Design of Zemplen 723

The New World Record Pedestrian Catenary Bridge in Sátoraljaújhely

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Abstract Long-span pedestrian bridges have become more and more popular around the world in the last decade. The municipality of Sátoraljaújhely in the North-Eastern region of Hungary wanted to join this international trend as they decided to build a bridge with a world record-breaking span as a new tourist attraction of Zemplen Adventure Park almost ten years ago.

Their long-awaited dream became true in June 2024 when Zemplen 723 was opened to the public. The new pedestrian catenary bridge has 700.0m span, the longest of its kind in the world at the moment. The length of the superstructure is 700.5m, while the total length of the bridge (including the abutments with glass balconies) is 723.7m and it connects two hills of the Zemplen Mountains. Hence the name Zemplen 723. It is a catenary bridge, meaning that compared to classic suspension bridges it has no pylons and hangers so the elevation of the pedestrian deck follows the parabolic profile of the main steel cables, similarly to the ancient Inca rope bridges. The two-directional walkway is 1.2m wide and it is 84m over the valley at midspan. The bridge is stiffened by a wind cable system and the overall static equilibrium is ensured by rock anchors.

The article aims to present the challenging design tasks of Zemplen 723. The general arrangement and some structural details will be introduced together with the static and dynamic behavior of the bridge. Besides, it gives an overview of the extraordinary construction procedure of the superstructure, which required the installation of 149 tons (6490m) of steel cable.

keywords : catenary bridge, pedestrian bridge, world record, steel cable

1 Introduction

1.1 Project

Tourism is a strategic sector for the municipality of Sátoraljaújhely. Many of their recent developments aim to attract more visitors to the town and to the North-Eastern region of Hungary. Zemplen Adventure Park is one of their most featured sources of income. It is located in the beautiful surroundings of the Zemplen Mountains and it offers several attractions for those who are seeking for active recreation (ski slopes, bobsleigh track, cable car, zipline etc.).
Joining the internation trend for building long-span pedestrian bridges, the municipality had decided to connect two hills, Szárhegy and Várhegy with an appr. 700m long structure that could link the ruins of the medieval castle of Sátoraljaújhely on Várhegy with the facilities of the Adventure Park on Szárhegy (see Figure 1). They had dreamt of a world record bridge that could become a flagship attraction both for the town and the region.

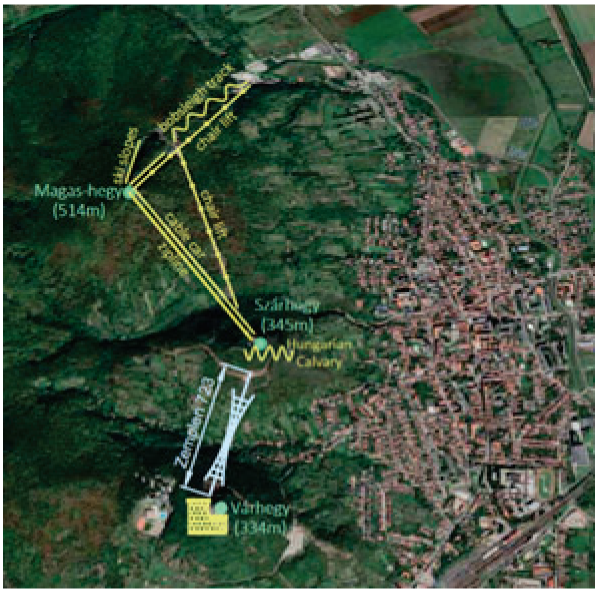

Figure 1: Location of the bridge on Google Maps

The project was launched in 2015 with a feasibility study prepared by a Hungarian designer firm, Pont-TERV Co. The location and the span of the future bridge had been defined and it was also determined that only a suspension bridge would be suitable for such a function and length. Almost 10 years have passed since then until the recent opening of the bridge in June 2024. The permit design and tender documentation were carried out in 2017-2018 followed by a rather long public procurement process. The contractor was chosen in 2021, who had 30 months to deliver the detailed design and build the bridge.

