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LEAKAGE ASSESSMENT OF WATER CONVEYANCE TUNNEL FOR HYDROPOWER PLANT VIA WATER BALANCE

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ABSTRACT

Leakage is a common problem for pressurized water conduit. Currently available leakage assessment methods require reasonable penetration of accurate metering and simultaneous flow measurements at critical locations continuously for a period. To address inadequacy of accurate flow meters, water levels were measured and converted to flows for assessment in this study. Meanwhile, to enable "simultaneous" measurements at the constraints of metering, manpower and transport, a steady state flow condition is maintained throughout the assessment period. This is done by keeping the driving force of the water conveyance tunnel being studied, which is the generated power of the downstream hydropower plant constant. Then, water balance was applied to the single set of average measurements taken at all critical locations for leakage assessment. This method has proven to be useful in assessing leakage condition for the system with metering, manpower and transport constraints. However, the assessment results may be affected by measurement performance.

Keywords: leakage assessment, water balance, water conveyance tunnel.

INTRODUCTION

Leakage is common in water conduit particularly those pressurized ones such as the water conveyance tunnel for the hydroelectric power plants. However, like other types of water loss, it is not desirable as it negatively affects the system cost, performance and safety.

Water leakage from water conveyance tunnel is costly. The leaked water, instead of being used for power generation, is lost from the system and left untapped. As a result, the same power can only be generated with higher input flow. Worse still, the water conveyance tunnel is inadequate to supply input flow for maximum power.

If leaks are not located in time and repaired accordingly, they will grow in size and present other problems. Sediments may infiltrate into the water conveyance tunnel and increases its head losses. If not removed in time, these infiltrated sediments may then travel downstream and cause turbine erosion.

On the other hand, unattended leaks are likely to expand and propagate and become both safety and financial hazards as in ruptured pipes or collapsed tunnel.

Unfortunately, despite of its prevalence, there is no foolproof solution yet to completely eliminate water leakage. Thus, water pipe network or conveyance tunnel shall be assessed periodically at least for cost, performance and safety concerns.

In water leakage assessment, the conservation of mass, i.e. water balance is applied to audit in detail the water entering to, exiting from and storing into the hydrologic system with clearly-defined boundary. From this assessment, the amount of water lost in the system can be estimated.

Two types of assessment, namely top-down and bottom-up, can be performed [1].

Top-down leakage assessments are implemented at the initial stage to screen out high-leakage sub-network from the complete network based on metered consumption and approximated losses. Two main approaches for this assessment are International Water Association, IWA and Water Services Regulation Authority, OFWAT [1-2].

Meanwhile, bottom-up leakage assessment may serve as the follow-up to top-down assessment and is performed on the identified sub-network. There are two approaches to carry out this assessment, namely 24 Hour Zone Measurement, HZM and Minimum Night Flow (MNF). Both approaches are adopted for a reduced zone of the network or District Metered Area, DMA. Besides, the duration of the assessments is limited. For HZM, the assessment lasts for 24 hours whereas MNF is usually performed during the low consumption period, typically 02:00 to 04:00 hour [3-5]. Moreover, both methods require acquisition of inflow and/or pressure data simultaneously and continuously for the entire assessment zone during the assessment period.

The last requirement is hard to come by particularly for network with poor metering penetration, as illustrated by the case study presented in this paper. In the case study, leakage assessment is applied on the water conveyance tunnel for a run-of-river type hydropower plant. Since there is only one water conveyance tunnel for this hydropower plant, there is no need to conduct top-down leakage assessment.

However, as there is no calibrated or reasonably accurate instrument available for either flow or pressure measurement, it is not feasible to perform bottom-up leakage assessment. Furthermore, the length of the water conveyance tunnel is long (8.5 km) and it covers an area of rough and hilly terrain, thus traveling back and forth among all incoming and outgoing points for measurements is unlikely. Therefore, this paper delves in to present a methodology for setting up and subsequently performing bottom-up leakage assessment in system with metering constraints.

The paper is laid out as follows. After this introduction, the relevant background information is

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given. This is followed by methodology, results and discussion. Finally, the main conclusions are drawn.

BACKGROUND

The case study used to illustrate bottom-up approach with metering constraints is the assessment of leakage for the water conveyance tunnel of Lower Piah Power Station (LPIA) in Perak, Malaysia. This water conveyance tunnel, which is also known as penstock or power tunnel by the hydropower community, is 8.5 km long and located underground.

