

International Journal of Statistics and Applied Mathematics

ISSN: 2456-1452
NAAS Rating (2026): 4.49
Maths 2026; 11(5): 08-15
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<https://www.mathsjournal.com>
Received: 05-02-2026
Accepted: 07-03-2026

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Mathematical modeling of the amplitude of saturated soil densities on field deformation

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DOI: <https://www.doi.org/10.22271/math.2026.v11.i5a.2311>

Abstract

Landslide-induced surge waves pose significant threats to infrastructure, ecosystems, and human life in mountainous regions characterized by heavy rainfall and terrain instability. This study aims to develop a mathematical model using soil with different densities to generate varying-amplitude waves that describe the dynamics of landslide wave propagation, providing an adequate basis for mitigating the risk of landslides. The objective of this study is to develop a mathematical model to describe the dynamics of a landslide wave propagation. Experimental data are computed using the Runge-Kutta method built into MATLAB to simulate the model's current and future dynamics. The mathematical model is used to simulate and analyze landslide wave propagation phenomena in affected areas. Experimentation results showed that different soil densities generated a maximum amplitude of 0.86m at an incline angle of 50° with other decline angles like 33.2° , and 24.2° that gradually decayed to 0.45m at the far field with a slope of 19.2° . These results showed precise prediction of amplitude waves at different zones on the landscape, thereby providing a reliable framework for understanding landslide surge mechanics, recommending its use in early warning systems, infrastructure planning, and necessitating the implementation of control strategies along the same region.

Keywords: Experimental validation, field deformation, ISPH, Landslide surge amplitude wave, Navier-Stokes equations

Introduction

Landslide waves are among the most devastating natural disasters, causing destruction of infrastructure, displacement of communities, and loss of human life. They commonly occur in areas with steep slopes, especially where human activities such as deforestation have destabilized the terrain. In Kenya, West Pokot and Elgeyo Marakwet Counties are prime examples of regions prone to recurrent landslides due to high rainfall that saturates the soil on steep escarpments.

This interacting phenomenon depends on landslide parameters that include pore pressure, internal shear strength, and density of the soil, among many other factors. Soil has different densities that aid soil movement down the slope when saturated.

Soil density plays a very important role during the triggering, propagation, and termination periods. There are various types of soil, namely loam, clay, and sandy soil. Each type of soil has a different soil density depending on the texture, elasticity, and viscosity of the soil. It has different characteristics depending on porosity and the compactness of the soil. Sandy soil has low density since the soil particles are loosely packed and porous, it is susceptible to landslides, and it has a range density greater than 1.75g/cm^3 [7]. Water enters the sandy soil easily since it has high soil gaps to fill between the grains, reducing the frictional strength that holds the slope together, causing a landslide. The loam soil has more density compared to sandy soil because the soil particles are closer to each other and more compacted, it has more frictional strength, which makes resistance to shear stress resulting to less destructive movement. It has a density range of between 1.3 and 1.4g/cm^3 . Clay soil has very close soil particles that make it compact, not loose. It has densities range that lies between 1.1 and 1.3g/cm^3 [7].

The three bags contain different types of soil. A physical experiment of soil densities was performed to determine the nature of amplitude waves. These waves, characterized by extreme mobility and amplitude, have the potential to cause havoc to the environment and human life during the propagation process.

These sliding bags have different types of soil material, which slide with different velocities and momentum to produce different amplitudes. The waves evolve differently along the laboratory flume to generate varying amplitude waves because every soil has varying soil density, viscosity, and elasticity. Understanding the dynamics of such waves is critical for predicting their impact and designing effective mitigation strategies. However, modeling such complex, nonlinear fluid-solid interaction poses challenges due to factors such as turbulence, terrain irregularities, and heterogeneous soil structures. This study aims to develop and validate a robust mathematical and computational model to simulate the effect of density landslide-induced surge wave propagation using experimental fluid dynamics and numerical method.

2. Literature Review

Landslides and their associated surge waves have been the subject of extensive global research due to their destructive nature and complex dynamics. Prior studies have investigated the mechanisms of landslide initiation, wave generation, and propagation using a variety of theoretical, numerical, and experimental approaches.

However, significant limitations remain in accurately modeling and predicting landslide-induced surge wave behavior in real-world conditions, especially in developing countries such as Kenya [19]. Laid the foundation for understanding landslide mechanics, identifying gravitational movement of soil and rock as the principal cause". He expanded on this, classifying landslide types and emphasizing their dependence on geological and hydrological factors. Later studies, such as those by [3] confirmed that landslides can occur across various environments, including offshore and onshore regions.

