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Simulation of River Bed Degradation with Bed Rock Erosion Downstream of the Reservoir

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ABSTRACT:

After the completion of a dam or a weir, coarser sediments could be trapped in the impounding water area. Part of inflowing sediment tends to deposit during reservoir operation. Over a period of time, the downstream river bed may gradually be degraded by the released flood flow which contains less sediment supply than that of reservoir inflow. River bed erosion caused by running flood may create problems of scouring the foundation of levees or bridge piers. In Taiwan, several river reaches downstream of the dams have the bed rock erosion problems that possess of complex mechanism. The hydraulic erosion and sediment abrasion are studied to estimate the degradation of bed rock. The numerical mobile-bed model is adopted to simulate erosion phenomena downstream of the Shihmen reservoir. The Shihmen Reservoir has the function of water supply for municipal and agricultural demand in the northern part of Taiwan. The Shihmen Reservoir is situated in the Dahan creek that is one of the major tributaries of the Tanshui River. In this research, the degradation tendency is investigated using bed rock erosion formulas. The simulated results provide further understanding of bed degradation mechanism.

Keywords: Degradation, Bed rock, Erosion mechanism

1. GENERAL INSTRUCTIONS

In Taiwan, many downstream alluvial rivers of reservoirs and dams are characterized by the presence and exposure of soft rocks on the river bed, due to lack of sediment supply. The soft rock consists of mainly mudstone and sandstone which is relatively weak (shear strength lower than 25.0 MPa) and subject to essential erosion during high flows. Therefore, soft rock erosion is an important river process in Taiwan. For example, a few kilometres of river channels downstream of the Chi-Chi Weir, Shihkang reservoir and Shihmen reservoir have experienced up to couple meters of rock scour since weir and reservoir construction (see Fig. 1). Much bed rock erosion is the result of interaction of hydraulic erosion and sediment abrasion. There are many researches of bedrock erosion and are usually classified to hydraulic and abrasive scour kinds. Tomkin et al. (2003) compared various empirical models for bedrock erosion, but, the results showed that they generally cannot explain observed behaviour because of the simple empirical approaches do not account for the varying channel capacity in different parts of the river and they account for the distribution of discharge with time. Therefore, in this study, building a bedrock erosion module into 2D hydraulic and sediment transport models, the variations in channel capacity and specific discharge time series are explicitly simulated. Similar to the 1D model of Greimann and Vandeebrg (2008), the 2D model would not estimate the local erosion caused from plunging jets downstream of spillways. Such erosion could be estimated using models developed by Bollaert and Schleiss (2005) and Annandale (2006). Bolaert and Mason (2006) applied the method of Bollaert and Schleiss (2005) to estimate scour in a plunge pool downstream of a dam. Therefore, this study would not apply such techniques similar to Annandale (2006) to estimate local rock scour downstream of dams; representative applications and procedures are reported by Frizell (2006; 2007). Besides, Sklar and Dietrich (2004) and Lamb et al. (2008) researched on the abrasion erosion. Sklar and Dietrich (2004) considered the abrasion erosion from bed load effect and Lamb et al. (2008) further considered suspended load influence and combining bed load effect to simulate bed rock erosion. However, in this study, only bed load effect is employed to estimate due to simplify model routing.

Water Resources Planning Institute (2009) already used the same method to verify parameters of bed rock erosion phenomenon. But, unfortunately, many bed rock erosion phenomena, mechanisms and rates do not agree with each domestic environment. Therefore, this study chooses exposed bed rock area in the downstream of Shihmen reservoir in Dahan River at northern Taiwan for the application case. Using of the hydraulic scour and sediment with rock abrasion in bed rock erosion model for parameter identification and verification. Then, the study would establish appropriate bed rock parameters in Dahan River and recognize which erosion mechanism would dominate bed rock erosion in Shihmen reservoir area.

