Reduction of Risks of the Operation of the Angat Multi-functional Water Structure (Philippines)

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Introduction
The Capital of the Philippines, Manila, is supplied with drinking water mainly from a water reservoir on the Angat River. The ever rising consumption of water has called for an increase of inflows into the reservoir by constructing a diversion tunnel transferring water from the Umiray River. The typhoon Nanmadol of the end of 2004 has revealed the vulnerability of this hydraulic complex, especially of the diversion tunnel. This tunnel was entirely filled with loam, wood and other ballast material after floods caused by the typhoon.

Development cooperation between the Czech Republic and the Philippines, in particular between “GEOtest Brno”, “Strojirny Brno” and the “Metropolitan Waterworks and Sewerage System (MWSS)”, began in 2005 and concentrated on the reduction of risks of the operation of the system, both of its hydraulic and hydroelectric parts. The work on monitoring risks of the operation of the hydraulic structures was divided into the following sections: the dam lake, the outlet structure with an adjacent mini hydroelectric power plant (MHPP), a barrage on the Umiray River and the inlet structure, and the tunnel transferring water from the Umiray River into the reservoir.

The typhoon Nanmadol, during its devastating passage across the site, most damaged the diversion tunnel. The major part of geological work was thus devoted just to the tunnel and the structures in the vicinity of its portals. The work in the tunnel is associated with operating problems because it is necessary to put it out of routine operation in order to inspect it. This is possible practically only when the operators of the inlet structure and the guards change, which is once in four to six weeks. Following the detailed description of the state of the lining of a selected section of the tunnel, a workflow was proposed to describe the lining of the whole tunnel tube using a video technique. In addition, the most significant water inflows into the tunnel were described, including their selected properties and the temperature of the walls of the tunnel. Their changes were also monitored.

Immediately after the first visit of Czech specialists to the inlet structure, a measure which should prevent any possible silting of the tunnel was proposed. The proposal of the Czech Party was accepted by the Philippine Party and implemented after its completion and elaboration. The outlet structure and the MHPP were damaged not only by the flood in 2004, but also by smaller floods in the subsequent years. It has turned out that the only long-term stability solution is to regulate the channel of the Macua River above as well as below the outlet structure and to carry out a complete reconstruction of the MHPP. On the dam reservoir, we focused only on the monitoring of bank changes. Besides a visual inspection in the first years, in 2008 we documented the banks on a digital video recording and registered the position of our boat by using a GPS. We monitored the shape of the slope on one of the landslides beneath the water surface by using sonar.

1. Background
The Angat dam and associated facilities were constructed for supplying the Capital of the Philippines, Manila, and the whole adjacent metropolitan area with water. They cover up to 90% of water consumption of the Capital. When we realize that it is the supply of the region having at least fifteen million inhabitants, any possible interruption of water supply means a great problem. The dam impounds a lake of about 700 million cubic meters of water at maximum backwater level. With the rising water consumption it has turned out that the Angat River is no longer capable of filling the dam lake. Therefore, at the beginning of the 1990’s, a tunnel was constructed. It transfers water from the neighboring Umiray River into the Angat retention area. The tunnel of 3.8 meters in diameter is 13 kilometers long. It normally transfers about 13 m³ of water per second into the dam lake. When water in the Umiray River is abundant, this amount increases up to 24 m³/s.

The area of interest lying in the tropical zone in the west of the Pacific Ocean is influenced by the airstream from ocean to continent. The amount of precipitation is strongly affected by the site location and shows its unevenness during the year. The dry period from January to March is followed by the period of typhoons when the average
monthly precipitation multiplies. The Umiray area lying near the coast on the windward side of the island is out of this trend. There, the course of precipitation has a different character, but the whole amount of precipitation falling during the year is also distinctly different. It is 1,460 millimeters a year on average that fall in Manila, 2,500 millimeters a year around Angat, and even 5,650 millimeters a year in the Umiray area. The greatest differences between the monitored places are in November and December, and, if the case may be, even in January. High precipitation in the Umiray River basin and thus also high flow rates in this river were the reasons why the tunnel conveying water from this river to the Angat dam lake was constructed.

