POLITECNICO DI TORINO

Master Degree course in Environmental And Land Engineering

Master Degree Thesis

Seismic And Electrical Tomographies For Characterization of Landslides

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Abstract

One of the most common and damaging geohazards, landslides have a significant impact on both human infrastructure and natural habitats. Prediction and risk assessment are particularly difficult due to their complicated dynamics, which are governed by geological, geomorphological, hydrological, and mechanical elements. Because of this, non-invasive geophysical techniques have grown in importance as instruments for examining and tracking unstable slopes. In this thesis, three geophysical techniques Resistivity Tomography (ERT), Seismic Refraction Tomography (SRT) and Multichannel Analysis of Surface Waves (MASW) are integrated to characterise a landslide in Italy. Rebuilding the landslide body's subsurface structure, identifying water-saturated areas, limiting the depth of the possible slip surface, and deducing the geomechanical characteristics of the constituent materials are the objectives. The experimental work is based on field data collection campaigns that are conducted using multichannel arrays for seismic measurements and multielectrode systems for resistivity along geophysical lines. The open source Python module pyGIMLi been used for data processing and inversion, enabling visible, repeatable, and adaptable inversion processes. By identifying conductive zones associated with infiltration paths and possible slip surfaces, ERT offers data on lithological differences and water content. In order to identify mechanical contrasts between stable and unstable layers, SRT makes it possible to image the distribution of P-wave velocities, which are connected to density, porosity, and degree of fracturing. In order to compute dynamic geomechanical characteristics and provide further limitations on the stiffness and deformation potential of the landslide materials, MASW generates shear-wave velocity models. A strong framework for defining the geometry of the landslide body, locating weak spots, and assessing slope stability is provided by the combined interpretation of these techniques. Additionally, the integrated methodology demonstrates how electrical and seismic methodologies complement one another, lowering uncertainties and enhancing the subsurface model's dependability. In summary, this thesis shows the value of integrating geophysical methods in landslide research in addition to providing a thorough description of the Pranola landslide. The findings, which demonstrate the potential of geophysical imaging as an affordable and non-invasive method for landslide hazard assessment, are anticipated to enhance future monitoring methods and risk mitigation measures.

Keywords: MASW, ERT, SRT, Landslide, Seismic Tomography, Electrical Tomography, Seismic Refraction

Contents

Chapter 1

Introduction

One of the main geohazards affecting many areas of the world is landslides, which are described as the downslope movement of debris, rock fragments, and loose earth elements [10]. Although several taxonomy schemes for landslides have been offered, the categorisation of Cruden and Varnes's [1996] is still the most often used [5]. This schema mainly characterises landslip events by their activity (including state, distribution, and morphodynamic style) and the kinematic characteristics of movement (such as speed, water content, and rock type).

Landslides show significant heterogeneity and occur on all types of geological substrates. The systematic characterization of such processes is inherently complex and frequently needs comprehensive, large-scale investigative endeavors [11]. These phenomena engender substantial loss of life and destruction of property, arising from a multitude of interrelated factors that compromise slope stability. Principal triggering mechanisms include topographic configurations; meteorological perturbations, such as intense precipitation, typhoons, and snowmelt-induced runoff; and geotectonic processes, notably seismic activity, volcanic eruptions, and elevated subsurface water saturation. The majority of landslide occurrences are associated with inherently unstable slopes, where hydrometeorological events act as critical catalysts by markedly amplifying the likelihood of slope failure [10].

In many parts of the world, landslides are seen as a common threat that seriously harms society. Due to their significant natural unpredictability and detrimental effects, they are still hard to anticipate. This restricts the potential to lessen the risk of landslides and its detrimental effects, especially the direct effects on the populace, such as fatalities, missing persons, and injuries [17]. Exorbitant costs for hazard reduction through extensive engineering interventions and methodical land-use planning are often beyond the means of low-income nations. On the other hand, developed nations are becoming less willing to invest in structural initiatives aimed at reducing the risks associated with geohazards. As a result, recent discussions highlight the need for early warning systems and land use regulations as practical ways to reduce fatalities and property damage without incurring the costs of large-scale, long-term ground-stabilization projects [8].

Strategic planning and thorough risk management can help reduce the socioeconomic harm caused by landslides. To lessen the risks connected with landslides, a number of mitigation projects have been implemented since 1977. However, in order to strengthen evidence-based decision-making processes and consolidate experiential knowledge, the effectiveness of these interventions requires systematic quantification [21].

Landslip body detection and characterisation require a multidisciplinary approach that incorporates ground-based and airborne techniques, geotechnical methodology, geophysical surveying, and geological context assessments. However, geotechnical and geological techniques have intrinsic limits when it comes to exploring subterranean structures; they are primarily limited to analysing drill samples and surface formations [9].

The present investigation focuses on a landslide in Pranola, Italy, employing Electrical Resistivity Tomography (ERT), Seismic Refraction Tomography (SRT), and Multichannel Analysis of Surface Waves (MASW) as primary geophysical methodologies. The study integrates open-source, Python-based platforms-specifically pyGIMLi-for inversion and visualization procedures, thereby ensuring methodological transparency, reproducibility, and computational adaptability [6]. The principal objectives of the research are as follows:

- To delineate the subsurface geometry and constrain the depth of the slip surface.
- To detect water-saturated zones and preferential pathways of fluid infiltration.
- To infer the mechanical characteristics of landslide materials through the analysis of P- and S-wave velocity distributions.
- To assess the efficiency and mutual complementarity of integrated geophysical techniques in landslide characterization.

Chapter 2

Geophysical model

Geological, geotechnical, and geophysical techniques can all aid in accurately characterising landslides. Due to their greater flexibility, speed, cost-effectiveness, non-destructiveness, and high-resolution determination of the landslide's internal structure, slip plane, hydrogeology, movement character, and mechanical properties, geophysical methods have gained popularity in landslide studies during the past 20 years [12]. Because of the strong lateral variations, one-dimensional (1D) geophysical techniques like vertical electrical sounding (VES), transient electromagnetics (TEM), and borehole logging are not commonly used for subsurface exploration in complicated geological contexts. Furthermore, because of the strong near-surface velocity contrasts and lateral velocity variations in fault zones, the high-resolution shallow seismic reflection method frequently suffers from diffraction and scattering phenomena, multiple reflections, and unsuccessful use of migration techniques, all of which affect the data quality [1,16]. Therefore, we used a multidisciplinary, near-surface geophysical method, employing seismic refraction tomography (SRT), electrical resistivity tomography (ERT), and MASW (Multichannel Analysis of Surface Waves) to examine the geologically complicated subsurface structure of the studied area.

2.1 Electrical Resistivity Tomography (ERT)

Electrical resistivity tomography (ERT) is a high-resolution and efficient geophysical technique that can produce 2D or 3D subsurface resistivity distributions. These distributions can usually be linked to spatial variations in the lithological composition and the presence of tectonic structures in the subsurface section under investigation. It has been frequently used to determine the effective depth of near-surface fault zones, their location, structural features, and the estimated width of the impacted zone. Additionally, this technique has been used in difficult geological contexts to define weathered and conductive zones and for geotechnical reasons to investigate bedrock depth, cracks, and subsurface air-filled spaces [7].

The introduction of modern instruments that can perform numerous voltage measurements for each current dipole concurrently, greatly lowering the measuring time and enabling the gathering of large datasets, has enabled the growing usage of ERT for many applications. Consequently, new multielectrode arrays and sequences have been made possible by these multichannel systems [14].

