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The Mechanics of Landslide Mobility with Erosion

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Summary

Erosion, as a key control of landslide dynamics,
significantly increases the destructive power by
rapidly amplifying its volume, **mobility** and impact energy.

No clear-cut mechanical condition has been presented so far for
when, how/how much energy the erosive **landslide** gains or loses,
resulting in **enhanced** or reduced **mobility**.

We pioneer a mechanical model for
the energy budget of an erosive landslide
that controls its mobility.

A **fundamentally new understanding** is that
the increased inertia due to the **increased mass is related to an entrainment velocity**.

With this, **the true inertia** of an erosive landslide **can be ascertained**,
making a breakthrough in
correctly determining the mobility of the erosive landslide.

Outstandingly, **erosion velocity** regulates the energy budget and **decides whether the landslide mobility will be enhanced** or reduced.

This provides **the first-ever explicit & complete mechanical quantification** of the state of **erosional energy** & a **precise description of mobility**.

This addresses the long-standing question of why many **erosive landslides generate higher mobility**, while others reduce mobility.

By **introducing three key concepts**: erosion-velocity, entrainment-velocity, energy-velocity, we demonstrate that **erosion & entrainment are essentially different processes**.

Landslides gain energy and **enhances its mobility** if the **erosion velocity** is **greater than the entrainment velocity**.

We **introduced two dimensionless numbers,**
mobility scaling and **erosion number**,
delivering explicit **measure of mobility**.

We establish **a mechanism of landslide-propulsion** providing
the **erosion-thrust** to the landslide.

Analytically obtained velocity indicates that
erosion controls the landslide dynamics and
well **represent erosive landslide velocities**.

We also **present a full set of dynamical equations** which
correctly includes erosion induced **net momentum production**.

Basic Balance Equations for Erosive Landslide: Mass, Momentum Balances

$$\frac{\partial h}{\partial t} + \frac{\partial}{\partial x}(hu) = E,$$

Based on:
Pudasaini and Krautblatter (2021a).

$$h\left[\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x}\right] + u\left[\frac{\partial h}{\partial t} + \frac{\partial}{\partial x}(hu)\right]$$
$$= h\left[g^x - (1-\gamma^m)\alpha^m g^z \mu^m - g^z\left\{\left((1-\gamma^m)K + \gamma^m\right)\alpha^m + (1-\alpha^m)\right\}\frac{\partial h}{\partial x} - C_{DV}u^2\right] + u^b E.$$

u^b: velocity of the eroded material

Eliminating Existing Erroneous Perception on Erosive Landslide, and Making a Breakthrough

$$u\left[\frac{\partial h}{\partial t} + \frac{\partial}{\partial x}(hu)\right] = uE$$

$$F = \frac{d}{dt}(mu) \text{ as } F = m\frac{du}{dt} + u\frac{dm}{dt}$$

This substitution is physically wrong!
but prevails in many existing models,
(for detail, see Pudasaini and Krautblatter, 2021a)

leading to erroneous momentum equation!!

Basic Erosional Landslide Equation

$$F = m\frac{du}{dt} + u^{ev}\frac{dm}{dt}$$

$$u^{ev} = u - u^b$$

velocity of eroded mass in the frame of reference of landslide

Fundamentally new understanding:
The **increased inertia** due to increased mass **is not related to the velocity of the landslide *u***,
but **it is associated with the entrainment velocity** in the inertial frame of reference of landslide, u^{ev}.

The Landslide Mobility Equation

Based on:
Pudasaini and Krautblatter (2021a).

$$\frac{du}{dt} = (\mathcal{A} + \mathcal{P}_M) - \mathcal{C}u^2$$

This is the first-ever physics-based model to directly quantify the erosion enhanced mobility!

$$\mathcal{A} = g^x - (1-\gamma^m)\alpha^m g^z \mu^m - g^z\left[\left((1-\gamma^m)K + \gamma^m\right)\alpha^m + (1-\alpha^m)\right]\frac{\partial h}{\partial x}$$ driving forces

$$\mathcal{P}_M = \left(2\lambda^b - 1\right)E^P$$ **mobility parameter:** **delivers overall mobility as additional force induced by erosion**

$\mathcal{C}$ viscous drag coefficient

$$u^b = \lambda^b u$$

$$\lambda^m = \left(1 + \frac{\rho^b}{\rho^m}\frac{\alpha^b}{\alpha^m}\right)\lambda^b$$ the erosion drift

$$E^P = \frac{g\cos\zeta\left[(1-\gamma^m)\rho^m\mu^m\alpha^m - \left(1-\gamma^b\right)\rho^b\mu^b\alpha^b\right]}{(\rho^m\lambda^m\alpha^m - \rho^b\lambda^b\alpha^b)}$$ erosion parameter

