Impact force of post-fire debris flows over erodible beds

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Abstract. After wildfire events, water repellent soil is often found in the subsurface layer of channel bed in the burnt area. Debris flows generated from burnt basins and ensuing entrainment of the channel bed pose imminent threat to infrastructure and human lives. However, the fundamental interaction mechanisms of debris flow overriding water repellent bed and resulting impact force on debris-resisting barriers have yet to be elucidated. In this study, physical flume experiments are conducted to simulate post-fire debris flows overriding and entraining a sand bed with varied wettability. Compared to a wettable bed, water repellent sediment exhibits a tremendous increase in the erosion depth and subsequent impact force on the barrier. The test results demonstrate that debris flows overriding water repellent sediment can be particularly hazardous and the effects of water repellency need to be captured by the design criteria of debris resisting barriers in burnt basins.

1 Introduction

Over the past few decades, with increases in average global temperature and extreme climatic events, the probability of wildfire and burnt area have increased markedly worldwide [1]. Wildfire can remove vegetation, lead the soil in the subsurface layer of hillslopes to be water repellent (i.e., hydrophobic), and cause dry ravel on these burnt hillslopes, delivering significant amounts of hydrophobic sediment to stream channels [2-4]. With a contact angle (CA) [5] larger than 90°, hydrophobic soil inhibits infiltration and leads to increase in surface runoff, preferential flows, and soil erosion during rainfall [6]. Post-fire debris flows that originate in the recently burnt hillslopes or catchments entrain a large amount of the water repellent bed sediment, exponentially increasing the destructive potential of the flow [7]. As one of the most important momentum exchange processes, debris flow entrainment has been extensively explored in field studies and laboratory flume tests in the literature to investigate the effects of water content of erodible bed [8-9], inclination and thickness of bed sediment [10], and flow composition [11]. Whilst water repellency has profound influence on the soil hydraulic and mechanical properties, the wettability of soil is commonly neglected in assessing bed entrainment [6], leading to uncertainties about the characteristics of post-fire debris flows and the efficiency of mitigating barriers in burnt areas. The specific objective of this study is to conduct a series of flume experiments to simulate the erosion of water repellent soil by debris flows. Erosion depths of bed sediment with varied wettability are obtained by using erosion columns to investigate the characteristics of entrainment of hydrophobic soil. With the installed rigid barrier, impact force from flows after entrainment is obtained to assess the mitigation system.

2 Methods

2.1 Flume modelling

In this study, a series of experiments are conducted by using a 3000 mm-long rectangular flume model (in Fig. 1). The flume has channel width of 200 mm and is inclined to 30° during tests. The upper 1500 mm length of the channel has a rigid bed and the lower 1000 mm has an erodible bed with a thickness of 45 mm constructed using loose sand sediment. A rigid barrier equipped with a load cell is installed at the end of the channel to measure the impact force of flows after entrainment.

Fig. 1. Flume model and instrumentation.

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Ultrasonic sensors are installed along the centreline of the flume at the start, middle and the end of the erodible bed to capture the flow thickness during the erosion process. A high-speed camera is mounted on the side to capture the movement of sediment. Erosion columns [12-13] buried in the bed sediment are used to measure the spatial distribution of entrainment depth as shown in Fig. 2(a). As the bed is scoured by the debris flow, nuts on the columns (in Fig. 2(b)) are removed together with entrained materials. Intact nuts remaining in the initial locations indicate undisturbed bed in the experiments. Only the final erosion depth is measured based on the numbers of removed nuts [4] while the instantaneous erosion time could not be measured using the current setup.

2.2 Material

Toyoura sand, a wettable quartz sand with a mean particle diameter of 0.2 mm and an initial contact angle around 50°, is adopted to construct the erodible beds. Toyoura sand is treated by adding either stearic acid or dimethyl dichlorosilane (DMDCS) to change the contact angles, which are commonly used for generating synthetic water repellent soils [5, 14-15]. Stearic acid with a mass ratio of 0.2g/kg is applied to get a contact angle around 90° as subcritical water repellent sand. DMDCS with a mass ratio of 0.05g/kg is added to achieve severe water repellency with maximum contact angle of around 130°.

A volume of 0.027 m³ debris-flow mixture with the same composition is used in all tests. Debris flow was initiated by releasing the debris mixture to simulate a dam breach. The debris-flow mixture consists of solid volumetric fraction of 55% and fluid fraction of 45%, which is comparable with the mixture in [11]. The debris solid volume fraction constitutes 8% Kaolinite clay and 92% Leighton Buzzard sand fraction C. Water is used as fluid phase in the debris mixture. This solid fraction is comparable with the mixtures used in USGS flume tests [16]. To assess the significance of different stress components, dimensionless numbers [16] of flow mixtures including Savage number (NSav) and Friction number (Nfrc) are calculated. Based on Nfrc = 10^3 and NSav < 0.1, the frictional stresses dominate the behaviour of debris flow used in this study.

2.3 Test programme

In total, ten laboratory experiments are performed using the flume model (in Fig. 1) at The Hong Kong University of Science and Technology. A summary of the test program is given in Table 1. Firstly, a control test (test ID: C) without erodible bed is conducted to investigate the flow kinematics. The remaining tests are setup with erodible bed of different contact angles (CA = 50°, 95°, 126°) and volumetric water content values (θw = 0, 20%, 30%) to study the effects of water repellency and water content of bed sediment on debris flows entrainment.