1.2 Main participants

The main participants of the project were the following:

- client: Municipality of Sátoraljaújhely

- contractor: Graboplan-Industrie Ltd.
- bridge designer: MSc Engineers and Consultants Ltd.

The main designer of the bridge was MSc Ltd. starting from the first conceptions of the design for approval phase until the detailed design. We were also responsible for the construction technology design and we had to deliver as-built drawings as well. The design was assisted by our following partners:

- Unitef Mérnök Co. (infrastructure, architecture and environment of the abutments, 3D visualization, obtaining building permits – design for approval and tender documentation phases)
- Dynamik Consulting Ltd. (dynamic analysis – design for approval phase)
- Geoexpert Ltd. (geotechnical design – design for approval and detailed design phases)
- BME Dept. of Engineering Geology and Geotechnics (geological measurements – design for approval phase)
- BME Dept. of Fluid Mechanics (wind tunnel tests – detailed design phase)
- Fluid-Lab Ltd. (CFD simmulations – detailed design phase)
- BME Dept. of Structural Engineering (independent calculations – design for approval phase; dynamic analysis – detailed design phase, static and dynamic load test)

2 Introduction of the structure

2.1 Requirements and conceptual design

Generally speaking, suspension bridges are those of which main load bearing elements are the suspension cables. Technically two subcategories may be distinguished between pedestrian suspension bridges: the classic suspension bridges and the catenary bridges (see Figure 2). In the former case the main cables are supported by pylons and the elevation of the pedestrian deck is determined by the length of the hangers which are connecting the main cables and the deck elements. Compared to classic suspension bridges, the catenary bridges have no pylons and hangers so the elevation of the pedestrian deck follows the parabolic profile of the main cables, similarly to the ancient Inca rope bridges. Long span (>350m) pedestrian bridges only exist with one of these two structural schemes (see Figure 3).

700m long span and a two-directional walkway with 1.2m width were prescribed by the Client. Enhancing the extreme experience for the visitors, photo points with widened walking platforms had to be designed in four sections, together with a bypassable glass floor in the middle of the bridge. Considering landscape architectural reasons, any tall structures (eg. pylons) rising above the silhouette of the hillsides were to be avoided. A structure providing clear view above the handrails was favorable both by the Client and the designer team due to its pleasant spatial experience

Figure 2: Classic suspension bridge (Charles Kuonen) versus a catenary bridge (Trift)

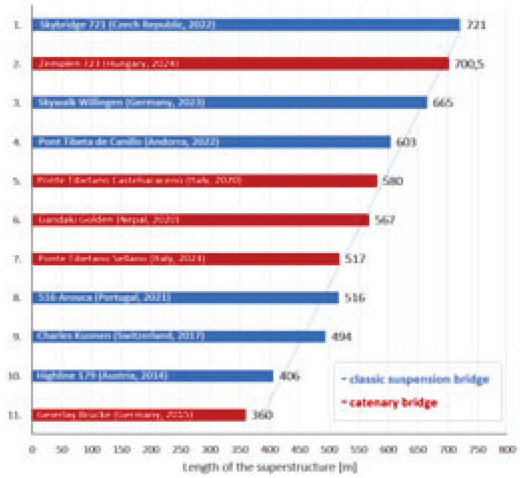

Figure 3: Comparison of existing long span pedestrian bridges

therefore a catenary bridge was chosen for elaboration, despite the fact that a more moderate elevation would have been possible with a classic suspension bridge.

