the pier and the diameter of the well foundations, which were not included in the available project documentation. On the other hand, the depth of the foundations had to be assumed based on construction plans of the old Banija Bridge [1]. The geotechnical conditions at the location of the bridge were also not available. However, they were assumed based on geotechnical investigations performed for the purpose of condition assessment of the case study embankments [4].

Visual inspection of the Banija Bridge with the use of drones confirmed the outcomes of the report from 2017 [3] and supplemented with additional information the existing bridge condition assessment. The results of the inspection in 2017 indicated a poor condition of the bridge, which resulted in a proposal of retrofitting project [2]. However, up to now, no retrofitting works have been performed on the bridge.

In the case of the Karlovac Bridge, a search for the project documentation was conducted in the archives of the city of Karlovac and the Croatian State Archives. However, the construction plans of the bridge could not be retrieved. It is likely that they have been lost/destroyed during the Croatian War of Independence between 1991-1995. The geometry of the bridge was thus obtained entirely from the 3D point cloud model. Due to the lack of design documents, several input parameters for numerical modelling of the bridge remain uncertain, e.g. thicknesses of elements that could not be visually inspected, the mechanical characteristics of the concrete and reinforcement, and depth of the pile foundations. On the other hand, relatively precise information regarding the geotechnical conditions at the site can be obtained based on geotechnical investigations performed for the purpose of condition assessment of the case study embankments [4].

A preliminary visual condition assessment of the Karlovac Bridge indicated that the bridge is in poor conditions and would require immediate retrofitting. Especially critical is the degradation of the Gerber hinges, which shows signs of water leakage, delamination of the concrete cover and corrosion of reinforcement. Detailed condition assessment of the bridge is thus warranted. This was, however, considered to be beyond the scope of this project. Nevertheless, a set of recommendations for further investigation works are provided in Section 4.2.2.

Based on the ambient vibration measurements, it was possible to identify the first seven and four vertical modal frequencies and shapes of Banija Bridge and the Karlovac Bridge. The mode shapes include both bending and torsional modes of the bridge deck. Better representation of the mode shapes was obtained for the Banija Bridge, which was a consequence of the more even distribution of sensors along the bridge. In the case of the Karlovac Bridge, the employed distribution was limited to one side of the bridge due to accessibility issues (measurements were performed under running traffic), which complicated the identification of modes shapes. The detection of horizontal mode shapes was not possible due to low excitations in the horizontal direction. This was a consequence of the traffic being the main source of ambient vibrations. Nevertheless, the obtained results still provide valuable data for model calibration in WP4.

The results of this deliverable will provide direct input for the numerical model in WP4. In the case of the Banija Bridge, the results of the performed investigations, combined with available project documentation, are judged to provide a sufficient basis for numerical modeling. On the other hand, the available data for numerical modelling of the Karlovac Bridge is still limited, which is mainly a consequence of the missing project documentation. Additional site investigations that would be required to obtain more reliable input data are considered to be beyond the scope of the project, as the cost of these unforeseen works would exceed the allocated time and budget significantly. It can be therefore concluded that very limited data will be available for numerical modelling of the Karlovac Bridge and large number of assumptions will have to be made in WP4.

8 References

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