ERT surveys can employ a variety of electrode arrays, including gradient, square, dipole-dipole, Wenner, Schlumberger, etc. To send the electric current into the ground, the electrodes are positioned on the surface. The voltage signals that are produced as a result are then measured. It has been applied to the study of complicated geology, including geothermal and volcanic regions, landslides, seismotectonic structures, hydrogeologic phenomena, environmental issues, and the flow and deposition of breccias and impact melt [3].

In addition to ERT, seismic techniques are proposed that, although not yet widely employed in soil sciences, may be especially promising and helpful in resolving geotechnical and environmental issues. The effectiveness of seismic methods for estimating ground velocity structures and mechanical properties has advanced in recent decades due to the development of subsurface characterisation studies. These methods have found numerous applications in a variety of fields, including landslides and waste disposal.

2.2 Seismic Refraction Method

Since the early 1960s, landslides have been studied using the seismic refraction technique. The lateral extent of landslides and the depths to the failure surfaces have been estimated using refraction surveys [15]. Because they use oversimplified geometry by splitting the substratum into discrete layers of constant velocity, conventional seismic refraction processing techniques (intercept time and delay time-based methodologies) are unable to reveal the actual subsurface structure in complex environments. However, more sophisticated and complex inversion algorithms have made the seismic refraction tomography (SRT) technique an important geophysical tool for subsurface investigation in such environments [2, 22].

The material of the slope, the geometry of the sliding surface, the mass movement of landslides, the physical characteristics of the media, and the impacts of water saturation on the slope may all be described using this geophysical technique. As a result, the development of new algorithms and advancements in field data collection systems have made this approach suitable [10]. Refraction surveys can be used to determine the extent of a slide mass and to gather information about the earthwork factor, rippability, and construction. In addition, the technique is reasonably priced, the equipment is portable, and the environment is not disturbed while using refraction surveys for landslip studies.

Understanding the elastic characteristics of geological materials by analyzing the propagation of seismic waves is crucial for both engineering geology and geotechnical engineering. Dynamic elastic moduli and empirical correlations with geotechnical factors can be obtained from the seismic wave records [4].

Regarding the surface materials, the mechanical and physical characteristics of rock and soil are closely related to shear wave velocity. Shear wave velocity structure serves as the foundation for stratigraphic division, ground quality assessment, and liquefaction estimation in engineering practice. It is also a crucial method for determining the dynamic properties of rock and soil, foundation bearing capacity, and engineering seismic parameters. Potential failure surfaces in a landslip can be identified by observing the deformation of soil mass that always occurs close to the sliding surface, interfaces, or weak interlayers with large fluctuations in shear wave velocity. Thus, it is useful to analyse a landslide's shear wave velocity in order to obtain key information about the sliding surface. (such the depth and shape, etc.). It is a useful resource for preventing landslide risks. [20]Soil mechanics and foundation engineering are increasingly interested in studying the shear wave (S-wave). The significance stems from the direct correlation between the S-wave velocity and the resistance of the soil structure that the wave travels through. One of the primary factors used to forecast the tension-deformation behaviour of soils subjected to dynamic loads-that is, deformation at low strain levels-is the dynamic shear modulus, which is derived from the S-wave velocities and the material densities. [13]. Since seismic velocities typically reveal notable discrepancies between the landslide mass and the underlying bedrock, P-wave seismic refraction tomography is most frequently used in landslide characterization contexts. However, because seismic velocities overlap, it is typically impossible to distinguish between the various units and the impact of geomorphic processes on slopes made up of identical sediments. Because P- and S-waves are impacted differently by variations in saturation, porosity, or elastic moduli, this can be avoided by using P- and S-wave SRT. Recently, saturation characteristics of shallow aquifers have been successfully detected by deriving Poisson's ratio from a combined imaging of P- and S-wave velocities [19].

2.3 MASW (Multichannel Analysis of Surface Waves)

The stiffness and structural characteristics of the soils have an impact on seismic procedures. One of these techniques, MASW, efficiently and highly precisely identifies the sliding body and slip surface in landslip sites [12]. One of the most popular non-invasive geophysical techniques for obtaining near-surface VS models is multichannel analysis of surface waves (MASW). When combined with additional geophysical or geotechnical data, VS can provide a more thorough site characterisation than when used alone. When combined with density and P-wave velocity (VP), VS can infer other geotechnical parameters, including bulk modulus, shear modulus, and Poisson's ratio, that are important for landslip engineering and characterisation, for instance [18].

Chapter 3

Test site and Field data Acquisition

3.1 Overview of the site survey

The Paroldo landslide in the Cuneo province (Piedmont Region, Italy) is the location of the chosen research area. This area has been the focus of multiple geophysical monitoring and education initiatives. In particular, the shallow deposits of a thick sequence of clayey and marly layers are affected by the active slope instability that is noted at the location. (SIFraP, ARPA Piemonte, code 004-20283-01).

Due to its frequent geomorphological features, including tension cracks, scarps, and minor displacements down the slope, the landslide is suitable for study and instruction. As part of the didactic effort, field data was gathered on March 27, 2025.

A combined geophysical research using seismic and electrical techniques was developed to identify water-saturated zones, limit the depth to bedrock, and investigate the interior structure of the landslide body. Location map of the Paroldo landslide from the SIFraP database.

Figure 3-1 shows the position of the geophysical surveys, the landslide boundary, and installed monitoring instruments (such as GPS benchmarks, inclinometers, and piezometers).

Figure 3-2 shows an aerial view of the Paroldo landslide's geophysical survey line. To enable collaborative analysis of seismic and electrical data, the arrangement comprises of 48 geophones for seismic refraction and MASW and 48 electrodes for ERT, both of which are placed three meters apart. Additionally, the line's beginning (E1-G1) and ending (E48-G48) locations are shown.

3.2 Acquisition of seismic data

Deploying a seismic line with 48 geophones spaced 3 meters apart allowed for a total spread length of 141 meters. Several shooting locations were activated inside and outside the array to ensure adequate coverage and ray penetration. Information gathering for seismic refraction tomography (SRT) and multichannel analysis of surface waves (MASW)

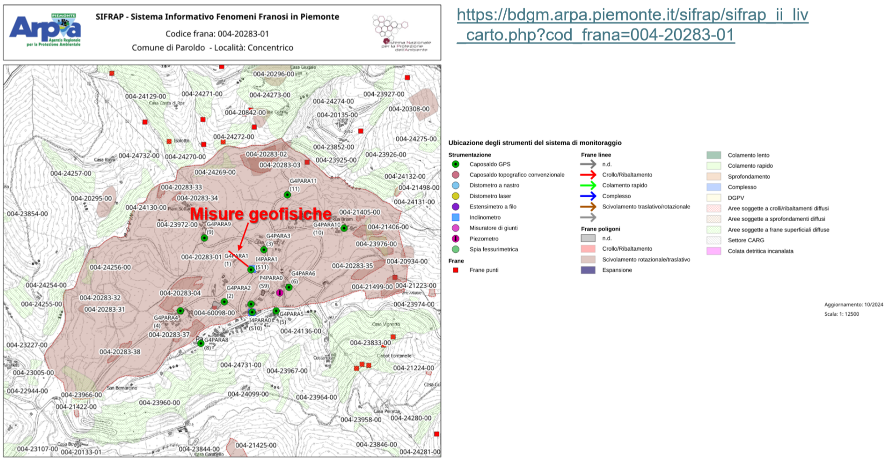

Figure 3.1. Paroldo landslide map - SIFraP.

