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An integrated geotechnical and geophysical investigation of landslide in Chira town, Ethiopia

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ABSTRACT

Landslides pose a significant threat to infrastructure, property, and human lives in many regions worldwide, including Chira town in Ethiopia. This study presents an integrated geotechnical and geophysical investigation aimed at identifying the contributing factors to landslides in Chira town, Ethiopia, with a focus on a recent landslide event. The methodology employed a combination of geotechnical and geophysical techniques to comprehensively analyze the landslide problem. The geotechnical investigation involved a detailed analysis of the soil characteristics in the area, including the composition of fine-grained soil and the determination of cohesion and angle of internal friction through triaxial testing. The geophysical investigation utilized electrical resistivity tomography to assess the subsurface soil profile. The findings revealed the presence of a massive basaltic tertiary volcanic rock layer underlying a very low resistivity layer of sticky clay soil. Through this study, it was established that rainfall, soil type, land use, elevation, and proximity to streams, slopes, and aspects were the main factors contributing to the landslide, accounting for 22.03%, 18.89%, 15.75%, 15.46%, 10.87%, 9.7%, and 7.5% of the overall influence, respectively. Based on these findings, the study proposes a range of interventions to enhance resilience against landslides, including surface drainage, the implementation of appropriate land use management practices, and the introduction of vetiver vegetation. The integration of geotechnical and geophysical methodologies provided a comprehensive understanding of the landslide problem in Chira town. The proposed interventions aim to inform future land use planning, infrastructure development, and disaster risk reduction efforts in the region. By expanding our knowledge of the mechanisms driving landslides, this study offers valuable insights that can be utilized in similar regions facing comparable geotechnical and geophysical conditions.

1. Introduction

Landslides are a widespread phenomenon in many parts of the world, causing significant economic and social impacts [1–3]. Several researchers have studied to the factors with the potential to trigger landslides, including rainfall, ground water, slope angle and

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steepness, soil properties, vegetation cover, and land use changes [4–8]. Recent studies by Refs. [9–12] show the negative impacts of climate change, land use changes, and unsustainable development on wetlands, soil erosion, and groundwater recharge in Iran. However, these factors can vary significantly depending on the geological and climatic conditions of the region under consideration.

In Ethiopia, landslides are a significant concern due to the country's rugged terrain, heavy rainfall, and rapid population growth [13–15]. The country has experienced several landslides in recent years, leading to loss of life and damage to infrastructure. Therefore, there is a need to understand the factors contributing to landslides in the region to develop effective strategies for mitigation and prevention. Even though many studies [16–21] have been conducted to analyze the cause of these landslides in Ethiopia, the use of integrated geotechnical and geophysical methods to investigate the factors contributing to landslides in specific regions is limited. This is particularly true for Chira town in the Oromia region of Ethiopia, which has experienced several landslides in recent years, posing a significant threat to its inhabitants and infrastructure. Therefore, an integrated geotechnical and geophysical investigation of landslides in Chira town can provide a more comprehensive understanding of the factors contributing to landslides in the region. The use of geophysical methods such as electrical resistivity imaging (ERI) can complement the geotechnical investigation and provide valuable insights into subsurface conditions, particularly in areas where access is limited or difficult [22–24].

Hence, the study aimed to conduct an integrated geotechnical and geophysical investigation of landslides in Chira town, Oromia region of Ethiopia, to provide a more comprehensive understanding of the factors contributing to landslides in the region. Based on the results of the investigation, the study proposed possible remedial measures to mitigate the impact of landslides in the region.

2. Methodology

2.1. Study area

Chira Town is situated in the Jimma Zone of the Oromia Regional State in southwestern Ethiopia (Fig. 1). The town received its official status as a town in 2007 and is located 100 km southwest of Jimma City, the capital of the zone, and 345 km away from the national capital, Addis Ababa. The altitude of Chira Town ranges from 1390 to 2980 m above sea level. The climate of the town is warm, humid, and subtropical with an average annual rainfall of 1955.4 mm, ranging from a maximum of 2967.8 mm to a minimum of 1414.1 mm. The area experiences rainfall throughout the year with relatively smaller amounts in January, February, and December, and the highest rainfall records in June, July, and August during the main rainfall seasons. The study area is characterized by a rugged volcanic mountainous terrain comprising of high to low relief hills.

The hydrological data showed that there were several streams and rivers flowing through Chira town. The area also had several wetlands and ponds, which played a crucial role in groundwater recharge and water availability for agricultural activities. The meteorological data revealed that the average annual temperature in Chira town was 20.4 °C, with maximum and minimum temperatures of 27.4 °C and 15.4 °C, respectively. The relative humidity ranged from 51.7% to 89.5%, with an average of 72.3%

2.2. Research methods

2.2.1. Field investigation

The first step of the investigation was to conduct a field investigation to collect data on the landslide event in Chira town. The field investigation involved mapping the affected area, identifying the boundaries of the landslide, and collecting information on the geotechnical and geophysical conditions of the site. The following field tests were carried out and.

a) Visual Inspection: This involved observing the site for signs of damage, including cracks in buildings, tilting of structures, and evidence of soil movement as shown in Fig. 2.

