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TECHNIQUES FOR SPECIAL FOLLOWING OF THE DEGRADATIONS DEVELOPMENT FOR A RAILWAY PASSAGE

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Abstract. Nowadays, most of the transportation infrastructure is already built, the main challenge being the maintenance of these structures in optimal conditions of safety and comfort for users. Therefore, in recent years, research in the field of bridge maintenance has focused on the development and implementation of special monitoring programs that can identify and warn transportation infrastructure managers of the appearance and development of degradation, and especially the possibility of collapse of the construction element in the near future. In addition to familiarizing readers with the structural design of the Constanta Bridge, this work proposes the presentation of the main technologies used for implementing the in-service behavior monitoring program, along with the arrangement of data acquisition units and a brief interpretation of the information provided by the monitoring system. In the conclusions of the article, the authors will draw attention to the bearing capacity of the structure, affected by the development of degradation processes and the need for emergency implementation of rehabilitation and strengthening works of the passage.

Keywords: *bridges, monitoring, rehabilitation, structural analysis, structural health monitoring.*

Rezumat. În zilele noastre, cea mai mare parte a infrastructurii de transport este deja construită, provocarea principală fiind reprezentată de menținerea acestor structuri în condiții optime de siguranță și confort a utilizatorilor. De aceea, în ultimii ani, cercetările în domeniul întreținerii structurilor de poduri s-au canalizat pe dezvoltarea și implementarea unor programe de urmărire specială, ce reușesc să identifice și să atenționeze administratorii infrastructurii de transport de apariția și dezvoltarea degradărilor, și, mai ales, de posibilitatea cedări elementului de construcție în viitorul apropiat. Prezenta lucrare își propune, pe lângă familiarizarea cititorilor cu structura constructivă a Podului Constanței, prezentarea principalelor tehnologii utilizate pentru implementarea programului de urmărire a comportării în exploatare, alături de modul de dispunere a unităților de captare a datelor și de o scurtă interpretare a informațiilor oferite de sistemul de monitorizare. În concluziile articolului, autorii vor trage un semnal de alarmă privitor la capacitatea portantă a structurii, influențată de dezvoltarea proceselor de degradare și a necesității implementării în regim de urgență a lucrărilor de reabilitare și consolidare a pasajului.

Cuvinte cheie: *poduri, monitorizare, reabilitare, analiză structurală, monitorizarea stării tehnice.*

1. Introduction

With time, constructions show various degradation due to environmental conditions and exploitation, primarily degradation of the materials used in the structure. Today, one of the biggest challenges for administrators is maintaining existing infrastructure [1, 2]. Thus, administrators and designers seek the best solutions for performing maintenance and repair work on bridges and overpasses on time [3, 4]. The solutions must also not be too costly, given the limited budget. For bridges that have been open for a long time, or whose age is approaching its maximum service life, or for those structures of particular importance for traffic flow, special monitoring programs have been recommended in recent years [5]. These aim to monitor the in-service behavior of structures, track the evolution of degradation, and alert the responsible staff in case of exceeding alarm thresholds, along with emergency remediation measures. Therefore, the Romanian National Railways Company (CFR S.A) has decided to implement a special monitoring program for the overpass on line 800, at km 6+645, which provides a crossing over the railway line, in Bucharest. The overpass was built in 1938, providing continuity of a highly important railway line, the CF 800 Bucharest Nord-Constanta, in the heart of the capital, over a major traffic artery, Calea Griviței. It carries traffic from two major national roads, DN 1A Bucharest-Ploiesti and DN 7 Bucharest-Pitesti, providing access to the city center. In 2014, after identifying potentially dangerous degradation during daily inspections, the administrator contracted a technical expertise. Its conclusions revealed a series of degradation affecting the structure, recommending the implementation of a long-term monitoring program.

The article aims to present the main technologies used for the implementation of the behavior monitoring program for the developed Constanța Bridge, along with the arrangement of data acquisition units. The main purpose of the article is to provide a solid starting point for future bridge and overpass monitoring projects, with the hope of increasing the use of this practice in the country's management system.

This work is part of a comprehensive research program in the field of development and implementation of modern bridge monitoring systems at a national level. The program is developed by the Faculty of Construction and Installations at the Technical University "Gheorghe Asachi" in Iași.

