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Effects of Roughness Elements Distribution on Overland Flow Resistance

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Abstract: Roughness elements are various in a mountain area; they include gravel and ground surface vegetation that often result in surface friction drag to resist overland flows. The variation and characteristics of flow resistance strongly impact the overland flow process and watershed floods. In view of the universal existence of natural vegetation, such as *Chlorophytum malayense* (CM) or *Ophiopogon bodinieri* (OB), and the sand-gravel bed of the river channel, it is important to understand the role of different types of roughness elements in flow resistance. This study was performed to investigate and compare through flume experiments the behaviors of overland flow resistance by the reaction of multi-scale configuration of different roughness elements. The result showed that the resistance coefficient gradually reduced versus the increase of flow rate in unit width and tended to be a constant when q = 3.0 l/s.m, Fr = 1.0, and Re = 4000 for slopes of 6 to 10 degrees. The gap of the vegetated rough bed and the gravel rough bed is limited to the same as the gap of the two types of vegetation, CM and OB. It was noted that the vegetation contributed to the increase in form resistance negatively and may lead to the mean resistance on decrease. To classify the flow pattern, the laminar flows were described by Darcy-Weisbach's equation. In the study the f-Re equation of vegetated bed was developed with $f = 5000/Re$. The friction coefficient for laminar flows can be regarded as the critical value for identifying the transformation point of the flow pattern.

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Introduction

All runoffs on the mountain slope arise in the form of overland flows. Runoff, soil erosion, scour and transport capacity are all dominated by the characteristics of overland flows on the ground surface (Hu and Abrahams 2004; Pan and Shangguan 2006; Shih and Yang 2009). The process and properties of an overland flow depend mainly on geomorphologic characteristics and precipitation conditions. Generally speaking, overland flows can be described with many hydraulic parameters such as flow velocity, water depth, flow resistance (f), flow patterns, flow regimes and so forth. However, it was noted in a number of studies that the resistance of a overland flow may be the essential parameter for the analysis of overland flows and watershed floods

(Emmett 1970; Abrahams et al. 1992; Weltz 1992; Barros and Colello 2001; Hu and Abrahams 2004, 2005, 2006; Zhang et al. 2010; Wang et al. 2014).

The overland flow resistance can be affected by such factors as rainfall, slope gradient, underlying roughness elements, etc. (Grosh and Jarrett 1994). The type of roughness elements concerned with overland flows are numerous and complex. It may be single or multiple objects, e.g., sand, gravel, vegetation, and even surface relief, etc. The effect of single type obstacles on overland flows can be found widely expounded in publications. Abrahams et al. (1992) discussed the overland flow resistance in semi-arid areas with gravel coverage, and achieved linear relationships between the resistance and the Reynolds number (Re). Gilley and Finkner (1992) studied stone zones and considered the influence of the roughness element size and the spacing between them on the flow resistance. Yao (1996) formulated the equation of the resistance coefficient within the range of the Reynolds number under different rainfall intensities. Musleh and Cruise (2006) demonstrated that the vegetation density and water depth strongly affected flow resistance in proportion to the unsubmerged vegetation on wide flood plains. Furthermore, there was a positive power function relationship between Re and resistance coefficient in the overland flow on geocell-supported slopes, and at the same time, a negative power function relationship was established between drag coefficients and the Froude number (*Fr*) (Wang et al. 2012). However, Li (2009) believed that the roles of rainfall and bed roughness elements were interrelated in respect of overland flow resistance.

As a very universal roughness element on mountain slopes, vegetation has been widely reported to be effective in slowing down overland flows and reducing soil erosion (Munoz-Carpena and Parsons 2005; Gharabaghi et al. 2006; Knapen et al. 2009; Zhang et al. 2010). The resistance mechanism of vegetation against overland flows has been under discussion. Oscillations of grass with flow to wear down its momentum would result in extra flow resistance (Palmer 1945). Shrub stems may bring about turbulent vortices and wakes to dissipate flow energy and increase resistance against fast flows (Li and Shen 1973). Weltz et al. (1992) investigated the flow resistance in an intermountain area covered by canopies, plant stems and cryptogams, but could not make distinct the trend of effective roughness coefficient associated with vegetation types (grass or shrub). Plant leaves and stems can increase effective surface friction drag and further impact flow resistance in vegetated areas (Abrahams et al. 1994). Ceramic tiles in comparison with organic litters, through experimental studies, would create retardation to a flow and higher flow resistance as a result of the organic litters tangling with and over tiles, which has a larger ratio of surface to volume because of surface tension (Dunkerley et al. 2001). Experiments on different conditions of the submerged vegetation convinced Wu and Yang (2014) that with the increase of the relative bending rigidity of submerged vegetation the flow resistance also increased, showing a positive correlation between them.