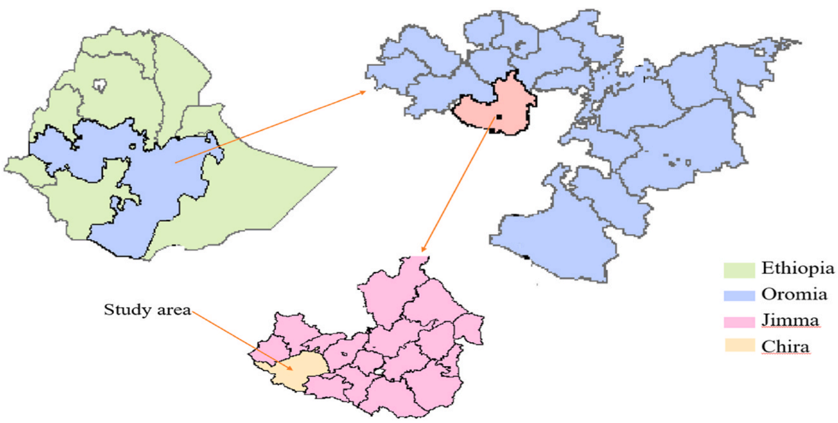

Fig. 1. Map of the study area.

b) Geomorphological Mapping: This involved mapping the topography and land use of the affected area, including the slope angle, aspect, and elevation.
c) Drilling: This involved drilling boreholes to obtain soil samples for laboratory testing.

2.2.2. *Geotechnical laboratory testing*

The soil samples obtained from the boreholes were tested in the laboratory to determine their physical and mechanical properties. Table 1 shows the summary of Geotechnical Laboratory Testing that have been conducted for this study.

2.2.3. *Geophysical investigation*

The geophysical investigation involved using electrical resistivity imaging (ERI) to evaluate the subsurface conditions of the site [25]. The ERI survey was carried out using a Wenner electrode array with a total of 24 electrodes spaced at a distance of 5 m. The survey was conducted in two parallel lines with a spacing of 10 m between them.

2.2.4. *Data analysis*

The data obtained from the field investigation, laboratory testing, and geophysical investigation were analyzed to determine the factors contributing to the landslide in Chira town. The data were analyzed using statistical methods, including factor analysis and correlation analysis, to determine the relative contributions of the various factors to the landslide.

2.2.5. *Remedial measures*

Based on the findings of the investigation, possible remedial measures were proposed to mitigate the impact of landslides in the region. The proposed measures included surface drainage, planting, vetiver vegetation, and proper land use management. Fig. 3 shows the summary of the methodology used for this study.

3. Results and discussion

3.1. *Geotechnical conditions*

Natural Moisture Content: The natural moisture content of soil samples was determined at various depths in the study area. The test was conducted on eight undisturbed samples, and during a tri-axial test on five samples. The values of natural moisture content ranged from 36.84% to 47.68% as shown in Table 1. These values were obtained during the dry season, and it is expected that the values would be higher during the rainy season. The high moisture content, especially during the rainy season, is a significant factor in the occurrence of mass movement in Chira town.

Specific Gravity Test Result: The specific gravity test was conducted on eight samples, and the results ranged from 2.67 to 2.80 as

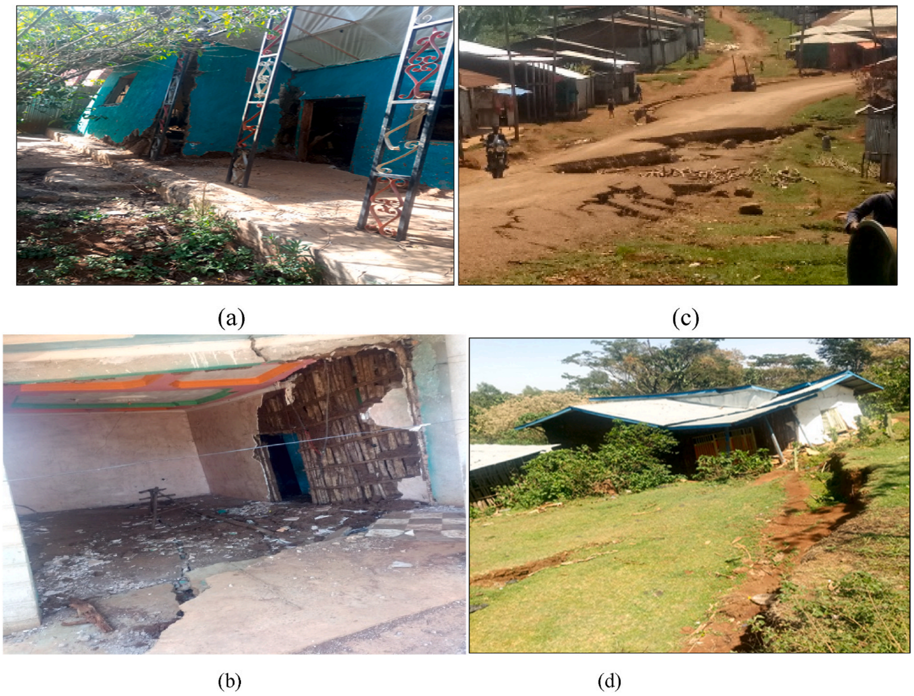

Fig. 2. Some cracks observed on the earth mass and effects on residential houses.

