Monitoring of Elastic Deformations of the Hydraulic Structure Gabčíkovo

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Abstract. The settlement and its calculations and monitoring are among the main factors influencing the structure and operability of hydraulic structures. Our paper focuses on the hydraulic structure Gabčíkovo which consists of the hydropower plant with an installed capacity of 720 MW and two navigation locks to ensure international ship transportation. Conventional geodetic methods of classical or very precise leveling with state-of-the-art measuring instruments are currently used to monitor deformations on navigation locks of hydraulic structure Gabčíkovo. In their subsoil, there are gravelly sediments to a depth of about 400 m. Under the gravel sediments, there are Neogene clays and silts. From the beginning of construction, deformations are measured on all structures using special tachymetric devices to monitor the elastic displacements. The obtained measured values are then processed in time dependences and compared with the limit values. During the current almost 30-year operation of the navigation locks, filling and emptying cycles, loading and unloading of the subsoil can be counted in the tens of thousands. The impact of the long-term operation, but especially the current innovation and modernization of navigation locks, aimed at increasing the safety and intensity of transport brings new knowledge and experiences. During the implementation of required improvement related to this project, the right navigation lock is empty for more than a year. The created technical conditions made it possible to monitor the influence of long-term unloading on the subsoil on the vertical displacements in detail. This unusual load condition is a motivation to present the results of measurements in the presented paper.

1. Introduction
At the beginning of the fifties of the 20th century, specialists began to discuss the Danube River's utilization between Bratislava and Budapest. A contract was signed between Czechoslovakia and Hungary in 1977 about the construction and the operation of the system Gabčíkovo-Nagymaros. The construction of the hydraulic structure began in 1978, but in 1990, the Hungarian government suspended all the construction works in their territory. Consequently, in 1991, the Slovak government authorized finishing the Gabčíkovo hydraulic structure project, building only the objects situated in the Slovak territory. The construction works culminated in October 1992 when the Danube River was dammed up in the 1851.750 km in the Čunovo profile. The most important objects that create the Gabčíkovo hydraulic structure are the Hrúšov Weir with Čunovo step objects, the inflow channel, the Gabčíkovo step, and the outflow channel. The weir was created by damming up the Danube channel...
with a system of Čunovo step objects and a dividing dyke of the weir that reduces backwater exclusively in the territory of Slovakia. The submerged area covers a surface of 2 578 ha. The operation level fluctuates between 130.10 m a.s.l. and 131.10 m n. m. The reservoir volume is 110.8 million m$^3$ at the maximum level and 195.6 million m$^3$ if the inflow channel volume is included. The Čunovo step objects include the withdrawal object of the Mosoni Danube, the inundated weir, the hydro powerplant, the central weir, the navigation locks, the water sports area, the dyke of the Danube channel, and the bypass weir. The inlet channel and the Čunovo step concentrate the hydraulic head and regulate the flow to the Gabčíkovo step. The channel also serves as a navigation track and participates in the outlet of water in case of a flood discharge. It is situated beyond the ground level, it is 17 km long, and its width varies from 350 to 734 m. The Gabčíkovo step consists of a hydropower plant and navigation locks. Its characteristic feature is the impressive design of the foundation of these objects, considering the extremely complicated geological conditions as the incidence of gravels in the depth of more than 300 m. The sealed construction pits with dimensions of approximately 400 m x 200 m and a depth of 60 m belong to the largest dam construction objects in the world. The hydropower plant with eight turbines with a total capacity of 720 MW processes the hydro potential of the Danube, and the navigation locks represent an inseparable part of the international navigation. There are many other effects of the hydraulic structure that we cannot forget to mention. The Hrušov Weir, the tributary system of the Danube, and other water areas have created ideal conditions for water sports, recreation, and tourism. It has been proven that the hydraulic structure is an environment-friendly construction that has contributed to the improvement of water conditions, especially in the tributary system of the Danube and the preservation of the riparian forests. The waters of the Danube from the Gabčíkovo step flow back to the stream through the outflow channel. It is 8.2 km long and 185 m wide at the bottom. The channel feeds into the Danube near the village of Palkovičovo [1].

