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The Impact of the Breakdown of the Sidoarjo Mud Dam on the Northeast Side Using the HEC-RAS Program

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Abstract: The eruption of the Sidoarjo mud, commonly known as the Lapindo mudflow, has continuously dumped slurry since 2006, necessitating the construction of an emergency containment embankment with limited engineering control and a high risk of structural failure. One of the critical locations is the northeast embankment segment (P.75), which is located near the residential zone of South Kalitengah, Gempolsari Village. This study aims to predict the flow direction and the level of impact of mud inundation if there is a breakdown of the embankment. Five dam breakdown simulation scenarios were performed using HEC-RAS by varying the Liquid Limit Index (LI), with the material behavior modeled as a non-Newton Bingham flow characterized by viscosity and yield stress parameters, supported by DEM based topography, Manning coefficients derived from land cover, and inflow hydrographs. The results showed that higher LI values led to slower settling times, longer and wider flow paths, shallower flow depths, and much larger inundation areas, extending to the residential sector. The simulated transport and deposition metrics were aligned with previously documented mudflow events, although the flat local topography led to slower accumulation. This study contributes an empirical LI-based rheological-hydrodynamic relationship to predictive hazard modeling and provides important insights for regional risk mitigation, emergency evacuation planning, and embankment strengthening strategies in mud volcanic disaster zones. In addition, a scenario-based sensitivity and uncertainty analysis was performed to assess the influence of rheological variations, surface roughness, and hydrographic parameters on inundation area and maximum depth, so that the interpretation of the results can be placed in the context of input limitations and numerical assumptions.

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Introduction

The Sidoarjo Mud Stream, also known as the Lapindo Mud Stream, is a hot mud volcanic eruption that has erupted at a drilling site owned by Lapindo Brantas Inc. since 2006 and is considered one of the largest mudflows in the world. The eruption has submerged at least 16 villages in three districts, and its potential impact is predicted to be widespread if the eruption does not stop naturally. Since the beginning of the incident, the mudflow has continued to increase in volume, requiring ongoing mitigation efforts to prevent broader social, economic, and environmental impacts. One of the main mitigation measures is the construction of an embankment to hold the mud, although this embankment was built in an emergency and had to compensate for the rapid increase in the volume of mud. This condition causes the embankment to be categorized as an unengineered embankment, so it has a high risk of collapse because it does not meet the technical standards of construction for long-term durability.

The construction of embankments is a key step to prevent mudflow into residential areas, vital infrastructure, and productive land (Połomski & Wiatkowski, 2023). However, as the volume of mud increases, the holding capacity within the walled area decreases, while the internal hydrostatic pressure increases. This contributes to the threat of embankment failure, which can result in sudden and widespread mudflow through the embankment. Previous studies have shown that embankments built from soil heaps without mixed engineering or material stabilization are at high risk of failure, especially when subjected to saturation conditions, systemic loads, and long loading durations (Xia et al., 2025). Short-term analysis of the final condition of the embankment construction suggests that the slope may be unstable, allowing cracks, wall deformation, and internal seepage to develop into piping and eventually collapse.

In addition to the instability of the retaining wall, the direction of mud flow is significantly influenced by the topography of the region. Based on the elevation mapping, the area around the embankment point is relatively flat with a slope of 2–4%, so the mudflow tends to move slowly but is widespread. Flat landscape conditions increase the potential for wider sedimentation and extend the inundation time, thereby increasing the risk of runoff into residential areas (Fatima, Atif, Benteng, & Azmat, 2025). Previous findings have also shown that an increase in the volume of sludge is accompanied by an increase in run-out length and an increase in the level of sludge deposition in low-lying areas. This poses a serious threat because residents living near the embankment may not have adequate evacuation time in the event of a sudden collapse.

Previous research has shown that the Sidoarjo Mudflow embankment was built quickly without adequate technical planning, resulting in low safety factors and vulnerability to failure in saturated conditions (Yang & Cheng, 2024). Rheological studies by (Chambon Career , 2018) confirms that the Sidoarjo Mud Flow is a non-Newton Bingham type material with a viscosity and yield stress influenced by the liquidity index (LI), meaning the flow continues even when the LI is slightly below the liquid limit. (Rudra, 2020) added that the 2-4% soft topography around the embankment caused the mudflow to spread laterally with a prolonged duration of inundation, making the escalation of the affected zone very likely if the embankment failed.

Furthermore, (Widjaja, 2019) It was found that the increase in the volume of mud is directly proportional to the expansion of inundation and runout flow, so that the capacity of the embankment will continue to decrease with the accumulation of materials. (Islas-Toski et al., 2024) emphasizes that physical mitigation strategies such as embankment elevation are not effective enough without dynamic modeling-based risk maps to support early warning and evacuation systems. These findings show a scientific gap, namely the lack of comprehensive modeling of the impact of levee violations using LI variations and hydrodynamic approaches. Therefore, this study is important to produce flow direction predictions, sediment distribution, and mitigation recommendations based on HEC-RAS simulations.

Previous studies have examined the behavior of mudflows and their impact on geological, social, and engineering systems, but detailed studies on numerically predicting the distribution of mudflows due to embankment failures are limited. The research conducted focuses primarily on structural mitigation, population relocation, and sludge discharge into the sea, but has not presented quantitative modeling that represents the relationship between the rheological characteristics of sludge and potential violation of containment areas. In fact, Sidoarjo mud tends to be non-Newtonian, with viscosity and yield stress parameters that vary according to the liquidity index (LI) (Widjaja et al., 2024). Therefore, its flow behavior needs to be analyzed as a Bingham material rather than a Newtonian fluid. The fluidity of the mud affects the flow direction, the speed of spread, the depth of inundation, and the duration of deposition in the affected areas, making this aspect a research gap that needs to be developed.

Furthermore, the correlation between the liquidity index (LI) and the sludge distribution is still limited, even though these parameters directly determine the flow phase, viscosity, and yield stress. In the case of the Sidoarjo Mud Stream, the LI value ranges from 0.80 to 1.15, indicating that the material continues to flow even if it is slightly below the liquid limit. This shows that despite its decreased consistency, the mud is still capable of significant lateral movement due to the internal pressure of the mud reservoir and the gravitational pull at low relief. Therefore, studying LI variations in numerical simulations is important for predicting the characteristics of flow distribution, including deposition area, runout length, and deposition time. Knowledge of the relationship between LI and flow behavior is essential for developing inundation risk maps and designing structural mitigation and evacuation measures.

