Effect of Bent Flexible Vegetation on Fluvial-bed Change Under Flood Conditions

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To understand the effects of vegetation on sand-bed, we designed three different densities and nine random distributions of bent flexible vegetation in flume experiments. Current velocity was controlled to be larger than the critical velocity and sediments were supplied upstream during the experiment to simulate the real river condition under flood conditions. Ultrasound Velocity Profiler (UVP) was used to measure the flow field and a high-precision laser scanner (F5, Mantis Vision) was used to measure the final topography of sand-bed in each experiment. The results showed that the evolutionary process of sand-bed can be divided into four stages; scouring stage, growth stage, supplement stage, and deposition stage, forming a dynamic cycle. The deposition was dominant in front of the vegetation area, while scour dominated the area behind the vegetation. However, in the vegetation area, sand-bed was mainly affected by the concentration and blockage effects of vegetation, so it changed from depositional to erosive as vegetation density increases. The findings from this study will provide crucial information towards river management through understanding the links between channel bed, flow and vegetation.

Key words: river vegetation, sediment transport, flood condition

1. INTRODUCTION

The frequency of heavy rains and typhoons caused by climate fluctuation has increased in recent years. Rains and typhoons cause a lot of sediments to move from mountains, hills, and plains into rivers and often result in serious sediment disasters. Therefore, understanding how sediments are transported in rivers is crucial. Generally, the existence of vegetation can change the flow conditions and the sediment transport characteristics of a river. When a current encounters single vegetation, the current would produce downward jet-flow and horseshoe vortex by the shape resistance of the vegetation. They would cause the riverbed be scoured around the vegetation. The scouring model is similar to that of a pier scour [*Raudkivi and Ettema*, 1983; *Melville*, 1997; *Melville and Chiew*, 1999]. Additionally, vegetation also reduces the critical velocity of incipient motion for sediments by increasing the drag force and lift force in the flow [*Tang et al.*, 2013; *Wang et al.*, 2015]. Consequently, the riverbed becomes unstable. On the contrary, vegetation can decrease the current velocity by supplying the drag coefficient to induce sediment deposition thereby stabilizing the riverbed [*Sand-Jensen*, 2003; *Wilson et al.*, 2008]. Moreover, roots and underground stems also can provide additional tensile strength for ground-holding to adsorb some insoluble colloids and organic debris [*Pollen-Bankhead et al*., 2009][]. It can effectively inhibit the re-suspension of the sediment and slow down the riverbank retreat which was scoured by the current [*Horppila and Nurminen*, 2001; *Horppila and Nurminen*, 2003].

In some extreme weather events, when a flood caused by rainfall or typhoon event sweeps past the riparian vegetation communities on the sandbank, stream-side, and floodplains, its high-sediment-concentration current will cause a series of complicated interactions with the vegetation communities. These interactions can be simply categorized into three different groups by their location. First, in the upstream of vegetation communities, the high-sediment-concentration current is blocked by the vegetation communities, so the water surface rises and the sediments are deposited in front of the vegetation communities. Secondly, in the downstream of vegetation communities, the current which crosses the top of the vegetation will deflect downward to scour the riverbed behind the vegetation communities. Finally, in central vegetation community, several counteractive forces influence each other, so the net effects on the current and riverbed are uncertain. For example, the vegetation can reduce the cross-sectional area of the flow channel, thus increase the current velocity, but the vegetation also can provide drag force to consume the kinetic energy of the current, thus decrease the current velocity [*Gurnell and Petts*, 2006; *Gurnell*, 2014]. Therefore, the different vegetation characters have different influences on the current and riverbed.

