A COMPREHENSIVE FIELD INVESTIGATION FOR REHABILITATION OF AN EMBANKMENT POND

Saied Saiedi[*], Teh Hee Min[**], Zahiraniza Mustaffa[**], Nabilah Abu Bakar[**], Kalaikumar Vallyutham [**], Amer Awad[***], S. Baharom Azahar S. Osman[****]

[*]*Associate Professor, Ph.D., Civil Engineering Dept.(CED), Universiti Teknologi PETRONAS (UTP), 31750 Tronoh, Perak, Malaysia; Phone: ++605 368 7284 , Fax: ++605 365 6716, E-mail: saiedsaiedi@petronas.com.my*
[**]*Lecturer, CED, UTP*
[***]*Senior Geotechnical Engineer, PhD, WorleyParsons Calgary, Canada (formerly: Associate Professor, CED, UTP, Malaysia)*
[****]*Senior Lecturer, CED, UTP*

ABSTRACT

Planning and implementation of a comprehensive field investigation for the rehabilitation of an embankment pond, damaged by bed erosion and liner rupture, are discussed. The pond can store 1.5×10^6 m^3 water and is formed by a peripheral 16-m-high embankment. It regulates the water issuing from the tailrace tunnel of a hydropower station. Insufficient energy dissipation of the flow from the tunnel caused serious bed erosion downstream of a large concrete apron leading to the rupture of a deep 2-mm-HDPE (high density polyethylene) liner of the pond floor. The pond floor is made of four layers placed on the compacted soil with an overall 1.2 m thickness. The waterproof liner in the mid-depth of the bed layers covers the whole pond floor and extends to the top of the embankment. Being a major part of the national power grid to help at peak hours, the station could not be shut-down during the study for more than a couple of days. This time limitation posed a serious challenge in drying the pond for a vital inspection of the damages. The study team planned and implemented a comprehensive intense site investigation during and after the pond was drained. The purpose of the site study was fourfold: (i) Provide for an accurate description of the damage. (ii) Collect data for later scale modeling and design studies. (iii) Find clues as to the cause and timing of the damages. (iv) Make use of the water drawdown to monitor concurrently the drainage flow to see if the pond was leaking. The field investigation was undertaken in two stages: (1) during drawdown and (2) after drying the pond. The first involved three actions: (1a) Concurrent discharge measurement at two river sections to detect contribution to the river flow by the seepage, if any, from the pond (1b) Monitoring the drainage from the perforated pipe network buried under the soil layers (1c) Instantaneous measurement of outflow from the pond and water level fall in the pond to validate the continuity equation. Major investigations of the second stage included: (2a) Visual inspection of the inner face embankment for signs of cracks or settlement (2b) A complete survey of the pond floor topography (2c) Photographical record of the damaged area (2d) Sediment samples from various places in the pond (2e) Visual inspection of all the appurtenant structures (2f) Electrical resistivity survey on selected places looking for cavities or seepage. Pieces of the large body of the data were then interrelated to one another as well as to the historical data such as those of the water level, discharge, precipitation, and piezometric levels. The investigation revealed that the damage must have happened soon after the operation of the pond eight (8) years prior to the investigation, the scour holes were progressing downstream, the embankment was safe, no significant water escape from the pond was detected, and the intruded sediment from outside was responsible for formation of several depositional islands. The rationales to attain major conclusions are presented. The data and the resulting insights from the field investigation were employed later in the physical modeling study and engineering design of the remedial modifications.

KEYWORDS: Engineering Field Investigation, Embankment Pond, Liner Rupture, Scour hole

INTRODUCTION

Investigation methods in water-related projects are commonly classified into five types (USACE 1993, Refsgaard and Henriksen 2004, Novak 2010): (i) Field investigation (ii) Analytical method (iii) Physical modeling (iv) Numerical (computerized) method (v) Hybrid model. Literature is abundant on the importance of field investigations as the basis of analytical, numerical and scale modeling studies. While the foundation of most applied research in water engineering works are the data obtained from site investigations, rarely are the procedures and rationales of the field explorations are reported in the literature. Valuable guides on the field investigations as needed for consultancy works in river engineering have been given in USACE (1993). Papanicolaou and Dermisis (2007) reported the procedure to evaluate the hydraulic performance several structures (riprap weirs, fish ladders, and grouted ripraps) through tests performed at site. It is hoped that an upcoming gathering of professionals in a symposium on field investigation in hydraulics (ISHPF 2010) will embrace experiences of practicing engineers and researchers on hydro-technical site investigations.

The present paper is a report of the planning and implementation of a comprehensive field investigation for a rehabilitation project on a damaged embankment pond. The objective of the paper is to introduce the steps and rationales in the undertaking of an intense filed investigation to collect the maximum data for addressing major

questions of the study. The data and findings of the filed study were used later for analytical and physical modeling parts of the same rehabilitation project.