2.2 General data

Its 700.0 m span is currently the longest among pedestrian bridges in the world. The length of the superstructure is 700.5, which also makes it the longest catenary bridge. Considering the size of the abutments with glass balconies the total length of the bridge is 723.7m, hence the name Zemplen 723. General informations about the bridge (see Figure 4):

- span: 700.0m
- length of the superstructure: 700.5m
- total bridge length (including the abutments): 723.7m
- width of walkway: 1.2m
- sag under dead load at midspan: 27.0m

- max height over the valley: 84,0m
- starting slope: $\sim$ 15%
- max. number of visitors: 300
- total amount of steel cables: 6490m (149 tons)

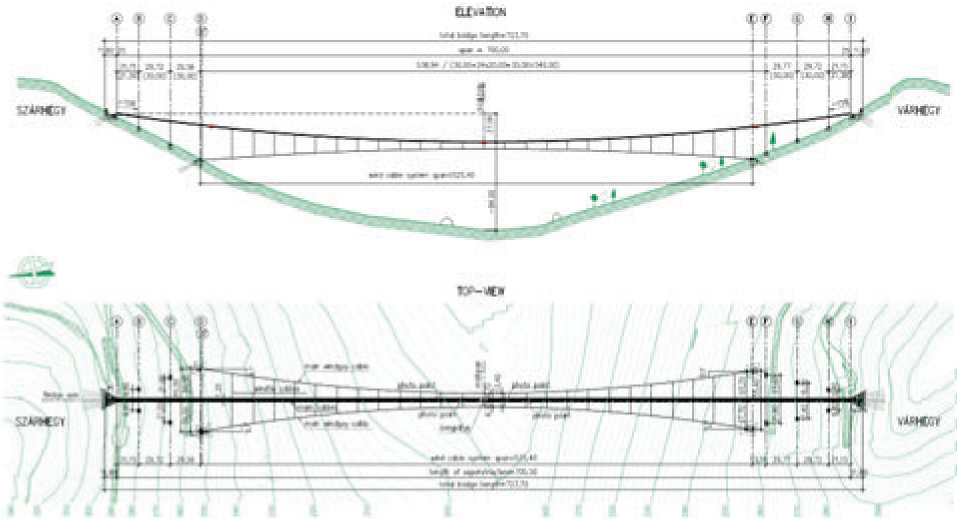

Figure 4: General arrangement of Zemplen 723

Figure 5: Global view of the almost ready bridge

2.3 Superstructure

The main load bearing elements are six steel cables running in a parabolic profile and defining the elevation. The bridge is stiffened by a wind cable system consists of two primary windguy cables and a series of secondary windtie cables (see Figure 6). The two main windguy cables have a reverse parabolic shape tilting towards the bridge axis. There are 6x2 additional fixed anchor cables at the starting sections of the structure. The main cables and the two windguys are FLC with a diameter of 70mm, while rest are OSS cables with a diameter of 18mm or 26mm. All the structural cables were delivered by Teufelberger-Redaelli. The secondary windties were applied in a unique sequence: apart from the ordinary connections every second pair was cross-tied below the cross-frames (see Figure 7). Thanks to this peculiar alignment a significant increase in the tortional stiffness was gained.

The deck builds up in a hierarchical manner. The pedestrian walkway is provided by 2m long gratings welded to longitudinal girders. These individual deck segments are supported by cross-frames in every 2 meters, which are sitting on the six main cables (see Figure 8).

This general cross-section varies at the four photo points where people can leave the general plane of the safety net and may stand on an additional platform above the structural cables (see Figure 9), thus resting and looking around without obstructing others. Another special feature of the bridge is the 8m long glass floor at the midsection that could increase the level of adrenaline in the visitors of the adventure park.

