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Estimation of the Duration of the Turbidity Current in a Reservoir

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ABSTRACT

During floods, a huge amount of sediment yield in the watershed of a reservoir is an important issue especially for aging dams. Sedimentation reduces a reservoir's capacity, affects the outlet works, and may impoverish downstream ecosystems. For this purpose, the duration of the turbidity current is essential in the operation of reservoir desiltation. An empirical formula is proposed in this paper to estimate the duration of the turbidity current. Inflow discharge, sediment concentration and reservoir levels are used as input to the proposed formula. An actual application to Shihmen Reservoir in northern Taiwan is conducted to demonstrate the advantage of the proposed formula. The estimated duration of the turbidity current is expected to be useful for flood control and sediment releasing operation of Shihmen Reservoir.

KEY WORDS: turbidity current, empirical formula, the duration.

INTRODUCTION

In recent years, the issues related to the sustainable operation and storage reservation of existing reservoirs are essentially important. The loss of active reservoir volume due to sedimentation was higher than the increase of reservoir capacity by construction, according to the report by Oehy (2007). Useful desiltation strategies and effective counter measures have been investigated in relative researches (Morris and Fan 1998; Lee *et al*. 2010a; Sumi *et al*. 2011; Lee *et al*. 2012).

Taiwan is an island situated at a geographical location with the special climatic condition that brings 3~4 typhoons to this island per year on the average. On the one hand, these typhoons often result in flood disasters that can cause serious damage to properties and sometimes with severe casualties. On the other hand, when typhoon or heavy rainfall occurs, the watershed may generate a great amount of sediment yield. Land development in the watershed could also accelerate soil erosion. In addition, earthquake-triggered landslides in mountainous areas could supply a large amount of sediment from upstream river basin. Sediment produced in upper basins may not be immediately delivered to lower basin owing to river aggradations. However, still great part of sediment can be transported and deposited in upstream river particularly during extreme rainfall events, which could generate turbidity current into a reservoir (Lee *et al*. 2014). As sediment is transported into a reservoir, deposition occurs due to flow velocity decrease. In general, the large size sediment may deposit quickly to form delta near the backwater region tail. The hydraulic phenomenon of delta area is similar to the shallow water in open channel flow. The sediment-laden inflow consists of two parts, bed load and suspended load. The bed load may deposit at the front set of the delta, and the suspended load may flow through the delta and deposit by sorting. When turbid inflow with finer suspended load continues to move, the turbulence energy decreases by resistance. The inflow may plunge into the reservoir to develop turbidity current and move toward downstream. On the downstream side of the plunge point location, the water near the surface in the reservoir can flow toward upstream due to continuity behavior of the flow. Fig. 1 illustrates the phenomenon of a turbidity current, flume and field measurements have shown that the occurrence of the turbidity current at plunge point location can be related to flow velocity, water depth and fluid density before plunge point location (Graf 1983).

To estimate the duration of the turbidity current is very important. It affects the reservoir operation. The one-hour early operation of outflow structures make 9×10^9 m^3, which 9/153 storage capacity, waste of water. Relatively, the one-hour late withdraw cause deposit leading to lower desilting efficiency. Therefore, a empirical formula is proposed to estimate the duration of the turbidity current in a reservoir. To save water resources and make higher desilting efficiency.

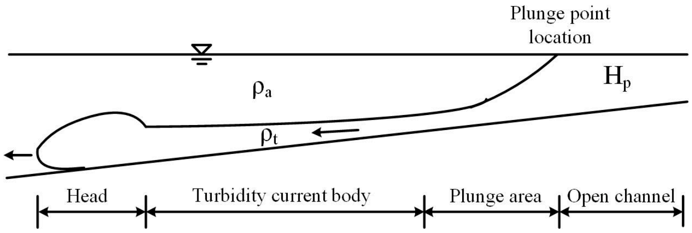

Fig. 1 Sketch of turbidity current plunging

SITE DESCRIPTION

The Shihmen reservoir is a multi-functional reservoir and its functions include irrigation, water supply, power generation, flood control and tourism. The irrigation area covers Taoyuan, Hsinchu and Taipei areas in the northern Taiwan for a total of 3.65×10^8 m^2. It is a major contributor in helping the agriculture in these areas. The reservoir supplies water to 28 districts and 3.4 million people, which provides major water resources for the livelihood of the people in the northern Taiwan. Making use of the water impoundment at Shihmen dam, the Shihmen Power Plant annually generates 2.3 hundred million KWH (kilowatt per hour) vitally contributing electric power demand and industrial development at peak hours. Another function of the reservoir is to mitigate flood damage on the downstream areas during typhoons and heavy rain seasons by reducing flood peak discharge.