In previous research work, researchers changed the vegetation characters such as densities (single or multiple), arrangements (staggered, columnar, or aligned), and rigidities (rigid, flexible, or mixed) to observe the interactions among the vegetation, current, and sediments by a series of flume experiments [*Nepf and Vivoni*, 2000; *Wilson*, 2000; *Okamoto and Nezu*, 2010; *Sanjou and Nezu*, 2010; *Chen et al.*, 2011; *Luhar and Nepf*, 2011; *Ghisalberti and Nepf*, 2002]. In different density experiments, the current could flow straight through the low-density vegetation and deposit sediment on both sides of the downstream wake to develop an open-bed formation. But, in the high-density vegetation condition, the Von-K´arm´an vortex would appear in the downstream wake and make sediment deposit again to develop a closed-bed formation [*Follett and Nepf*, 2012]. Additionally, the vegetation density also could affect the type of maximum scour hole and the deposition dune. Even if the density remained consistent, the different arrangement types of the vegetation could have different results of the erosion and the deposition. Particularly, the influence of the longitudinal change of the spacing length was found to be more significant than the latitudinal change of the spacing length [*Chen et al.*, 2012]. In different rigidity experiments, the flexible vegetation has the smaller shape resistance than the rigid vegetation, so it is easily bent by a current. The bending leaves of the flexible vegetation have a function of protecting the riverbed and slowing down erosion [*Chen et al.*, 2012].

Moreover, the above researches focused on the normal flow conditions (i.e. experimental velocity was less than the critical velocity and there was no sediment input during the experiment). Flood conditions were rarely discussed. Therefore, we designed a series flume experiments to observe the situation of vegetation under flood conditions. In order to simulate the situation of sediments moving from mountains, hills, and plains into rivers, the experimental velocity was designed to be greater than the critical velocity and continually supplied sands in the upstream during the experiments. In addition, we also changed the density and arrangement of vegetation in the flume experiments to observe the effects on a channel.

2. METHOD

The experiments were conducted in a 15m length, 0.6m width, glass-sided recirculation flume system. The structure of the flume system is shown in Fig. 1(A). The head tank was located upstream of the main channel to keep a constant water head. At the entrance of the main channel, a honeycomb flow straightener was installed to steady the current. A right-angle wedge, 0.4m length, 0.6m width, and 0.1m height, was set 1.8 m after the flow straightener. Then, an acrylic block, 3m length, 0.6m width, and 0.1m height with quartz sand (SiO_2, D_{50} = 1.22 mm) glued to its top surface to keep the same surface roughness as the sand area that followed. The sand area of 4.8m length by 0.6m width was filled with quartz sands to a height of 0.1m. Behind the sand area, a sand-trap was laid to collect sand transported by the current. At the exit of the main channel, a tail-water gate was installed to control the water depth to 0.1 m. Finally, an underground water tank was used to collect water, and a recirculation pump was used to raise the water back to the head tank to form a closed loop. Each experiment had continuously running water for 10 hours then turned off the recirculation pump to stop the current. A water discharge rate of 0.03 m^3/s was set to give an initial velocity of 0.5 m/s under no vegetation. This velocity was greater than the critical velocity, as a result quartz sand was slightly eroded to simulate flood conditions. Concurrently, the quartz sand was supplied at a rate of 0.35 kg/min from a sand-supplying device located at the beginning channel bed area.