Recent investigations [13] highlighted that rainfall-induced changes in pore water pressure are key triggers of shallow landslides. While these findings are essential, they largely focus on landslide initiation rather than the propagation phase of landslide surge waves. Moreover, these studies seldom account for landslide mobility or the rheological behavior of highly viscous mudflows during long-distance travel.

The analytical solution for the surge generated by a two-dimensional landslide block moving down the slope based on one-dimensional linear phreatic equations was derived by [21]. [11] used Navier Stokes equation and SPH method to simulate the surge generated by the free fall of a rigid rectangular body, where the dynamic balance of the forces acting on the rigid body determined its displacement.

The role of rainfall intensity and soil saturation in slope failure was discussed by [21]. Their work, although insightful, primarily relies on empirical correlations and does not delve into detailed dynamic modeling of surge waves post-landslide. Similarly, [17, 8] recognized the significance of soil-water interaction and capillary forces in slope instability, but these studies do not adequately address how such conditions influence wave energy transmission downstream.

Tsunami-like waves caused by landslides have also attracted interest. [13] concluded that the 1998 Papua New Guinea tsunami was more likely triggered by an underwater landslide

than the earthquake itself. These conclusions underscore the need to focus on surge wave modeling rather than seismic parameters alone. Nevertheless, these studies lack an integrated approach that combines experimentation, validation, and dynamic simulation for inland landslides.

Experimental investigations by [20] and [9] demonstrated how physical models could replicate wave behaviors under controlled conditions. [6] advanced this by considering the shape and volume of landslide bodies. While useful, these experiments were primarily limited to 2D models and assumed idealized boundary conditions that may not reflect natural terrain variability. Numerical approaches, including the Boussinesq and Navier-Stokes models, have been developed to simulate landslide-induced wave dynamics [12, 6; 9].

In particular, the Smooth Particle Hydrodynamics (SPH) and Incompressible SPH (ISPH) methods have gained attention for their ability to model complex free-surface flows [15, 14]. However, most of these studies treat landslide motion as a known input, either as a predefined function, a constant value, or experimental data [16, 4, 7]. This assumption significantly limits their predictive capacity in real-time hazard assessment, where landslide motion is inherently uncertain and spatially variable.

"Reference [11] attempted to overcome this by introducing coupled fluid-structure interaction in ISPH models". However, their models do not fully simulate boundary contact, which is critical in terrain-influenced landslide propagation. Additionally, while [2] pointed out that surge wave propagation remains unrepresented in SPH literature, few studies have tackled this omission systematically, particularly for high-mobility mudflows in steep, vegetated terrains common in tropical highlands. Regionally, studies in Kenya have focused more on landslide risk mapping and environmental triggers [18], with minimal integration of mathematical or computational modeling.

These studies highlight critical anthropogenic triggers like deforestation, slope modification, and poor drainage, but they do not provide dynamic predictions of landslide wave impacts. This lack of predictive modeling limits the ability of policymakers and engineers to implement timely mitigation strategies. Although extensive research has addressed landslide triggers and some aspects of wave generation, few studies have combined validated physical experiments with dynamic numerical modeling to simulate landslide wave propagation in realistic topographies.

Moreover, the influence of fluid-solid interaction, turbulence, and variable terrain slopes on surge wave amplitude and runout distance remains insufficiently explored, especially in the African context. Therefore, this study fills a critical gap by integrating experimental results of different soil densities to generate amplitude waves with the ISPH model-based numerical modeling to simulate near-field and far-field landslide wave propagation. By validating the model with physical experiments and applying it to a Kenyan terrain setting, the research provides a robust framework for early warning, infrastructure planning, and environmental risk management.

3. Dynamic model for landslide propagation.

The SPH 2-D depth-integrated numerical model was adopted. For predicting the runout distance of mud-flow, flow velocity, composition of the deposition, and final volume of mudflow [14]. The model solved three-dimension Navier Stokes equation using Fourier transform methods. Numerical

solution was carried out using the Runge-Kutta algorithm's inbuilt in MATLAB; to simulate the current and future dynamic models, it predicted the runout distance of mud-flow, velocity, composition of the deposition, and final volume of mudflow.

