Conference Paper, Published Version

Zhang, Yaoxin; Jia, Yafei; Yeh, Keh-Chia; Liao, Chung-Ta

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12th International Conference on Hydroscience & Engineering
Hydro-Science & Engineering for Environmental Resilience
November 6-10, 2016, Tainan, Taiwan.

Erosion Control Plans for JiJi Weir Downstream Channel

Yaoxin Zhang[1], Yafei Jia[1], Keh-Chia Yeh[2], Chung-Ta Liao[2]
1. National Center for Computational Hydro-science and Engineering, The University of Mississippi
University, MS, USA
2. National Hazard Mitigation Research Center, National Chiao Tung University
Hsinchu, Taiwan

ABSTRACT

In this study, CCHE3D model, with a soft bedrock erosion module, was applied to evaluate the erosion control plans for the downstream channel of the JiJi Weir in the Chushui River, Taiwan. The channel suffers from a serious channel incision over the soft rock bed. The erosion module and the numerical model were validated using available field data and observations; and optimal plans were proposed to minimize this erosion problem within the 6km channel reach from the JiJi Dam to Mingchu Bridge. Numerical simulations have shown that the proposed designs would reduce the soft rock erosions significantly in the head-cut zone near the JiJi Dam and the main incised channel.

KEY WORDS: Bedrock erosion, Stream power, 3D numerical model, Channel incisions, Erosion control.

INTRODUCTION

JiJi Weir was built across Chuoshui Creek, the longest river (178.6km) in Taiwan flowing from the east to the west of its watershed about 4323km^2. The local precipitation and geomorphology patterns strongly affect the flow and sedimentations modes both within the Reservoir and the downstream channel of the JiJi Weir. Within the 5km stretch downstream from the dam, the channel bed is featured with easy-to-be-eroded fine lithology layers of mud, shiver, and sandstones, thus resulting in a severe channel incision and head-cut development problem during typhoon seasons. Fig. 1 shows the incised soft bedrock channel at downstream of the JiJi Weir. The thalweg of the incised channel is about 10m lower than the original bed.

To protect the JiJi Weir and its downstream channel from serious channel erosions, the Water Resources Agency (WRA) proposed some erosion control plans, in which multiple weir structures are to be installed along the downstream incised channel. This study is aimed at evaluating those erosion control plans and thus searching for optimal designs by using a 3D numerical model, CCHE3D (Jia, 2013), with capabilities in simulating the soft bedrock erosion.

Extensive researches have been carried out for understanding and describing the physical mechanisms (i.e., abrasion, plucking, and cavitation) of soft bedrock erosions mathematically. For examples, Annandale (1995) proposed a conceptual framework to correlate the flow energy to the earth mass erodibility by introducing the erodibility index. Whipple and Tucker (1999) considered the stream power to dominate the bedrock erosions. Whipple et al. (2000) developed the conceptual models for plucking, abrasion, and cavitation in terms of the relationship between the bed shear stress and erosion rate by studying the field erosion processes. Sklar and Dietrich (2001) identified the sediment supply as an important factor for bedrock erosions due to abrasion. Sklar and Dietrich (2004) proposed a mechanistic bedrock erosion model by saltating bed load based on their work in 2001. Lamp et al. (2008) extended Sklar and Dietrich (2004)'s work further by considering the impacts from not only the bed load but also the suspended load.

Fig. 1 Soft bedrock channel at downstream of JiJi Weir (Photo by Zhang, Y., Nov. 2015; look at downstream)

From the previous studies, the impacting factors for the bedrock erosions were identified as follows: bedrock erodibility (strength), stream power, shear stress, sediment supply, and grain size. Accordingly, two types of models (Lai et al., 2011), namely, the hydraulic scour model (stream power-based, Annandale, 1995 and 2006) and the abrasive scour model (Sklar and Dietrich, 2004) have been widely used in the applications with numerical simulations. Jia et al. (2009) incorporated the abrasion-based bedrock erosion model into CCHE2D model (Jia and Wang, 1999) to study the channel incision at downstream of the JiJi Weir. Lai et al. (2011) proposed a hybrid bedrock erosion model by combing the abrasion-based model and the stream-power based model. Liao et al. (2013) implemented a stream-power based soft bedrock erosion model into a 2D mobile-bed model EFA (explicit finite analytical) to study the channel morphological process in an uplifted reach of Ta-An by earthquake in Taiwan. In addition to a 2D bedrock erosion model, Jia and Zhang (2013, 2014, and 2015) first developed a 3D bedrock erosion model by extending Liao et al. (2013)'s work to CCHE3D (Jia, 2013) to continue to study the channel incisions problems in Taiwan.

