

Contributions of geophysical methods in determining the causes of lake shore landslides - The case of Bau Trang, Bac Binh district, Binh Thuan province, Vietnam

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Abstract: Landslides pose a significant threat to infrastructure, human safety, and the environment, particularly in areas with weak geological formations. This study investigates the causes of landslides along the Bau Trang lake shore in Bac Binh District, Binh Thuan Province, Central Vietnam, using a combination of geophysical methods: Electrical Resistivity Tomography (ERT), Ground Penetrating Radar (GPR), and vibration measurements. ERT was employed to assess soil resistivity and water saturation levels, while GPR provided insights into subsurface structures. Additionally, vibration monitoring was conducted to evaluate the impact of off-road vehicle activity on soil stability. The results revealed the presence of saturated low-resistivity soil layers, which contribute to ground weakening and increased landslide susceptibility. Furthermore, mechanical vibrations induced by tourism-related activities were identified as a major destabilizing factor. These findings provide a scientific basis for formulating mitigation strategies aimed at reducing landslide risks and preserving the ecological integrity of the Bau Trang lake area.

Keywords: Bau Trang Lake, Landslide; Geophysical methods; Electrical Resistivity Tomography; Ground Penetrating Radar; Vibration Measurement

1. Introduction

Landslides are among the most severe natural disasters, causing significant damage to human lives, infrastructure, and the environment worldwide. In regions with complex terrain and weak geological structures, landslides are becoming increasingly frequent due to the combined effects of natural conditions and unsustainable human activities. Areas composed of sand and thin sediment layers, which are highly susceptible to erosion, are particularly vulnerable to slope failures and instability [1, 2].

Bau Trang Tourist Area, located in the semi-arid region of Hoa Thang Commune, Bac Binh District, Binh Thuan Province, Central Vietnam, is one of the country's most renowned natural attractions. Recognized as an "Ecotourism Destination" in Vietnam's Top 100 in 2013, the site welcomes tens of thousands of visitors annually. However, on May 3, 2023, at approximately 10:30 am, a landslide occurred along the Bau Ba lake shore of Bau Trang lake. This event raised significant public concern and had negative consequences for the environment, the area's reputation, and the tourism economy. The area mainly comprises sandy soil with low cohesion in addition to intensive off-road vehicle activities that have exacerbated soil instability, particularly in regions near the lake shore. As a result, Bau Trang is currently facing an escalating risk of landslides driven by both natural forces and uncontrolled tourism activities.

The following geophysical techniques were employed to investigate the hydrogeological structure in Bac Binh District: (i) Vertical Electrical Sounding (VES) using the Schlumberger configuration; (ii) Seismic refraction survey; and (iii) Electromagnetic methods, including Magnetic Resonance Sounding (MRS), Transient Electromagnetic Sounding (TEM), Very Low Frequency (VLF), and Ground Penetrating Radar (GPR). The measurements obtained from these techniques enabled a statistical assessment of the geophysical parameters for each method, providing a foundation for the interpretation of subsequent geophysical results [3]. This study employs geophysical methods, including Electrical Resistivity Tomography (ERT) to identify soil layering and water saturation levels, Ground Penetrating Radar (GPR) to investigate subsurface structures, and vibration measurements to evaluate the impact of tourism activities on soil stability. The findings will provide a scientific foundation for developing protective measures and implementing stabilization strategies to mitigate landslide risks in the study area.

2. Methodology

2.1. Study area

The Bau Trang lake system comprises two lakes, Bau Ong and Bau Ba, situated in Hoa Thang Commune. This is a coastal commune in Bac Binh District, situated 35 km northeast of the district center, with a 23 km-long coastline. It borders the East Sea to the east and south, Hong Phong Commune to the southwest, and Binh Tan Commune, Luong Son Town, Hong Thai Commune, and Cho Lau Town to the north. The study area, where the landslide occurred, is located on the left shore of Bau Ba lake (Figure 1).