Figure 3.2. Geophone and electrode layout.

was the aim of the seismic survey. P-wave velocity models were obtained by inverting initial arrival timings selected from the refraction data, and S-wave velocity profiles were produced by extracting dispersion curves from the surface-wave data and then inverting them. Each shot could be recorded more than once thanks to acquisition technology, which also made signal stacking possible to increase the signal-to-noise ratio. Due to the many soil types and background noise at the landslide site, this strategy was crucial.

3.3 Acquisition of electrical data

An electrical resistivity tomography (ERT) study was conducted concurrently along the same line using 48 electrodes spaced 3 meters apart to guarantee full alignment with the seismic architecture.

A multielectrode system that automatically switched between multiple current and potential electrode combinations allowed for the collection of a huge dataset. The Wenner-Schlumberger array was employed to balance the resolution and depth of the research.

By integrating seismic and electrical lines, the chosen survey method offers a standardized framework for the collaborative evaluation of resistivity and velocity models. As previously suggested in the literature, this integrated strategy should improve the subsurface reconstruction's dependability and decrease inversion ambiguities.

Chapter 4

Methodology

The geophysical methodology was created to provide an integrated technique to look at the landslide body's subsurface structure. There were multiple key phases in the methodology; Several shot locations and a variety of geophones were used to gather seismic refraction data in order to guarantee sufficient ray coverage throughout the landslide slope.

A multi-electrode device with various grid configurations was used to simultaneously collect electrical resistivity tomography (ERT) data. Both Wenner-Schlumberger and dipole-dipole electrode configurations were used in this study's ERT survey. The Wenner-Schlumberger array is especially well-suited for photographing stratified subsurface formations and penetrating the bedrock due to its greater depth penetration and sensitivity to vertical resistivity fluctuations. The dipole-dipole array, on the other hand, is better at identifying lateral heterogeneities like faults or slip surfaces because it has a higher lateral resolution and is more sensitive to horizontal resistivity differences. The simultaneous usage of both arrays guarantees complementing information, despite the fact that the dipole-dipole configuration is typically more susceptible to noise and offers shallower penetration than Wenner-Schlumberger. A more dependable reconstruction of the landslide geometry is produced by this integrated approach, which also decreases interpretation ambiguities and increases the resilience of the inversion results. Sensitivity to subsurface mechanical (velocity) and hydrogeological (resistivity) disparities was guaranteed by these complementary measurements. The seismic data was thoroughly examined to determine the initial P-wave arrivals.

A manual picking method was employed to ensure reliability, with modifications made for trigger delay and false negative timings. The travel-time dataset was then put together into a structure that was compatible with inversion.

The inversion was carried out in a Jupyter Notebook environment using the open-source pyGIMLi software. At each iteration of the iterative damped least-squares algorithm, which compared computed journey times to observed datasets, the velocity distribution was modified to lower the root mean square deviation (RMS). A smoothing restriction was applied to stabilize the inversion and stop unwarranted velocity oscillations. Along the seismic line, two-dimensional P-wave velocity (Vp) models were produced

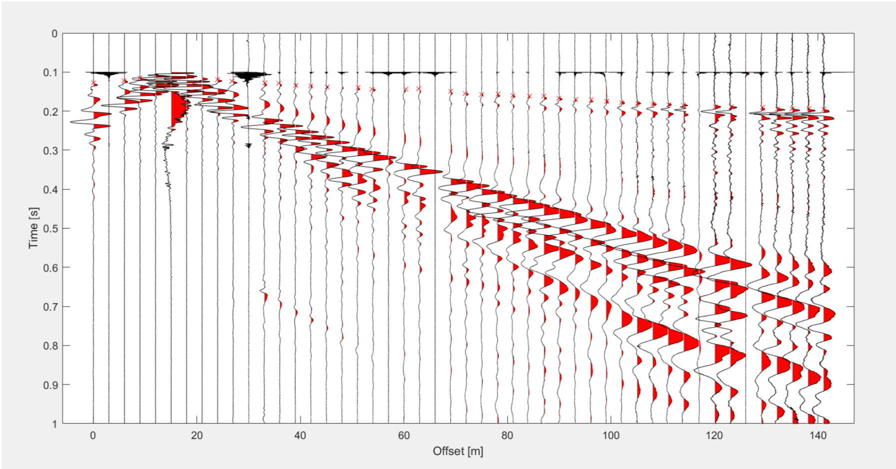

Figure 4.1. Example seismic shot gather, shown as wiggle traces (black) with positive amplitudes highlighted in red. Red crosses represent the manually selected first arrivals used for refraction tomography. The x-axis indicates the source-receiver offset (m), while the y-axis shows the travel time (s).

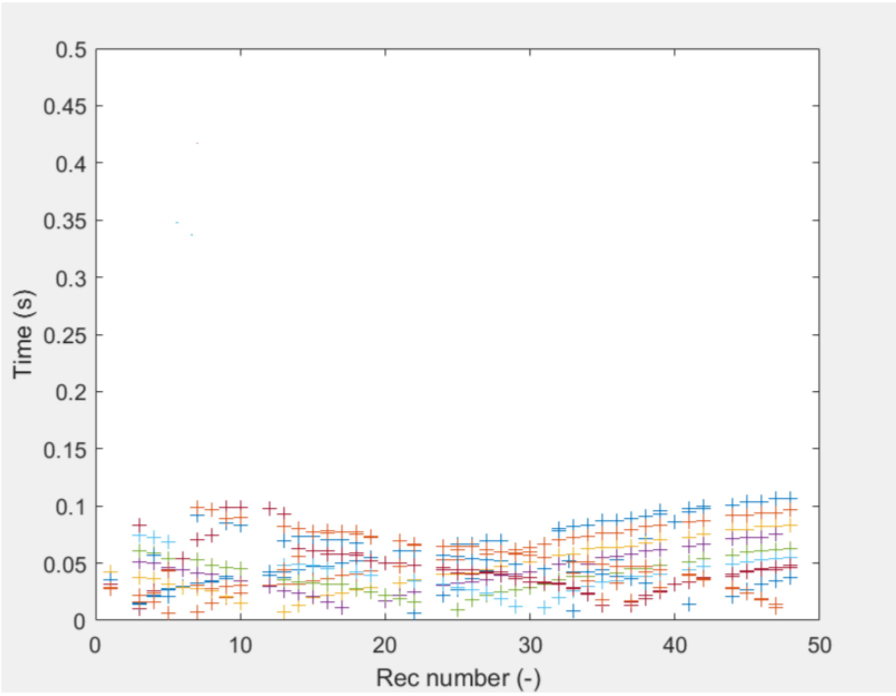

Figure 4.2. To make first-arrival picks, 12 shot records are used. Each source point's travel time (s) is shown next to its receiver number. Reliable first-break identification along the seismic line is suggested by the consistent linear trends, and each colored series represents a distinct shot point.

