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An innovative physical model for studying landslide dynamics in forests with controlled tree breakage

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ABSTRACT: Field observations show that forests can act as natural barriers that reduce landslide runout by dissipating energy during impact and enhancing resistance through tree entrainment. However, although recent physical modelling has indicated how forest spatial configuration can enhance energy dissipation, most studies idealised trees as rigid, unbreakable elements, and therefore overlooked the critical role of tree failure in landslide dynamics. This study presents a new 1g physical flume model for studying landslide–forest interactions with an explicit consideration of tree failures. The flume utilises tree elements that are designed to fail at calibrated bending moments to model the mechanical behaviour of forests during flow-like landslide impact. A new dimensionless number is introduced to characterise the failure of tree elements, and its performance is validated through a series of flume tests.

1 INTRODUCTION

The role of vegetation in landslide initiation has been extensively studied over recent decades and there is a broad consensus that slopes covered by trees or shrubs are less susceptible to shallow instability and surface runoff. More recently, attention has shifted toward the potential of vegetation to control landslide mobility, with the aim of mitigating long-runout events that can pose severe hazards to local communities. Field investigations in Alaska and China showed that debris-flow runout distances within forests can be reduced by around 50% (Booth et al. 2020) and 35% (Wang et al. 2017). Fundamentally, vegetation can act as a physical barrier that promotes grain interlocking and friction mobilisation during interactions between the moving material and tree stems (Fig. 1).

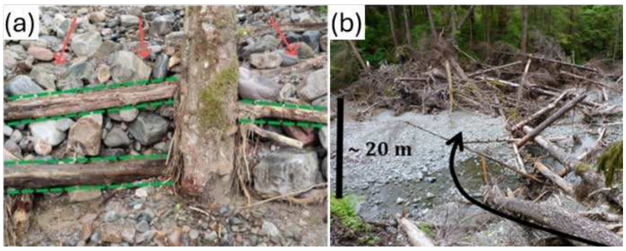

Figure 1. Field observations of landslide–forest interaction: (a) interlocking between tree stems and grains in the UK; (b) landslide material retained by failed trees in the US (Booth et al. 2020).

Physical modelling has also been used to study how forest spatial configuration and grain size (e.g., Liu et al. 2026) influence landslide–forest interaction mechanisms. However, previous studies typically idealised trees as rigid unbreakable elements, thereby neglecting the critical role of tree failure in landslide dynamics (Fig. 1).

In this study, we introduce a new scaling method for tree failure induced by landslide impact, which provides a basis for designing physical flume tests on landslide–forest interactions. Preliminary validation results using a single tree element as well as a new physical flume model are reported.

2 SCALING OF LANDSLIDE–FOREST INTERACTION

The Froude number is widely used to characterise dynamic similarity in flow-like landslides. However, when a landslide impacts breakable trees, an additional dimensionless parameter is needed to scale impact-induced tree failure. Fig. 2 shows a schematic of a flow-like landslide impacting a breakable tree oriented normal to the slope surface. Tree uprooting can be characterised by the ratio of the driving bending moment generated by the combined hydrostatic and hydrodynamic impact force (M_{i}) and self-weight (M_{w}) to the maximum resisting bending moment (M_{m}) the tree–root system can sustain, expressed as follows:

$$N_{\mathrm{tree}} = (M_{\mathrm{i}} + M_{\mathrm{w}})/M_{\mathrm{m}} \tag{1}$$

$$M_{\mathrm{i}} = \frac{1}{4}\rho_{\mathrm{f}} h^2 D \left(\frac{2}{3} g h + 2v^2\right) \tag{2}$$

$$M_{\mathrm{w}} = \frac{1}{8}\rho_{\mathrm{t}} \pi D^2 H (H \sin\theta - D \cos\theta) \tag{3}$$

where ρ_f is the bulk density of the landslide, h is the flow depth, D is the tree diameter, g is the gravitational acceleration, v is the flow velocity, ρ_t is the density of the tree trunk, H is the the tree height.