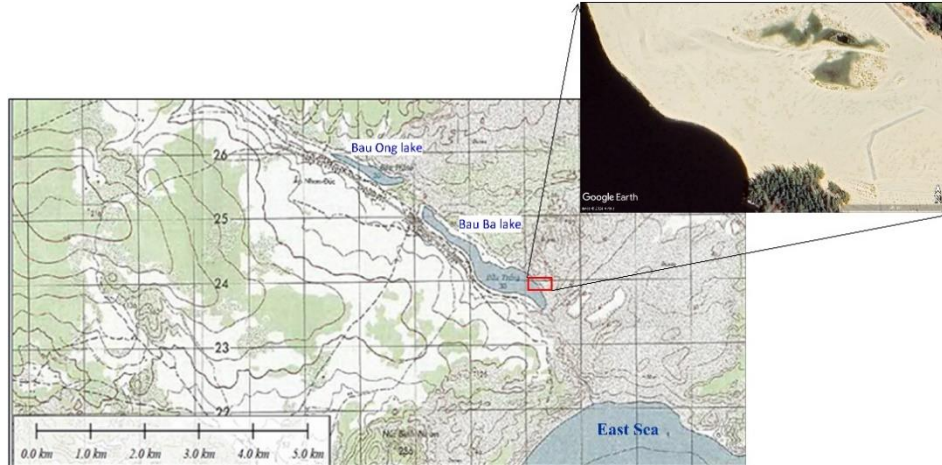


Fig. 1. Site location of study area

2.2. Geophysical techniques

To understand the geological structure and determine the causes of landslides, we employed three different geophysical methods, each providing important information to create a comprehensive picture of soil stability. ERT measurement was conducted along the AD1 line, 300 meters long, extending from the beginning of Bau Ba lake shore. GPR method was carried along 8 survey lines, labeled L1 to L8. The lines are spaced 5 - 10 m apart, with lengths ranging from 80 to 125 m, totaling 760 m in GPR survey lines. Survey line L4 aligns with AD1. And vibration monitoring was carried out over 8 days; the monitoring point was placed close to the Bau Ba lake shore (Figure 2).

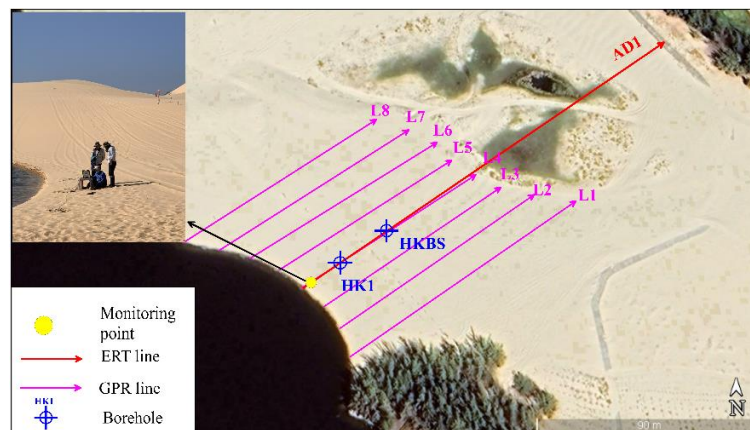


Fig. 2. Monitoring point, ERT line AD1, GPR lines L1 - L8, and 2 boreholes (HK1, HKBS)

2.2.1. Electrical Resistivity Tomography

ERT method was employed to measure soil resistivity, a key parameter for assessing water saturation levels and soil uniformity. The Wenner configuration was used with an electrode spacing of $a = 5.0$ m along the survey lines, enabling high-resolution imaging at depths ranging from 0 to 20 m. This configuration is widely applied in geological surveys due to its superior signal-to-noise ratio, which minimizes measurement noise [4, 5].

Field measurements were conducted using the SAS 4000 system (Sweden), a direct current (DC) electrical exploration device with advanced capabilities, including a broad measurement range for potential and current. The instrument ensures high-precision measurements of transmitted current and secondary potential variations. Data processing was performed using RES2DINV, a widely used software for inversion in electrical surveying. The results demonstrated that the ERT method effectively identified low-resistivity

soil layers, indicating waterlogged or saturated zones. These areas are particularly susceptible to landslides, as soil saturation significantly reduces load-bearing capacity.