REGULATING POND, DAMAGE, AND REHABILITATION PROJECT

POND

The large embankment pond is situated between the tailrace tunnel and the downstream river. **Figure 1** shows the layout and the details of the pond. The pond has a volume of $1.5\times10^6\,m^3$ with a plan area of approximately 800 m×300 m. It stores temporarily the outflow of a hydropower station before it is released to the river. The reservoir of the respective large hydropower dam receives additional water from several adjacent rivers. Therefore, the usual discharge from the turbines during high electricity generation is greater than the capacity of the river, making it necessary to reduce the outflow by routing through the pond reservoir. The outflow from the turbines is the inflow (*Q1*) to the pond. The sequence of this submerged flow is as follows: issuing from a 6 m underground tailrace tunnel (labeled as *1* in the figure), moving through a diverging stilling basin, rushing over a wide concrete apron (labeled as *2-1* in the figure) with two series of baffle blocks, moving slowly towards the outlet structure (labeled as *3* in the figure) on the other end of the pond, and finally joining the river through two large box culverts. The terminal part of the tailrace tunnel, stilling basin, and the concrete apron combined, is referred as tailrace outfall structure (TOS labeled as *2* in the figure). The pond floor is made of five layers placed on the compacted soil with the total of 1.2 m thickness. **Figure 2** shows the layers. From the top, the layers are 0.3-m screened rockfill (D_{50}=50 mm), 0.3-m-sand filter (D_{50}=1.5 mm), 2-mm-HDPE (High Density Polyethylene) liner, 0.3-m-fine sand filter (D_{50}=2 mm), and 0.3-m-medium gravel filter (D_{50}=13 mm). HDPE liner covers the whole pond floor and extends to the top of the 16 m-high-embankment providing for impermeability of the pond.

THE FIRST ENCOUNTER WITH THE DAMAGE

Eight (8) years after commissioning the pond, it was found out that the pond floor in front of TOS was seriously eroded and the protecting HDPE liner was ruptured endangering the pond including the opposite embankment. This is how it was noticed: On a day when the water level was lowered for operational reasons, a big piece of the ruptured HPPE liner was partly visible on the water surface a few tens of meters from the end of TOS. It was first mistakenly seen as '*a strange black snake*' moving in water. The observation triggered a closer look by the operator using boat and divers. It was revealed that the '*dancing black object'* was one of a few pieces of ruptured liner still attached to the bed. The murkiness of the water, caused by incoming sediment laden surface runoff during rainy days, did not allow a clear picture of the floor but it was obvious that two soil layers above the liner had been washed away before the liner was partially floated. It was also obvious that the underlying layers too were now exposed to the flowing water.

IMMEDIATE INSPECTION

The prospect of propagation of the bed erosion, both in depth and towards the opposite embankment, was grave for the operation of a hydropower that was an integrated part of the national power grid. The operator decided to partially drain the pond to conduct a preliminary inspection. The emergency arrangement with the national power grid was made, the outlet structure (box culverts) was fully opened, and the water level was lowered in about 14 hrs to 0.4 m of water depth. A quick visual inspection showed that the ruptured area was still far from the opposite embankment. A crude survey of the bed in front of TOS was conducted and the pond was refilled the following day as serious electricity generation demands did not permit immediate shutdown of the station. The owner decided to continue the operation of the station cautiously (*i.e.*, with low to moderate electricity generation) for a few weeks before a competent consultant began a planned investigation. This wait period was justified based on four facts: (i) The ruptured area was still far enough from the opposite embankment. (ii) No significant escape of the pond water had been observed from the embankment in previous regular inspections. (iii) The 'accidental' discovery of the damage in year 8 of the operation left a reasonable margin of hope for the safety of the pond for another few weeks. (iv) The opposite embankment (the most exposed to potential damage) did not show any serious sign of physical defect such as crack or settlement.

CAUSE OF THE DAMAGE

<u>Cause:</u> With some preliminary hydraulic calculation of the flow from the tailrace tunnel into the stilling basin and the concrete apron, it became clear that both critical velocity and critical shear stress were too large for the unprotected top soil of the pond floor downstream the apron. The lack of a transition region between the concrete apron and the top soil layer was against the common practice in the design of energy-dissipating structures below spillways, gates and culverts where riprap or gabion is used to protect the bed against erosion. The erosion of the top two layers

exposed the liner to sever hydrodynamic pressures of the flow making it susceptible to various modes of failure. It was obvious that this mechanism had contributed to the damages.

Rehabilitation Project: An expert team, including the present authors, was assigned to conduct a study towards finding the cause of and solution for the damages. A major part of the investigation was physical modeling of the erosion in front of TOS. **Figure 3a** shows the prototype TOS and its downstream bed floor as seen from the opposite embankment after the pond is drained for inspection. The scale model of the same part of the pond with a geometric scale of 1:36 is seen in **Figure 3b**. The experiences from the design and construction of the physical model itself has been reported elsewhere (Saiedi and Vallyutham, 2007). A few of practical and theoretical challenges in scale modeling of the erosion have been discussed by Saiedi *et. al* (2009). The analysis of the liner rupture has been also elaborated by Saiedi *et. al* (2010). The present paper reports the planning and implementation of the field investigation at the onset of the rehabilitation project.

Major Questions of the Study: Major questions of the rehabilitation study were first identified as below and general lines of action for each were decided among which site investigation played a fundamental role. **Table 1** contains the approach towards the answers to the major questions.

a. What exactly happened?
b. Why did it happen?
c. When did it happen?
d. How did it happen? (Process?)
e. Is the pond leaking?
f. Is the opposite embankment safe?
g. Is there any structural damage?
h. What are the necessary rehabilitation works?
i. How to secure the pond for future?

FIELD INVESTIGATION

NECESSITY

It was seen essential to go beyond the preliminary description of the damage by the client. Being an indispensable part of the national power network, the station was basically utilized to help at times of high demand, mostly from 11:00 *a.m.* to 3:00 *p.m.* every day. The client first preferred not to stop the station even for a couple of days. Once the damage was detected, the client conducted a crude inspection of the damage and a quick survey of the damaged area while the pond was not fully drained. The possibility of a new inspection using high-end equipment was initially considered as an alternative to complete drying of the pond. However, it was rejected on the ground that the water in the pond was too murky to see and measure the features of the floor damage. Faced with the paramount role of visual inspection of the damage demanded by the authors, the client made an emergency arrangement for 24 hrs of access to the pond: ½ day (afternoon) on the first day immediately after the power demand declines plus the following daylight hours. This effectively meant 1-day shutdown of the station.

