Investigation on plunge point location and turbidity current movement in the Shihmen Reservoir

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Abstract

Since the completion of a reservoir, sedimentation process decreases reservoir storage and woody debris affects the operation of power plant in many montane areas, especially in the northern Taiwan. As turbid density current travelling through a reservoir, successful operation of a sluicing outlet depends on accurate prediction of sediment transport. In-situ measured data of sediment concentration distribution during sediment release operation through bottom outlets can help understand sediment-sluicing efficiency from the reservoir. However, field measurement of the turbidity current in a reservoir is relatively difficult because of large water depth, an unsteady fluid mechanism, and harsh environments during a flood. The Shihmen reservoir is important for water supply, irrigation and flood control in northern Taiwan. Empirical equation is considered to estimate the plunge point location of turbidity current and verified with the field observations. A user interface is developed in this study to display the plunge location, movement velocity, body thickness and sediment concentration of turbidity current. For turbidity current venting, the plunge point location and turbidity current movement estimation can provide real-time information to assist the operations of bottom outlets and sediment bypass tunnels. In the future, coping with rainfall runoff prediction, the prediction of turbidity current movement can also expect to improve the desiltation operation of the Shihmen reservoir. The study results can be applied to the related disaster prevention issues on water resources sustainable, reservoir sedimentation and water treatment capacity.

Keywords: plunge point location, turbidity current, woody debris, display interface

1 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 (Oehy and Schleiss 2007). Desiltation strategies and countermeasures have been investigated by many researches (Morris and Fan 1998, Lee *et al*. 2010, Sumi *et al*. 2011, Lee *et al*. 2012). During flood event, the sediment-laden flow it may disappear at the upstream reach of a reservoir. This phenomenon frequently observed from the air is an indication of plunging flow that also indicates the presence of turbidity current. The plunge point location may be fund at a sharp transition between turbid water and clear water, or by the accumulation of floating woody debris around. If there are suitable conditions for measuring in the field during flood, the presence of turbidity current might be obtained by sediment concentration and velocity profiling equipments, which distinguishes the inflowing and impounded waters (Morris and Fan 2009).

If heavy rainfall drops in the watershed, the river flood carries not only high sediment concentration water but also woody debris. Woody debris produced from upstream watershed provides habitats for aquatic communities in the river system. However, during flood, dead wood is subjected to floating into reservoir, and it may damage hydraulic structures such as spillway gates, or clog the hydropower turbine. If the floating woody debris sinking and deposition, it may cause the difficulty to dredge sediment from the reservoir bottom. When turbidity current developed, due to continuity assumption, turbidity current flow near the bottom would induce an upper circulation to trap woody debris and trap location close to plunge point. When the density of woody debris dense than turbidity current owing to sediment cladding and water uptake effects, some of woody debris may flow with the turbidity current and migrate near the bottom. The field survey showed that when woody debris flowed with the turbidity current into hydraulic works, such as power plant, the structures were damaged and clogged by woody debris. Therefore, to avoid the woody debris flowing into the intake was an important concept of intake operation. The applicable methods to prevent woody debris flowed into the reservoir or intakes have two strategies. The one is to set floating barriers at downstream to prevent woody debris flow into the reservoir and the other method is to build a skimming wall to guiding woody debris flow cross the intake (Auel *et al.* 2011). In general, the floating barrier most commonly used to trap woody debris in a reservoir.

Therefore, the present study selects Shihmen reservoir as a research area. Two empirical formulas are adapted to calculate the head velocity and plunge point location of turbidity current. The variation of the plunging location of turbidity current is investigated and field observation of woody debris is compared to the estimated results. Moreover, a user friendly display interface is established to analysis plunge point location and turbidity current movement in the present study.

2 Site description

The Shihmen reservoir (Fig. 1) has a natural drainage area of 762.4 km^2. It is formed by the Shihmen dam located at the upstream reach of the Dahan River flowing westward to the Taiwan Strait. 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. 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 surface area of the water 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. From survey data in 2014, the storage capacity was estimated to be 67% of its initial capacity. Based on particle size distribution sampled from outflow discharge. Due to serious deposition problem in 2004 induced by Typhoon Aere, the stratified withdrawal facility was built beside the dam site in 2009 to ensure water supply capacity (Fig. 2) and one of the penstocks of power plant was modified in 2012 to vent turbidity current (Fig. 2). The stratified withdraw facility with three intakes (at EL.220 m, EL.228 m, EL.236 m) was finished in Dec. 2009. Moreover, two planned sediment bypass tunnel (named Amouping and Dawanping) are designed to reduce sedimentation problem in Shihmen reservoir (Fig. 2).