The Shihmen reservoir has a natural drainage area of 762.4 km^2. It is formed by the Shihmen dam located in the upstream reach of the Dahan River flowing westward to the Taiwan Strait (Fig. 2). The Shihmen dam completed in 1963 is a 133 m high embankment dam with six spillways, one bottom outlet, two power plant intakes and two flood diversion tunnels. The elevations of the spillway crest, bottom outlet, power plant intake and flood diversion tunnel are EL.235 m, EL.169.5 m, EL.173 m and EL.220 m, respectively (Fig. 3). The design discharge of six spillways, one bottom outlet, two power plant intakes and two flood diversion tunnels are 11,400 m^3/s, 34 m^3/s, 137.2 m^3/s and 2,400 m^3/s, respectively. With a design water level of EL.245 m, the reservoir pool has 16.5 km in length and the impounding area has 8.15 km^2. The initial storage capacity was 0.31×10^9 m^3, and the active storage was 0.25×10^9 m^3. Due to a lack of desilting works, most of the incoming sediment particles had settled down rapidly along the reservoir since the dam was commissioned. Based on the survey data, the longitudinal bed profile along the reservoir had accumulated a significant amount of sediment after dam completion (Fig. 3). From recent survey data in 2013, the storage capacity was estimated to be 67% of its initial capacity. Based on particle size distribution sampled from outflow discharge in 2013 Typhoon Soulik, the sediment deposition was classified as silt or clay (Fig. 4).