Plenty of researches of recent years on the dynamic correlations between vegetation and overland flows have reached rather few results aimed at analyzing on how the spatial distribution of natural vegetation caused variations in flow resistance. Weltz et al. (1992) pointed out by their qualitative researches that the percentage of vegetation-coverage affected the overland flow resistance. Abrahams et al. (1994) also believed that the lowering of the resistance was due to the quantity adjustment in vegetation development. These studies focused on the percentage of vegetation-coverage but ignored the internal effects of vegetation-covered channel beds. In order to further understand and reveal the influence of the spatial distribution of vegetation on the overland flow resistance, a series of flume experiments were carried out by using natural plants enumerated in this study. Generally speaking, grasslands were often selected as the obstacle to overland flows in many previous studies. Prairies of shortgrass, mixed-grass, tallgrass were taken as obstacles (Weltz et al. 1992). Hill slopes in the grasslands were also selected for studies conducted at Walnut Gulch, where the vegetation consisted of Chihuahuan desert grassland dominated by *Bouteloua* spp., *Andropogon bardinodis,* and *Hilaria belangeri* (Abrahams et al. 1994). In addition, perennial ryegrass was considered as the obstacles under investigation (Pan and Shangguan 2006). Similar to perennial ryegrass and mascarene grass, *Chlorophytum malayense* (CM) and *Ophiopogon bodinieri* (OB), two common species of short grass, were used for preventing soil erosion and urban greening in Southwest China, also regarded as widely distributed variety on the watershed side slope. Therefore, *Chlorophytum malayense* and *Ophiopogon bodinieri* were choices for analyzing the effects of the natural vegetation on the characteristics of overland flows.

Most of the above-mentioned studies on overland flow resistance are focused on the effects of the hydrodynamic characteristics rather than on the roughness element distributions. So, this study aims at the two other questions from another perspective: (a) whether or not there exists the effect of changing assemblage of different roughness elements on the resistance coefficient in overland flows, and (b) how to look at the relationship between flow resistance coefficients and the impacting factors on the basis of a series of overland flow experiments regarding the different spatial distributions of roughness elements. This study is to better understand the influence of the spatial distribution of roughness elements on the hydraulic characteristics of overland flows and on flow resistance. The findings can provide basic reference for exploring the law of overland flow resistance relevant to several types of roughness elements and to obstacles that may change in spatial distribution on mountain slopes.

1 Materials, Apparatus and Method

A flume experiment was conducted in the State Key Laboratory of Hydraulics and Mountain River Engineering of Sichuan University, China. The experiment apparatus was the flume 6.9 m in length, 0.5 m in breadth and 0.3 m in depth, made up of 0.003 m thick walls and bottom of Plexiglas (Figure 1).

Experimental process:

As shown in Figure 1, water enters the flume in the form of overflows from a head tank and over a plate weir which was to have the input flow in equilibrium; θ is the bed slope, which can be adjusted from the end of the flume. The inflow volume is controlled by a valve. Pebbles are deposited along the leading edge of the flume to keep the water stabilized before entering the test section which is 1.5 m in length along the flume at a distance of 1.5 m from the upstream end and of 3.0 m to the downstream end. The experiment is carried out in four batches. The first batch is on a fixed smooth bed and the other three on different vegetated rough beds. The second batch uses a rough bed without vegetation, which consists of 0.08 m thick soil underneath and 0.02 m thick layer of uniformly overlying gravels 0.01 - 0.02 m in granularity. The third patch is made with a rough gravel bed with CM distributed on top in different ways. The bed for the fourth patch is vegetated with OB.

CM or OB plants for the second patch are planted in the rough bed in three distribution patterns (Figure 2). The first pattern is in a rectangular with the plants grown laterally at intervals of 0.12 m, namely 4 in a row, and lengthwise at intervals of 0.15 m. The arrangement for the second pattern is all the same as the first one in arranging the vegetation elements except for the rows staggered. As for the third pattern, it differs only in the lengthwise spacing expanded to 0.3 m.

The discharge (Q) is evaluated by measuring the water volume with a container at the lower end of the flume. Due to the complexity involved in overland flows irrelative to velocity measurements (Dunkerley et al. 2001; Li et al. 1996; Li and Abrahams 1997), the flow velocity is measured by dye tracing techniques in this study. The residence time of the dye tracer in the experiment is recorded by a clock so as to calculate the mean surface velocity. This procedure repeats 5 times for an averaged flow velocity to obtain.

Therefore, the mean flow velocity along a cross

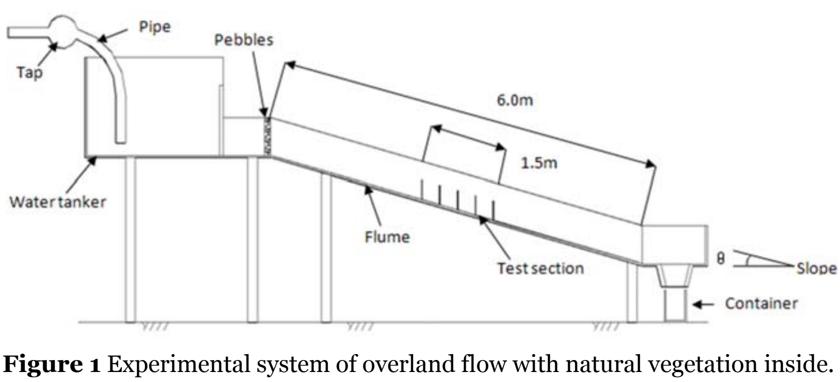


Figure 1 Experimental system of overland flow with natural vegetation inside.

