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Loading test of the Rákóczi Danube bridge in Budapest

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Abstract

In frame of the tramway network development in Budapest a new tramway line has been established on the south part of Budapest, which crosses the Danube on the Rákóczi-bridge. The bridge superstructure is a continuous double-cell steel box girder having 6 spans with the largest span of 98.52 m. The bridge was originally designed to carry four traffic and two tramway lanes, however the tramway line was only built on the bridge in 2015 and opened for the traffic with an increased tramway load level than originally planned. Related to this tramway network development the required static calculations and the loading test of the Rákóczi-bridge was executed by the BME Department of Structural Engineering. A complex loading test program was developed to check the static and dynamic behaviour of the bridge structure using 20 trucks and 4 trams having the total weight of 1040 tons. The loading test program involved local and global loading conditions investigating the local and global structural behaviour of the bridge under the combined effect of the truck and tramway loads. An extended dynamic loading test program was also carried out to investigate the dynamic behaviour of the bridge under the trucks and tramways separately. The current paper focuses on the results of this complex loading test program.

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Keywords: loading test, Rákóczi-bridge, mixed tramway and road brige

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1. Introduction and description of the bridge structure

A new tramway line has been established on the south part of Budapest, which crosses the Danube on the Rákóczi bridge. Before opening the new and heavier tramway line, the static check and the loading test of the bridge was made by the BME Department of Structural Engineering. A complex loading test program was developed to check the static

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and dynamic behaviour of the bridge structure. The current paper focuses on the observations and measurement results of this loading test program and presents the typical structural behaviour of the Rákóczi Danube bridge and its specialities coming from the mixed traffic condition. The aim of the loading test is the analysis of the structural behaviour and the static check of the load carrying capacity of the bridge before opening the new tramway line. Thus the bridge is an existing bridge opened for traffic in 1993, the current load testing program concentrated on the structural elements in the closed region of the tramway line, which were not loaded and checked in the past.

The bridge superstructure is a continuous girder having 6 spans 49.26 + 4 x 98.52 + 49.26 m = 492.6 meter. The cross section of the bridge is a double cell box section having longitudinally stiffened flanges and webs. The width of the traffic lanes is 2 x 8.0 m, between them the tramway lines are located with a width of 2 x 3.3 m. The total width of the tramway and the carriageway is 24.54 m. The depth of the box girder in the middle spans is a constant value of 3600 mm, which reduces in the side spans to 3100 mm. The distance between the webs at the bridge deck is 17142 mm, which reduces at the bottom flange level to 13100 mm. The web thickness is 21 mm at the largest part of the bridge, which are increased up to 40 mm in three steps in the mid-span regions. The thickness of the bridge deck is 12 mm, supported by closed section longitudinal stiffeners in a distance of 300 mm. The longitudinal stiffeners have trapezoidal cross sections with a depth of 300 mm and a thickness of 8 mm. Tapered cross girders are placed at each 4105 mm along the longitudinal axis of the bridge. The thickness of the lower flange varies between 12 mm – 30 mm. The webs and the lower flange are also supported by longitudinal stiffeners. The web stiffeners have trapezoidal cross sections having 200 mm depth and 6-8 mm thickness. L-type longitudinal stiffener with a thickness of 8 mm are placed on the middle web plate and on the upper part of the side webs. The bridge was designed by the Hungarian designer office UVATERV Zrt, and the tramway line has been erected by the A-Híd Zrt. The typical cross section of the bridge and the location of the loading vehicles can be seen in Fig. 1.

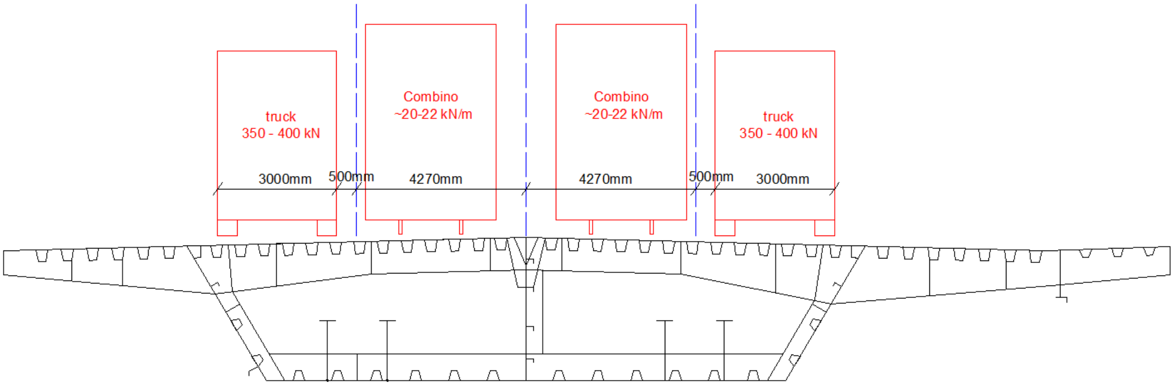

Fig. 1. Cross section of the bridge.