2.2.2. Ground Penetrating Radar

GPR is a modern geophysical technique that utilizes high-frequency electromagnetic waves (10-3000 MHz) to investigate shallow subsurface structures. Electromagnetic waves are transmitted into the ground and reflected back upon encountering variations in electromagnetic properties. These reflected signals are recorded and visualized as subsurface images. Data processing is conducted using specialized software to enhance interpretation.

The Zond 12e system (Latvia) equipped with an unshielded 150 MHz antenna was employed [6, 7]. The propagation of electromagnetic signals is primarily influenced by three physical parameters: electrical conductivity, dielectric permittivity of the medium, and equipment frequency. In areas with sandy soil (high porosity) or elevated moisture content, GPR signals are strongly attenuated, resulting in signal loss on the radar profiles. This attenuation is a critical indicator for identifying potential landslide-prone zones in the study area.

2.2.3. The vibration measurement

The vibration measurement method is based on monitoring the propagation of elastic waves in a continuous medium under dynamic forces. Vibration sources may be natural (e.g., earthquakes, volcanic activity) or artificial (e.g., vehicles, machinery). Elastic waves in the medium are classified into two primary types: longitudinal waves (p-waves), which propagate in the direction of wave travel, and transverse waves (s-waves), which propagate perpendicular to the wave direction. Longitudinal waves are commonly used to assess soil properties. Additionally, surface waves, generated by near-surface vibration sources, play a crucial role in geophysical studies. Their maximum displacement amplitude is observed near the source but decreases significantly with distance. The propagation velocity of surface waves (v_s) is slightly lower than that of longitudinal waves (v_p).

Vibration measurements were conducted using a three-dimensional (3D) geophone, capable of recording movement along the XYZ axes. Geophones were positioned 1-2 meters from the lake shore, with a 5-meter spacing between them. The Lab Jack U6 vibration measurement device (United States) was used to record data, consisting of a controller and a signal recorder that collects the three displacement components of vibration through the geophones. Electrical signals from the geophones were digitized via an A/D converter. The results of vibration measurements provide insights into the effects of anthropogenic activities on the soil.

3. Results and Discussion

3.1. Assessment of landslide potential at Bau Ba lake shore using ERT and GPR

The ERT survey line AD1 was set up in the landslide area, with a length of 300 m, starting from the lake shore into the sand dune area in the southwest-northeast direction. On the electrical resistivity profile, three resistivity zones can be distinguished (Figure 3):

+ Zone 1: resistivity changes complexly. This zone extends from the lake shore to about 50 m inland along the horizontal direction; its thickness is approximately 10 m from the ground surface.

+ Zone 2: resistivity is ranging from 35 to 500 Ωm (light blue to blue color). This zone extends along the entire survey line and tends to dip gradually from the lake shore inland; at a depth of 10 to 70 m; it is predicted to be an aquifer. Within the first 50 m from the start of the line, it represents a saturated zone, while the remaining part is a water-bearing zone.

+ Zone 3: resistivity is more than 500 Ωm . This resistivity zone is distributed in two zones: the first zone from 100 m to the end of the line, with a thickness of up to 30 m; and the second zone from the start of the survey line to 100 m, at a depth of 25 m from the ground surface.

The AD1 resistivity profile runs through two boreholes, HK1 and HKBS. The drilling results indicate that the groundwater level is at a depth of 1.93 m, and an aquifer is present at a depth starting from 20 m.

On all 8 GPR profiles, a horizontal stratification structure consisting of 5 layers can be identified, reaching a depth of up to 30 m (Figure 4 and 5), with electromagnetic wave velocity ranging from 0.07 to 0.12 m/ns (calculated using the depth migration method) [8]. Notably, from line L3 to line L8, the GPR signals are significantly attenuated and completely lost in Layers 4 and 5 from the start of the line (Bau Trang lake shore) extending 40 to 50 m inland, at a depth of 10 m. Figures 4 and 5 are the processed GPR profiles of L4 and L7, showing the distinct stratification in the study area as described above (L4 coincides with ERT line AD1).

