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Response of slope surface roughness to wave-induced erosion during water level fluctuating

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Abstract: The bank slopes in hydro-fluctuation areas of reservoirs or lakes suffer from severe erosion due to an absence of protection. Waves are one of the important external forces that cause bank erosion and slope failures. However, the processes and quantified impacts of wave-induced erosion on slopes remain unclear under different water level-fluctuation conditions. This paper focuses on the characteristics of wave-induced slope erosion under three conditions: water level dropping (WLD), fixed (WLF) and rising (WLR). A steel tank with glass pane was used to simulate the wave-induced slope erosion in the three treatments. The slope elevation data were collected by using the method of the pin meter for every 15 minutes from the beginning to the end, a total of 5 times during all treatments. These data were processed by using software (SURFER 9.0) to get the slope micro-topography and the erosion volume. Then the temporal and spatial change of slope erosion was analysed according to the erosion amount or erosion rate calculated based on bulk density of slope soil. The results demonstrated that the soil erosion rates for different water level changing treatments are in the following order: WLR>WLD>WLF. For the erosion spatial variation, the middle part of the slope was the major source of sediment in the WLD. The upper part of the slope was the major source of the sediment for the other two treatments. Compared with the standard deviation (SD), the coefficient of variation (CV) based on the SD is more representative of variations in the soil surface roughness (SSR). Furthermore, the good fit between the SSR and soil erosion rate have the potential to be used to predict soil erosion. Above all, the injection angle of the wave determined the rate of erosion to some extent, and the fall-back flow of the wave could also influence the extent of erosion, deposition, and bank morphology. It is vital to choose the appropriate index (SD or CV) in the three water levels to improve the prediction accuracy. This paper could provide scientific knowledge to manage reservoirs or river banks.

Keywords: Bank erosion; Erosion rate; Micro topography; Soil surface roughness; Breaking point

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Introduction

Large number of dams and reservoirs have been constructed for the purpose of hydropower, irrigation, flood regulation, providing drinking water, pisciculture, etc. (Zhang and Lou 2011; Tang et al. 2018). Meanwhile, the water-level-fluctuating zone (WLFZ) was formed due to a seasonal hydrological regime (Zhang et al. 2018). For example, Three Gorges Reservoir has a WLFZ of about 30 m (Figure 1a) and covers an area of approximately 349 km² (Bao et al. 2015a, b; Wang et al. 2016). The reservoir bank is highly vulnerable to the hydrological characteristics of flow events, which may lead to unexpected morphological effects of bank in the WLFZ (Powledge et al. 1989; Limber and Barnard 2018), such as increasing the riparian erosion rates (Abaci and Papanicolaou 2009; Vietz et al. 2018). The water level fluctuation usually brings several environmental issues, in which bank collapse is one of the most serious ones (Duan and Julien 2010; Shi 2011). Furthermore, the wave-induced erosion cannot also be ignored (Figure 1b; Priestas and Fagherazzi 2011). Reservoir bank collapse not only causes the soil erosion but also the sediment deposition that may reduce the storage capacity of the reservoir and

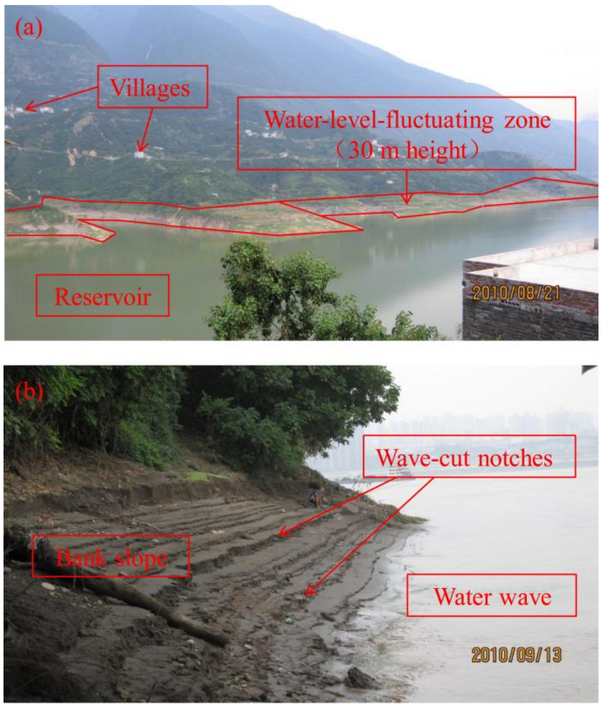

Figure 1 The water-level-fluctuating zone (a) and wave-induced bank erosion (b) in the Three Gorges Reservoir.

affect flood safety (Svendsen et al. 2009). Understanding the effects of the wave on the bank erosion with water level fluctuation can therefore have significant implications for the riparian land management and application of effective measures.