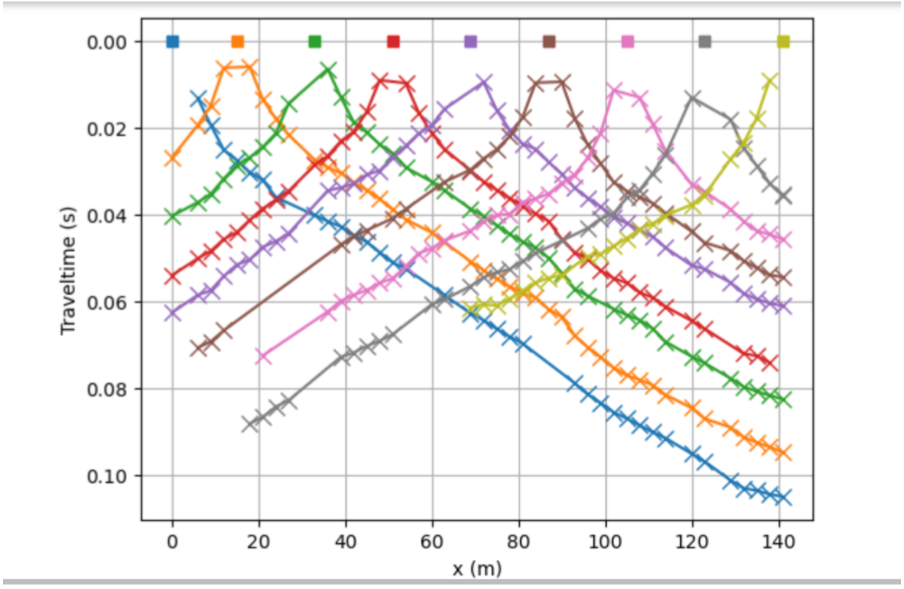

Figure 4.3. Travel-time curves for manual first-arrival picking are given as a function of source-receiver distance. Each coloured line represents a separate shot point, while red crosses indicate the chosen first arrivals. The travel-time information serve as input for seismic refraction tomography inversion.

by the inversion. Velocity sections highlight lateral and vertical changes in the subsurface to highlight differences between the loose debris from landslides and the underlying stable bedrock. The distribution of shear-wave velocity (Vs) was determined using the Multichannel Analysis of Surface Waves (MASW) approach. The frequency-velocity (f-VR) dispersion properties of Rayleigh waves obtained along the seismic line serve as the foundation for this technique.

The process included two essential steps: Dispersion curve extraction involved computing frequency-velocity spectra for each shot gather using a changing receiver window. By stacking, the signal-to-noise ratio improved, and the fundamental mode of Rayleigh waves was discovered. As shown in figure 4.4, dispersion curves were then manually selected to determine the most reliable frequency-velocity couples for inversion.

Inversion of dispersion curves -The selected dispersion data were inverted to produce one-dimensional Vs profiles, which were then merged to create a two-dimensional tomography along the seismic line. This method allowed us to determine the vertical and lateral changes in shear-wave velocity within the landslide body.

In addition, generated S-wave velocity (Vs) profiles, which were then integrated with Vp models to compute elastic parameters such as shear modulus, Young's modulus, and Poisson's ratio.

The dynamic Poisson's ratio was calculated as follows:

$$\nu = \frac{V_p^2 - 2V_s^2}{2\,(V_p^2 - V_s^2)}$$

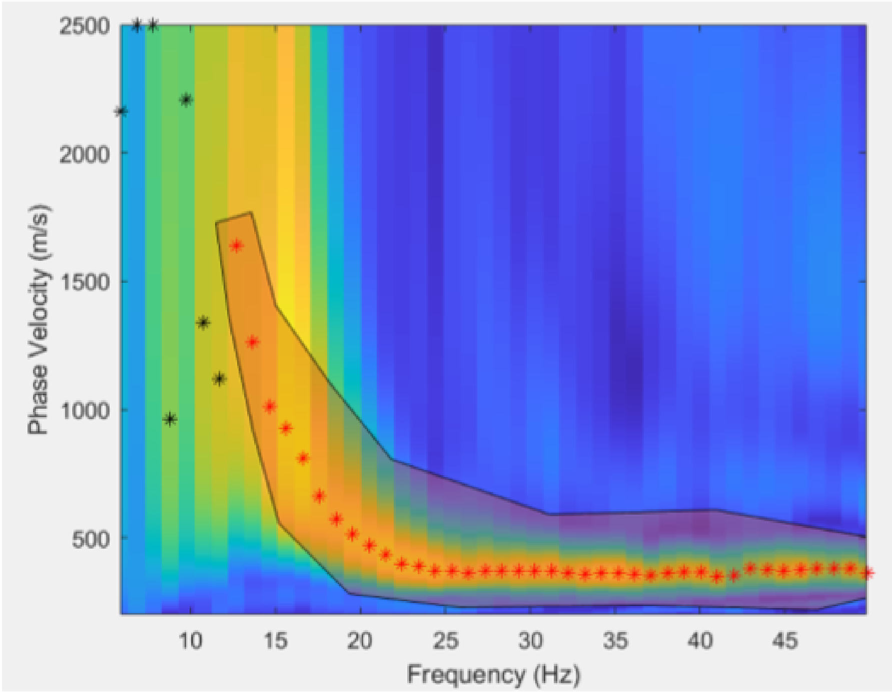

Figure 4.4. Example of frequency-velocity (f-VR) spectra and dispersion curve selection for MASW analysis. The fundamental Rayleigh mode is indicated and manually selected as the input for Vs inversion.

Vp represents the compressional wave velocity, and Vs is the shear wave velocity. The shear modulus was calculated from Vs and density (ρ) as follows:

$$G = \rho V_s^2$$

The calculations assumed a bulk density of 1900 kg/m^3, which is common for shallow landslide materials. Finally, the Young's modulus was calculated as:

$$E = 2G(1 + \nu)$$

SRT velocity models were compared to resistivity tomograms from ERT to show lithological boundaries, discover probable sliding surfaces, and characterize the landslide mass.

In certain cases, complementary information such as shear modulus, Young's modulus, and Poisson's ratio were derived using seismic P- and S-wave velocities to determine the mechanical properties of the slope materials.

Chapter 5

Results

The geophysical survey conducted at the Paroldo landslide site obtained complementary seismic and electrical datasets, which were processed and inverted to characterize the underlying structure.

This chapter presents the results of seismic refraction tomography (SRT), surface wave analysis (MASW), and electrical resistivity tomography (ERT). Together, these methodologies enable the detection of lithological differences, the delineation of the potential slip surface, and the assessment of hydrogeological conditions within the landslide body. Twelve shot records were collected along the seismic profile, which consisted of 48 geophones spaced 3 m apart. The raw seismic data was visually examined, and the first arrivals were manually selected to assure accurate identification of the P-wave onset times.

Figure 4.1 depicts a shot gather, with the red crosses representing the manually selected first arrivals. The travel-time picks from all twelve shots were combined into a single dataset.

Figure 4.2 shows the travel-time curves shown as a function of receiver number for each shot. The similar linear trends seen across various offsets validate the hand- picking technique and assure enough ray coverage across the landslide slope.

Before being inverted using travel-time tomography, the generated dataset was imported into the pyGIMLi framework. The final chi-square value was less than 1, indicating a stable and well-constrained solution, after the inversion strategy iteratively decreased the root mean square (RMS) variance between the calculated and observed travel times. A distinct shooting location is represented by each color in Figure 4.3, which displays the chosen travel time imported into Jupyter Notebook.

5.1 Seismic Refraction Tomography: Vp Results

Figure 5.1 depicts the final P-wave velocity (Vp) tomogram obtained after seismic refraction inversion. The velocity distribution ranges from roughly 500 m/s in the shallowest region of the profile to around 1800 m/s at deeper depths.