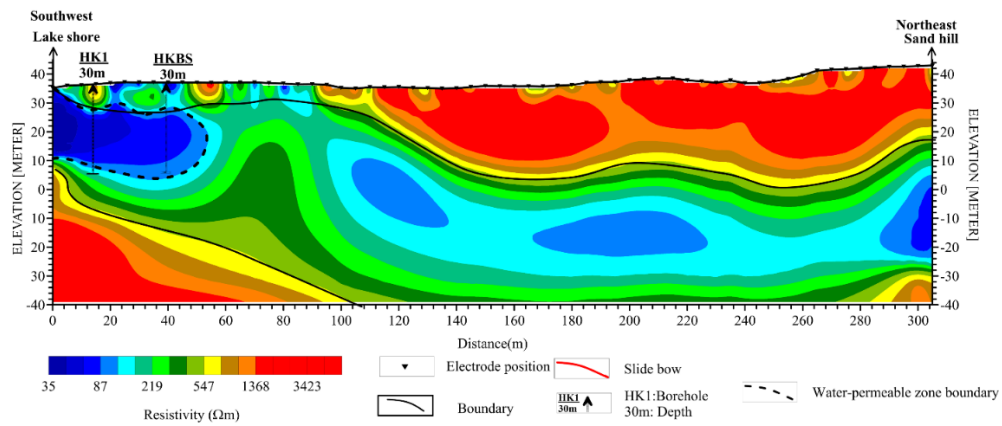


Fig. 3. ERT profile of AD1 line

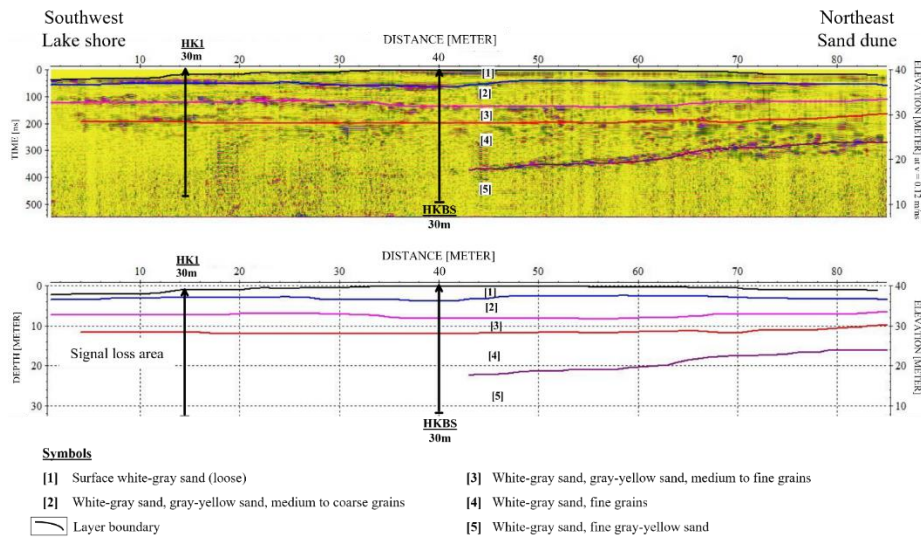


Fig. 4. GPR profile of L4 line

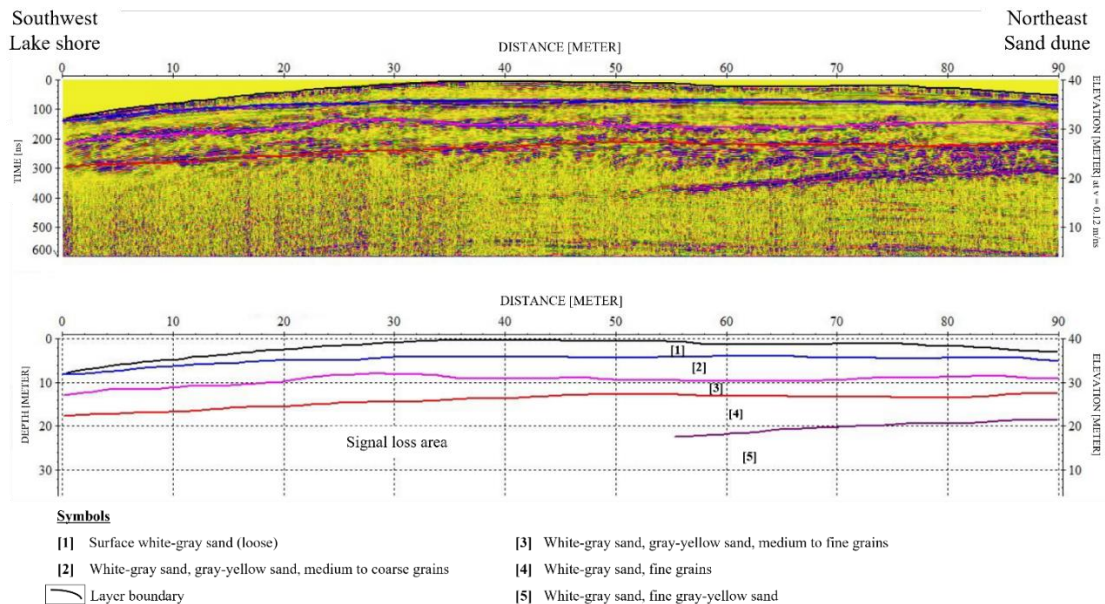


Fig. 5. GPR profile of L7 line

ERT, GPR, and borehole drilling collectively reveal a saturated zone extending 40 to 50 m inland from Bau Trang lake shore, at depths of 20 to 30 m. This saturated zone transitions into a water-bearing formation that extends and dips northeastward along survey line AD1. Based on these findings, we predict a potential slip zone along Bau Ba lake shore starting from line L8 to line L3, parallel to and about 40 to 45 m away from the lake shore in the northwest direction (Figure 6).



Fig. 6. Slip zone predicted from the geophysical results

3.2. Assessment of vibration impact on Bau Ba lake shore

3.2.1. Identification of vibration sources