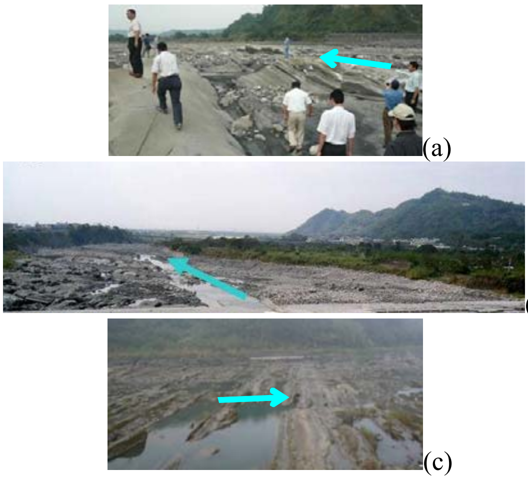

Figure 1. Photographs showing exposed bed rock at downstream of (a) Chi-Chi weir (b)Shihkang reservoir (c)Shihmen reservoir

2. DESCREPTION OF SHIHMEN RESERVOIR DOWNSTREAM

The Shihmen reservoir is a multi-functional reservoir and its functions include irrigation, water supply, generating electric power, preventing flood and recreation. The Shihmen reservoir 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. The Dahan River is one of the three tributaries of the Tamshuei River which flows westward the Taiwan Strait. A map of the watershed area of the Shihmen reservoir is presented in Fig. 2. The Shihmen dam was constructed in 1963 is a 133.1m high embankment dam with spillways, permanent river outlet, and power plant intake and flood diversion tunnels controlled by tailrace gates. The elevations of the spillway crest, permanent river outlet, and power plant intake and tunnel spillway are EL.235 m, EL.169.5m, EL.173m and EL.220m, respectively. The total discharge of spillways is 11400m^3/s, permanent river outlet is 34m^3/s, power plant intake is 137.2m^3/s and tunnel spillway is 2,400m^3/s. With a maximum water level of EL.245 m, the reservoir pool is about 16.5 km in length and forms a water surface area of 8.15 km^2. The initial storage capacity was 30,912x 10^5 m^3, and the active storage was 25,188x 10^5 m^3. Due to a lack of sufficient desiltation facilities, incoming sediment particles have settled down rapidly along the reservoir since the dam was completed. Based on the survey data, the Shihmen reservoir has accumulated a significant amount of sediment after dam completion. The depositional pattern has become wedge-shaped since 2000.

From identification by the parameters of the turnover rate of water(CAP/MAR=total capacity/Mean annual runoff) and sediment(CAP/MAS=total capacity/Mean annual inflow sediment) (Sumi, 2011), the life of Shihmen reservoir is reduced from 188 year to 55year due to Chi-Chi earthquake effect (Fig. 3). Fig. 4 show the variation of deposition volume from reservoir is constructed. The mainly deposition volume happened in 1964 year and 2004 year after reservoir is constructed and typhoon AERE attacking, respectively. The Fig. 4 also shows that the Chi-Chi earthquake does not affects deposition volume obviously in recent 10 years. Therefore, the mainly deposition volume is result from typhoon effect. Based on recent survey data in 2010, the storage capacity was estimated to be 67.07% of its initial capacity.

Fig. 5 shows the cross sections below the Shihmen reservoir and Fig. 6 shows the mainly variation area of bed elevation from section 86 to section 90. According to the degradation of section 90, there is about 9m be eroded after Shihmen reservoir is constructed. However, the starting year of bed rock erosion is not recorded clearly. But, based on 2004 field survey of Northern Water Resources Bureau, bed rock is exposed and mainly exposed area was from section 90A to section 82. Therefore, the bed elevation of 2004 was adopted as a initial geographic condition to simulate bed rock erosion.