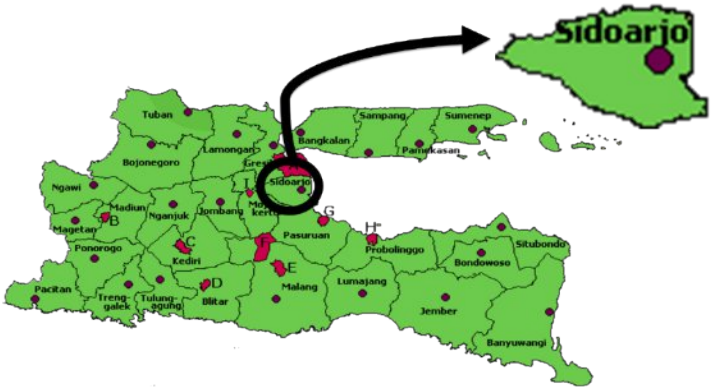


Figure 1 Location of Sidoarjo Mud Map

Geotechnical investigations have been carried out at the P.75 embankment point, one of the locations with the highest vulnerability to collapse according to the 2017 PPLS Working Area Map. Core drilling results showed that the N-SPT value was 6-15 strokes/foot, with the soil type being low plastic mud clay, categorized as having medium density. These soil conditions are not ideal as long-term retaining materials due to their high permeability and potential for lateral deformation under wet loads and extreme saturation conditions (Liang et al., 2021). This reinforces the conclusion that the embankment has a low level of structural safety when faced with the constant pressure of the growing mud pool. Therefore, further investigation is needed to understand changes in soil characteristics, the relationship between mud rheological parameters, and potential failure mechanisms that can impact the surrounding community.

Based on this description, this study is important not only to understand the behavior of mudflows after potential failures but also to provide a scientific basis for decision-making regarding mitigation, evacuation, and spatial rezoning of disaster-prone areas. This study aims to analyze the potential distribution of mud flows in the event of dam damage at point P.75, predict the affected areas using a numerical modeling approach, and identify potential technical and humanitarian implications. The results of this study are expected to contribute to the development of mud volcano hazard studies based on hydrodynamic modeling and provide a scientific basis that can be used by policymakers in mitigation planning and disaster risk reduction strategies.

Research Methods

Mudflow

Sludge flow occurs when the moisture content is equal to or greater than the liquid limit [6]. In other words, a sludge flow occurs when the liquidity index (LI) is greater than or equal to one (LI ≥ 1). In the classification of certain mass movements, mudflows can occur at concentration-based values (Cv) between 0.35 and 40 (Wang et al., 2024). The magnitude of the Cv value can be calculated using Equation (1). Sidoarjo mud ranges from 0.35 to 0.39, with a Liquidity Index (LI) value between 0.80 and 1.15 (see Table 2). Therefore, even though the LI value is less than 1, Sidoarjo mud is still included in the mudflow classification.

$$C_v = \frac{1}{1 + G_s \times w} \tag{1}$$

Where, Cv = sediment concentration by volume, Gs = specific gravity, w = moisture content

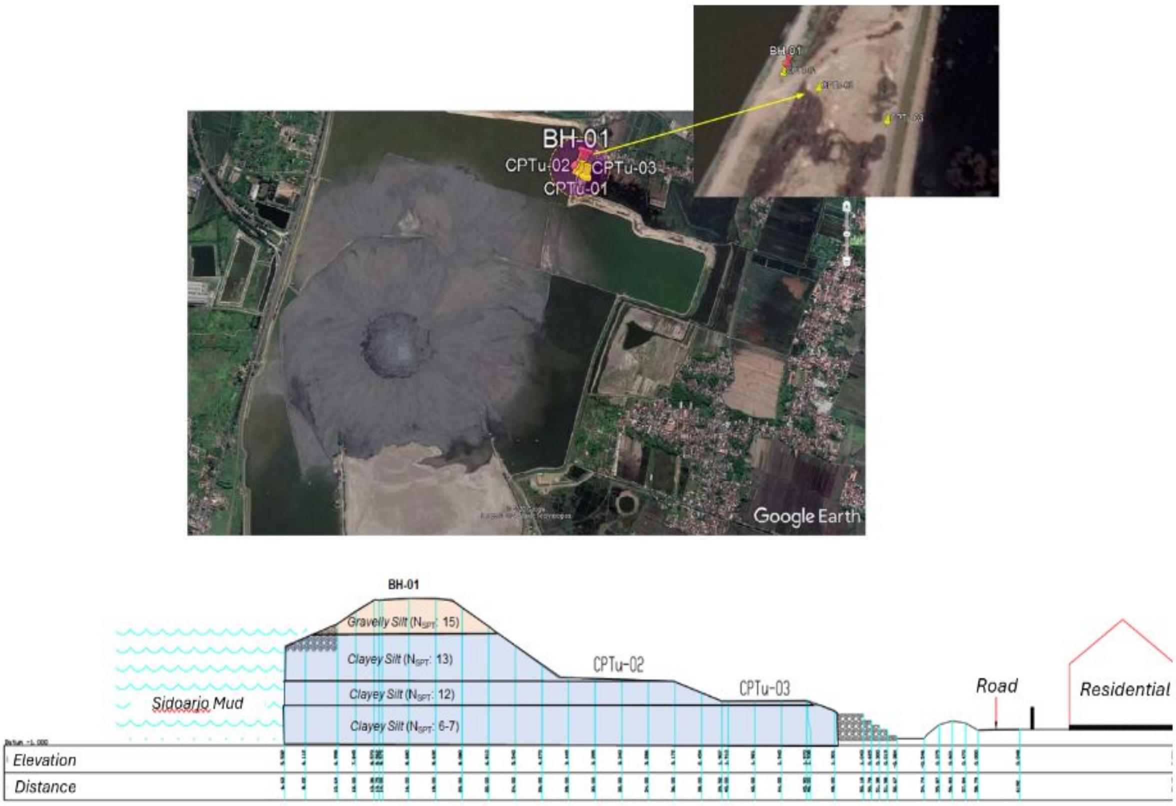


Figure 2 Geotechnical Investigation Point Map and Core Drilling Investigation Results

Mudflow Rheology

The selection of rheological models and input parameters is carried out so that the modeling procedure can be replicated. The parameters of yield stress (τy) and plastic viscosity (η) were obtained from laboratory tests on Sidoarjo sludge samples (see Table 2) and then mapped against the Liquidity Index (LI) to build rheological scenarios. The implementation of non-Newtonian flows is carried out through the Mud and Debris Flow module on HEC-RAS 2D by selecting the Bingham formulation on the Non-Newtonian Transport Editor. Within this framework, τy and η are treated as effective parameters representing the macroscopic behavior of slurry at the modeling scale, so that measurement uncertainty and material spatial variability are considered at the sensitivity analysis stage (Gibson & Sánchez, 2021).