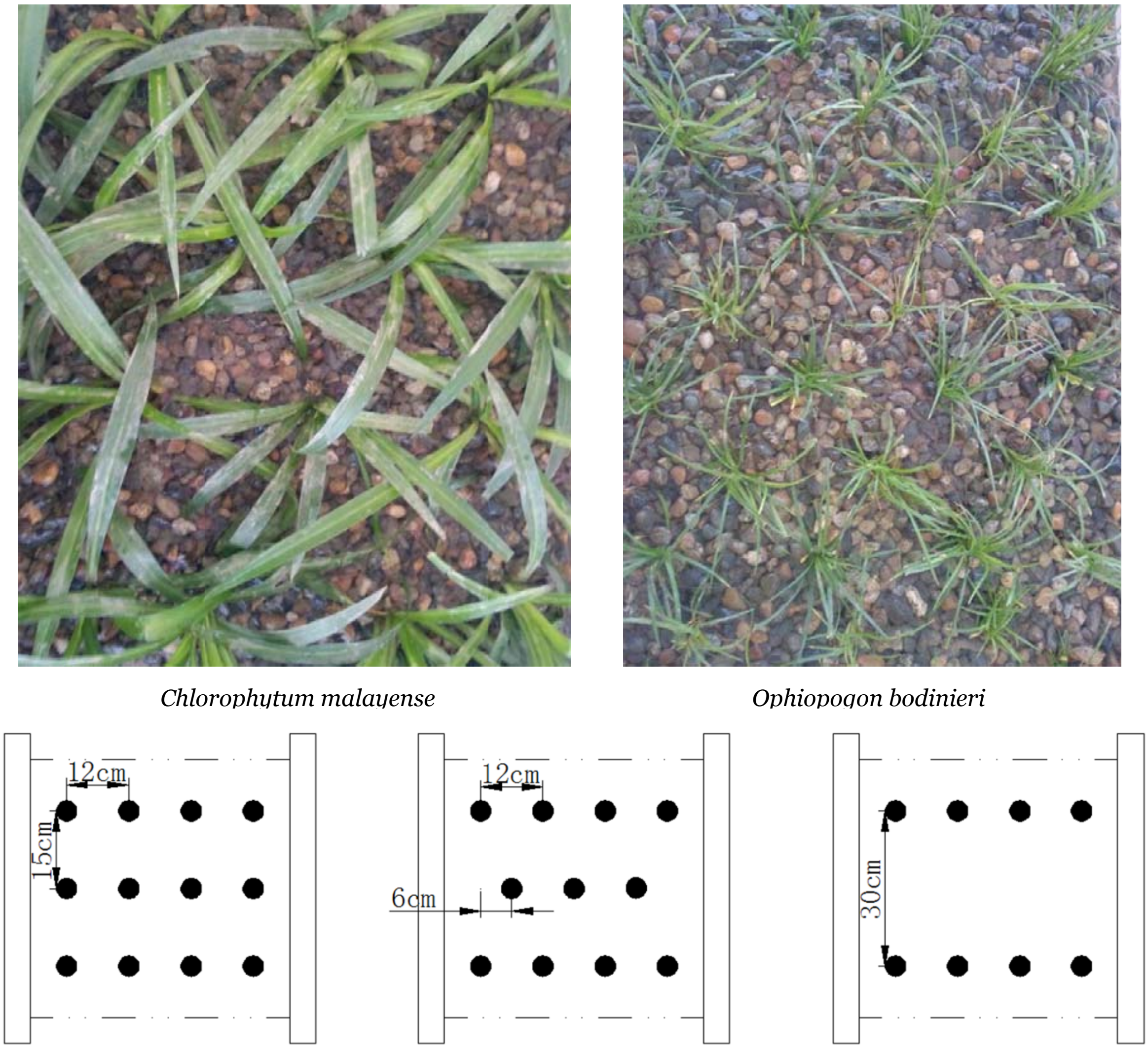


Figure 2 Layout forms of natural vegetation in flume.

section area can be obtained with the measured surface velocity multiplying a correction coefficient which represents the relationship between the mean flow and the surface flow with respect to an overland flow. The value of the correction coefficient has been studied by some researchers. Emmett (1970) found that the value if in the range 0.5 to 0.6 would increase with *Re* for laminar flows and if at a range 0.8 for turbulent flows. Luk and Merz (1992) derived a mean correction coefficient of 0.75 for both transitional and turbulent flows. Thus, this study has chosen 0.75 as the correction coefficient. The kinematic viscosity ν is determined as water temperature dependent. The mean flow depth h was calculated by the following equation (Smith et al. 2011; Hu and Abrahams 2006).

$$h = {}^{q}\!/_{v} \tag{1}$$

where q is flow discharge per unit width called herein unit flow rate that equals Q/w; w stands for the flume width, and v the mean flow rate. Subsequently, the resulted flow depths are adopted to estimate the other parameters such as the Froude number.

There are other methods of evaluating the flow resistance such as the Manning coefficient and the Chezy factor, as well as the Darcy-Weisbach resistance coefficient. Among these, the latter is rather essential for overland flows which can be better characterized physics of flow resistance. The Darcy-Weisbach friction factor f is then determined by:

$$f = 8ghs/v^2 \quad (2)$$

where g is gravitational acceleration, s is energy slope to be calculated by $s = \sin\theta$, θ is the flume slope gradient; v is the mean flow velocity, m/s.

The Reynolds number ($Re = vR/\nu$) ranging from 572 to 4515 corresponds to the flow regime including laminar, transitional and full turbulent flows. The Froude number ($Fr = v/\sqrt{gh}$) ranges from 0.34 to 3.76.

