# Landslide disaster risk reduction through Bioengineering at Soldha, Kangra, Himachal Pradesh - A case study

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## Abstract

Landslides is a major problem in the frontal part of the Himalayan region due to topographic variations, fragile lithology, thick overburden material, seismic activity, steep slope angle, high rate of precipitation during monsoon and anthropogenic activities. These landslides not only cause major damage to the property and life lines, but also disturb the natural fabric of the ecosystem by uprooting number of trees. Vegetation has the capability to protect the loose overburden soil by expanding their roots network and protect the soil from further erosion. The Soldha Land slide is one such zone, which had moved down slope by 30–40 m on 23rd October 2013 night after a prolonged rainfall from 15th June to 15th September 2013 and caused loss of property and ecosystem. The study of slope material shows its composition as well-graded sand and less than 30% gravels which reflected the weak and weathered condition. Since bioengineering technique is found to be very useful method in ameliorating slope stability and maintain ecological balance, therefore, the grain size and chemical analysis have been performed to understand its water holding capacity and type of nutrients and micronutrient present in the soil. The chemical parameters like pH, organic carbon, and macronutrients such as Nitrogen (N), Phosphorus (P), Potassium (K), and micronutrient Cu, Fe, Zn, and Mn present in soil have been determined from 55 samples to suggest the type of plant to be planted for reducing the further landslide risk in the region.

## Introduction

The Frontal Himalayan belt is seismically and tectonically active and subjected to a lot of erosion and deposition due to high rainfall during the monsoon season (Chandra 1992; Mahajan et al. 2010, 2022). The seismic potential of the region is well reflected in the activity along with major longitudinal and transverse features in the region which runs along and across the Himalayan range (Gansser 1964; Mahajan and Kumar 1994; Narula and Shome 1992). The highly devastating 1905 Kangra earthquake (Ms 7.8) had caused major destruction in the study region at that time. The study region is lying on the hanging wall of the Jawalamukhi Thrust, one of the splays of MBT, and several landslides zones have been identified by various authors in the region along with the MBT or its splays due to the active nature of these thrusts in this part of Himalaya (Anabalgan et al. 2008; Sharma and Mahajan 2019).

Further, neotectonic activities in Himalayan terrain due to a high level of strain accumulation due to the northward movement of Indian landmass against Eurasia, lead to an increase in slope instability along the Himalayan region. Himachal Pradesh is a hill state in the northwest Himalayan region of India and the majority of the population is residing in the frontal part of the Outer- and Lesser Himalayan regions, which are prone to landslide activities due to fragile lithology and complex tectonic regime. The presence of steep slope, slope instability, slope angle, and the inherent properties of the slope material, fragile lithology, thick overburden material above less resistant rocks, and presence of fissure zones and active tectonic thrust/faults and anthropogenic activities cause a high rate of landslide movements during monsoon season (Anbalagan 1992).

Landslides are one such natural geological hazard that causes loss of lives, property, ecosystem, environment, disruption of communication, transport, and siltation of drainage channels and reservoirs. In India, landslides affect about 15 percent of the land area every year exceeding 0.49 million km2. Natural disasters (i.e. volcanic eruptions, landslides, earthquakes, tsunamis, etc.) including those that originate from geophysical and geological reasons can occur anywhere in the world and destroy lives, property, and the environment. The loss of vegetation causes damage to the carbon pool and can have global significance in climate change directly or indirectly. The Landslide susceptibility map (LSM) generated from the Analytic Hierarchy Process (AHP) method with 76.77% landslide prediction efficiency for this region can be used for planning future developmental sites by the area administration along with bioengineering mitigation methods (Sharma and Mahajan 2018).

During the landslide movement, a huge amount of debris, small and big boulders moves downslope and are being deposited or fanning out near the toe area or sometimes blocking the river systems/roads and agricultural land.

The present study is focused on the Soldha slide zone which is situated in Niangal village near Mandi-Pathankot national highway no. 20 in district Kangra, Himachal Pradesh, India. This location falls on a survey of India toposheet no. 52D/3 between 32° 15' 04"N Latitude and 76° 04' 30"E Longitude (Fig. 1). This area falls under the Brahl or Bhed Khad in district Kangra from where the local tributaries drain the Beas river basin. The Soldha landslide zone is 0.78 km long along the displaced hillock and covers an area of 0.25 km2 with an altitudinal variation from 715 m at the toe to 977 m at the scarp zone. The slope gradient measured along sections 'a-b' (see inset picture) of landslides zones ranges between 977 (top), 815m (middle), and 715 m (bottom) of a landslip (Fig. 2; also see Mahajan et al. 2022).

This slide zone falls in the sub-humid regime of the Kangra region where maximum rainfall occurs in the monsoon season i.e. July to September with annual precipitation up to 1751 mm as per the groundwater information booklet for district Kangra. According to the rainfall data from NRSA, the area has witnessed excessive rainfall from August 2013 and 7th October 2013 with a maximum rainfall of 80 mm in a day, which led to the failure of this slide zone in October 2013 (Fig. 3).

To decrease the risks associated with pre-and post-landslides, it is important to map landslide-prone areas and take up necessary mitigation measures like physio-mechanical engineering (geotechnical) or bio-engineering measures depending on the lithology, slope, and its importance such as crating of slopes soil, applying retaining wall, etc. If the appropriate measure will not be applied which are depending on the slope, material involved in areas of slide activity, and soil parameters; then there may be damage to the property and ecosystem and the environment in general.

Considering the slide zone location and material involved, the extent and location of the slide zones, it is important to protect the slopes from surface tension and to reduce the risk of further sliding. Therefore, the chemical analysis of the soil has been performed to know the types of plantation to be planted to save the slide zone from further movement and improve the growth, and in turn help in maintaining the ecosystem.

Although bioengineering has been in use for a long time, however, understanding the factor that influences the effectiveness of the applications are important, like geology of the study area, grain size, type of soil, slope of the slide zone, porosity of the soil, climatic conditions and nutrients of the soil for appropriate implementation of bioengineering applications (Raut and Gudmestad 2017; Vashistha et al 2011).

## Geological Set Up And Field Observations

Geologically, the study area is bounded by several longitudinal thrusts running in the northwest-south-eastern direction. Figure-4 shows the tectonic setup along with seismic activity in the region and reflects the active nature of the fault. The Soldha slide zone is lying on the hanging wall of the Jawalamukhi Thrust separating Middle Siwalik sandstone to the north from Upper Siwalik Conglomerates to the south. The landslip area forms the part of Middle Siwalik Sandstone with Clay intercalations and most of the surface of the slide zones comprises rock fragments of buff-coloured sandstone and intercalation of clay stones. The slopes are mainly south facing and the southern part of the slide zone is covered with debris material derived from the first and second detachment zones of the slide.

The Soldha slide was triggered on 22nd October 2013 night and has completely devastated the agricultural, residential, and forest land. The slides zone had developed land fissures and cracks in the residential houses which allowed them to understand that slide is about to move and thus they vacated the houses; saving the lives of so many residents of the areas. Around 3 AM on 23rd October 2013, a massive mass movement had occurred as per reports from residents and developed deep crevasse in the topsoil trending N80E and S80W. This facilitated the downward movement of the huge chunks of topsoil and rocks along with houses and agricultural fields, trees, etc. (Fig. 5).

The impact of this movement was so intense that the houses, trees, and agricultural land were shifted to about 40–60 m away from their original positions (Fig. 6). Concomitant to this movement, evidence of massive subsidence occurring is also reported. Along with this event, the comparatively highly sloping terrain of the adjoining hilly area comprising of more indurated sandstone sliced out and developed a prominent scarp in a semi-circular fashion, which is still visible from a considerable distance (Fig. 5). After about an hour, a second event took place on a higher elevation and developed another scarp just upstream of the previous one, which resulted in a large scale damage of the forest land and threatened to the houses on the right side (Fig. 5), and the direction of this movement seems to be almost perpendicular to the previous movement.