2. Strategy and program of the loading test

The program of the loading test has been developed and executed using the following strategy:

- The bridge was loaded by the assortment of 20 trucks and 4 trams in different loading arrangements. The trucks have four axles and its total weight were ~35 tons for each (700.62 tons for all the trucks). The length of one truck is 8950 mm with a width of 2400 mm. The applied trams are Combino trams having the total weight of ~85 tons (~340 tons for the 4 trams) and the total length of 53990 mm having 12 axles. The distance between the axle-pairs along the longitudinal axis of the tram are 8470 mm and 9375 mm. The width of the tram is 2400 mm with a wheel distance of 1435 mm.
- The complete loading test program was executed within two days. The structural behavior of the bridge was checked by 35 static and 12 dynamic load cases. In all the load cases the deflection of the superstructure and the strains at 109 locations inside of the box girder were measured.
- After the static loading the influence lines at the measured points were also determined using 109 strain gauges under the loading of 4 trucks running parallel on the bridge and under 1 or 2 Combino trams.

- The natural frequencies of the superstructure in vertical and horizontal directions were determined using accelerometers. The bending related eigenmodes in vertical and as well as in horizontal directions were determined and the vibration related to torsion was also measured.
- After the static loading a complex dynamic test program was performed. The dynamic test contained load cases using 1 or 2 trams running parallel trough the bridge with a velocity of 5, 20, 40 and 60 km/h. The dynamic test program contained load cases with breaking and acceleration of the trams on the bridge. The dynamic structural behaviour has been also investigated using 4 trucks running parallel on the bridge with a velocity of 5, 20, 40 and 60 km/h.
- During the dynamic loading test program the movement of the bearing system at the bridge end was also measured and the maximum longitudinal displacements are determined which are caused by the loading and braking effect of the vehicles.

The applied trams have been loaded by sand bags simulating the effect of passengers. The applied sand bags substituted the effect of 221 people (maximum allowed on this tram) with the average weight of 70 kgs. The sand bags were uniformly distributed along the trams, therefore the maximum axle loading did not exceed 100 kN ± 5 kN. The loading of the trams and the trucks represented in one span of the bridge 17 kN/m uniformly distributed load over the tramway lanes and 12 x 350 kN (4200 kN) concentrated loads on the traffic lanes. The applied static load level during the loading test was 67% of the design traffic load level of the bridge. The bridge had a previous loading test in 1995. That time the applied load level was 75% of the design traffic load, but concentrated above the carriageway. In the current test program the loads are concentered in the region of the tramway lanes, above the structural elements which were not tested at the previous loading test program. A typical load case can be seen in Fig. 2 focusing on the combined loading of trams and trucks in the same time.

Fig. 2. Typical loading situation during the loading test using 12 trucks and 4 trams in one span.

3. The static load testing program and its results

The static loading test has two aims, and therefore it contains two significantly different parts. The first aim is the static check of the load carrying capacity of the structural elements under the tramway lanes and to analyze their structural behavior under the concentrated loading of the trams (local, transversal measurements). During these load cases the cross girders, the diaphragms, the middle web plates and all the structural elements (longitudinal stiffeners), which are loaded directly by the trams are tested. A total number of 15 different load cases have performed and measured to check local structural behavior of the bridge deck system. One tram and one truck moved parallel on the bridge and stopped in 15 different locations. At each loading step the deformations of the cross girders and the stresses in the bridge deck were measured. The second aim of the loading test is the analysis of the global structural behaviour and to check the load carrying capacity of the main girder under the mixed loading of trams and trucks (global, longitudinal measurements). During the global loading situations 20 trucks were applied on the carriageway and 4 trams in the tramway line. All the 6 spans have been loaded at least one time in the test program. For each span the vehicles were placed to represent the extreme values of the positive and negative bending moment and to simulate the maximum reaction forces for the piers and abutments. In all the global loading situations the deformed shape of the bridge was measured and the stresses were also determined in 109 points of the box girder investigating the structural behaviour of the main girder and the deck system. The schematic layout of several load cases (global loadings) are presented in Fig. 3.