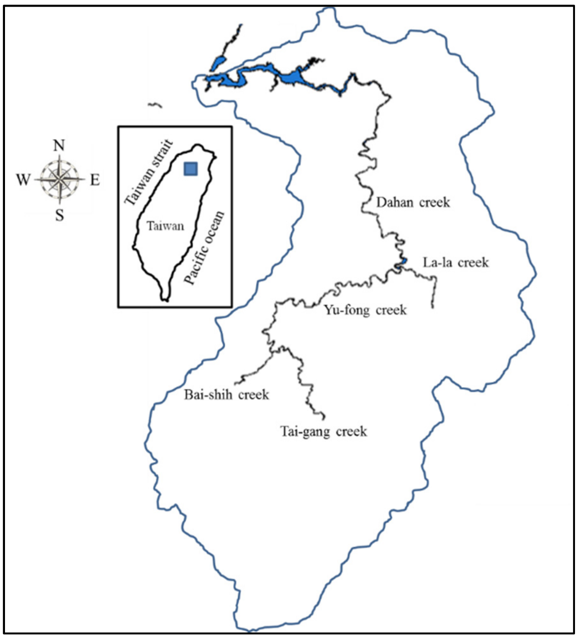

Fig. 1: Watershed area of the Shihmen reservoir

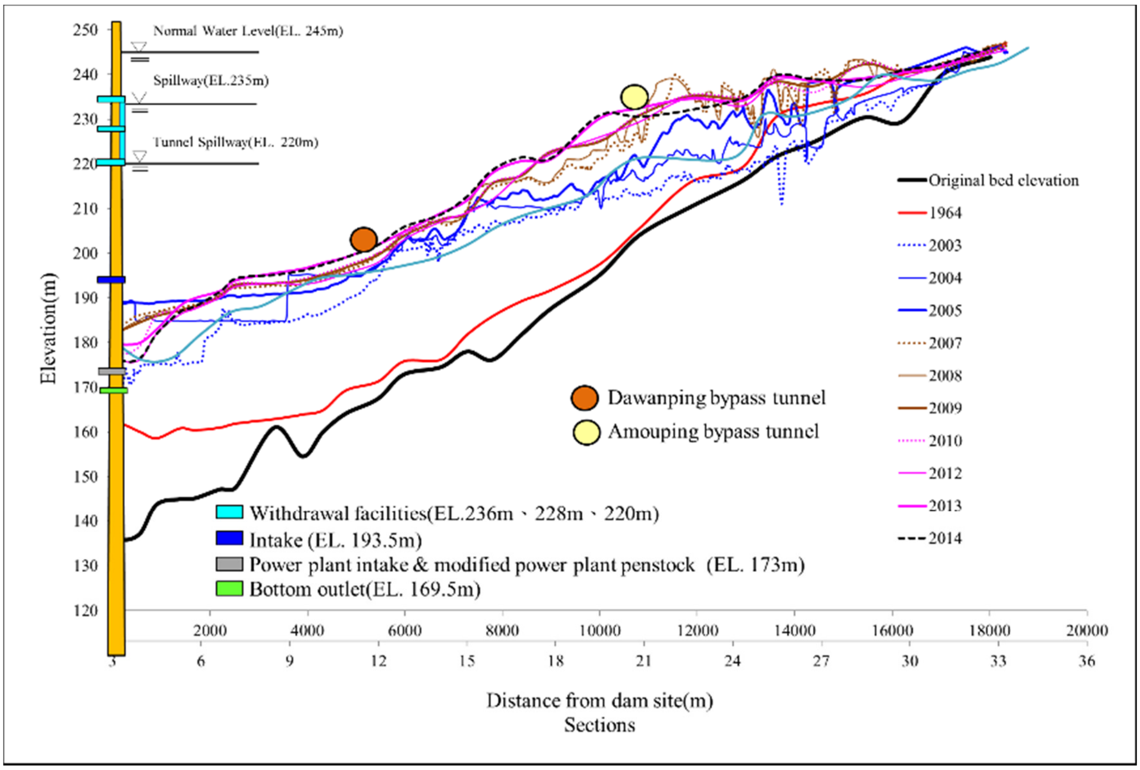

Fig. 2: Sketch of hydraulic works elevation and longitudinal thalweg of Shihmen reservoir

