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Modeling the Combined Effects of River Stage and Groundwater Flow on Riverbank Stability before and after Dam Removal

Shih-Wei Chiang[1], Dong-Sin Shih[2], Ming-Wan Huang[3], Chung-Ta Liao[3], Keh-Chia Yeh[4]
1. Engineering Division, Agricultural Engineering Research Center
Taoyuan, Taiwan
2. Department of Civil Engineering, National Chung Hsing University
Taichung, Taiwan
3. Disaster Prevention and Water Environment Research Center, National Chiao Tung University
4. Department of Civil Engineering, National Chiao Tung University
Hsinchu, Taiwan

ABSTRACT

Pore-water pressure variation within a riverbank has been recognized as a significant factor for riverbank stability. The riverbank stability was analyzed mostly by the limit equilibrium method in the related studies. To obtain realistic estimation of pore-water pressure, this study proposes a practical numerical model by coupling groundwater flow modeling to riverbank stability analysis in order to deal with the combined effects of river stage and groundwater table. In the following, the downstream of New railway bridge in the Dajia River was chosen as a study case. The soil properties including unit weight of soil, friction angle and grain size distribution were determined by experimental tests and empirical equations. The changes of river stage before and after dam removal were applied by the simulated results from the WASH123D modeling. The process of riverbank retreat was investigated with respect to river stage hydrographs during flood return periods of Q_{20}, Q_{50} and Q_{100}. The simulated results show that riverbank failure was triggered 3 times for all scenarios. The retreat lengths of Q_{20}=2.76m, Q_{50}=3.29m, Q_{20}=3.68m and Q_{20}=2.41m, Q_{50}=3.18m, Q_{20}=3.46m before and after dam removal were obtained respectively by modeling.

KEY WORDS: riverbank stability; pore-water pressure; limit equilibrium method; riverbank retreat; WASH123D

INTRODUCTION

During a flood, large water discharge and rapid changes in water level would induce strong erosion, especially for meandering channel or contraction of cross-section. The riverbank adjacent to a river may be continuously eroded due to various water forces. Riverbank retreat would cause floodplain land loss and might induce water flow directly acting on the embankment structure. Once scour depth of embankment foundation is increasing, embankment failure would be further induced and would become a serious problem.

The riverbank composed of cohesive material tends to fail in block sliding along planar failure plane. Over the past decades, the stability of riverbank was usually analyzed based upon the limit equilibrium method. Changes in pore-water pressure within riverbank have been investigated and recognized as an essential factor in riverbank stability. Therefore, the interaction between river stage and groundwater table should be taken into consideration for evaluating riverbank stability.

The purpose of this study is to investigate the behavior of riverbank retreat before and after dam removal by the case analysis for Dajia River. The evaluation model would be developed by integrating groundwater flow simulation and physical mechanisms of riverbank stability. The river stage obtained by WASH123D (Yeh et al. 1998, 2006) modeling would be taken into account for the boundary condition of groundwater flow simulation and erosion estimation as well. The influences of before and after dam removal on riverbank retreat were investigated under different hydraulic conditions.

METHODS

Study case location

In this study, a reach of Dajia River was selected as a study case. Dajia River is located in central region of Taiwan and occupies mainly Taichung City and some parts of Nantou County and Yilan County. It has a total mainstream length of 124.2 km, basin area of 1,236 km^2 and average annual flow of about 31 m^3/s. A reach about 1 km between New railway bridge and Houfon bridge was applied to examine the riverbank stability in Fig. 1.

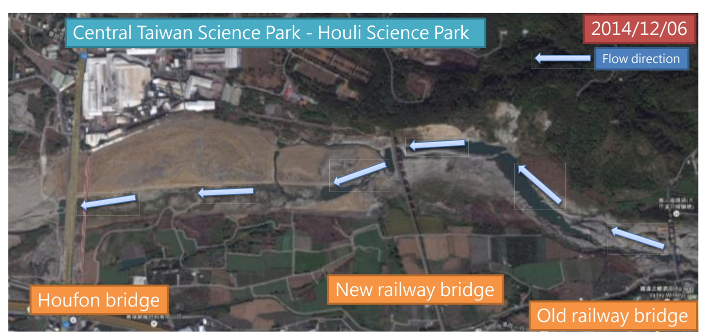


Fig. 1 Channel profile of the selected reach of Dajia River

Groundwater flow modeling

The unsteady groundwater flow problem can be governed by one-dimensional Boussinesq's equation with a local rectangular Cartesian coordinate system as shown in Fig. 2. The governing equation can be written as follows (Bear 1972):