Figure 2. Watershed of Shihmen reservoir (Lee et al., 2007)

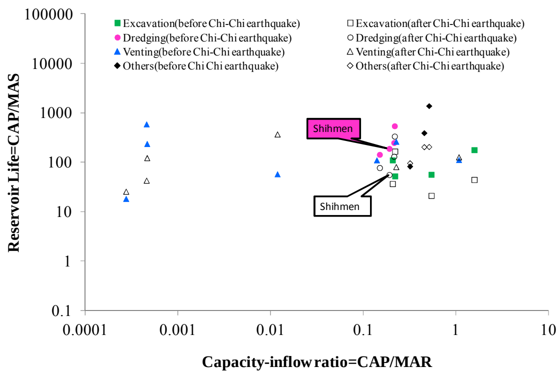

Figure 3. Reservoir characteristics in Taiwan

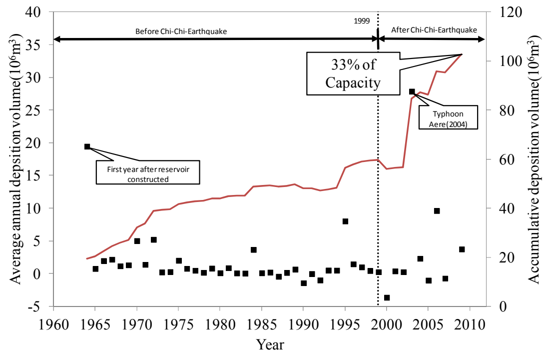

Figure 4. Variation of sedimentation in Shihmen reservoir

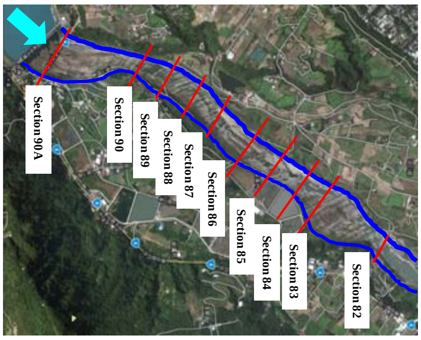

Figure 5. Mainly bed rock area and cross sections

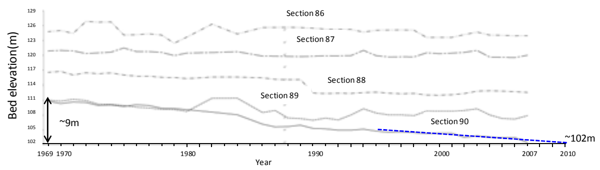

Figure 6. Variation of bed elevation at each cross section

3. DESCREPTION OF BED ROCK EROSION MODEL AND SIMULATED CONDITION

In this study, we employed that the hydraulic scour and abrasive scour be modelled separately to simulate bed rock erosion. And, mainly content is following the results of Water Resources Planning Institute report (2009). Therefore, both models are incorporated into 2D mobile bed model. Field survey should be conducted to determine whether the study site is hydraulic scour dominant, abrasive scour dominant, or both play important roles. Model simulation results may also be used through post-analysis to assess the dominant scour mechanism.

The presented rock erosion model follows the results of Greimann and Vandeburg (2008) with minor modifications. The rock scour rate is computed by combining both the stream power based hydraulic scour model with excesses shear tress and the bed load abrasive scour model as follows:

$$E = k_p U (\frac{\tau}{\tau_{cri}} - 1)^n (1 - \frac{c}{c_{tr}}) + E_a \qquad (1)$$

Where, E =total rock erosion rate (m/s), k_p =hydraulic erodibility, U =depth averaged flow velocity (m/s), τ , τ_{cri} =bed shear stress ; critical shear stress for hydraulic scour (Pa), c , c_{tr} =thickness of rock cover ; transition thickness (m); n =empirical exponent and E_a =abrasive scour rate (m/s). The first term on the right hand side of equation (1) represents the hydraulic scour rate and it is set to be a function of the stream power (τU) (Annandale,2006). The above form has the advantage of being dimensionally consistent as opposed to the dimensional equations used in many existing models such as that of Tomkin et al. (2003) and it is also consistent in form to the cohesive sediment transport relationships. The c / c_{tr} term represents the armour effect and $c_{tr} = 0.1m$ was used as the transition thickness above which zero rock erosion is expected. Besides, n=1 is used in this study as no concrete data suggest the use of nonlinear relations. Therefore, two empirical parameters are needed for the hydraulic scour: k_p and τ_{cri} . The dimensionless erodibility parameter k_p can be a calibration parameter in the numerical model and it is also probably can be a site specific value. Based on the results of Greimann and Vandeburg (2008) and Water Resources Planning Institute report (2009), the value of k_p is set from 4.0*10^{-6} to 1.0 downstream of the weir if abrasive scour is ignored. In this research, the same value is adopted. The critical stress τ_{cri} may be estimated using the Annandale (2006) approach, field test, or numerical model test in comparison with field data. With the Annandale method the critical stream power may be related to the critical shear stress as (Greimann and vandeburg, 2008). According to the calibration results of Water Resources Planning Institute report (2009) in Chu-Chi weir and Shihkang reservoir, the value of τ_{cri} is between 100 Pa and 300 Pa. Therefore, this study also follows such range in Shihmen reservoir.