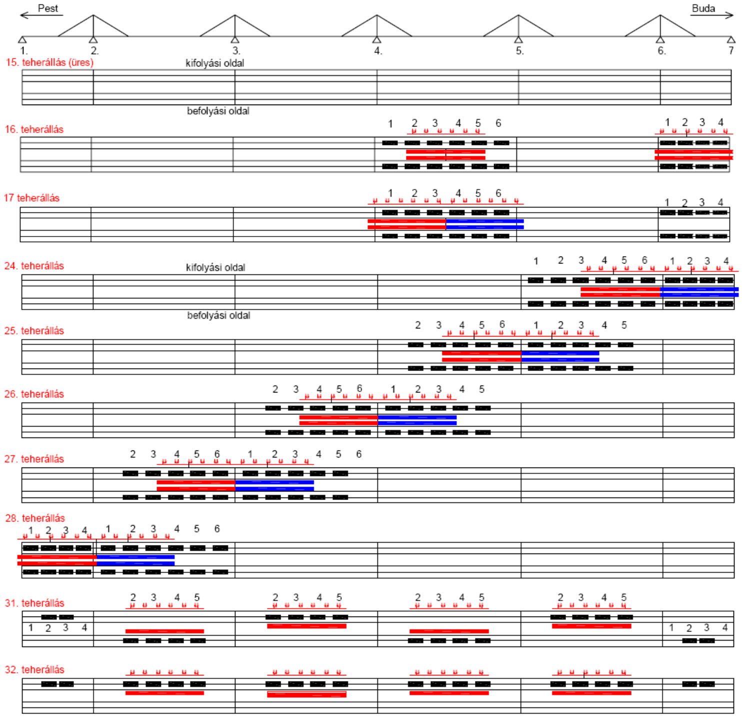

Fig. 3. Cross section of the bridge.

To be able to compare the measured results to the calculated values a detailed finite element model was developed. All the structural elements contained on the shop-drawings are implemented in the numerical model (all the stiffeners, ribs, diaphragms) using shell elements. On the detailed and realistic FE model the deformations and stress distributions under the applied loads were determined and studied. Based on the measured deflections it was concluded that the measured tendencies gives good agreement to the calculated results. The measured deflections in all load cases were smaller than the calculated values, its ratio varied between 70-88%. The maximum deflection of the cross girders is 9,2 mm and the maximum deflection of the side spans is 19,4 mm, while the maximum value for the internal spans is 78 mm. The maximum residual deformation of the superstructure did not exceed 10% of the measured maximum deflection, which fulfills the requirements of the relevant Hungarian standards [1] and [2]. It has to be mentioned that this loading test was not the first loading of the structure, therefore no large residual deformations were expected before the measurements. During the load testing an intensive temperature increase could be observed, which caused significant additional deformation in the bridge structure. The main part of the measured residual deformations were caused by this temperature increasing effect, thus the residual deformations were developed continuously during the load testing, what is the typical effect of temperature increase. A typical deflection shape can be seen in Fig. 4.

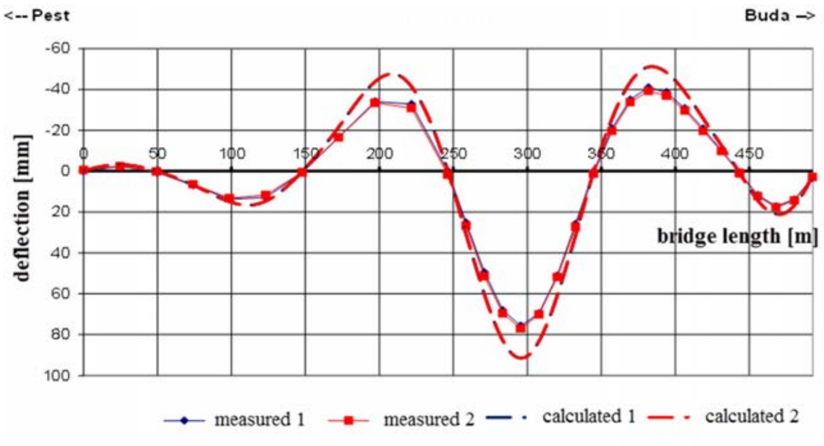

Fig. 4. Typical measured deflection shape.