### Table 1. Test programme.

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Wettability</th>
<th>Contact angle CA (°)</th>
<th>Volumetric water content θw (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>Subcritical</td>
<td>50 ± 2.8</td>
<td>0</td>
</tr>
<tr>
<td>W 0</td>
<td>Wettable</td>
<td>50 ± 2.8</td>
<td>0</td>
</tr>
<tr>
<td>W 20</td>
<td>Wettable</td>
<td>94 ± 5.7</td>
<td>20</td>
</tr>
<tr>
<td>W 30</td>
<td>Wettable</td>
<td>126 ± 3.4</td>
<td>30</td>
</tr>
<tr>
<td>S 0</td>
<td>Subcritical</td>
<td>50 ± 2.8</td>
<td>0</td>
</tr>
<tr>
<td>S 20</td>
<td>Water repellent</td>
<td>94 ± 5.7</td>
<td>20</td>
</tr>
<tr>
<td>S 30</td>
<td>Water repellent</td>
<td>126 ± 3.4</td>
<td>30</td>
</tr>
<tr>
<td>R 0</td>
<td>Water repellent</td>
<td>50 ± 2.8</td>
<td>0</td>
</tr>
<tr>
<td>R 20</td>
<td>Water repellent</td>
<td>94 ± 5.7</td>
<td>20</td>
</tr>
<tr>
<td>R 30</td>
<td>Water repellent</td>
<td>126 ± 3.4</td>
<td>30</td>
</tr>
</tbody>
</table>

3 Results

3.1 Debris flow entrainment

Figure 3 shows the final erosion depth profile at each erosion column along the centreline of bed sediment with 30% volumetric water content and three different contact angles. The duration of entrainment process in each test ranges from 0.32 s to 0.35 s. The maximum erosion depth in wettable bed (test ID: W_30) is about 12 mm, while maximum erosion depth in the subcritical water repellent bed (test ID: S_30) and water repellent bed (test ID: R_30) reaches 39 mm and 42 mm, respectively. Under similar-sized debris flows, a high variability of erosion depths as well as a high variability in spatial patterns of erosion is observed along the bed profile. The largest erosion depths are mostly found in the initial 200 mm length of the bed sediment. Further downstream, the erosion gradually decreases along the bed. Additional erosion peaks are always observed in hydrophobic sediment. The spatial variability in erosion depth, i.e., peaks and valleys may be controlled by the flow dynamics as described in [4; 11]. After reaching the erodible bed, the overriding flow imposes shearing forces to mobilize a large volume of bed material as the first erosion peak. The eroded bed then may deflect the overriding flow and decrease shearing forces, leading to the observed erosion valley. This modified trajectory causes the flow to land and impact further downstream along the bed, making another erosion peak. Compared to two peaks in the subcritical water repellent bed (test ID: S_30), a third erosion peak close to the barrier location is observed in water repellent bed (test ID: R_30). The total integrated amount of erosion depth in R_30 is twice than that in S_30, indicating water repellent soil is more easily removed by overriding flows.
3.2 Impact force

The severity in downstream hazard after entrainment of erodible bed is evaluated using the impact force measured on a rigid barrier installed at the end of the flume. The hydrodynamic model [17] is used to quantify debris flow impact force, as follows:

\[
F = \alpha \rho v^2 h w
\]  

where \( \alpha \) denotes hydrodynamic pressure coefficient, \( v \) represents the frontal flow velocity, \( \rho, h \) and \( w \) are the density, thickness, and width of debris flows, respectively. The hydrodynamic coefficient \( \alpha \) in different erodible bed sediment cases is back calculated with input values of the measured peak impact force value and the impact flow velocity and depth of control test. The hydrodynamic pressure coefficient is a dimensionless measure of impact force on the barrier. The higher the value of \( \alpha \) compared to 1.0, the larger the impact force on the barrier.

Figure 4 shows the variation of hydrodynamic coefficient (\( \alpha \)) with soil moisture content in variedly wetted erodible beds. When increasing the volumetric water content of erodible bed from 0 to 30%, the impact force increases, irrespective of the wettability of sediment. The decrease of \( \alpha \) in wettable bed with 20% volumetric water content (test ID: W_20) corresponds to the minimum erosion depth as matric suction within unsaturated wettable bed improves the sediment strength, comparable with the findings in [12]. For water repellent soil with contact angle of 126°, the impact force against a rigid barrier increases by 80% compared with the non-erodible bed condition. The larger hydrodynamic coefficient for a hydrophobic erodible bed highlights the inadequacy of existing guidelines for designing mitigation structures against post-fire debris flows. More tests would be conducted with varied flow types (e.g., surface runoff and hyper-concentrated flows in burnt areas) and bed condition (e.g., burnt ash layer on top of hydrophobic soil) to further improve the hazard assessment of post-fire debris flows.

4 Conclusions

In this study, physical flume experiments are carried out to study the influence of water repellency of erodible bed on debris flow entrainment and impact against a rigid barrier. The amount of basal erosion increases with the increase in the contact angle of bed sediment. When the volumetric water content of the erodible bed is 30%, the maximum erosion depth in water repellent bed can reach up to four times that of wettable bed. Similarly, when contact angle of erodible bed increases to 126°, impact force increases by 80% compared with the non-erodible bed condition. The larger hydrodynamic coefficient for a hydrophobic erodible bed highlights the inadequacy of existing guidelines for designing mitigation structures against post-fire debris flows. Further work would be conducted with varied flow types (e.g., surface runoff and hyper-concentrated flows in burnt areas) and bed condition (e.g., burnt ash layer on top of hydrophobic soil) to further improve the hazard assessment of post-fire debris flows.

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References