TEAM

The site investigation team consisted of academic staff (Ph.D., 2), research officers (M.Sc., 2), trainee lecturers (B.Sc., 3), technicians & surveyor (3), and graduate student (1). No undergraduate student was engaged for safety and insurance considerations. All members, except for the surveyor, were equipped with a digital camera and were asked to document (photo, video film, note taking, voice recording) everything significant or curious they encountered. Several walkie-talkies facilitated communication and coordination among members. The photos, clips, and notes were then collected, clarified, matched and summed up by the project leader.

MAJOR ACTIVITIES AND A SUMMARY OF THE DAMAGE

Knowing that this 24-hr-site visit would be the only chance to get a real-life picture of the damage, the authors planned a comprehensive filed investigation. The major tasks were listed as in **Table 2** and person(s) were assigned for each task. Time was divided into two parts: 1. Water level drawdown. This began in the evening of the 1st day. 2. Dry pond inspection. This took both morning and afternoon of the 2nd day. By the evening of the 2nd day, all site visit tasks were accomplished. The site investigation tasks were accomplished in 24 hrs.

A summary of the damages is given in **Figure 4**: The photo in Figure 4a had been taken when the water depth was 3.9 m and the discharge was 105 m^3/s. In Figure 4b, the pond is near dry so that the full extend of the sand bar (deposited from surface runoff coming through chute 1) and the first row of the baffle blocks are visible. Water depth in Figure 4c is about 6 m. Many details on the damages, erosion, liner rupture, structural elements of TOS and depositional islands are clearly labeled in Figure 4a.

TACKLING THE MAJOR QUESTIONS

LEAKAGE FROM THE EMBANKMENT: ELECTRICAL RESISTIVITY SURVEY

The electrical resistivity survey (ERS) was conducted during dry pond inspection on four locations in the pond as labeled by *ERS* in Figure 1. The work was carried out using the *ABEM Terrameter SAS 4000* with automatic

electrode selector *ES 464* unit. Each survey was done by stretching a 100 m cable with electrode spacing of 2 m. Processing of the data yielded pseudo-sections on the basis of which cavities and wet spots could be spotted. Four locations were attempted: Survey 1 on inner slope of the embankment opposite to TOS; Survey 2 on the inner slope of the embankment on top of the outlet structure (box culverts); Survey 3 on the inner slope of the embankment between the access road to the outlet and the embankment crest (between labels 9 and 5 in Figure 1); and Survey 4 on the pond floor near TOS. The aim of Surveys 1 and 3 was to ensure the slopes are safe. The aim for Survey 2 was to check if the soil surrounding the box culvert is free from cavities and piping. The purpose of Survey 4 was to screen the pond foundation for big holes. The processed data from Surveys 2 and 4 did not make practical sense and they were discarded. For Survey 2, this was attributed to the presence of reinforce concrete and flowing water through the culverts. The soil in Test 4 was not as drained as it was hoped first. This led to erroneous readings. The maximum penetration depth of the ERS setup was known to be 12 m. This was less than the height of the embankment (16 m) if the ERS equipment was installed on the crest of the embankment. Therefore, it was decided to lay the cable in Surveys 1 and 3 on the face of the inner slope for the penetration depth to reach the embankment foundations. In both tests, some spots were detected with very low resistivity at depth 4~12 m. This was deeper then the depth at which liner was laid. Normally, very low resistivity indicates water or wet ground condition. This was attributed to the precipitation on the previous day. This test actually confirmed the ability of the electrical resistivity equipment to detect underground wet spots. These two tests were regarded successful. The pseudo-sections did not show any sign of cavities or wet regions. While this was a good sign for the stability of the embankment itself, it could not rule out yet the feared escape of water from the deeper parts of the pond foundation in large erosion depressions. This latter concern was addressed as reported below.

SEEPAGE THROUGH THE POND FLOOR: WATER QUALITY STUDY

After the safety of the opposite embankment was ensured by both visual inspection and ERS, the next major risk was the probable strong seepage from the depth of the pond foundation. Now that it was clear that the waterproof liner was ruptured in a large area in front of TOS, it was legitimate to fear that the depression might have propagated deep into the foundation resulting in cavities towards the river where they could naturally drain. Such propagation could be associated with significant water loss from the pond floor into the river because the river had been long the natural drainage course of the groundwater of the hillside, a region that the tailrace tunnel is coming from. There were three ways to detect if there was significant water loss from the pond: From the river flow measurement, from the continuity equation in the pond during drawdown, and from water quality considerations. They are discussed below.

River flow measurement: Two narrow sections of the river were selected upstream of the culvert in the afternoon of the 1st day before the drawdown of the pond began. The river discharge, released steadily from the dam, was low. The width of both sections was smaller than 6 m with the maximum depth of 0.85 m. The distance between two sections was 540 m alongside the length of the pond. Quick survey of the sections was performed to yield the cross sectional areas, *A1 and A2*. The velocity measurements at several verticals across the section were taken to obtain the average cross-sectional velocity, *V1* and *V2*. It was found that the discharges $Q1=V1\times A1$ and $Q2=V2\times A2$ were approximately the same (≈3.40 m^3/s) within a reasonable error margin of 8%. This indicated that there was not a significant leak from the pond into the river.

