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Support vector regression tree model for the embankment breaching analysis based on the Chamoli tragedy in Uttarakhand

Keywords: embankment breaching, multi-objective data, catastrophic collapses, rock-ice avalanche, Chamoli tragedy

Introduction

The degradation of earth fill or rock fill components by water flow, either over or through levee bodies or the surrounding foundation, is the primary source of wall breaches in hills and bridges. Water flow through dam bodies causes pipe or seepage failure, whereas water flow over dam bodies generates flash floods in reservoirs and accompanying exterior erosion. Overtopping, piping/seepage, slips, and other difficulties have all been identified as important causes of embankment dam failure, according to a prior investigation on the dam collapse data (Li et al., 2021). Whatever the nature of the accident factors, multiple field investigations and theoretical studies have demonstrated that the final failure mechanisms of hydraulic structures are either superior power or pipeline failure. Landslide barriers, as opposed to hydraulic constructions, are constructed quickly and are made up of a diverse mass of significant sector or rockfill parts (Donghui et al., 2016). Furthermore, in catastrophe dams,

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there are no drain zones to maintain pore pressure and no impermeable or filter sections to stop drainage flow.

Landslide waterfalls, on the other hand, typically have a large width to height ratio (representing their hydraulic gradient) and softer upstream and downstream slopes, which may reduce the likelihood of pipe and slope collapse. Upstream to downstream slope percentages of earth-filled dams are normally 1 : 1 to 1 : 2; upstream and downstream slope ratios of clay core rock-fill dams are typically 3 : 1 to 5 : 1 and 1 : 3 to 1 : 2, respectively; and cementitious face rockfill dams are typically 1 : 1.50 to 1 : 1.13 (Samela et al., 2015). The upstream and downstream slope ratio is influenced by the cohesion and friction angles of landslide dam bodies, which typically range from 1 to 3 and have higher to higher percentages than embankment dams. Overtopping failure in landslide dams is thus more common than pipeline failure (Aksoy, Kirca, Burgan & Kellecioglu, 2016).

Landslide dams, like embankment dams, can break fatally due to overtopping or pipeline failure. In this context, it is critical to emphasize that technical solutions are frequently used to reduce the danger of dam breaches once landslide dams have been formed (Khanduri, 2019). Diverting input water upstream, utilizing pumps or syphons for drainage, constructing drainage tunnels through abutments, and constructing sewage spillways through dams are all popular engineering risk reduction strategies (Xu et al., 2009). Spillway excavation, which has been shown to be an effective disaster mitigation strategy, is most commonly used to reduce the peak breach flow of large dammed lakes. As a result, while studying the dynamics causing landslide dam failures, engineering precautions should be considered (Gariano & Guzzettai, 2016). Physical model testing is the primary technical tool for evaluating the mechanisms involved in slope and landslide river flooding. The next sections (Khanduri, 2020) detail the government's breach processes for man-made and natural dams made of earthfill and rock-fill materials, where the collapse was triggered by which factor or pipe line.

The majority of people, particularly in India, are aware of the destruction in Kedarnath and the Idukki valley. This is partly due to the extensive media coverage it received as a result of the unfortunate deaths (Rautela, 2013). This tragedy, however, ravaged the whole Higher Himalayan area of Uttarakhand, from the Kali river valley in the east to the Yamuna river valley in the west, with 5 of the state's 13 districts – namely, Rudraprayag, Chamoli (Fig. 1), Uttarkashi, Bageshwar, and Pithoragarh – being affected the most.