3.1 Governing equations for the mudflow propagation process.

The governing fluid flow is modeled using the Navier-Stokes equations, enforcing conservation of mass and momentum. The precipitation model was derived using an odd Fourier series expression as shown below ^[11]

$$R \eta(t) = \frac{k}{\eta} \sum_{\eta=1}^{\infty} \frac{\sin(2\eta-1)t}{(2\eta-1)} \quad (1)$$

where k and η are curve fitting parameters, determined from experimental validations.

Conservation mass equation is expressed as

$$\eta \rho_{\omega} \nabla = 0 \quad (2)$$

where η is the height of the wave surface, ρ_{ω} is the density of the soil. ∇ is the divergent operator.

The differential expression derived from the conservation of momentum follows:

$$\frac{du}{dt} = -\frac{1}{\rho_m} \nabla p + g + \nu \nabla^2 u + \tau_{sps} \quad (3)$$

where u is the particle velocity vector. t is the time, ρ_m is the density of mixed fluid, p is the particle pressure, g is the gravitational acceleration vector, μ is the laminar kinematic viscosity and τ is the sub-particle scale (SPS) turbulence ^[15].

3.2 Energy

Energy components considered include:

$$E_K = \frac{1}{2} \rho_{\omega} m_s v^2, \quad (4)$$

$$E_p = \rho_{\omega} g h \quad (5)$$

E_p denoted the potential energy. E_k is the kinetic energy of water percolating through the rocks. v_s is the speed of the fluid entering the soil. ρ_{ω} is the density of water. m_s mass of the sliding body and g is the gravity.

3.3 Turbulence Modeling

Turbulence viscosity also known as eddy viscosity is used to model the effect of turbulent structure and on momentum transport in the transport in turbulent flow.

The concept is introduced to simplify the analysis of turbulent flow. Sub-particle scale (SPS) turbulence is approximated using eddy viscosity:

$$\tau_{ij} = \rho_{\omega} \left(2\nu_t s_{ij} - \frac{2}{3} k \delta_{ij} \right) \quad (7)$$

Where ν_t is the turbulence eddy viscosity, s_{ij} is the strain rate tensor, k is the turbulence kinetic energy, and δ_{ij} is the Kronecker delta function. ρ_{ω} is the density of water. The eddy viscosity ν_t is derived and later compared with the modified smagorinsky mode.

Derivation of eddy viscosity: Kinematic viscosity of sub-grid eddies was written as the product of velocity and length.

$$V_{sgs} = \frac{m^2}{s} = \frac{m}{s} m$$

$$\text{But } \frac{m}{s} = u \text{ (velocity)}$$

$$V_{sgs} = u_0 \times l_0 \quad (7)$$

Where V_{sgs} was the kinematic viscosity, u_0 was the velocity and l_0 was the length.

To calculate the velocity gradient and the length of the eddy (the length scale)

$$\text{Velocity scale} - \Delta u = l_0 * \frac{du}{dy}$$

$$u_0 = l_0 * \frac{du}{dy} \quad (8)$$

The velocity gradient in different directions with the strain rate tensor was obtained by

$$s_{ij} = \frac{1}{2} \left(\frac{du_i}{dx_j} + \frac{dv_j}{dx_i} \right) \quad (9)$$

The magnitude of the strain rate tensor can be calculated using the matrix given below.

$$s_{ij} = \begin{pmatrix} 0 & \frac{1}{2} \frac{du}{dy} & 0 \\ \frac{1}{2} \frac{du}{dy} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad (10)$$

The magnitude of the strain tensor is

$$|s_{ij}| = \sqrt{s_{ij} s_{ij}} = \frac{1}{\sqrt{2}} \frac{du}{dy} \quad (11)$$

To obtain the strain tensor for the velocity scale u_0 multiply $\sqrt{2}$

$$u_0 = l_0 \cdot \sqrt{(2s_{ij} s_{ij})} \quad (12)$$

Since sub-grid viscosity is

$$V_{sgs} = u_0 \cdot l_0 \quad (13)$$

Substitute for the velocity scale (u_0) to V_{sgs}

$$V_{sgs} = l_0 \cdot \sqrt{2s_{ij} s_{ij}} \cdot l_0$$

$$V_{sgs} = l_0^2 \sqrt{2s_{ij} s_{ij}} \quad (14)$$

The fraction of sub-grid length was taken as a fraction of the cell size. The fraction was the Smagorinsky coefficient, calculated as

$$C_s = \frac{l_0}{\Delta}$$

and

$$l_0 = c_s \Delta \approx 0.1413 \quad (15)$$

Hence eddy viscosity

$$V_\tau = V_{sgs}$$

Calculated Smagorinsky c (0.1413) $\approx$ computed Smagorinsky c (0.1)