2. The Constanța Bridge presentation

Although the structure that is the subject of this study is known as the Constanța Bridge, it is actually a passageway that provides continuity for the Bucharest-Constanța railway 800 line, over one of the most important road arteries in Bucharest, namely Calea Griviței. Due to its location in the middle of a curve, the passageway's length is 28.70 m, a measurement taken along the left side of the railway line's parapet. If we measure the distance between the joints located approximately in the middle of the longitudinal support walls' coronations, the result is a significantly shorter length of 18.35 m.

If we analyze the passageway from the perspective of its distance between the infrastructures, the result is a distance between the vertical faces of the two portals of 17.89 - 17.93 m (Figure 1). This light is divided symmetrically in relation to the pier located in the central section of the passageway.

Figure 1. The Constanța Bridge.

Figure 2. The railway line

In order to ensure maximum railway transport capacity and due to the high importance of the served line, the passageway was built with a total width measured between the parapets, at the joint level on portal C1, of 32.42 m, a width that corresponds to the service of 5 railway tracks (Figure 2).

In terms of building material, the passageway is made of reinforced concrete. An interesting feature is that the superstructure is composed of two asymmetric structures next to each other (Figure 3). This composition can demonstrate the importance given to this structure, highlighting the need to increase the capacity of circulation, with industrial development and the significant increase in railway traffic on the Bucharest-Constanța direction.

Analyzing the structure in cross-section, we notice the presence of 20 main girders (Figure 3) connected by means of a reinforced concrete slab placed at the level of the upper flanges of the beams. Due to the specificity of the communication path, the slab supports the 5 railway lines through a reinforced concrete trough.

Figure 3. The superstructure.

Each structure is composed of 9 main beams, located in the railway lines area. In the center of the viaduct there are 2 adjacent beams, separated by a longitudinal groove. The main beams have a width of 50 cm and a height of 1.20 m, dimensions that were measured between the intrados plane and the lower flange of the beams.

All 10 beams of each structure rest directly on the three piers, being connected at the support level and in the central section through the cross-girders. These have an average width of 30 cm, maintaining the same height as the beams.

The infrastructures of the viaduct, consisting of two abutments and one pier (Figure 1), are founded directly. According to the existing documentation in the Technical Construction Book, the foundation base has a width of 5.50 m and a thickness of 1.50 m.

The abutments are massive, built of concrete, their elevation is plastered, with coping, at the base there is a plastered plinth.

The pier of the viaduct (Figure 4) has a length of approximately 34.00 m, measured at the level of the plinth. The elevation of the pier is composed of 20 columns built of reinforced concrete. In the central area of the pier, there are 8 columns for each superstructure, with a polygonal section, similar to that of a circle with a diameter of 50 cm. The columns in the end areas have an oval section, with dimensions of 50×100 cm, developed along the pier.

As it is a viaduct, it is also important to mention the configuration of the crossed communication path. Thus, the clearance between the abutments' elevations is 17.89-17.93 m, it includes 2 sidewalks with a width of approximately 1.00 m each and 2 areas for road and tram traffic with a width of 7.78 m each, separated from the pier elevation by a 0.70 m wide area.

Figure 4. The Constanța Bridge pier before rehabilitation works.

Figure 5. Traffic jam at the entrance of passage.

3. Reasons for the special following of the degradations

In February 2014, the facility administrator conducted a routine inspection on the site, identifying a series of deteriorations whose arrangement and extent could have endangered the safety of both railway, on the railway 800 line, and road traffic, on Griviței Road.

The first step in launching the rehabilitation works was the contracting of a specialized Technical Expertise, which identified and thoroughly described the deterioration state of the structure in August of the same year.

According to the Expertise, although the conclusions were that the structure was in good technical condition, the passage presented a series of degradations and deteriorations whose extent could lead to the imposition of traffic restrictions and even endanger the safety of users.

Some of the largest problems identified were:

-The road traffic is very heavy (Figure 5), this being due to the clear passage height under the bridge, and the passage lighting is only designed for 2 lanes of road traffic in each direction and 2 tram lines. On the passage area, Griviței Road has undergone a series of expansions over time, currently having 3 lanes of traffic in each direction and 2 tram lines.

