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# The Repairs of the Hydraulic Structures of Orlík and Slapy after more than 30 Years of Operation

## 1 Introduction

During 1995 and 1996, the joint stock company Povodí Vltavy, a.s., ("the Company") carried out repairs for the two most significant elements of the cascade on the river Vltava which are the hydraulic structures of Orlík ("HS Orlík") and Slapy ("HS Slapy"). Causes and characteristics of the defects were very similar in relation to both hydraulic structures. However, the realization of the repairs depending on possibilities of how to handle water passages during the construction process was quite different. In our article, we would like to inform you briefly about both repairs and compare the stages of the work.

## 2 The characteristics of HS Orlík

The HS Orlík is situated upstream on the river Vltava approximately 87 km, south of Prague, and creates a main part of the Vltava´s cascade. It is utilised to produce peak load electricity where its large accumulation capacity enables to use the water efficiently in the next river's leg. The heavy, straight, concrete dam was built during 1956-1966, whereas the operations started already in 1960. The length of the dam crest is 450 m and its height is up to 90 m in the deepest point of the river valley. Thus, a reservoir of 720 $m^3$ in capacity has arisen. Three 15 m wide spillway crests on the right side of the dam have 8 m high steel gate segments, which serve to transferring aggressive water. In lower blocks, two bottom intakes of 4 m in diameter are placed. A peak load water power station with four Kaplan turbines of absorption capacity of 4x150 $m^3/s$ is located on the left dam side. Water economic and energy facilities of the dam have their own stilling basins separated by a splitter.

## 3 Causes of dam ruptures

Probably due to time and financial pressures in setting the hydraulic structure into operation, the earthwork in the tail race of the plant was not completed, furthermore both stilling basins were shortened as opposed to the original proposal. Approximately, 150 m from a mouth of draught tubes on the left bank, an unexcavated rock remained close to the vertical wall in the river bed and reached up to more than one third of the transmissive profile of the river stream. This resulted in objectionable baffle of the water stream to the right behind the splitter between the stilling basins when the turbines were operating. The objectionable changes of flow were confirmed by the model research of both 1958 and 1991. Rebounding

the water stream from the plant to the right bank resulted in undermining an end sill of the water stilling basin, and ensuring hydraulic filling to a channel under a canal lift.

Employees of the Company were, of course, aware of these facts many years and measured regularly any changes in the dam. The outcomes were continually discussed with employees of the technical and security supervision department of the authorised organisation. In 1980, a fracture of a concrete slab behind a stilling basin was identified where a scour reached the depth of up to 4 m. Therefore a partial improvement was carried out during 1981-1983. A concrete seal was made and the scour was filled out with a heavy riprap and concrete pyramids.

## 4 Preparation of the repair

After the action in 1983, the crew of HS Orlík along with divers examined regularly the stilling basins and the channel every-two years. The scour kept on renewing step by step and the cave under the stilling basin slab expanded. In 1983, the divers produced a video record that acknowledged manual measurements and showed that the last improvement was not effective. Representatives of the Company consulted the issue with the employees of the technical and security supervision department and designers of the Hydroproject Praha company which was the chief designer organisation of the whole dam. Although the parties involved stated the security and the stability of the stilling basins, is not questioned, a decision was agreed upon to make a complex maintenance including the elimination of the cause, i.e. the rock ledge on the left bank.

A detailed examination was carried out in the course of two day shut down, of HS Orlík and drawdown of HS Kamýk in the spring of 1995. Except for the above mentioned parties, representatives of potential suppliers were invited to participate in the examination. Precise topographic and photogrametric measurements of the whole area were performed which provided the parties with the following:

1. A scour with the volume of 4,600 $m^3$ and depth of up to 4.5 m behind the stilling basins. The scour went below the concrete slab, a space of the cavern was estimated to be 100 $m^3$.
2. Stony sediments of 3 m high at maximum and ca 5,100 $m^3$ in volume reached up to 250 m behind the right section of the water stilling pool.
3. A flat scour of 1 m deep and 3,200 $m^3$ in volume existed behind the power stilling pool.
4. A mild slope of 279 m above the sea level (i.e. a sill of the stilling basin) behind the water tailrace on the left embankment risen to 281.50 m above the sea level where a steep rock goes up to 285.00 m above the sea level.
5. Further failures such as fractured pavements, walls, etc.