Table 1
Summary of geotechnical laboratory testing.

No.	Name of laboratory test	Objective of the test	Standard method
1	Particle Size Distribution	To determine the distribution of particle sizes in the soil	ASTM D 422-63
2	Atterberg Limits	To determine the natural moisture content, specific gravity, liquid limit, plastic limit, and plasticity index	ASTM D4318
3	Specific gravity test	To determine the dry density and bulk density of the soil	ASTM D792-20
4	Free Swell Test	To determine free swell value of the soil to evaluate its swelling potential	ASTM D4546
5	Triaxial Test	To determine the shear strength parameters of the soil, including cohesion and angle of internal friction	ASTM D4767-11

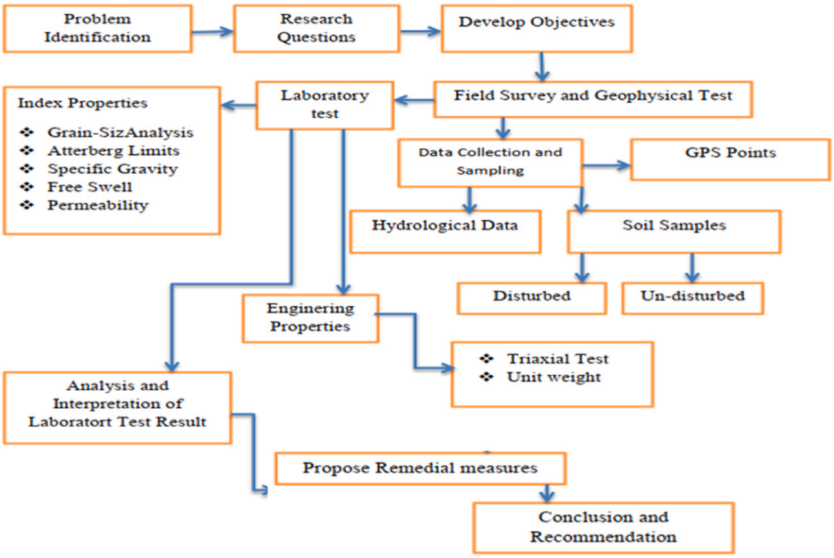

Fig. 3. Flow chart diagram of research design.

shown in Table 1. Based on this test, the soil type in the study area was dominated by clay and silty clay soils. These types of soil are weaker and often have multiple weak points, which contribute to the Chira town landslide.

3.1.1. Atterberg limits test results

The Atterberg limits test was conducted on eight soil samples to determine their consistency. The results showed that the liquid limit (LL) ranged from 67.70% to 71.31%, the plastic limit (PL) ranged from 30.64% to 35.73%, and the plasticity index (PI) ranged from 33.60% to 39.47% as shown in Table 2. The values decreased from top to bottom, as depth-dependent factors affecting soil plasticity behavior become smaller. These results provide important information about the soil's properties, which can help to identify potential slope instability and landslide risks.

3.1.2. Soil classifications

The research area had predominantly fine-grained soils as it can be seen from Fig. 4, with clay (CH) in three of the five test pits and silt (MH) in the other two. Such soils lose shear strength when exposed to high moisture content, making them susceptible to slope instability, especially during the rainy season. Fine-grained soils are more vulnerable to saturation than coarse-grained soils due to their structure and inter-particle forces. Clay soils, with poor permeability, generate pore pressure as groundwater levels rise,

Table 2
Results of some of geotechnical laboratory results.

Test pit designation	Depth (mm)	Moisture content (%)	Specific gravity (Gs)	Liquid Limits (LL)	Plastic Limits (PL)	Liquidity Index (LI)	% Finer than 0.075 mm	Unit weight (kN/m^3	Free swell (%)
TP1	1.5	43.63	2.69	71.31	35.16	0.23	98.23	19.01	25.00
	2.8	47.66	2.67	70.26	35.73	0.35	96.76		
TP2	2.4	36.84	2.70	68.45	31.01	0.16	97.66	19.86	33.33
TP3	1.5	38.67	2.80	70.11	30.64	0.20	94.57	19.06	36.36
	2.4	40.17	2.74	69.91	35.11	0.15	94.68		
TP4	2.7	42.85	2.69	67.70	34.10	0.24	92.68	18.09	27.12
TP5	2	39.74	2.73	70.77	34.81	0.14	98.12	19.40	41.22
	2.7	40.69	2.79	69.37	31.27	0.25	98.55		