$$S\frac{\partial h}{\partial t}=K\frac{\partial}{\partial x}\left(h\frac{\partial h}{\partial x}\right)+I \qquad 0\le x\le l \tag{1}$$

$$h(0,t)=H_1(t) \tag{2}$$

$$h(l,t)=H_2(t) \tag{3}$$

$$h(x,0)=H_0(x) \tag{4}$$

where S is the specific yield; h is the height of water table; K is the hydraulic conductivity; I is the recharge rate from infiltration; x and t are the space and the time coordinates; l is the length of the domain. $H_1(t)$ and $H_2(t)$ are the time fluctuating height of water table at the boundaries and $H_0(x)$ is the initial height of water table across the domain.

The finite difference numerical method was applied in this study. Once the groundwater table is obtained by modeling, pore-water pressure could be estimated by assuming changes hydrostatically with distance above or below the groundwater table.

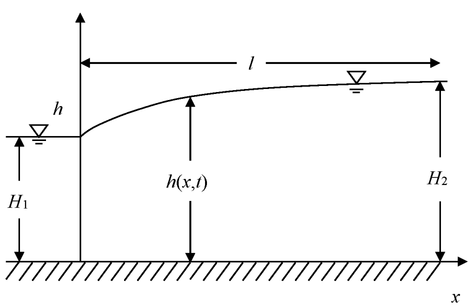


Fig. 2 Schematic diagram of groundwater table profile

Riverbank stability formulation

A riverbank stability analysis algorithm, based on limit equilibrium method was used to assess whether riverbank failure will occur. The forces considered for riverbank stability analysis are shown in Fig. 3. Riverbank stability can be evaluated by the factor of safety (*FS*) expressed as (Osman and Thorne,1998; Darby and Thorne, 1996):

$$FS=\frac{c'L+S\,tan\varphi^b+[W\cos\beta+P\cos(\alpha-\beta)-U]tan\varphi'}{W\sin\beta-P\sin(\alpha-\beta)} \tag{5}$$

where c' is the effective cohesion; L is the length of the failure plane; φ^b is the angle used to determine the rate of increase in shear strength due to increasing matric suction; β is the failure plane angle; α is the angle of riverbank; and φ' is the effective friction angle of the soil.

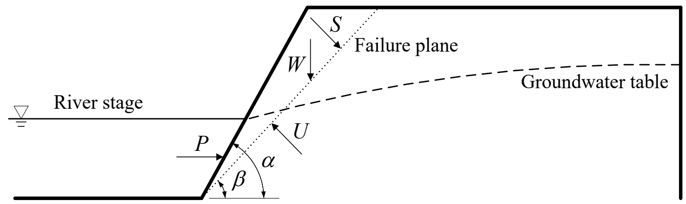


Fig. 3 Conceptual diagram of forces considered for riverbank stability analysis

Erosion determination

The average boundary shear stress in a river is generally estimated by the following (Henderson, 1966):

$$\tau_0=\gamma_w DS_0 \tag{6}$$

where τ_0 is boundary shear stress; γ_w is unit weight of water; R is hydraulic radius; S_0 is channel slope. The erosion flux could be determined by:

$$\varepsilon=\begin{cases}0 & \tau_b\le\tau_c\\ k_d(\tau_b-\tau_c)^a & \tau_b>\tau_c\end{cases} \tag{7}$$

where k_d is erodibility coefficient (m^3/N-s); τ_c is critical shear stress (Pa); τ_b is boundary shear stress (Pa); a is empirical coefficient ($a=1.0$ is commonly applied). Erosion length within a given time interval would be obtained by:

$$L_e=\varepsilon\Delta t=k_d(\tau_b-\tau_c)^a\Delta t \tag{8}$$

where L_e is erosion length; Δt is time interval.

Field tests

We conducted field tests in order to determine soil properties in situ for further simulation. Two sites around section number 29 were selected for testing as shown in Fig. 4. The situation of in situ measurement is as shown in Fig. 5. The soil properties could be determined and concluded as follows: unit weight of 22.6~22.9 kN/m^3, friction angle of 38°~39° and hydraulic conductivity of 10^{-2}~10^{-4} cm/sec.