The debris of this mass movement resulted in the development of new depressions and localized drainage patterns (Fig. 6). However, one thing is significant that the direction of this large mass movement had not remained one-directional probably due to the undulatory nature of mobilization resulting in the development of the large-scale crevasses and displacements along the agriculture terraces (Fig. 6b). The whole displaced mass has come to stand still at the contact margins of the thrust running in the area. This may be due to the fact the change in lithology along the thrust has acted as a barrier to the moving mass of soils and rocks. The local stream has completely changed its course by about 40 m from its original course and does not exist presently (Fig. 6d). The water of the stream is now dammed because of the shift in drainage pattern downstream as there is no further outlet available for clearance of the pounded water, and later on, a small outlet path was created for its clearance. At the contact margins of the thrust, the development of localized perched aquifers is another observation observed in the field after the event now.

# Grain Size Analysis

The soil samples from different parts of the slope material were collected from the Soldha slide zone for grain size analysis as shown in Fig. 7. The analysis was performed from the samples collected from various locations of the slope material procured using field methods by digging the top material up to a depth of 2 to 3 m. To perform the grain size analysis sieve shaker with sieves of different sizes (0.075 mm to 4.75 mm) as per Indian Standard (IS- 2720 part 4-1985) have been used. The result shows that 60 to almost 90% soils have sandy composition from the scarp region, whereas overall slope material shows 14–37% gravel percentage (Table-1). The silt and clay have very little composition on the surface, but the percentage of fine silt + clay is 0.2 to 9% as per grain size analysis, which settles down and makes the soil impermeable at depth and the topsoil is sandy in a highly porous composition.

The middle to the lower part of the slide zone has fine soil composition, which is also reflected from the filed photographs (Figs. 5 and 6). The analysis of the soil sample for the Soldha landslide indicates that soil falls in the 'SW' classification, which signifies well-graded sand with little fines and more than 15% gravels according to Indian Standard (IS – 1498–1970). It is represented by a wide range of particle distribution ranging from sandy to gravel composition, which has indicated toward high weathering and brecciated slope material near the thrust contact (Middle Siwalik Sandstone and Clay) plus the weathering from the fluvial processes in a watershed area with high drainage density with the presence of several gullies.

Table 1
Grain size analysis of the slope material from Soldha Landslide

| Grain size Sample (SLS) | Composition | | | Cu (Coefficient of Uniformity) | Cc (Coefficient of Curvature) |
|---|---|---|---|---|---|
| | Gravel (%) | Sand (%) | Silt + Clay (%) | | |
| SLS-1 | 29.8 | 69.8 | 0.4 | 11.7 | 1.01 |
| SLS-2 | 3.8 | 92.2 | 4 | 28.0 | 2.29 |
| SLS-3 | 26.2 | 73.6 | 0.2 | 11.8 | 1.02 |
| SLS-4 | 30.4 | 69.1 | 0.5 | 11.5 | 1.35 |
| SLS-5 | 28.2 | 71.5 | 0.3 | 9.0 | 1.0 |
| SLS-6 | 26.3 | 73.3 | 0.4 | 7.7 | 1.06 |
| SLS-7 | 26.2 | 71.4 | 2.4 | 12.5 | 1.36 |
| SLS-8 | 37.5 | 60.87 | 1.63 | 14.8 | 1.29 |
| SLS-9 | 14.2 | 76.6 | 9.2 | 7.5 | 1.28 |
| SLS-10 | 26 | 72.6 | 1.4 | 8.3 | 1.01 |
| SLS-11 | 27.2 | 66.8 | 6 | 43.1 | 2.32 |

# Mitigation Measures Using Bioengineering

The Himalayan ecosystem has inherent property to recover itself from natural and manmade damage. The numbers of shrubs and small plants have already grown in the slide region since 2013 and vegetative growth not only increases the soil resistance to further movement, but also absorbs excess water from the soil. Since the soil is sandy in nature, the increase in vegetative growth will also help in changing the soil characteristic from sandy to loamy soil. Numbers of field studies have indicated the use of bioengineering application in stabilisation of the slope being cost effective and its effectiveness in preventing soil from further erosion and arresting mass movements (White, 1979; Raut and Gudmestad 2017; Singh et al. 2002; Lammeranner 2005; Vashistha et al 2011; Steinacher 2009; Lan 2020).

The grain size analysis reveals that the soil is sandy in nature and the subsurface bedrock is sandstone and most of the precipitation goes inside the slide body due to less water holding capacity of the soil. It is important to have plantation which can significantly increase the water holding capacity at the surface and contribute to maintain the slope stability. The shear strength of the soil can be increased by transferring the shear stress in to the soil to tensile resistance in the roots (Varnes, 1984, Gyssels 2005; Vashistha et al 2011). The shear strength of the soil gets increased by mycorrhizal fungi networks of plant roots and ground suction or reduced pore water pressure due to evapotranspiration. The plant root's mycorrhizal fungi networks help in root-soil binding and also supply nutrients to plants for their growth, thus increasing the soil stability.

Therefore species having fast growth having acclimatisation with the local environment with potential root system have been suggested to protect the slope. Trees through interception, infiltration, evaporation, storage, leaf drip, pool formation, water uptake, and transpiration regulate surface erosion. Furthermore, evapotranspiration reduces not only the moisture content but also the weight of the soil mass and helps in the stabilization of landslips. In order to understand the type of the plant to be planted which can increase the resistance of the soil and water holding capacity of the soil, a chemical analysis of the soil has been performed by taking 55 samples from different parts of the slide body.

# Chemical Analysis Of Soil

The chemical analysis of the soil always stands helpful to understand the qualitative characteristics of the soil, which is essential to monitor before recommendation of particular plant species for any region. The plants have capability to mark decent growth based on soil parameters in sufficient concentration apart from the suitable environmental conditions, otherwise plant growth is generally reduced. The bioengineering method to a major extent relies on the soil chemistry associated with the different soil parameters. Therefore, soil pH, organic carbon, and macronutrients such as Nitrogen (N), Phosphorus (P), Potassium (K), and micronutrient Cu, Fe, Zn, and Mn present in soil have been determined from 55 samples collected from the slide body to suggest planting of different species to avoid future landslide risks in the region (Fig. 7). The methodology of chemical analysis of soil samples is as under for each parameter.

# Soil Ph

The pH represents the negative logarithms of $H^+$ in a solution. The soil sample solution was prepared with distilled water in the ratio of 2.5:1 (soil: water) and thereafter the pH of all the samples was recorded through a calibrated pH meter with standard solutions (pH 4 and 9).

## Soil Organic Carbon

The organic carbon from the soil samples was determined using the Walkley and Black Wet digestion method, which defines the chromic acid reduction by the presence of organic matter and was carried out to measure the content of unreduced chromic acid. The soil samples were treated with sulphuric acid and kept at 120°C to oxidize the organic carbon. Back titration of potassium dichromate ($K_2Cr_2O_7$) was done with ferrous ammonium sulfate [$(NH_4)_2SO_4.FeSO_4.6H_2O$)] standard solution in presence of diphenylamine and phosphoric acid ($H_3PO_4$) to make a distinct colour in the solution. At that point of change of colour during titration from violet to bright green, the volume of ferrous ammonium sulfate used was recorded from the burette.