The uppermost 5–10 m had low velocities (500–800 m/s, blue-cyan colors), indicating unconsolidated deposits producing the landslide body. These results imply a soft material

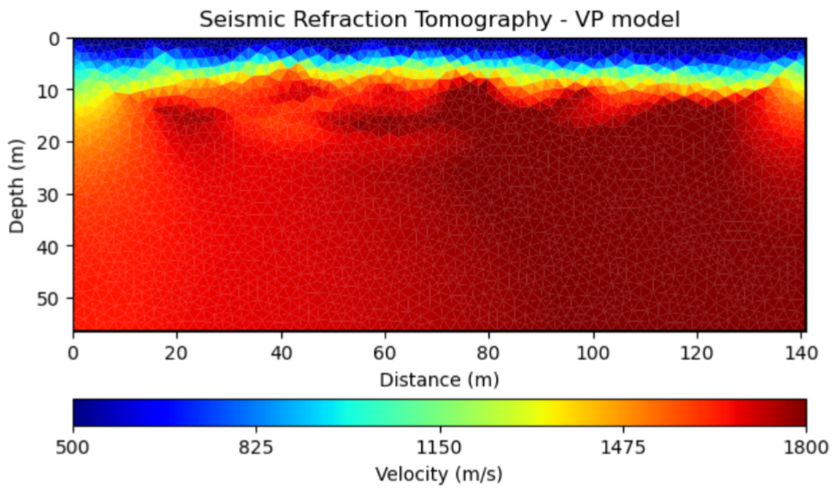

Figure 5.1. final P-wave velocity (Vp) tomogram. Low velocities (500–800m/s, blue to cyan) imply unconsolidated landslide deposits, whereas higher values (above$\approx$ 1400 m/s, orange to red) indicate a more competent substratum.

with low compaction, which is consistent with the expected geomorphological situation.

Velocity gradually increase to 800–1400 m/s at intermediate depths (10–25 m). This change indicates materials that are more compressed but still not very strong. The reddish color velocity below 25–30 m exceed 1400–1800 m/s, suggesting a more competent substratum that probably corresponds to broken but comparatively intact bedrock.

Lateral differences are also seen along the profile: Between 60 and 130 m, a zone with significantly higher velocities (aproaching 1800 m/s) occurs at a shallower depth, indicating a thinner landslide cover and shallower bedrock. In contrast, the center of the profile has a thicker low-velocity layer, indicating a deeper deposit of sedimentary material. Overall, the Vp model emphasizes the contrast between loose landslide deposits and the more competent underlying substrate, giving significant limits on the depth to bedrock and internal variability of the landslide body. The graphic depicts the radiation coverage map from the seismic refraction tomography inversion. The horizontal axis shows the profile distance in meters, while the vertical axis shows the depth.

The number of seismic rays traveling through each model cell is shown by the color scale, which goes from light to dark green. The inversion results are more credible when the regions colored in darker green correspond to areas with a higher ray density and more seismic wave paths intersecting the model. These zones are therefore better constrained by the observed data. Conversely, areas with little to no ray coverage are highlighted by lighter colors and white gaps. In these cases, the inversion is mostly reliant on regularization and smoothing, and the resulting velocity estimates should be carefully assessed.

The final P-wave velocity (Vp) tomogram obtained after the seismic refraction tomography inversion is shown in the image above. The vertical axis shows the depth, and the

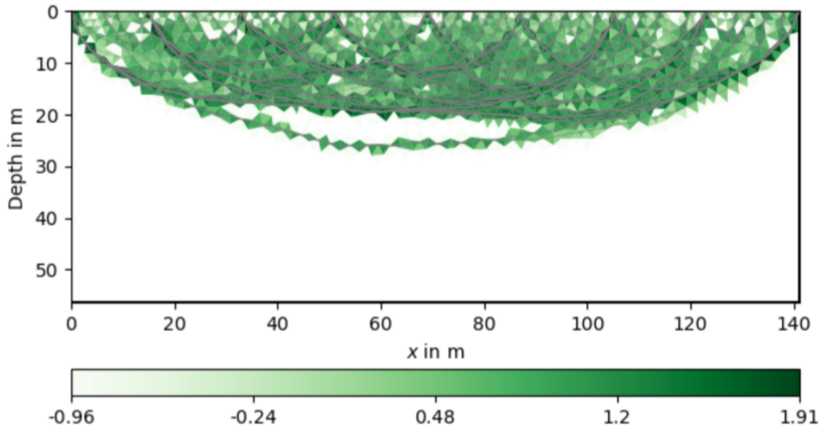

Figure 5.2. Ray coverage map for the seismic refraction tomography inversion. Darker green areas represent higher ray density and better model limitation, while lighter areas correlate to places with limited coverage and greater uncertainty.

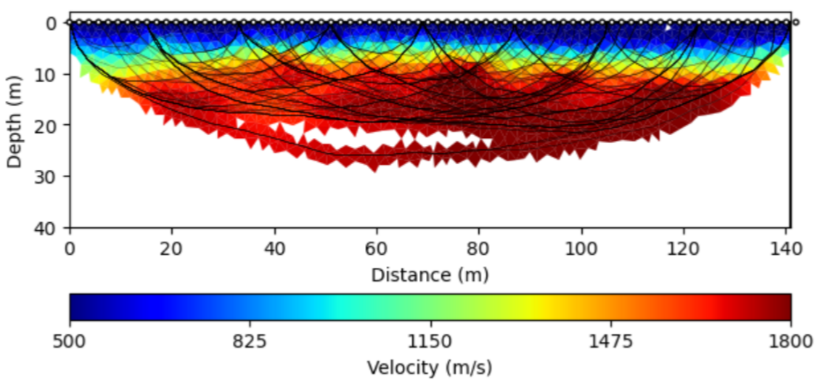

Figure 5.3. final P-wave tomogram for velocity (Vp). While high values (1200–1800 m/s) imply compacted debris and bedrock, low values (500–800 m/s) reflect loose landslide deposits.

horizontal axis shows the profile distance. Seismic velocity in meters per second is represented by the color scale. Low velocities (about 500–800 m/s, blue-green hues) in the shallow subsurface suggest loose, unsecured, and potentially water-saturated landslide deposits. Velocities progressively increase to 1200–1800 m/s (orange-red hues) at deeper depths, indicating the transition to competent bedrock and more compacted material.