- The tram traffic (Figure 6) through the passage generates strong vibrations in the immediate vicinity of the pile, which has led to multiple deteriorations, including the safety structure of the passage.

Figure 6. The tram traffic in the passage.

Figure 7. The marginal girder.

The following degradations were identified at the superstructure level:

-The marginal beams have numerous signs of impact due to the violation of the safety height (Figure 7).

-Due to advanced age and repeated impacts, the reinforcement at the bottom fiber of the girder is exposed, rusty, some of the reinforcing bars are even broken, which leads to a pronounced decrease in the carrying capacity of the girder and, implicitly, the entire structure.

Figure 8. Degradations of the pillar support [6].

The infrastructure was also found to have significant degradation issues, including:

-The pillar supports show severe degradation of the concrete cover layer, with reduction in section, complete corrosion of reinforcing steel, cracks oriented along the elements, and friable concrete (Figure 8).

-The elevations of the piers and abutments are severely degraded, with extensive areas of fallen plaster, segregated concrete, voids, and exposed reinforcement.

The civil society has raised concerns about the structure through articles in local and central press, presenting the situation in an exaggerated manner (Figure 9). This has led to expedited procedures for rehabilitation works and a special monitoring process was instituted to keep track of the real-time appearance of the danger of collapse and the progression of the degradation.

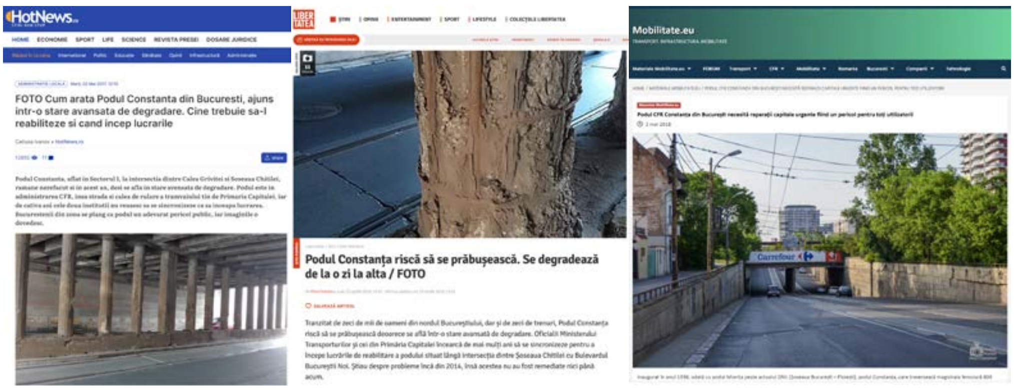

Figure 9. The impact of the mass-media [7-9].

4. Behavior tracking technologies in operation

The behavior monitoring of the bridge during operation was carried out on the piles and girders. The following activities were undertaken:

- periodic visual inspections;
- installation of markers at the level of cracks in piles, girders and abutments;
- installation of a video system with cameras at the level of each ramp, with the purpose of monitoring railway and road traffic;
- determination of the position of the reinforcement, the distances between bars and the concrete coverage;
- determination of the concrete resistance of the main structural elements;
- determination of the corrosion of the reinforcement;
- installation of sensors at the level of piles and abutments for identification of the structure's vibration modes in static and dynamic regime.

Due to the specificity of the structure and the identified degradation, the team of specialists responsible for designing the behavior monitoring system decided to install multiple types of technology, targeting the following aspects:

- video monitoring of railway traffic and how the structure reacts to different loads;
- monitoring the evolution of cracks;
- establishment of the reinforcement scheme, this aspect becoming important after the finding of the small volume of information available from the construction of the bridge;
- determination of concrete strength;
- recording of deformations through modern systems that use precision fiber optics.

4.1. Monitoring the evolution of cracks in the bridge's structural resistance

This stage will focus on carrying out a crack survey. This survey was used as input data for the analysis of crack opening, position, and length, and also indicating their evolution over time.

The survey methods were purely visual, with the infrastructure, superstructure, and access ramps area being analyzed up close. Additionally, in this stage, glass markers were installed (Figure 10), readings being taken at least once a week.