## Nitrogen

The presence of nitrogen from the soil samples (20 g each) was known through the alkaline potassium permanganate method in which potassium permanganate ($KMnO_4$) was used to extract nitrogen fraction from the organic nitrogen. Firstly, the samples were wrapped in Kjeldahl's distillation flask and moistened using distilled water. In a conical flask, 25 ml of boric acid solution (2%) was taken and the end of the delivery tube of the distillation flask was carefully dipped in it. Then, 100 ml 2.5% sodium hydroxide (NaOH) and 100 ml 0.32 $KMnO_4$ were added to the distillation flask, and to avoid loss of ammonia gas, a cork was fitted well. Finally, the boric acid solution that contained ammonia was titrated against the $H_2SO_4$ (0.02N) and the colour changed from bluish-red to pinkish-red was recorded as an end point.

## Phosphorus

The ascorbic acid reductant method was used for the determination of phosphorus from the soil samples collected from the Soldha Landslide region. This method defines the reduction of ammonium phosphomolybdate [$(NH_4)_3$ $PO_4.12MoO_3$] complex by ascorbic acid ($C_6H_8O_6$) in the presence of antimony potassium tartrate [$K(SbO)C_4H_4O_6.1/2H_2O$] (also see Kumar et al. 2019; Kumar and Mahajan 2020). Firstly, to prepare the stock solution, a 12 g ammonium molybdate was dissolved in 250 ml distilled water and in it, a 290.8 mg [$K(SbO)C_4H_4O_6.1/2H_2O$] solution prepared with 100 ml distilled water was added. In that solution, 1 litre of 5 N $H_2SO_4$ was also added and the final volume was thus fixed to 2 litres using distilled water. Then, 200 ml of 1.056 g of L-ascorbic acid was prepared and added to the stock solution and labelled as a mixed reagent.

Thereafter, a 1 g of soil sample was taken in a 100 ml plastic bottle and 20 ml bicarbonate extract, which was prepared 1 litre in volume using a 42 g sodium carbonate and distilled water. Further, 1 g of Darco-G-60 was also added and content was kept on an orbital shaker for 30 minutes. The process was followed by taking 5 ml of bicarbonate extracts (0.5N $NaHCO_3$; pH 8.5), in a standard flask, and volume was adjusted to 10 ml. Then the 5 ml of mixed reagent was added to it and the per cent transmission was determined using calibrated colorimeter at 882 nm.

## Potassium

A 5 g soil sample was taken and 50 ml of 1 N sodium acetate ($NH_4OAc$) was added to it. The content was kept undisturbed for 15 minutes and then placed on an orbital shaker for 5 minutes. Then, the content was filtered using Whatman No.-1 filter paper. The instrument Flame Photometer was firstly calibrated and then all the prepared samples were run one by one. The readings were recorded and the final concentration of potassium from the samples was calculated in kg/ha.

## Micronutrients

Generally, micronutrients are available in very minute concentrations in soil. Their determination from the soil samples of the Soldha Landslide region was done using Diethylene Triamine Penta-acetic Acid (DTPA) method and the instrument Atomic Absorption Spectrophotometer (AAS). The DTPA method was used to extract copper (Cu), iron (Fe), zinc (Zn), and manganese (Mn) from the soil samples using 0.005 M DTPA, 0.1 M triethanolamine (TEA), and 0.01 M calcium chloride dihydrate ($CaCl_2.2H_2O$). To prepare samples, a 1.967 g DTPA and 14.92 g TEA were weighed and mixed in a beaker using 200 ml distilled water. A solution of 1.47 g of $CaCl_2.2H_2O$ in 200 ml distilled water was also prepared. Thereafter, both these solutions were mixed and adding further distilled water, the final volume was adjusted to 1 litre. The pH of the solution was adjusted to 7.3 by adding 1N HCl. The instrument AAS was calibrated and then micronutrients concentration in the samples was determined.

## Soil Parameters Spatial Dependency

The spatial dependency of the soil parameters such as OC, N, P, K, Cu, Fe, Mn, and Zn were understood via the semivariogram derived using ArcGIS 10.1 software. The semivariogram is based on the eqn-1 that describes mean square variability among sampling points located near to each other and having a distance 'h' (Wang et al. 2013; Kumar et al. 2021).

$$\gamma(h) = \frac{1}{2m(h)} \sum_{i=1}^{m(h)} [Z(X_i + h) - Z(X_i)]^2 \quad \ldots\ldots\ldots\ldots\ldots [1]$$

Where, Z(Xi + h) marks the value of sampling points at two different locations (i.e. Xi and Xi + h), whereas m(h) represents the pairs of observation separated by Z(Xi). Further, the Exponential model (eqn-2) and Gaussian model (eqn-3) were used to check the degree of spatial variability as (see Kumar et al. 2021):

$$\gamma(h) = C_0 + C\left[1 - exp\left(\frac{-h}{A_0}\right)\right] \ldots\ldots\ldots\ldots\ldots [2]$$

$$\gamma(h) = C_0 + C\left[1 - exp\left(\frac{-h^2}{A_0^2}\right)\right] \ldots\ldots\ldots\ldots\ldots [3]$$

Where, h represent lag interval, C and C0 mark structural (≥ C0) and nugget variance (≤ 0), respectively, while the range (degree) parameters are indicated by 'A' (Reza et al. 2019).

## Results And Mitigation Measures

Landslides can be prevented using direct and indirect mitigation measures There are two types of landslide prevention techniques: direct and indirect. The direct methods are like retaining and anchoring walls, restraining piles, alleviating pressure by excavation, restoration of slopes using reinforced earth, and rock reinforcement, whereas the erosion control strategies, as well as improvements in surface and sub-surface drainage, are examples of indirect methods. In this study, the potential of bioengineering measures to control the erosion have been envisaged. To identify the plants to be planted for controlling the erosion as well as to retain landmass from further movement downslope, the subsoil chemical properties, depth of the slip surface and lithology has been determined using the geological and geophysical methods.

The grain size analysis of the slope material revealed that sand (60.87 to 92.20%) is the major constituent; followed by gravel (14 to 37%) and silt + clay (0.2 to 9%). This signifies that the slope material is composed of well-graded sand with little fines and more than 15% gravels according to Indian Standard (IS-1498-1970). The Coefficient of Uniformity and Coefficient of Curvature significance ranged 7.5–43.1 and 1.0- 2.32, respectively. The soils are sandy with soil organic carbon content ranging between 0.25 to 0.40%, indicating deficient in humus and related soil microbes.

The soil pH in a range of 8.1 to 10.3 indicated the alkaline nature of soils. The soil nutrient analysis revealed that increasing trend for N and decreasing trend for K, Fe, and Zn from top to bottom of the landslip zones. Alkaline soil has characteristics of deficient microbial activity and low availability of plant nutrients. Soil analysis revealed low soil organic carbon, low phosphorus (P) and manganese (Mn), and high Copper (Cu) content. Soil organic carbon content is below 1%, available soil nitrogen (31.36 to 95.44 kg/ha) and Phosphorus (3.57 to 39.06 kg/ha), which indicate that the soil quality is poor in nature. Low manganese (4.82 to 5.52 ppm) and high copper (1.43 to 6.02 ppm) and iron (150 to 617 ppm) content indicate the occurrence of non-saline alkali soils.