On 7 February 2021, at around 10.45 AM, a part of the Nanda Devi Glacier in Uttarakhand's Chamoli area, near Joshimath, erupted, resulting in a deadly glacial avalanche with an embankment. It is geologically adjacent to the Main Central Thrust (MCT) in the Indian Himalaya, a seismically active and extremely vulnerable tectonic zone (Khanduri, 2017). A glacier fracture near the Raini hamlet has inun-

FIGURE 1. Chamoli tragedy affected region
Source: https://economictimes.indiatimes.com.

dated the Tapovan area of Joshimath in Uttarakhand's Chamoli district. As a result, the flash flood in the Dhauliganga, Rishi Ganga, and Alaknanda rivers is reminiscent to the 2013 Kedarnath catastrophe, which was caused by a Himalayan tsunami. The most recent tragedy resulted in multiple deaths and property damages, as well as full devastation to the Rishiganga and NTPC hydroelectric generating stations in Dhauliganga and Rishiganga. A significant portion of the enormous flood destroyed other infrastructure, such as bridges and roadways. Under the guise of Operation Jeevan, the NDRF, SDRF, and ITBP continue to carry out rescue and relief activities, saving numerous lives (Khanduri, 2021).

Background of the event

A large landslide happened on 7 February 2021, in the remote Chamoli district of northern India's Uttarakhand state. The avalanche originated on the Ronti Glacier, which is located at 79.732° E longitude and 30.3750° N latitude. Because the catastrophic flood was discovered in the middle of the day in the Rishi Ganga river, a tributary of the Ganges, it was first described to as a 'glacial' burst or glacial lake outburst flood disaster (Rana et al., 2021). As a result, the occurrence was named a rock ice avalanche. However, satellite pictures indicated that the source location is mostly made up of ice-covered bedrock, with no lake or lake burst involved. According to seismic waveform data gathered by the Indian Institute of Remote Sensing (IIRS) at Mandal and Nainital stations, the occurrence occurred about 4:52 UT (10:22 AM local time), as see in Figure 2. The vast majority of those killed or missing in the ensuing flood worked on the Tapovan-Vishnugad and Rishi Ganga hydropower projects, both of which were seriously damaged by the tragedy (Valdiya, 2014).

FIGURE 2. Outburst of avalanche of ice rock
Source: https://english.jagran.com.

Individual families of 4–5 people own land ranging from 0.3 to 0.8 ha in this area. The area's primary bio-resource is forest, which includes subtropical pine, Himalayan wet temperate forest, oak, and mixed forest types. Human and animal population growth is harming this forest cover. The presence of farming on steeper slopes (> 60°), as seen in Devpuri and Patal Kharak, indicates that population pressure has compelled people to employ unusual slopes (Rautela & Pande, 2006).

Geographical and administrative setup of Uttarakhand

Uttarakhand, India, is located in the country's northwest and became the country's 27th state in 2000, after splitting from the state of Uttar Pradesh. As seen in Figure 3, Uttarakhand shares its northern border with Tibet, its eastern border with Nepal, its southern border with Uttar Pradesh, and its western border with Himachal Pradesh. Garhwal and Kumaun are the 2 divisions of the state, each with 13 districts. Pauri Garhwal, Tehri Garhwal, Chamoli, Haridwar, Dehradun, Uttarkashi, and

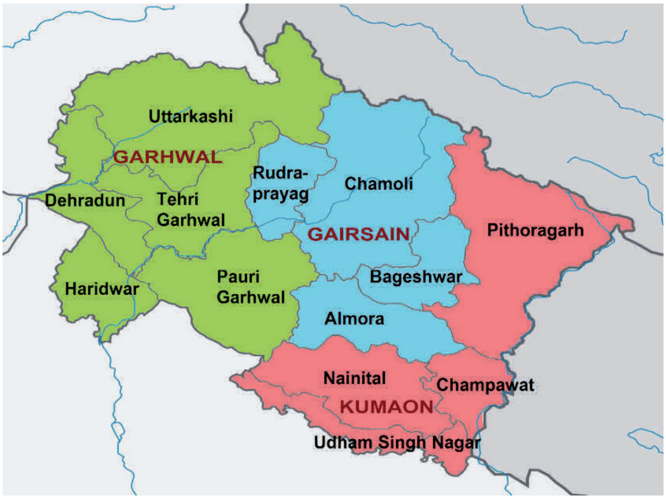

FIGURE 3. Uttaraghand landmark
Source: www.shutterstock.com.