Figure-1 shows the schematic of Lower Piah Power Station with its incoming and outgoing measuring locations. Six intakes and three exits are listed in Table-1, in the order of flow.

Table-1. List of incoming and outgoing measuring locations for lower piah power station.

Measuring Location	Incoming / Outgoing
Sungai Toor	Incoming
Sungai Piah	Incoming
Upper Piah Power Station	Outgoing
Toor Diversion Weir	Outgoing
Sulieh	Incoming
Chier	Incoming
Dindap	Incoming
Beltek	Incoming
Piah Outfall	Outgoing

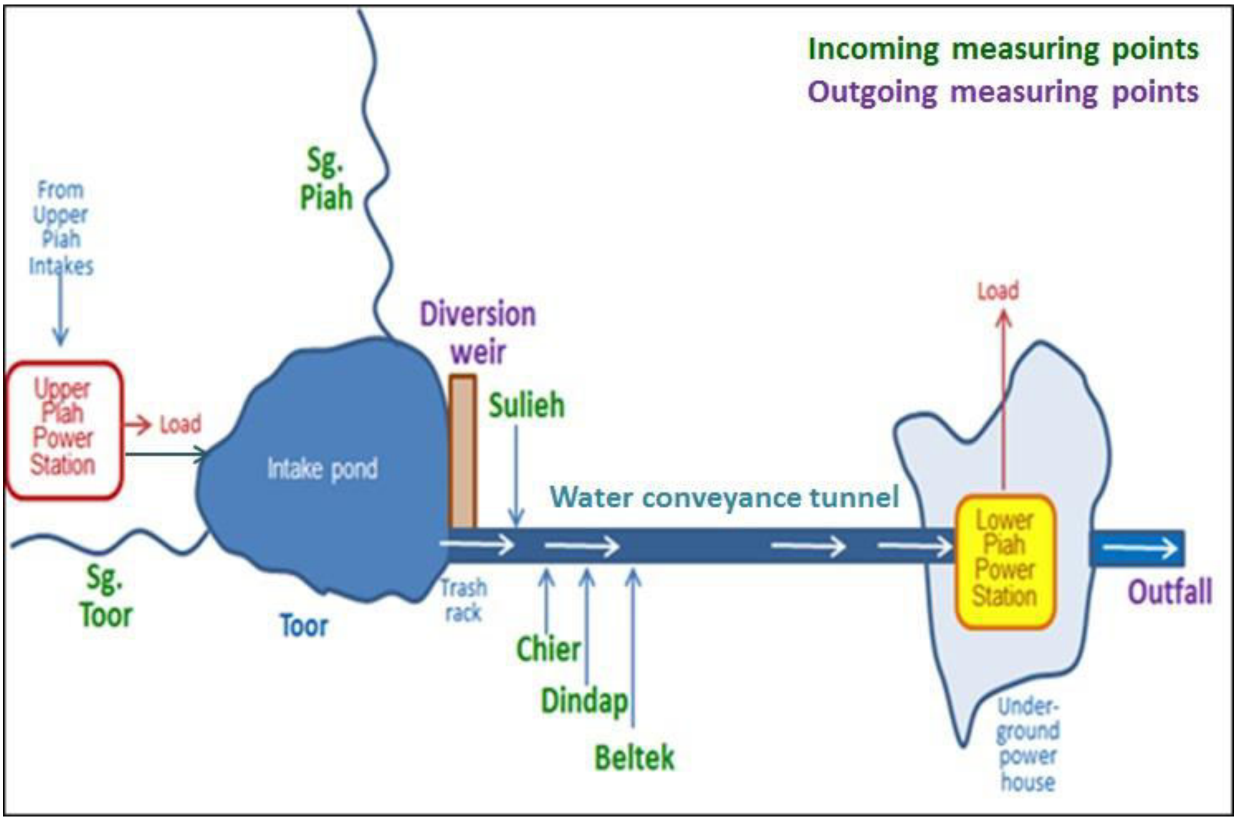

Figure-1. Schematic of lower Piah power station with its incoming and outgoing flow measuring locations.

METHODOLOGY

Setting up for bottom-up leakage assessment

There are two constraints to be addressed, namely inadequacy of measuring instrument and lack of manpower and transport to conduct measurements at all measuring locations simultaneously and continuously.