The Soldha area is an active landslide zone due to tectonic activity and warrants for landslide disaster risk reduction to avoid recurrent loss of property and life. Bioengineering has the potential to reduce landslide disaster risk and it is a low cost and eco-friendly technique as compared to other civil engineering measures. Vegetation is the basic ingredient of bioengineering and warrants for choice of plant species based on edaphic climatic conditions of landslide area to be treated, slope gradient, the severity of landslide, etc. Further, different landslide zones like depletion and accumulation zones, partially stabilized landslide zones warrant different approaches for risk reduction. The best fit models for the observed soil parameters are found to be Exponential (N, P, Fe, and Zn) and Gaussian (OC, K, Cu, and Mn) (see Fig. 8; Table-2), which are also identified by Reza et al. (2019) for Tinsukia, Assam, India. The spatial dependency among various soil parameters is found to be strong (N, P, Cu, Fe, and Zn) moderate (K and Mn), and weak (OC). Kumar et al. (2021) in their study of another region also had indicated three types of spatial dependency among the same parameters.

# Bioengineering Approach For Landslide Depletion Zone

The area within which the displaced material lies below the original ground surface is usually denuded, exposed, and steep. The mulch treatment is amongst the techniques of establishing a vegetative cover and checking erosion leading to its stabilization. The plantation of grasses and shrubs on these denuded slopes, the exposed face of the loose soil and the waterlogged area may help in arresting the surface erosion and adding organic matter to the soil. Seed broadcasting of local native trees, shrubs, herbs, grasses, and climbers' species before the onset of monsoons will also help in the management of landslips through increased vegetation cover and maximizing water use before it reaches the slip surface. The slope area can be prepared into vast seedbeds by rounding off the tops, regarding or reshaping, and finally raking the topsoil about 20 mm thick for mulch treatment.

Table 2
Semivariogram and model characteristics of different soil parameters

| Parameter | Model | Nugget ($C_0$) | Partial sill (C) | Sill ($C_0$ + C) | Nugget/Sill (%) | Spatial dependency class | Root mean square error |
|---|---|---|---|---|---|---|---|
| OC | Gaussian | 0.059 | 0.01 | 0.1 | 85.51 | Week | 0.257 |
| N | Exponential | 455.5 | 1494.1 | 1949.6 | 23.36 | Strong | 42.01 |
| P | Exponential | 0.03 | 83.41 | 83.4 | 0.04 | Strong | 8.56 |
| K | Gaussian | 8726.7 | 3396.1 | 12122.8 | 71.99 | Moderate | 101.3 |
| Cu | Gaussian | 0.158 | 1.984 | 2.1 | 7.38 | Strong | 1.41 |
| Fe | Exponential | 0.51 | 19987 | 19987.0 | 0.003 | Strong | 103.7 |
| Mn | Gaussian | 0.016 | 0.026 | 0.0 | 38.10 | Moderate | 0.167 |
| Zn | Exponential | 0.03 | 2.24 | 2.3 | 1.32 | Strong | 0.19 |

Locally available grass seeds and root slips should be dibbled 150 to 200 mm apart from each root and row. The natural mulch of locally available leaves, twigs, branches from nearby vegetation, straws, agricultural wastes, etc., can be sprayed to cover nutrient deficit landslide, minimize the evaporation, enhance moisture absorption capacity and protect the topsoil layer against the beating action of raindrops. It is necessary to spread the seed at a rate of 5 kg per acre or to dibble the root slips of locally available grasses almost 150 mm apart and row to row and plant to plant. By performing such action, soil erosion can be avoided during rainfall, and the risk of seeds and nutrients being swept away with the topsoil can be minimised. As a result, vegetation quickly establishes itself and spreads to cover the entire hillside.

## Bioengineering Approach For Landslide Accumulation Zone

**The area mainly comprises displaced rock fragments and loose boulders, gravels and soil above the bedrock material. The planting of cuttings/plantlets of easy to root local native species of Agave, Lannia, Ipomeia, Jatropha, Anthrocephalus, Erythrina, etc., at the downhill side can be helpful in protecting the slide areas from further gullies erosion. The deep-rooted trees in the slide zones have different effects on the slope stability at different slope angles. After stabilization of landslip through grasses, and shrubs, the local native tree seedlings are to be planted along the contour of the landslide to protect the soil from the adverse effect of rainfall.**

**The tree plantation at a slope angle of 20 and 35° has a good reinforcement effect as compared to the slope angle of 50 to 60°. According to Lan et al. (2020), the slope angle of 20–35° is very effective to intercept sediments, inhibit sediment slide and prevent collapse. Since the slide is highly porous fine clay and silt are being deposited at depth near the slip surface, it is important to increase the water-holding capacity of the soil on the top by planting those particular species which could achieve the target very well. Secondly, the deep-rooted plant will decrease the water content, which is being increased at the slip surface due to the porous nature of the topsoil. The list of species to be planted at different zone of the slide zones is listed in Table-3.**

Table 3
List of plant species suggested for planting at Soldha Landslide

| Sr. no. | Botanical name | Local name | Sr. no. | Botanical name | Local name |
|---|---|---|---|---|---|
| A. Grass species | | | 21 | *Terminalia bellirica* | Behada |
| 1 | *Eulaliopsis binata* | Bhabar, Bagar | 22 | *Phyllanthus emblica* | Amla |
| 2 | *Hetropogon contortus* | Lambu | 23 | *Pinus roxburghi* | Chir Pine |
| 3 | *Sorghum nitidum* | Lunji | 24 | *Morus alba* | Mulberry |
| 4 | *Cenchrus purpureus* | Napier | 25 | *Ficus roxburghi* | Trimbal |
| 5 | *Cynodon dactylon* | Dhoob | 26 | *Diospyros melanoxylon* | Kendu |
| 6 | *Tripidium bengalense* | Munj | 27 | *Grewia optiva* | Beul |
| 7 | *Dendrocalamus strictus* | Bamboo | 28 | *Pyrus pashia* | Kainth |
| B. Tree species | | | 29 | *Acacia catechu* | Khair |
| 1 | *Bauhinia variegata* | Kachnar, Karal | 30 | *Cassia fistula* | Kener |
| 2 | *Terminalia bellirica* | Bahera | 31 | *Celtis australis* | Khidak |
| 3 | *Cordia dichotoma* | Lasura | 32 | *Pistacia integerrrima* | Kaakarasingi |
| 4 | *Butea monosperma* | Dhak, Plah | 33 | *Toona ciliata* | Toon |
| 5 | *Dalbergia sissoo* | ShishamTali | 34 | *Melia azadirachta* | Derech |

| Sr. no. | Botanical name | Local name | Sr. no. | Botanical name | Local name |
|---|---|---|---|---|---|
| 6 | *Acacia nilotica* | Kikar | C. Shrub species | | |
| 7 | *Albizia lebbeck* | Siris, Sarin | 1 | *Vitex negundo* | Bana |
| 8 | *Albizia procera* | Siris | 2 | *Dodonaea viscosa* | Maindhor |
| 9 | *Morus alba* | Tut | 3 | *Punica granatum* | Anar, Doran |
| 10 | *Syzygium cumini* | Jaman | 4 | *Zizyphus jujuba* | Ber |
| 11 | *Tamarandus indica* | Imli | 5 | *Agave americana* | Ram ban |
| 12 | *Terminalia arjuna* | Arjun | 6 | *Flemingia semialata* | Bara Solpan |
| 13 | *Azadrichta indica* | Neem | 7 | *Opuntia ficus india* | Kaiktus |
| 14 | *Prosopis juliflora* | Khehri | 8 | *Adhatoda vasica* | Basuti |
| 15 | *Moringa olifera* | SananSuhanjua | 9 | *Carissa carandas* | Karonda |
| 16 | *Bombex ceiba* | Semul | 10 | *Lawsonia inermis* | Hina |
| 17 | *Sesbania sesban* | Jayantika | 11 | *Muraya cunningham* | Curry Leaves |
| 18 | *Wendlandia grandis* | Panshera | 12 | *Berberis aristata* | Chitra |
| 19 | *Mallotus philippines* | Kamala Tree | 13 | *Ipomea fistula* | Morning Glory |
| 20 | *Lannea coromandelica* | Indian Ash Tree | 14 | *Woodfordia fruticosa* | Dhawi |

## Discussion And Conclusion

Considering the location of the slide zones along the thrust boundary and triggering factors i.e. seismicity and rainfall, the chances of slope and creep movement is inevitable and that had also increased during 2013. The slope geometry determined by Mahajan et al., (2022) indicated the degree of weathering and brecciating of sandstone and clay stones of the Middle Siwalik Formation where most of the material is weathered broken and sandy in nature. Field survey indicated high drainage density with higher value of hypsometric intervals indicating ongoing geomorphological adjustments to achieve a stability of the region (Mahajan et al. 2022). The loose sandy topsoil has the capacity to infiltrate rainwater down to the slip surface. Thus to arrest further infiltration of water to the slip surface and decreasing the pore spaces, it is important to understand such mitigation measures which can lead to increasing the water holding capacity of the soil.