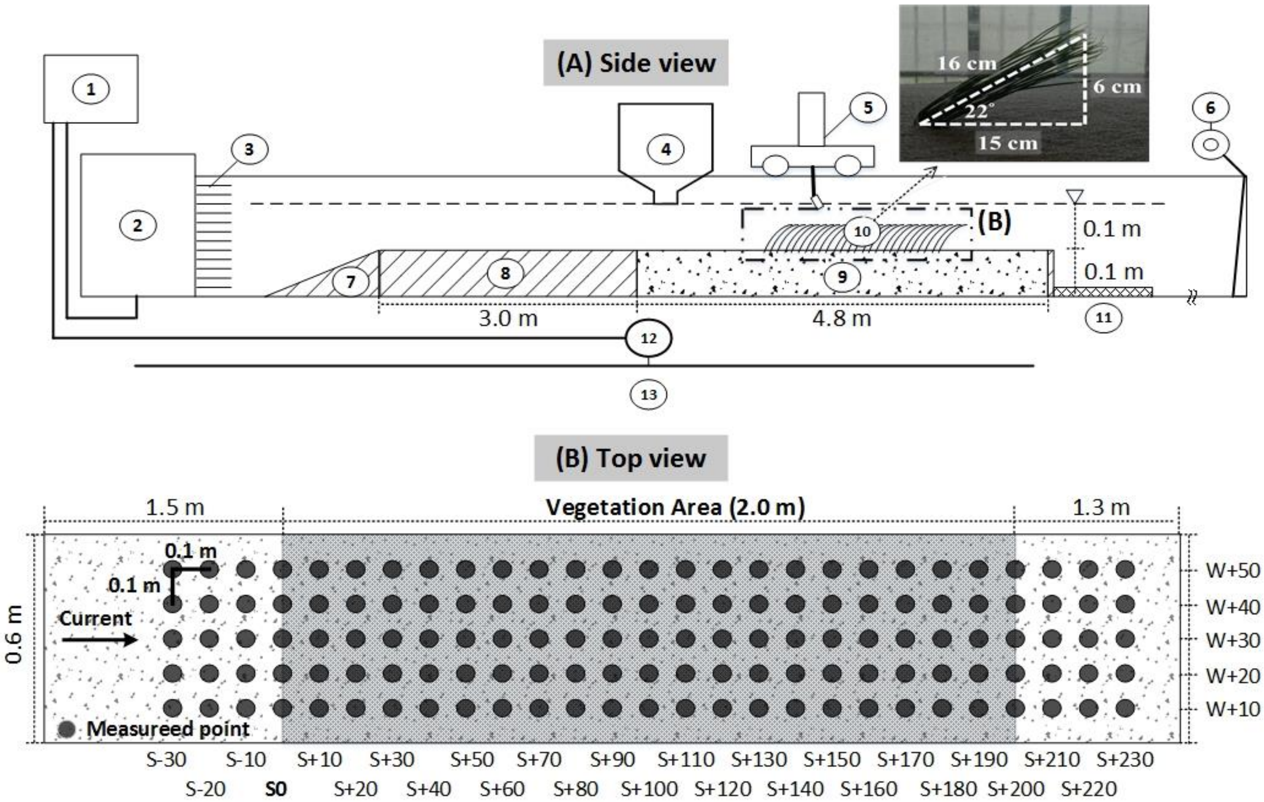

Fig. 1 The flume system used for the experiments. (A) Side view of the flume system where; 1. Head tank. 2. Water storage tank. 3. Flow straightener. 4. Sand-supply device. 5. UVP. 6. Tail-water gate. 7. Right-angle wedge. 8. Acrylic block. 9. Quartz sand area. 10. Vegetation area. 11. Sand trap. 12. Recirculation pump. 13. Underground water tank. (B) Top view of the measured area. Dots represent measuring points. Vegetation models were randomly placed in area between S+0 and S+200.

Before the experiment, we arranged the vegetation models, which were made of flexible plastic material, in the sand-bed area at 2m long by 0.6m wide. Individual vegetation model was arranged on grid points randomly determined by their X and Y coordinates on a 1cm x 1cm grid system drawn in this area. The vegetation was inserted into the bed at an angle of about 22°.

Three different vegetation densities were designed: 33.33 (test 1~3), 66.67 (test 4~6), and 100 (test 7~9) stems/m^2. Each density was triplicated, although each replicate was with a different random distribution pattern as described earlier. Five hours after the start of an experiment, we started measuring velocities and turbulence intensity of the flow field using an Ultrasound Velocity Profiler (UVP) [*Met-Flow*, 2006]. Turbulence intensity was represented by the root mean square (RMS) of velocity. The entire channel totally contained 135 measuring points, shown in **Fig. 1(B)**. At each point, measurements were made at thirteen depths, at intervals of 0.5 cm, ranging from 2 to 8 cm under the water surface. Each velocity and turbulence was the result of average measurement 2000 times. The measuring frequency was 20 Hz. After turning off the pump, we measured the final topography of the entire sand-bed, which totally had 45000 point cloud data from S-150 to S+330, using a high-precision laser scanner (F5, Mantis Vision). The precision of the scanner was 0.5 mm.

3. RESULTS AND DISCUSSION

3.1 The influence of single vegetation on the sand-bed

We observed the process of sand-bed evolution around the single vegetation during the experiments. The mainly evolutionary process could be divided into four stages, as follows: (A) scouring stage; (B) growth stage; (C) supplement stage; and (D) deposition stage. The flowchart are shown in **Fig.2**.