Rudraprayag are part of the Garhwal division, whereas Almora, Bageshwar, Champawat, Nainital, Udham Singh Nagar, and Pithoragarh are part of the Kumaun division (Indian Standard [IS], 1983).

Due to its position in the middle range of the Himalayan Mountains, the state comprises 53,483 km^2 and 86.07% of its total area is classed as hilly. The lowest point is 200 m in the south and the highest point is 8,000 m in the north. Aside from political divisions, the state is split geographically as follows:
– Upper hills include Uttarkashi, Chamoli, Rudraprayag, Pithoragarh, and Bageshwar.
– Middle hills – Tehri-Garhwal, Garhwal, Almora, and Champawat, as well as the hill areas of Nainital and Dehradun's Chakrata tehsil.
– Foothills – the rest of Dehradun, Haridwar, Udham Singh Nagar, and Nainital.

Socio-economic condition

Uttarakhand has a population of 10,086,292 people and observed a population growth of 18.81% between 2001 and 2011, somewhat higher than the national average of 17.64%. Despite the state's expanding population, the average population density is 189 people per km^2, which is less than half of the national average of 382 people per km^2. This is due to a scarcity of habitable land, since forest occupies 61.91% of the territory and glacial terrain covers 13.73% (Fig. 4).

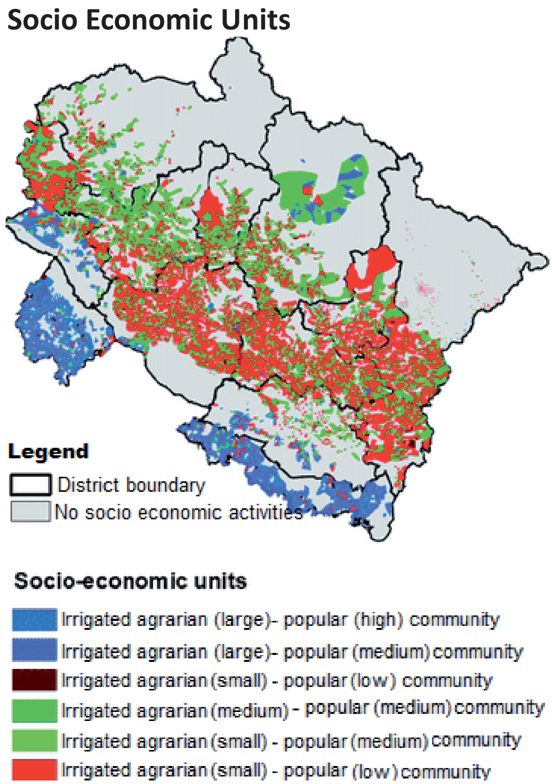

FIGURE 4. Socio-economic representation of Uttarakhand
Source: Kumar and Bhattacharjya (2020).

Because Uttarakhand is home to India's main pilgrimage circuit as well as other tourist spots, the state has a substantial floating population. As a result, tourism-related industries such as hotels and transportation are growing, and in 2012, 27 million people visited the Uttarakhand Festival of Tourism in 2013. While tourism is growing, farming, forestry, horticulture, and livestock production continue to be the key sources of revenue in Uttarakhand. Despite the difficult terrain, agriculture accounts for 21.72% of total land surface and employs 7,585% of the population (Kayal, 2010). Farmers mostly cultivate grains, and agriculture contributes for 22.41% of the state's GDP. Uttarakhand is witnessing a huge population expansion as a result of the state's demographic qualities, as well as an inflow of pilgrims and visitors. People are becoming increasingly reliant on agriculture for a living, and the tourist sector is growing.

Geological condition

While hydrological catastrophes are the most common, Uttarakhand is located in a tectonically sensitive location and has been hit by a number of seismic events in the past (Fig. 5). Between 1803 and 1999, there were 36 earthquakes with Richter magnitudes greater than 5.0, with 12 earthquakes with magnitudes larger than 6.0 occurring solely in the 21st century (Heim & Gansser, 1939). The most recent and important earthquakes, both of which caused substantial damage, were the Uttarkashi earthquake in 1991 and the Chamoli earthquake in 1999.