Substitute l_0 with $c_s \Delta$

$$V_\tau = (C_s \Delta)^2 |S| \quad (16)$$

The eddy viscosity v_τ was calculated using a modified Smagorinsky model [10]

$$v_\tau = (C_s d_0)^2 |S|$$

where C_s was the Smagorinsky constant, $C = 0.1$ and d_0 Was the particle spacing representing the characteristic length scale of the small eddies? $|s| = \sqrt{(2s_{ij}s_{ij})}$ was the local strain rate.

4. Experimental Setup and Model Validation.

This study adopted [9] an experimentation setup, where an experiment was performed in the laboratory flume measuring, width 0.45m, length 20 m, and water depth (h) of 2m. The mass of three rectangular gauges of soil each measure 3kgs. The slope angle was 45° . The shape of the laboratory flume was a semicircular cylindrical shape, lubricated to provide free fall flow of different densities of mudflow downslope.

Three measured soil densities were placed in different gauges to slide on the flume; gauge A ($\rho_a = 2650 \text{ kg/m}^3$), gauge B ($\rho_b = 2550 \text{ kg/m}^3$) and gauge C ($\rho_c = 2450 \text{ kg/m}^3$). Each gauge contains different types of soil with different densities, and slides down the flume with different velocities. Other parameters remained constant. A small quantity of soil from each bag was placed in a gauge, slid freely down the slope at 50° , 33.2° , 24.4° and 19.2° until stopped at the bottom of the flume. Each checkpoint, P, Q, R, and S, measured 8 m, 14.5m, 20.9m, and 27.2m, with checkpoint P at 8 m as the starting point for capturing experimental data ($x=0$). Results for points P to S were recorded and analyzed, and different graphs were plotted for points P, Q, R, and S for free surface amplitudes.

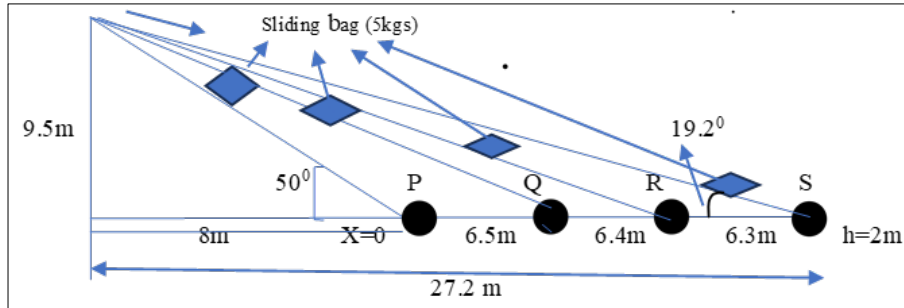


Fig 1: Experimental diagram for validation (m)

A. Initial and Boundary Conditions

The table below shows different parameters used in a landslide experiment.

Table 1: Landslide model input data

Related parameters	Specific numerical
Density of Bag A (kg/m^3)	2650
Density of Bag B (kg/m^3)	2550
Density of Bag C (KG/m^3)	2450
Coefficient of friction	0
Grid size (m)	0.05
Mass of soil (kg)	5
Depth of the water (m)	2

B. Control equations of the mudflow propagation process.

Conservation of mass equation as seen in equation (2).

$$\eta \rho_\omega \nabla \cdot u = 0$$

Where u is the particle velocity. ∇ is the divergence operator.

ρ_ω is the density of water. This gave rise to differential expression derived from the conservation of momentum as drafted in equation (3).

$$\frac{\partial u}{\partial t} = \frac{-1}{\rho_m} \nabla p + g + \mu \nabla^2 u + \frac{1}{\rho_m} \nabla \cdot \tau$$

The computational model had boundary limits set since the solid walls had no slip limit, and the fluid velocity was. The gradient and its flow variables were fixed to be zero at the fluid-solid interface. The upper part of the laboratory flume was fixed as a free surface boundary. It meant that the liquid pressure was equal to the gas pressure, and the normal velocity on the free surface was set to be zero. The other four boundaries corresponding, their flow flux and shear stress were equal to zero. Initially, the speed of the landslide body was also zero.

C. Results and Analysis

Table 2: Experimental results for point P($x=8\text{m}$).