This study presents the applications of the CCHE3D bedrock erosion module to study the channel incisions and erosion control problems in the downstream channel of the JiJi Weir. The numerical model was calibrated and validated using field data. Based on the evaluations of the multiple alternatives, an optimal control plan, involving multiple weir implementations and the channel side-excavations, was proposed to control the development of the channel incision and head-cut propagation.

3D BEDROCK EROSION MODEL

CCHE3D model (Jia, 2013) is solving fully 3D RANS equations based on a partially staggered structured mesh system, and its integrated bedrock erosion module is based on the stream power method (Liao et al. 2013), where the soft rock erosion rate, is only related to the rock erodibility index (Annandale,1995) and the flow stream power which is proportional to bed shear stress, as shown in Eq. (1) and (2):

$$E = K_s U(\frac{P}{P_{cm}} - 1)^c = K_s U(\frac{\tau U}{P_{cm}} - 1)^c \quad (1)$$

$$P_{cm} = aK_h^b \quad (2)$$

where K_s = non-dimensional coefficient; U = depth-averaged velocity of flow (m/s); P = stream power of flow (kw/m^2), $P = \tau U$, τ= shear stress (N/m^2); P_{cm} = critical stream power (kw/m^2); K_h = rock erodibility index; and, a, b, and c are site-specific calibrated parameters. In 2014, the improved 2D stream power method with lateral erosion capabilities was developed and integrated into CCHE2D soft-rock module, which has been successfully applied to Ta-An Creek of Taiwan (Jia and Zhang, 2014). A factor S_b representing high slope zones is identified:

$$S_b = \max(\frac{S}{k \cdot S_R}, 1.0)^r \quad (3)$$

Where S is the local bed slope computed in an element, S_R is a reference slope of the simulation area, it is currently represented by the average slope of all wet elements in a domain. The power r is empirical and needs to be calibrated. In the tests, it is found the r=1.5~5.0. It can be seen this factor is effective only when the local bed slope is larger than the reference slope. k=1~3 is the coefficient to adjust the reference slope, which filters out small slope area from erosion. With this factor, Eq. (1) is modified to:

$$E_{bb} = K_s U(\frac{P}{P_{cm}} - 1)^c S_b \quad (4)$$

Where E_{bb} is the erosion rate applicable to both softrock bed and bank erosion.

With r = 0, Eq (4) will convert back to Eq. (1). In current study, the method is integrated with CCHE3D soft-rock module so that both the stream power method and the abrasion method can be used in both CCHE2D and CCHE3D models.

EROSION CONTROL PLANS

As early as in 2007, WRA proposed a few erosion control plans to prevent the channel incisions and head-cut development. Jia et al. (2009) and (2013) applied the 2D abrasion-based bedrock models and 3D stream power-based bedrock models respectively to evaluate those plans. They investigated the effects of the numbers, locations, and heights of weir structures installed within the channel, and their simulation results confirmed the effectiveness of the weir structures on the erosion reductions.

In 2014, WRA proposed some new erosion control plans. One of the plans, as shown in Fig.2, is to install a comb-like weir structure, a curved high drop structure and a straight drop structure between the survey cross sections JiJi-27 to JiJi-21, and CS-115 to CS-116. In addition to the weir structures, side-excavations along the right floodplain were also proposed to widen the channel and reduce the flooding risk.

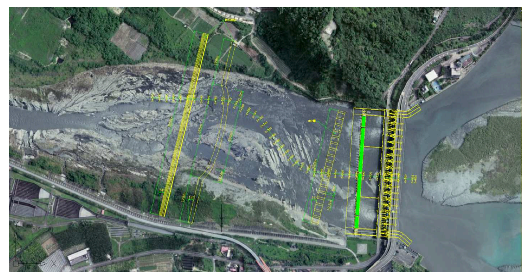

Fig. 2 Top view of one erosion control plan

In this study, different erosion control plans with combinations of weir structures and side-excavation designs were evaluated by using CCHE3D bedrock erosion model.

MODEL CALIBRATIONS

The study domain covers the 6km long channel stretch from the JiJi Weir to the Minchu Bridge as shown in Fig.3. Fig. 4 shows the distribution of bed rock erodibility index surveyed in 2014, varying from 310 (high rock strength) to 29 (low rock strength).