Figure 10. Glass marker for monitoring crack evolution.

4.2. Video surveillance of the structure

The purpose of this technology is to monitor the real-time flow of traffic through the bridge and on the railway. Video cameras were mounted on each access ramp. The captured data was transmitted in real-time to a control center.

In addition to the continuous monitoring of the structure, another advantage of this technology is the minimization of response times by competent authorities to any incidents or accidents that occur in the area, as the system instantly alerts of their occurrence.

4.3. The position determination of the reinforcement, the distance between bars, and the concrete cover for the reinforcement

In areas of the passage with major degradation and pronounced cracks in the structural integrity, non-destructive tests have been carried out. These aimed to locate the reinforcement, determine the position, the diameters of the bars used in the construction of the targeted element, and measure the remaining concrete cover layer after degradation occurred.

The non-destructive testing was performed using a Profomet 5+ model Scan Log5+ (Figure 11), consisting of a display unit, scanner, and universal probe.

Figure 11. ScanLog 5+ profometer [10].

Figure 12. Digi Schmidt hardness tester [11].

The measurement was performed by positioning the probe parallel to the direction of the targeted reinforcement. In this way, 3 successive passes were made over each set area. The displayed data includes the diameter of the reinforcement, the concrete cover of each bar, and the distance between it and the point of origin of the measurement.

4.4. Determination of the compressive concrete strength

Another important parameter for the viability of the structure is the value of the compressive strength of the concrete in the main load-bearing elements. This parameter has undergone various changes over the period of operation, mainly due to environmental and usage factors of the structure.

The test targeted the concrete in the bridge piles, main beams, and columns. Given the specificity of the targeted monitoring, the tests performed were non-destructive. The determination was made using a Digi Schmidt (Figure 12) hardness tester.

The device consists of the hardness tester itself and a display and data storage unit. The measuring technology is based on recording the rebound distance. With the help of internal conversion curves, the device converts the rebound value into the compressive strength of the concrete and displays its f_{ck}value.

4.5. Determination of the reinforcing steel corrosion

Corrosion is the chemical process that occurs at the surface of reinforcing steel and results in a substantial reduction of the affected steel bars' cross-section. This phenomenon is especially common in construction elements where the minimum concrete coverage of reinforcing bars was not respected during construction, where the concrete has a high degree of porosity, or where the element has cracks with openings exceeding 0.3 mm.

Thus, in the site, areas with rust stains were identified, the main sign given by the structure of corrosion occurrence.

The determination was non-destructive, using the CANIN+ (Figure 13) system for measuring the potential electromagnetic fields of affected concrete elements. The system determines changes in potential grades per unit length, drawing attention to different affected areas.

Unidentified and unmitigated, the corrosion process can ultimately lead to structural failure.

Figure 13. CANIN+ measurement system [12].

4.6. Structural Deformation Monitoring

During the design of the entire structural monitoring system, the issue of using high-precision topographical methods was raised. After analyzing the possibility, it was concluded that due to the high rigidity of the elements and their small dimensions, these systems would not be capable of providing the necessary information regarding the time behavior of the passage under traffic.

Thus, the specialist staff sought other solutions, focusing their attention on interferometric fiber optic sensors installed on the piles.

The system consisted of 12 sensors each mounted on a pile column and 6 sensors mounted at the level of the main girders (Figure 14). The length of each sensor was a minimum of 2 meters for each column and a minimum of 5 meters for those mounted at the girder level.