The abrasive scour is based on the model of Sklar and Dietrich (2004) and adopted model is presented as following:

$$E_a = \frac{0.08 R_b g Y}{k_v \sigma_T^2} q_s (\frac{\tau}{\tau_c} - 1)^{-0.5} \left[1 - (\frac{u_*}{w_f})^2 \right]^{1.5} F_e \qquad (2)$$

In which E_a =abrasive scour rate (m/s), $R_b = \rho_s / \rho - 1$, ρ_s =is sediment density and ρ is water density, g=gravity (m/s^2), k_v =rock erodibility parameter (-), Y=modulus of elasticity of rock (Pa), σ_T =tensile strength of rock (Pa), q_s =sediment supply per unit width (kg/m/s), τ , τ_c =bed shear stress and critical shear stress

(Pa), w_f =sediment fall velocity (m/s), u_* =shear velocity (m/s) ; $\sqrt{\tau/\rho}$ and F_e =fraction of exposed bedrock.

There are three parameters needed to be determined for abrasive erosion: $\mathrm{k_v}$, Y and σ_T. $\mathrm{k_v}$ is a dimensionless parameter representing rock erodibility and it may be estimated in the laboratory that presented by Sklar and Dietrich (2004), but it needed to be calibrated for field applications. Based on the calibration results of Chi-Chi weir and Shihkang reservoir, its value was calibrated to be from 10 to 1000 at different cross sections if only abrasive scour is present. Y is the rock modulus of elasticity (Pa) and σ_T is the rock tensile strength (Pa). Based on the relative values in similar locations, Y and σ_T can be measured in the field. Note that, the fraction of the exposed bed is represented by F_e in the abrasive model equation (2). In addition, it can be chosen the same as the hydraulic scour, i.e. $F_e = 1 - c/c_{tr}$. However, $F_e = 1 - q_s/q_t$ is used to represent the fraction of bedrock exposure with the sediment transport capacity per unit width (kg/m/s).

On the other hand, the sediment transport equation of Parker (1990) was adopted. Besides, due to the initial bed condition is from 2004 year, the simulated boundary condition is also from 2004year. Fig. 7 shows the hydrograph of boundary condition and combines apparently hydrological events from 2004 year to 2008 year to simulate bed rock erosion. The first part from 2004 year to 2006 year was used for calibration parameters and from 2006 to 2008 year was used for verification duration. Fig. 8 presents the simulation mesh and initial bed elevation from section 90A of upstream boundary and Yuanshan weir of downstream boundary. The simulated mesh was locally increased to improve simulation accuracy.