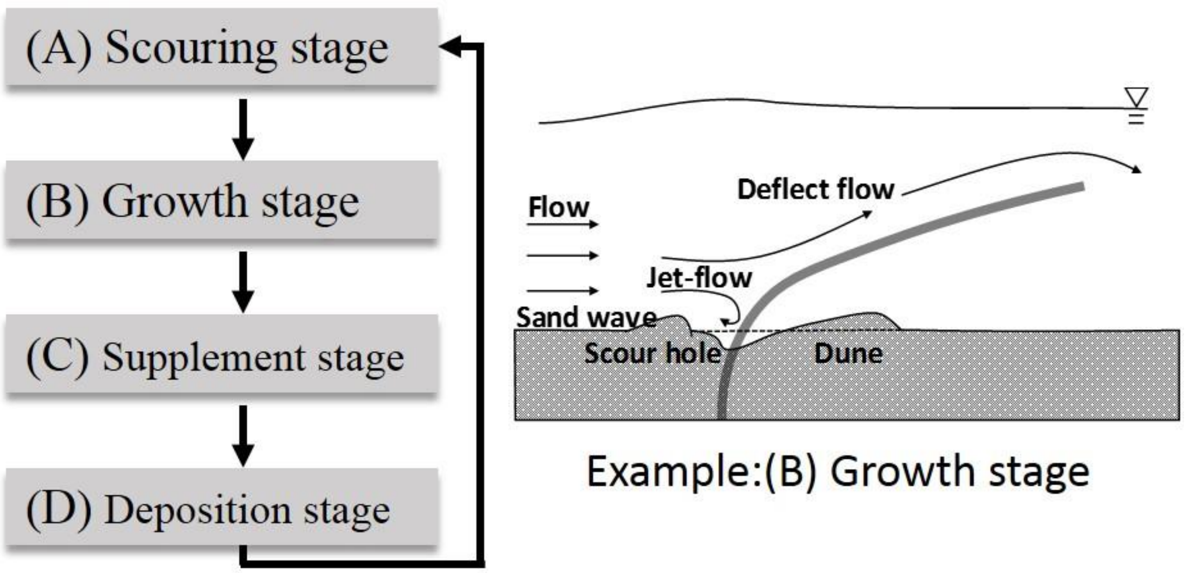

Fig. 2 Flowchart of the dynamic process of the sand-bed evolution.

In the first stage, scouring stage, the sand-bed was affected by the downward jet-flow in front of the vegetation and the horseshoe vortex in the both sides of vegetation. This effect made a small scour hole appear around the vegetation. Then, the sands, which were transferred from the scour hole by the current, deposited to form a small dune behind the vegetation. At the same time, a lot of sands converged to form a sand wave in the upstream and gradually moved to the downstream.

In the second stage, growth stage, the scour hole, which was affected by the downward jet-flow, grew toward the upstream and the dune, which was affected by the flowing current, grew toward the downstream. The volume of both was gradually increased. At the same time, the sand wave was close to the front end of the scour hole.

In the third stage, supplement stage, the sand wave entered the scour hole. It filled the scour hole to make the scour hole disappear. Then, the residual sands moved to supply the dune. That made the slope of the upstream surface of the dune become gentle.

In the fourth stage, deposition stage, the sand of dune was transferred continuously to further downstream by the flowing current. That made the slope of the downstream surface of the dune become gentle. Then, the depositional sand made the dune to have the bulge at the center and low at both ends. Finally, the process of sand-bed evolution would recover to the first stage and the new scour hole and sand wave appeared again.

From the above results it is observed that the sand wave was the most important factor in the entire evolutionary process, as it had a recovery function. It made the sand-bed reach a dynamic cycle in the evolutionary process. Therefore, the process of sand-bed evolution was different between the normal condition and flood condition, because the sand-bed did not reach the final equilibrium stage, which was proposed by Chen, et al., 2012 in their normal condition experiments, under flood condition.

3.2 The influence of vegetation communities on the sand-bed

We observed the final sand-bed topographies of three different vegetation densities, 33.33, 66.67, and 100 stems per square meter, in the vegetation area (S0 ~ S+200). The topographies of 33.33 stems/m^2 experiments are shown in **Fig. 3**. In these minimum density experiments, most of the sand invaded the entire vegetation area to form a depositional sand-bed. The cross-sectional area for water passage was not significantly reduced, so the rate of velocity increase was inconspicuous. In addition, because the distance of each vegetation was wide, we found some evolutionary processes of sediment, which were caused by the single vegetation, on the sand-bed. **Fig. 3(a)** represents the type of scouring stage; **Fig. 3(b)** the type of growth stage; **Fig. 3(c)** the type of supplement stage; **Fig. 3(d)** the type of deposition stage.