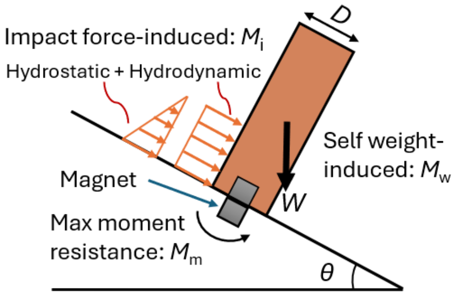

Figure 2. Schematic of forces exerting on a tree.

The M_m is typically measured using field tree-pulling tests (e.g., Singh 2024). To focus on the critical failure condition and post-failure flow behaviour, this study has simplified different tree uprooting strengths using interchangeable magnets, while controlling basal roughness with sandpaper. Laboratory actuator tests are performed to determine M_m for each tree-magnet configuration.

3 PRELIMINARY RESULTS

Fig. 3 shows a preliminary experimental validation of the proposed N_{tree} using dry granular flows impacting a tree element with varying M_m. The observed tree failures indicate that as N_{tree} decreases, the onset of tree failure is progressively delayed. No failure is observed when $N_{tree} < 1$.

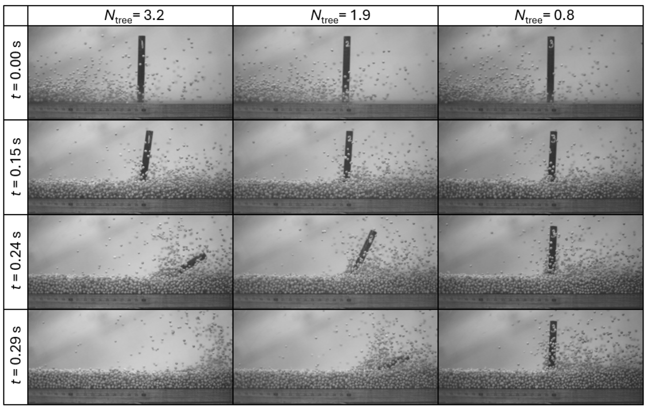

Figure 3. Observed impact kinematics for varying N_{tree}.

The results shows a good performance of the proposed N_{tree} in characterising landslide impact on a single tree. Further validation for landslide impact on arrays of trees is underway on using a new flume model with adjustable slope angles, as shown in Fig. 4.

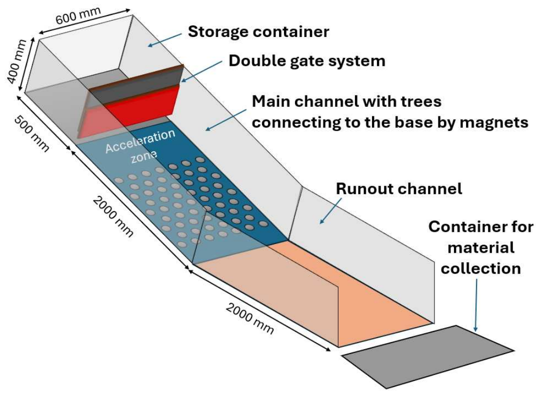

Figure 4. Schematic of the new flume model.

4 CONCLUSIONS

A new dimensionless number N_{tree} is proposed and validated using single-tree physical tests. It represents the inverse factor of safety against tree uprooting and may also serve as a proxy for the resistance that trees impose on the flow. Preliminary results indicate that for $N_{tree} > 1$, decreasing N_{tree} delays the onset of failure, while no failure occurrs when $N_{tree} < 1$. This parameter provides a basis for forthcoming flume experiments to quantify how forests with breakable trees influence landslide runout mitigation. Note that tree breakage is idealised as brittle failure using magnets, while ductile tree responses in the field may lead to different uprooting and entrainment processes.

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