Rheology can be defined as the science that studies the relationship between deformation and flow caused by shear stress and shear force (Kulichikhin & Malkin, 2022). Rheology describes the flow of fluids and the deformation of solids. As explained earlier, a sludge flow is a non-Newtonian material in a viscous liquid state where LI is equal to or greater than 1. Under these conditions, the void ratio is relatively high. Material movement will still occur even with a LI of less than 1, and is still included in the mudflow classification if it has viscosity and yield stress parameters.

As a non-Newtonian material, the sludge flow has two important parameters: yield stress (τy) and viscosity (η). When the shear stress (τ) is lower than τy, the material will not move. However, if the shear stress exceeds the yield stress, the material will move and form a flow controlled by the viscosity parameter (η). The Mohr-Coulomb approach cannot be used in the case of mudflow (Aghighi & Asgari, 2020). A suitable model for mudflow is the Bingham model. The Bingham model is a simple model in which the viscosity of the soil during movement is considered constant, as shown in Figure 3.

The results of the parametric test found that the value of a single constant η can represent the average η value without significant changes in the predicted deposition results (or the soil mass moving at a high shear strain rate). A lower η value will control soil flow if the surface is too rough. Generally, after the soil is settled, the controlling factors are the shear force that occurs and the roughness of the soil surface (Manning coefficient, n). Therefore, the Bingham model can predict the behavior of mudflows, especially in the simulation of transport and deposition areas.

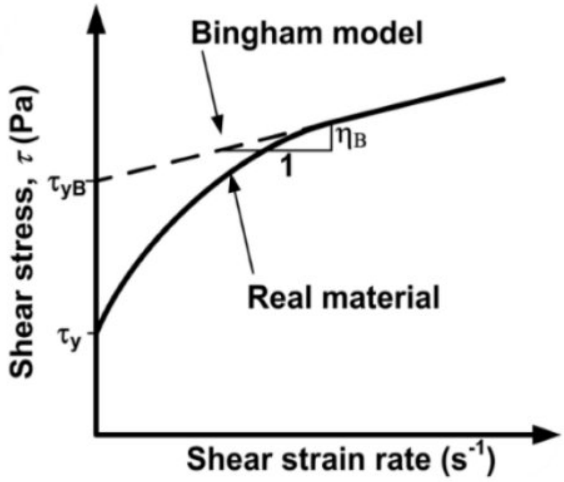
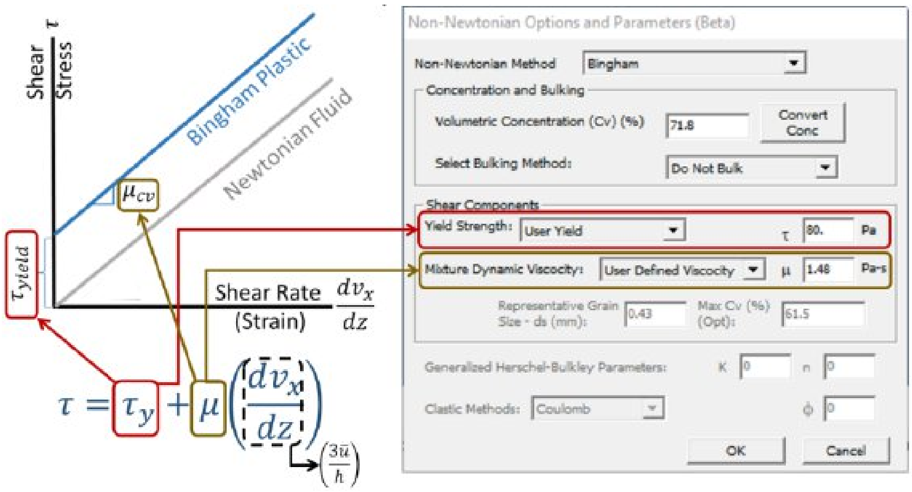


Figure 3 Material behavior in Bingham's model

HEC-RAS Program

HEC-RAS is a program developed by the U.S. Army Corps of Engineers (USACE). It is used to model one-dimensional uniform flows and one- and two-dimensional non-uniform flows, as well as non-Newtonian material flows (Barik, 2023).

In general, the HEC-RAS program has adopted the Bingham model. The required parameters include the values Cv (volume concentration coefficient), τy, and η, as shown in Figure 4.



Non-Newtonian Method: Bingham
Volumetric Concentration (Cv) (%): 71.8
Select Bulking Method: Do Not Bulk
Yield Strength: User Yield τ 80. Pa
Mixture Dynamic Viscocity: User Defined Viscocity μ 1.48 Pa-s
Representative Grain Size - ds (mm): 0.43
Max Cv (%) (Opt): 61.5
Generalized Herschel-Bulkley Parameters: K 0 n 0
Clastic Methods: Coulomb ϕ 0

Figure 4 Bingham's Model on the HEC-RAS Program

To simulate a ruptured dam using the HEC-RAS program, the data required includes topographic data in the form of a Digital Elevation Model (DEM), Sidoarjo mud material parameters, Manning coefficient, and inflow hydrograph. A flowchart of the simulation steps can be seen in Figure 5.

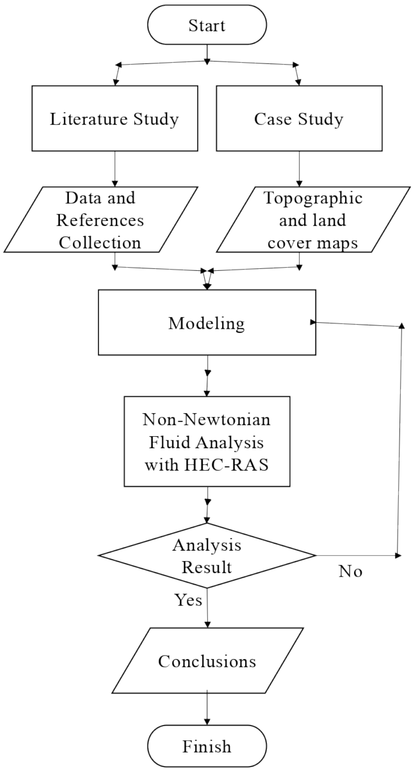


Figure 5 Simulation Flow Chart

Topographic conditions

Topographic conditions using DEM data based on measurements made by PPLS in 2018, (Pusat Pengendalian Lumpur Sidoarjo (PPLS), 2018). Generally, the sloping topography around the embankment is relatively flat, with a slope of 2-4%, as seen in Figure 6.