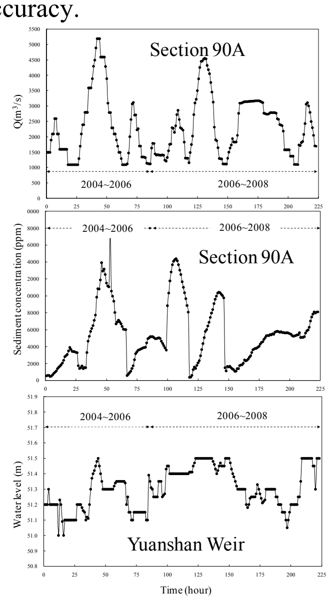

Figure 7. Boundary conditions of inflow and outflow

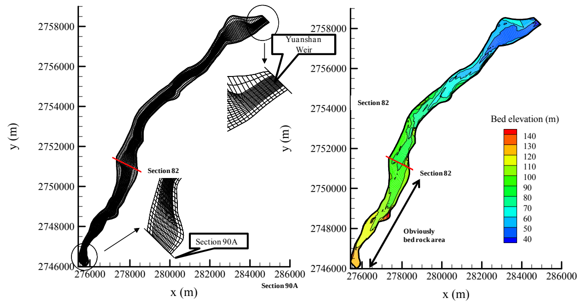

Figure 8. Simulation mesh and initial bed elevation in 2004

4. SIMULATION RESULTS AND DISCUSSION

Due to the lack of field test, the hydraulic erosion and abrasion erosion parameters from refer to the values of Shihkang reservoir and Chi-Chi weir (Water Resources Planning Institute report, 2009). Table 1 lists the reference data from Shihkang reservoir area and Chi-Chi weir area and calibrated values of $\mathrm{k_v}$, Y, σ_T, k_p and τ_{cri} from 2004 year to 2006 year in this study. The calibrated values indicated that $\mathrm{k_v}$, σ_T and τ_{cri} at same order between three areas. But, Y and k_p presented couple order difference, especially Y. Therefore, the value of Y needed to measure in the field to adopt proper value. Fig. 9 shows the variation of bed elevation from 2004 year to 2006 year and the figure also shows the bed elevation tendency of downstream river is erosion, especially at section 78 and section 75. However, the erosion area of field survey presents cross section erosion performance between section78 and section 87 and simulated result presents mainly channel erosion phenomenon. Fig. 10 shows the comparison of measurement data and simulation results at section 85, section 87 and section 89. Mainly part of each cross section was choosing for comparison. The figure shows the fine agreement results at main channel of section 85 and section 89, except section 87. The simulation results indicated that employed model can deal with mainly bed rock erosion at deep channel, but, weakly simulate at flood plain or widely cross section. Integrated to say, the bed rock tendency can preliminary describe by presented model, but, precisely erosion depth and range is needed to improve. Fig. 11 shows the variation of bed elevation from 2006 year to 2008 year and the figure also shows the bed elevation tendency of downstream river is erosion as 2004 year to 2006 year, especially at section 78 and section 75 downstream. However, the erosion area of field survey obviously presents cross section erosion performance between section 75 and section 87 and simulated result still presents mainly channel erosion phenomenon. Fig. 12 shows the comparison of measurement data and simulation results at section 85, section 87 and section89. Mainly part of each cross section was also choosing for comparison. The figure shows that the relative fine agreement results at main channel of section 85, section 87 and section 89. Based on the field survey at section 87 from 2004 to 2008, the variation during 2004 to 2006 is erosion but during 2006 to 2008 is deposition. The simulation results pointed out adopting model can deal with mainly bed rock erosion at deep channel and also sedimentation mechanism at flood plain or widely cross section if those sections possess sedimentation and bed rock erosion at the same event. The results also presented that the sediment transport equation of Parker (1990) is suitable in Dajia River, Chosui River and Dahan River. Overall to say, the bed rock tendency can preliminary describe by presented model, but, precisely erosion depth and range is needed to improve.

Table 1 Relative parameters of bed rock erosion

Sections	Modulus of elasticity Y (Pa)	Erodibility parameter K_V	Tensile strength σ_T (Pa)	Hydraulic erodibility K_P	Critical shear stress τ_{cri} (N/m^2)
Shihkang Reservoir Area (Dajia River)					
	$7*10^6$	50	$5*10^6$	$4*10^{-6}$	200
Chi-Chi Weir Area (Chosui River)					
	$7*10^6$	75	$5*10^6$	$1*10^{-6}$	225
Shishmen Reservoir Area (Dahan River)					
85~82	$5*10^{10}$	50	$1*10^6$	$4*10^{-6}$	200
87~85	$1*10^{11}$	50	$1*10^6$	$7*10^{-7}$	200
88~87	$5*10^{10}$	50	$1*10^6$	$7*10^{-7}$	200
90A~88	$5*10^9$	50	$1*10^6$	$7*10^{-7}$	200