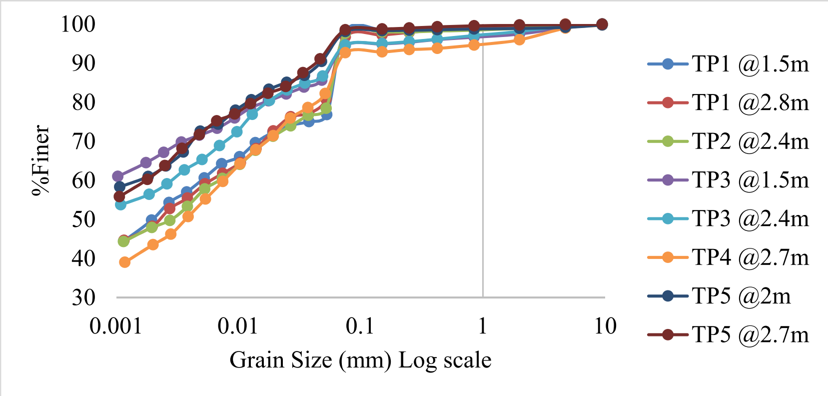

Fig. 4. Result from grain size analysis of Chira town landslide Soils.

increasing the risk of sliding. Soil type is crucial in slope stability analysis.

3.1.3. *Unit weight*

The unit weight determination test was conducted to determine the density of compacted in-situ soil in the study area. The dry density of soils ranged from 1.289 g/cm^3 to 1.481 g/cm^3, while the bulk density ranged from 1.844 g/cm^3 to 2.024 g/cm^3.

The free swell test was performed on five soil samples, and the results showed that the soil in the study area did not have expansiveness properties. The free swell values ranged from 25.00% to 41.67%, indicating that the soil had a low degree of expansion, with values below 50%.

3.1.4. *Permeability test*

The Falling Head Method test was conducted on five soil samples to determine the coefficient of permeability since the dominant soil type in the study area was fine-grained soil. The results of this test indicated that the soil in the study area was categorized as clay and silt soils, with coefficient of permeability values ranging from 6.23E-05 to 9.95E-07. The very small values of the coefficient of permeability, coupled with the high water content, can lead to the development of positive pore pressure, which can disperse soil particles and reduce the soil's shear strength, thus increasing the likelihood of landslides.

3.1.5. *Triaxial test*

The triaxial UU test was performed to determine the undrained shear strength of saturated cohesive soil in the study area (Table 3). This test helped determine soil characteristics, including unit weight, elastic modulus, cohesion, and angle of internal friction. Five soil samples were tested in the Ethiopian Construction Design & Supervision Works Corporation Laboratory. The slope of the linear line on the stress-strain curve was used as the Elastic Modulus of the soils (Fig. 5a and b).

3.2. *Gemorphological conditions*

A 2D resistivity sections of various towns along the impacted slopes show heterogeneous structures in both horizontal and vertical directions. Zones of low to high resistivity are observed in all vertical profile sections, with the body of the landslide consisting of clayey, silty, and moist materials with low resistivity. A geological layer profiling image (Fig. 6) identifies subsurface lithology and formation depth, with a massive resistivity of about 448 Ωm indicating basaltic tertiary volcanic rock overlaid by very low resistivity (<10 Ωm) sticky clay soil. This soil has low hydraulic conductivity, causing pore pressure and weight increment over the volcanic rocks, reducing soil shear strength and causing landslides. Fig. 7 shows a profiling image of geological layers with varying electrical resistivity values, including thick clay soil, highly weathered ignimbrite, and highly weathered ignimbrite with clay soil. The formation promotes the development of pore water pressure. Fig. 8 displays the distribution of subsurface lithological characteristics in terms of their lateral and depth positions. The lithology consists of a moderate amount of weathered and fractured ignimbrite, heavily decomposed ignimbrite with clay soil, and barely weathered ignimbrite rock. The weathered and fractured formations serve as the

Table 3
Summary of triaxial UU test result of Chira landslide soils.

No.	Test type	Standard method	Soil test results				
			TP1 @2.4 m	TP2 @2.4 m	TP3 @2.4 m	TP4 @2.7 m	TP5 @2.7 m
1	Triaxial Test	ASTM D 2850					
	C (Kpa)		41.81	38.06	37.42	26.07	43.28
	Ø (Degree)		18.45	22.56	17.25	15.65	18.02