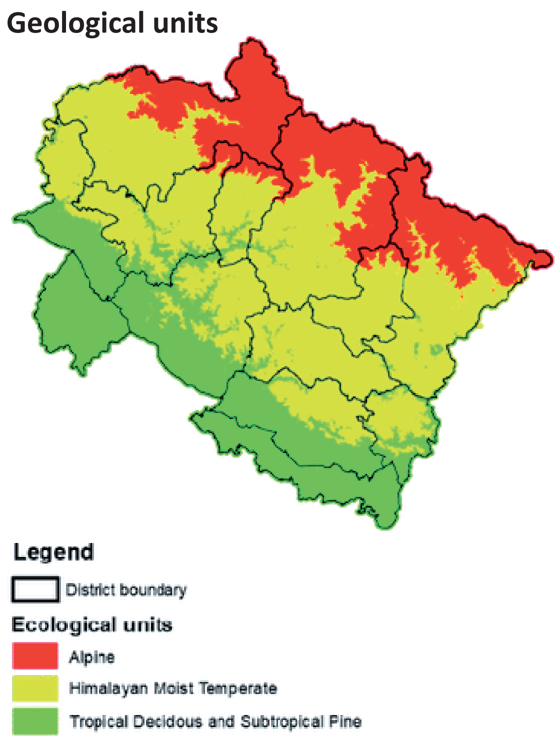

FIGURE 5. Geological condition of Uttarakhand

Source: Socio-Ecological Systems (SESs) – Identification and Spatial Mapping in the Central Himalaya.

The Uttarkashi earthquake had a magnitude of 6.6, and home collapses resulted in the loss of life. Roads and bridges were also severely destroyed, causing rescue efforts to be delayed. The Chamoli earthquake in 1999 had a Richter scale magnitude of 6.8. The earthquake damaged over 90% of the dwellings in the Chamoli district, with the majority of them being non-engineered buildings that stood after the earthquake (Valdiya, 1980). This earthquake also damaged school buildings since the roofs were composed of slate or galvanized corrugated iron and the walls were not linked to the roof, allowing them to collapse easily.

Parameters causing embankment breaching

Effect of slope

Higher embanking walls, which are always unstable, were necessary for terracing steeper slopes. The residents relocate to upslope locations that are generally considered unsafe for human settlement by any measure. This is mostly due to the lack of effective alternatives, which has led residents to neglect the terrain's fragility. Recent development efforts, especially those involving watershed management, have increased terrain deterioration.

Changes in slope gradient are a common source of landslides and other types of mass waste. A change in slope gradient alters the internal tension of the rock or soil mass, whereas a change in shear stress alters the distribution of equilibrium conditions (Fig. 6).

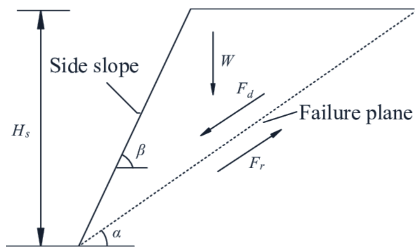

FIGURE 6. Failure plane of slope
Source: own elaboration.

Human-caused changes in slope height, on the other hand, increase shear stress and the creation of fractures in weak zones, which can become saturated with water and break, as witnessed in the Devpuri region.

Water pressure due to blockages

Water tanks and check dams were built along the channel routes above the Patal Kharak and Suri Kharak. During the disaster, debris and trees gathered on these structures, creating a larger natural barrier that hinders the flow of the canals. All of the dams burst within minutes due to increasing water pressure, resulting in a deadly flash flood downstream. Road construction is a major source of harm in the Patal Kharak and Devpuri neighborhoods. A massive quantity of debris has accumulated on the steep slopes as a result of road building, impeding streams during cloudburst occurrences and producing natural dams.