Continuity Equation: Early morning of the 2nd day, the water level in the pond was low enough around the entrance of the outlet structure for the flow to go smoothly over the edge of the entrance, like a spillway flow, and passing through two rectangular weirs, see **Figure 5b.** Note that Figure 5a shows the outlet structure and the spillway as seen from the opposite embankment near chute 3. The head above the weir crest was measured and the weir flow rate (Q_o) was computed at 5 min intervals. The pond water levels were recorded simultaneously. Each water level corresponds with a water volume *S* in the pond. Within a short time interval of $t_2-t_1=\Delta t$, the volume released through outlet structure is $\Delta O= 0.5\times(Q_{0,t1}+ Q_{0,t2})\times\Delta t$. On the other hand, the reduction in the storage is $\Delta S=S_{t2}-S_{t1}$. With no significant leak from the pond, $\Delta O=\Delta S$ must hold true. This was approximately the case with computations at all 5 minute intervals. Maximum of such average outflow was computed as 0.316 m^3/s. This reconfirmed the assumption of no significant leakage from the pond.

Water Quality Studies: The groundwater originating from the upland area in the hillside moves towards the river in the absence of the pond. With pond construction, the underlying network of perforated pipes (Figure 1) collects the groundwater and directs it towards the v-notch weirs (Figures 5c,d). Samples from each of the weir flow were taken at ½ hr interval during the field investigation: before and during drying of the pond. Samples were also taken from various points of the pond: tailrace tunnel, channels leading to each of the chutes, a ditch collecting embankment seepage (near label *7* in Figure 1), and two small streams on the hillside fed from groundwater. The samples were analyzed for the following properties: pH, Turbidity (NTU), Iron (mg/L), Manganese (mg/L), color (mg/L PtCO), Nitrogen (mg/L), Magnesium (ppm), Calcium (ppm), and TTS (mg/L). Distinct differences between properties of weir flows with those of the pond water effectively ruled out the possibility of significant leak from pond to the drainage network.

WHEN DID THE LINER RUPTURE HAPPEN?

The question of when the ruptured happened was the toughest question of the study. It could potentially be the most vital question too because the answer could help the answer to another important question as to why it happened. It was not the calendar date that mattered but it was the hydraulic conditions associated with the date when the failure occurred. In other words, the calendar date would lead to the specific water depth, inflow discharge, and outflow discharge that constituted the flow characteristics through TOS and the eroded area. The answer lied in the drainage record of the pond. The following explains how the drainage record could logically lead to the answer.

Basic Facts: Any speculation about the date of the liner rupture must be based on a few facts.

Fact 1. The network of perforated collector pipes, shown in Figure 1, is laid underneath the lowest soil layer as in Figure 2. It collects groundwater and reduces the pore water pressure underneath the waterproof liner. With the waterproof liner, the drained flowrate is not affected by the pond water level but it is affected by the piezometric pressure of groundwater that in turn depends on the water table and groundwater conditions of the upland area (hillside).

Fact 2. The liner rupture and the subsequent erosion of the underlying layers would expose the perforated pipes to the pond water that in turn would suddenly increase the drainage flow through the respective pipe. Considering the drainage network in the eroded area in front of TOS, the potential target would be the central longitudinal collector pipe (Figure 1) that leads to v-notch weir No. 1 (*VW1*; see **Figure 5c**). **Figure 5d** shows a view of three *VW*s at the last step of the spillway chute near the riverbank.

Fact 3. All the historical daily data available on the average outflow through *VW1*, *VW2* and *VW3* (receiving drainage from *LD1*, *LD2* and *LD3*, respectively) were plotted together with the daily precipitation throughout the operation years. With a lag time of a couple of days, the drainage flow showed an overall similar pattern to that of precipitation on the catchment in terms of increase or decline with time. Denoting the outflow of a v-notch weir by Q_{VW}, the relations $Q_{VW1}>Q_{VW2}>Q_{VW3}$ consistently held true. This was expected because considering the natural route of groundwater flow from the hillside to the river, the piezometric head of groundwater decreases from the hillside to the riverside. As examples, the drainage in the period of January to June 2000 were as follows: Q_{VW1} (belonging to the riverside drain *LD1*) varied between 0.2 to 1.0 L/s with an average of 0.8 L/s, Q_{VW2} (belonging to the central drain *LD2*) varied between 1.0 to 4.5 L/s with an average of 3.2 L/s, and Q_{VW32} (belonging to the hillside drain *LD3*) varied between 1.9 to 5.5 L/s with an average of 4.2 L/s. At no time throughout the available record was there any sudden increase in Q_{VW2} (nor in the other two: Q_{VW1} and Q_{VW3}) that was not associated with previous rainy period. However, a sudden rise in the drainage immediately after the damage could not be completely ruled out. There are two reasons for this. Firstly, the flow from v-notch weirs was taken manually only once a day. Secondly, there were numerous large gaps and missing data (up to a few days) in the record.

Fact 4. Beginning from an hour before the drawdown (evening of the 1st day) to a few hours after competition of drawdown (morning of the 2nd day), v-notch weir discharges were measured every ½ hr. The records showed no significant change compared to previous days indicating there was no connection between water level in the pond and the drainage flow. In other words, it seemed that the pond water did not enter the drainage network through the pond floor.

Putting the Facts Together: Facts 2 and 3, combined, validate the hypothesis that not long after the damage to the floor, the segments of the damaged collector pipes must have been clogged by a mixture of sediment, from silt (intruded from surface runoff) to sand and gravel (already in the bed layers). This hypothesis goes with Fact 4 showing that the blockage of the drainage in the damaged area had persisted throughout the years. Noting from Figure 1 that there are only three uPVC pipes in the damaged area (one *LD* and two *TD*s), the local damage could not block the whole drainage system because there were enough bypass routes for the groundwater through other parts of the network of perforated pipes. That was why the flow record from *VW1* (*LD1*, partially destroyed after the damage) never stopped or decreased suddenly.