The project team has only two portable electromagnetic flow meters. To address the inadequacy of measuring instrument for flow measurements, the water levels were measured instead of the flows for all measuring locations to perform leakage assessment.

To enable the conversion from water levels to flows, the correlation between these two variables for all intakes and exits were established first. This requires the measurements of both water level and flow for all locations. Water levels were measured using measuring tape at ±2 mm accuracy. Meanwhile, the flows were calculated using velocity-area method, standard weir equation or the general formula for hydraulic machines.

Table-2 lists all measuring locations with the type of hydraulic component they belong to and the corresponding flow computation method.

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Table-2. Type of hydraulic component and the corresponding flow computation method for all measuring locations of lower Piah power station.

Measuring Location	Hydraulic component	Flow computation method
Sungai Toor	Natural stream	Velocity-Area
Sungai Piah	Natural stream	Velocity-Area
Upper Piah Power Station	Hydraulic machine	General hydraulic machine formula
Toor Diversion Weir	Manmade weir	Standard weir equation
Sulieh	Natural stream	Velocity-Area
Chier	Manmade weir	Standard weir equation
Dindap	Natural stream	Velocity-Area
Beltek	Manmade weir	Standard weir equation
Piah Outfall	Manmade channel	Velocity-Area

Velocity-area method is applied to natural streams and manmade channel. The velocities of the streams or channel were measured using electromagnetic flow meters with accuracy at ± 0.5% of reading plus 5 mm/s for the range from -5 to 5 m/s and their areas (widths and depths) were measured using measuring tape.

For the manmade weirs, the flows were computed using standard weir equation according to the respective type of weir, based on the measured dimensions such as width and length of the weir as well as the height of the water surface elevation above the weir surface, measured sufficiently upstream of the weir face. The weir for Toor Diversion is ogee type. For ogee weir [6], the flow is

$$Q = \frac{2}{3} C_{d_o} \sqrt{2g} L_e H_d^{1.5} \quad (1)$$

Q = flow,
C_{d_o} = the coefficient of discharge at head H_d,
g = gravitational acceleration,
L_e = effective length of the weir,
H_d = head inclusive of the velocity of the approach head

The coefficient of discharge at H_d, C_{d_o} is dependent on the ratio of weir height, P to H_d. Figure-2 illustrates the variation of C_{d_o} to P/H_d ratio.

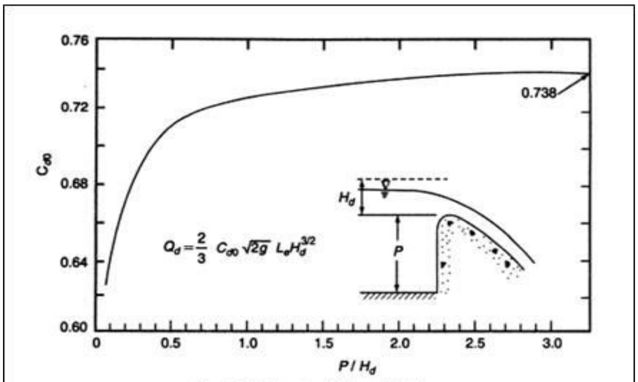

Fig. 7.13 *Variation of C_{do} with P/H_d*

Figure-2. Variation of C_{d_o} to P/H_d [6].

Meanwhile, both Chier and Beltek are broad-crested type of weirs. For this type of weir, the standard equation [6] is

$$Q = \frac{2}{3} C_d \sqrt{2g} L\ H_1 \quad (2)$$

C_d = the coefficient of discharge,
L = length of the weir in the traverse direction of flow,
H_1 = height of the water surface elevation above the weir surface, measured sufficiently upstream of weir face

The coefficient of discharge, C_d is dependent on the ratio of H_1 to the width of the weir in longitudinal direction, B_w. Figure-3 shows the classification of weir based on H_1/B_w ratio.