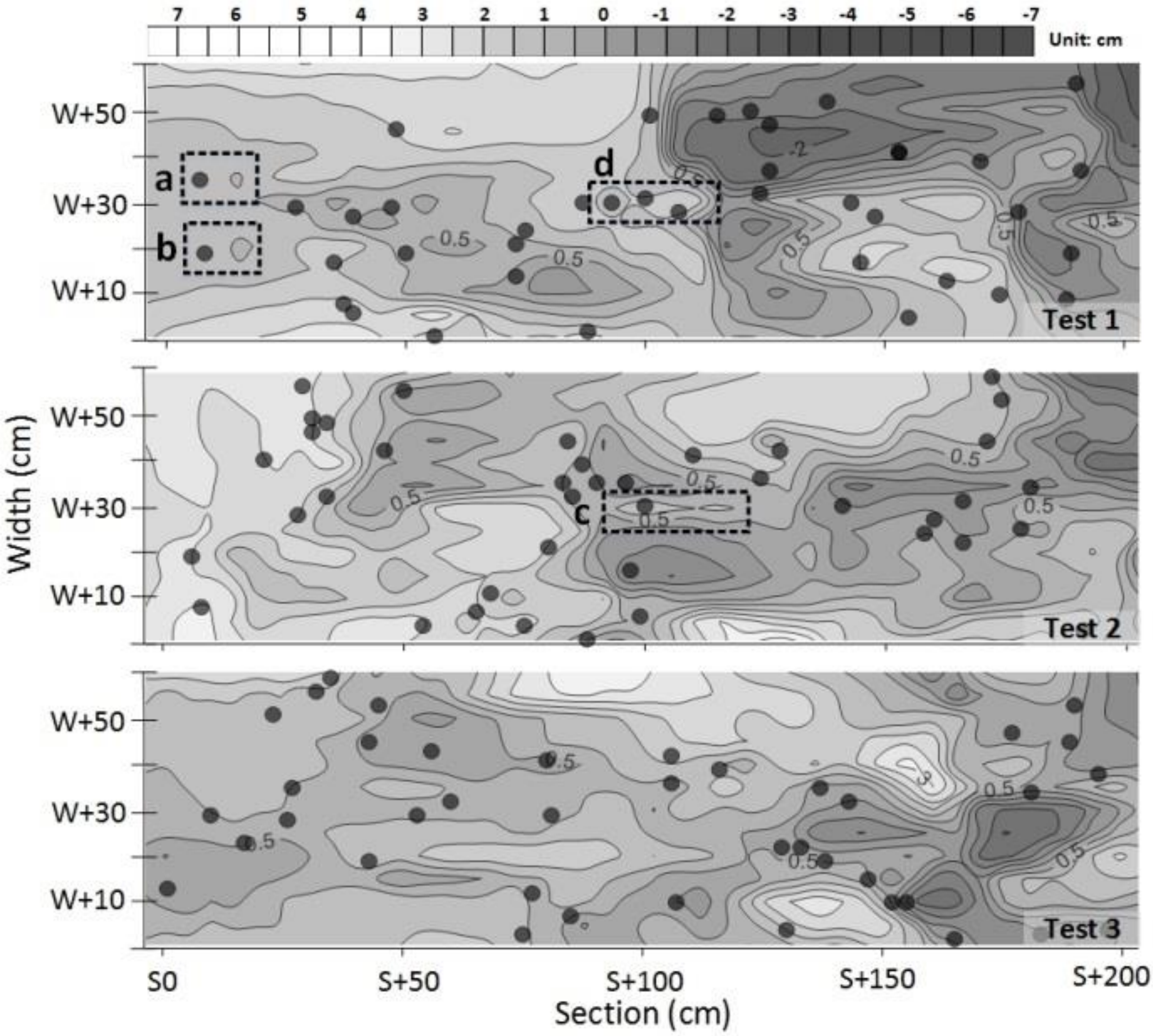

Fig. 3 The final sand-bed topographies after the 33.33 stems/m^2 experiments. (a) The dune type of the scouring stage. (b) The dune type of the growth stage. (c) The dune type of the supplement stage. (d) The dune type of the deposition stage. Black dots represent vegetation. Color-bar on top shows topographic height.