Many studies have been reported regarding the bank erosion linked to the collapse mechanisms (Darby and Thorne 1996; Amiri-Tokaldany et al. 2007). Mass failure and fluvial erosion were regarded as the two main interactive processes of bank collapse (Swartenbroekx et al. 2010; Volz et al. 2012). Nagata et al. (2000) indicated that bank failure occurred throughout the entire fluvial process and was triggered by the flow. The bank erosion rate was proved to be linearly related to the nearshore velocity of the flow, which was the difference between the cross-sectional average velocity and the depth averaged velocity (Ikeda et al. 1981). Afterwards, Rinaldi and Nardi (2013) found that the changes of the pore water pressure lead to the bank mass failure owing to the flow into the banks. When the unsaturated pore water pressure was slowly close to saturation, bank erosion rates increased owing to the soil strength decreased (Owoputi and Stolte 2001; Rockwell 2002). In addition, direct corrosion and slumping have been identified as two main processes of bank erosion (Hooke 1979; Davis and Gregory 1994; Duan 2005). The former appeared to be more directly controlled by river flow conditions and the latter mainly by soil moisture conditions.

Furthermore, a considerable amount of research has recently concerned the numerical models linked to the bank failure (Langendoen and Simon 2008; Langendoen et al. 2009; Evangelista et al. 2015). Modelling bank failure has developed from the definition of a bank retreat rate, related to the single parameter, such as the near bank excess velocity (Chen and Duan 2006; Constantine et al. 2009; Iwasaki et al. 2016). Kamal et al. (2016) simulated the non-cohesive bank using the 2D depth-averaged numerical model based on the date from the laboratory flume experiments and found that the numerical model was capable of reproducing the main features of the bank failure. A one-dimensional (1D) numerical model involving slope stability analyses was developed by Tingsanchali and Chinnarasri (2001), whereas Wang and Bowles (2007) developed a three-dimensional (3D) slope stability model, both of them have considered cohesion effects. Although the bank failure processes including many complicated elements which were hard to be modeled, amounts of flume experiments have been developed to improve the prediction accuracy of the numerical model by the interpretation of the physical models.

The wave, as an obviously important external force that induces bank erosion, has been studied for years. Some researchers found that the combination of wind-generated and boat-generated waves, together with the flow characteristics was not negligible factors in the bank erosion (Hagerty et al. 1981, 1983). Then Oswalt and Strauser (1983) further demonstrated that boat-generated waves were important driving forces to the bank erosion on small rivers. Besides, some studies also have been conducted to understand the process and mechanism of wave-induced slope erosion. In addition to the transport of sediment particles due to the velocities of the water flow under waves, the sediments on slopes may become unstable and then collapse under wave loads (Hooke 1979). Furthermore, the effects of wave characteristics on slope erosion have also been reported. Coops et al. (1996) found that the erosion of bank profiles was clearly related to the distribution of the wave energy over the slope, and the wave energy was quadratically related to wave height (Denny 1988). Tonelli et al. (2010) pointed that wave energy dissipation was maximized just above the marsh platform elevation, whereas wave reflection was reduced at the marsh edge. Spence (1982) found that the critical wave height that caused the soil surface to be scoured was related to the depth of the wave-mixed zone. Nanson et al. (1994) agreed the erosion rate of the channel banks depended on the wave frequency as well as the balance between wave energy and the resistance of the bank sediment, and concluded that riverbank erosion can be sharply reduced by controlling the maximum wave height to less than 30 cm.

Currently, predictions or simulations of banks, coasts, or river erosion are mostly based on the effects of water erosion and gravity erosion (Begin 1981; Armstrong et al. 2011; Midgley et al. 2012; Simon et al. 2013). Only a few researches have focused on the development of wave-induced erosion model. Evangelista (2015) used a numerical code of two-phase model based on experimental data of wave erosion of sand dike to obtain the reasonable predictive capability of the dike profile evolution. Moreover, great relationship between the wave-induced bed shear stress and wave patterns was obtained by Lim et al. (2013) using the SWAN wave model. However, the quantitative description of wave-induced erosion processes is still insufficient, especially the effects of water level fluctuations are always ignored. In addition, soil surface roughness is identified as one of the factors controlling surface runoff and soil particle transport (Jester and Klik 2005). However, its effects on soil erosion remains uncertain (Romkens et al. 2002). Some researchers reported that the erosion force of runoff and the transport capacity of the flow are reduced owing to the surface roughness decreasing the flow velocity (Johnson et al. 1979; Zheng et al. 2014). Meanwhile, Helming et al. (1998) found that dramatic surface variations may increase soil erosion and scour through concentrated flow. Therefore, it is necessary to figure out the responses and effects of soil surface roughness to wave-induced erosion on slope.

Flume experiments were carried out to simulate the wave force on bank slope with water level fluctuation. The aims of this study were to (i) quantify the change of micro-topography on the slope surface during the wave erosion processes when the water level was dropping, fixed, and rising; and (ii) estimate the temporal and spatial variation of the erosion rate on the slope during water level fluctuation. The results of this study can not only provide a theoretical basis to establish a wave-induced erosion prediction model but also provide a scientific reference for protecting a river or reservoir bank.

1 Materials and Methods

1.1 Experimental device

A tank with a 250 cm length, 50 cm width, and 60 cm height made of a steel frame and plexiglass was used to test the wave erosion (Figure 2). An outlet with a faucet was installed in one bottom end of the tank to control the water level dropping speed by adjusting the discharge rate. The water level rising speed was controlled by adding water directly through the pipes into the tank. In order to better observe experimental phenomena, a platform with a 15 cm height, 50 cm width and 60 cm length was built on the other side of the tank using bricks and cement.