Time(s)	0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7
Bag A	2	2.87	2.4	1.77	1.7	1.77	2	2.3	2	1.9	1.95	2.1	1.96	1.98	2.0
Bag B	2	2.86	2.39	1.77	1.69	1.76	2	2.29	2	1.89	1.95	2.1	1.96	1.97	2.0
Bag C	2	2.85	2.39	1.76	1.7	1.76	1.9	2.3	1.9	1.89	1.95	2.1	1.96	1.97	1.99

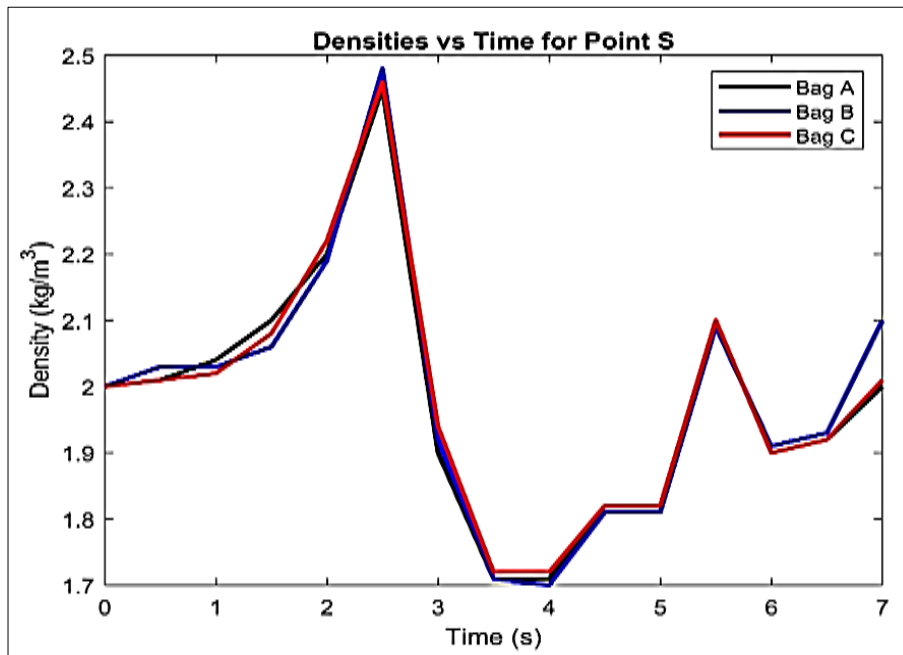


Fig 2: Different amplitude waves produced by different densities.

1. Observation at point(x=8m).

At approximately 0.6 second, initial amplitudes of 0.87 m, 0.86m, and 0.85m were observed after sliding bag A on a flume with a wave velocity of 0.85m/s compared to numerical simulated peak height of 0.88m. It produced a trough of 1.7 m at 2 second. The second wave peak was produced at 3.2 seconds with a velocity of 0.24 m/s and an amplitude of 0.3 m.

The texture of the soil was rough, with low capillary and a large particle size. It easily drained; it did not hold water for a long time. It was observed that bag A contained soil with high density that slid with high velocity down the elevation to the

far field away from the wave generation area. The initial wave potential energy increased with an increase in the density amplitude of the waves. It was suspected that the bag A contained sandy soil since it has a low binding force and high permeability, which easily gets saturated, leading to shear strength.

Potential energy dissipation was increased by the decreasing soil densities of the three-soil type because soil with high density produced high initial kinetic energy, taking longer to dissipate potential energy.

D. Experimental results for Point Q (x=11m).

Table 3: Experimental results for point Q of soil with different densities

Time	0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7
Bag A	2	2.2	2.3	2.86	1.8	1.7	1.72	1.85	2.3	2.1	1.9	1.95	2.04	2.1	1.9
Bag B	2	2.18	2.3	2.85	1.8	1.67	1.71	1.84	2.3	2.08	1.9	1.94	2.03	2.09	1.89
Bag C	2	2.17	2.29	2.85	1.79	1.7	1.71	1.84	2.29	2.09	1.89	1.94	2.03	2.07	1.87