Therefore mitigation of slide using bioengineering application has been proposed in the study considering all factor mentioned above. The main advantage of bioengineering application in slope stability and slope protection is that it can control both soil and water saturation of soil and help in binding the soil. The chemical parameters determined from soil samples indicated the soil suitable for plant species to root in the region. The spatial dependency among various soil parameters is found to be strong (N, P, Cu, Fe, and Zn) moderate (K and Mn), and weak (OC) that may be due to their different sources. The foliage does not allow the direct precipitation on the soil; thus protects the soil from runoff and arrests slope movement. As the Soldha slide zone is sandy in nature where whole of the precipitation percolate down to the slip surface and allow the landmass to move, but increasing plantation will promote the water holding capacity of the soil by mixing with the bio-organic material of the plants and mycorrhizal fungi networks of plant roots and also reduced pore water pressure due to evapotranspiration. Bioengineering application will change the landscape of the slide and thus environmentally viable to maintain the ecosystem of the region. The efforts will also be a regulating factor in increasing the carbon pool and thus directly or indirectly help in the global warming mitigation efforts. Since the vegetation will depends upon soil properties, lithology of the region, soil type, climatic conditions and altitude; it is important to choose native vegetation for stabilisation of slopes which grow fast in the region. If the vegetation will be properly planted and maintained, it can protect the slope, increase the water holding capacity and in turn also increase the water level of the region with the time and theses plantation will not need much efforts and cost. The naturally regenerated seedlings/root slips/cuttings of trees, shrubs, and grasses from nearby forests help in the early re-vegetation of the landslips. The pioneer invasive species like *Ageratum conzoides*, *Eupatorium*, *Lantana camara*, among others, which colonizes the disturbed sites like landslips naturally through seed dispersal by wind, water, animal and soil seed bank should be allowed to complete their life cycle as they help in adding organic matter in soil and their roots bind the soil. Mulching with leaves, litter, twigs, branches, and agricultural waste as a cover to landslide is suggested. Belly benching with cuttings of Moringa, Morus, Vitex, Agave, Lannia, Ipomoea, Jatropha, Anthrocephalus, and Erythrina on the slide is also suggested. Among the suggested species, grasses can be planted in the intimate mix through earth balls/seed broadcasting/slip planting initially; followed by planting of shrubs and trees in contour trenches through direct seed sowing by dibbling or broadcasting or in deep pits backfilled by non-alkaline soils and soil amendments (FYM or any suitable amendment) of the nursery raised seedlings and root slips of grasses.

Since the surface soil mass is sandy in nature and is highly porous in state; thus in order to increase the water holding capacity of the soil on the surface, there is a needs to plant grasses and legumes which will help in soil binding, adding soil organic matter, and improving soil water retention, and make the site suitable for colonization of shrubs and trees. This will also help to reduce the infiltration of water to the slip surface where fine clay and silt form an impermeable layer and allow the overburdened debris material to move along the slip surface. Further plantation of deep-rooted deciduous trees in the central part of the slide zone will help in evapotranspiration and thus reduce the water content at the slip surface. Since the whole slide zones presently look like a deserted piece of land so applying bioengineering method will help in reducing the risk of further movement of landmass downslope. To stabilize the Soldha area landslips naturally, further research is needed to understand the mechanism involved and stability achieved.

## Declarations

#### Competing Interest:

The authors have no relevant financial or non-financial interests to disclose. There is no competing interest.


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# Author’s contribution:

All the authors contributed to the study conception and design, analysis, and interpretation. All authors read and approved the final manuscript.


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## Figures

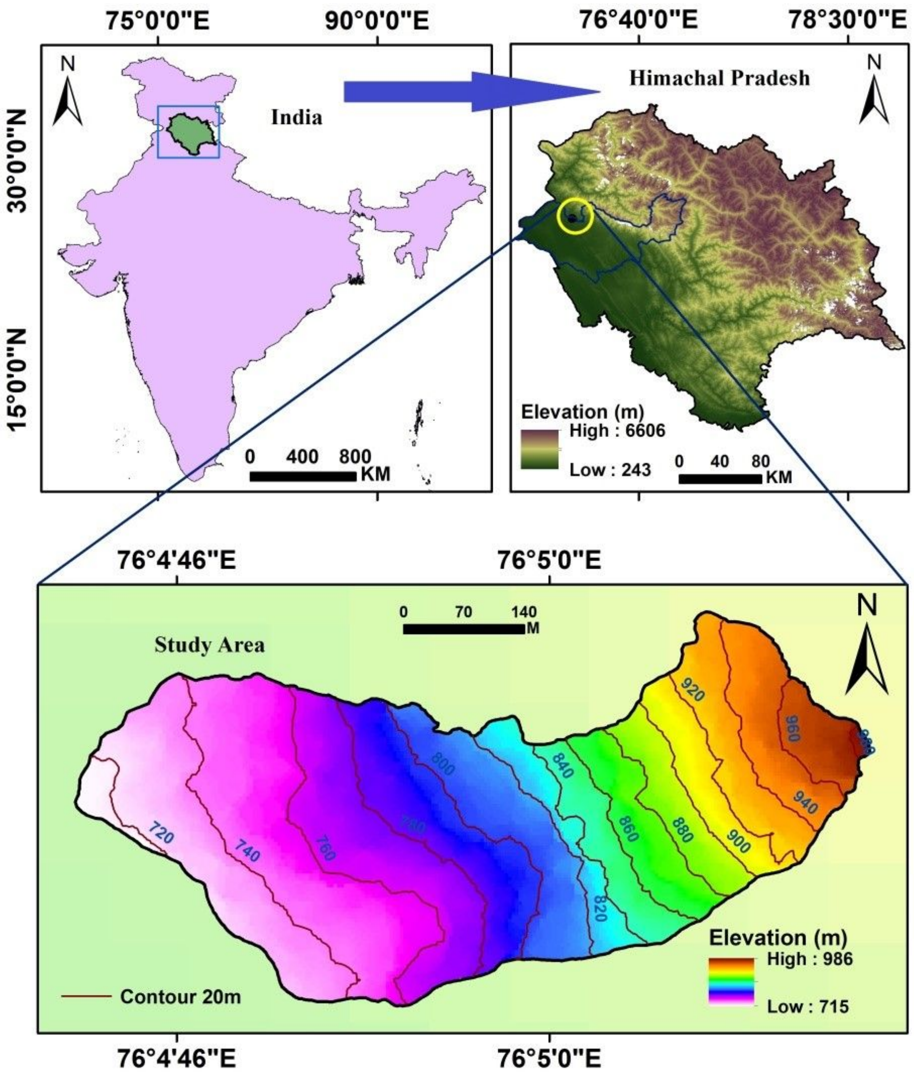



Figure 1

Location map of Soldha slide zones in Kangra District Northwest Himalaya. The Jawalamukhi Thrust is shown in the inset (right-top), which is just below the slide zone