The wave-generation system, which was placed on the side of the outlet, consisted of three parts, including the wave plate, speed motor and time relay. The wave plate was fixed at the bottom of the tank and could rotate around the shaft of the bottom. The speed motor pulled the wave plate to make it rotate around the shaft to make the wave. It controlled both the height and forward velocity of the wave. The time rely made the wave plate regularly swing to create continuous waves in a set frequency.

The pin metre method was used to measure the micro-topography (Wolman 1959; Vandekerckhove et al. 2001). The experimental device is shown in Figure 3. A wood plate placed on the top of the slope and fixed on the tank of steel frame, with a 52 cm length, 52 cm width, and 2 cm thickness had 121 small holes arranged in 11 lines and 11 columns. 121 iron pins, 50 cm in length and 2 mm in diameter. When these pins were slightly inserted into the small holes until gently reaching the slope surface during test, a digital camera was used to take pictures of the steel rules welded in a row. The height of the pins out of the plate were read on the computer, then converted to the height of the measuring points of the slope.

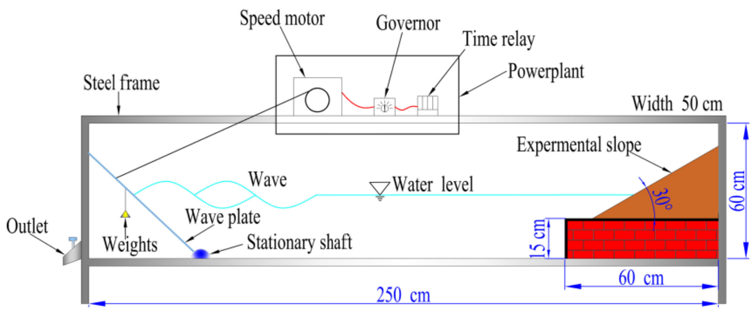

Figure 2 The sketch map of the experimental installation.

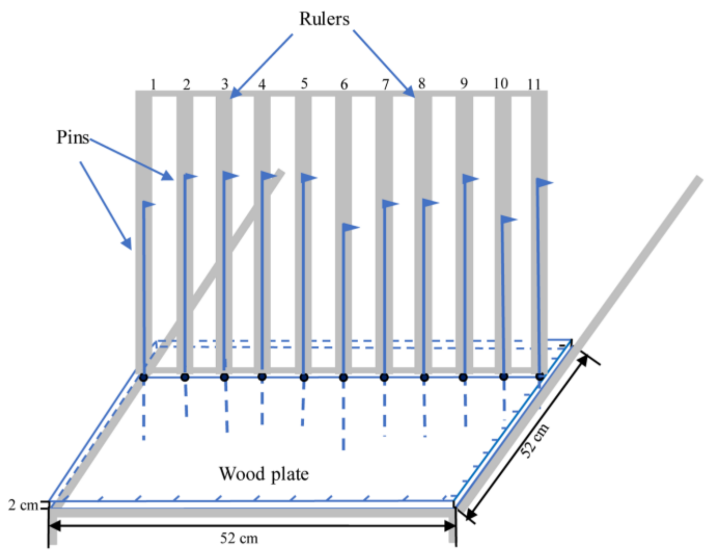

Figure 3 Experimental device map of the pin meter method.

1.2 Test soil slope layout

The tested soil, typical yellow brown soil from the WLFZ of Three Gorges Reservoir (E 106°50'-110°50', N 29°16'-31°25') was prepared for the research (Qian et al. 2016). The soil collected from the top layer (0-30 cm) was air-dried and sieved through a 5 mm mesh in order to remove roots and weeds. The particle size distribution was determined by using Malvern Mastersizer 2000 laser diffraction device (Malvern Instruments Ltd. UK), and the soil consisted of 20.0% clay (<0.002 mm), 55.9% silt (0.002 to 0.05 mm) and 24.1% sand (0.005 to 2 mm). The bulk density for the tested soil was 1.30 g/cm^3 by the method of core cutter used.

The area of steep slope (>25°) is about 71.48 km^2 which contribute approximately 55.29% soil loss related to the WLFZ in Three Gorges Reservoir (Wu et al. 2012; Tang et al. 2013). Therefore, a steep slope with gradient of 30° was designed to simulate the effect of the wave on the steep slope. The soil slope that was paved on the platform was 50 cm width and 50 cm length in horizontal projection. The slope line was drawn on the plexiglass tank before packing. And then the wood plate was placed along the slope line when packing was performed layer by layer (5 cm depth per layer) to obtain a uniform average bulk density of approximately 1.3 ± 0.05 g cm^{-3}. After packing, the soil was soaked with water until surface flow occurred by using an electric sprayer to further reduce the variability caused by packing (Xiao et al. 2017).

1.3 Design of the experiments

There were three treatments of water level fluctuation, including the fixed (WLF), dropping (WLD), and rising (WLR) test, and each treatment was in triplicate. The water level was set at 2/3 of the slope, namely, 35.0 cm height, in the WLF test. In the WLD and WLR tests, the initial water levels were 35.0 cm and 19.4 cm height, and ended at 19.4 cm and 35.0 cm, respectively. The WLD and WLR were at an average speed of 0.26 cm/min. During the tests, the wave height, forward speed, WLD and WLR speed were set according to the model scale and gravity similarity principle based on the records in the Three Gorges Reservoir (Li et al. 2002). The wave parameters were designed as follows: the wave height was approximately 8~10 cm, the frequency was 30 times/min, the wave speed was approximately 1.0 m/s.