Then, in the 66.67 stems/m^2 experiments, the topography of erosion and deposition was half and half. The current was easily impeded by the vegetation to produce a backwater when current came from the sparse vegetation area into the dense vegetation area. The backwater was a low velocity and opposite direction current, so it easily caused the sediment deposited toward the upstream and formed a new sandbar.

Finally, in the 100 stems/m^2 experiments (**Fig. 4**), most sand-bed was erosive. The vegetation and other vegetation were very close to affect each other, so the flow field was very complicated in this area. Therefore, we are difficult to observe the phenomenon described above. Only in few area with dense vegetation like **Fig. 4 (a) ~ (c)**, the dense vegetation could provide a lot of resistance to deposit many sediments behind the denser vegetation. These sediments formed a large dune, which was like an island in the river, and gradually extend to downstream.

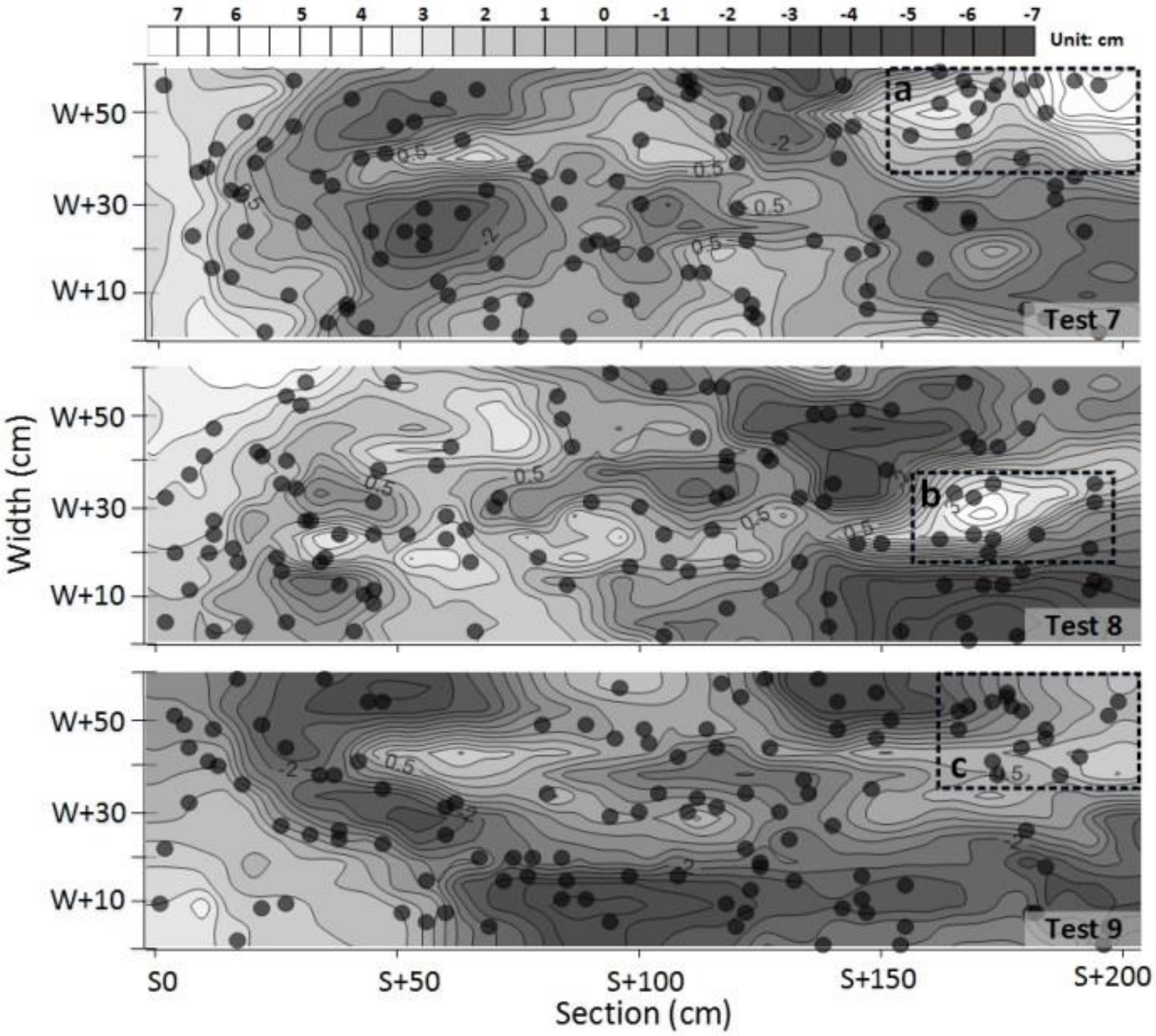

Fig. 4 The final sand-bed topographies after the 100 stems/m^2 experiments. Black dots represent vegetation. Color-bar on top shows topographic height. The Rectangular area was island location of developing toward the downstream.