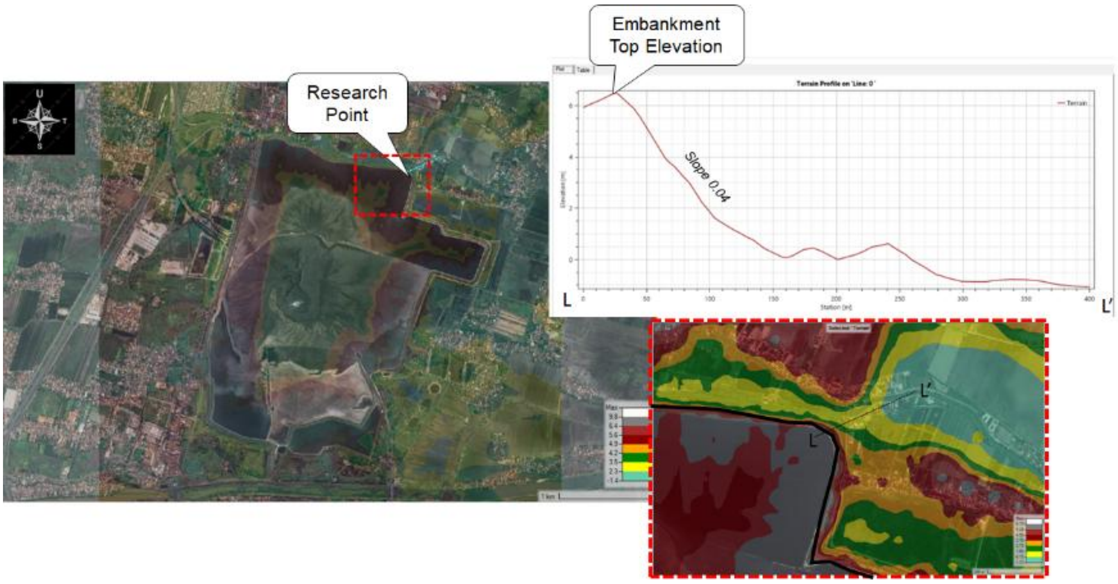


Figure 6 Topographic Condition Map

Land Cover Conditions

Land cover information is used to determine the Manning coefficient (Table 1) or the level of surface roughness. In 2019, the National Geospatial Information Agency obtained land cover conditions (Soliman, Morsi, & Radwan, 2022). The condition of land cover around the embankment can be seen in Figure 7.

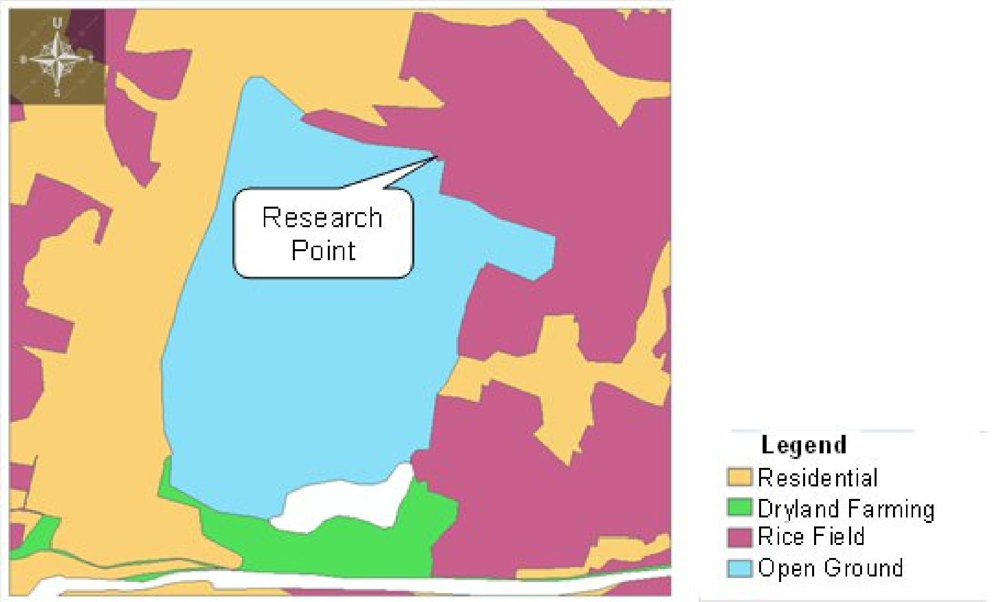


Figure 7 Map of Land Cover Conditions

Table 1 Manning Coefficient

Nope.	Land Cover	Manning Coefficient
1	Housing	0.03
2	Dryland Agriculture	0.02
3	Rice Fields	0.05
4	Open Ground	0.03

Hydrographic Inflow

The mudflow hydrograph represents the relationship between discharge and time used as hydraulic and soil parameters (Figure 8). This is determined based on the assumption of the volume of mud that will come out in the event of a dam burst, assuming the volume of mud is 122,000 m3, based on PPLS data in 2020.

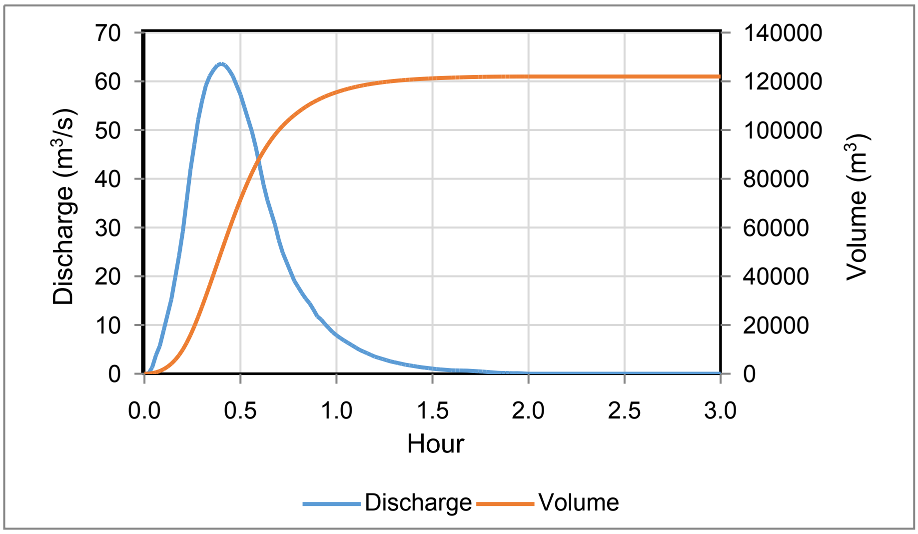
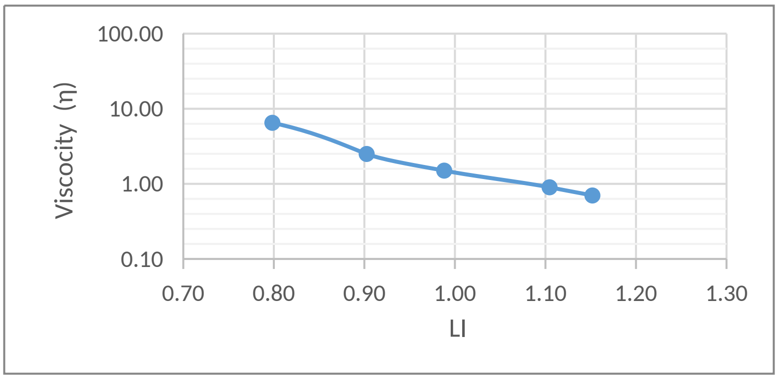