The test lasted for 1 hour according to the WLD and WLR speed combined with the height. The slope elevation data were obtained by the pin metre method every 15 minutes from the beginning to the end during the tests. The coordinate axis was established at the bottom of the slope in order to obtain the three-dimensional coordinates of 121 points. Then these data were meshed by use of the software (SURFER 9.0), generating the 3D Wireframe Map.

1.4 Data processing

The amount of soil loss from the slope was calculated as:

$$M = V \times \rho \tag{1}$$

where M is the amount of soil loss, ρ is bulk density, V is the volume of eroded soil obtained by comparing the digital elevation model (DEM) based on the slope elevation data which were collected at the different times. The DEM of slope at the different times were generated using SURFER software version 9.0 (American Golden Software Corporation).

The soil surface roughness (SSR) is an indicator of the quantification of micro-topography, which can be expressed by the standard deviation (SD) and coefficient of variation (CV) of slope elevation (Garcia-Moreno et al. 2008, 2010). The SD accounts for the random and oriented soil roughness, and was calculated as:

$$SD = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left[Z(x_i) - \overline{Z}\right]^2} \tag{2}$$

where x_i is the point elevation measurements, $Z(x)$ is the elevation at location x, $\overline{Z}$ is the average value of the set $\{Z(x_i)\}$ and N is the number of data points considered.

The CV was calculated as:

$$CV = \frac{SD}{\overline{Z}} \tag{3}$$

2 Results

2.1 Micro-topography and erosion quantification

Figure 4 shows that the micro-topography of the slope was obviously different among the three treatments of water level fluctuation. In the WLD process, a layer of the wave-cut notch was formed on the slope near the water surface. The eroded soil was deposited at the lower one-third of the slope (Figure 4a, 30 min). As the water level continually dropped, a second layer of wave-cut notch was formed at approximately 5 cm below the first layer. After a long period of scouring, the slope foot was smoothed (Figure 4a, 60 min).

During the WLF and WLR treatment, wave-cut notches were formed on the slope near the water surface during the first 15 minutes (Figures 4b and 4c). Then, the wave-cut notch disappeared later under the continuous effects of the waves, but the processes of disappearance were different between them. For the WLF, the slope was first subjected to wave breaking pressure, and the wave-cut notch was formed gradually. Then, the lower part of slope was increasingly hollowed out by the flow along the slope, and the upper part collapsed due to gravity. For the WLR, the position of the wave attacking slope continually moved upward. Then, the lower wave-cut notch was gradually washed away by the downward water flow.

2.2 Soil surface roughness (SSR)

Figure 5 indicates the variation of SD and CV at different positions of the slope at different times