Improper drainage

According to reports, the road sides lacked adequate drainage systems. The Khansar Gad valley lacks a meteorological observatory. The sole observatory in the vicinity, Gairsain, is 15.5 km away. The Gairsain observatory reported 16 mm of rainfall on 12 July 2007, indicating that this is a rather brief occurrence. It had been pouring non-stop for over 6 h before to this incident. bedding planes or joints. The aperture of the rough joints enlarges owing to dilatation when the slide begins (Pol et al., 2022). As a result, the sliding plane works as a natural water channel. Because of poor surface drainage, infiltration rates are significant in the overburden area, creating increased pore-water pressure and restarting the slope.

Hydrostatic stress in old landslide areas

As a result of the poor hydrological conditions, secondary structural vulnerabilities in the host rocks, debris, and pre-existing slip surfaces in previous landslide zones are also reactivated. Rain and melt water penetrate rock joints, causing hydrostatic tension. Rain raises soil pore water pressure, which reduces shear resistance (Grämiger et al., 2020). The bulk of the surface layers in this area are loose, unconsolidated soils connected by Pleistocene solifluction lobes. Because clay predominates in such debris cones and terraces, they become impermeable when water penetration exceeds a critical limit as pore water pressure increases. Water rushes up the hill, bringing with it tones of dirt, rock, and other debris.

The difficulty is exacerbated by the height of the embanking wall and the outward slope of the terraces. Because of the tremendous bulk of the soil and the regular rains, these terraces have become unstable. Lithology is one of the key causes of slope instability. In the study region, quartzites produce steep slopes because they are unweathered, hard, massive, and resistant to weathering, whereas phyllites form depressions and valleys because they are prone to weathering and erosion. Older alluvium is often exceedingly compacted and durable, whereas slide debris is often loose with low shear and erosion resistance. In geology, phyllite is classified as R3 rock and is part of the moderately strong rock group The R4 grade jointed quartzite and meta-basics are classified as strong rock. Massive Kalu Kharak quartzite has an R6 classification and is considered an extremely strong rock.

Agricultural practices

Because agriculture is the primary source of income for the slope's inhabitants, there is an urgent need to create alternative agricultural practices or encourage non-land-based economic activity in this region. Landslides have been documented in a few locations as a result of a change in slope gradient induced by terrace and construction excavation. We are all aware that the mountain agricultural system cannot be seen just through the lens of field farming; significant contributions from the sectors of animal husbandry and conservation are also necessary. In this context, we also urge that suitable grazing sites be chosen in eco-fragile zones, as grazing has been shown in multiple studies to worsen soil erosion and landslide occurrences.

Cloudbursts

Cloudbursts are thunderstorms or convectional precipitation caused by the fast condensation of locally formed cumulonimbus clouds. Such events are widespread in the Higher Himalayan valley slopes, where agriculture terraces can be seen. The majority of landslides are restricted to agricultural grounds since most of the area's residents live above the destabilized landslide debris and solifluction lobes, where cultivable fields are easily prepared. Villagers are converting steep mountain slopes into geologically and structurally unsound agricultural terraces. The current study discovered that structural, lithological, and geomorphological variables all have a major impact on landslides during cloudburst occurrences. Landslides were especially prevalent in this area during the monsoon rains, as water is a significant inducer of land sliding. Land use practices and settlements have considerably contributed to the loss of lives and property in terms of man-made impacts.

Road construction

Road development has had a crucial influence in the devastating landslides. The roads in the area were poorly designed and built, resulting in slope instability and massive debris generation. Instead of maintaining the side drain, road construction personnel dumped debris and big chunks of quartzite on the gullies and steep slopes. As a result, comprehensive slope stability evaluation is critical, rubbish should be disposed of in appropriate areas, and correct drainage systems are essential since water seepage causes stability issues. Long-term solutions should involve appropriate drainage, such as culverts and hillside catch water drains. To prevent the negative effects of future cloudbursts, it is necessary to identify and analyze vulnerable areas in the region, as well as establish strategies and programs for execution.