Accepting the best available explanation for the drainage observations above, it was clear that the scrutiny of the available drainage record could not reveal the day when the damage progressed to the depth of the floor. To find the answer from the field data and investigation, the last resort was to identify the days in which the station operated with highest discharges through the tailrace tunnel ending at TOS. From the available trustworthy records (covering 92% of the whole period), there were less than 10 days when the flow was greater than 110 m^3/s for a couple of hours. The timing of the flows was known as the flow was registered automatically. The drainage data of the respective days were scrutinized. No meaningful correlation could be drawn between the large flow (& larger water levels) in the pond and the drainage variation. Since the drainage record was taken manually at unspecified times of the days, it could not be decisively ruled out that the failure to collector pipes (and the associated sudden change in the drainage flow) did not occur on those specific high-flow-days. Therefore, the question of the date of the damage was left to the hydraulic study on a scale model of the pond to be answered later.

LINER RUPTURE MECHANISM

Although time limitation did not permit to pump out all the water retained in several big depressions, it was obvious that several large irregular-shaped rocks have covered a large area of the pond floor underneath the HDPE Liner.

This was revealed with full clarity in the pre-construction clean-up (**Figure 6c**). It looked like layers below HDPE liner sat effectively on the sharp edges of some of these rocks in a large area in front of the concrete apron. Once the top layers were removed by strong shear stress of the flow, the liner was exposed to dynamic water pressures that eventually tore the liner (**Figure 6b**). Out of six (6) major ruptures noticed, no particular one was exclusively along the seam. Majority of the ruptures had occurred within the pieces of HDPE 6-m-wide strips. Two underlying layers were soon washed away and the liner was frequently banged on the rocks by the flowing water.

EROSION EVOLUTION AND SEDIMENTATION

The focus of the rehabilitation study was on the erosion of the pond floor by strong flow from TOS that led to the liner rupture. This required profound sedimentation investigation. The following describes various field investigations related to erosion-deposition and their relevance to the big picture of the rehabilitation study.

Sediment pile in front of chute 1: An obvious shortcoming of the original design was the free intrusion of sediment laden surface runoff into the pond through baffled chute 1. While the baffles duly dissipated the energy of the flow, no provision had been made to stop the sediment from entering the pond. Figures 4a and 4b show the huge pile of sediment at various water depths. Figure 4c shows how the incoming sediment could easily deposits at the toe of the chute next to TOS in the absence of significant flow velocity when the pond is operating with a depth of 6 m. Figure 4b could help imagine how part of the same sand bar is pushed towards the diverging stilling basin mixing with strong flows from the tunnel. This additional sediment continually mixed with the pond contributing to some depositional islands around TOS. A thorough survey of the sediment pile was performed and sediment samples were taken from various places of the chute and its upstream stream. The information and the data were input to several sedimentation tests and analyses later. A small gravity dam was proposed in the diverging entrance of the upstream channel of chute 1.

Detailed survey of the damaged area: In addition to a general survey of the pond floor topography, a refined survey was conducted in the damaged area in the vicinity of TOS. Given the limited time and with presence of water in deep scour holes, the surveying posed serious practical and safety challenges. The topography was constructed and compared to a crude survey previously done by the client immediately after the damage was noticed. The comparison provided much insight into the dynamics of the flow and evolution of the topography between these two surveys. **Figure 7** shows two examples of evolution of erosion along two lines, 4 m and 8 m away from the edge of the concrete apron. The horizontal axis is parallel to the edge, the origin lies on the axis of symmetry of TOS and the vertical axis shows the erosion depth. The growth of the erosion and the profile migration are clearly seen from the plots. Although the flow through TOS is fairly symmetric, none of the erosion profiles downstream of the apron was symmetric because the flow beyond the apron is inclined towards the outlet structure by the pull of the outflow from the pond. Some of these features were simulated in the scale modeling studies later.

Depositional Islands: Eight (8) depositional islands were recognized, measured, and sampled, see Figure 4d. The positions, compositions, and shapes of these islands allowed firm conclusions about the amount of erosion from the pond bed layers, sediment contribution from the surface runoff (through chute 1 in particular), flow circulation inside the basin, actual near-bed shear stresses and flow velocities around TOS, and the evolution of the pond bed in the absence of rehabilitation. Among interesting findings of the study was that the neglect of the original designer in letting in large amount of sediment with surface runoff to the pond turned out to act as a 'blessing in disguise' after the scour led to the liner rupture: The external sediment, pulled from the sand bar in front of chute 1, mixed with the flow, filled some depressions and acted like the materials needed for artificial nourishment for the area susceptible to constant erosion.

CONCLUDING REMARKS

The planning and implementation of a multi-faceted field investigation were discussed as related to a rehabilitation project on the damages to a large regulating embankment pond. Major damages included two parts. (i) Big scour holes downstream of the concrete apron of an energy dissipation structure below the tailrace tunnel of a hydropower station, and (ii) multiple rupture of a waterproof liner in the damaged area. The pond was in use on a daily basis as the regulating storage for the release of the water from the tailrace of a hydropower station. The vital role of the station in helping the national power grid in peak hours as well as a reasonable hope for the short term safety of the pond made it near impossible to stop the operation for more than a couple of days to conduct site investigation. Faced with two conflicting needs, namely inspect the dry pond and continue to operate the pond, a thorough intense site investigation was accomplished in 24 hrs. The plan aimed at collection of as much data as possible within a short time in order to answer the maximum number of major questions of the rehabilitation study. On top of the major concerns and questions of the study were a realistic picture of the damage, the timing of the damage, damage mechanism and process, whether the pond was leaking, safety of the embankment, remedial modifications, and preventive measures. It was shown how the site investigation was planned and what the rationales were in utilizing the data obtained from each activity. The major findings of the study were:

a. The scour holes were progressing gradually, endangering larger area of the pond.
b. The damage must have happened in the early stage of the pond operation eight (8) years before it was noticed.
c. No water loss from the pond foundation or the embankment could be found or substantiated.
d. The embankment was free from detectable cavity and wet regions beneath the liner.
e. The sediment laden surface runoff from chute No. 1 had to be stopped as the intruded sediment contributes to formation of several depositional islands reducing the live capacity of the pond.
f. Energy dissipation structures of TOS had to be enhanced to protect the pond floor against scour.