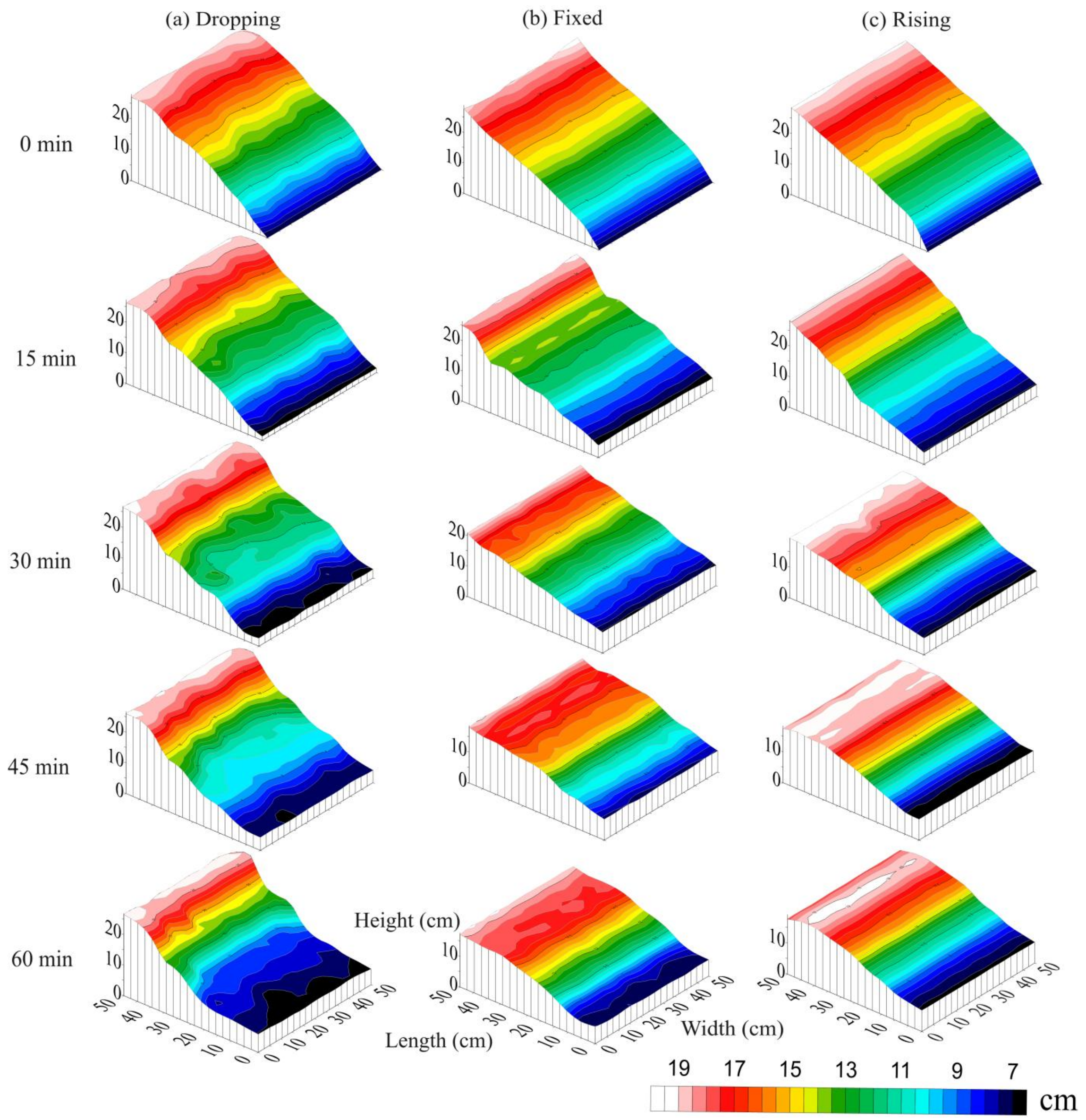

Figure 4 Topography changes of the slope for different water level changing process: (a) dropping; (b) fixed; (c) rising.

for three water level treatments. For the WLD (Figures 5a and 5d), the SD reduced slightly from the beginning to the end, from approximately 2.7 cm to 2.4 cm. However, the CV increased slightly during the whole process, from approximately 17.0% to 18.5%. For the WLF (Figures 5b and 5e), the SD and the CV were greatly reduced during the first 45 mins and then increased during the last 15 mins. This indicates that the slope topography underwent a great change during the last 15 mins. For the WLR, the SD almost did not change during the first 15 mins (Figure 5c). However, the CV increased slightly by approximately 2.0% in the first 15 mins (Figure 5f). In the next 15 mins, the SD and the CV drastically reduced. In the last 30 mins, the SD decreased slightly from 1.6 cm to 1.4 cm, and the CV decreased slightly by approximately 2.0%.

The average values of SD and CV in the WLD were the largest and most stable among the three treatments for all times (Figure 5). It indicates that the WLD had the highest SSR and lowest SSR changing rate among the three treatments. For both of SD and CV, the fluctuation of the curve around the average line represented the changing values on different position. The WLD had more intense fluctuations than that of both the WLF and