Hu and Abramhams (2005) designed a series of mobile bed tests using different bed slopes between 2.7°-7.5° to explore the impact of sediment movements on the overland resistance. Then through the experiments with some cylinders inclined of less than 11.4°, Hu and Abrahams (2006) divided the composition of resistance into different forms corresponding to the mobile bed. Li (2009) observed the experimental plots all sloping at 2° in the field, and concluded that the total resistance is a more complicated non-linear superposition relation between individual resistance components. Most of the previous experiments were designed with slopes of 2-12°. Pan and Shangguan (2006) by using slopes of 3-15° found that with the slope increasing the Froude number increased while the resistance coefficient decreased. On the other hand, the hydraulic characteristics of the overland flow on the sand bed and vegetated bed were analyzed in reference to slopes ranging 5°-25° in our previous studies. Yi et al. (2011) measured the hydraulic characteristics of overland flows and further discussed the method of calculating the flow resistance on the smooth and adhering sand beds sloping at 15°, 20° and 25°, respectively. Yan et al. (2012) discussed the relationship between the overland flow resistance coefficient and the Reynolds number on a artificially vegetated flume sloping at 5°, 10° and 15°. Wang et al. (2013) observed the hydraulic parameters of overland flows and analyzed the local head losses on a mobile vegetative bed sloping at 20° and gave a presentation (2014) of the effect of different slopes on flow movements and overland flow resistance according to a series of flume experiments conducted on the beds installed with a gradient of 15°, 20° and 25°, successively. Ye et al. (2014) discussed the influence of vegetation characteristics on the hydraulic parameters of overland flows on the bed with slope variable of 11°, 13°, 15° to 18°. In all the above literature there seemed to lack analysis of the spatial distribution of natural vegetation responsible for the varying flow resistance. For comparing the characteristics of flow resistance with the natural vegetation expounded in literature, this study involved the natural vegetation in experiments done on two different bed slopes of 6° and 10°, and furthermore, these results were later used as the basis for the other experiments done on larger slopes. Thus, four flow rates and three patterns of

Table 1 Experiment conditions and related hydraulic parameters

Rough elements	Case	Surface rough condition	Bed slope	Unit discharge (10^{-3} m²/s)	Resistance coefficient	Reynolds number	Froude number
Smooth	1	Smooth	6°	0.60-4.02	0.09-0.39	572-3852	1.46-3.00
			10°	0.61-4.59	0.10-0.44	602-4515	1.78-3.76
Gravel	2	Gravel (10-20 mm)	6°	1.34-4.26	0.52-4.90	1421-4540	0.41-1.26
			10°	1.12-4.03	0.97-9.74	1196-4292	0.38-1.20
Chlorophytum malayense	3	Rectangle (15×12cm)	6°	1.16-3.75	0.67-5.47	1262-4038	0.39-1.12
			10°	1.21-3.53	0.85-9.47	1377-4034	0.38-1.27
	4	Isosceles triangle (15×12cm)	6°	1.23-3.74	1.03-3.70	1334-4056	0.47-0.90
			10°	1.32-3.67	1.53-5.36	1477-4093	0.51-0.95
	5	Rectangle (30×12cm)	6°	1.11-3.74	0.53-4.16	1238-4179	0.45-1.26
			10°	1.30-3.70	1.18-5.83	1448-4124	0.49-1.09
Ophiopogon bodinieri	6	Rectangle (15×12cm)	6°	1.36-3.97	0.73-7.09	1446-4233	0.34-1.06
			10°	1.39-3.75	1.35-10.35	1486-3794	0.37-1.01
	7	Isosceles triangle (15×12cm)	6°	1.35-3.85	1.31-2.76	1385-3961	0.55-0.88
			10°	1.35-3.94	1.60-12.21	1395-4058	0.47-1.40
	8	Rectangle (30×12cm)	6°	1.48-3.66	0.45-3.03	1600-3945	0.54-1.36
			10°	1.37-3.89	0.71-6.40	1480-4195	0.47-1.40

vegetation configuration were also adopted for a total of 64 experiments whose parameters were all given in Table 1.

2 Results and Discussions

2.1 *Fr*~*q* relation

The flow pattern can be classified as subcritical, critical, and supercritical according to the Froude number (*Fr*). The results shown in Figure 3 indicate that the characteristics of the Froude number varied a lot about experiments done on the smooth bed and rough bed undergoing the same unit flow rate. For example, the Froude number greater 1.0 for the smooth bed implies that the flow whereon is supercritical. However, *Fr* in the range of 0.34 to 1.4 is derivable from the rough beds, (see Table 1). The relationship between *Fr* and *q* indicates that *Fr* approximates 1.0 when q =3.0 *l*/s.m, and the flow becomes subcritical or critical when $q < 3.0$ *l*/s.m. Jing et al. (2007) believed that the rough bed can motivate the flow pattern to transform from supercritical to subcritical ones with the increasing roughness coming into effect under the same flow rate. The similar tendency suggested in this study can be found when the smooth bed is switched into the rough bed with gravel or vegetation on top. It should be noted that in these cases there is only slight difference occurring between different vegetation configured.