During the monitoring period, we observed that from 9:00 am to 12:30 pm, many pickup trucks and off-road vehicles passed by or stopped 2 to 3 meters away from the monitoring point. Their speeds were estimated to be between 30 and 50 km/h. The weight of the pickup trucks ranged from 2.0 to 2.4 tons, and the off-road vehicles ranged from 400 to 500 kg. Besides, many tourists visited the area for sightseeing or photography, especially during holidays, Saturdays, and Sundays (Figure 7a and 7b). This indicates that pickup trucks and off-road vehicles are the main sources of traffic-induced vibration in the Bau Trang lake shore area.

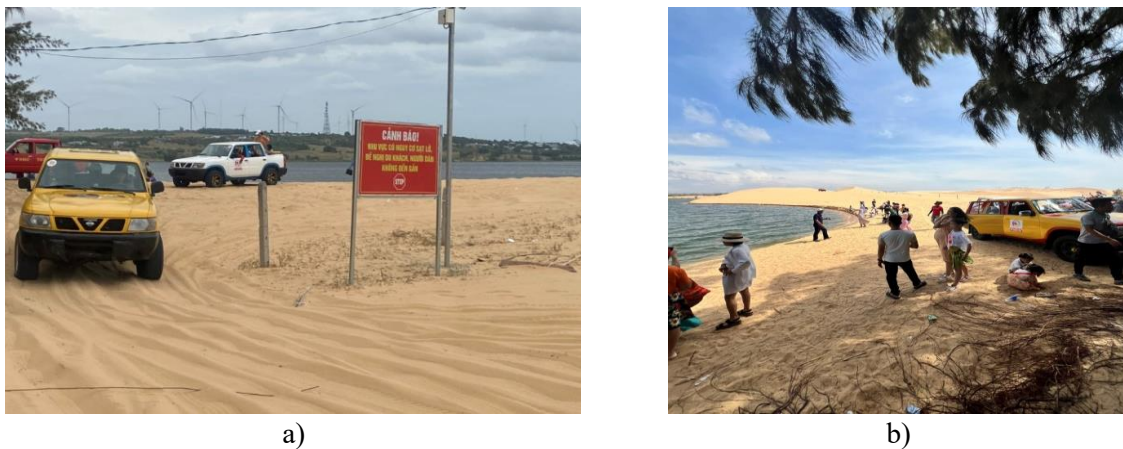


Fig. 7. a) Pickup truck activity; b) Tourists taking photos and sightseeing

3.2.2. Vibration velocity and acceleration at the monitoring point

The vibration velocity of the ground/sand is calculated using the formula [9]:

$$v = S/G \tag{1}$$

where: v is the vibration velocity of the ground (m/s); S is the measured electrical signal (V) obtained using the U6 vibration meter; $G = 28.8$ (Vs/m) is the sensitivity of the device.

The acceleration a of the ground vibration is then determined by:

$$a = \Delta v / \Delta t \tag{2}$$

From Formulas (1) and (2), the maximum velocity and acceleration values at the monitoring points during the measurement period were calculated (Table 1).

Tab. 1. Maximum vibration velocity and acceleration at the monitoring points

Day/month/year measured	Time measured	Maximum velocity	Maximum acceleration
		$v(\text{mm/s})$	$a(\text{mm/s}^2)$

01/12/2023	09h30 - 12h15	0.29	1.47
02/12/2023	09h30 - 12h16	0.24	1.04
27/01/2024	09h05 - 11h45	0.47	2.45
28/01/2024	10h00 - 12h00	0.19	1.29
24/02/2024	10h00 - 11h00	1.42	7.77
25/02/2024	10h05 - 11h05'	2.89	14.39
02/3/2024	09h30 - 11h30	0.50	2.91
03/3/2024	09h20 - 12h20	0.50	2.45

Monitoring data indicate that on February 25, 2024, the peak vibration acceleration reached a maximum value of 14.39 mm/s². At this level, the acceleration falls within Intensity VI on the MKS-64 scale, corresponding to a "Strong" classification [10]. Vibrations of this magnitude are clearly perceptible by people and may cause noticeable movement of light objects, though they typically do not result in significant damage to well-constructed buildings.

The fluctuating dynamic forces exerted on sandy ground surfaces by the wheels of moving vehicles generate stress waves that propagate into the subsoil. These waves significantly affect the properties of cohesionless (loose) soils, while their impact on cohesive (clay) soils is comparatively lower. Although vehicle-induced ground vibrations are generally weaker than seismic events, their prolonged action can lead to soil settlement and vibration-induced flow in loose, dispersed soils. Under such conditions, the shear resistance of these soils - particularly those with cohesion - may decrease markedly. Furthermore, as vibration intensity increases, the soil's porosity coefficient rises, resulting in vibrocompaction [11].

The reduction in shear resistance due to vibrations is a key factor influencing soil strength. Under sustained vibration, loose, non-cohesive soils can experience substantial settlement, primarily due to changes in porosity during the vibration process. Consequently, the activity of pickup trucks and off-road vehicles constitutes a major source of traffic-induced vibrations, destabilizing the soil foundation and contributing to landslides along the Bau Ba shoreline.

4. Conclusion

This study highlights the effectiveness of geophysical methods in assessing landslide susceptibility along the Bau Trang lake shore. ERT and GPR surveys identified a saturated soil layer extending 40 - 50 meters inland at depths of 20 to 30 m, which significantly weakens the soil's load-bearing capacity. Additionally, vibration monitoring demonstrated that traffic vehicle activity induces mechanical stress, further destabilizing the area. The peak vibration acceleration recorded was 14.39 mm/s², indicating significant ground movement that contributes to slope failure. These results confirm that both natural factors, particularly geological and hydrogeological conditions and anthropogenic activities (tourism-related vibrations) are major contributions to landslide of Bau Ba lake shore.

The findings will provide a scientific basis for proposing the effective protective measures and implementing stabilization strategies to mitigate landslide risks of Bau Ba lake shore. To mitigate future risks, recommended protective strategies include: (i) restricting traffic activity near unstable slopes, (ii) reinforcing slopes with appropriate stabilization techniques, and (iii) implementing continuous geophysical monitoring for early instability detection.

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