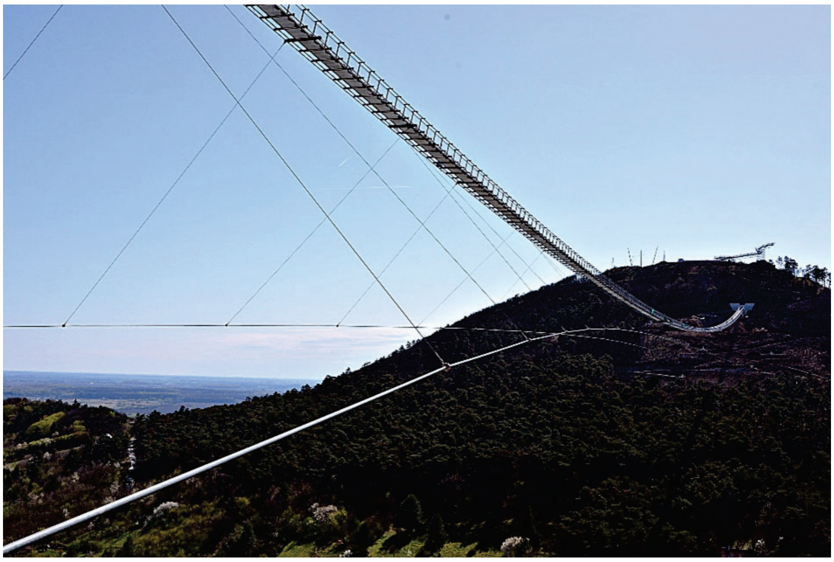

Figure 6: Wind cable system

2.4 Substructures

The large tensile forces of the main cables (FEd 6x3000kN) are carried by steel structures being integrated into the reinforced concrete abutments. The overall static equilibrium is ensured by 21x23m long strand anchors embedded into dacite rock. They are positioned in a fan-like arrangement both in the vertical and horizontal directions. Apart from their structural function

Figure 7: Sequence of normal and cross ties

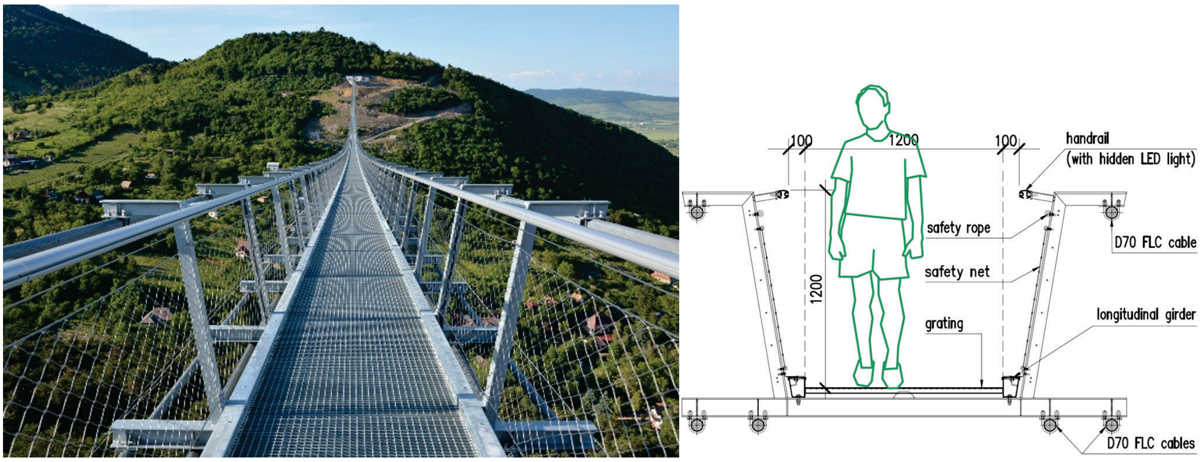

Figure 8: Photo and drawing of the general cross section

the abutments also serve as the gates of the bridge therefore their architectural shaping by Unitef Mérnök Co. was of high importance. The massive, multi-storey structures are designed to fit in the hillsides as wedges (see Figure 9). The anchorage chambers can be entered from the bottom floor, while the bridge deck can be approached from the middle floor, together with a service room. The top floor with a glass balcony serves as a lookout point, in order to get a proper top-view of the entire bridge (see Figure 10).
The main wind cables have large reinforced concrete substructures each being secured by 4x23m rock anchors. The 6x2 individual tie cables at the starting sections of the bridge are connected to heavy block-like substructures, but rock anchors were not required in those cases.