Strain gauge measurements were also executed in all load cases. The aims of the strain gauge measurements were the analysis of the structural behaviour of the main girder, the cross girders and the longitudinal stiffeners under the tramway lanes. The main part of the strain gages were placed therefore in the region of the tramway, however several strain gauges were also placed on the extreme fibers of the main girder to check the global structural behaviour of the bridge. The strategy of the strain gauge measurements and the general layout of the strain gauge locations are shown in Fig. 5. The total number of 109 strain gauges were placed on the structure and the strains were measured during the static and dynamic loadings as well.

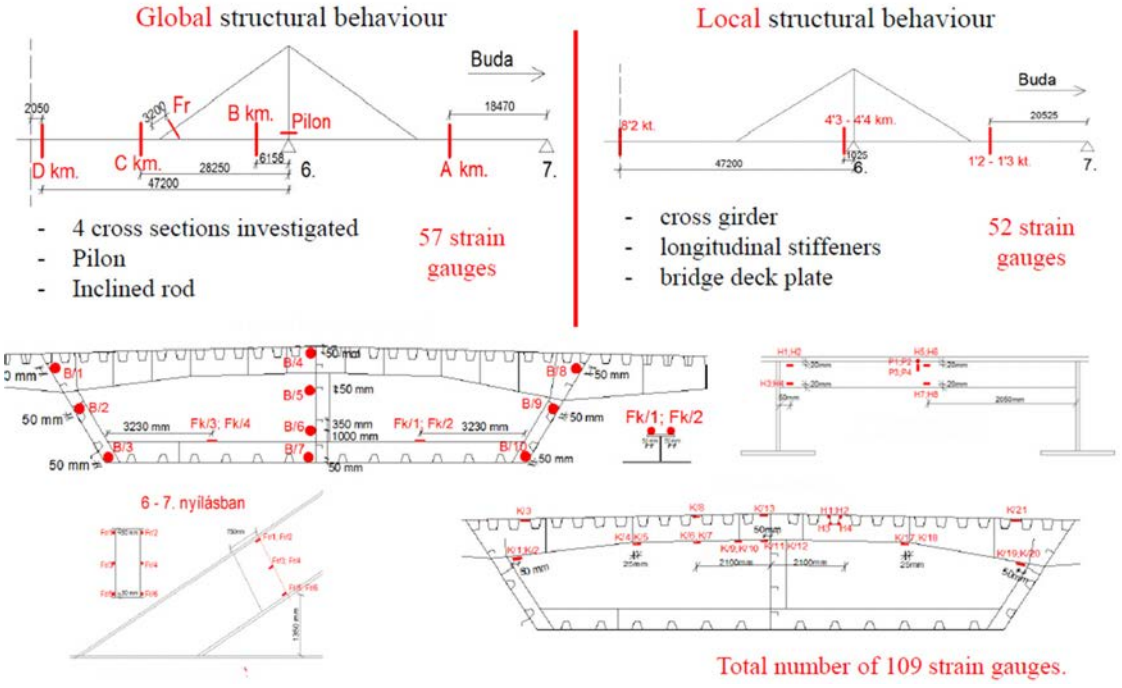

Fig. 5. Layout of the strain gauge measurements.

To be able to evaluate the results of the measurements and to check the structural behavior of the superstructure the measured stresses are compared to calculated values. The developed numerical model is a full shell model, with that the comparison of the measured and calculated stresses could be made with large accuracy. Two typical stress distribution diagrams are presented in Fig. 6 for the mid-span and for the internal support region. The diagrams compare the measured and calculated stresses during the test load. The two diagrams in Fig. 6 proves, that a good agreement was found between the measured and calculated values in the main girder and as well as in the cross girders and in the bridge deck system.