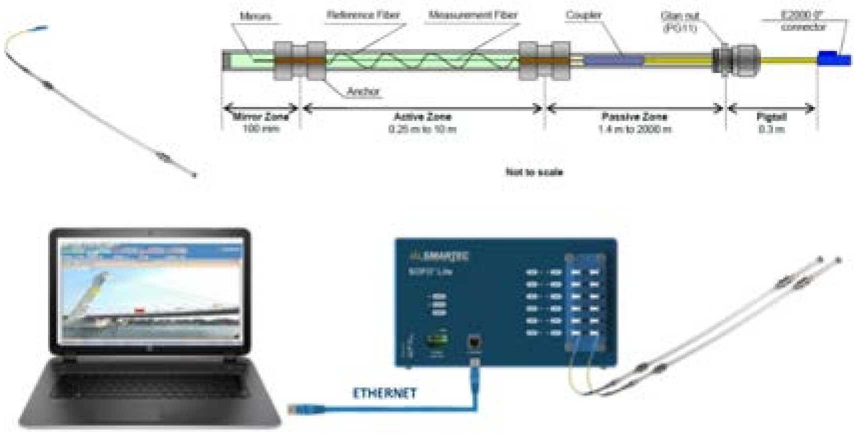

Figure 14. Fiber Optic Sensor-Based Monitoring System [13-15].

Also, for increased data accuracy, 4 triaxial accelerometers were installed. They monitored the vibration mode of the piles, especially in dynamic regime, under the useful loads. The accelerometers were triaxial with a data capture range of +/-4 G, sensitivity of 1μG, and operating frequency of 0 + 500 Hz.

5. Data capture units arrangement

During the design of the monitoring works, the exact installation points of all the data capture units were selected (Figure 15), regardless of their specificities. By closely analysing, the degradation state of the structure and its evolution over time, it was determined that data should be recorded from the main load-bearing elements with the highest depreciation in the technical state evaluation, namely the main beams and pier piles.

For crack monitoring, glass indicators were installed as follows:

- At the location of cracks affecting the pier piles (Figure 10), to highlight the stress state and crack evolution over time, determining if the crack is active or passive. For better data accuracy, at least 50% of cracks will be monitored.
- In the case of cracks affecting the main beams, due to their importance, all cracks will be monitored, following their evolution under traffic, regardless of the cause of appearance and position (cracks in the bearing area due to shear force or cracks in the central area due to bending moment).

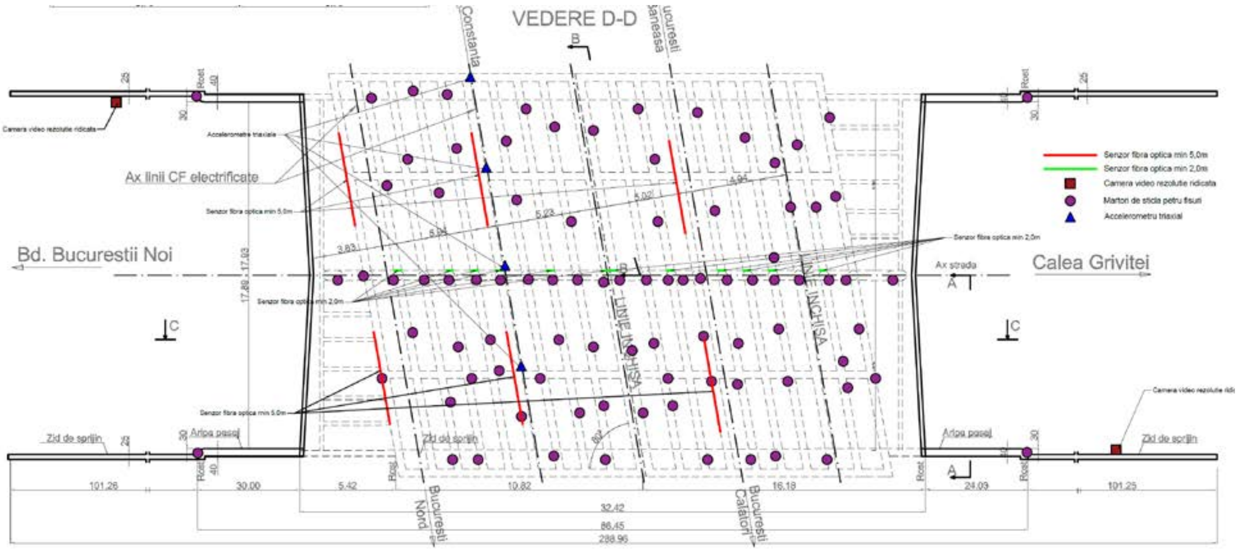

Figure 15. Position of the principal monitoring sensors.

To monitor how the structure reacts as a whole, in terms of temperature variation and horizontal forces from rail traffic, two indicators will be installed at each joint level between the elevation of the arches and the wings of the bridge and between the wings and the retaining walls.