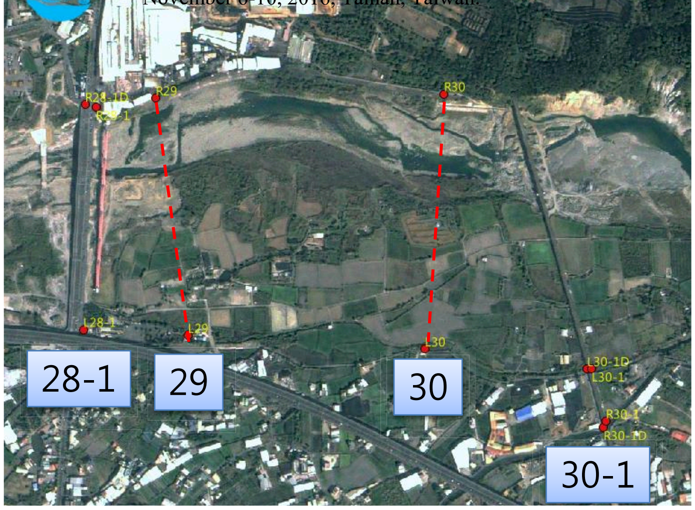
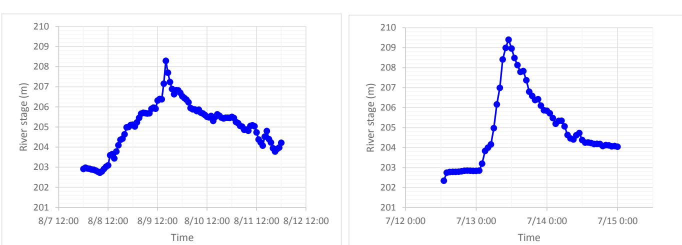


Fig. 4 Field test for soil properties near section number 29

Fig. 5 Field test for soil properties near section number 29

Hydraulic condition

For groundwater simulation, river stage is one of the boundary conditions which would determine groundwater table and pore-water pressure distribution. In this study, the changes of river stage before and after dam removal were used by the one-dimensional simulated results from the WASH123D modeling. Two events, Typhoon Morakot in 2009 and Typhoon Soulik in 2013, the river stage changes with time were obtained respectively by WASH123D modeling as shown in Fig. 6.



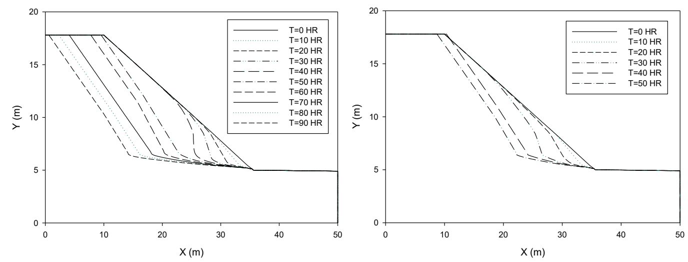
(a) (b)

Fig. 6 River stage changes of section number 29 during (a)Typhoon Morakot; (b)Typhoon Soulik

RESULTS AND DISCUSSION

Riverbank retreat for typhoon events

Without considering bed scour, whole processes of riverbank retreat for Morakot and Suli typhoon events are plotted in Fig. 7. Flood duration in Typhoon Morakot was longer than which in Typhoon Soulik. Therefore, the erosion in Typhoon Morakot was also more serious and induced more times of riverbank collapse. There were 7 collapse at 42, 48, 55, 63, 71, 79 and 88 hours for Typhoon Morakot which would produce riverbank retreat length of 9.39m. The collapse occurred 3 times for Suli typhoon respectively at 39, 47 and 56 hours and riverbank retreat length of 1.27m would be produced. The simulated results shows that flood duration would be an essential factor to determine riverbank retreat when the erosion is continuously in the transportation of soil particles of the riverbank.



(a) (b)

Fig. 7 Riverbank retreat conditions with time for (a)Typhoon Morakot; (b)Typhoon Soulik

Riverbank retreat for return period discharge

For the investigation of riverbank retreat before and after dam removal, different return periods of Q_{20}, Q_{50} and Q_{100} would be taken into account to determine the changes of river stages. The simulated results from WASH123D modeling indicates that the river stages would have little difference in varying with return period while nearly no difference before and after dam removal. For the peak level, Q_{20} would be 213.56m (before dam removal) and 213.52m (after dam removal); Q_{50} would be 214.17m (before dam removal) and 214.19m (after dam removal); Q_{100} would be 214.27m (before dam removal) and 214.27m (after dam removal). The simulation results of riverbank retreat for each case are as shown in Fig. 8. For Q_{20}, collapse occurred three times throughout the flood period, the retreat length of about 2.76m (before dam removal) and 2.41m (after dam removal). For Q_{50}, collapse occurred three times throughout the flood period, the retreat length of about 3.29m (before dam removal) and 3.18m (after dam removal). For Q_{100}, collapse occurred three times throughout the flood period, the retreat length of about 3.68m (before dam removal) and 3.46m (after dam removal). Total length of riverbank retreat before and after dam removal for return period events are summarized in Table 1.