Laterally, the model shows heterogeneity: a thicker low-velocity zone in the middle of the profile indicates a buildup of colluvial deposits, while higher velocities appear at shallower depths between 60 and 130 m along the line, suggesting a shallower bedrock surface and a thinner landslide cover. As shown in Figure 5.4 The inversion quality was measured by comparing the measured first-arrival travel times with the forward-calculated

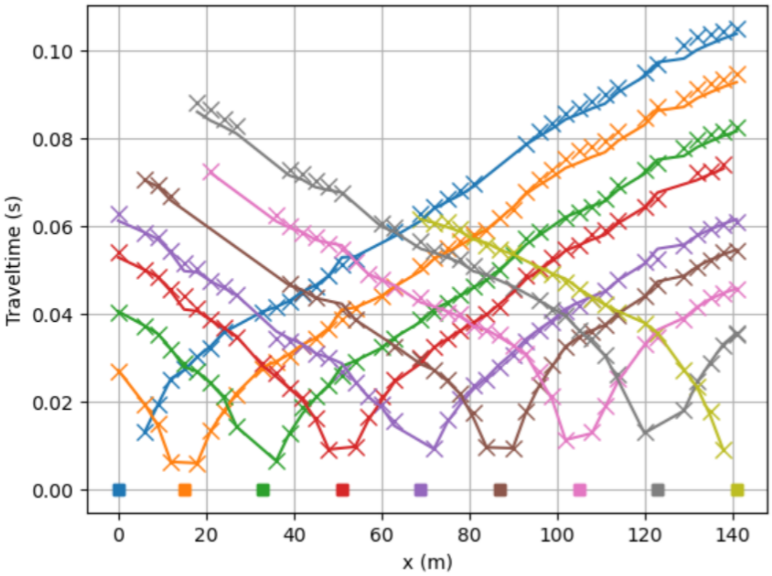

Figure 5.4. Comparison of observed first-arrival travel times (crosses) with calculated travel times from the final tomographic model (lines).

times derived from the final velocity model.

The two data sets match each other quite well, and the residuals fall well within the designated error range. This tight fit shows that the inversion technique was reliable and that the final tomogram faithfully captured the data that was recorded.

5.2 Surface Wave Analysis (MASW) : Vs Results

As illustrated in the figures 5.5 and 5.6, the first set of inversion results concerns the distribution of P-wave velocity (Vp) and S-wave velocity (Vs) along the examined profile.These tomograms provide vital information on the mechanical and hydrological parameters of the landslide body.

P-wave velocities (Vp) range from between 600 and 1000 m/s in the immediate subsurface to between 2000 and 2500 m/s at deeper depths. The lowest values indicate that the landslide cover is composed of loose, unconsolidated colluvial deposits (green and blue hues). In line with such results are significant porosity and partial or total water saturation, which reduces the stiffness of the material. While velocities can surpass 2000 m/s in competent bedrock, the gradual increase in Vp with depth indicates the transition to more compacted sediments. The thickness of the landslide deposits is not uniform, as seen by lateral differences in Vp. The bedrock surface emerges at shallower depths in some areas, whereas the central portion of the profile has a protracted low-velocity zone, suggesting thicker accumulations of unstable material.

S-wave velocities (Vs) are significantly lower, ranging from 200–300 m/s near the surface and 500–600 m/s in deeper, more compacted zones. Unlike Vp, which is heavily

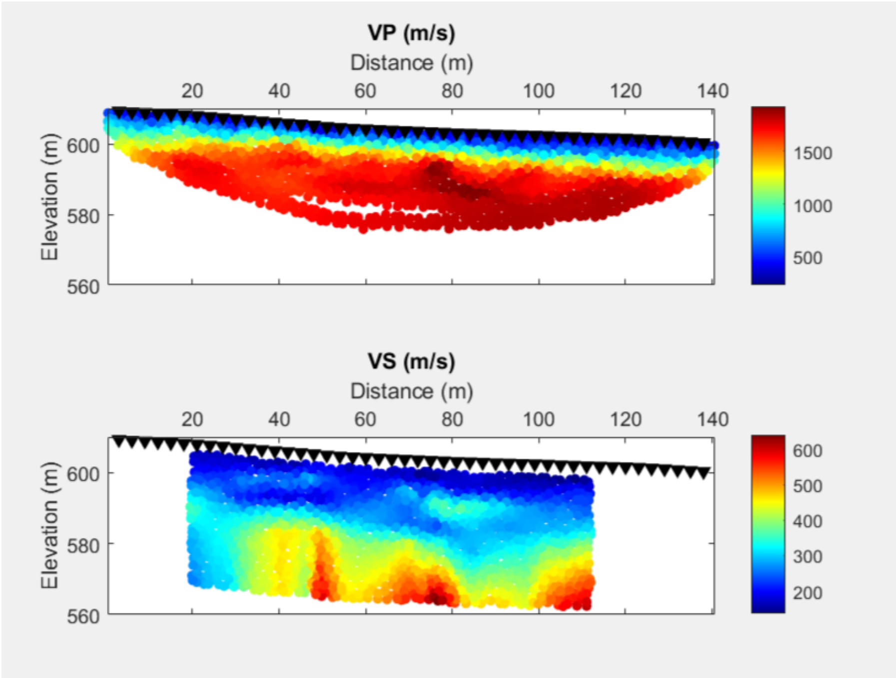

Figure 5.5. To preserve surface topography, P-wave (Vp) and S-wave (Vs) tomograms are shown with actual elevation. This picture shows how high-velocity bedrock and low-velocity landslide material differ, and how slope morphology affects subsurface geometry.

controlled by both the mineral structure and the pore water, Vs is predominantly affected by the medium's shear strength and rigidity. Thus, low Vs values indicate weak, flexible materials within the landslide body, whereas higher Vs values indicate stiffer units approaching bedrock conditions. The combined analysis of Vp and Vs shows the presence of mechanically weak horizons in the upper few meters, which are most sensitive to deformation and sliding.

When the two tomograms are compared, they show complementary aspects: Vp emphasizes lithological contrasts and potential zones of saturation, while Vs emphasizes the mechanical abilities of slope materials. They work together to provide a more reliable delineation of the landslide body and depth to bedrock, reducing interpretation difficulties that would otherwise exist if only one velocity field was examined.

These seismic velocity distributions are also used to derive elastic parameters like Poisson's ratio, shear modulus, and Young's modulus, which are explained in the following section.

5.3 Mechanical Parameters determined by Vp and Vs

In order to Better understand the geotechnical properties of the landslide material, Poisson's ratio (v), shear modulus (G), and Young's modulus (E) derived from the seismic

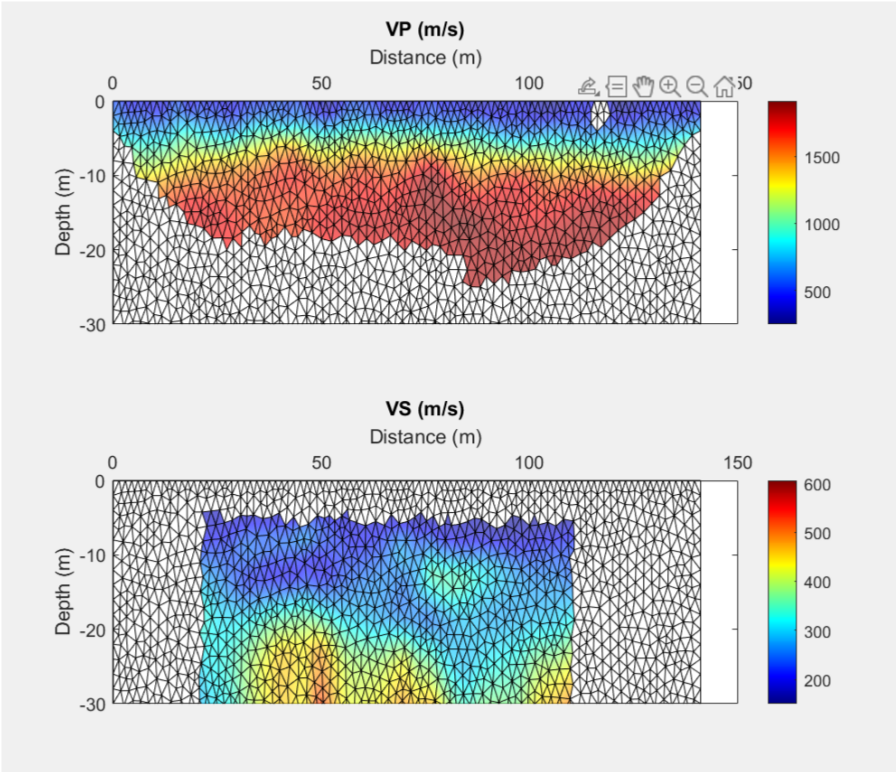

Figure 5.6. P-wave (Vp) and S-wave (Vs) tomograms were plotted as depth sections, with depth measured downward from a flat standard line. Low velocities (Vp ≈ 500–800 m/s; Vs ≈ 200–300 m/s) indicate loose landslide deposits, whereas higher values indicate more compacted material and bedrock.