![Figure 1. Birds view of the Gabčíkovo step (napalete.sk)](napalete.sk)
2. Navigation locks

The navigation locks are located on the left side of the Gabčíkovo step. Their useful length is 275 m and width 34 m. The bottom of the locks is at 103.00 m a.s.l., and the crest of the walls is at 133.10 m a.s.l. The upstream segment gate can be lowered below a lock sill (level of 123.0 m a.s.l.), the downstream gate is supported by a bridge, and the lock sill (level of 103.00 m a.s.l.). In addition, there are temporary backup gates in front of the upstream segmental gates, with a height of 5.0 m, i.e., from elevation 123.0 to 128.0 m a.s.l. (figure 2).

![Figure 2. Schematic cross-section of navigation locks](image)

The lock filling system has a lock still at the level of 119.0 m a.s.l. with four inlets for each lock. The dimensions of the inlet openings are 4 x 4 m. The filling system consists of a system of channels in the foundation slab (97.0 m a.s.l.) and gaps in the bottom of the navigation locks. The locks are emptied using the same system, with control valves with a lock still (97.0 m a.s.l.) to the outlet object with two channels 8 x 8 m for each lock. These channels form one object and are mouth into the stilling basin of the hydropower plant on its left edge. The bridging of the locks is on the downstream lock head with a bridge (124.02 m a.s.l.), i.e., 8.2 m above maximum navigation water level. The safe entry and exit of vessels into and out of the locks shall ensure lock cuts. The upstream lock cut bottom is at the elevation of 117.50 m a.s.l. Its length is 410 m, and the width is 180 m. The downstream lock cut has a length of 285 m, a width of 180 m, and its elevation is at 103.0 m a.s.l. The height difference of levels (up to 23 m) between the inflow and outflow channel, the locks also serve as outlets in case of operation failure of the Gabčíkovo hydropower plant units. During floods, navigation locks bypass water by longitudinal culverts (2 x 610 m³.s⁻¹) or by upstream gates (2 x 1200 m³.s⁻¹) to transfer water through the Gabčíkovo step [2].

3. Analysis of the settlement development of the navigation locks

To analyze the time development of the settlement of navigation locks, we had available data files from the beginning of construction to the present. In dilatation joints, control geodetic points are installed on the surface of all walls of the lock chambers and in their vicinity (figure 3). Geodetic measurements are performed by very precise leveling by the Water Management Enterprise, i.e., a section of technical and safety supervision from the beginning of construction to the present. The geodetic control points were installed gradually during the construction and the current operation. Figure 3 depicts the location of the control geodetic points. We highlighted points in which measurement results are presented in the paper.
In the following sections, we present selected results of measurements of geodetic control points. The measurements started in 1986, but it is clear from the available data that the settlement of the locks cannot be correctly interpreted and compared with each other until damming the Danube River due to the different beginnings of the individual measurements. Therefore, the relevant period with comparable data about the settlement of locks is after the damming of the Danube, i.e., from 1992 until the present.

3.1. The highest displacement values
The highest values of the settlement were measured on the right wall of the right lock chamber (figure 3), i.e., the highest value at the last measurement was the settlement of the point KVB-114, 177 mm [3]. However, together with KVB-111 and KVB-112, these points had been installed and have been measured since 1986, so they show the highest settlement values, although there are minor differences between them. It should be noted that the increment is only 50 mm since the damming of the Danube. Other points on the right wall of the right chamber were installed later, so they have smaller values of settlement in the overall time course. Therefore, an important milestone was the damming of the Danube on October 30, 1992. At that time, almost all geodetic control points were already installed on the surface of the lock's walls. It can be stated that until the damming of the Danube and the commissioning of the locks, the settlement of the chambers was caused by loading, i.e., changes in the stress states in the foundation joint. After filling the inflow channel and the filling system by water, the load of the foundation joint also increased, and the process of consolidation of the subsoil began.

Since 1992, the significant values of displacements according to measured data are observed on the left wall of the right lock and the right wall of the left lock. The highest settlement values were observed in KVB-133, approximately 101 mm (figure 4), which is located in block 5-6 of the left wall of the right chamber, KVB-149 (97 mm) and KVB-148 (93 mm), located in block 4-5 of the left wall but the left lock chamber (figure 5) [3].