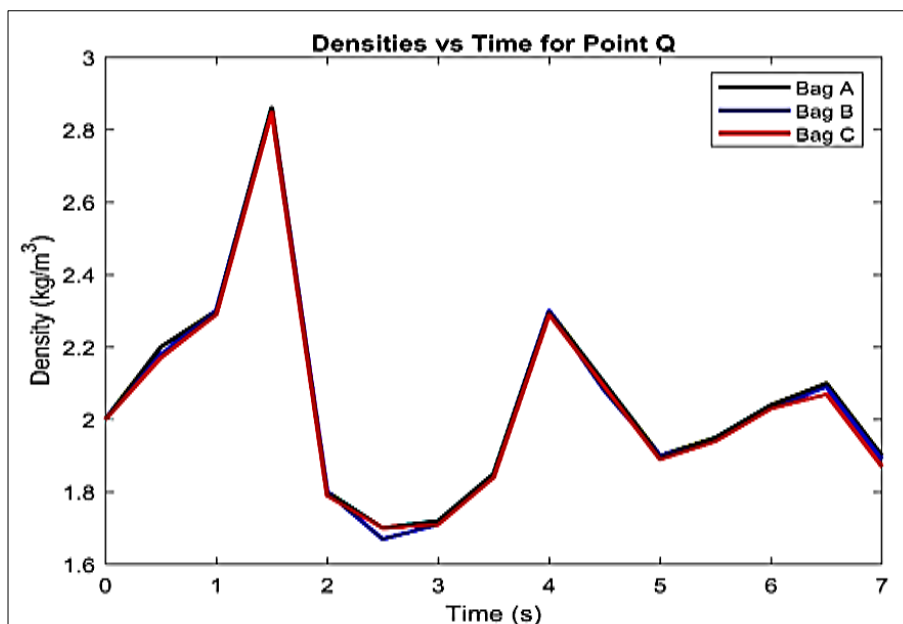


Fig 3: Comparisons of amplitude waves generated by different densities at the source.

2. Observation at point Q (x=11m).

At approximately 1.5 second, peak heights of 0.86m, 0.85m, and 0.84m waves were produced by sliding gauge B down the flume elevator with respect to horizontal height of 2.m. It was observed that the soil texture was not less rough compared to the soil in gauge A. It was also found that the soil did not drain as fast as the soil in gauge A. It was inferred that gauge B contained loam soil. A trough of 1.7m was produced at approximately 3.2 second minimum point of the graph. The

second peak height occurred at 4.2 seconds with an amplitude of 0.35m; the second wave crest was produced as a result of the emission of the wave peak during the landslide surge. At approximately 7 seconds, amplitude waves are produced in groups and travel linearly at group velocity, not as a single column propagation. The sudden total energies stored in the form of kinetic and potential energy remain unchanged.

E. Experimental results for point R(x=14m).

Table 4: Results of soil with different densities at point R

Time s	0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7
Bag A	2	2.04	2.1	2.5	2.45	1.8	1.72	1.72	1.9	2.3	2.1	1.9	1.89	2	2.1
Bag B	2	2.03	2.09	2.4	2.44	1.79	1.71	1.72	1.88	2.2	2	1.9	1.89	1.99	2.08
Bag C	2	2.04	2.08	2.3	2.44	1.8	1.7	1.71	1.87	2.1	1.99	1.89	1.87	2	2.07

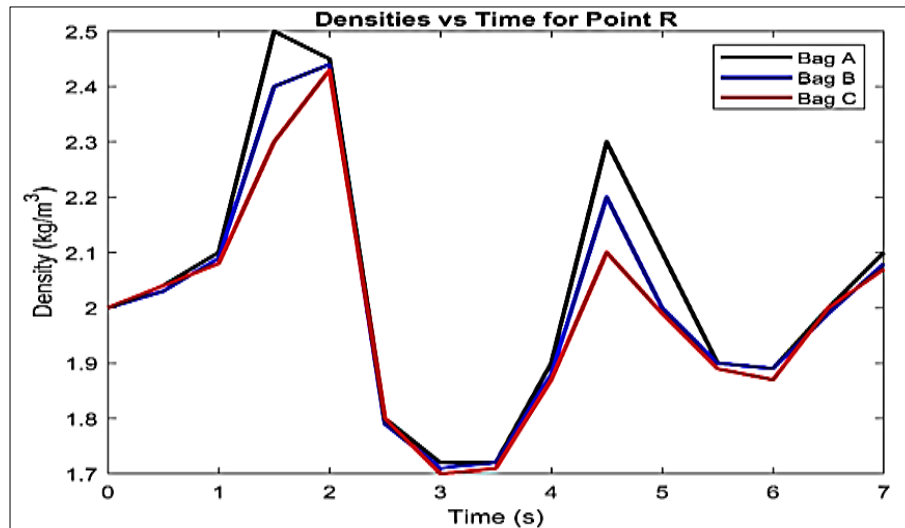


Fig 4: Comparison of amplitude waves at point R.