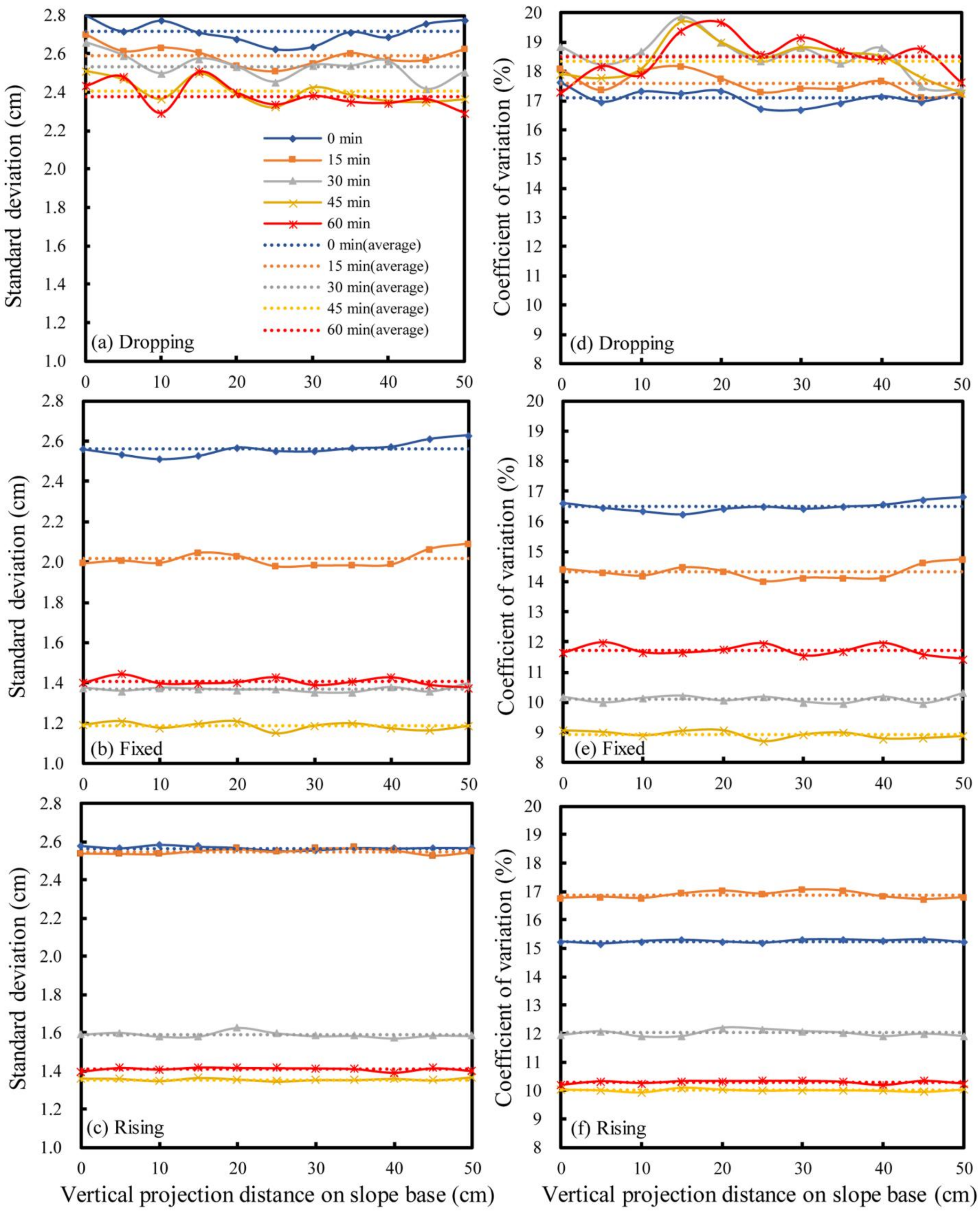

Figure 5 Changing of the standard deviation (SD) and coefficient of variation (CV) for the soil surface roughness for different parts of the slope in different water level changing processes: (a, d) dropping; (b, e) fixed; (c, f) rising.

WLR. This indicates a more uneven slope surface in the WLD than the other two treatments.

The average change rates of SD and CV for the entire slope of the three treatments followed the order of WLD<WLR<WLF (Table 1). For the WLD, the SD of the average speed decreased by 7.5% throughout the process while the CV in the 15 min was much larger than at other times. This indicates that the topography of the slope had the largest change during the first 15 min for WLD. For the WLF, the SD and the CV were reduced by 53.7% and 45.8% in the first 45 mins, respectively and

Table 1 The average change rate of standard deviation (SD) and coefficient of variation (CV) for soil surface roughness of entire slope in different water level changing process.

Time (min)	Dropping				Fixed				Rising			
	SD (cm)	Change rate (%)	CV (%)	Change rate (%)	SD (cm)	Change rate (%)	CV (%)	Change rate (%)	SD (cm)	Change rate (%)	CV (%)	Change rate (%)
0	8.6	/	54.3	/	8.1	/	52.4	/	8.2	/	48.5	/
15	8.6	-0.1	70.0	28.9	6.4	-21.4	45.5	-13.2	8.1	-1.1	53.6	10.5
30	8.1	-6.6	58.9	8.5	4.4	-46.6	32.1	-38.7	5.0	-38.4	38.2	-21.2
45	7.7	-11.2	58.4	7.6	3.8	-53.7	28.4	-45.8	4.3	-47.4	31.8	-34.4
60	7.6	-12.2	58.9	8.5	4.3	-47.7	35.5	-32.3	4.5	-45.4	32.7	-32.6
A-V	8.1	-7.5	60.1	-13.4	5.4	-42.3	38.8	-32.5	6.0	-33.1	41.0	-19.4

Note: The change rates of SD and CV in different time period are over that in 0 min. Positive value means increase, negative value means decrease. A-V represents average value.

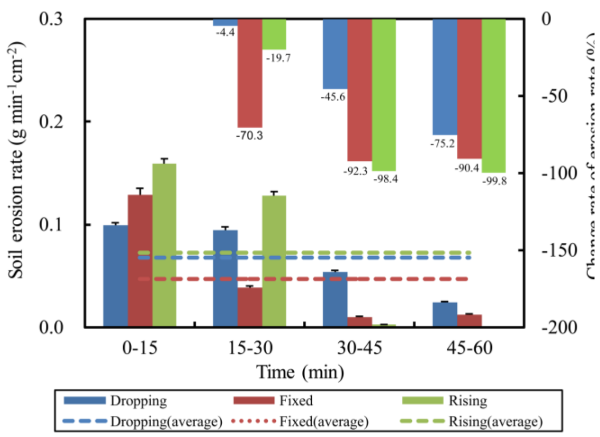

Figure 6 Soil erosion rates and change rates for different periods during the three treatments of the water level dropping, being fixed and rising. A negative value denotes a decreasing soil erosion rate.

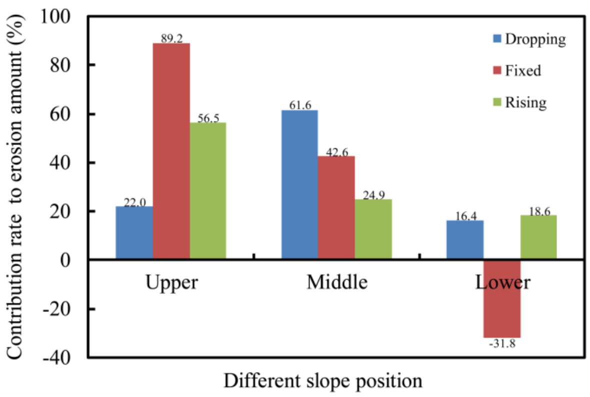

Figure 7 Contribution rate to the erosion amount on different slope positions during three treatments of the water level dropping, being fixed and rising. Positive value means erosion, negative value means deposition.

then increased slightly in the last 15 mins. This indicates that the slope topography gradually changed to be flat after erosion and deposition. For the WLR, the SD decreased by 1.1% while the CV increased by 10.5% in the first 15 mins. Then, the SD and CV decreased by 38.4% and 21.2% in the next 15 mins, respectively. In the last 30 mins, both of them decreased slightly. This indicates that the topography of slope changed very quickly in the second 15 mins.