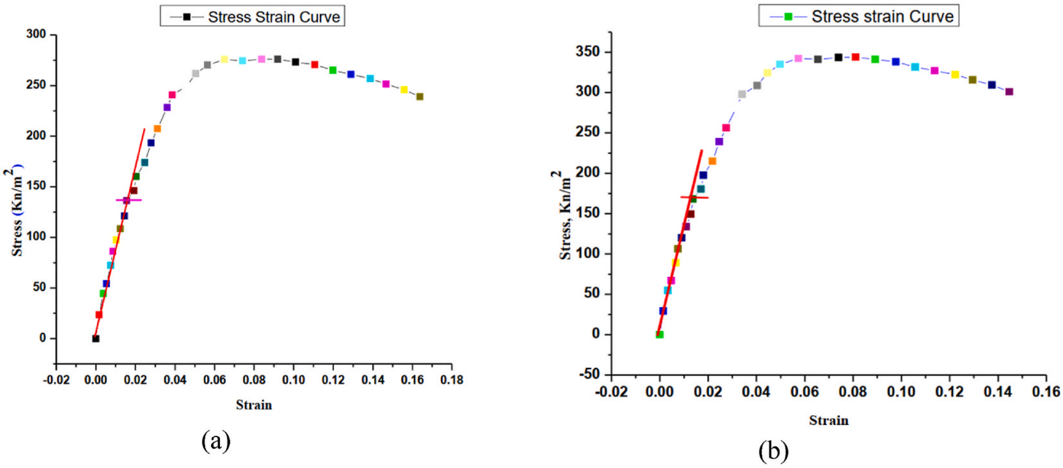

Fig. 5. Stress-strain curve of triaxial test.

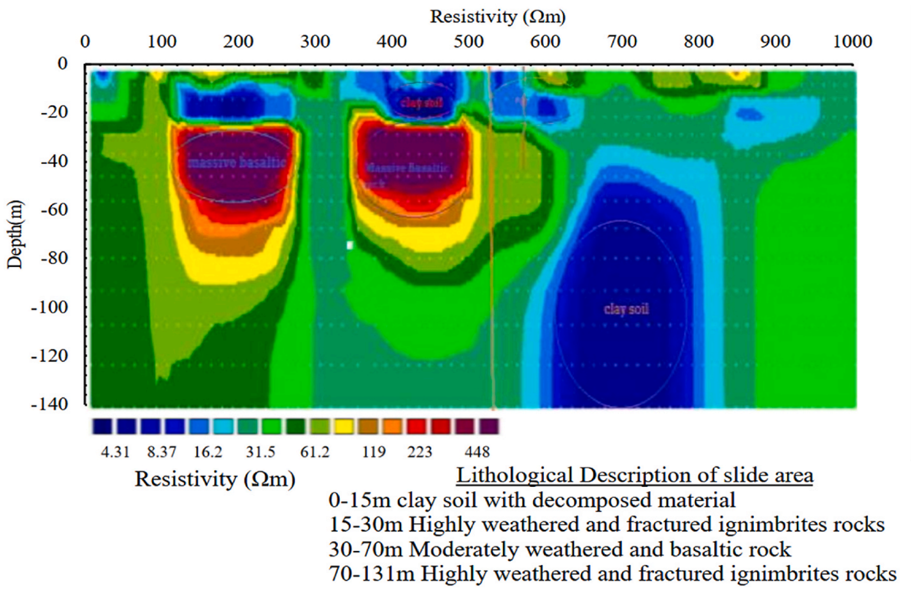

Fig. 6. Muje Ber site electrical profiling 1.

stream flow line. The ground on both sides is divided into different layers based on their electrical resistivity capacity, indicating the formation of each layer. Multiple layers suggest the presence of an unconfined aquifer with several fractures that can trigger sliding.

Fig. 9 depicts various lithological formations along the center of the sliding mass. It has been observed that the subsurface is made up of various stratified formations. In the third layer, which is about 7 m thick, the clay soil is overlaid by highly fractured, weathered basaltic rock and slightly fractured basaltic rock. Because of the fractured formations that cover the clay formation, it is extremely prone to sliding if surface water flows in or groundwater rises and saturates the formation. It facilitates the development of pore water pressure in the clay layer.

3.3. Causes and triggering factors of landslides in Chira town

3.3.1. Rainfall analysis

The Chira area's rainfall characteristics were analyzed using a 36-year record from 1985 to 2020, with missing values filled through multiple imputation, Fig. 10. Annual analysis revealed increasing rainfall from 2014, culminating in a record high in 2016. This heavy rainfall caused cracks on the ground surface and decreased soil strength, leading to landslides in the Chira town. Meanwhile, the monthly analysis showed that the Chira area receives rainfall throughout the year, with the highest amounts falling in May–September, and particularly in June–August. Overall, these findings suggest that recent rainfall records may be responsible for the observed