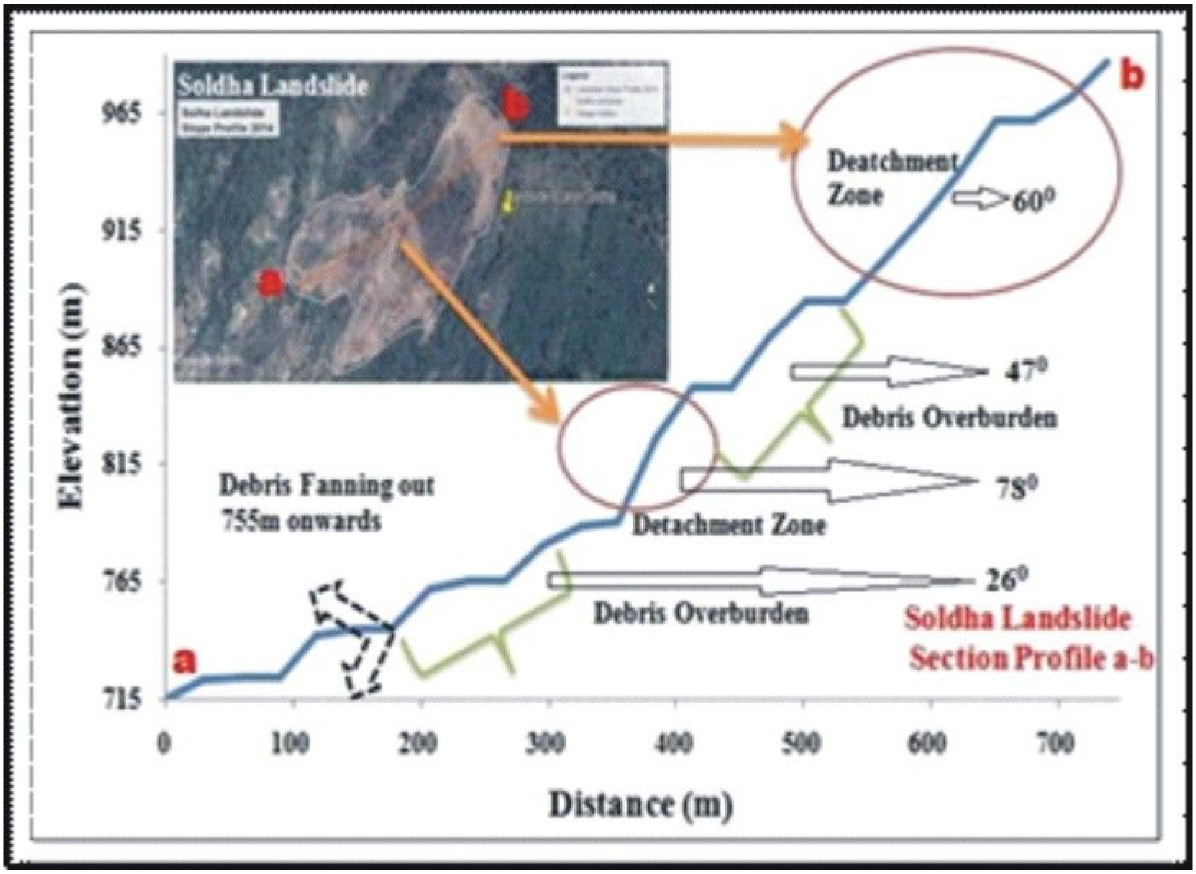



Figure 2

The slope gradient along 'a-b' section of Soldha slide zone (after Mahajan et al. 2022)

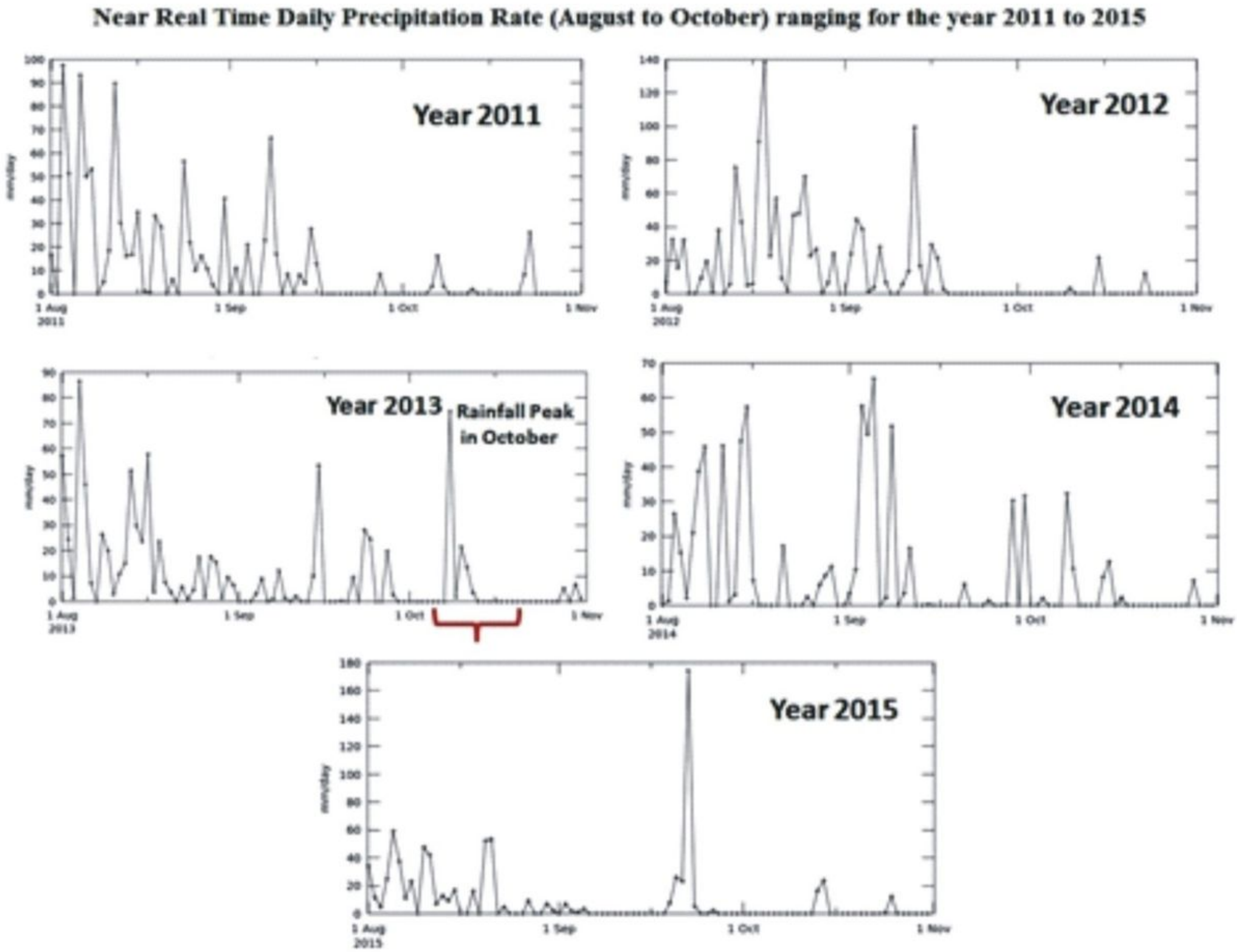



**Figure 3**

Rainfall data of August to October for 2011-2015 (Source: NASA Earth; after Mahajan et al. 2022)