The vital role of field investigation in design studies of water engineering projects has been emphasized sufficiently in the literature. However, rarely have the planning and details of the investigations been reported in research publications. The lessons and experiences from the present report of the site investigation can enrich the existing literature on practical challenges in obtaining rigorous evidence required for the associated analytical, scale modeling or numerical analyses.

LITERATURE CITED

ISHPF (2010), "*International Symposium on Hydraulic Physical Modeling and Field Investigation*", Proceeding, Sept. 13-15, Nanjing, China

Hughes, S.A. (1993). "*Physical Models and Laboratory Techniques in Coastal Engineering*", New Jersey, World Scientific Publishing.

Novak P. (2010), "Introduction to Hydraulic Modelling: Principles, Methods, and Applications", Routledge, 512 pp

Papanicolaou A.N., Dermisis D.C. (2007), "Field Investigation of Hydraulic Structures Facilitating Fish Abundance and Passage through Bridges in Western Iowa Streams", *Proceedings of the 2007 Mid-Continent Transportation Research Symposium*, Ames, Iowa, August, Iowa State University Publishing Co.,

Refsgaard J.C., Henriksen H.J. (2004), "Modeling guidelines- terminology and guiding Principles", *Advances in Water Resources*, Vol. 27, 71-82

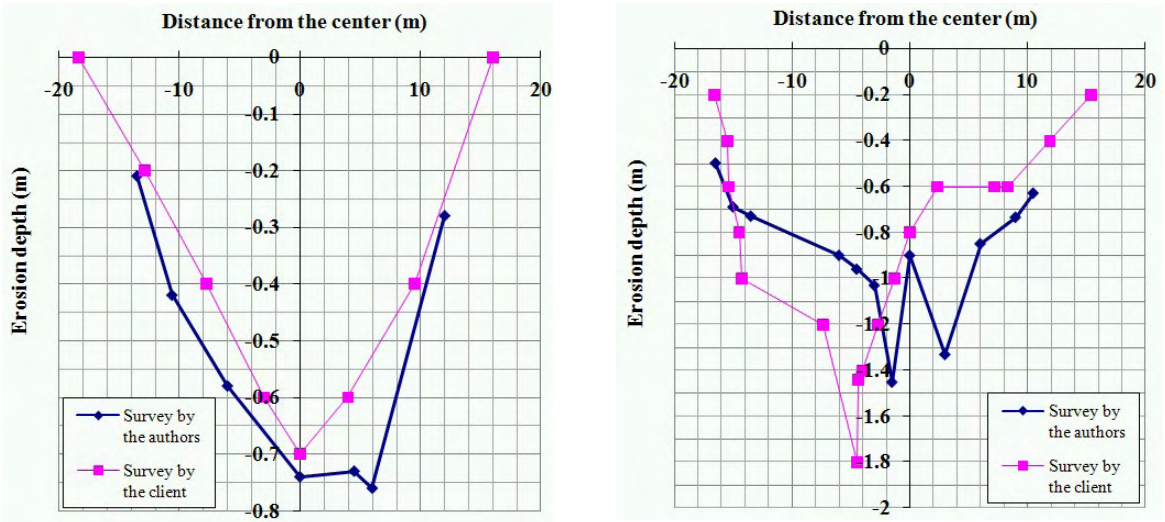
Saiedi S., Vallyutham K. (2007), "Experiences in Design and Construction of a Hydraulic Model for Energy Dissipation and Erosion Studies", 5th *International Conference on Dam Engineering*, Laboratório Nacional de Engenharia Civil (LNEC), 14-16 Feb., Lisbon, Portugal

Saiedi S., Mustaffa Z., Hee Min T., Abu Bakar N. (2009), "Challenges in Physical Modeling of Erosion", *Physical Modeling Application & Technology (PHYMAT 2009)*, Seminar at National Hydraulic Research Institute of Malaysia (NAHRIM), 15 Dec, Key Note Paper

Saiedi S., Awad A., Azahar S.B. (2010), "Lessons from Bed Erosion and Liner Rupture of a Large Storage Pond", *GEO2010*, Canadian Geotechnical Society (CGS), Calgary, Canada, 12-16 September (to be published)

USACE (1993), "*River Hydraulics*", US Army Corps of Engineers, Engineer Manual EM 1110-2-1416, Oct., 176 pp

==========



a. 4 m away from the edge of the apron **b.** 8 m away from the edge of the apron