The necessary video cameras for monitoring the traffic served by the structure, both road and rail, will be installed on each ramp. The cameras have opposing directions, thus ensuring high clarity of the recorded data.

The ScanLog5+ level was used for all piles (Figure 16), one of the columns, and a beam, easily analysing the structure's reinforcement, degree of degradation, and concrete coverage. The determination took place during a site visit on 12/19/2018, targeting the structure's characteristic areas.

Figure 16. Data capture for structural reinforcement.

The concrete compressive strength was determined for all piles, 2 main girders, column elevations (Figure 17) and bridge wings. This determination becomes a key factor in decision-making regarding the rehabilitation work to be performed, as concrete is one of the most important building materials and the available strength determines the chosen rehabilitation solution and type of materials to be used.

Figure 17. Determination of the compressive strength of concrete in pile columns.

Figure 18. Installation of optical fiber at the pile column.

As previously noted in the previous chapter, to ensure a high level of quality in rehabilitation work, corrosion of the reinforcement must be identified and eliminated. The testing was performed using the CANIN+ system during the same site visit. The targeted areas were the pile column pilings and the most severely degraded girder.

To monitor the evolution of structure deformations over time, the 4 triaxial accelerometers were mounted on main beam no. 6, positioned as follows:

- 2 accelerometers were placed in the center of the opening;
- 1 accelerometer was placed at the pile level;
- 1 accelerometer was placed at the column level.

Optical fiber was installed at each pile column (Figure 18). The main goal was to record the structure's behavior under traffic.

6. Data recorded during the monitoring of behavior in operation

With the installation of the entire operation behavior monitoring system for the Constanta overpass in Bucharest, a comprehensive monitoring process was launched. It lasted throughout the first half of 2019, with the behavior in operation of the structure being highlighted from the first days of monitoring.

The monitoring system for the vibration evolution of the bridge under traffic loads has revealed serious resistance problems of the bridge. The vibration modes varied from the expected and calculated ones during the design phase of the system.

The main causes of structural vibrations were the trams and trolleybuses passing through the bridge. These generated the largest dynamic loads that propagated to all structural elements, as seen in Figure 19.

Additionally, the monitoring system was able to capture the structure's reaction to an earthquake recorded on January 31st, 2019. As such, the evolution of vibration mode graphs (Figure 20) shows a significant jump. At the same time, the monitoring system alerted the monitoring team about the situation.

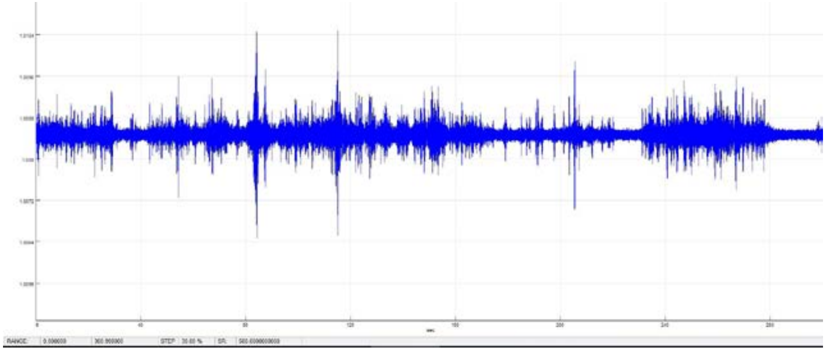

Figure 19. Evolution of structural vibrations.

After analysing the cause of the jump, the monitoring team was unable to find any structural explanation, learning from the media that the earthquake occurred in the Vrancea area and the waves propagated towards Bucharest. Thus, the effectiveness of the concept in alerting the occurrence of situations with a high potential risk for users was demonstrated.