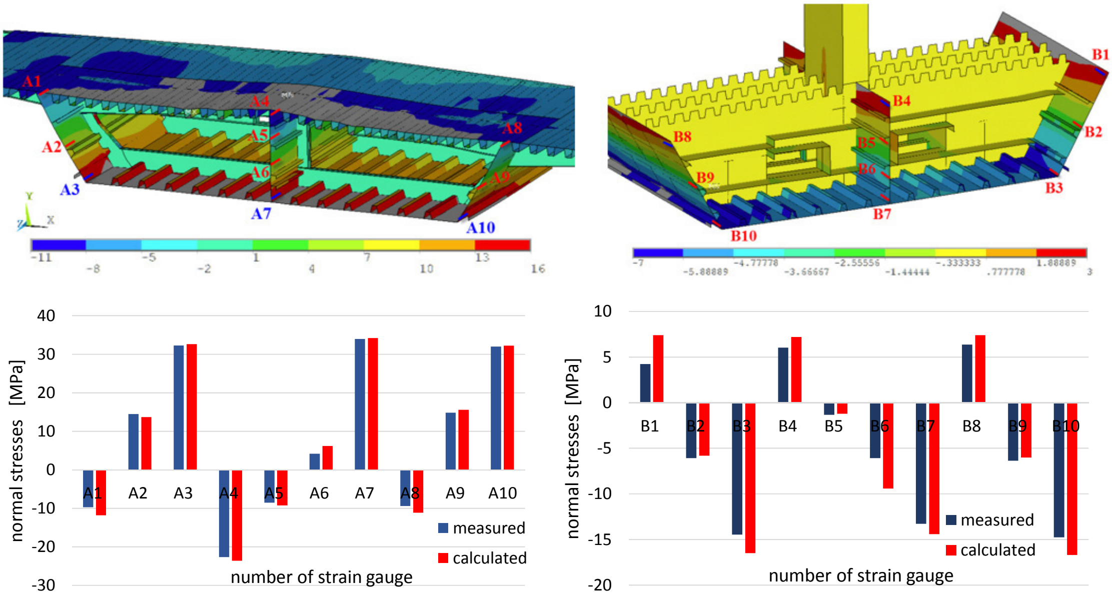

Fig. 6. Typical stress distribution diagrams and comparison of measured and calculated stresses.

The measurements proved that the bridge structure behaves as it is supposed in the static calculations and it proves the applicability of the developed FE model and the designed behaviour of the bridge. The measured stresses on the box girder proved that the global static behavior of the bridge under the trams is similar as assumed in the static calculations, the real stress values are very closed to the computed values. However the measured stress extreme values also proved, that the bridge deck system is adequate to the static, stability and fatigue verifications as well under the planed tramway line.

4. Dynamic loading test program and its results

The eigenfrequencies of the structure are measured without traffic load using electric accelerometers. The measurements showed, that the first vertical bending eigenfrequency is 1.22 Hz (calculated 1,07 Hz), the first torsional eigenfrequency is equal to 3,61 Hz (calculated 3,04 Hz). It can be observed, that the measured eigenfrequencies are close to the calculated values, but always larger that the numerically computed ones. The reason of that can be, that the public works placed on the bridge has a significant weight, what is comparable to the traffic load. The numerical model contained the design value of all the public works, but a larger part of this weight was not present on the structure at the time of the load testing. This difference in the loading situation (permanent loads) can cause the small difference in the measured and computed eigenfrequencies.

The aim of the dynamic load testing is to check and study the dynamic behavior of the structure under the dynamic loading of the trams and trucks separately. The focus of the dynamic loading test is the determination of the dynamic factors for all the investigated structural members. Therefore strain measurements were executed at all the 109 strain gauges and using the differences between the slow and fast loading situations the dynamic factors were determined.

The dynamic test program contained many load cases using 4 trucks and 1 or 2 trams separately. All load cases were applied with different velocities between 5 – 60 km/h, as presented in Table 1. The program has three independent parts. In the first part 4 trucks were moved parallel on the bridge in 5 runs with different velocities (5-20-40 and 50 km/h). The braking and acceleration of the trucks are investigated during the test. In the second and third part 1 or 2 trams were moved on the bridge with different velocities between 5 - 60 km/h and the braking and acceleration of the trams were also tested. The strains during the dynamic loadings were continuously measured on the 109 strain gauges with 50 Hz frequency (which is significantly larger than the eigenfrequency of the structure). A typical measurement result under the dynamic loading can be seen in Fig. 7. The typical vibration in the measured stresses can be clearly seen on the diagram, what is the bases of the dynamic factor determination.

Table 1. Program of the dynamic loading test.

4 trucks running parallel		
1. run	5 km/h	from Buda side
2. run	20 km/h	from Pest side
3. run	40 km/h	from Buda side
4. run	50 km/h	from Pest side
5. run	40 km/h + bracking	from Buda side
1 Combino tram		
1. run	5 km/h	from Buda side
2. run	20 km/h	from Pest side
3. run	40 km/h	from Buda side
4. run	60 km/h	from Pest side
2 Combino trams running parallel		
1. run	5 km/h	from Buda side
2. run	40 km/h	from Pest side
3. run	40 km/h + bracking	from Buda side