Parameters regression analysis with support vector regression model

Using multivariate linear regression, a linear connection is formed between the response variable and one or more explanatory factors (MLR). The response variable is sometimes referred to as the 'dependent variable', whilst the descriptive variables are referred to as the 'independent variables'. Linear regression is defined as

$$y = a_0 + a_1 \cdot x_1 + a_2 \cdot x_2 + an \cdot xn + n = 1, 2, \ldots, m,$$

where y is the dependent variable, an is the model parameter, xn is the independent variable, and m is the random error component.

The MNLR methodology is a statistical method for fitting appropriate non-linear functions to collected data to maximize the determination coefficient. The connection is represented as a non-linear function between independent and dependent variables that may be used to calculate model parameters. The MNLR models can handle a variety of functions, including exponential, logarithmic, and power functions, with the power function being most suited to the dam-break scenario.

The regression tree (RT) method is then used to split the feature space and to choose the most significant features and discard the rest. Furthermore, we construct the support vector regression (SVR) model using the RT methodology's key variables as well as the RT method's prediction outputs, which are used as additional input information in the SVR input vector space. The inclusion of RT output as an input feature increases the complexity of the feature space and improves class separability. The proposed hybrid RT-SVR model's robustness is based on the selection of important features and the incorporation of RT model regression results into the SVR model. The suggested hybrid RT-SVR paradigm's informal work-flow. To train and build a decision tree model that estimates important attributes, a regression tree approach is utilized. The RT technique prediction result is employed as an extra feature in the SVR model's input feature space. To create an appropriate SVR model, the needed RT input variables are then retrieved, along with an extra input variable (RT output). The SVR approach is employed with a Gaussian kernel function for non-linear regression challenges, and regression results are reported. This technique is a two-step pipeline strategy that starts with RT feature selection and then uses SVR to increase its performance by using all of the RT algorithm's outputs in an additional analysis. Our suggested model may be utilized to identify important characteristics that will achieve a certain aim in order to address a water quality problem, as well as to estimate boiler output pH using critical causal process factors. The system was designed to address the issue of water quality, but it may also be used to manage other complicated linear systems.

The root mean square error (*RMSE*) is a statistic used to calculate the absolute difference between observed and simulated data. This statistical metric has a value between 0 and +, with lower values suggesting better simulation results. The Nash–Sutcliffe efficiency (*NSE*) (Shrestha et al., 2023) is the normal state of the least-squares error function, expressing the ratio of residual variance to data variance for evaluating the effectiveness of existing theories. The *NSE* value ranges from –1 to +1, with +1 being the best. As a result, if this value exceeds 0.5, the model performs a simulation properly. The coefficient of determination (R^2) is a model accuracy metric that shows the relationship between observed and predicted values. This index also indicates a portion of the observed value range that may be justified by simulated values. The *RMSE*, *NSE*, and R^2 indices are as follows:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{n}\left(Q_{s,i} - Q_{o,i}\right)^2},$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(Q_{s,i} - Q_{o,i}\right)^2}{\sum_{i=1}^{n}\left(Q_{o,i} - \overline{Q_o}\right)^2},$$

$$R^2 = \frac{\left[\sum_{i=1}^{n}\left(Q_{s,i} - \overline{Q_s}\right)\left(Q_{o,i} - \overline{Q_o}\right)\right]^2}{\sum_{i=1}^{n}\left(Q_{s,i} - \overline{Q_s}\right)^2 \sum_{i=1}^{n}\left(Q_{o,i} - \overline{Q_o}\right)^2},$$

where $Q_{s,i}$ is the simulated weight, $Q_{o,i}$ is the observed weight, s is the average of parameter weights, o is the average of parameter observed weights, I is the number of steps, and n is the total number of parameters in the above relationships.

Sensitivity analysis of parameters

In general, the soil erodibility coefficient (k_d) and critical shear stress can influence landslide dam breaches (c). Furthermore, for a large dammed lake, spillway excavation is recognized as an effective disaster-reduction approach. The impacts of k_d, c, and spillway excavation on the landslide dam breach were investigated using a parameter sensitivity analysis.