Figure 7. Evolution of the scour profile in front of TOS from the field study

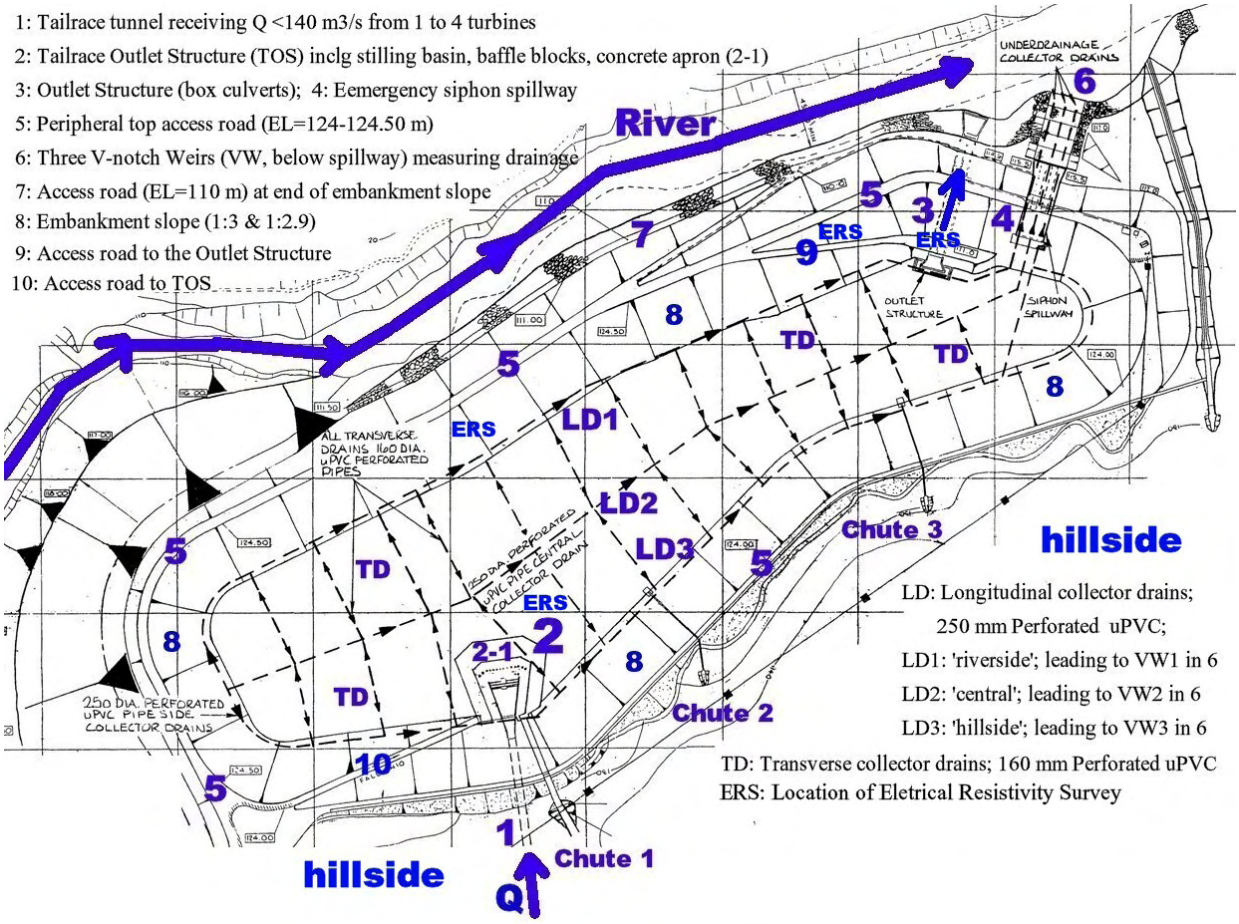


Figure 1. Embankment pond layout and details

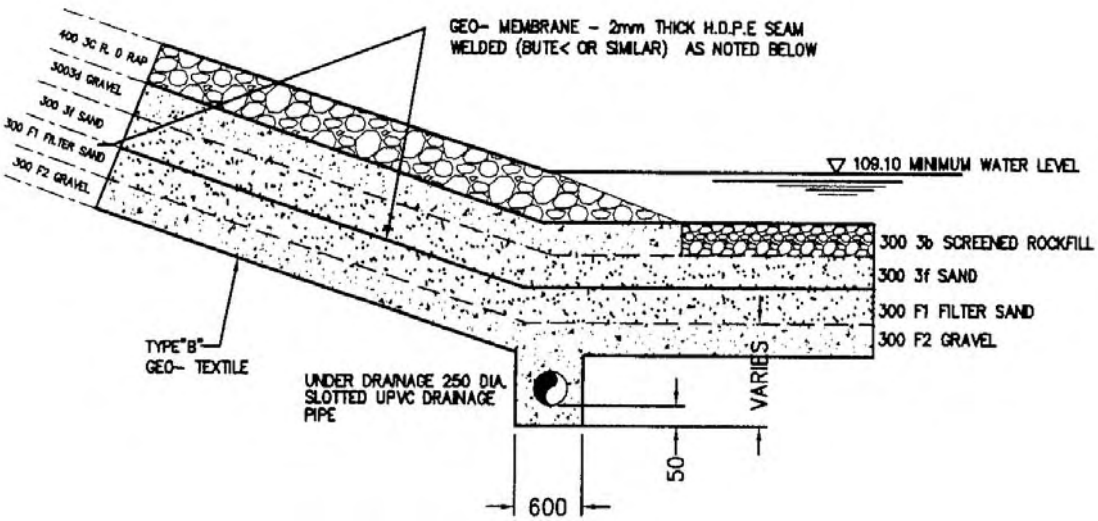
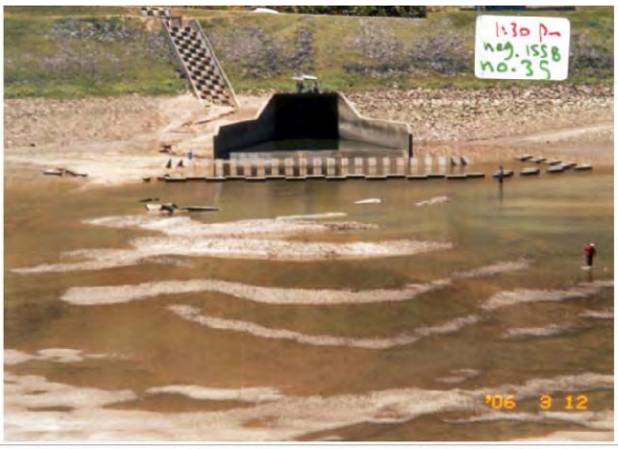