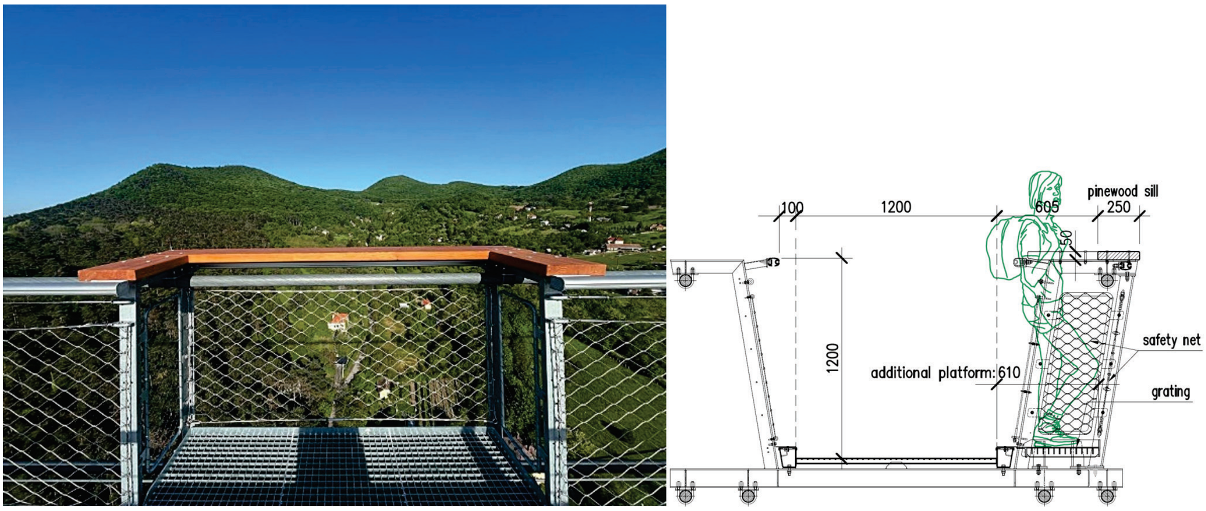

Figure 9: Photo and drawing of the cross-section at the photo points

Figure 10: Photo of the almost ready abutment on Várhegy (by Attila Gulyas)

2.5 Additional systems

Fulfilling the request of the Client, the bridge is equipped with several additional elements and systems. It can be illuminated by LED lights hidden inside the handrails (see Figure 11) and medium intensity obstacle lights were installed in three sections in order to follow aviation regulations. The behavior of visitors is observed by security cameras, and intercom units are placed for making emergency calls to the operator room. The weather conditions (the wind speed in particular) should be monitored in real time for the sake of safe operation so meteorological stations were set up at the abutments and at the middle of the bridge.

Figure 11: Top view of the illuminated bridge (by Attila Gulyas)

3 Structural analysis

3.1 Static behavior

Catenary bridges show a geometrically nonlinear behavior, meaning that apart from the applied materials and element sections their overall stiffness largely depends on their geometry as well. The cable tensile force (which mainly determines the stiffness) and the sag are inversely proportional. The design was largely driven by the nonlinear FE analysis which was carried out with a global 3D beam model taking both the geometrical nonlinearity and the construction sequence into account. The final geometry and force state of the structure were the results of a time consuming parametric iterative procedure. Apart from satisfying the strength demands of the Eurocode standards, the bridge needs to have sufficient lateral and tortional stiffness. On the other hand, keeping the comfort of the visitors in mind the starting slope needed to stay moderate which set a certain limit to the sag and thus the cable forces. Despite being a pedestrian bridge, the global governing action is not the pedestrian load thanks to the visitor limit (300 visitors and 10 staff members) but the potential icing combined with wind load. Compared to "regular" bridges the calculated displacements are rather large at the midspan. A maximum of ±4,5m lateral sway and +0,5m/-2,6m vertical displacements are expected due to extreme meteorological conditions and live loads.