However, the time trend of the vertical displacement development signals a gradual decrease in settlement increments. While the average annual settlement increments in the initial period after the damming of the Danube (1992-1997) were about 5 mm per year, since 2005, the annual settlement increments are less than 1.5 mm per year, with an indication of consolidation. Since 2014, we can say that settlement has subsided, and all measurements oscillate depending on the current loading state and year season (figure 4 and figure 5).
Figure 4. The time development of the vertical displacement of the block 5 – 6

Figure 5. The time development of the vertical displacement of the block 4 – 5

3.2. The lowest displacement values
The lowest values of the settlement of control geodetic points, which have been observed since 1992, were found on the left lock chamber's left wall of KVB-170 and KVB-171 was approximately 55 mm. However, it is also possible to interpret the development of the settlement, which is shown in figure 6. According to the vertical displacement development, the settlement was stabilized after 2009. These geodetic control points are located on the left wall of the left lock, the lower lock's head [3].
3.3. Vertical displacement during innovation and modernization

In order to increase the safety and intensity of navigation on the Danube, the Gabčíkovo step is undergoing a comprehensive innovation and modernization of the technological equipment of the locks, the usable space of the locks, the sliding parts of the technological equipment, and related components of the structure. In addition, there will be a comprehensive innovation and modernization of the hydraulic system of the filling and emptying system of lock's chambers and the sealing of the subsoil and expansion joints (figure 7).

Figure 6. The time development of the vertical displacement of the block 4 – 5

Figure 7. The right navigation lock during the innovation and modernization
During the innovation, the lock chamber and its filling system had to be emptied entirely, thus reducing the load on the foundation joint. We compared the measurements before the reconstruction (22.11.2018) and during the innovation (10.11.2020) for a better idea. The measurements show that the entire right lock began to rise (figure 8), as did the right part of the left navigation lock. The highest lifts are observed on the left wall of the right navigation lock. On the right wall of the right lock, we observe approximately the same displacement values as on the right wall of the left lock. The minor differences in displacements are on the left wall of the left lock because the left lock was still in operation, i.e., the load on the left side of the lock's chamber still had a significant effect [4].

**Figure 8. Differences in vertical displacements before (22.11.2018) and after the start of innovation (10.11.2020)**

During the innovation, such significant displacements are no longer observed. Since 10.11.2020, most of the measurements have oscillated in a range around ± 0.5 mm. More considerable differences were observed only on the central wall in the right lock chamber, where the maximum differences during the innovation increased about 1.0 to 1.5 mm (figure 9).

**Figure 9. Comparison of the latest measurements (21.4.2021) with measurements before the innovation (10.11.2020)**
4. Results and discussions
By measuring and observing, we monitor the behavior of hydraulic structures in real-time. At the same time, we prevent failures and possible economic damage not only on the hydraulic structure itself but also in the downstream area. In addition to economic damage, technical safety supervision aims to prevent losses of human lives. The measured parameter within the monitoring must be verified with the assumptions in the project or the computational model.

The analysis of measurements at the locks in Gabčíkovo shows that the settlement values of KVB geodetic control points, which are built into the walls of the navigation locks since damming of the Danube (1992), show a range from 32 to 95 mm. The results show that larger settlement values with more than 70 mm, occur on expansion joints on the walls between the chambers, i.e., blocks L4, L5, and L6. In terms of predicting the settlement values of the right navigation lock, we note that after 2005 (or 2000), the average annual increments decreased significantly to values of about 1 to 1.5 mm per year, compared to 4 - 8 mm per year in the initial stage of putting the hydraulic structure into operation (1992 - 1997). The average settlement of the right chamber in 2013 reached the value of 130 mm (since 1986). Since 2013 the settlement is minimal rather, it is only a matter of elastic deformations depending on load state, the operation of the locks, and the season. We can find the proof in the measurements that have been carried out during the innovation since 2018. After emptying the right navigation lock and lightening the foundation joint, the upward movement of the lock chamber is apparent.

The beginning of the innovation of the left lock is planned for the summer of 2021. We assume that the left chamber will behave similarly, i.e., marked lifts will be observed in the left navigation lock, while the right lock should settle slightly after its filling. However, our assumptions will be confirmed or refuted only by further measurements of the Gabčíkovo navigation locks.

5. Conclusions
It is obvious that monitoring is an integral part of assessing the safety of a water structure. With the help of measurements, we can obtain valuable information that was not known when designing the hydraulic structure or acquiring new information, i.e., inverse modeling using the measured data. Also, using current computer technology and automated measurements, we are able to respond faster and more efficiently to changes that could endanger the operation and safety of the hydraulic structure. Based on available information and all measurements, it is planned to build a 3D finite element model of navigation locks in the future, predicting the behavior of navigation locks under different load conditions in the future. The lessons learned could later be used to solve similar tasks on hydraulic structures in Slovakia and abroad.

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