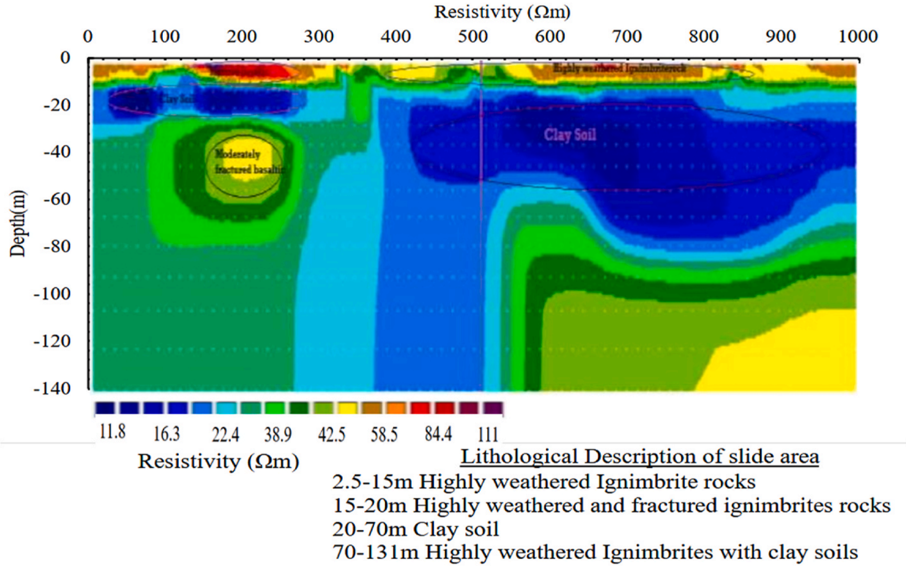

Fig. 7. Muje Ber site electrical profiling 2.

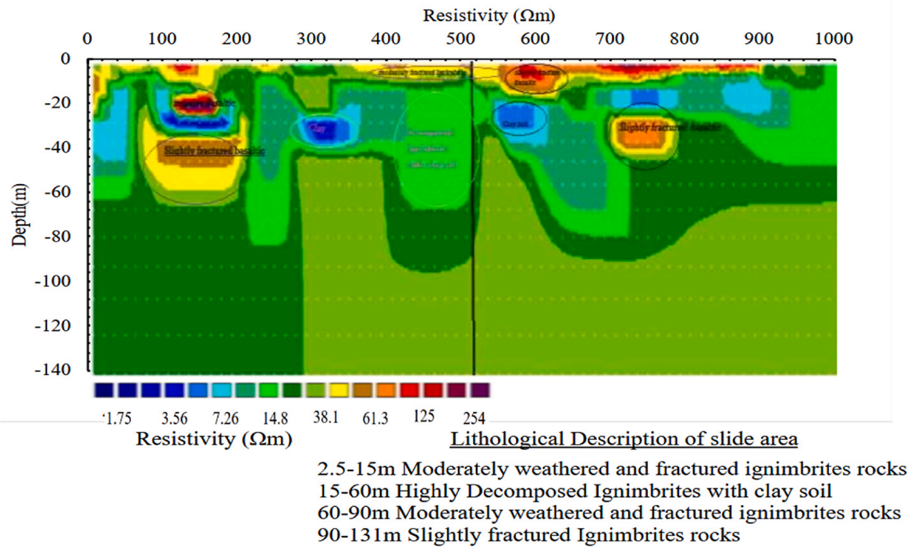

Fig. 8. Muje Ber site electrical profiling 3.

landslide activity.

3.3.2. *Slope aspect*

The aspect from DEM was classified into ten classes, with past landslides revealing the maximum occurrence on slopes inclined towards the south (32.4%), followed by the northeast (19.1%) and southwest (17.6%). This susceptibility is due to high weathering in the South, which weakens soil shear strength. Sunlight intensity is also high in the south, particularly from 11:00 a.m. to 6:00 p.m. in Ethiopia, leading to increased weathering and landslides in this direction.

3.3.3. *Curvature*

Curvature was grouped into negative, flat, and positive values. Flat slopes had the highest landslide susceptibility, while convex slopes had the lowest. Concave slopes had a high risk due to water accumulation, while runoff dispersal in convex slopes led to lower landslide probability. Thus, curvature and slope shape should be considered when evaluating landslide susceptibility.

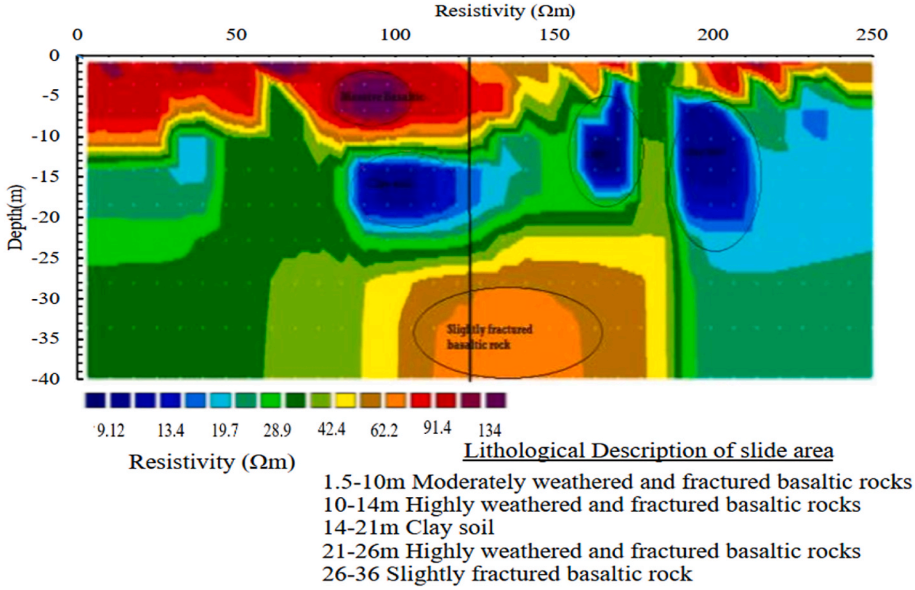

Fig. 9. At the back agriculture office site electrical profiling.

