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# Response of roll wave to suspended load and hydraulics of overland flow on steep slope

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ABSTRACT

A roll wave is frequently observed in overland flow and it can accelerate the soil erosion on slopes. However, the feedback effect of eroded sediment on roll wave has not been studied. The aim of this study was to investigate the response of roll wave to sediment concentration and overland flow hydraulics on steep slope. The experiment was carried out in a hydraulic flume. The unit flow rate varied from 1.0 to 3.0 × $10^{-3}$ $m^3$ $s^{-1}$, and sediment concentration from 0 to 400 kg $m^{-3}$. The sediment transport was dominated by suspension. Slope gradient was 9°. As the sediment concentration increased, the critical slope length for roll wave formation increased, implying that the suspended sediment in flow could inhibit the formation of a roll wave. The roll wave in overland flow is a short water long wave. The roll wave length increased with the increasing sediment concentration, while the wave frequency and velocity decreased. The decreased wave velocity meant a decrease in flow erosion potential caused by a roll wave. Roll wave frequency and velocity significantly increased with Reynolds number, Froude number and mean flow velocity, and decreased with the hydraulic resistance, while there were no notable relationships between roll wave length and overland flow hydraulics. Both roll wave frequency and velocity had the strongest dependency on Froude number and could be estimated by the linear equations between them. When the sediment concentration was larger than 300 kg $m^{-3}$, all the roll waves in overland flow disappeared due to the high sediment supply. The results indicated that the suspended sediment can ease the acceleration influence of a roll wave on soil erosion and should be considered in the soil erosion models.

## 1. Introduction

Free surface instabilities of flows are often observed in inclined open channels and a succession of perturbation occurs in the flow. This kind of undulating flow movement is called roll waves. A roll wave is undesired by the civil engineers, since it can periodically increase the flow depth and make the water overflow channel banks or runoff conduits which were designed to contain even more flow (Brock, 1969; Di Cristo et al., 2009). A roll wave can also cause flow intermittency at the channel outlet and produce pronounced local maxima of sediment concentration at their fronts (Liu et al., 2005). If the roll wave occurs in debris flow, the damage can be devastating since the large boulders and rocks traveling with the flow are very dangerous to the people, animals and crops in the path of the wave. It is thus worthwhile to investigate the characteristics of roll wave as well as its development process to mitigate the damage of roll wave as far as possible.

Most studies demonstrated that the formation of roll wave was closely related to flow resistance. Cornish (1934) speculated that the flow resistance played a major role in forming a roll wave, and if there were no resistance, no roll wave would happen. However, Rouse (1938) found that the roll wave would also not occur if the flow resistance were sufficiently large. Dressler (1949), Longo (2011), Smith et al. (2011) and Wang et al. (2014) emphasized that in order to obtain the roll waves, the flow resistance must be less than a certain critical value. Thomas (1937) also derived a necessary condition for roll wave formation based on the flow resistance. It can be seen that both too less or too much resistance are not conducive to the formation of a roll wave, and it only possibly occurs under a certain range of flow resistance.

Critical Froude number is widely used as the criteria separating the existence of the roll wave or not (Arai et al., 2013; Jeffreys, 1925; Smith et al., 2011; Thual, 2013). Several researchers, among them Ishihara et al. (1954), Benjamin (1957), Yih (1963, 1977) and Ferreira et al. (2015) indicated that for laminar flow down an inclined plane, the roll waves tended to form when the Froude number was greater than 0.58. Julien and Hartley (1986) found that roll wave was observed in laminar, subcritical flow at a Froude number as low as 0.74. For the turbulent flow in a rectangular channel with constant friction factor, Stoker (1957), Liggett (1975) and Armanini and Recchia (2006) found a critical Froude number of 2.0. Some other researches, like Koloseus

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and Davidian (1966) and Berlamont and Vanderstappen (1981), highlighted that the critical Froude number had strong dependency on velocity profile, Reynolds number and friction law.

Generally, the development of roll wave can be divided into three phases (Brock, 1969; Di Cristo et al., 2010; Zhang, 2011): (1) the initial development phase, in which both the roll wave period and length are relative small, the wave length varied 2–10 cm, and the waves do not overtake and combine with other waves; (2) the transitional development phase, in which roll waves begin to overtake each other, increasing their period; and (3) the mature development phase, in which the wave shape is quite obvious, and the wave period increases with the distance due to the significant roll wave coalescence. Zanuttigh and Lamberti (2002) studied the evolution of roll wave by numerical simulation, and showed that the natural roll wave cannot reach the final regime shape, but the wave height and period continuously increased with the channel due to the coalescence.

The stability of roll wave was affected by many factors, especially the flow uniformity and underlying bed. Bohorquez (2010) has shown that a small non-uniformity of the flow depth could make the flow more stable and prevent the formation of roll wave. Balmforth and Mandre (2004) explored the effect of bed topography on roll wave and found that the low-amplitude bottom topography tended to destabilize the turbulent flow and lowered the critical Froude number required for instability, while at large amplitude, the trend reversed and the onset of roll wave occurred at higher Froude number; the latter was proven by Balmforth and Vakil (2012) who reported that the stabilizing effect is much more pronounced when large bed forms are accounted for over an erodible bed. Colombini and Stocchino (2005) presented a related study of the competition between roll wave and other erosional instabilities using linear theory. The bed forms influenced the roll wave stability mainly through the hydraulic jump that often arise in flow downstream of the steepest part of the bed forms (Colombini and Stocchino, 2008; Parker and Izumi, 2000). The interaction between bed forms and roll wave implied that the sediment transport may have a significant feedback influence on roll wave, because the roll wave could affect the transport of bed and suspend sediment and localize soil erosion near the wetting front as the flow evolves downhill (Bohorquez and Fernandez-Feria, 2008), which further caused the emergence of different forms on the erodible bed.