The CCHE3D bedrock model was calibrated by using Typhoon Matmo in 2014 (peak discharge = 4980 cms) and validated by using Typhoon Morakot in 2009 (peak discharge = 12600 cms), which will also be used for all evaluation cases (see Fig. 5).

According to the calibrations, the calibrated parameter set (a = 0.005, b = 0.75, and c = 0.2) in Eq. (1) and the high slope erosion parameters (r = 1.0 and k = 4.0) for the lateral erosion in Eq. (4) will be used for all validation and evaluation simulations

Fig. 3 Study domain and computational mesh

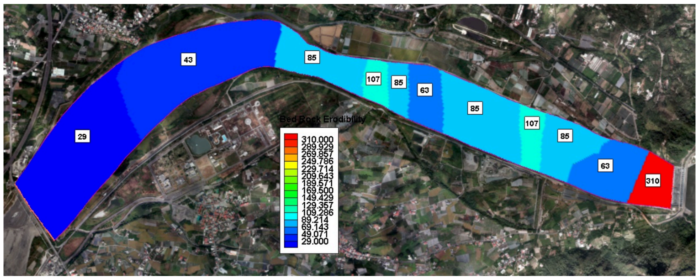

Fig. 4 Measured bedrock erodibility index

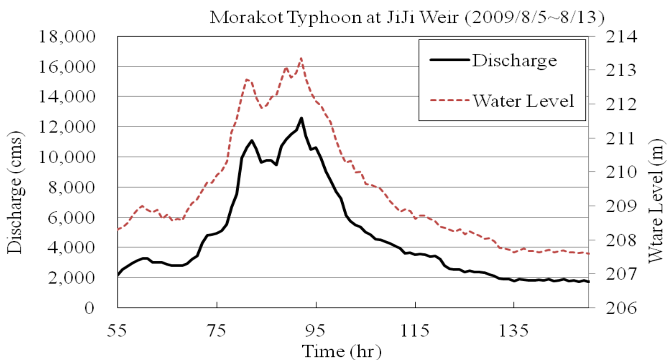

Fig. 5 Typhoon Morakot

Based on the evaluations, it is concluded that the weir structures are effective in reducing local erosions between JiJi-30 and JiJi-20, while the excavation is effective in the widening reach from CS-112 to CS-115.

OPTIMAL DESIGN

Fig. 6 shows the historical channel thalweg profiles of the downstream channel from 1998 to 2014. As can be seen, the slope of the head-cut reach is 0.0412, the incision reach is 0.0057 and the transition reach 0.0028. The head-cut reach and the incision reach are of bare rock channel, actively eroded; the transition reach is sometimes partially covered with sediments, showing alluvial river morphologic and sediment transport features, and thus considered to be more stable. In this study, it is assumed the channel will be stablized if the bed slope can be reduced to 0.0028 approximately by installing erosion control weirs in the channel.

Since the head-cut development has reached to the JiJi Dam, seriously threatening the safety of the dam structure, the protection of the upstream head-cut zone (from JiJi-30 to JiJi-22) is considered as the first priority. The high weir structure at JiJi-25 is capable of significantly reducing the bed rock erosions in the reach from JiJi-26 to JiJi-22. As for the reach from JiJi-30 to JiJi-26, a weir structure is planned at CS-115, and the small reservoir behind this weir structure is designed to slow down the flow and thus reduce the erosion.

For downstream of the head-cut zone, the deep incised channel (from CS-109 to JiJi-26) is characterized with U-shaped cross sections, so deeper channel side-excavations are proposed. The widened channel will reduce the main flow velocity and water surface elevation, which is beneficial to bank protection during floods in additional to promote sediment deposition. To enhance the erosion reduction effects, two additional low-headed weirs are suggested to be installed at CS-111 and CS-113 in this reach to further control the flow and erosion. To prevent the development of a second head-cut between CS-108 and CS-109 (see Fig. 6), a low-headed weir structure is proposed as well to be installed at CS-108.5.