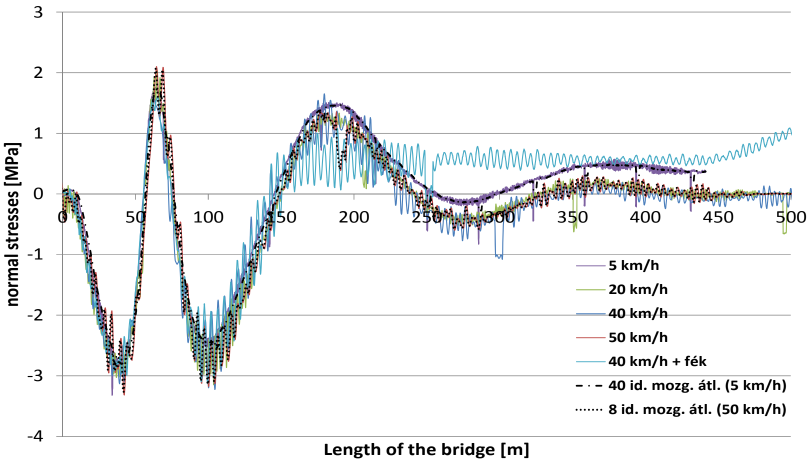

Fig. 7. Typical result of the dynamic loading test.

The largest dynamic factor of the main girder is measured under the loading by the 4 trucks with the velocity of 50 km/h and its value is 1.10. The largest dynamic factor caused by the Combino trams is significantly smaller (1.05). The maximum dynamic factor measured on the cross girders is 1,15 caused by the trucks and 1,06 caused by the trams. The largest dynamic effect is observed on the pilon and in the internal support region. The maximum measured dynamic factor is 1.24 due to the trucks and 1.08 due to the trams. The measurements proved that the trucks give the ultimate loading condition for the dynamic factors, which means that by opening the new tramway line increase in the dynamic effects are not expected on the bridge. Based on the measured results the final conclusion could be drawn, that the trams caused at all the measured locations in all the tested runs significantly smaller dynamic effects than the trucks, what can be explained by the better dynamic properties of the new trams, than the trucks used in the testing. On the other hand based on the measurements the bridge satisfies the criteria of the Hungarian standard -ÚT 07.01.12:2011 [3].

Measurements are also executed at the bearing system of the bridge. The horizontal movement of the bridge superstructure on the bridge abutment was measured. In order to increase the accuracy and confidence of measurements, three independent measurement techniques are applied. The first technique is based upon a total station with automatic target recognition (ATR) function. The instrument is able to automatically track and measure the prism with 10 Hz frequency, the actual frequency of measurements was about 6-7 Hz. The prism was fastened on the bridge superstructure and the total station was set up on the abutment. The distance between the total station and the prism was about 1.9 m, therefore 1 mm displacement corresponded to 109 second rotation. According to the specification of the instrument the accuracy of angle measurement and automatic target recognition together is about ±1.4 second. It means, that the accuracy of the displacement measurements is about ±0.01 mm. The arrangement of instruments are shown in Fig. 8.

Fig. 8. Layout of the measuring station: a) theodolite and digital camera, b) laser interferometer.

The second measurement technique is a classical alignment measurement. A piece of a steel tape is placed on the bridge structure along the expected direction of displacement. A digital microscope camera was attached to the telescope of the theodolite, and the view of the telescope was recorded in a digital video film. The video was split into digital images, the frame frequency was 15 fps. As the bridge moved, the image of steel tape moved as well compared to the crosshairs in the diaphragm of the theodolite. Based on the movement of the digital pictures the displacements could be evaluated automatically by digital image processing techniques. For the evaluation process a template matching algorithm of the software OpenCV [4] was used. The accuracy of this measurement method is less than ±0.01 mm. The third technique is to measure the distance variation of two points by laser interferometer. The reference mirror was recorded during the moving of the bridge. The accuracy of our laser interferometer (Renishaw XL-80) is at least ±0.001 mm, the frequency of measurements was set to 10 Hz. Our conclusion was that all the three methods could be used effectively, and resulted the same displacement with relative large accuracy.

References

[1] e-UT 08.01.25: „Közúti hidak nyilvántartása és műszaki felügyelete. Kiegészítő adatok és vizsgálati szempontok” (hungarian design standard).
[2] e-UT 08.01.61: „Hídvizsgálat I., Megépült közúti hidak teherbírás-vizsgálata” (hungarian design standard).
[3] e-ÚT 07.01.12:2011: Erőtani számítás, Közúti hidak tervezése (KHT) 2 (hungarian design standard).
[4] Howse, J.: OpenCV Computer Vision with Python. Packt Publishing, 2013. pp122.