2. The Typhoon Nanmadol

At the beginning of December 2004, rain precipitation of the typhoon Nanmadol was higher than 1,200 mm on Luzon. The gauging station at the Angat dam recorded 986 mm of precipitation on 3 December. The local airstream, together with the rugged terrain, markedly affected the precipitation total at the individual sites. At the IPO station, about four kilometers away, only 33 mm were measured. It is likely that the local differences could not only have increased but also have decreased the total precipitation. It is natural that such extreme conditions (precipitation, wind, water level fluctuation) must also be recorded in the landscape surrounding the dam and associated structures. During the typhoon, the banks of the reservoir were rid of all vegetation. The affection reached not only the height of the backwater of the reservoir, but the vegetation cover was swept away up to the height corresponding to the maximum waves due to the surge. We should realize that the airstream during the typhoon Nanmadol reached up to 320 km/hour. The reservoir banks were hit up to a level of 230 mm because of the above-mentioned events.

During the typhoon, there was both erosion by runoff and enormous seepage of water into the cover with frequent subsequent liquefaction of debris and loams and their flow down the slopes into brooks and rivers (Fig. 1 left). The mere movement itself of such bodies causes catastrophic consequences. The velocity of movements of such slope deformations is very high and can reach up to tens of kilometers per hour. In case of an uninhabited tropical forest, “only” devastation of the vegetation cover occurs. The accumulation parts of slope deformations were immediately washed out in rivers and carried away into valleys farther downstream or even into the Angat reservoir itself. The density of the mixture of water and the drifted material can increase up to 1.4 g cm$^{-3}$ at this moment, hence increasing the erosion activity of rivers. In this way, the banks of the Umiray River were rid of all vegetation and the Quaternary cover up to a height of ten meters above the usual water level in the river (Fig. 1 right).

Fig. 1 Mudflows on the Umiray's slopes and the bank erosion

A specific problem caused by slope deformations was transport of tropical vegetation. It is natural that mudflows removed not only small forms of the vegetation cover, but also full-grown trees, mostly rare exotic tree species. A considerable part of this organic material ended up on the dam lake surface. The operator of the dam has a special vessel for such purposes, with which he removes the trees from the dam reservoir to avoid their decomposition and thus the deterioration of the impounded water. Because the cutting and transport of tropical trees is prohibited at the site of the dam, the trunks were used on site for the reconstruction of damaged objects or for the construction of objects replacing demolished buildings.
3. The Issues of the Individual Structures

Part of Czech development aid was also the effort to document the state of all structures of the Angat dam and associated facilities after the passage of the typhoon, except for the dam itself and all structures adjacent to it (the side dam, the emergency spillway, the hydroelectric power plant, and the objects of the water scheme management). The work was carried out according to the requirements of the Philippine Party and was modified according to the development of the situation at the site.

3.1 The Dam Lake

Within the stay of Czech engineering geologists in 2008, the basic physical documentation of the Angat reservoir banks was commenced. The banks were inspected from a boat, with participation of the MWSS staff. The whole inspection was documented on a video recording for in-house evaluation. Parallel to the video recording, photo documentation was also taken. It was stated during the inspection of the reservoir banks that there was a phenomenon of bank changes in the backwater area of the reservoir. It was found out that there were indications of fossil slope deformations that had almost certainly been produced prior to the construction of the dam and associated facilities. In addition, small and moderate slope deformations were identified. At the same time, it was stated that there were manifestations of bank changes, being usually called as “bench making” at many places on the banks of the reservoir. Another feature documented on the banks of the Angat reservoir is suffosion. Sometimes, suffosion holes are grouped in rows or suffosion nests. This phenomenon is not rare, but, on the other hand, does not cause sharp deformations of the reservoir banks. We stated that none of the identified manifestations of the bank changes is dangerous for the operation of the dam and associated facilities. According to the video recording, it is possible to begin with the zoning of the reservoir banks anytime in relation to abrasive transformation and stability. Geotest Brno is preparing the methodology how to fulfill this task by means of a television recording of the inspection of the banks and the parallel recording of the boating route using a GPS.