velocity models that give aditional information about the subsurface's stiffness and deformation behavior. In unconsolidated and somewhat saturated soil, the Poisson's ratio readings are rather consistent, generally falling between 0.3 and 0.4. This demonstrates the significant porosity of the landslide deposits and their vulnerability to volumetric deformation under stress. There is noticeable lateral and vertical fluctuation in the shear modulus (G). Very low values (< 0.1 GPa) are found close to the surface, suggesting weak, pliable materials that are vulnerable to slope failure. G rises (>0.3–0.4 GPa) at deeper depths, signifying the proximity to bedrock and a change toward stronger, more rigid layers.

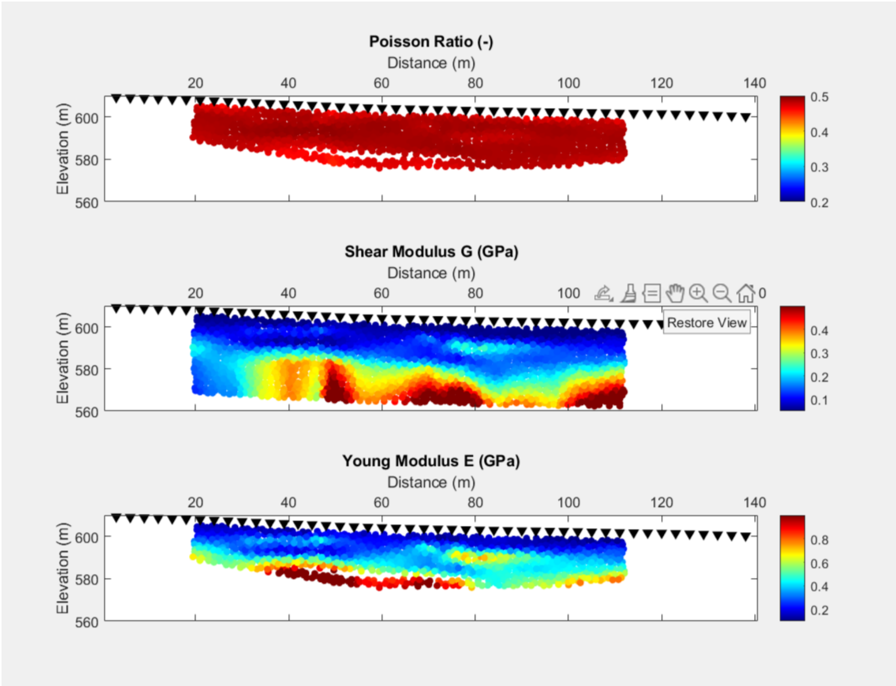

Figure 5.7. Young's modulus (E), shear modulus (G), and Poisson's ratio in connection to actual elevation. By confirming weak shallow deposits and stronger zones at depth, the results show how slope topography affects mechanical behavior.

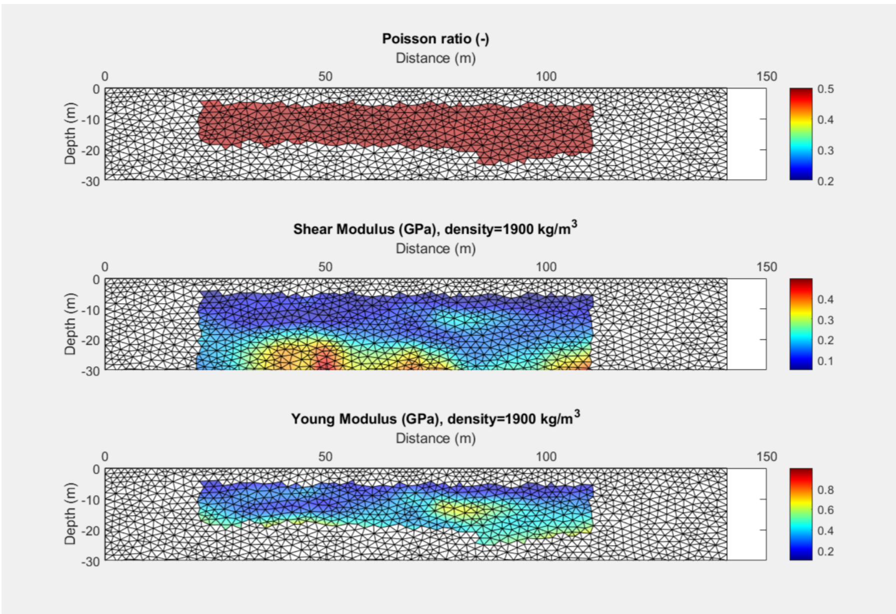

Figure 5.8. Poisson's ratio, shear modulus (G), and Young's modulus (E) plotted versus depth. Low values near the surface indicate weak landslide deposits, but larger values at depth suggest tougher material and bedrock transition.

The upper half of the profile has greater values (up to ≈0.8 GPa) at depth. This value measures the total stiffness of the material, validating the distinction between weak landslide deposits and stronger underlying formations. These mechanical parameter distributions, when combined, clearly indicate the landslide body as a zone of weak rigidity and mechanical competency above a more stable subsurface. Such data are critical for assessing slope stability and determining the depth and shape of potential sliding surfaces.

5.4 Electrical Resistivity Tomography (ERT) Results

Using 48 electrodes spaced 3 meters apart, the electrical resistivity tomography (ERT) survey was conducted along the same path as the seismic readings. Dipole-Dipole (DD) and Wenner-Schlumberger (WS) electrode designs were tested. The inverted 2D resistivity models serve as the foundation for the geological interpretation, whereas apparent resistivity pseudosections offer an initial visual representation of the data coverage and quality.

In the inverted models, resistivity values range from about 18 to 33. $\Omega \cdot \text{m}$ The lower resistivity zones (≈18–23 $\Omega \cdot \text{m}$) are interpreted as clayey and marly deposits with a higher moisture content in agreement with the geological setting of the landslide. Higher resistivity values (>25 $\Omega \cdot \text{m}$) found at deeper depths, on the other hand, are consistent with thicker, less saturated layers and may signal the shift to bedrock.

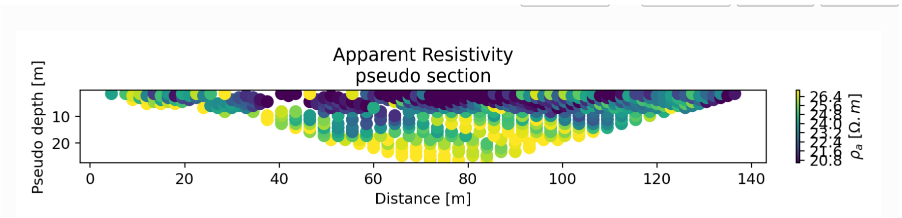

Figure 5.9. Dipole-Dipole apparent resistivity pseudosection before inversion.