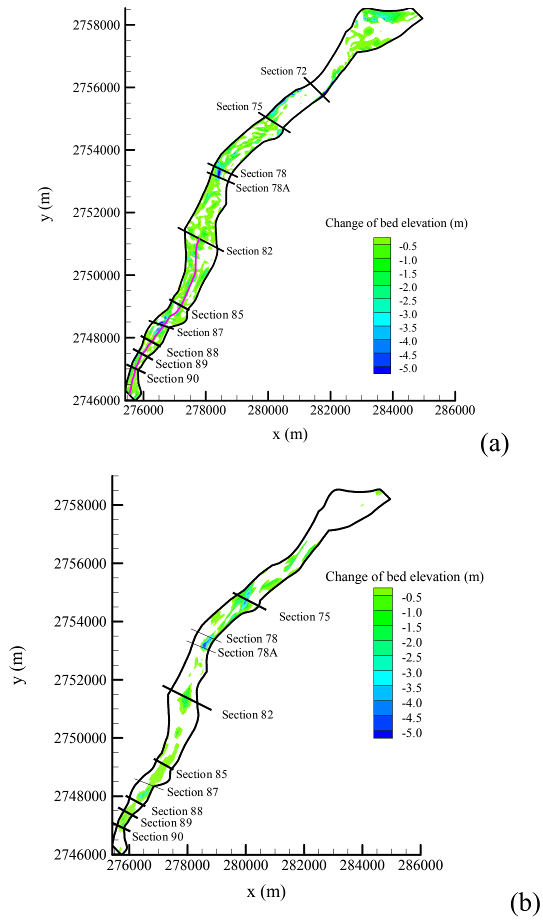

Figure 9. Change of bed elevation from 2004 to 2006 (a) Field survey (b) Simulation result

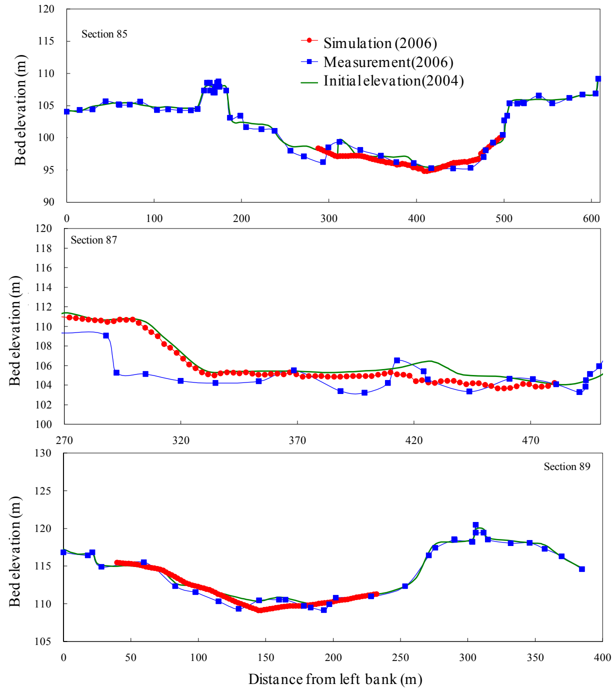

Figure 10. Mainly comparison of bed elevation from 2004 year to 2006 year in section 85, section 87 and section 89