From the above results, we find that the sand-bed was affected by two main influences in the vegetation area. One was that the vegetation could increase current intensity by decreasing the cross-sectional area for water passage. The large current intensity easily scoured the sand-bed to form an erosive sand-bed. In addition, the vegetation decreased the current intensity by supplying shape resistance. The small current intensity promoted sediments to deposit and form the depositional sand-bed. Therefore, the form of sand-bed depended on the current intensity and vegetation resistances in the vegetation area. If the vegetation resistance was greater than the current intensity, the sand-bed was depositional such as **Fig. 3**. Conversely, if the current intensity was greater than the vegetation resistance, the sand-bed was erosive such as **Fig. 4**.

3.3 The influence of vegetation on sediment transportation

We compare the amount of sand-bed sediment change before and after each experiment. The results were shown in Table 1.

Tab. 1 Average amount of sand-bed sediment change per m^2

Density (stems/m^2)	Upstream area (kg/m^2)	Vegetation area (kg/m^2)	Downstream area (kg/m^2)
33.33	+5.57	+22.93	-38.28
66.67	+17.22	+1.19	-35.63
100	+31.31	-24.38	-20.81

Note : + means deposition; - means erosion

The amount of sediment increased in the upstream area, mainly due to the blockage effect of vegetation. If the current was blocked by obstructions, part of the kinetic energy would be converted to potential energy and cause the phenomena of flow velocity decrease and water level increase. These phenomena could promote the sediment to deposit in this area and to form the depositional bed. As the vegetation density increased, the sediment which was blocked by vegetation also increased. In the vegetation area, the amount of sediment was increased in the 33.33 stems/m^2 and 66.67 stems/m^2 experiments. However, the amount of sediment was reduced in the 100 stems/m^2 experiments. This change was caused by the vegetation's effects of concentration and blockage. As the vegetation density increased, the influence of concentration effect would be greater than the blockage effect. Therefore, the sand-bed changed from depositional to erosive in the vegetation area. Finally, the amount of sediment was always decreased in the downstream area. The reason was that the current above the vegetation could deflect to downward when leaving the vegetation area. This deflective current scoured the sand-bed, so the amount of sediment was decreased in the downstream area. A special feature was that the erosive amounts, 38.28 kg/m^2 and 35.63 kg/m^2, were not obviously different between the 33.33 stems/m^2 and 66.67 stems/m^2 experiments, respectively. Moreover, it reduced to 20.81 kg/m^2 in the 100 stems/m^2 experiments. The reason for this difference was that the sand-beds of vegetation area were depositional in the 33.33 stems/m^2 and 66.67 stems/m^2 tests, so the downstream sand-beds were only affected by the deflective flow to scour. Nevertheless, the sand-bed of vegetation area was erosive in the 100 stems/m^2 tests, such that the downstream sand-bed was not only scoured by the deflective flow but also got a supplement of sediments from the erosive vegetation area to slow down the scouring.

4. CONCLUSIONS

From the results, we can conclude that: 1. The existence of sand wave made the sand-bed to be divided into four stages, scouring stage, growth stage, supplement stage, and deposition stage, in the evolutionary process and follow these stages to form a dynamic cycle. 2. The topography of sand-bed was mainly affected by the concentration and blockage effects of vegetation. In addition, the backwater caused that the sediments deposit to form a sandbar and develop toward upstream, and the dense vegetation caused a lot of sediments deposit to form an island and develop toward downstream. 3. The sand-bed was always depositional in front of the vegetation area and erosive behind the vegetation area. However, the sand-bed in the vegetation area changed from depositional to erosive as vegetation density increases. The findings from this study will provide crucial information towards river management through understanding the links between channel bed, flow and vegetation.

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