2.3 Slope erosion

Figure 6 shows that the soil erosion rate of different water level changing treatments followed the following order: WLR>WLD>WLF. The erosion rate of the WLR in the first 15 mins was the largest, and then decreased by 19.7% in the 15-30 mins. In the later 30 mins, the erosion rates were very small (close to zero). For the WLF and WLD, the erosion rates were gradually decreased from the first 15 mins to the end. The decrease rate of the WLF was larger than that of the WLD.

The slope along the vertical projection length direction was divided into three parts: lower part (0-20 cm), middle part (20-35 cm) and upper part (35-50 cm), shown in Figure 4. The spatial distribution of the contribution rate to the erosion amount is shown in Figure 7. It indicates that the upper and middle parts of the slope were the main sediment sources. The upper part in WLF and WLR treatments contributed 89.2% and 56.5% to erosion amount, respectively. The middle part contributed 61.6% in WLD treatment. Meanwhile, not all of the eroded soil was transported out of the slope, as 31.8% of the sediment was deposited in the lower part of the slope in the WLF treatment.

2.4 Relationship between the SSR and erosion rate

Figure 8 shows that the good coefficients of determination (R^2) were identified to strengthen the relationship between the SSR (SD and CV) of the entire slope and the soil erosion rates in the three water level treatments. These R^2 were larger than 0.70, except for the CV in the WLD which had an R^2 of 0.34. Thus, the SSR has potential to be used to predict the soil erosion rate.

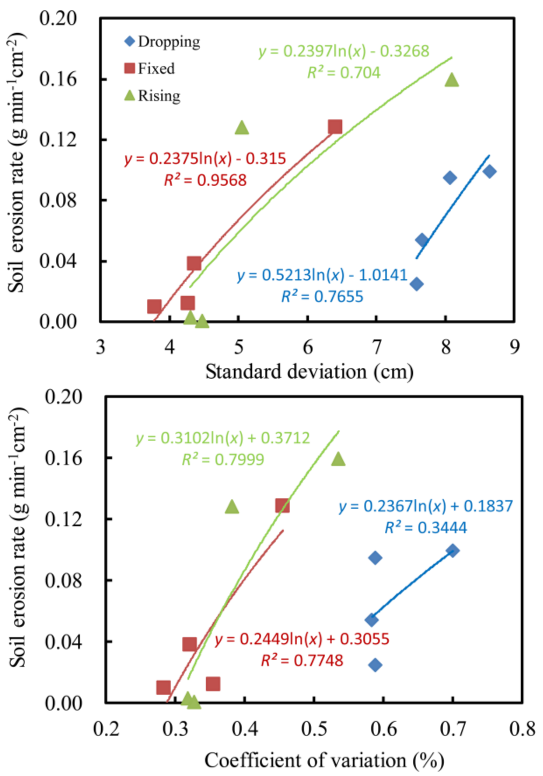

Figure 8 Relationship between the indexes of the soil surface roughness: standard deviation (SD) and coefficient of variation (CV) of the entire slope, and the soil erosion rates in the three treatments of the water level dropping, being fixed and rising.

3 Discussion

3.1 Wave-induced slope erosion

Figure 6 shows that the majority of the slope erosion happened in the first 15 mins for the WLF treatment. This may because the wave breaking point was fixed at a slope position near the water surface, and the slope was rapidly eroded by the continuous hitting of the wave (Tonelli et al. 2010). After 15 mins, the slope at the fixed water level flattened (Figure 4b, 30 min). The effects of the wave breaking pressure on the slope decreased because of the lower injection angle of the wave (Khalifa and Zahra 2014). However, the collapse of the upper slope could provide abundant sediment. Therefore, the soil erosion rate was still relatively high. From 30 to 60 mins, the soil erosion rate dropped to a very low level because the upper slope was completely eroded (Figure 4b). The falling back flow along the slope was the only driving force that took away soil particles (Doro and Aidun 2013). However, the transporting capacity of the slope surface flow was limited because of the great resistance of the tank water to the falling back flow.

As for the WLD and WLR, the soil erosion rate was maintained at a high level in the first 30 mins (Figure 6). This could be ascribed to the fact that the changing breaking points of the wave with a dropping or rising water level could continually provide energy to breakdown the soil particles by wave hitting and transport the sediment by falling back flow (Sambe et al. 2011; Mohsin and Tajima 2014). Meanwhile, with the change of the water level, the slope could be exposed to the continual wave, providing enough soils as sediment sources (Vincent and Hanes 2002). After 30 mins, for the WLD the water level dropped to the middle or lower part of slope where the deposition occurred. That led to a smaller slope gradient, resulting in less of an injection angle of the wave and thus a lower wave breaking pressure on the slope (Okamura 1993). For the WLR, the water level was raised to the middle and upper parts of the slope, where the soil was completely eroded in the first 30 mins. This was because the lower part was eroded at first, and the middle and upper parts collapsed due to the gravity without the support of the lower part (Chaudhry and Naseem 2000). Finally, in the last 30 mins very limited sediment was taken away from the slope by the falling back flow along the slope.