Roll wave is more prone to form in the overland flow due to the very shallow flow depth and steep slope. The splash of raindrops can also undermine the stabilities of overland flows and promote the roll wave formation (Pan and Shangguan, 2009). The occurrence of the roll wave in overland flow has significant effects on soil erosion development, since it affects the hydraulics and hydrodynamic force distribution of the flow. Using one-dimensional St. Venant equations, Liu et al. (2005) investigated the dynamics of periodic roll wave in overland flow and indicated that the existence of roll wave could increase the flow shear stress and augmented the potential of soil erosion. Prasad et al. (2005) reported that roll wave contained a significant portion of the total kinetic energy of flow and acted as primary energy source in transporting eroded sediment in shallow flow. Zhang (2011) explored the critical conditions for flow instability in laminar and turbulent overland flow, and concluded that the critical Froude number varied between 0.5–0.7 for laminar flow and 1.59–2.22 for turbulent flow.

As mentioned above, there had existed some research in the literatures that investigated the roll wave characteristics in overland flow and the possible effect of roll wave on soil erosion and sediment transport. However, the feedback effect of the eroded sediment on roll wave has not been studied, especially at high sediment concentrations. The objectives of this study were to evaluate the potential effects of sediment concentration on roll wave characteristics, as well as the possible relationships between roll wave length, frequency/period, velocity and hydraulics of overland flow on steep slope under a wide range of sediment concentrations and hydraulic conditions.

## 2. Materials and methods

### 2.1. Experimental conditions and treatments

The hydraulic flume used in this study was 8 m long, 0.50 m wide and 0.25 m deep, with a smooth fixed bed made up of plexi-glass. The slope of the flume could be adjusted manually. Soil was collected from Yangling District, Shaanxi Province, China. The soil was air-dried, gently crushed, and then passed through a 1-mm sieve to remove gravel and residues. The particle size distribution of the test soil was shown in Table 1, with the median diameter $d_{50}$ of 0.012 mm. A 1-m$^3$ water tank, installing an electric stirring device, was used to mix the water and soil (Fig. 1(a)). Then the sediment-laden runoff was pumped into a head tank at the upper end of the flume and flowed naturally over the flume.

To simulate the influence of sediment concentration on roll wave of overland flow, twelve sediment concentrations were selected according to the slope erosion and sediment transport characteristics in the Loess Plateau of China. The sediment concentrations were 0, 30, 60, 90, 120, 150, 180, 200, 250, 300, 350 and 400 kg m$^{-3}$, respectively. Water samples were collected at the outlet of the flume to determine the actual sediment concentration. Flow discharges were 0.5, 0.75, 1, 1.25, and $1.5 \times 10^{-3}$ m$^3$ s$^{-1}$, respectively. They were controlled by a series of valves and measured directly by a calibrated flow meter on the inflow pipe. The flume was adjusted at 9°, which was a common gradient in China.

Experimental observation showed that the dominant mode of sediment transport was suspended load along the whole flume. It is evident as a result of the very low settling velocity of the particles due to the small size and the high flow velocity. Bohorquez and Fernandez-Feria (2008) also proved that the sediment transport was dominated by suspension for the particles ≤ 1.0 mm. Transient or permanent deposition of sediment occurred at the water-bed interface for some tests with the combinations of high sediment concentration and low flow discharge, but the deposition yield was very few and the particles were basically uniformly spread flat out on the whole bed (the largest average deposition thickness was only 0.12 mm). No obvious bed forms existed. For this reason we have neglected the possible bed slope change produced by the deposition as well as its influence on roll wave.

### 2.2. Experimental measurements

Prior to each test, the sediment concentration, flow rate and flume slope were adjusted to the designed values. After flow became stable, the flow depth and roll wave characteristics were measured. The side-view schematic diagram of flow in the flume and the roll wave and particle motion in flow at low and high sediment concentrations were shown in Fig. 1(b)–(d), respectively. The flow depth was measured using a digital level probe (SX40-A, Chongqing Hydrological Equipment Factory) at the section of 0.5 m above the lower end of the flume. The resolution of the digital level probe was 0.01 mm and the accuracy was 0.04 mm. For each test, nine flow depths were measured across the section and the average of the nine depths was considered as the mean flow depth of the test.

Because of the limitations of the measurement instruments, only the critical slope length for roll wave formation, roll wave length and period/frequency were measured. The critical slope length was visually observed and the value was read according to the scale marked on the flume. The roll wave length was also visually observed and measured using a steel square at the section of 7–8 m from the upper to the lower end of the flume. Six roll wave lengths were measured and the average of the six lengths was the mean roll wave length of the test. The roll wave period/frequency was measured using a digital stopwatch. The travel time of ten roll waves over every cross section (1 m interval from upslope to downslope) of the flume was recorded with five replicates. The one roll wave period was obtained by dividing the travel time