Figure 8 Hydrographic Inflow

Characteristics of Sidoarjo Mud

The characteristics of Sidoarjo mud were obtained from field samples tested at the UNPAR Geolab laboratory in 2019. The various moisture content (w) varied, and various LI values were applied to establish the relationship between LI, τy, η, and Cv. (Figure 9 and Table 2).



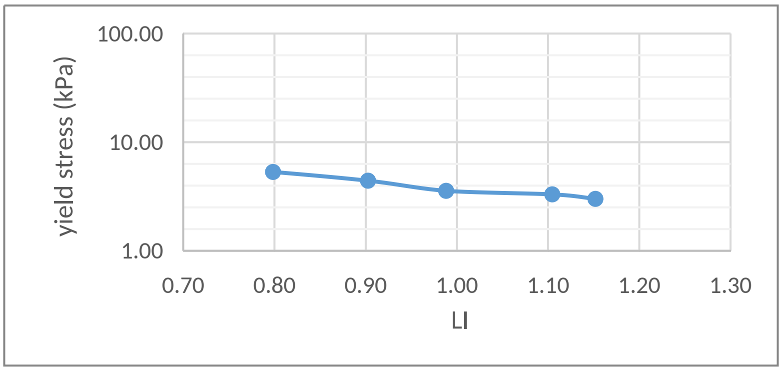


Figure 9 Relationship Curve Between LI, Yield Stress, and Viscosity

Table 2 Results of the Sidoarjo Mud Laboratory

LI	w (%)	Melt Stress (kPa)	Viscosity (Pa · s)	Concentration by Volume (Cv)
0.80	60.86	5.32	6.50	0.39
0.90	63.69	4.42	2.50	0.38
1.00	66.02	3.57	1.50	0.37
1.10	69.18	3.31	0.90	0.36

Sensitivity and Uncertainty Analysis

Sensitivity and uncertainty analysis was performed to assess how strongly modeling results were influenced by the variability of input parameters and numerical assumptions. The main sources of uncertainty in non-Newtonian flow modeling include breach parameters that make up the output hydrograph, rheological parameters (τy and η), surface roughness coefficients (Manning n), as well as DEM resolution, mesh size, and time steps that affect numerical diffusion (Wahl, 2004; Gibson & Sánchez, 2021).

The sensitivity test design uses a one-parameter (one-at-a-time) and scenario-based approach. Rheological sensitivity was evaluated through five LI scenarios (0.80-1.15) that mapped τy and η changes based on laboratory data. To quantify realistic uncertainty ranges, key parameters are recommended to be varied around baseline values: Manning n (±25%), peak discharge and/or input hydrograph volume (±30-50%), and τy and η (±20%) as per HEC-RAS-based runout analysis practices. In advanced research, the probabilistic method of the first-order second-moment approach (FOSM) can be used to combine the contribution of the variants of each input to the output variants (Ghahramani et al., 2024).

Results and Discussion

Results

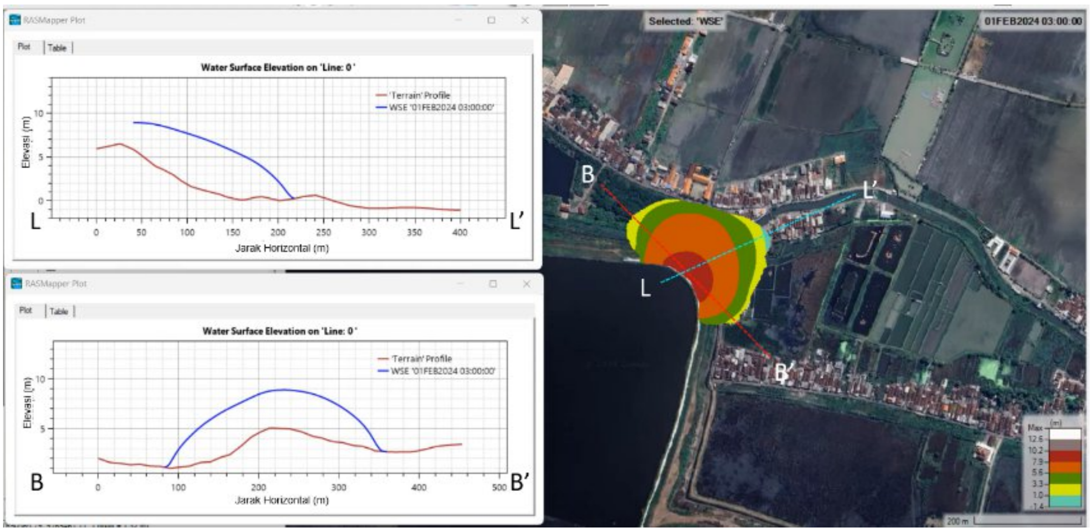
The simulation was carried out using the embankment failure method to determine the deposition area that occurs when mud flows out of the embankment. Five scenarios were used in this simulation by varying the LI values to determine the deposition time, flow length, flow width, maximum flow depth, and deposition area. The results of all the scenarios carried out can be seen in Figure 10. The general direction of the movement of the mud flow is in a northeasterly direction from the embankment survey point. If there is a dam rupture at the review site, the mudflow will have an impact on residential areas around South Kalitengah Hamlet, Gempolsari Village, Tanggulangin District.

Table 3 shows that variations in LI values affect deposition time, flow distance and width, flow depth, and deposition area. The larger LI value makes the slower deposition time, higher distance flow, higher flow width, shallow flow depth, and larger sludge flow deposition area. This is also because higher LI values correlate with higher moisture content, making the material more liquid and influencing the behavior of the sludge flow. When compared to the various mudflow events collected from different studies by (Widjaja & Florencia, 2022), length, flow depth, and deposition time all show the same trend, as can be seen in Figure 11.