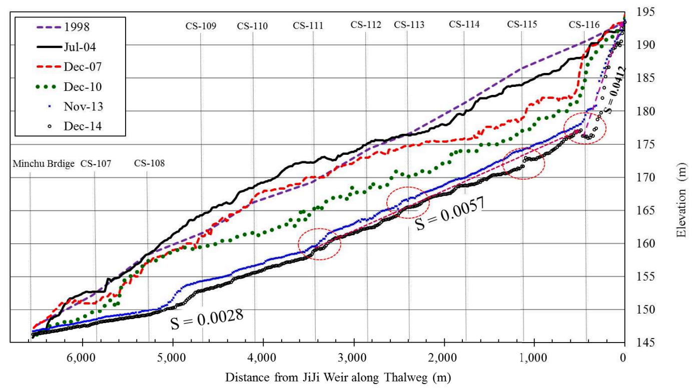

Fig. 6 Historical longitudinal profiles

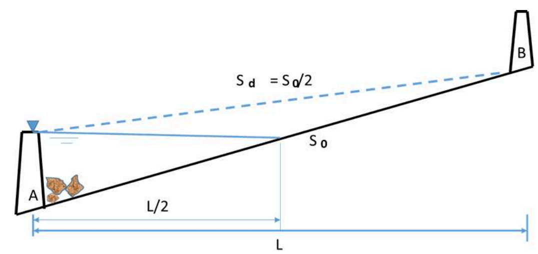

Fig. 7 Sketch of determination of weir height

The height of the four weirs at CS-108.5, CS-111, CS-113, and CS-115 are determined in such a way that the small pools formed behind the weirs can approximately protect half of the reach between weirs (slope equal to zero). As illustrated in Fig. 7, the bed slope of the reach between Weir-A and B is S_0, the pool behind Weir-A can affect an area about half of the reach (L/2). Sediments would fill up the pool behind Weir-A because the surface slope is significantly reduced. Before the deposition filled the channel segment the bed slope behind Weir-B is larger than S_d (= S_0/2) and it reaches to S_d after the segment is filled-up which is the highest slope possible in the design channel. The new established bed slope would be about half of the initial slope S_0. The protected channel would be stable and filled with sediment. According to this idea, the top elevations of the five weirs are determined as follows

Table 1. Elevations of Weir Structures

Weirs	CS-108.5	CS-111	CS-113	CS-115	JiJi-25
Elevation (m)	155.5	163	170	177	188

The bedrock erosion simulation results of the optimal design were compared with those of the case without any structures and engineering measures, which leads to the erosion reduction map. As shown in Fig. 8, the reductions are focused along the main deep channel, and more reductions were observed in the pool formed by the weirs. Between JiJi-25 and JiJi-22, more reductions occurred on the right side (north branch), where the serious head-cut developed.

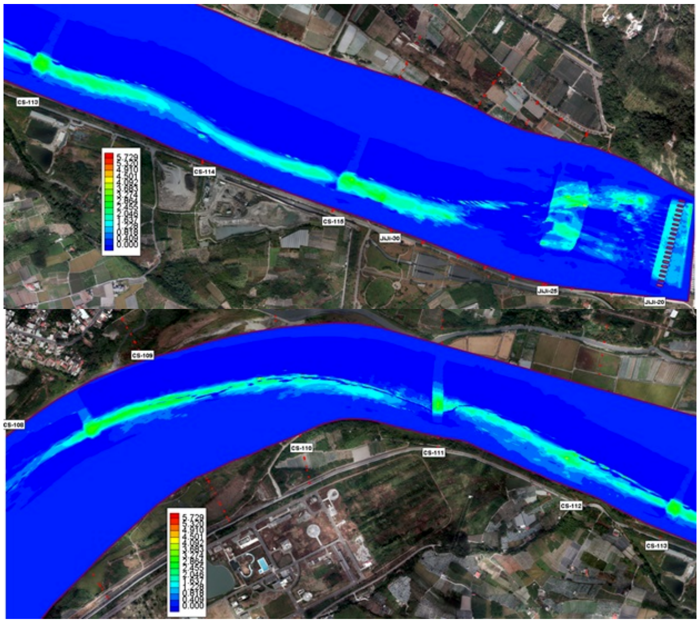

Fig. 8 Erosion reductions for optimal design

CONCLUSIONS

In this study, CCHE3D bedrock erosion model was developed and applied to evaluate the erosion control plans proposed for the downstream of JiJi Weir, which is suffering from serious channel incisions. An optimal plan, considering five weir structures and excavations along the right floodplains, was proposed based on the evaluations results and the channel evolution analysis. The significant effects of the optimal design on the erosion reductions has been proved by the 3D numerical simulations.

ACKNOWLEDGEMENTS

This work is a result of research sponsored by National Chiao Tung University of Taiwan under Research Agreement No. 300212267A and The University of Mississippi.

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