Figure 2. Layers forming the pond floor and the collector drain

Table 1. Major questions facing the study for rehabilitation of the damaged pond and major ways to address the questions

No.	Major Questions	Logical Line of Action	Remark
1	What exactly happened?	Site Inspection & Field measurements	(i) Study of the available photos, videos and internal reports on the detection of the damage and preliminary investigation (survey of the damaged area under water) (ii). Conducting a thorough field investigation during and after while drying the pond.
2	Why did it happen?	a) Physical modeling studies b) Desk engineering/analytical studies c) Numerical Simulation	Item (c) was intended initially to obtain the velocity and pressure fields on (& downstream) of TOS to compute both the dynamic forces on the baffle blocks and bed shear stress over the pond floor (sediment transport). It was discarded for time considerations because scale model studies were yielding sufficient insight.
3	When did it happen?	a) Scrutiny of the historical data b) Local investigation c) Physical modeling studies	On (a): (i). Presuming the liner rupture leads to water leak through the pond floor, the record of drainage through perforated drain pipes ending at the V-notch Weirs was the target of special scrutiny. (ii).The history of electricity generation (directly proportional to Q from turbines) was explored to identify dates/timing of highest flow through TOS.
4	How did it happen? (Process)	a) Physical modeling studies b) Site Inspection & Field measurements c) Desk engineering/analytical studies	Item (b) did not give any particular clue as to the damage date. Items (a) and (c) both showed the inadequacy of the original design in terms of the bed protection in front of TOS. It was concluded that the damage must have happened in the early days/weeks of operation under moderate to high discharges associated with two/three of active units (turbines).
5	Is the pond leaking?	a) Field measurements b) Desk/engineering/analytical studies c) Scrutiny of the historical data	On (a): (i). See 2.a.i above. (ii). The flow in a small drain near the outer slope of the riverside embankment was watched during and after water drawdown. (iii). The river discharges at two sections, far from each other alongside the pond embankment, were measure simultaneously to see if the probable leak from the pond causes any difference.(iv).The most probable place for the leak was near LD2 (central longitudinal collector drain; see Figure 1) making one to expect increased outflow from VW2.
6	Is the opposite embankment safe?	Site Inspection	Electrical resistivity test was performed on the embankment to look for suspected cavities and or wet regions.
7	Any structural damages?	Site Inspection	No damage to hard structures was detected.
8	What are the necessary rehabilitation works?	Site Inspection	(i) Removal of the intruded silt from surface runoff. (ii). Clean-up of the pond floor. (iii). Reconstruction of the eroded bed layers below and above the liner. (iv). Repair of the HDPE liner.
9	How to secure the pond for future?	a) Physical modeling studies b) Desk engineering/analytical studies c) Implementation of the remedial works	(i). Improved energy dissipation of the flow through TOS by additional baffle blocks. (ii). A protected transition region between the concrete apron and the pond floor surrounding the apron. (iii). A sediment barrier on the stream leading to chute 1 to stop intrusion of sediment with surface runoff.



Tailrace outfall structure, chute 1 & baffle blocks

a. Prototype TOS and bed floor

b. Scale model of TOS and bed floor

Figure 3. Actual and scaled TOS viewed on the centerline from the opposite embankment

Table 2. Major activities during 24 hrs of field investigation

No.	Activity	Time	No. of persons[1]
1	Photography (still photo + video)	effectively always	10
2	Planning and coordination with station operator and team members	always	1
3	Record of water level changes in the pond during drawdown (TOS and the outlet structure)	Evening, 1st day	2
4	Samples of water from various places of the pond	during dry down	2
5	Samples of drainage water from v-notch weirs	every ½ hr	1
6	Visual inspection of the inner slope of the embankment	morning, 2nd day	1
7	Visual inspection of all appurtenant structures[3]	morning, 2nd day	1
8	Detailed inspection of the damaged area	afternoon, 2nd day	2
9	Surveying the pond floor topography	2nd day	3-5
10	Sediment sampling from the pond floor, all depositional islands, various locations of the damaged area, three chutes, and stream leading to chute 1	2nd day	4
11	Electrical resistivity survey	2nd day	3

[1] The team had 11 members. Most team members participated in more than one task.
[2] The pond had never been fully dried so it was necessary to inspect the slope from inside for signs of erosion, settlement and crack.
[3] These were TOS-related structures (diverging stilling basin, end sill, ramp, baffle blocks, concrete apron), outlet structure (box culverts), and siphon spillway.

a. TOS under 3.9 m of water; Q=105 m^3/s; the sediment pile below chute 1

b. Chute 1, sediment pile, TOS

c. TOS under 6 m of water

d. Summary of the damages; pond is effectively dry; concrete apron perimeter and damaged area are marked; 8 depositional islands are labled

Figure 4. Views of the pond before and after the dry pond inspection

a. View from Chute 3 to outlet structure and siphon spillway

b. low flow through the entrance of the outlet structure

c. measuring drainage through V-notch Weir 1

d. Three outlets of the drainage pipes below siphon

Figure 5. Pond at the final stage of dewatering and v-notch weirs

a. Exploring the big depression in front of TOS

b. Ruptured liner

c. Damages downstream of concrete apron; ruptured liner; un-leveled hard rocks below liner (all photos before construction of the rehabilitation)

Figure 6. Liner rupture