Figure 10 shows that the movement of mud generally spreads in all directions but is relatively northeasterly, away from the embankment, according to topographic conditions. The length of the flow is denoted as L-L' and the width of the flow as B-B'. The depth of the flow varies, with the deepest point in the middle between the embankment and the mud deposition boundary becoming shallower as it gets closer to the deposition boundary. Similarly, the surface height of the mud decreases as it moves away from the embankment.

Figure 11 shows the same trends generated by simulation results and past mudflow events. However, there is a striking difference in the relationship between LI and the time of deposition. The flat topographic conditions make the mud flow slower. When compared to other mud flow topographic conditions that have occurred, the topography at the Sidoarjo mudflow location is much flatter than others. (see Figure 12).

The results of the analysis can actually be further processed to create a risk map; However, this paper does not address that aspect. In addition, efforts to prevent the spread of mud in the event of a dam burst include building channels or ditches around the embankments and building embankments after canals to block the flow of mud towards settlements. Mitigation efforts can be seen in Figure 13.



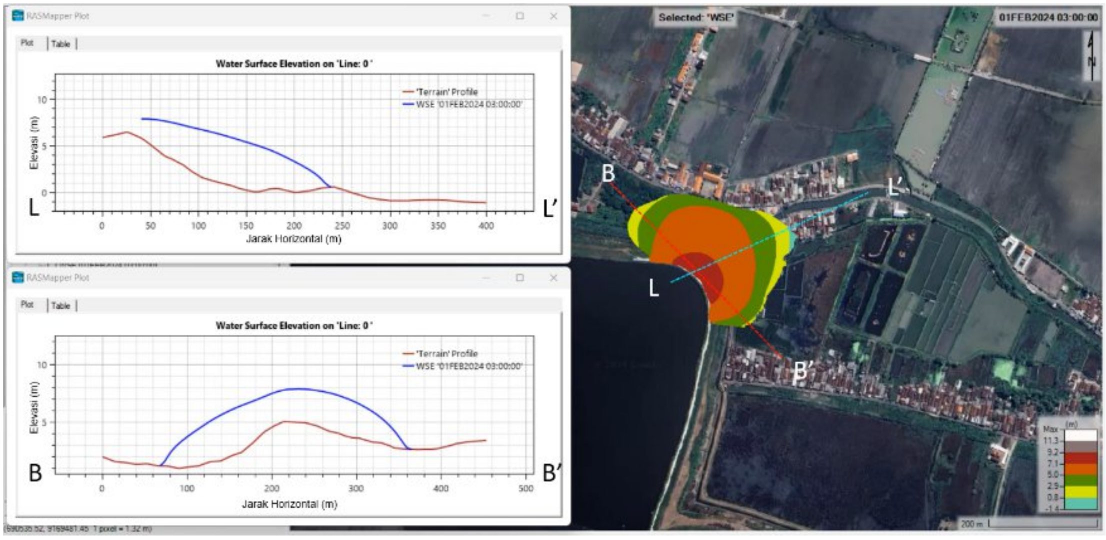
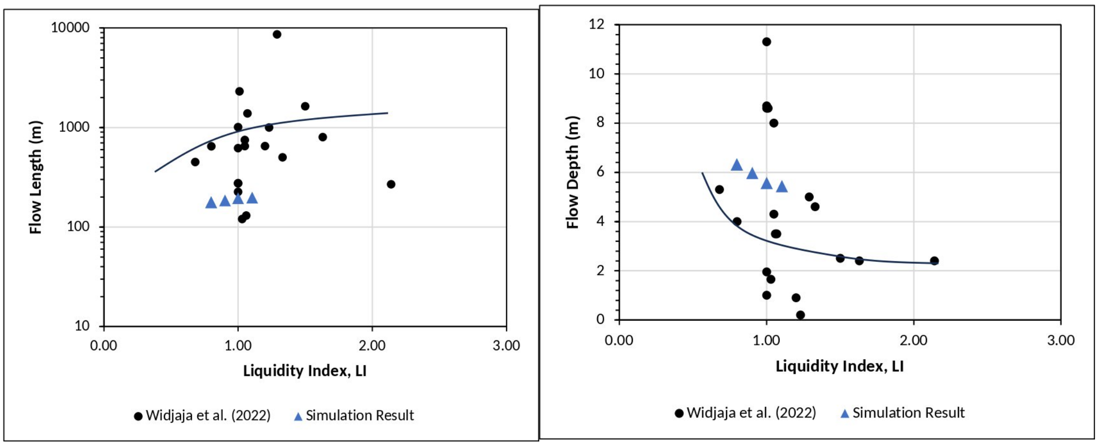


Figure 10 Example of Mud Simulation with LI 0.80 and 1.10 Results Using HEC-RAS

Table 3 Summary of Mud Flow Simulation Results Using HEC-RAS

LI	Deposition Time	Flow Distance (m)	Flow Width (m)	Maximum Depth (m)	Deposition Area (m²)
0.80	1 Hour 24 Minutes	177.20	276.45	6.32	31,704
0.90	1 hour 26 minutes	184.67	282.27	5.97	33,587
1.00	1 Hour 30 Minutes	194.71	294.38	5.57	37,040
1.10	1 hour 33 minutes	197.79	297.00	5.44	37,982
1.15	1 hour 36 minutes	200.35	301.97	5.14	38,924