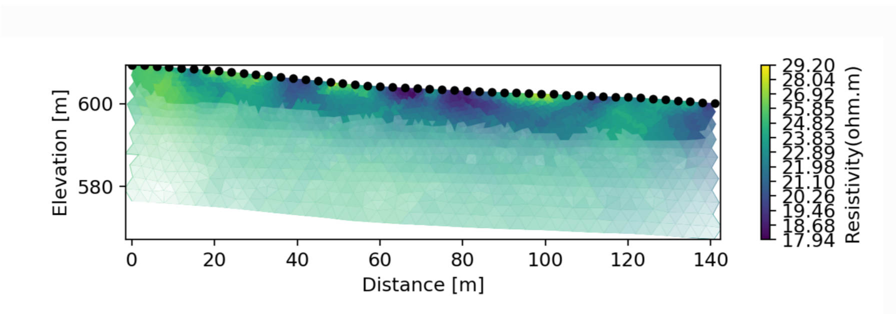

Figure 5.10. The Dipole-Dipole array was used to create a 2D inverted resistivity model. The section reveals conductive patches along the profile that may indicate clay-rich or water-rich zones by resolving lateral resistivity differences (≈18–29$\Omega \cdot \text{m}$).

Localized conductivity anomalies in the profile are highlighted by the Dipole-Dipole inversion illustrated in Figure 5.10, especially between 60 and 100m. These anomalies can point to weak spots or preferred penetration zones inside the landslide body. However, the Wenner-Schlumberger inversion, as shown in Figure 5.12, offers a smoother vertical trend and a greater resolution of the resistive substratum's depth. The comparison shows that the two arrays are often complementary: the WS array offers greater deep penetration, while the DD array improves lateral resolution and identifies heterogeneities more successfully. The conductive shallow horizons discovered by ERT overlap with low Vp and Vs zones when compared to the seismic results, confirming their characterization as loose, water-saturated colluvial deposits. Seismic models show, however, that velocity and resistivity both rise with depth, indicating the approach to the more compact substratum.

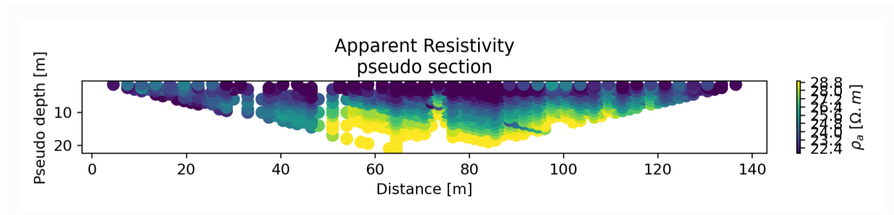

Figure 5.11. a pseudosection of apparent resistivity (Wenner-Schlumberger) before inversion.

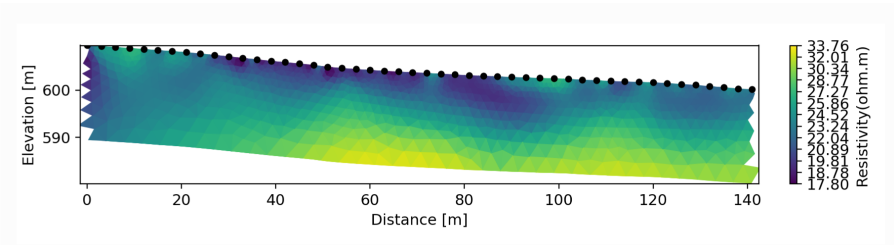

Figure 5.12. The Wenner-Schlumberger array was used to create a 2D inverted resistivity model. With lower resistivities close to the surface and larger values at depth, the model highlights the vertical resistivity distribution and the depth to the resistive substratum.

5.5 Integrated interpretation: SRT + MASW + ERT

An accurate image of the landslide body is produced by interpreting the electrical resistivity (ERT) and seismic (Vp, Vs) data together. The existence of soft, clay-rich, water-saturated deposits that are prone to deformation is confirmed by shallow low-resistivity anomalies in ERT that correspond to low Vp and Vs zones. In contrast, the change to more compact and competent layers–likely related to the underlying bedrock–is marked by the slow increase in resistivity with depth, which coincides with an increase in seismic velocities.

By resolving lateral variances and highlighting potential weak zones or preferential water paths within the landslide, DD arrays clarify interpretational uncertainty, whereas WS arrays offer consistent information on the depth to the resistive substratum.

Chapter 6

conclusion and suggestion

6.1 Conclusion

To analyze the Pranola landslide, this thesis used an integrated geophysical technique that included seismic refraction tomography (SRT), multichannel analysis of surface waves (MASW), and electrical resistivity tomography (ERT). The objective was to characterize the subsurface structure, define the slip surface, and evaluate the geomechanical parameters of the landslide body.

- The results demonstrated that SRT (Vp models) was able to capture the difference between the competent substratum underneath and loose, unconsolidated landslide deposits. Higher velocity (aproaching 1800 m/s) signify a transition to bedrock, whereas lower velocities (500–800 m/s) correspond to colluvial and water-saturated materials.

- With reference to the stiffness and shear strength of slope materials derived by MASW (Vs), a greater degree of competency was observed in layers possessing higher Vs values($>500m/s$) at depth. Whereas, their lower counterparts having lower Vs (200-30 m/s) illustrated weak layers, which rendered them to a high probability of collapse.

- An understanding of the rigidity contrasts that govern slope instability was gained from the mechanical features (ν,G, E) derived from Vp and Vs, which confirmed the existence of soft, flexible deposits atop a rigid surface.

- In addition to seismic results, ERT tomograms showed areas that might act as slip surfaces by identifying conductive zones linked to high moisture content and possible infiltration pathways. Particularly, ERT identifies relatively low resistivity values ($\approx$18–23 $\Omega\cdot$m), which are characteristic of materials that are water-saturated and clay-rich within the landslide body.

It was concluded that the application of the seismic and electrical techniques not only resulted in the reduction of ambiguities but also contributed to the increment of reliance upon the interpretation, which will eventually lead to a more precise reconstruction of the landslide geometry.

6.2 Suggestion

A variety of similar topics in this realm could be exposed to further investigation in the prospective research studies with the aim of supporting and elaboration of the fruits of the current study. In particular, some noteworthy points are mentioned below:

- Time-lapse monitoring: Repeated ERT and seismic surveys could detect seasonal or rainfall-induced changes in water content and stiffness, providing early signs of slope instability.
- 3D surveys: Moving from 2D profiles to 3D geophysical imaging would better capture the landslide's spatial variations and complicated geometry.
- Coupling with geotechnical data: Better calibration of geophysical parameters would result from combining laboratory testing, in-situ shear strength measurements, and borehole logging.
- Numerical modeling: The resulting mechanical characteristics can be used in slope stability models to objectively examine failure mechanisms and improve risk prediction.

The study concludes by showing how effective it is to combine seismic and electrical geophysical techniques for landslide characterization. Not only do the results give a clear account of the Pranola landslide, they also demonstrate the wider potential of non-invasive geophysical imaging as an economical way to monitor and analyze landslide hazards.

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