The State of Energy and Mobility of an Erosive Landslide

$u^b = \lambda^b u$

Mass flow **mobility** will be **enhanced**, **reduced** or remains **unchanged** - depending on whether **mobility generator $P_{M_{eg}}$**:

This becomes **the game-changer!**
and explicitly **tells us the state of mobility**, and
ultimately **regulates the destructive power** of landslide.

$$\mathcal{P}_{M_{eg}} = \left(2\lambda^b - 1\right)$$

game-changer!

$\left(2\lambda^b - 1\right) > 0$	$\lambda^b \in (1/2, 1)$	inertially **weaker** bed **substrate**: **mobility enhanced**
$\left(2\lambda^b - 1\right) < 0$	$\lambda^b \in (0, 1/2)$	inertially **stronger** bed **substrate**: **mobility reduced**
$\left(2\lambda^b - 1\right) = 0$	$\lambda^b = 1/2$	inertially **neutral** bed **substrate**: **mobility unchanged**

Out of $2\lambda^b$, one is from momentum production, another from inertia.
So, **without inertia effect**, **landslide mobility will never be enhanced**, would only be reduced!

$\lambda^b = 0$, is **physically impossible** (Pudasaini and Fischer, 2020),
however, this refers to the situation in many previous erosion models!

The Erosion-, Entrainment-, and Energy-Velocity: New Concepts with Mechanics

$u^b = \lambda^b u$

$u^e = u^b$ Erosion-Velocity

$u^{ev} = u - u^b$ Entrainment-Velocity

$u^{env} = u^b - \left(u - u^b\right)$ Energy-Velocity

Erosion and entrainment are different phenomena!

Erosion is a process by which bed material is mobilized.

Entrainment is another process by which eroded material is entrained and taken along with by the flow.

Energy-velocity is associated with net momentum production

$$u^{env} = u^b - \left(u - u^b\right) = u^e - u^{ev}$$

The **energy**, and thus the **mobility**, of an erosive landslide is **fully controlled** by **erosion-velocity.**

Energy velocity associated with net momentum production clearly **delineates three excess energy regimes**: **positive, negative**, or **zero**, resulting in **enhanced**, **reduced** or **unaltered mobility** of the erosional landslide:

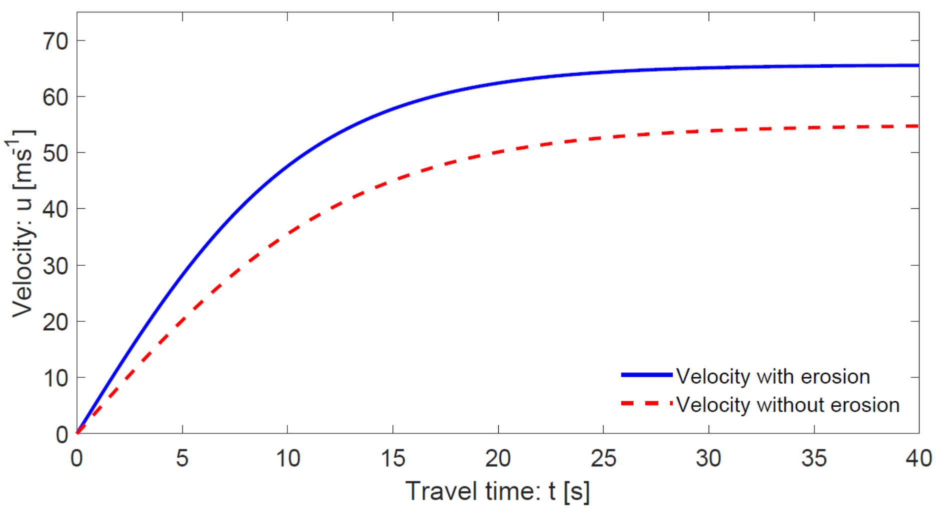
- The landslide **gains energy** in erosion if the **energy-velocity is positive**, $u^{env} > 0$. $\lambda^b > 1/2$,
- The landslide **loses energy** even in erosion if the **energy-velocity is negative**, $u^{env} < 0$. $\lambda^b < 1/2$
- The landslide **energy remains unchanged** if the **energy-velocity is zero**, $u^{env} = 0$. $\lambda^b = 1/2$