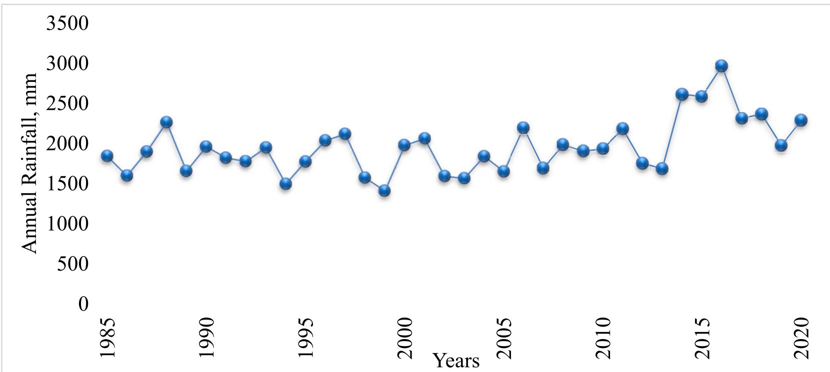

Fig. 10. Annual rainfall analysis of Chira town.

3.3.4. Elevation

Elevation was classified into seven classes for the landslide hazard analysis. From the results, most of the landslides have occurred at elevations between 2077 and 2107 (45.6%), followed by 2048 and 2077 (38.2%). The study area has complex geographical topography. Some parts of the area are flat, while others have high elevations. This variation in elevation causes the tendency of runoff to affect the shear strength of the soil.

3.3.5. Land use/land cover

For land use and land cover, the study area was classified into four land use and land cover classes: urban and built-up; agricultural land, grassland; and forest land. The distribution of the past landslides shows that the landslides have occurred within all land use and land cover classes. As depicted in Fig. 11, the landslide's severity has, however, occurred in urban and built-up areas. This is due to the fact that the activities done due to urban development, like deforestation, result in additional loads that increase the driving force and decrease the stability of slopes in the study area.

3.3.6. Slope angle

The slope angle has a significant impact on slope stability, as an increase in shear stress can cause slope failure. For this study, the slope angle was extracted from a DEM and classified into five categories (Fig. 12). Analysis of past landslide occurrences shows that slopes with a range of 5–12° had the highest percentage of landslides.

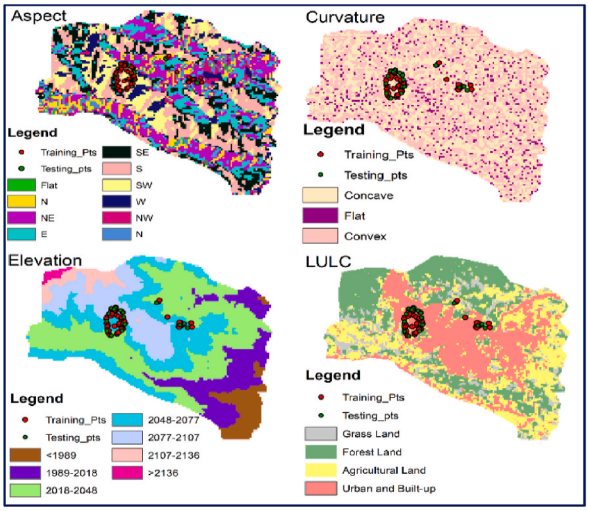

Fig. 11. Aspect, curvature, elevation, and land use/land cover factors.

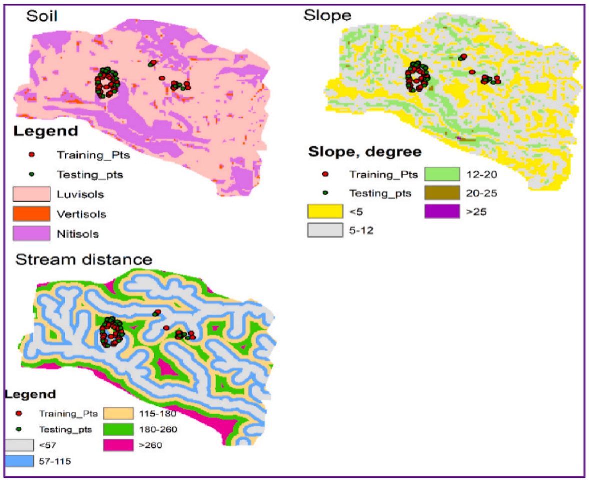

Fig. 12. Slope, soil, and stream distance factors.