Some features of the wave, e.g., height, injection velocity, and frequency, could influence the slope erosion (Benumof et al. 2000; Ruggiero et al. 2001; Trenhaile and Kanyaya 2007). In this study, the features of the wave were controlled and kept constant. Therefore, the water level change could obviously contribute to wave erosion. During erosion processes, the changing water level continually changes the injection point of the wave on the slope, and thus changes the effect position of the erosion driving force. The fall-back flow of a wave could also influence the extent of the erosion, deposition, and bank morphology (Hooke 1979). In addition to the individual effects of the wave, the river flow along the bank and rainfall could also contribute to the bank erosion (Saynor and Erskine 2006; Artemi and Doerr 2007). The comprehensive effects of those external forces on the bank erosion should be researched in the future.

3.2 Soil surface roughness

The SSR was used to describe the micro-topography changes by using two indexes: SD and CV. The SD represents the change of slope height relative to the average height, reflecting the fluctuation of the slope surface, while the CV reflects the slope topography by eliminating the influence of changing the average height. According to Table 1, the average SD was gradually reduced while the average CV increased for the WLD. That could be attributed to changing the average height (Figure 4). In addition, two layers of the wave-cut notch were formed one after another, resulting in a decrease in the average height of the slope. This kind of geomorphology is conducive to siltation and is detrimental to reservoir flushing and muddying (Valero-Garces et al. 1999). For both the WLF and WLR, their SD and CV showed similar trends (Table 1) because of the slight change in the average height of the slope after 15 mins (Figure 4).

The Random Roughness index (RR) is one of the most widely used soil surface roughness indexes (Currence and Lovely 1970). The oriented roughness should be considered due to the parallel action of the waves on the slope (Abrahams and Parsons 1990; Zheng et al. 2014). In this study, the SD was used to characterize both the random roughness and oriented roughness (Garcia-Moreno et al. 2008, 2010). However, the waves action may dramatically change the average height of the slope. This may lead to the SD not being able to accurately describe the change in the micro-topography. Thus, the CV may represent the variation of the soil surface roughness better than the SD, because it eliminates the influence of changing the average height (Garcia-Moreno et al. 2008).

3.3 Applications and future research needs

The good fit between the SSR (SD and CV) of the entire slope and soil erosion rate for the three water level treatments were found (Figure 8). Although the data from simulated experiments in laboratory may different with that from natural slope (Evangelista 2015), the logarithmic functions also have the potential to be used or provide a possible way to predict the erosion rate, especially when data other than the SSR is difficult to obtain. For example, the slope erosion under water is hard to predict because very limited information can be obtained. The SSR is a factor that can be easily obtained in this situation, and it may be used to predict soil erosion.

The different position and degree of soil erosion or deposition under three water level treatments may be caused by the changing injection point of the wave on slope. Therefore, to reduce the impact of wave-induced slope erosion, it is necessary to consider the effects of changing injection point on slope. The erosion control efficiency could be improved by focusing on the potential serious damaged slope position based on the spatial distribution of erosion.

This study used a homogeneous and straight slope, which may not reflect the true condition of a bank slope. In the WLFZ, the reservoir water pressure, soaking time and dry-wet alternating amplitudes of the soil on the bank slope have obvious spatial vertical gradients (Poulos 1972). In addition, the soil properties at different elevations on the slope may vary (Thorne 1981). The slope erosion processes on non-cohesive and cohesive soil banks with or without vegetation were completely different (Michaelides et al. 2009; Liu et al. 2014; Yu et al. 2015; Zhong et al. 2016, 2018). These factors need to be studied further.

4 Conclusions

The effects of wave-induced slope erosion under three treatments were studied. The soil erosion rates for the different water level treatments were in the following order: WLR>WLD>WLF. Erosion mainly occurs during the first 30 minutes in the WLR. For the WLF and WLD, the erosion rates gradually decreased from the first 15 minutes to the end, and decreased faster for the WLF than the WLD. For the erosion spatial variation, the middle part of the slope was the major source of sediment for the WLD, while the upper part of the slope was the major sediment source for the WLF and WLR. The injection angle of the wave determined the rate of erosion to some extent, and the fall-back flow of the wave could also influence the extent of erosion, deposition, and bank morphology. The result can provide engineering practice reference to prevent the wave-induced slope erosion.

Both the SD and CV showed a more uneven slope surface for the WLD than for the other two treatments. The CV could describe the variation in the soil surface roughness better than the SD on account of the influence of the changing average height eliminated. The good fit between the SSR and soil erosion rate have the potential to be used to predict slope erosion. Furthermore, it is vital to choose the appropriate index (SD or CV) in the three water levels to improve the accuracy of prediction. To develop the prediction model, the interactions between hydrologic elements, hydrodynamics, sediment transport processes and geotechnical aspects should be taken into account and be studied in the future.

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