3 Methods

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-Moghadam *et 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 modified empirical formula is expressed as:

$$U_f = \sqrt{a(\frac{\rho_t - \rho_a}{\rho_a})gbh_p} \quad [2]$$

where h_p = the depth of plunge point location, a = velocity coefficient, b = thickness coefficient is defined as 0.72 (Yu, 1991). Observed data in Typhoon Soulik (2013), In Typhoon Trami (2013), in Typhoon Soudelor (2015) and in Typhoon Dujuan (2015) were collected to calibration the velocity coefficient, a (Chen *et al*. 2016).

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 head region.

Experiments and numerical simulations for investigating 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. Among them, empirical entrainment formulas using densimetric Froude number which express the plunging condition as follows:

$$\frac{U_p}{\sqrt{\frac{\Delta\rho}{\rho_a}\mathrm{gh_p}}} = \mathrm{F}_{rd} \quad [3]$$

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 may range from 0.45 to 1.00.

4 Results

Typhoon Megi (2016) is adapted as the study event. Fig. 3 shows the investigation route of woody debris observation and plunge point location in Shihmen reservoir. Several locations show that the turbid water flowed toward Shihmen dam and woody debris trapped obviously around section 25 and section 26 areas on 09/28/2016 14:00. It indicates that the plunge point location of turbidity current might happened near section 27 at specific moment. Based on the estimation of densimetric Froude number at the same time, the value is about 0.64. For the convince of operational personnel, a display interface has been developed in this study to display the plunge location, movement velocity, body thickness, sediment concentration of turbidity current, etc. Fig. 4 shows the simulation interface of turbidity current movement using eq. [2] and eq. [3]. The current display interface shows the information about general introduction of Typhoon

Megi, edit functions, estimated plunge point location, simulation duration and simulation results. The interface shows the average head velocity is about 0.38 m/s and average body thickness is about 27.48 m. In addition, the estimated plunge point location of turbidity current agree with the field observation. It indicates that the densimetric Froude number can applicably describe the plunge point location of turbidity current in Shihmen reservoir. The suitable value of densimetric Froude number for the estimation of plunge point location is about 0.64.