We have modified the usual typology of abrasive transformation of banks on dam lakes for the needs of the zoning of the Angat reservoir banks as follows: abrasion-accumulation bank, abrasion-erosion bank, discontinuous abrasion-erosion bank, abrasion-slide bank, and neutral bank. The common classification was extended by the type of discontinuous abrasion-erosion bank. The abrasion-erosion bank has one abrasion cliff formed at the level of the most frequent water surface. The cliff is usually of uniform or continuously variable slope. It is formed in rocks which are rather more resistant to abrasion. The discontinuous abrasion-erosion bank (“bench-making”) has a row of small abrasion cliffs formed at levels corresponding to water surfaces with a greater frequency of occurrence. It is usually formed in less resistant and densely jointed solid rocks where the orientation of discontinuities combined with the orientation of the bank and the directions of prevailing winds is favorable for the creation of “benches”.

Fig. 2. Landslide on the Angat reservoir and sonar measurement
When inspecting the banks, we also carried out experimental sonar measurements with the aim to identify the shape of the reservoir bottom at the site where the existence of a slope deformation had been anticipated. The results of measurements are given in Figure 2. When processing the given area, we applied all documentation techniques available. The result is a comparison of sonar measurements, the video recording of the inspection boating, the measurements of the location by means of a GPS and the photo documentation of an aerial inspection of the site as well as the inspection of the area of interest from a boat. Modern sonar devices enable to determine not only the course of a reservoir bottom, but also provide information on its character. In our case, the soils beneath the water surface are very mushy down to a depth of about 30 meters. We can thus declare that they largely consist of Quaternary sediments washed out by abrasion. The assertion that this part of the bank is affected by sliding is supported by the shape of the bottom detected at a depth of 30 to 50 meters. We can see its “buckling”, which is typical of landslides, in the lower part of the slope. This, together with the possibility to determine the zone of depletion from the inspection of the area from a helicopter as well as from a boat, leads us to the conviction that this part of the bank is affected by sliding.

3.2 The Outlet Structure, the Mini Hydroelectric Power Plant and Their Adjacent Vicinity

The object of the power plant and the outlet of the diversion tunnel are placed on the confluence of the Macua and Bayto Rivers. During floods accompanying the typhoon Nanmadol, the complex of facilities at the outlet from the tunnel, including the power plant, was put out of operation and damaged (Fig. 3 bottom left). The diversion tunnel was virtually all silted with deposits during the above-mentioned flood. They streamed from the Umiray and Ravitan Rivers into the tunnel together with a flood wave. The deposits in the tunnel at the outlet to the power plant were a chaotic mixture of organic and inorganic materials compacted by the pressure of the flowing water (Fig. 3 top right). The flood sediments were unsorted and comprised a whole spectrum of soils from the finest clays to coarse gravels, including an organic admixture. Also, the electrical installations and mechanical equipment of the power plant were damaged and largely destroyed (Fig. 3 bottom right). Damages to the building parts of the complex itself of the power plant and the outlet were limited. However, the groundwork of the approach to the power plant on the right bank of the Macua River, including the bridge to the object swept away by a breaker during the flood, were considerably damaged.