The soil erodibility coefficient (k_d) was multiplied by 0.5, 1.0, and 2.0 to test the model's sensitivity, while all other parameters remained fixed (Fig. 7). The sensitivity analysis findings for k_d are displayed (Fig. 8). Breach hydrographs with varied k_d*s* values were created because breach flow discharge is critical for disaster consequences.

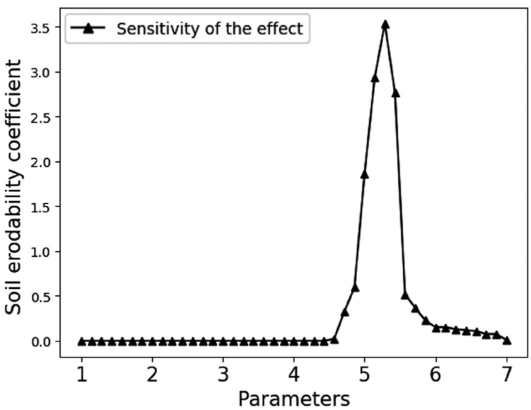

FIGURE 7. Soil erodability coefficient
Source: own elaboration.

Because the height of the landslide dam had a direct influence on the storage capacity of the dammed lake, the output parameters of peak breach flow and breach breadth rose significantly for the dam without a spillway.

However, the eventual breach size increased somewhat with increasing k_d due to the rising soil erodibility coefficient with depth and the quick attenuation of hydrodynamic conditions in the case of a big peak breach

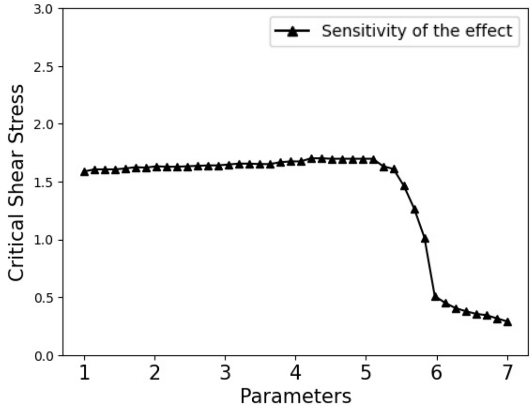

FIGURE 8. Critical shear stress

Source: own elaboration.

flow (Fig. 9). According to the sensitivity analysis results, peak breach flow and peak discharge time were more susceptible to the erodibility coefficient, but breach size was less sensitive.

Furthermore, the water overtopped the landslide dam crest for the dam without a spillway, and the time to peak discharge happened, according to the findings of numerical calculations. The dam's released water storage was approximately 784 million m^3, whereas the dam with a spillway was 615 million m^3. Furthermore, because the dam lacked a spillway, the dam breach method took less time. As a result, spillway excavation may lower the peak breach flow while concurrently increasing the elapsed time of the dam breach, which is an effective disaster mitigation strategy. As a result, for a dammed lake with a substantial reservoir capacity, spillway excavation should be the initial technical intervention.

Peak breach flow was also the most sensitive of all output parameters, fluctuating by more than 50% for different soil erodibility coefficients. As a result, selecting k_d precisely is crucial for numerical simulation of the landslide dam breach process.

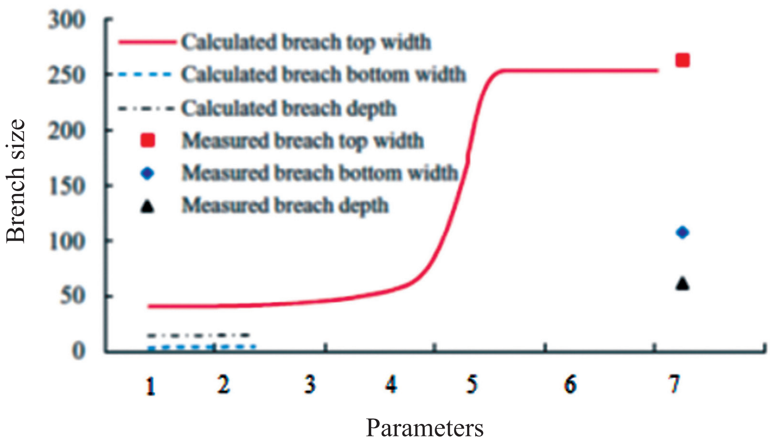

FIGURE 9. Brench size

Source: own elaboration.