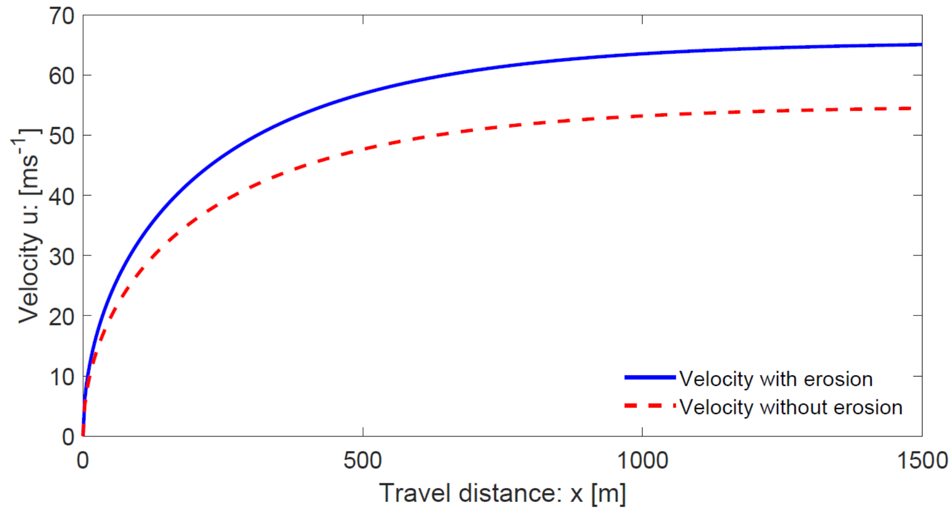
$\lambda^b > 1/2$; $u^e > u^{ev}$ results in **landslide-propulsion**, emerging from **net momentum production**, that provides the **erosion-thrust** to the landslide.

Analytical Solution to the Landslide Mobility

$$\frac{du}{dt} = (\mathcal{A} + \mathcal{P}_M) - \mathcal{C}u^2$$

$$u(t) = \sqrt{\frac{\mathcal{A} + \mathcal{P}_M}{\mathcal{C}}} \tanh\left[\sqrt{(\mathcal{A} + \mathcal{P}_M)\mathcal{C}}\,(t - t_i) + \tanh^{-1}\left(\sqrt{\frac{\mathcal{C}}{\mathcal{A} + \mathcal{P}_M}}\,u_i\right)\right], \qquad u(x) = \sqrt{\frac{\mathcal{A} + \mathcal{P}_M}{\mathcal{C}}\left[1 - \left(1 - \frac{\mathcal{C}}{\mathcal{A} + \mathcal{P}_M}u_i^2\right)\frac{1}{\exp(2\mathcal{C}(x - x_i))}\right]}$$





Time and **spatial evolution** of landslide **velocity** with and without **erosion**.

Erosion enhances the landslide velocity and thus its mobility.

Dynamic pressure with erosion is about 42% higher than the same without erosion (~ 68% at t = 15s).

These contrasts in velocities result in completely different run-out and deposition scenarios.

This clearly **manifests the importance of correct inclusion of erosion** in modelling landslide dynamics and run-out.