Identified defects corresponded with situations of speed fields taken during the model research. It was recommended that improvements be made in the shortest time possible.

## 5 The repair

Project documents of the repair of the dam were worked out by Hydroproject Praha, a.s. Six specialised construction companies were offered to take part in the tender concerning the realization. A construction division 05 of the joint stock company Vodní stavby, a.s., became a winner.

Key tasks of the project were as follows:

- Improvements of river-bed scours would be made through heavy stony armouring of sorted aggregates mixed up with concrete; surface layer of 1 m in depth would be made of stones in concrete.
- The cave under the slab of the stilling pool would be saved through concrete pumping in; holes of 150 mm in diameter drilled from the slab surface would serve to caulk the cave by concrete.
- The rock ledge on the left bank would be excavated; so as not to threaten the stability of the left bank wall. The resulting transversal profile would not match the ideal proposal of the original project. Blasting work had to be avoided within the rock excavation in order not to break the grout curtain below the dam body.
- Sediments near the right bank would be excavated, placed or spread in the river bed.
- Furthermore, the pavements on the right embankment would be reconstructed and other improvements of those sites carried out which would be usually under water surface.

The repair has been achieved along with several adjustments in accordance with the project. The main features of the work done are as follows:

- concrete 1,305 $m^3$,
- rock excavations (class no. 5 and 6) 2,667 $m^3$,
- sediment excavations (class no. 4) 9,994 $m^3$,
- grouting 22,3 t,
- pavement improvements 1,480 $m^2$.

Most of the activities happened in the period of October 6 to 27, 1995. In this period, an operator of hydraulic power plants of the Vltava's cascade agreed to stop the operations in HS Orlík and HS Kamýk. Consequently, the water surface in a pool of HS Kamýk had been lowered before the work could start in the dry river bed. Thus the supplier had enough space to perform the work and its major task was to utilise all machinery and facilities available, and to co-ordinate the activities in order to meet the time schedule.

## 6 Handling the water passage

HS Orlík is the most significant determining part of the Vltava's cascade that comprises nine stages. We will not deal with it in the following paragraphs. The levelling stage for the peak load power plant of HS Orlík is HS Kamýk. HS Slapy and its levelling pool in Štechovice have been built up downstream. There is only one more hydraulic structure above Prague called HS Vrané. Its capacity does not appear to be principal in respect with handling water passage.

The successful running of the repair was conditioned within the whole cascade upon perfect preparation and co-ordination which were set ready and managed by the employees of the water resources control centre of the Company in Cupertino with energetical control centre. Such a capacity balance of both HS Orlík and HS Slapy had to be prepared in advance in order to get water free-status at HS Orlík during the repair procedures. At the same time, a sufficient water flow had to be secured in Prague so as not to exposure water intake of a water processing plant to danger and limit the navigation on the lower course of the rivers Vltava and Labe.

The above mentioned, required the following actions to be taken:

1. Since September 1995, the water surface was gradually lowered up to 344 m above the sea level in the water supply reservoir HS Orlík, i.e. 10 m below the maximum and 7.6 m below the current operational level. Based on our calculations, this measurement allowed to accumulate confluents to the reservoir safely during the reconstruction - the capacity of 227 mil $m^3$ was available.
2. HS Slapy had to indicate as high surface level as possible in order to allow water passage under this cascade stage. The surface level before commencing the work stood at 270.80 m above the sea level whereas a decrease of 77 mil $m^3$ of water caused a surface drop of 7.3 m down to 263.50 m above the sea level after the work completion.
3. HS Kamýk whose backwater end, touches on the stilling basins of HS Orlík decreased the water level in order to enable the work to be continued in the dry river bed.

## 7 Conclusion

With respect to faultless course of the repair, there was no need, to prolong the repair schedule. Also the hydrologic situation and average rainfall were of very favourable nature which resulted in rising the reservoir surface to 350.70 m above the sea level in HS Orlík as at November 30 when it was set into operation.

The work has been completed in required extent and quality. It is obvious within the operations of the plant that hydraulic conditions were enhanced substantially in the river bed. The duration of the improvements will be proved through longer-term operations including the transfer of inundation water via water resources facilities of the hydraulic structure in discussion.