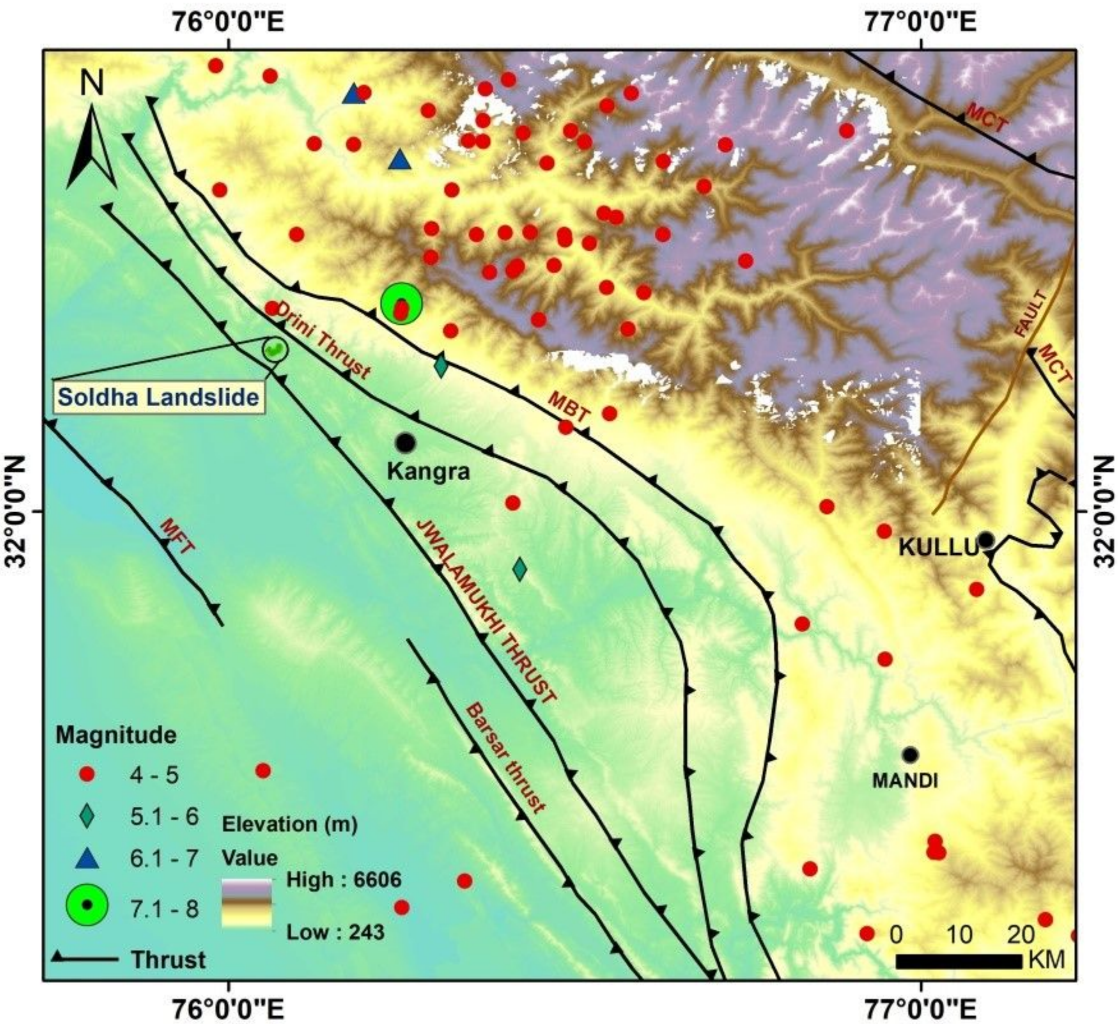



Figure 4

Seismotectonic map of the study region and location of Soldha slide zone with respect to Jawalamukhi Thrust and other tectonic features in the region.

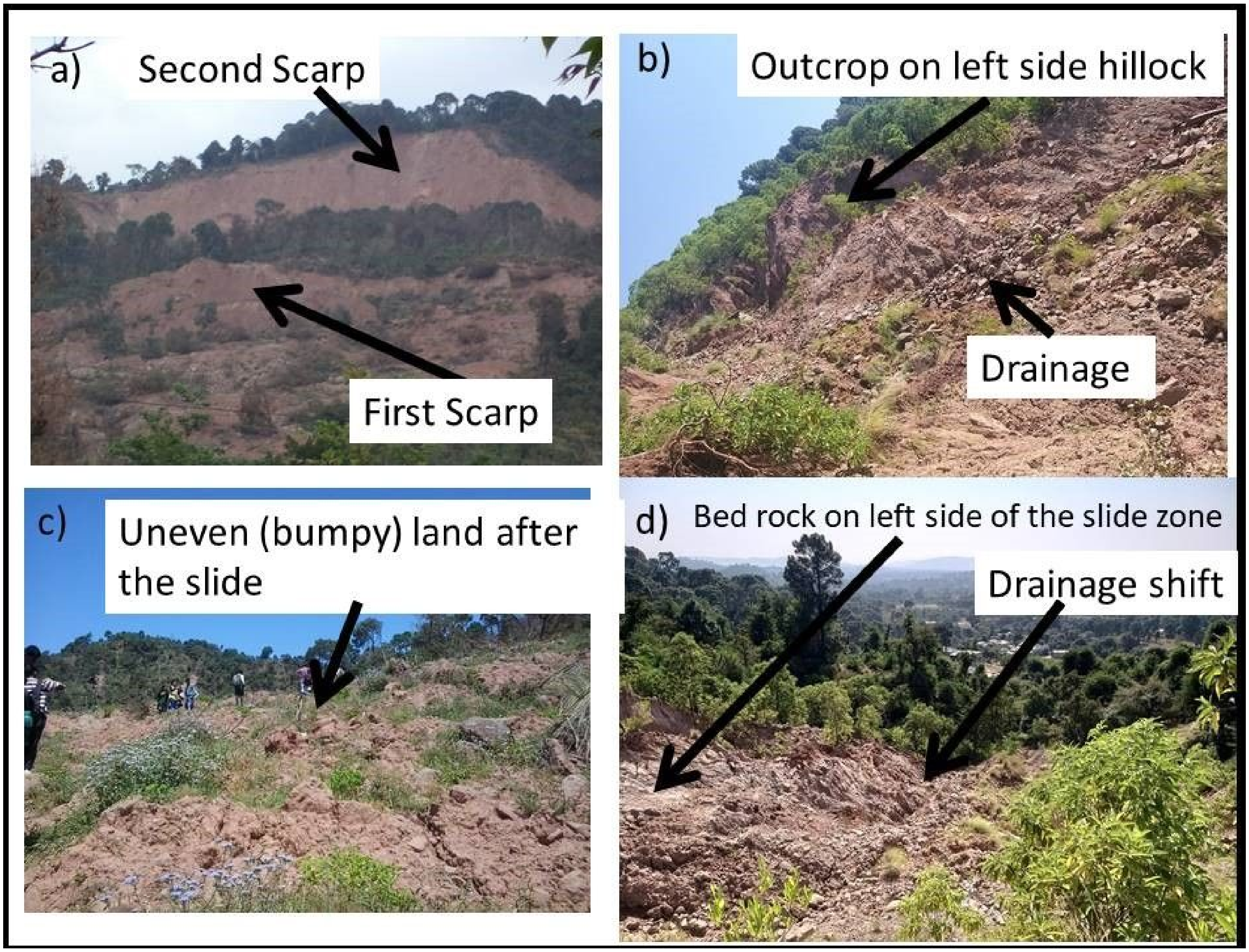



**Figure 5**

Field photographs taken after the event shows: a) First Scarp region, second detachment zone, b) displacement of rocks and drainages on left side of the slide zones, c) uneven and bumpy agricultural land after the slide occurrence with uprooting of trees and d) drainage shift on southwest part of the slide zone