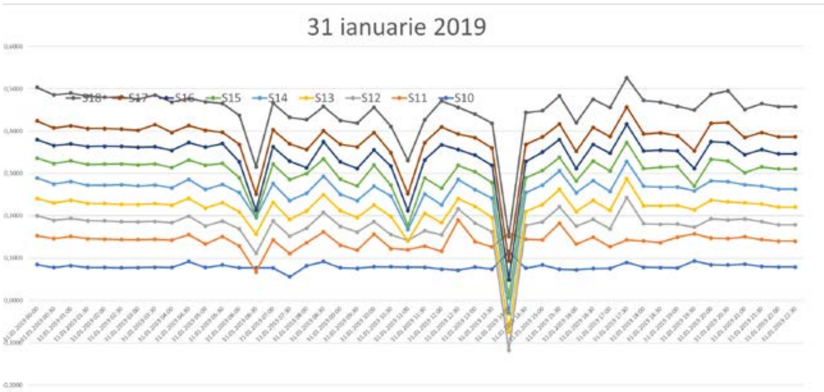

Figure 20. Recording of the earthquake on 01.31.2019.

Regarding the monitoring of crack evolution, as shown in Figure 21, it was identified a significant settling at both piers, on the side towards Calea Griviței, highlighted by the opening of cracks on the right side of the piers and their ascending evolution. The settling occurred immediately after the earthquake on 01.31.2019.

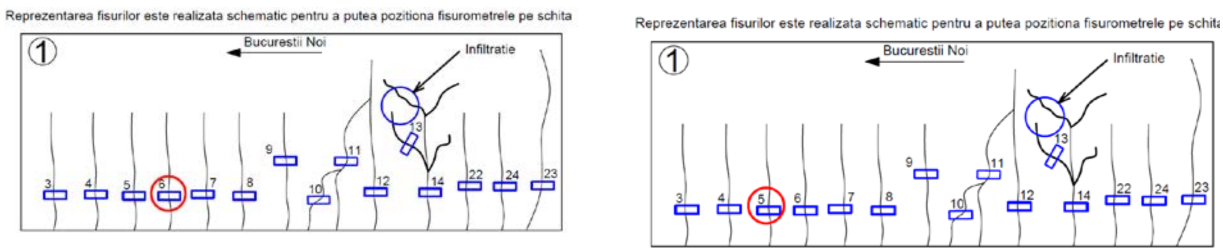

Figure 21. Evolution of cracks.

7. Conclusions

The purpose of this article is to familiarize readers with the tracking technologies of the behavior during operation used in the Constanta Passage in Bucharest. This article can be a solid starting point for future bridge and overpass tracking projects.

Following a thorough analysis of the recorded data, the following conclusions can be drawn regarding the targeted structure:

1. After a service life of over 80 years, despite no repair, reinforcement, or rehabilitation works, the carrying capacity of the entire structure is visibly reduced but does not exceed the limit threshold imposed by standards for user safety, thus not posing a threat to the structural integrity of the bridge.
2. The analysis of the cracking state of the structure shows the presence of degradation processes in advanced stages of development, which significantly contribute to the reduction of the overall resistance and stability of the bridge.
3. The current state of degradation, at time T=0, does not immediately and directly threaten the local resistance and stability of the pier piles or the bridge as a whole structure of resistance.
4. The identified state of degradation at the level of the pylon elevation columns does not immediately and directly endanger the local resistance and stability of the pylon.
5. Graphs of variation will be prepared, at times T=1...T=n, in which the evolution of degradation processes (cracking state, static and dynamic behavior of the bridge structure) will be analyzed. Based on the analysis of the time variation of the general degradation state of the structural resistance, after at least 3-4 measurement stages, conclusions can be drawn and conclusions regarding the viability of the structure can be issued with certainty.
6. In case of a strong earthquake, the widespread cracking at the level of the resistance structure will be the main source that can severely affect the functionality of the bridge, which will not collapse, but in this case, the immediate closure of railway, road and pedestrian traffic in the bridge will be required to avoid serious accidents.
7. It is recommended to carry out the consolidation and rehabilitation works of the bridge as soon as possible to avoid severe degradation of the structure in case of a strong earthquake that would force the closure of the bridge's circulation.

This work is part of a complex research program developed by the Faculty of Construction and Utilities at the "Gheorghe Asachi" Technical University in Iasi. The research focuses on the study of bridge maintenance methods, the development of modern systems for monitoring their behavior in use, and the adaptation and application of these systems to bridges in our country.

Conflicts of Interest: The authors declare no conflict of interest.

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