The sensitivity analysis results showed that the soil erodibility coefficient had a significant influence on the landslide dam breach process, but the soil critical shear stress had a minor impact. Furthermore, early spillway excavation in dammed lakes with large reservoir capacity can considerably lower the peak flow generated by a landslide dam failure. However, given the growing rate of the water level rise and construction capacity, the spillway's construction circumstances and sectional design should be evaluated holistically.

Conclusion and discussion

Cloudbursts and other comparable occurrences have already wreaked havoc in the Uttarakhand area, where population density and construction activity have skyrocketed. Every year, floods inundate 4–5 villages in Uttarakhand, causing devastating destruction to life and property, yet we are still lacking a well-developed plan for dealing with such calamities. Landslides threaten over 300 communities in the Garhwal Himalaya, yet little is being done for preparation. Based on this research, the following recommendations have been offered for dealing with similar crises:

– The actual origin of a breach is unknown, and experts are still unable to predict the likelihood of a cloudburst occurring. The current threshold value for this occurrence is unknown. As a result, scientists will need a regional climatic-hydrological atlas in the future to establish the association between water activities and landslide activity.
– Despite the lack of awareness of the region's geographical peculiarities, several development activities are ongoing. These procedures should only be implemented after thorough expert examinations. Several regions have been identified as having extremely high hazards, necessitating the development of risk management methods for these areas.
– Some spots inside villages were discovered to be particularly safe via study, and such regions should be recognized in a village-level disaster management plan that should be considered for any future development plans.
– The most damage was seen in regions where homeowners built houses near seasonal or permanent streams. Depending on the site conditions, structures should have a minimum edge distance of 4 to 5 m. Houses should be constructed on non-erodible stratum and have an impermeable drain floor. On steep terrain, RCC-framed constructions with large plinth beams are safe. In this hilly location, a study of drainage systems, whether permanent or seasonal, is critical to lowering mortality in Devpuri-like situations.

– Overhanging boulders and overburden (thickness > 1 m) from steep slopes should be removed to reduce potential future danger.
– Planting trees native to the region with site species may increase slope stability, visual appeal, and the area's micro-ecosystem.
– Given the vulnerability of the region, the government and non-governmental organizations should work together to create a volunteer, community-based watch, monitoring, and alert system. This will be beneficial not only during a crisis, but it will also instill required self-confidence (and hence self-reliance), which is a fundamental goal of any effective recovery program. Despite major R&D operations and knowledge establishment at many institutions and universities, the transfer of expertise to user agencies remains a hurdle. User agencies may occasionally request that the institutions address specific problems. However, there is no framework in place to transmit expertise from R&D institutes to implementing agencies or to refresh knowledge. Capacity-building programs for this sort of research and information dissemination to user organizations are crucial.

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Summary

Support vector regression tree model for the embankment breaching analysis based on the Chamoli tragedy in Uttarakhand. This study used the analysis to provide considerable support of historical distortion in the Himalayan Chamoli tragedy of 2021. According to multi-objective data and survey results, a precursor event occurred in 2016, and a linear fracture grew at joint planes, suggesting that the 2021 rock ice avalanche will fail retrogressively. To analyze breaching, this study considers seven distinct criteria such as slope, water pressure, and faulty drainage, hydrostatic stress, agricultural operations, cloudbursts, and road building. Based on these characteristics, the support vector regression (SVR) model is utilized to analyze the sensitivity of the link between these parameters. The application of support vector regression analysis on the Chamoli instance confirmed our conclusion that embankment breaching causes glacier retreat and other consequences in increasing sensitivity to the characteristics of fractured rock masses in tectonically active mountain belts. Recent advances in environmental monitoring and geological monitoring systems can be used with the proposed SVR model to provide further information on the location and time of the impending catastrophic collapses in high hill regions.