The experience obtained during the repair helped the employees of the company prepare and implement a similar action realized under the stilling pool of HS Slapy.

## 8 The characteristics of HS Slapy

HS Slapy was constructed in 1956 on the river Vltava approximately 33 km north of Prague. Similarly to HS Orlík, its primary purpose is to produce electricity, handle water passages and partially protect from inundation waters. The structure consists of straight, heavy, concrete dam with its crest of 260 m long and 65 m high above the basement.

Three 15 m wide spillway crests have 8 m high steel gate segments which serve to transferring aggressive water. In outer blocks, two bottom intakes of 4 m in diameter are located. A spillway water power plant with three Kaplan turbines of absorption capacity of 3x100 $m^3/s$ is located at the heel of the dam. All outlet facilities have a common stilling basin. The reservoir of the hydraulic structure has capacity of 270 mil $m^3$.

## 9 The causes of dam ruptures

The stilling basin below the dam is 95 m long and 5 m deep. A vertical wall on the right side of the stilling basin was shortened during the construction process and finished right behind its sill. The wall is followed by a slope of 1:1 up to 1:1.5. The slope in the length of 95 m and height of 6 m was improved by bagwork combined in the lower part with concrete cube of 0.8 m edge. Steel gabions were covered by concrete slabs.

The vertical wall continues on the left side behind the stilling basin sill as far as to a rock wall that stands out in the transmissive profile and narrows down the river bed of ca. 80 m wide by 15 m.

The greatest impact on the flow behind the dam had a hindrance directly in the river bed. Three rock protrusions in the height of 2 to 4.3 m above the river bottom were left behind the stilling pool nearly in the middle of the transmissive profile. The fact that the land grading has not been finished might have the same cause as that of HS Orlík. The obstacle and partial contraction of the left side of the river profile directed the water stream during the operation of the dam in a bank lining of the right side behind a wall of the stilling basin. Particularly adverse influence had the operation of the bottom outlet when transferring inundation water. Steel gabions kept on falling apart gradually (also influenced by corrosion of steel netting); concrete cubes were dissolved partly and concrete slabs were sinking in formed caverns. Conditions of the protection were monitored in details; regular measuring and photo surveying were carried out by reduced water surface of HS Štechovice. Owing to impossible access of the right embankment, the repair was delayed and various implementation variants prepared.

## 10 Preparation of the repair

The last measurements of 1994 showed a deteriorating tendency which forced the employees of the Company to start intensive preparation work of the repair. The old bank lining should be replaced by new and more flexible one. Based on original suggestions, the repair was expected to take 24 days with the flow regime of 12 working hours in the dry river bed and 12 hours of transferring the necessary flow and stopping the work. A part of the repair would naturally become an elimination of the rock remainder in the river bed which would result in improving hydraulic conditions behind the stilling pool. In the process of selecting a supplier in May 1996, a large portion of the bank lining fell down during the transfer of inundation flows which resulted in a bank scour of ca 400 $m^3$. That is why the project documents had to be expanded and the concept of the repair realization changed utterly.

The engineering firm, FG Consult, proposed the following solution for reconstruction to be carried out by the company Vodní stavby Praha: after elimination of the remainder of the original lining, a steel concrete sill of 96 m long built in the slope heel and anchored each 1.5 m through steel piles into the bedrock. A new slope protection adjusted for a slope of 1:2 was made up of heavy rubble masonry placed on beaching. Original concrete cubes of 1.3 t each were used for 40% of the slope. A transition between the wall of the stilling basin and new bank lining is created by steel concrete slabs of 152 $m^2$ in shape of the area broken down. At the same time, a reconstruction of the lining was performed on the opposite bank and the rock in the bed was excavated.

In respect to the scope of work, the original time of completion could not be accepted and the additional work was scheduled for the period of 3 months.

## 11 The repair realization

The company Vodní stavby Praha was chosen out of four companies to realize an additional repair since it proved to be competent in the case of the dam repair of HS Orlík.

The following regime of construction was discussed. In the period of September $10^{th}$ to October $3^{rd}$, the water power station in Slapy was out of operation. Thus the below mentioned activities could have been executed - elimination of rocks in the river bed (volume of 417 $m^3$) without explosives, stripping down the lining of the right bank, construction of a reservoir and temporary bridge to access the construction site from the left bank. The land reservoir with tight stone-pitching wall along the whole bank being reconstructed; the bridge of 84 m long was based on continuous steel beam of four fields.