![Fig. 3 Damages after the typhoon Nanmadol](image-url)
An engineering-geological survey for a proposal of protective measures on the object of the power plant and on the tunnel inlet was largely conceived, because of survey work carried out prior to their construction, as a re-interpretation of the previously obtained data and as their comparison with the current state of the site. The identified geological structure was evaluated in relation to the occurrence and consequences of hazardous geological processes which took place in the area of interest during the typhoon Nanmadol and the flood caused by it. The data relevant for the area of the power plant had to be identified and then interpreted for the evaluation of engineering-geological and geotechnical conditions.

In the conclusion of the engineering-geological evaluation of the combined structure, it was recommended to adopt measures ensuring the trouble-free operation of the hydraulic work. Our recommendations proceeded from the results and from the overall engineering-geological evaluation of the site. Because of sedimentation of a large amount of sand and gravel, we recommended to consider a possibility of dredging the channels of both the rivers. Within the provision of the continuous flow of water in the river, it is necessary to modify the cut-off of the rock spur for the Macua River. During flooding, organic material accumulates in front of the cut-off, the flow reduces and the water level in the river rises up to such a height that it practically reaches the combined structure. We propose to slightly widen the cut-off and especially to modify its direction in such a way as to ensure the continuous direction of the river flow in this river section (Fig. 4). Without the dredging and the modification of the cut-off, we will not reach the state for the water levels at the inlet to the turbines and at the outlet from them to be in the required relation. The river bottom is currently higher than the outlet from the turbines.

![A Cut-off - status quo](image1)

![B Cut-off - designed measures](image2)

*Fig. 4 Possible modification of the cut-off*

Part of the project is also a complete reconstruction of the MHPP designed by “Strojírny Brno”, where the overall concept of the power plant has been changed: the propeller turbines with fixed runner blades will be replaced with the latest fully adjustable Kaplan S-turbines and the new control system will be adapted to remote monitoring and control. The machine floor of the power house will be watertight and control cabinets will be placed on a new top floor where a new access door will be located.

### 3.3 The Diversion Tunnel

The tunnel connecting the Angat and Umiray Rivers can be considered as the key object in the Umiray – Angat system. One of the basic sources available to us is a geological section through the tunnel. Besides the original data, the geological section also shows plotted faults, the location of which was identified from the interpretation of satellite scenes and other base maps. The work itself in the tunnel had to be adjusted to its operating regime. The tunnel is put out of operation for a period of about 12 hours only once in four to six weeks. It is necessary to deduct from this period about three to four hours needed for all water to flow from the tunnel. First during the time of the tunnel shutdown, the crew (including the military guards) must be changed at the inlet structure and provisions for another six weeks must be renewed. Only the remaining time can be used for geological work.

The most interesting feature in the tunnel is numerous water inflows. These cannot be overlooked in the tunnel, and it can be said with a little exaggeration that they are countless. Water flows into the tunnel through joints between the slabs of the lining, drilled holes in concrete segments and cracks that form (Fig. 5 top). Both old repaired and new cracks are visible on the slabs of the lining. Abundant sinter crusts are formed by water seeping through cracks and joints and flowing down the surface of the segments. The occurrence of inflows, cracks and sinter crusts is not uniform in the tunnel, and differs from place to place. Within monitoring work we prepared an overview of the occurrence of old cracks according to the documentation of the approval procedure. We mapped
new cracks in two 100-m long testing sections by visual control in 2008 and repeated this documentation in 2009. We stated that certain cracks detected in 2008 had already been covered by sinter crusts and we found cracks that had been newly formed. It can generally be said that cracks parallel to the axis of the tunnel prevail in a large majority (Fig. 5 bottom left), but we also documented cracks perpendicular to the tunnel (Fig. 5 bottom right). Besides the “manual” visual control, we documented the whole tunnel tube experimentally on a video recording. The video recording stored in an electronic carrier is just now being processed in our laboratories.