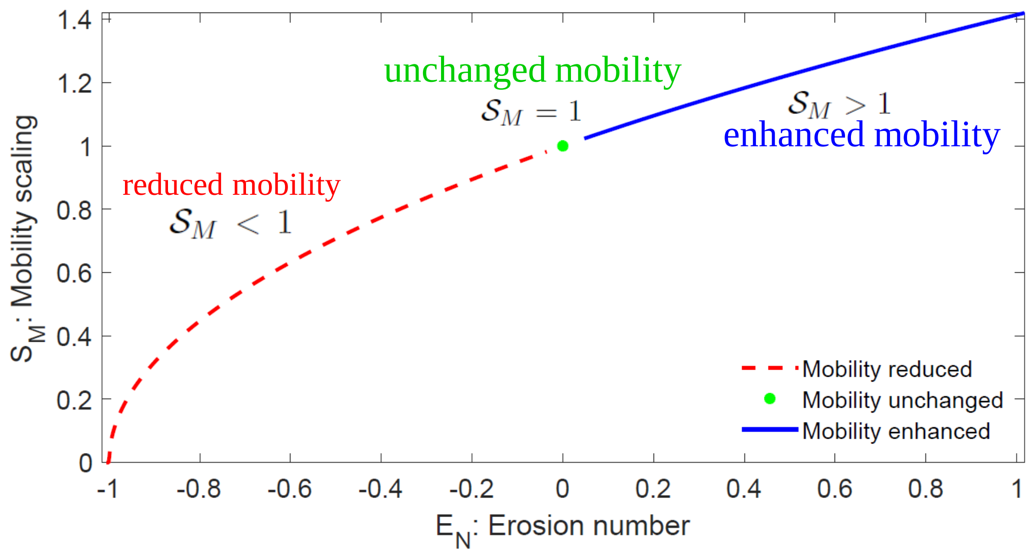
The Mobility Scaling and Erosion Number

$$\mathcal{S}_M = \sqrt{1+\frac{\mathcal{P}_M}{\mathcal{A}}}, \quad \mathcal{E}_N = \frac{\mathcal{P}_M}{\mathcal{A}}$$

Two novel dimensionless numbers

$$u(x) = \mathcal{S}_M\, u_{n_{er}}(x), \quad u_{n_{er}}(x) = \sqrt{\frac{\mathcal{A}}{\mathcal{C}}\left[1-\frac{1}{\exp(2\mathcal{C}x)}\right]},$$

that scale landslide mobility through velocity



SM exactly quantifies the **contribution of erosion** in landslide mobility.

Technically, this is the most **attractive** & pleasant feature of the **mobility scaling**.

Non-linear dependency of mobility scaling S_M on erosion number E_N.
Three distinct mobility regimes are indicated.

While P_M delivers **overall mobility** as **additional force induced by erosion**, **mobility scaling S_M** provides us with the **direct & explicit measure of mobility** by contrasting the landslide dynamics without erosion from that with erosion.

Complete Set of Dynamical Landslide Equations with Erosion

$$\frac{\partial h}{\partial t} + \frac{\partial}{\partial x}(hu) = E, \qquad u^b = \lambda^b u$$

$$\frac{\partial}{\partial t}(hu) + \frac{\partial}{\partial x}\left[hu^2 + (1-\gamma^m)\,\alpha^m g^z K \frac{h^2}{2}\right]$$
$$= h\left[g^x - (1-\gamma^m)\,\alpha^m g^z \mu^m - \{1-(1-\gamma^m)\,\alpha^m\}\,g^z \frac{\partial h}{\partial x} - C_{DV} u^2\right] + 2\lambda^b E u,$$

One half of $2\lambda^b E u$ emerges from the **momentum production** derived from the effectively reduced friction (as in Pudasaini and Fischer, 2020), while the other half originates from the correct understanding of **inertia** of the entrained mass that has not yet been considered in any models.

However, mechanically and dynamically, **this makes a huge difference**, and thus, is a **great advancement** in simulating landslide with erosion.

New model makes **a complete description** of full dynamical model for erosive landslide by considering **all aspects** associated with **erosion-induced momentum production** & correct handling of **inertia**.

Real Flow Simulations

To follow with www.avaflow.org

Implications

As the dynamic pressure is proportional to the square of velocity,
dynamic pressure with erosion can be much higher than the same without erosion.

The **large contrast in velocity with and without erosion** results in
completely different run-out, much more **extensive** for erosive landslides.

Technically, this provides very **important information** for landslide **practitioners** in
accurately determining **landslide velocity** with erosion.

We constructed two **innovative** dimensionless numbers, **mobility scaling & erosion number,**
providing a **direct measure of landslide mobility with erosion**
to **precisely quantify** the **significance of erosion**.

We derived full set of **dynamical equations which correctly includes**
erosion induced change in inertia and momentum production:
a great advancement in **fully simulating landslide with erosion**.

This clearly suggests the **importance** of correct representation **of erosion** in
modelling the **landslide dynamics** and run-out.

References:

Pudasaini, S.P., Krautblatter, M., 2021a. The mechanics of landslide mobility with erosion. arXiv:2103.14842. https://arxiv.org/pdf/2103.14842.pdf.

Pudasaini, S.P., Krautblatter, M., 2021b. The landslide velocity. arXiv:2103.10939. https://arxiv.org/pdf/2103.10939.pdf.

Pudasaini, S.P., Fischer, J.-T., 2020. A mechanical erosion model for two-phase mass flows. International Journal of Multiphase Flow 132, 103416. https://doi.org/10.1016/j.ijmultiphaseflow.2020.103416.

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The multi-phase mass flow simulation tool

www.avaflow.org

Thank you!