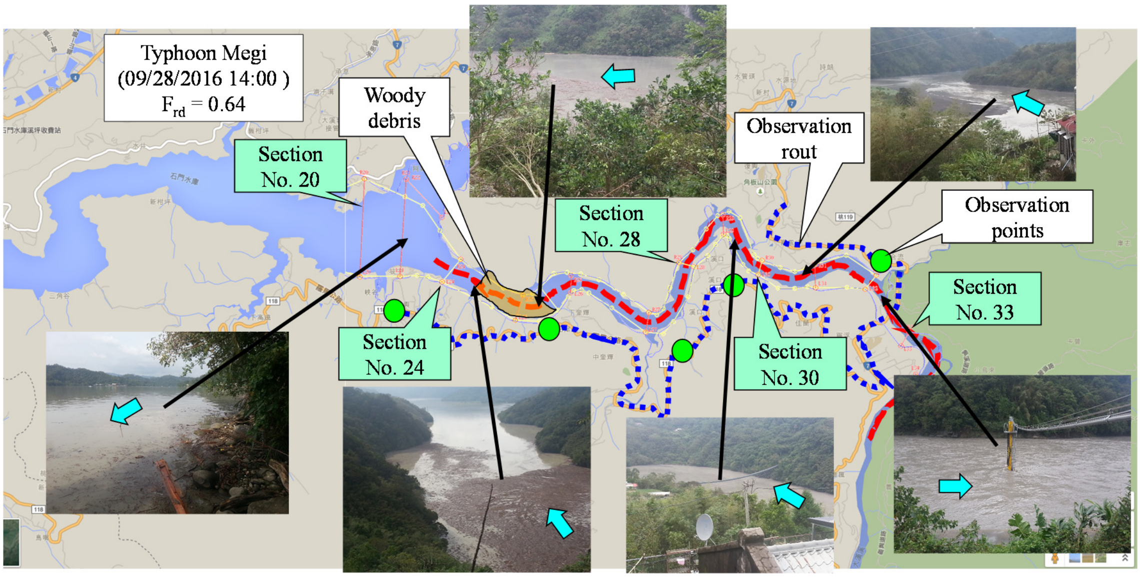

Fig. 3: Field investigation of woody debris location

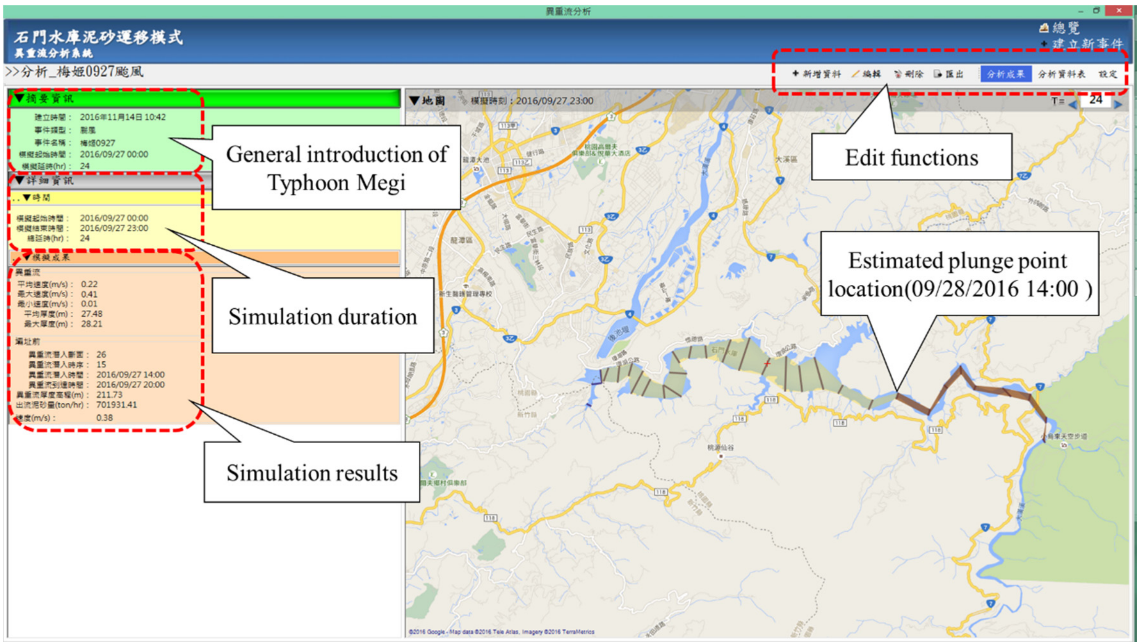

Fig. 4: Simulation interface of turbidity current movement

5 Conclusions

For turbidity current venting, estimation of plunge point location and turbidity current movement can provide usefully information for the operation of bottom outlets and sediment bypass tunnels in Shihmen reservoir. After Typhoon Aere in 2004, modification of several existing outlets to increase the sediment sluicing capacity was also an important task. The powerhouse penstock modification was a major project undertaken to improve the sluicing capacity, which was completed in June, 2012. According to the experimental results of the physical model, the venting tunnel at powerhouse resulted in effective sluicing efficiency with higher outflow sediment concentration than those by other existing hydraulic facilities. Therefore, In-situ measured data of sediment concentration distribution during sediment release operation through bottom outlets can help understand sediment-sluicing efficiency from the reservoir. However, field measurement of a turbidity current in a reservoir is still relatively difficult because of large water depth, an unsteady fluid mechanism, and harsh environments during a flood. In this study, empirical formula is considered to estimate plunge point location of turbidity current and compared to the field observation results. The collected information of gathering locations of woody debris is applied to calibrate the parameter of empirical formula. The gathering location of woody debris can also help to estimate the location of plunge point and the suitable location of settling floating barriers. Furthermore, the simulation interface of turbidity current is also developed in this study to display the plunge location, movement velocity, body thickness, sediment concentration of turbidity current. The calibrated value of densimetric Froude number to estimate plunge point location is presented in this study. In the future, coping with rainfall runoff prediction, the prediction of turbidity current movement can also expect to improve the desiltation operation of the Shihmen reservoir.

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