Generally, the river stage for large-scale flood would produce great scour and would further cause serious riverbank retreat. However the flood duration are the same for all cases, the occurrence of collapse were limited to three times even Q_{100} would be larger than Q_{50} and Q_{20} for the peak level. Therefore, the retreat length would not have dramatic rise with flood scale. In addition, nearly no difference of river stages before and after dam removal under the same flood duration would have little influences on riverbank retreat.

Table 1. Summary of total length of riverbank retreat before and after dam removal for return periods of Q_{20}, Q_{50} and Q_{100}

Scenarios	Before dam removal	After dam removal
Q_{20}	2.76m	2.41m
Q_{50}	3.29m	3.18m
Q_{100}	3.68m	3.46m

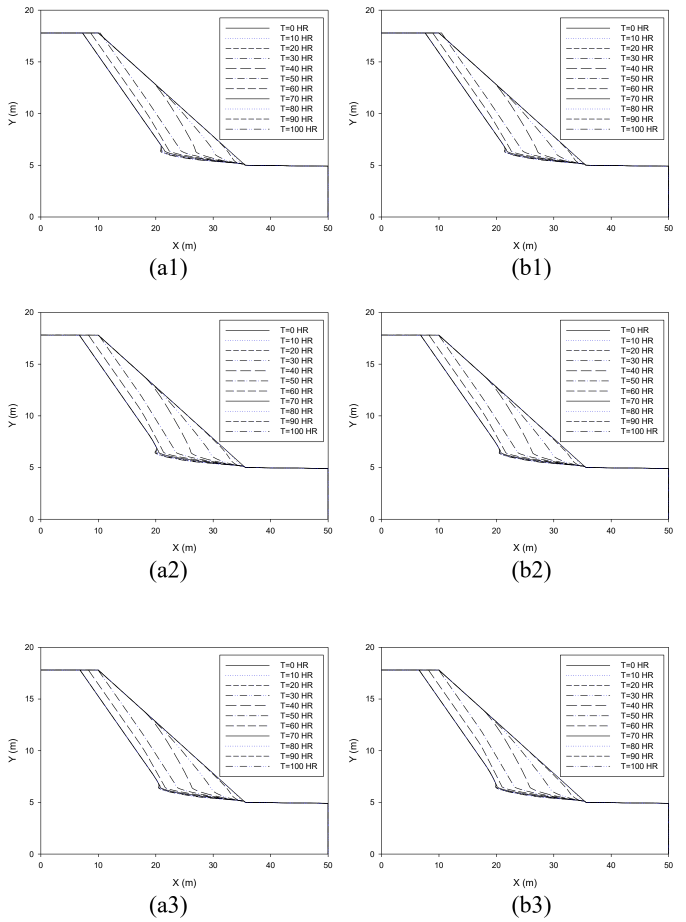


Fig. 8 Riverbank retreat conditions with time before dam removal (a1)Q_{20}; (a2)Q_{50}; (a3)Q_{100}; after dam removal (b1)Q_{20}; (b2)Q_{50}; (b3)Q_{100}

CONCLUSIONS

In this study, the reach between New railway bridge and Houfon bridge of Dajia was selected as a study case. In order to understand the process of riverbank retreat, we developed an evaluation model based on limit equilibrium method. The model has ability to predict the changes of erosion length, riverbank collapse and riverbank retreat length with consideration of river stage variations provided by WASH123D modeling. The proposed model could reasonably estimate riverbank retreat length. After soil properties of the study reach was obtained by field measurement. The effects of river stage on riverbank retreat would be evaluated by modeling. A flood characteristics would determine riverbank retreat length since riverbank retreat is a result of erosion and riverbank collapse occur repeatedly. The results from two events of Typhoon Morakot and Typhoon Soulik shows that the flood duration would dominantly determine retreat length. Besides, the results of return periods of Q_{20}, Q_{50} and Q_{100} also indicates that retreat length would not have dramatic rise with flood scale under the same flood duration. There is a little difference in riverbank retreat length since the river stages would nearly no difference of river stages before and after dam removal.

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