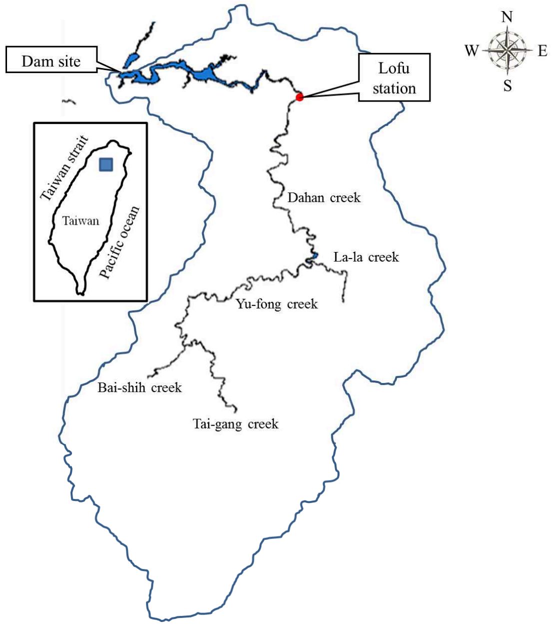

Fig. 2 Watershed of the Shihmen reservoir

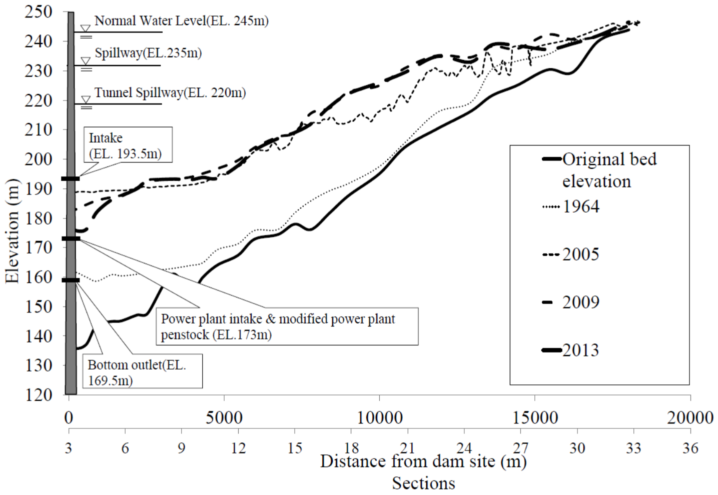

Fig. 3 The elevations of outflow structures and the bed profile change

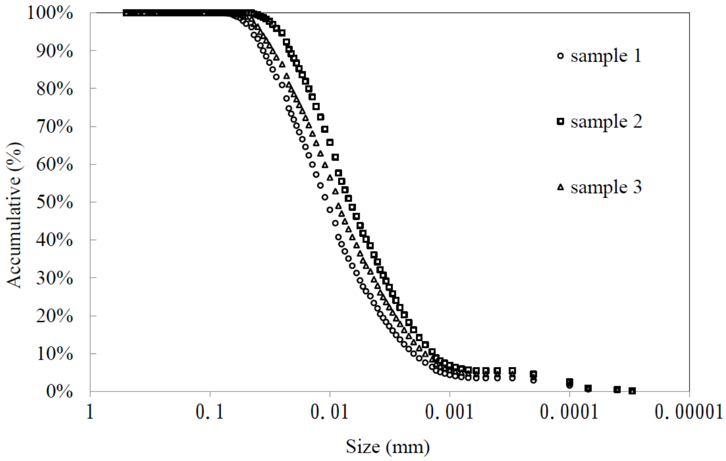

Fig. 4 Outflow sediment size sampled in Typhoon Soulik

METHODOLOGY

Extensive field studies and laboratory experiments have been conducted to thickness, vertical velocity structure and head velocity toward downstream of turbidity current in various sections (Graf, 1983; Dallimore et al., 2001; Lowe et al., 2002; Fathi-Moghadamet al., 2008; Ghazal and Khosrojerdi, 2010; Nasrollahpour and Ghomeshi, 2012; Stagnaro and Bolla Pittaluga, 2014). Many researchers (De Cesare et al., 2001) also studied the dynamics and impacts of turbidity current on reservoir sedimentation. Based on experimental data, Turner (1979) found the turbidity current head velocity (U_f) toward downstream at quasi-uniform width and without bottom friction and mixing could be expressed as:

$$U_f = \sqrt{2(\frac{\rho_t - \rho_a}{\rho_a})gh} = \sqrt{2g'h} \qquad (1)$$

where ρ_t = density of turbidity water; ρ_a = density of ambient clear water, h= the height of the turbidity current body.

In this study, according to Eq. 1, turbidity current head velocity is estimated from the depth of plunge point location instead of the height of turbidity current body, the proposed empirical formula is expressed as:

$$U_f = \sqrt{a\left(\frac{\rho_t - \rho_a}{\rho_a}\right) b g h_p} \tag{2}$$

where h_p = the depth of plunge point location, a = velocity coefficient, b = thickness coefficient defined as 0.72 (Yu, 1991).

Furthermore, Typhoon Trami in 2013, Typhoon Soulik in 2013 Typhoon Soudelor in 2015 and Typhoon Dujuan in 2015 observed data are collected to calibrate the velocity coefficient, a.

The plunge phenomenon defined as the transitional flow from homogeneous open channel flow to stratified, incursive flow. The flow field divided into fourth distinct regions, named open channel, plunge area, turbidity current body and the head region as shown in Fig. 1. Several experiments and numerical simulations of plunge point location had been presented. Most of the studies focused on the vertical pattern distribution or plunge point location variation during flow reached steady state. Therefore, several empirical entrainment formulas using densimetric Froude number which was proposed to express the plunging condition as follows:

$$\frac{U_p}{\sqrt{\frac{\Delta\rho}{\rho} g h_p}} = F_{rd} \tag{3}$$

where U_p = average velocity of plunge point location; $\Delta\rho = \rho_t - \rho_a$; g = gravitational acceleration; F_{rd} = densimetric Froude number.

The mentioned parameter, F_{rd} is experimentally ranged from 0.45 to 0.55 (Ellison and Turner, 1959; Alavian, 1986), 0.49 (Farrell and Stefan, 1988), 0.68 (Akiyama and Stefan, 1985), 0.77 to 1.00 (Schlapfer, 1987). Integrated these research results, when plunge point location happened, the densimetric Froude number ranged from 0.45 to 1.00.

Figure is the flowchart of arrival time estimation. The detail procedures of the proposed model are started as follows.

Step 1: Calculate densimetric Froude number of every section
In this step, the Eq. 3 is adapted to calculate the densimetric Froude number of every section.

Step 2: Calculate depth of plunge point location and distance form plunge point location to the dam
The plunge point location which densimetric Froude number ranged from 1.00 to 0.45 are determined. The depth of plunge point location and distance from plunge point location to the dam are calculated.

Step 3: Calibrate velocity coefficient, a
In this step, the Eq. 2 is adapted to calculate the turbidity current head velocity. The arrival time at the Shihmen dam can be estimated by using the distance from plunge point location to the dam and turbidity current head velocity. Comparison estimated and observed arrival time at the Shihmen dam, the optimum velocity coefficient, a, is determined.