3. Observation at point R (x=14m).

The Peak height generated by the slide bag C for the three soil densities is; 0.45m, 0.44m, and 0.42m, respectively, at 2 second. The characteristics of the amplitude waves of point R were almost equivalent to those of point P. Amplitude waves produced by the three far points Q, R, and S were the same.

At 3.1 second a trough was observed with a minimum amplitude of 1.7m. At 4.2 second an amplitude of 0.3 m was generated that had decayed compared to the previous stream of amplitude waves.

F. Experimental results for point R (x=17m)

Table 5: Results of soil with different densities at point S

Time(s)	0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7
Bag A	2	2.01	2.04	2.1	2.2	2.45	1.9	1.71	1.71	1.82	1.82	2.1	1.9	1.92	2
Bag B	2	2.03	2.03	2.06	2.19	2.48	1.92	1.71	1.70	1.81	1.81	2.09	1.91	1.93	2.1
Bag C	2	2.01	2.02	2.08	2.22	2.46	1.94	1.72	1.72	1.82	1.82	2.1	1.90	1.92	2.01

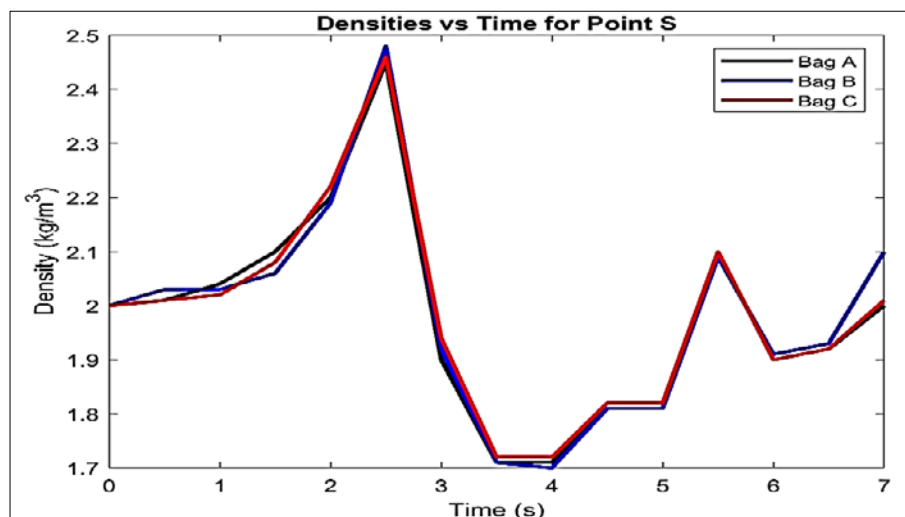


Fig 5: Comparisons of amplitude waves at the far field point R.

4. Observation at point S($x=17m$)

The peak heights of 0.42 m, 0.41m, and 0.40 m were generated at point S after 2.2 second. The texture of the soil was smooth; it was observed that the movement of the gauge containing the soil was slow, the soil was sticky with high elasticity and viscosity. It was suspected that the soil might be clay. At 4.8 seconds, a 0.4m amplitude wave was produced by bags containing different densities of soil. The bags slid down the elevated flume with low velocity that produced similar amplitudes due to the reduced gradient that led to the decrease of soil velocity and momentum down the slope to the flat land.

5. Discussion

The observations made from experimentation are compared with numerical simulation results for the production of amplitude waves using soil densities, providing insight for the prediction of landslides.

Three sliding bags A ($\rho_a = 2650kg/m^{-3}$), bag B ($\rho_b = 2550kg/m^{-3}$) and bag C ($\rho_c = 2450kg/m^{-3}$) containing soil bags with different densities were slid on the laboratory flume. Other parameters remain constant.

Experimentation results were compared with the simulated results, which showed that soil with different densities produces amplitude waves that evolve differently as it propagates down the slope.

They produced average amplitude waves that measure 0.86m, 0.85m, 0.82m, and 0.80m for the four points P, Q, R, and S. This experimental results study agreed well with Henrich's test results. These amplitude waves measurements were compared against their numerically simulated peak height of 0.87 m, 0.85m, 0.83m and 0.81m, both produced amplitude waves that were almost similar with an error of 1.15% compared to the experimental results.