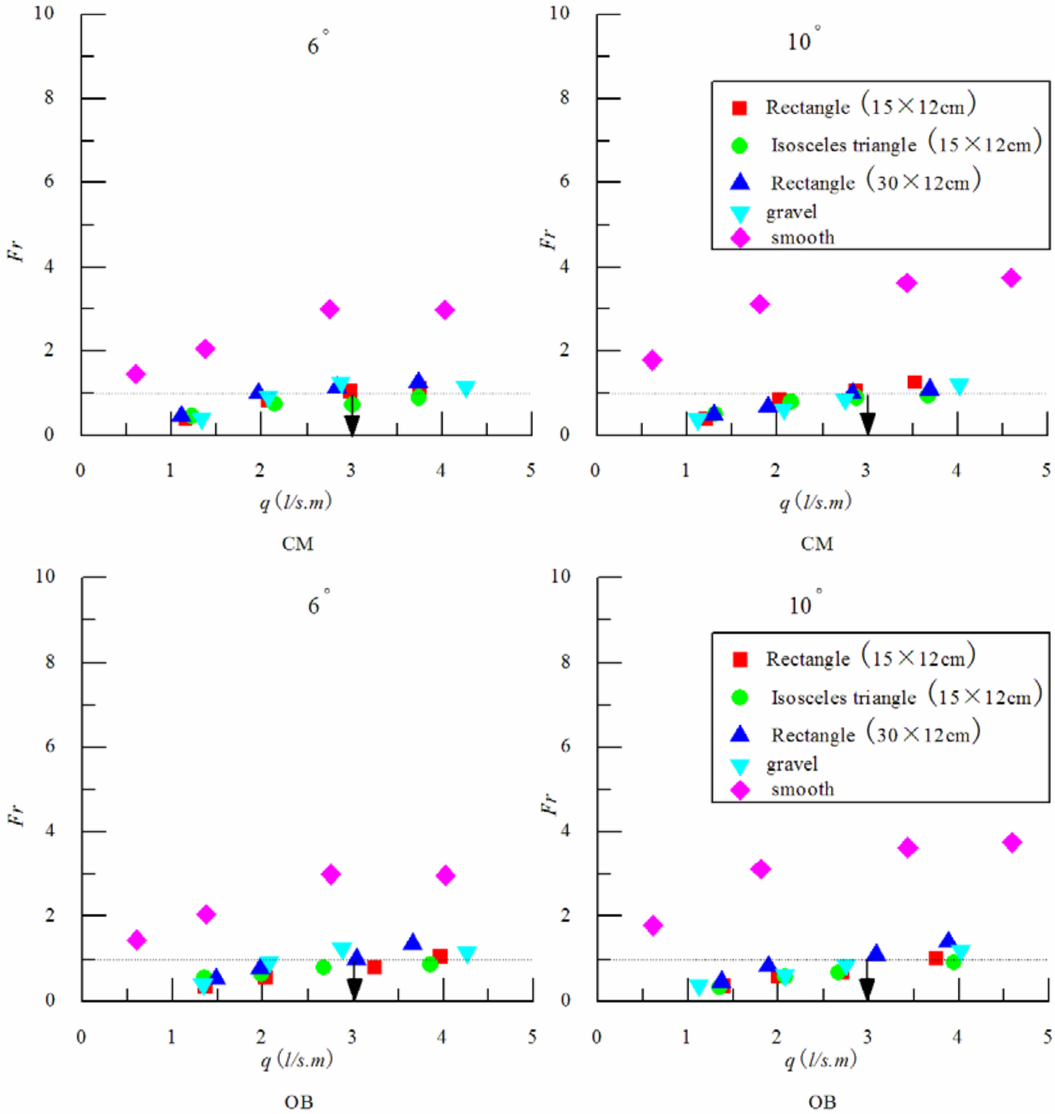


Figure 3 The unit discharge *q* against *Fr*.

The Froude number derived from the obstacle of CM is a little bigger than that of OB, indicating that the layout forms (rectangle or triangle) has little influence on the flow pattern. Similarly, by the same discharge, with the slope on the increase, the gap among the same layout forms is little.

2.2 *f*~*q* relation

Figure 4 shows the distribution of the resistance coefficient *f* against the unit flow rate *q* for both configurations of CM and OB. All the graphs are plotted with the same range of the unit discharge from 0.4 to 4.7 *l*/s.m. The *f*~*q* graphs show *f* decreases with *q* increasing in respect to slope in the range of 6°or 10°. When *q* is less than 3.0 *l*/s.m with *q* on the increase, the resistance coefficient decreases obviously. Whereby the discharge has a considerable influence on the resistance. When *q* is more than 3.0 *l*/s.m, the resistance coefficient approaches to a constant. It can be explained that when the discharge increases toward a certain value, the mean water depth also increases with reduction in the influence of roughness elements on the flow resistance, and so the resistance coefficient appears on very small change, for which a scaling analysis can be adopted as below.

The Darcy-Weisbach friction equation gives the derivative of resistance coefficient $f = 8ghs/v^2$, where noticeable is that the numerator is related to *h* known as gravity scale, and the denominator is related to v^2 known as inertial scale. The resistance coefficient, therefore, to a certain extent, represents the ratio of gravity scale to inertial scale. The ratio exhibits a contrary to the Froude number characterized by inertial scale (v^2) and gravity scale (*h*). The results of the *Fr*-*q* relation (see Figure 3), therefore, confirms the *f*-*q* inverse relation shown in Figure 4.