Measurements in the tunnel provided a whole spectrum of new information. One of the most important measurements in the tunnel was the measurement of temperature of the lining. We measured the temperature in the mode of continuous measurement with the regular readout of the measured quantity by an infrared thermometer OmegaScope OS 530 HRE from a moving service rail car in the tunnel for the first time in 2007. The thermometer was stabilized on the body of the service rail car so that the angle of pointing and the distance of the gauge from the tunnel lining were kept the same, when possible, over the entire period of measurement. The temperature was read out every 65 meters (50 slabs). The detected differences were surprisingly high; the main anomalous zone is found from the stationing of 5,500 meters to that of 8,200 meters. In that section of the tunnel, temperature decreases as compared to the normal field. If we expected a smooth course of temperature, then the magnitude of the temperature anomaly in the center of the tunnel would reach practically three degrees. The cause of cooling of the rock mass must be sought in groundwater flow. Measurements in 2008 and 2009 confirmed the results of the first measurements.

The first measurement of selected physical parameters of groundwater was made by an instrument Tester HI 98129 of the company HANNA INSTRUMENTS GmbH in 2007. The measurement of selected inflows into the tunnel took place during the inspection tour of the tunnel. The tester is equipped with probes for measuring the pH, electrical conductivity and temperature of a liquid. Before measuring, it was necessary to calibrate the pH probe of the instrument by means of a pH reference solution. The measurement itself was carried out so that a water sample was taken from a selected inflow and readouts were made after stabilizing the tester. It turned out that water inflows into the tunnel were stronger than we had anticipated until the moment of documentation. The largest inflow was recorded at 8,272 meters where about 6.5 l/s flew into the tunnel.

Changes in the measured parameters were also similarly surprising. Perhaps it is the most surprising in pH. These values vary from 7.58 (11,258 m) to 10.4 (3,656 m). The temperature of the influent water ranges from 21.9 °C (8,274 m) to 26.2 °C (9,056 m). The minimum conductivity, 92 µS/cm, was detected at 8,274 meters and
the maximum value, 1,017 µS/cm, was measured at 11,258 meters. In order to better know the character of the groundwater, we compiled cross graphs from all measurements made in the collected water samples. The cross graphs for the relations water temperature – pH and water temperature – conductivity show no relationship or any clustering of points into subunits. The cross graph tracing the relationship between the conductivity and the pH appeared as the most important (Fig. 6 left). In this case, it is clearly evident from the graph that the points are clustered into two separate areas, only one point lies quite outside. Concurrently with a field measurement, we collected water samples. After the preliminary in-office processing of the results of measurement in the tunnel still in the Philippines, we took one sample from each group and transported it into the laboratories of Geotest Brno. The results of the laboratory examinations confirmed the results of field measurements. We applied modified Piper diagrams for hydrogeochemical evaluation. The majority abundance of ions for the individual sampling points is plotted in a diagram in the right-hand part of Figure 6. Both the diagrams show two basic facts. Repeated sampling confirmed that the individual groundwater samples defined sharply different hydrogeochemical environments. Hydrogeochemically (in relation to the formation of the chemistry of groundwater), it is a highly stable environment.

Agreement in the abundance of the individual ions in the groups is very high, and the repeated sampling confirmed the definition of the geological environment of the formation of groundwater according to the first round of monitoring. Based on the expedient measurements and laboratory analyses performed, we can state:

- Sample 5469: Water with a medium TDS and a high pH. Hydrogeochemically, it is water of Na – SO₄ type with a low portion of calcium and hydrogencarbonates. It has an increased content of fluorides. It is, therefore, probably water with a certain residence time in the volcanic rock environment. Due to the relatively low contents of calcium, magnesium and hydrogencarbonates, this type of water can be aggressive to concrete – by leaching.
- Sample 6298: Water with a low TDS and a neutral pH. Hydrogeochemically, it is water of Ca – Na – HCO₃ type. It is, therefore, probably water with a very short residence time in the rock environment, i.e. fast-flowing precipitation water. This sample probably characterizes groundwater in zones of rock fracturing (tectonic zones??). Due to the low content of dissolved substances, water aggressivity to concrete can be anticipated – leaching.
- Sample 8600: Water with a high TDS and a neutral pH. Hydrogeochemically, it is water of Ca – SO₄ type with a low content of sodium. It is, therefore, water with a long residence time in the rock environment. It can be anticipated that the water ascends along a deep tectonic line at the boundary of volcanic rocks (SO₄) and limestones (Ca). Water aggressivity to concrete structures is given by the higher content of sulfates.