Step 4: Calculate the arrival time at Shihmen dam
The arrival time at the Shihmen dam is determined by optimum velocity coefficient, a, distance from plunge point location to the dam and turbidity current head velocity.

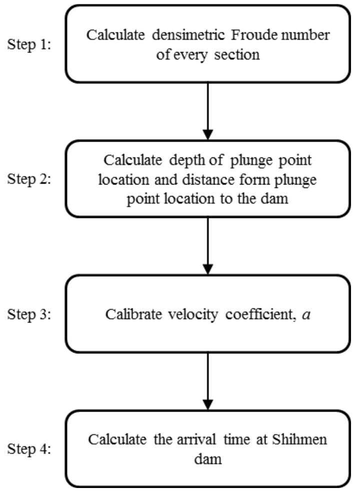

Fig. 6 Flowchart of arrival time estimation

RESULTS

Figures 7, 8, 9 and 10 show the results of plunge point location and arrival time at the Shihmen dam on every hour. Based on the densimetric Froude number ranged from 1.00 to 0.45, the plunge point location is determined where the turbid water plunged into the reservoir bottom from upstream to downstream. At the meanwhile, if turbidity current happened and started to move downstream, the turbidity current body is superimposed on every hour. In addition, the velocity of turbidity current head is moving downstream on competition condition. After the turbid water plunged into the reservoir bottom, it gradually becomes stratified in the bottom of the reservoir (Fan and Morris, 1992a; Yu et al., 2004). The turbidity current, a gravity-driven flow, occurs because of density differences between the sediment-laden flow and ambient stagnant water, which often governs the deposition process in reservoir sedimentation by transporting fine materials. The plunging current can move as an underflow over long distances toward the dam to form a submerged muddy lake. Based on estimation results of plunge point location, it is gradually moving to downstream and changing with inflow discharge and sediment concentration. The first arrival of turbidity current head depends on plunge point location, the velocity of turbidity current head, movement distance and starting time. The arrival time at the Shihmen dam in Fig. 7, 8, 9 and 10 are evolved as an upside down the parabolic line at dam site from starting time. After movement competition of each plunge point location per hour, the earliest arrival of turbidity current head shows the earliest arrival time at the Shihmen dam in Fig. 7, 8, 9 and 10. Then, the coefficient a can be adjusted using observed timing at the dam site. In the meanwhile, the value of plunge point location, velocity of the turbidity currents head, duration of the turbidity current and the densimetric Froude number at plunge point location could be evaluated. According to Eq. 1, the coefficient a affecting the velocity of turbidity currents head in constant cross-section flumes is 2. Estimated results of the coefficient a in Eq. 2 using observed data of sediment concentration between inflow section and dam site are illustrated in Table 1.

Based on the observed data of sediment concentration between inflow section and dam site, the coefficient *a* is calibrated using four typhoon events. Comparison with the coefficient values of *a* derived from experimental flume of Eq. 1 and Eq. 2 in table 2, the presented coefficient *a* which estimated from field data shows slightly smaller value owing to the 3D topographic effect of field reservoir. The lateral and vertical hydraulic dispersion effect and concentration dissipation factor affect the velocity of turbidity current head. However, the velocity coefficient, *a*, is proposed from 0.80 to 1.55 for the velocity of turbidity current head and preliminary suggested implementing in the field.

CONCLUSIONS

In this paper, an empirical formula is proposed to estimate the duration of the turbidity current in the Shihmen Reservoir. The arrival time of the turbidity current at the Shihmen dam can be estimated by using the distance from plunge point location to the dam and turbidity current head velocity. Comparing the estimated and observed arrival time at the Shihmen dam, the velocity coefficient, *a*, is determined. Using field measurements of inflow sediment concentration in the four typhoon events, the velocity coefficient *a* in the empirical formula Eq. 2 was calibrated to have the range from 0.8 to 1.55. The proposed formula can provide reasonable estimation of the arrival time of the turbidity current for the sediment desiltation operation in the Shihmen Reservoir.