For the invariant slope and different vegetation configured, there is no apparent distinction in *f*-*q* relation noted in respect to CM and OB. While the rectangular layout containing the intervals lengthwise of 0.15 m and laterally of 0.12 m between neighbor plants, (Case 3 and Case 6) the gap here is bigger than in other distributions. The flow resistance induced by OB is greater in comparison with that by CM. It is clear that both CM and OB are of flexibility and emergent. With flows pushing on the plants, their stems vibrate in response. It is known for certain that CM has higher flexibility to vibrations of larger magnitude. In accordance with studies of flow resistance induced by aquatic vegetation (Yang and Choi 2009; Aberle and Järvelä 2013), the more flexible the vegetation, the lower the flow resistance will be in result. Therefore, the effect of the vegetation flexibility on the overland flow resistance is applicable for the flows of rivers or open-channels. The vegetation configuration results in the variation of flow resistance. In this study, it is observable that the flow resistance resulted from the isosceles triangular layout (15 × 12cm) is on the whole smaller than that from the rectangular layout (15 × 12cm). In comparison, the vegetation density (vegetation number per unit area) is the same whether the vegetation elements are staggered in the former case or not in the later case.

But with the isosceles triangular (15 × 12mm) and the rectangle (30 × 12mm) layouts, under the same conditions of flow rate and spacing between plants, the increase in the row interval with the decrease in the vegetation density can have an impact on the flow resistance.

2.3 *f*~*Re* relation

The relationship between *f* and *Re* is illustrated in Figure 5 wherein it is clear that *f* decreases significantly with the increase of *Re*. It should be noted that *f*, with respect to all cases, approaches to a local constant as *Re* becomes greater than 4000. Meanwhile, the unit flow rate is roughly 3.0 *l/s.m* when Fr approximates 1.0 and *Re* = 4000.

The *f*~*Re* negative relation is consistent with Huthoff (2009) who presented increments in the form drag with the size of wakes, and as a conclusion agrees with our preliminary studies on the different roughness elements such as particles of different granularity and artificial vegetation configuring (Yi et al. 2011; Wang et al. 2013; Wang et al. 2014; Ye et al. 2014). But the *f*-*Re* negative relation makes a difference from the previous studies by Abrahams (1994) who suggested that the trend of *f*-*Re* is predominantly for negative sloping for shrublands and the positive sloping or upward convex relation for grasslands. By comparison of the experimental conditions, *Re* worked out by