After analyzing the different characteristics of soil, it was found that bag A contained sandy soil because the soil particles are loosely packed and porous, water molecules easily occupy high soil gaps between the soil grains, reducing the frictional strength that holds the slope together, causing a landslide. It is susceptible to landslides and has a density greater than $1.75g/cm^3$ ^[7].

Sandy soil has low elasticity and apparent viscosity; it easily gets saturated and slides easily down the slope to produce high-amplitude waves at the source field. It contains soil with high density that produces high kinetic energy^[5]. It was also observed that bag A slid with high velocity and covered a long distance from the source area. Soil with high density generates high-amplitude waves that are hazardous to both human life and the environment. This led to land deformation by producing gully erosion and gorges.

The initial wave potential energy grows with the increased density of the soil. The efficiency of wave generation is low in soil with a large density compared to the lighter soil^[11]. The soil with low density produces amplitudes faster since the soil slides down the slope with high velocity.

The amplitude waves decayed progressively for the three points (P, Q, R, and S) due to energy dispersion, which transfers partial energy of the main peak to the trailing waves^[5].

Wave length of the trailing wave begins to reduce, causing reduced velocity of wave propagation from the front, forming a backward wave group. It formed a wave train with continuous decaying amplitudes.

The highest peak height of waves at point P, which was produced by bag A, contained a high density of soil that produced greater kinetic energy.

During the experiment, the second amplitude wave was considered as an emission peak created by the surge after hitting the endpoint boundary. Measurement for Point S (far field) showed wave groups that are propagating linearly with group velocity instead of single column propagation. Their energy is stored in both kinetic and potential energies, with the total energy remaining unchanged.

6. Summary and Conclusion.

This paper addressed a significant research problem caused by amplitude waves generated by different soil densities on landslide surge wave propagation using a quantitative approach. It involved collecting and analyzing numerical data to reach valuable conclusions.

Quantitative experimental data is collected through in-depth observation. Numerical solutions were carried out using the Runge-Kutta algorithm's inbuilt in MATLAB, to simulate the current and future dynamics of the model.

Both experimental and numerical simulation results, as presented in figures 2 to 4, showed the effect of the incompressible smooth particle hydrodynamic (ISPH) model in solving the dynamics of landslide-induced surge waves caused by different soil densities, on the field deformation of land that affects the livelihood of people and their environment.

Experimented amplitude waves produced different soil densities similar to [9] test results. Soil with the highest density ($\rho_a = 2650kg/m^{-3}$) slid with high velocity over a long runout distance, it generated high-experimented amplitude waves (0.86m) at the near field gauge, which was similar to the simulated results of 0.87m, it produced an error of 1.15%. The amplitude waves caused land deformation and destruction of roads by lateral and gully erosion.

It was observed that amplitude waves decayed progressively from point P ($x=8m$), source field, to point S ($x=17m$), far field, due to energy dispersion that is transferred from the initial waves to the trailing waves that follow closely. At this point, the potential energy and the kinetic energy are equivalent^[22].

The Soil with small densities produces low amplitude, which was lower than the previous wave peaks, indicating energy decay of amplitude waves. It increased the bottom friction of erosion soil.

It encouraged deposition of sand, which was economically important for construction purposes. These findings align with the literature, where wave amplitude attenuation is attributed to factors such as bottom friction and material deposition^[1]. Simulation and experimental results, as well as deductions derived from the study, helped to determine where to put up the town, hospital, and social amenities. It helped to develop an early system for disaster preparedness.

It was recommended that accurate and reasonable algorithms should be introduced to optimize the research details of the chrematistics of the landslide. For the deformation of the landslide, the process of validation should be pursued as a long-term goal, for simulating experimental benchmark cases, as they become available.

This research acknowledges limitation of previous data collection, which hampered the predictability of landslides. It was found that some areas that are landslide-prone had no previous rainfall data, even though the landslide happened perennially; the verification of the described model was limited.

By addressing gaps in prior models, such as predetermined landslide motion, the ISPH approach provides a more realistic

simulation of fluid-solid interactions, as evidenced by the results in Figures 2 to 5. The findings enhance the ability to predict landslide occurrences and their impacts, supporting early warning systems and mitigation strategies like afforestation and structural reinforcements. This work improves existing models and offers a valuable tool for researchers and policymakers to protect lives, properties, and economic livelihoods in landslide-prone regions.

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