3.2 Dynamic behavior

In spite of the favorable influence of the wind cable system, this type of structures has significantly lower tortional stiffness than bridges with massive continuous longitudinal girders. This has a huge impact on the dynamic behavior and they are more prone to tortional vibrations.
The bridge is sensitive to intentional tortional excitations by pedestrians but the vibrational displacements are limited by the supporting effect of the wind cable system. On the other hand, due to its function as the element of an adventure park the usual comfort criteria for pedestrian vibrations

are not necessarily relevant here and the excitement factor is rather expected.
The initial aerodynamic assessment showed that the structure may be susceptible to flutter in case of total icing of the deck grating. The aeroelastic phenomenon may be induced by the pressure difference above and below the solid plane of the iced deck (see Figure 12) and by the synchronization of the vertical and tortional vibration modes (see Figure 13). A thorough CFD and wind tunnel analysis verified that the unstable condition can actually occur after reaching a certain critical wind speed. But the classic method of wind tunnel analysis doesn't take the nonlinear behavior of the structure into account, neither vertically nor in torsion, which were experienced during the static analysis. Therefore a unique FEM process was developed by the experts of BME in order to analyze the post-critical flutter behavior. The results showed that after the start of the dynamically unstable condition, the displacement and force amplitudes come to a steady state within a certain amount of time and the increments remain under structurally safe boundaries thanks to the damping effect of the wind cable system.
Despite all this the bridge should be closed under unfavorable weather conditions (>10m/s wind speed, snowing, icing) for safety reasons and the stuff members needs to remove snow and ice from the deck in winter as fast as possible.

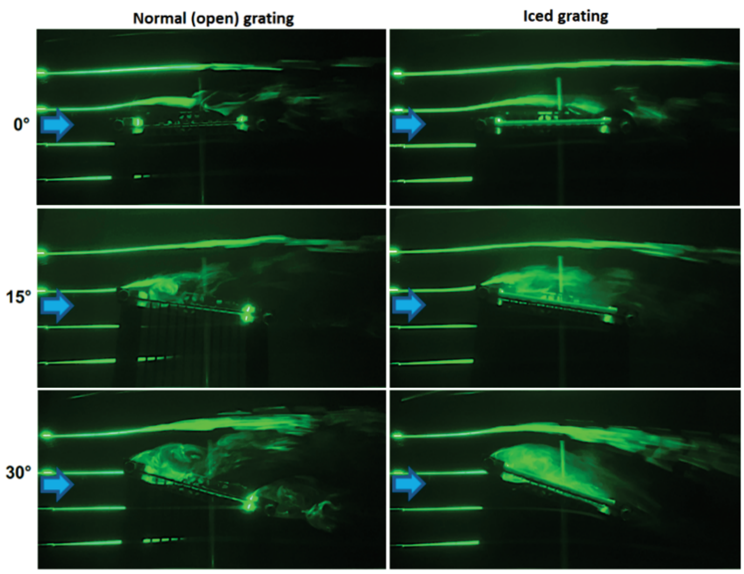

Figure 12: Windflow around the bridge deck in case of open and iced grating [1]