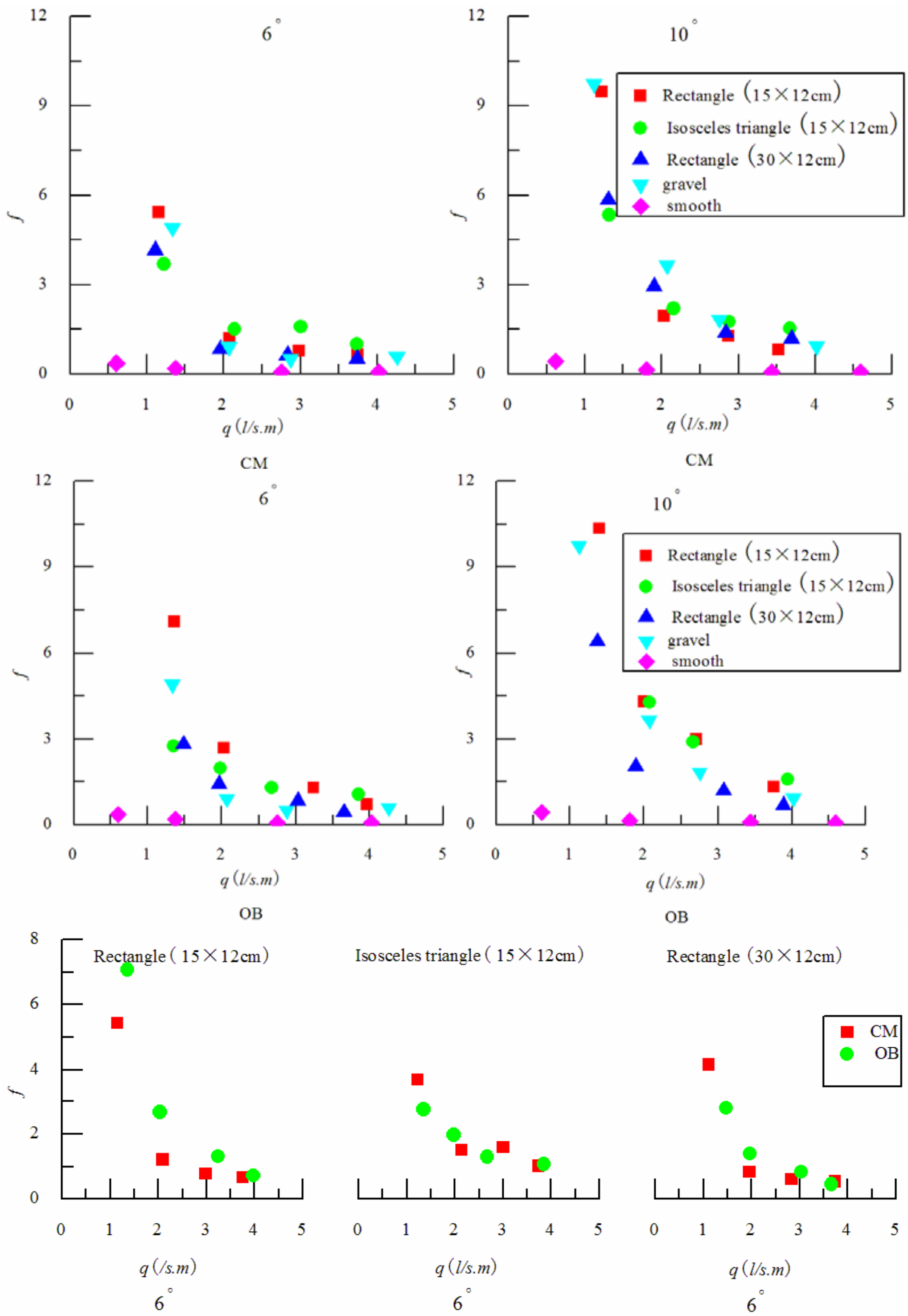
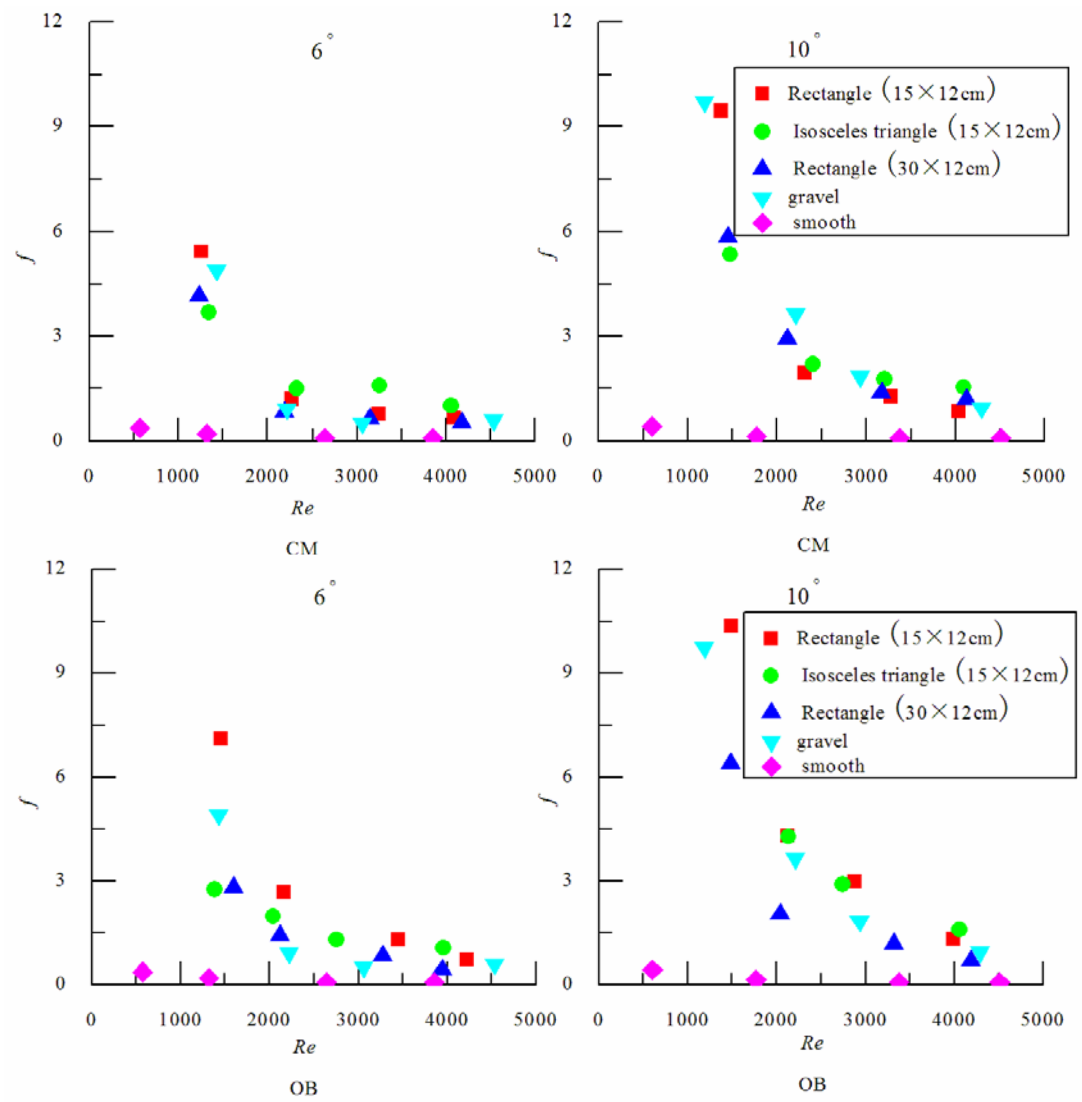


Figure 4 Darcy-Weisbach friction factor *f* (vertical axis) against the unit discharge *q*.

Abrahams et al. (1994), is much smaller than that in this study ranging from 86.5 to 450.2. This indicates that the *f*-Re relation behaves not only inversely, but also corresponds to the generalized relation between the Darcy-Weisbach friction factor and the Reynolds number according to the findings by Turner et al (1978).