3.4 The Inlet Structure

The typhoon Nanmadol also considerably damaged the inlet structure of the tunnel (Fig. 3 top left). The highest precipitation of the entire system of the Angat dam and associated facilities was in the basin of the Umiray and Ravitan Rivers during the typhoon Nanmadol. This fact can be derived from the overviews of precipitation at individual gauging stations as well as from the visible consequences of erosion of the banks of the Umiray River and the large amount of material that was drifted by rivers. The floods damaged and destroyed individual concrete structures, and, moreover, the whole place of the inlet structure was covered with deposits of gravel, loam and driftwood as shown in the picture.

Only the concrete body of the barrage jutted out of the original complex of the inlet structure after the typhoon, and the concrete structure of the barrage itself remained relatively undamaged. The supply canal and the tunnel portal were not visible at all on the ground surface shortly after the flood because they were covered with a layer
of gravels brought by the Ravitan stream. The slabs covering the supply canal were also damaged and the canal itself, similarly as the tunnel, was silted with variable material. It is likely that the cover slabs have not held the pressure of the flood wave and the weight of the new sediments.

The basin of the Umiray River around the inlet structure was observed on satellite scenes of both normal and high resolution. It was found that the extent of slope deformations produced after the passage of the typhoon had not been uniform. A more profound cause of this feature has not been further investigated.

However, the question how to secure the inlet structure in order to prevent further silting of the tunnel with ballast material was the most relevant. The answer was both relatively simple and cheap and consisted in the possibility of closing the tunnel. We believe that the most suitable solution is a steel self-closing gate. The closing gate must be watertight to exclude the possibility of its bypassing and subsequent damage. In our opinion, the activation of the closing mechanism should be possible in the following ways: automatically by a monitoring sensor, by command from a control room, or manually on site.

4. Conclusion

The tunnel connecting the Umiray River with the Angat water reservoir must be considered as one of the key elements of the drinking-water supply system of Manila, the Capital of the Philippines. The Philippine water managers have become aware of its need for decades because the amount of water conveyed into the dam lake by the Angat River has not satisfied the needs of the expanding metropolis. Besides ensuring the need of water, it is necessary to keep being aware of its vulnerability. For this reason it is essential to properly protect the whole work, especially from adverse effects and their consequences. For the needs of designs of protective measures, it is necessary both to obtain a variety of single information and findings on the geological structure of the wider vicinity, and to repeatedly observe the selected structures and features of the topography, on the basis of which it is possible to proceed as much effectively and economically as possible in designing and constructing protective measures.

Similarly as it is necessary to obtain information on the geological structure of the area, it is also necessary to gather data on the weather and the technical conditions of the operation of the dam and associated facilities. The operator of the work has its functional system consisting in measuring the basic data on the Umiray River (the inlet structure) and on the Angat, IPO (the afterbay dam) and MESA (the water treatment plant) reservoirs. We believe that it would be appropriate to add to this system one more station on the mini hydroelectric power plant. According to what we could see and what materials we could assess, the Macua River belongs rather to the precipitation conditions that exist on the Umiray River than to those on the reservoirs.

The multi-disciplinary approach of specialists of diverse fields, engineering geologists and geotechnicians, hydrogeologists and hydrologists, geophysicists and specialists in remote sensing, meteorologists, designers of building, engineering and electrical equipment, and last, but not least, also specialists in crisis management has proved itself in ensuring all necessary background documents and in processing the results of measurement.

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