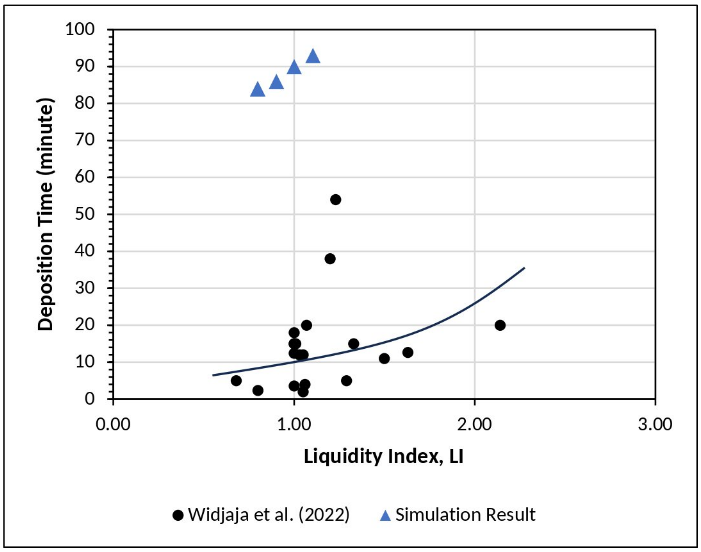


Figure 11 Comparison of simulation results with previous mudflow events

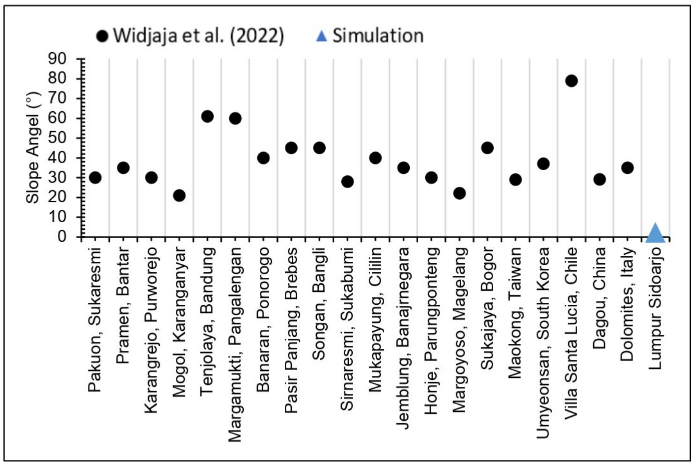


Figure 12 Topographic conditions at various mudflow locations

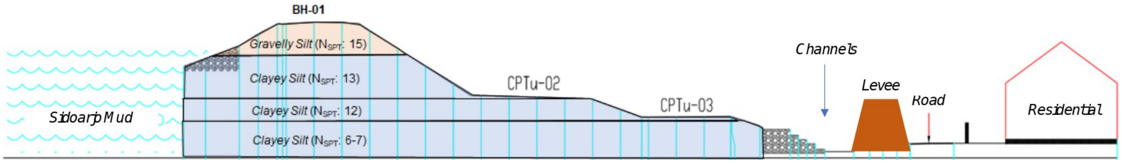


Figure 13 Mitigation Design for Dam Damage

Sensitivity and Uncertainty Analysis

From a sensitivity point of view, the change in output between LI scenarios shows a systematic response. The increase in LI from 0.80 to 1.15 increased the runout distance from 177.20 m to 200.35 m and expanded the deposition area from 31,704 m² to 38,924 m². At the same time, the maximum depth decreased from 6.32 m to 5.14 m, so that the flow was more spread over the relatively flat topography. The normalized sensitivity index is used to compare the sensitivity between metrics, i.e. S = (ΔY/Y)/(ΔP/P), with P being LI and Y being the output metric. Value |S| The larger ones indicate the output is more sensitive to parameter changes. Table 4 summarizes the relative changes and normalized sensitivities based on the simulated LI range.

Table 4 Summary of output sensitivity to LI variations

Output metrics	LI 0.80	LI 1.15	Change (%)	S Sensitivity
Flow Distance (m)	177,20	200,35	13,06	0,30
Flow Width (m)	276,45	301,97	9,23	0,21
Maximum Depth (m)	6,32	5,14	-18,67	-0,43
Deposition Area (m^2)	31.704	38.924	22,77	0,52

The deposition area showed the greatest sensitivity (S≈0.52), while the maximum depth showed the negative sensitivity (S≈-0.43). These findings are consistent with the viscous flow runout literature that places loose volume, surface roughness, and rheological parameters as the main contributors to inundation area variability and maximum depth (Ghahramani et al., 2024). In the context of embankment breaking, hydrographic breach uncertainty is seen as the most dominant because the breach parameter prediction method can have a large uncertainty distribution between formulations (Wahl, 2004). Therefore, the results in this study are interpreted as scenario-based deterministic estimates that need to be complemented by a probabilistic approach (e.g. FOSM or Monte Carlo) when the input range is available in more detail.

Discussion

The simulation results show that the value of the Liquidity Index (LI) directly affects the dynamics of the mud flow during the failure of the embankment. LI variations result in significant changes in deposition time, flow length, flow width, flow depth, and deposition area. The higher the LI value, the more liquid the sludge material will be, allowing the flow to move further and spread more widely, but the depth of the flow becomes shallower. This simultaneously expands the sludge deposition area and slows down the deposition time. The trend of mud flows that tend to turn northeast is in line with the morphological conditions of the area, where the slope of the soil leads to flow away from the embankment and towards the built area in South Kalitengah Hamlet. This situation highlights the potential threat of flooding to settlements in the event of dam failure.

These findings are in line with research by (Adesina, Dia, Dada, & Addey ,Adesina et al., 2022), which shows that increased moisture content in the sludge correlates with increased flow distance and deposition area due to decreased material cohesion. The consistent trend between the simulation results and the historical record in Figure 11 confirms that LI is a key parameter in predicting the behavior of mudslides. In addition, these results also support the findings (Baker, Baas, Malarkey, & Jacinto 2025) states that the rheological characteristics of the mud significantly determine the movement pattern of the material in sloping areas, where low viscosity increases the runout distance. Research by (Dodman et al., 2022) It also shows that areas with flat morphologies, such as Sidoarjo, tend to experience slower deposition but wider lateral spreads, which ultimately increases the potential impact on infrastructure and settlements.

The contribution of this study lies in the use of LI variation scenarios based on actual field conditions to predict the sludge flow mechanism using HEC-RAS. This approach not only provides a representative predictive model but also supports risk-based decision-making. In addition, the simulation output can be used as the basis for hazard zoning design, adaptive land use, and structural mitigation strategies through the engineering of guide channels and secondary embankments. These findings enrich the study of mud hydrodynamics by providing empirical evidence that liquidity index variation is the primary controller of flow runout patterns in flat-contoured mud extrusion areas.

However, this study still has limitations, namely the failure to formulate the results of the analysis into a detailed risk map and the failure to consider other external variables such as extreme rainfall, anthropogenic loads, and geotectonic changes. Therefore, future research is recommended to integrate hydrological-spatial modeling, land deformation modeling, and multi-hazard scenario-based risk mapping. In addition, the development of machine learning-based prediction models can be an advanced approach to improve the accuracy of mud runout projections in the event of dam damage. The integration of a permanent mitigation system with an early warning system based on pore pressure sensors is also recommended to minimize potential damage to built-up areas and ensure the safety of residents if the material overflows again in the future.