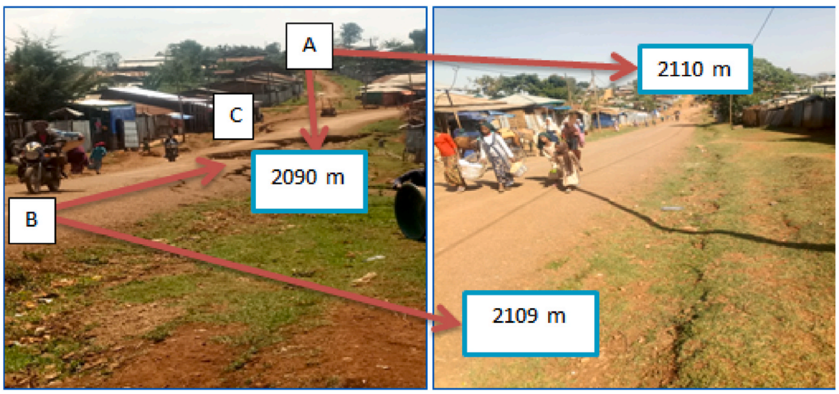

Fig. 13. Effect of elevation difference on pore pressure development.

3.3.7. Soil type

The study area was classified into three soil classes: luvisols, vertisols, and nitosols. Luvisols were the dominant soil type, with low nutrient retention and erosion risks (Fig. 12). Past landslide occurrences were found to be highest in the luvisol class of soil, which has a tendency to accumulate clay and produce positive pore pressure, leading to landslides.

3.3.8. Stream distance

A river network is formed due to the interaction of various factors such as geological structures, topography, and slopes. Stream distances in the study area were derived based on Euclidean distance and grouped into five classes (<57, 57–115, 115–180, 180–260, and >260). Landslides were found to be most frequent at stream distances of <57 and 180–260. The proximity of slopes to the river is more critical than their steepness, as bank erosion and river incision have a significant impact on slope stability, initiating mass movement in the study area.

3.3.9. Groundwater condition and elevation difference

Groundwater conditions vary due to rainfall and elevation differences, caused by infiltration or aquifer decline in dry seasons. Runoff from higher elevation and stored at lower elevation can increase groundwater, as shown in Fig. 13. Increased groundwater weight weakens the earth mass and reduces shear strength of weak layers, increasing driving force over resisting forces and facilitating landslides. Chira town's groundwater level varied between 5 and 16 m in different locations, affecting pore water pressure and earth mass stability. The slope's elevation and weather conditions, causing groundwater fluctuation, are considered a triggering factor for Chira town landslide.

3.4. Proposed remedial measures

3.4.1. Design of surface drainage

Certainly, implementing proposed remedial measures in a sustainable manner is crucial for effective landslide prevention in Chira town. Several studies have shown that nature-based solutions, such as constructing green roofs, retention ponds bioswales, and permeable pavements, are effective in reducing surface runoff and increasing infiltration rates [26–28]. Therefore, a similar approach could be implemented in Chira town to minimize the amount of water seeping into the subsurface and stabilize the slopes.

3.4.2. Vegetation

Vegetation helps prevent landslides by binding soil particles together, reducing pore water pressure, and intercepting rainfall, thereby reducing erosion and soil displacement [29–31]. Plant roots increase the soil's shear strength, making it more resistant to failure [32–34].

3.4.3. Land use management

The expansion of urbanization in Chira town was one of the main triggering factors, according to the analysis of landslide causal factors conducted using GIS and site visits. Effective land use management can prevent landslides in several ways [6,35–37]. First, it involves careful planning of land use, considering the slope gradient, soil type, and land use history, to identify areas that are at risk of landslides. Avoiding development and land use in these areas can reduce the likelihood of landslides. Second, land use management can involve the use of appropriate land management practices, such as terracing, grading, and drainage, to minimize soil erosion and reduce the accumulation of water on slopes. This can help to maintain slope stability and reduce the risk of landslides. Finally, land use management can also involve the establishment and maintenance of vegetation cover, which can increase soil stability and reduce the risk of landslides.

4. Conclusion

This study investigated the causes and characteristics of the Chira landslide in order to provide insight into landslide prevention and remediation measures. The geotechnical and geophysical investigations showed that the dominant soil type in the area is highly plastic, low permeability, and has a high swelling potential, which can easily initiate landslides during heavy rainfall. The occurrence of the landslide was triggered by several factors including soil type, land use, elevation, and distance to stream, slope, aspect, and curvature. To mitigate the effects of future landslides in the area, several remedial measures have been proposed, including surface drainage, planting, vetiver vegetation, and land use management. However, there are limitations to this study. For instance, the study only focused on a single landslide event, and further research is needed to examine the impact of the proposed remedial measures in preventing landslides. Future research directions should include a broader investigation of landslides in the region, examining the relationship between soil types and landslide occurrence, and assessing the effectiveness of various remediation measures. Overall, the findings of this study have important implications for landslide prevention and management in Chira town and other regions with similar geological and environmental conditions.

Author contribution statement

Worku Firomsa Kabeta: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.
Mulatu Tamiru: Conceived and designed the experiments; Performed the experiments; Contributed reagents, materials, analysis

tools or data; Wrote the paper.

Damtew Tsige; Hashim Ware: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

The data that has been used is confidential.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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