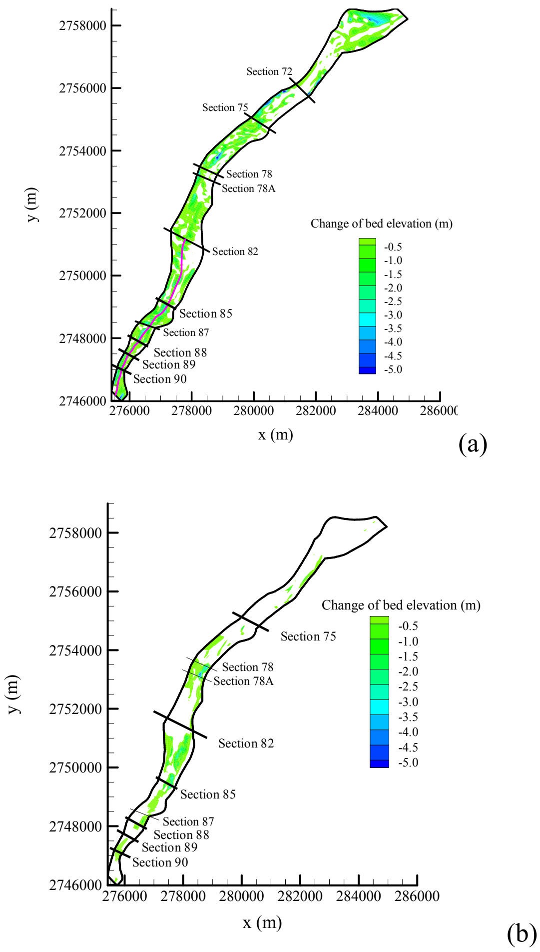

Figure 11. Change of bed elevation from 2006 to 2008 (a) Field survey (b) Simulation result

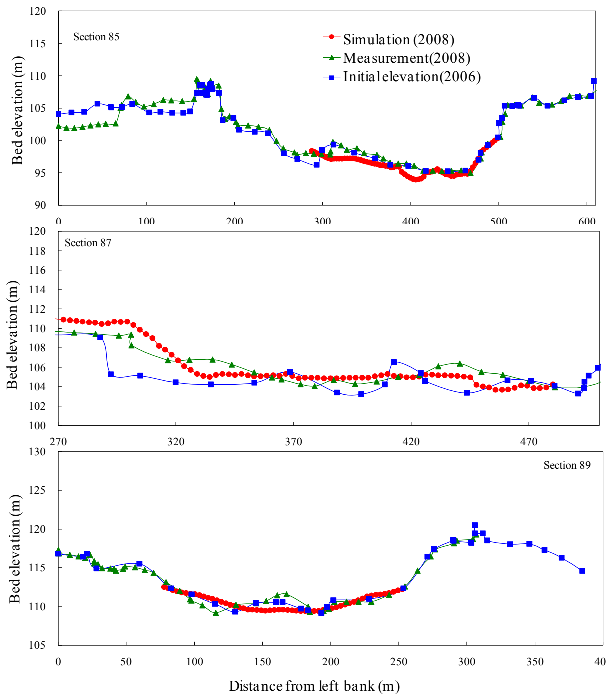

Figure 12. Mainly comparison of bed elevation from 2006 year to 2008 year in section 85, section 87 and section 89

5. CONCLUSIONS

In past 10 years, the downstream river bed gradually be degraded by the released flood flow after reservoir or weir was constructed and the gradation reason result from less sediment supply that of reservoir outflow in Taiwan. Over a period of time, the remained sediment at the downstream would be flushed out to the sea and bed rock would finally expose. This study focuses on the bed rock erosion with hydraulic mechanism and sediment abrasion methods in Shihmen reservoir downstream. Five parameters were pointed out, three of them (Y, σ_T and τ_{cri}) can be measured and specified from field test and two of them (k_v and k_p) needed to calibrate from calibration and verification. According to the historical data and field survey, it is realized that bed rock exposed from 2004 year. Therefore, from 2004 year to 2008 year was separated as calibration period and verification duration. The simulation results show that the simulated bed rock tendency can preliminary describe by presented model, but, precisely erosion depth and range is needed to improve. Besides, the adopted sediment transport equation of Parker (1990) is suitable to use in Dajia River, Chosui River and Dahan River. According to the simulation results of Shihmen reservoir downstream, the bed rock erosion parameters are calibrated to Y is from $5*10^9$ to$1*10^{11}$, k_v is equal to 50, σ_T is equal to $1*10^6$, k_p is from $4*10^{-6}$ to $7*10^{-7}$ and τ_{cri} is equal to 200. Moreover, due to the obviously difference of Y between field survey and simulation result, combining Y, σ_T and k_v to be a new parameter is probably attempted to try. In addition, the abrasion erosion in this study only considered bed load effect. Therefore, combing bed load and suspended load effect was reasonable to improve simulation accuracy and the scheme of Lamb et al. (2008) is a good method to replace the equation of Sklar and Dietrich (2004) in this study.

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