In next days, the construction proceeded below a protective reservoir when turbines operated and the water surface was reduced a little. Furthermore, several short cycles were agreed upon within the construction process when the flow was stopped completely.

As opposed to the situation of HS Orlík, this work was of more complicated nature. Due to poor caulking of the reservoir at a point where pile planks touched the bedrock, every movement of water level influenced the power of leakage. Also the flow velocity around abutments of the bridge construction had to be monitored necessarily. The work in the reservoir progressed in very tough conditions and individual work activities were hard to co-ordinate in timely manner at some stages. This lead to certain time delays which together with relatively unfavourable hydrologic situation increased a danger of flooding the construction site when transferring potentially inundation water flows.

## 12 Handling the water passage

Handling the water passage in case of HS Slapy was far more troublesome compared to the repair below HS Orlík. There is no reservoir of sufficient water volume between HS Slapy and Prague which would ensure a minimum flow off of HS Vrané that is determined by handling regulations of the Vltava´s cascade in the amount of 40 $m^3/s$.

More importantly, a sufficient space of storage volume in HS Orlík had to be built up for partial catchment of inflows in the cascade because only limited water amounts could be transferred over HS Slapy. The water level in HS Orlík was reduced to 346.50 m above the sea level, i.e. 7.5 m below the maximum water level (and 5.1 m below the maximum level of the storage space respectively).

The work carried out in the framework of the first stage required the operation of HS Slapy to be stopped for 10 hours during daylight and the surface level was kept in a pool of HS Štechovice at a maximum of 215.00 m above the sea level, i.e. 4.6 m below the maximum level of the compensation pool. It enabled to create a communication pathway in the river bed and do required preparatory activities including rock excavations. In that time, the water for Prague was emptied from the compensation basin of HS Vrané. Necessary water volumes were re-filled through HS Slapy during night hours. Despite a limited flow through the water power station, the pathway in the river bed had to be restored each morning. At this stage, two cycles of 30 hours without any flow were agreed upon which was the longest time possible to secure needed flows from HS Vrané.

The limitation of flows went on during the work in the compensation pool. Several measurements of hydrodynamic backwater in the course of various flow regimes in the pool of HS Štechovice had to be performed so as to avoid overtopping the pool. The surface in its profile was maintained at 2.2 m below the maximum level of the compensation pool. The flow of 180 $m^3/s$ results in hydrodynamic backwater of additional 1.5 m which makes the operation in the space left very difficult. In the second half of October, the situation was complicated through inundation status on tributaries of HS Orlík when the storage volume was filled up during five days and the surface rose up to the retention space. Appropriate actions in the whole cascade allowed to manage the situation so that bottom outlets of HS Slapy

had not to be used to transfer the water which would damage seriously the construction site. The third stage of the construction process also required sensitive actions, i.e. liquidation of the pool and bridge. The activities were executed in an intermittent manner from both a dry location and ship; requirements on water level changed daily then.

Finally, the repair was finished successfully on November 30th. Thanks to outstanding collaboration of both the control centre of the Company and the energetical control centre with the provider of the work, neither the construction itself was not put in jeopardy nor any unpleasant situation occurred in other sections of the river and emerged in the production of electricity.

## 13 Summary

In 1995 and 1996, the Company implemented two significant repairs of the dams of the key sections of the Vltava´s cascade - HS Orlík and HS Slapy. The causes of failures were the same in both cases, i.e. the earthwork was not completed during the construction process in the river beds below the silling basin which resulted in adverse hydraulic conditions below the dam. In case of HS Orlík, a failure of the bottom of reservoir was in question; in case of HS Slapy, damage of the bank lining straight behind the stilling basin appeared. Both hydraulic structures were repaired including removal of the causes, i.e. remainders of rocks in the river beds. While all work in HS Orlík's case proceeded on dry site without operation, the "dry" work in HS Slapy was combined with activities in the compensation pool accompanied by temporary bridge access to the site. It required greater efforts to control and handle river flows and surface levels on the whole lower section of the cascade on the river Vltava. Both repairs have been completed successfully. Their durability will be tested through the longer term load and different regimes of water transfers.