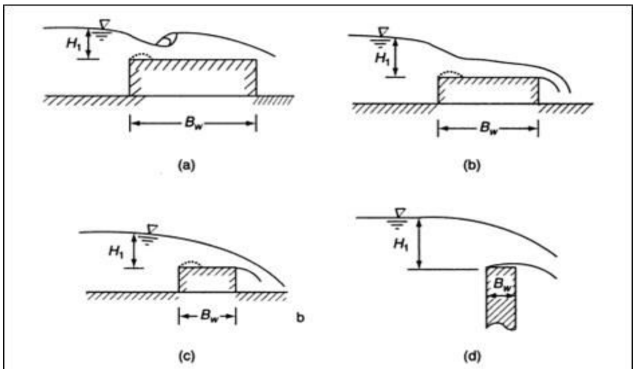

Fig. 7.17 (a) *Long-crested weir* ($H_1/B_w \leq 0.1$)
(b) *Broad-crested weir* ($0.1 \leq H/B_w \leq 0.35$)
(c) *Narrow-crested weir* ($0.35 \leq H_1/B_w \leq 1.5$)
(d) *Sharp-crested weir* ($H_1/B_w \geq 1.5$)

Figure-3. Classification of weir based on H_1/B_W ratio [6].

For broad-crested weir, the coefficient of discharge is

$$C_d = 0.02(H_1/B_w) + 0.521 \quad (3)$$

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Finally, for the discharge from Upper Piah Power Station, the general formula of hydraulic machine was used.

$$Q = \frac{P}{\eta \rho g H} \tag{4}$$

P = generated power,
η = overall efficiency,
ρ = density of water,
H = gross head, i.e. forebay elevation − tailrace elevation

Based on the measured water levels and calculated flows, the correlation between these variables can be found via

$$Q = kH_e^{1.5} \tag{5}$$

k = stage-discharge (Q versus H_e) coefficient,
H_e = effective head or depth

Equation (5) was derived from the equation for free or restricted flow below. As shown, $k = W_e \times C_v \times \sqrt{2g}$.

$$Q = A_e \times C_v \times \sqrt{2gH_e}$$
$$Q = W_e \times H_e \times C_v \times \sqrt{2gH_e}$$
$$Q = W_e \times C_v \times \sqrt{2g} \times H_e^{1.5} \tag{6}$$

A_e = effective wetted area,
C_v = coefficient of velocity,
g = gravitational acceleration,
W_e = effective width of flow area

The other constraint is shortage of manpower and lack of transport to conduct the measurements of water level concurrently and continuously. To ease this logistics issue, only one set of few average measurements was taken at all sites. This means the assessment is only a snapshot rather than continuous trends of the actual leakage condition.

Even in the case of taking one set of measurements, it is not possible for two teams of researchers and technicians to cover seven measuring locations at the same time. Note that during the assessment period, Sulieh has been shut down for sediment flushing maintenance and thus is not required for measurement. Besides, the data of generated power for Upper Piah Power Station has been archived continuously and can be retrieved after the assessment period.

Taking all these constraints into consideration, one possible way for pseudo-simultaneous leakage assessment is by ensuring steady state flow condition throughout the assessment period. To achieve this, the driving force of flow in the water conveyance tunnel, namely generated power from Lower Piah Power Station was kept constant from at least four hours before the assessment (i.e. the approximated travel period for steady state flow from Toor Intake to Lower Piah Power Station) to the end of the assessment period. Besides, the water level or spillage (if any) from Toor Diversion Weir is maintained. Moreover, the precipitation condition at all measuring locations are monitored to ensure no rain event in the stated period.

Performing bottom-up leakage assessment

Before the start of measurements, the project team ensured that a fixed level of power has already been generated for at least 4 hours from Lower Piah Power Station. Then, station personnel were informed to continue keeping the generated power at that level until the end of the assessment.

Next, the project team, which was split into two, started the measurements of water level from the most upstream measuring locations, i.e. Sungai Toor, Sungai Piah, followed by Toor Diversion Weir, Chier, Dindap and Beltek. Note that measurement was not performed at Sulieh as it was shut down for maintenance during the assessment period.

Unfortunately, the project team was unable to complete the measurement at Piah outfall on the same day. Hence the water level at Piah Outfall was measured the next day after ensuring that Lower Piah Power Station has generated the same power output from at least one hour before the measurement (i.e. the approximated travel time for steady state flow from Lower Piah Power Station to Piah Outfall) to the end of the measurement period.

In addition, the power generation data at Upper Piah was retrieved via online historian.

After that, the flows for all measuring locations were computed based on the measured water levels as in (5). The incoming and outgoing flows were then totaled up respectively for comparison to assess the leakage condition via the water conveyance tunnel.