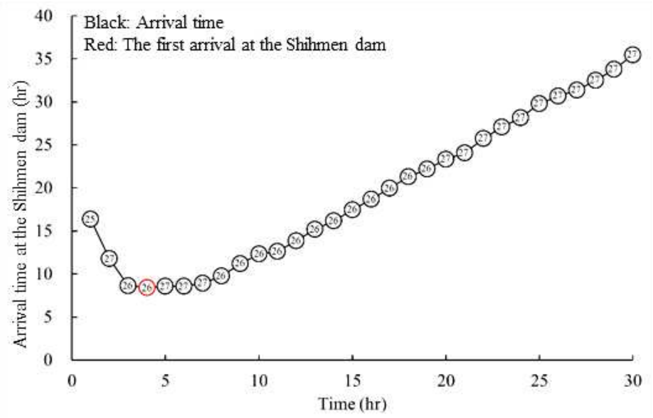

Fig. 7 Plunge point location (the number in the circle means cross section) and arrival time at the Shihmen dam during Typhoon Trami

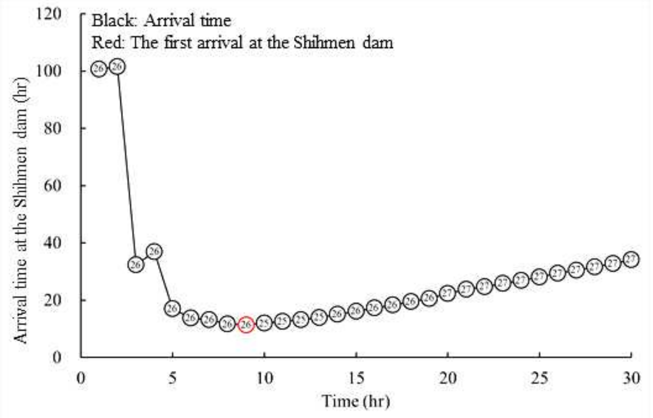

Fig. 8 Plunge point location (the number in the circle means cross section) and arrival time at the Shihmen dam during Typhoon Soulik

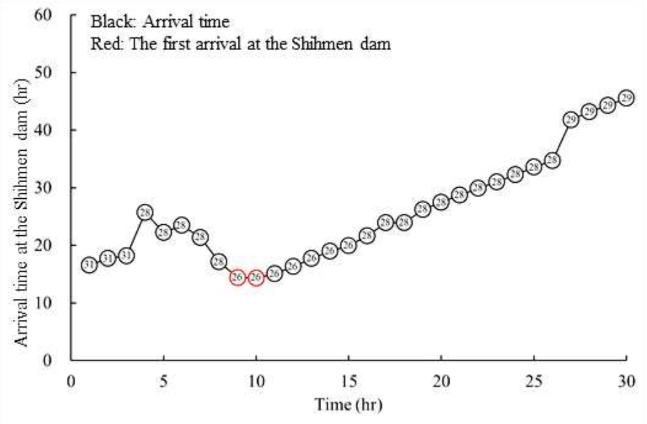

Fig. 9 Plunge point location (the number in the circle means cross section) and arrival time at the Shihmen dam during Typhoon Soudelor

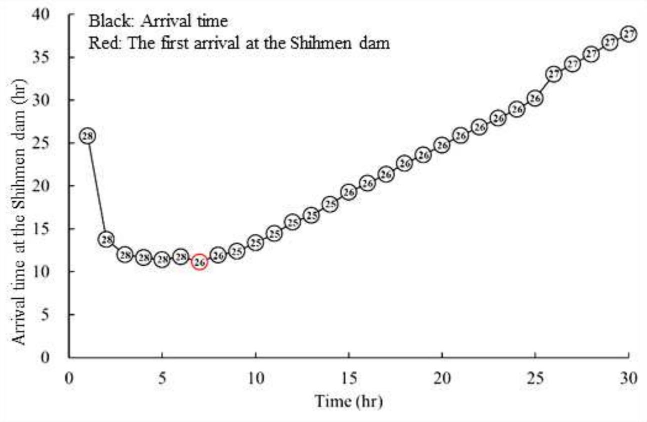

Fig. 10 Plunge point location (the number in the circle means cross section) and arrival time at the Shihmen dam during Typhoon Dujuan

Table 1. Values of hydraulic patterns

Typhoon events	*a*	F_{rd}	Plunge point location (section)	Turbidity current head velocity (m/s)	Duration of the turbidity current (hr)
Soulik	1.55	0.91	26	1.23	2.40
Trami	1.50	0.78	26	0.68	4.40
Soudelor	0.80	0.66	26	0.67	4.40
Dujuan	1.15	0.63	26	0.95	3.20

Table 2. Velocity coefficient, *a*, values

Equations	*a*
Equation (1)	2.00
Equation (2)	0.80~1.55

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