Conclusion

An increase in the Liquidity Index consistently affects the behavioral characteristics of the sludge flow, which is indicated by an increase in flow length, distribution width, and deposition area, while the depth of the flow becomes shallower and the deposition time increases. This pattern is in line with previous trends in mudflow events, thus reinforcing the validity of the tendency that material liquidity levels are the main controlling factor in flow dynamics. In addition, the influence of topography proved significant, where the flatter contours of the soil slowed down the deposition process due to a decrease in the gravitational driving force. The contribution of this research to the development of science lies in the provision of a quantitative basis for predicting the flow behavior and distribution of mud sedimentation through the parameters of the Liquidity Index and the integration of land morphological characteristics, which can be used in geotechnical modeling, earth disaster risk mitigation, spatial planning, and improved accuracy of flow simulations in the case of future mud flows. Methodologically, this study shows that the rheological variability represented by LI most strongly affects the maximum deposition area and depth. However, the uncertainty of the hydrograph breach, Manning n interpretation, and topographic resolution and numerical arrangement still have the potential to shift the magnitude of the prediction; therefore, follow-up research is recommended applying multi-parameter sensitivity tests and probabilistic quantification (e.g. FOSM or Monte Carlo) to obtain a more robust hazard range.

References

Adesina, R. B., He, Z., Dada, O. A., & Addey, C. I. (2022). Cohesiveness of the Nigerian Mahin mud coast sediment: Implications for erodibility and morphodynamic modelling. *Journal of African Earth Sciences*, *189*, 104503. https ://doi.or g/10.1016/j.jafr earsci. 2022.104503

Aghighi, M. A., & Asgari, R. (2020). Determination of low and high mud weight shear failures at borehole walls using the modified 3-D Mohr–Coulomb failure criterion. *Arabian Journal of Geosciences*, *13*(17), 884.

Baker, M. L., Baas, J. H., Malarkey, J., & Jacinto, R. S. (2025). Using Mixed-clay Sediment Gravity Flow Rheology as an Indicator for Flow Velocity and Runout Distance. *Particulate Gravity Currents: Theory, Experiments, and Environmental Applications*, 163–184. https://doi.org/10.1002/9781394216727.ch11

Barik, S. (2023). Multi-scale analysis of solute dispersion in non-Newtonian flows in a tube with wall absorption. *Physics of Fluids*, *35*(3). https://doi.org/10.1063/5.0130789

Carrière, S. R., Jongmans, D., Chambon, G., Bièvre, G., Lanson, B., Bertello, L., Berti, M., Jaboyedoff, M., Malet, J.-P., & Chambers, J. E. (2018). Rheological properties of clayey soils originating from flow-like landslides. *Landslides*, *15*(8), 1615–1630.

Dodman, D., Hayward, B., Pelling, M., Broto, V. C., Chow, W., Chu, E., Dawson, R., Khirfan, L., McPhearson, T., & Prakash, A. (2022). *Cities, Settlements and Key Infrastructure. In: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. https://doi.org/10.1017/9781009325844.008

Fatima, R., Atif, S., Fort, M., & Azmat, M. (2025). Channel morphology of the Indus, and the growing risk of floods related damages in the Indus River basin. *Natural Hazards*, 1–33.

Ghahramani, N., Adria, D. A. M., Rana, N. M., & … (2024). Analysis of Uncertainty and Sensitivity in Tailings Dam Breach-Runout Numerical Modelling. *Mine Water and the …*. https://doi.org/10.1007/s10230-024-00970-w

Gibson, S., & Sánchez, A. (2021). HEC-RAS Mud and Debris flow: user and technical reference manual v6. 1. 2021 234 J. *Ccanccapa Puma*.

Islas-Toski, M., Cuevas, E., Pérez-Cisneros, M., & Escobar, H. (2024). Agent-based evacuation modeling: Enhancing building safety in emergency scenarios. *Smart Cities*, *7*(6), 3165–3187. https://doi.org/10.3390/smartcities7060123

Kulichikhin, V. G., & Malkin, A. Y. (2022). The role of structure in polymer rheology. *Polyme rs*, *14*(6), 1262. https://doi.org/10.3390/polym14061262

Liang, Y., Long, W., Su, P., & Yang, F. (2021). Causes and treatment measures for deformation of retaining soil and slope. *Arabian Journal of Geosciences*, *14*(7), 546.

Połomski, M., & Wiatkowski, M. (2023). Impounding reservoirs, benefits and risks: A review of environmental and technical aspects of construction and operation. *Sustainability*, *15*(22), 16020. https://doi.org/10.3390/su152216020

Pusat Pengendalian Lumpur Sidoarjo (PPLS). (2018). *Penyusunan Rencana tindak Darurat (RTD)*. Kementerian Pekerjaan Umum Dan Perumahan Rakyat Direktorat Jenderal Sumber Daya Air.

Rudra, K. (2020). Combating flood and erosion in the lower ganga plain in India: Some unexplored issues. In *Disaster studies: Exploring intersectionalities in disaster discour se* (pp. 173–186). Springer.

Soliman, M., Morsy, M. M., & Radwan, H. G. (2022). Assessment of implementing land use/land cover lulc 2020-esri global maps in 2d flood modeling application. *Water*, *14*(23), 3963. https://doi.org/10.3390/w14233963

Wahl, T. L. (2004). Uncertainty of predictions of embankment dam breach parameters. *Journal of Hydraulic Engineering*. https://doi.org/10.1061/(ASCE)0733-9429 (20 04)130:5(389)

Wang, B., Zhao, Z. hai, Huang, X., Gu, G., Du, X. hua, & Yang, Y. (2024). Developmental characteristics of loess mudflow and correlation analysis with influencing factors. *Frontiers in Earth Science*, *12*, 1373126. https://doi.org/10.3389/feart.2024.1373126

Widjaja, B. (2019). Landslide and mudflow behavior case study in Indonesia: Rheology approach. *IPTEK Journal of Proceedings Series*, *3*, 93–97. https://doi.org/10.1296 2%2Fj23546026.y2019i3.5849

Widjaja, B., & Florencia, L. (2022). *Empirical Relationship To Explicate Mudflow Behaviour*.

Widjaja, B., Pratama, I. T., Hartono, I., & Limowa, B. (2024). Laboratory Study on Vallejo and Scovazzo's Methods in Estimating the Rheology Parameters of Bentonite and Kaolinite

Muds. *Civil Engineering Dimension*, *26*(1), 51–62.

Xia, B., Zheng, G., Zhou, H., & Diao, Y. (2025). Failure mechanisms and characteristics of high-filled embankments with different types of basal reinforcement. *Transportation Geotechnics*, *51*, 101528. https://doi.org/10.1016/j.trgeo.2025.101528

Yang, Z., & Cheng, X. (2024). High fill slope collapse: Stability evaluation based on finite element limit analyses. *Transportation Geotechnics*, *44*, 101156. https://doi.org/10.1016 /j.trgeo.2023.101156