The flow resistance for the vegetated rough bed (CM and OB) is consistently greater than that for the smooth bed. Based on some previous



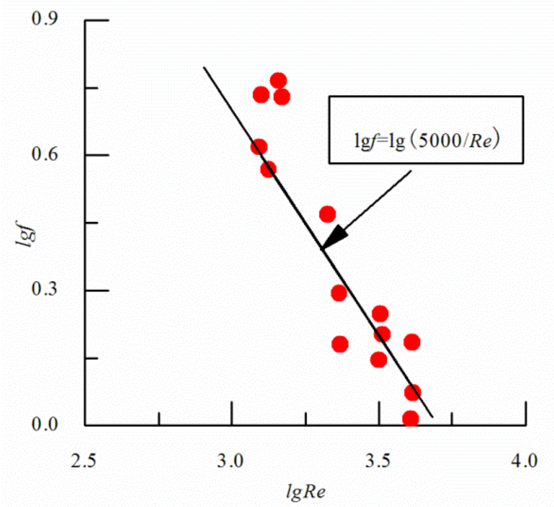


Figure 5 Darcy-Weisbach friction factor *f* against Reynolds number *Re*.

studies (e.g., Barros et al., 2001; Zhang et al., 2010), the Darcy-Weisbach resistance is a compound resistance, an integration of a few external factors such as surface (grain) resistance, wave resistance, and form resistance. Water flows give rise to vortexes, wakes and secondary dissipation of energy on the gravel bed having possibility of increasing the resistance. The form resistance is relevant to the vegetation bunches as well as the flow conditions. In this study, CM and OB are planted on the rough gravel bed so as to divide the whole bed into sections. The vegetation protruding above the gravel surface tends to generate flow resistance. However, based on the studies on the flows passing through two cylinders, the pulsation in the vortex zone between two cylinders becomes weakened as the water table raised and the flow velocity decreased, which results in the decrease in the drag coefficient averaged for the two cylinders (Wang et al., 2005). Similar to the cylinder test, the existence of vegetation may counteract the development of vortexes, wakes and lead the flow resistance to decrease. By the way, even smaller results can be observed when compared with what is going on with the rough gravel bed. Thus the vegetation is to be known, to some extent, as a negative effect on the form resistance.

According to Li and Shen (1973), the flow resistance in laminar flows can be described by the Darcy-Weisbach equation:

$$f = \frac{k_t}{Re} = \frac{k_0 + Ai^b}{Re} \tag{3}$$

where k_t and k_0 are friction coefficients, A is an empirical coefficient and b stands for the raindrop effect. Therefore, for the indoor flume experiments without precipitation reaction, the equation can be changed to the form as below:

$$f = k_0 / Re \tag{4}$$

Julien (2002) demonstrated that the value of k_0 differed from that derived from the rough surface. Based on the tests conducted on the short grass prairie, the laminar flow k_0 was 3000-10000. Chen (1976) pointed out that for impervious surfaces the flow was defined as of laminar type with Re<1000 for the impervious smooth surfaces, but the flow resistance for vegetated surfaces is much greater if compared with that on impervious smooth surfaces. The parameter k_0 for laminar flows may be as high as up to 10^5.

The range of Re shown in Figure 4 of this study presents the Re less than 5000, namely between 3000 and 10000 as proposed by Julien (2002). Therefore, the value of k_0 here can be assumed to be 5000 with the equation adjusted to the form as follows:

$$f = 5000 / Re \tag{5}$$

The fitting relation with log-log scale as shown in Figure 5 can be obtained according to the experimental data. Compared by Chen (1976) with the *f*-*Re* relation ($f = 5000/Re$) in vegetated surface layers, the constant 5000 in this study is much smaller than 50000. Furthermore, on the basis of the range of k_0 (Julien 2002), the determined value of 5000 is feasible for the analysis of *f*-*Re* relation.

3 Conclusions

This paper aims at providing an insight into the overland flow resistance due to different roughness elements. There are three types of roughness elements, namely smooth, sand and vegetated bed. Different bed slopes were used in this study. Both non-staggered and staggered vegetation configurations (rectangle and triangle layout) were made for experiments. The main results are as follows:

(1) For all roughness elements designed for different bed configurations, the flow resistance coefficient approaches to a constant when q = 3.0 *l*/s.m with *Fr* and *Re* approximating 1.0 and 4000, respectively. Significant difference of the Froude number for the smooth bed and rough bed were observed under the same unit flow rate. The Froude number for the planting of *Chlorophytum malayense* (CM) which is some more flexible is generally greater than that of *Ophiopogon bodinieri* (OB). It should be noted that the flow pattern is less influenced by the vegetation configuration (i.e. rectangle and triangle layouts).

(2) The decreasing vegetation density (decrease only in spacing between individual vegetation rows) tends to reduce the flow resistance. The spacing among plants may impact the flow resistance. The flow resistance is not significant due to the vegetation in action as expected. For this evidence is available in the turbulence characteristics of flows passing through multiple cylinders. Wakes acting behind the vegetation is more likely to counteract the development of the vortices that play a positive part to increase the flow resistance.

(3) The resistance in laminar flows can be described by the Darcy-Weisbach equation. Among different experimental conditions, k_o for laminar flows is special and feasible at the range of 5000 in analyzing the *f-Re* relation (Julien 2002), thus taken as the critical value to classify the transformation of flow patterns.

So far the effects of roughness elements distribution on overland flow resistance have been developed only in laboratory and only on gentle slopes. More detailed studies on the microscopic flow structure and energy dissipation mechanism are still needed for exploring the substantial characteristics of the overland flow resistance. And the experiments would be extended to the overland flow resistance of steeper slopes. On the natural hill slopes, more factors besides vegetation distribution patterns may impact the effects of overland flow resistance. The influence of these factors needs further discussion through experiments.

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