RESULTS AND DISCUSSION

While carrying out the measurements to establish water balance for leakage assessment, Lower Piah Power Station has kept the power output of turbine-generator no. 2 at 25 MW and shut down the other turbine-generator for at least 4 hours. Besides, Sulieh was closed for maintenance. Thus, the flow over Sulieh is bypassed and not channeled into the water conveyance tunnel for power generation at Lower Piah Power Station. As a result, this flow was excluded from the flow computation for water balance.

Table-3 shows the stage-discharge coefficients that was calibrated (before the measurement), water levels or effective depths measured during steady state flow condition and the calculated flows for all measuring locations except Upper Piah Power Station.

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Table-3. Earlier-calibrated stage-discharge coefficients, measured effective depths and the corresponding flows for all measuring locations (except upper Piah power station) during steady state flow condition.

Measuring Location	k	H_e	Q
Sungai Toor	10.097	0.490	3.463
Sungai Piah	11.350	0.119	0.466
Toor Diversion Weir	32.641	0.040	0.261
Chier	3.320	0.265	0.453
Dindap	9.847	0.076	0.206
Beltek	1.594	0.218	0.162
Piah Outfall	5.050	1.269	7.219

To complete the water balance under steady state flow condition, the discharge from Upper Piah Power Station was calculated as in (4) based on the recorded data given in Table-4.

Table-4. Data recorded during steady state flow condition for upper Piah power station.

Variable	Symbol	Engineering Unit	Value
Generated power	P	MW	5.4
Overall efficiency	η	%	80.66
Density	ρ	kg/m^3	997
Gravitational acceleration	g	m/s^2	9.781
Gross head	H	m	261

Consequently, the incoming and outgoing flows during steady state flow condition used to establish water balance for leakage assessment were summarized in Table-5 and Table-6, respectively.

Table-5. Incoming flows for the water conveyance tunnel of lower Piah power station.

Incoming Measuring Location	Calculated Flow (m^3/s)
Upper Piah Power Station	2.630
Sungai Toor	3.463
Sungai Piah	0.466
Sulieh	Not applicable
Chier	0.453
Dindap	0.206
Beltek	0.162
Total Incoming	*7.380*

Table-6. Outgoing flows for the water conveyance tunnel of lower Piah power station.

Outgoing Measuring Location	Calculated Flow (m^3/s)
Toor Diversion Weir	0.261
Piah Outfall	7.219
Total Outgoing	*7.480*

Based on Table-5 and Table-6, it can be observed that total outgoing flows exceeded total incoming flows by 0.100 m^3/s during steady state flow condition. This indicates no traceable leakage via the water conveyance tunnel of Lower Piah Power Station. Possible reasons for higher total outgoing flows include measurement uncertainties and additional, unidentified water source into the network. Figure-4 illustrates the water balance for the water conveyance tunnel of Lower Piah Power Station during steady state flow condition.

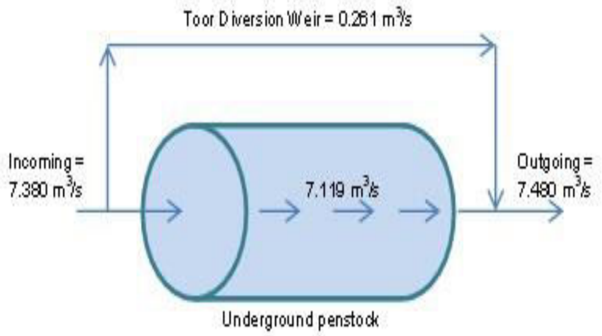

Figure-4. Water balance for the water conveyance tunnel of lower Piah power station during steady state flow condition.

The leakage condition for pressurized water conduit such as the water conveyance tunnel for hydropower plant has been successfully assessed by taking water balance at a steady state flow condition, i.e. in a snapshot. This success conforms to our understanding, since the method used is similar to the widely-practiced MNF method for bottom-up leakage assessment, whereby both are conducted for a relatively low-fluctuating flow condition within a short period of time. Nevertheless, as the measurement uncertainties may influence the results of leakage assessment, high-accuracy meters shall be used in the process to ensure the success of assessment.

CONCLUSIONS

Taking water balance for a steady state flow condition, i.e. in a snapshot has proven to be feasible in assessing leakage condition via pressurized water conduit. This method is particularly useful for those with constraints such as inadequacy of accurate flow meters, shortage of manpower and problem of moving around.

In the future work, the practitioner should tackle this method's reliance on high-accuracy meters. Possible approaches include integration of the measurement results with statistical analysis and finding the minimum numbers of measurements required for conclusive results.

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