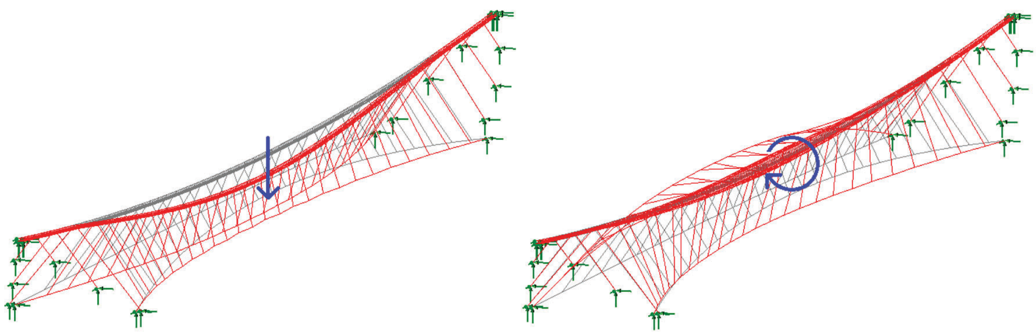

Figure 13: First vertical and tortional eigenmodes

4 Construction of the superstructure

The construction of the superstructure was a unique procedure without any precedent in Hungary. MSc Ltd. was responsible for the conceptional design of the construction technology and the detailed planning of the different stages together with the design of necessary temporary structures. The main phases were always preceded by thorough preparations and calculations together with the engineering team of the contractor.
The erection of the six main cables required two temporary supporting cables and a 10ton tow cable. Each main cable was towed individually from the launching abutment to the other side by being laid onto a “pulling track” which was formed by the two temporary cables and roller wheel supports at every $\sim$30m (see Figure 14). The necessary towing force could be sufficiently decreased and controlled with this method so the target abutment could be approached by $\sim$20m. The final operations of connecting the cable forks were carried out by strand jacks with the maximum pulling force of $\sim$800kN.
Before the installation of the deck, the main wind cables were first moved to their approximate designated longitudinal position by being hanged on the inner bottom main cables. Due to their self-weight those inner bottom cables significantly deflected, therefore the cross-frames and walkway segments could be installed on the remaining four main cables proceeding symmetrically from both abutments to the middle (see Figure 15). The 100-150kg elements were moved into position by gantry cranes rolling on the top cables.
One of the most spectacular phases was the erection of the wind cable system. The secondary windtie cables had to be connected to the main wind cables and to the cross-frames of the deck. Then they were systematically lowered down (see Figure 16) and as the weight of the wind cables was taken over by the top and outer bottom main cables the inner bottom cables rose until they became align with the deck. Once the entire system was hanging below the bridge, the four endpoints of the main wind cables were pulled and connected to their substructures with the help of construction machines and hydraulic jacks, reaching the maximum of 1200kN cable force. Finally, the 6x2 individual windtie cables had to be connected to their reinforced concrete blocks with manual lever chain hoists (see Figure 17).
Each phase was monitored by height measurements and verified by the calculations to make sure that the global geometry developed as planned. Taking the daily temperature changes of the structure into account and the consideration of cable creep were especially challenging. The construction of the superstructure took appr. 10 months including the winter period of 2023-2024. The technology worked fine and according to the previous expectations so the bridge could be constructed with high geometrical precision.

5 Epilogue

After the successful static and dynamic load test procedure carried out by the BME Dept. of Structural Engineering the bridge was opened to the public in June 2024. To the greatest delight of the municipality the bridge is very popular and it has already made a very positive impact on the number of visitors of the entire adventure park.

Figure 14: Towing of the main cables

Figure 15: Installation of the deck elements

Figure 16: Lowering the wind cable system

This was one of the most challenging projects in the history of our bridge designer firm thanks to the numerous engineering problems that we had to face starting from the geometrical optimization, through the analysis of dynamic behavior, until the installation of the superstructure, all without any earlier knowledge. Although similar structures have ancient roots, the modern versions of long span pedestrian bridges have started to develop only in the last decades meaning that compared

Figure 17: Connecting the individually fixed windties at the starting sections of the bridge

to other bridge types a relatively small number of examples and almost no relevant international literature is available. Thus we would like to congratulate to the designers and creators of such structures worldwide who most certainly had to go through the same challenges relying many times only on their engineering intuitions. We consider ourselves lucky that we could be part of this grandiose project which will hopefully contribute to the prosperity of Sátoraljaújhely and its region.

6 References

[1] BME Dept. of Fluid Mechanics – Aerodinamikai szakértői jelentés 2. (Szélcsatorna-vizsgálat) – KIV-H-I-06 (2022)