**Figure 6**

Field photographs showing a) displaced and damaged houses, b) development of crevasses and undulating nature of material with uprooting of tress, c) ponding and shifting of drainage on left side, and d) piling of debris material at the toe of the slide zone (Mahajan et al. 2022)

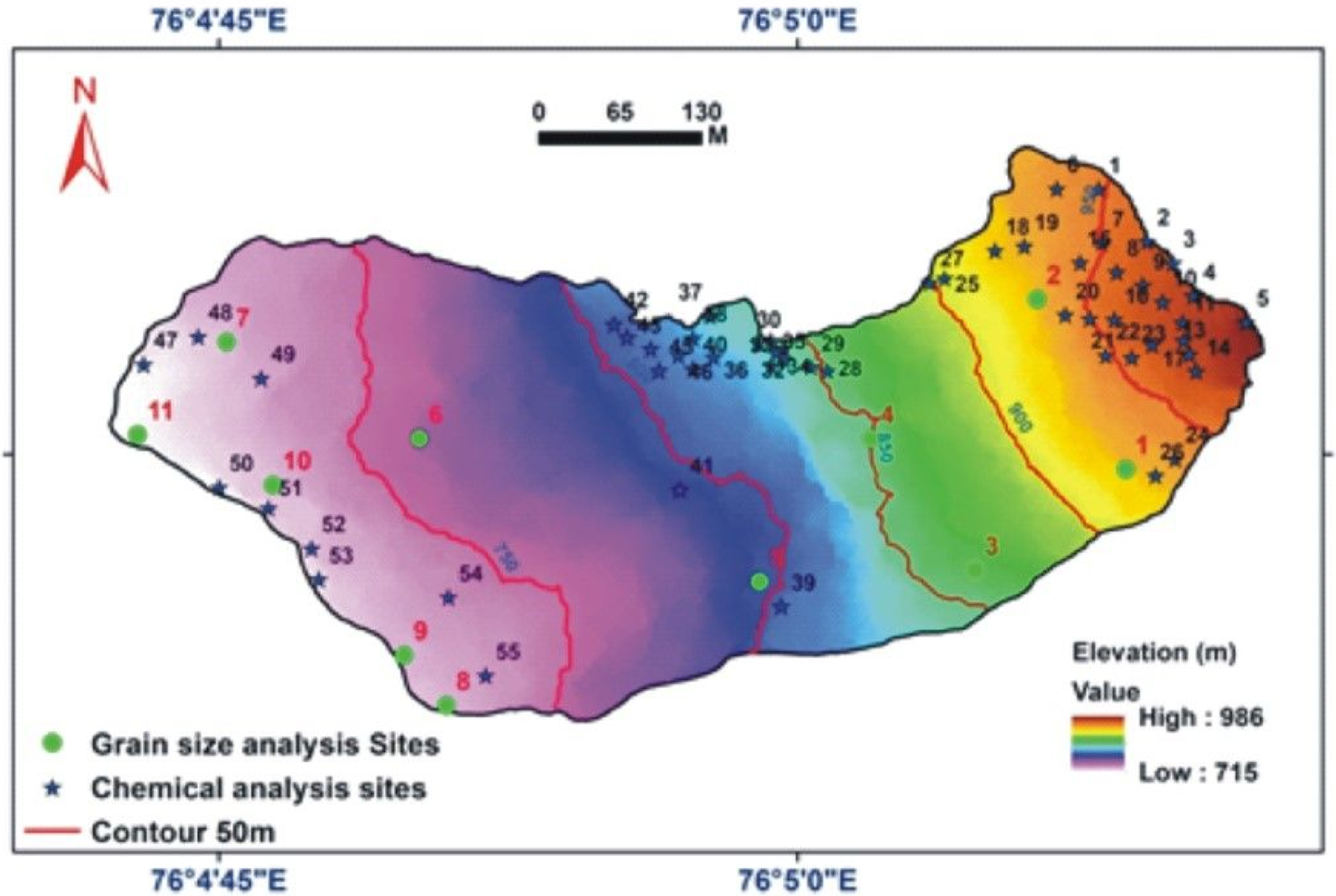
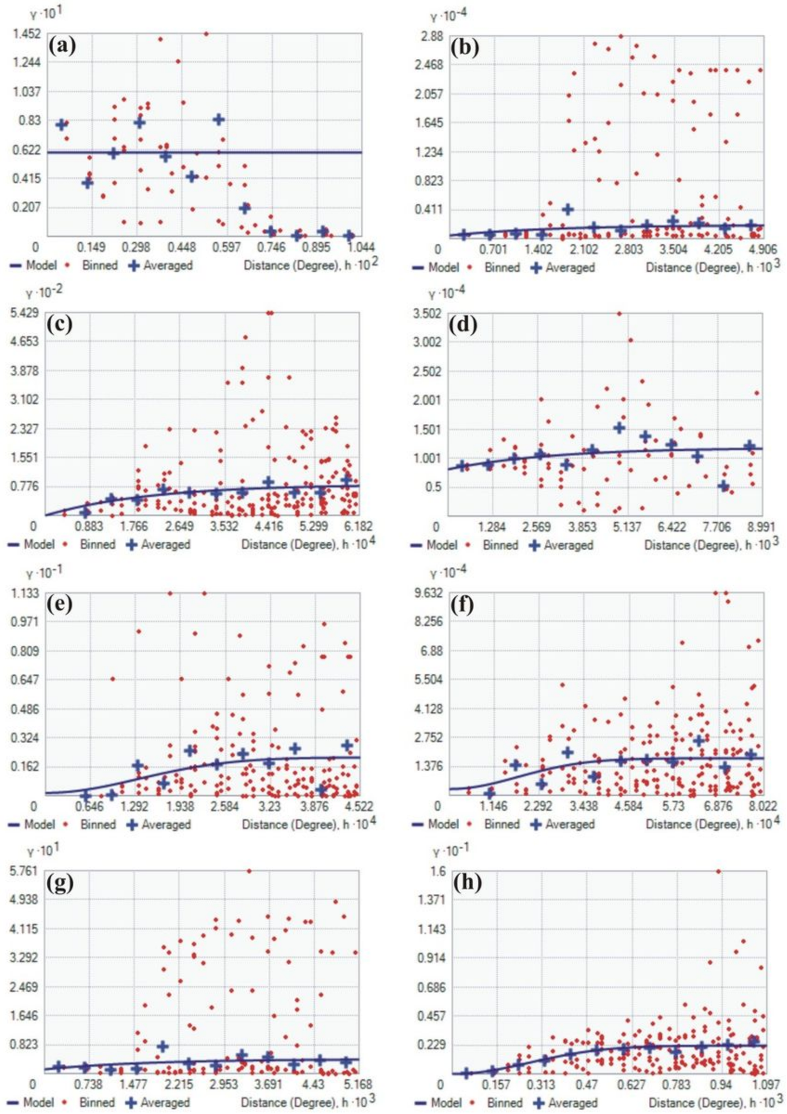



Figure 7

Locations of soil sampling for grain size and chemical analysis at the Soldha Landslide site



## Figure 8

Semivariogram representing models of physico-chemical parameters in Soldha Landslide slope material: a) organic carbon, b) nitrogen, c) phosphorus, d) potassium, e) copper, f) iron, g) manganese, and h) zinc