Landslide Simulation through Seismic Refraction Tomography

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ABSTRACT

The critical importance of characterizing complex landslide environments for effective geohazard assessment is widely recognized. In this study, the utility of Seismic Refraction Tomography (SRT) for detailed subsurface investigation was rigorously demonstrated through synthetic modeling and inversion. A robust methodological framework was established, encompassing the generation of a realistic 2D subsurface velocity model and the simulation of seismic travel time data. Subsequently, accurate inversion techniques, employing the Finite Element Method (FEM) and Delaunay Triangulation (DT), were applied to reconstruct the internal geological structure. The resulting analysis of synthetic travel times and inverted velocity models, including the clear delineation of velocity contrasts and an assessment of ray path coverage, effectively validated SRT's capability in mapping subsurface features pertinent to slope stability. This approach is considered to confirm the potential of integrated geophysical simulations, thereby enhancing the understanding of landslide dynamics and providing a powerful tool for reliable subsurface characterization, which is crucial for informed geohazard assessment and mitigation strategies.

Keywords: *SRT*, Landslide, *Finite Element Method (FEM), Synthetic Modeling, Inversion*.

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1. *INTRODUCTION*

Geological hazards represent a significant and ongoing challenge globally, profoundly impacting human safety, critical infrastructure, and ecological stability. These phenomena frequently disrupt societal functions and economic activities, often leading to substantial long-term consequences. Among the spectrum of natural dangers, landslides stand out due to their widespread occurrence and destructive potential. Fundamentally, a landslide is characterized as the gravitational movement of earthen materials, rock, debris, or soil, down a slope, a process scientifically termed "mass wasting." A typical landslide area and its constituent parts are schematically depicted in Figure 1, illustrating the diverse scales and forms these events can manifest [1].

The inherent complexity of landslide formations, which integrate intricate geological structures, varied geomorphological features, and dynamic hydrogeological conditions, poses a formidable challenge for near-surface geophysical investigations. Nevertheless, recent innovations in both two-dimensional and three-dimensional geophysical methodologies have ignited considerable interest. These advancements enable more precise estimations of landslide volume, detailed characterization of the physical properties of the materials involved, and effective tracking of groundwater pathways within and around active landslide masses. Due to the highly heterogeneous nature of these environments, a multi-methodological geophysical approach has become indispensable for achieving reliable data. The specific combination of techniques is primarily determined by the anticipated variations in the subsurface physical parameters at a given site [2].

Geophysical methods, especially Seismic Refraction Tomography (SRT), are indispensable for investigating landslides and characterizing subsurface conditions. SRT, in particular, employs seismic waves to create detailed models of underground structures. This capability is crucial for pinpointing faults and geological boundaries that could act as triggers for slope instability. The method proves particularly valuable for forecasting landslide movements, especially in areas with steep topography, thereby significantly contributing to effective risk assessment and the informed design of infrastructure. While both geophysical approaches offer essential insights, it's important to acknowledge their inherent challenges, such as the complexity of data interpretation and the influence of various environmental factors [3].

SRT offers invaluable capabilities for understanding complex landslide dynamics by generating models of subsurface architecture based on seismic wave propagation. This approach provides critical insights into fault zones and the varying material properties that directly influence slope stability. Research has demonstrably proven SRT's efficacy in challenging steep topographies, where it has been successfully employed to delineate slip surface geometries, analyze the dynamics of unstable soil masses, and evaluate the influence of water saturation on slope behavior [3].

Beyond these primary applications, SRT is also utilized for post-event structural integrity assessments. Furthermore, its capacity to facilitate the creation of robust velocity models through time-based inversion significantly refines landslide prediction, particularly in intricate geological environments [4], [5]. Complementary techniques, such as ambient seismic noise analysis, have additionally contributed to mapping components of sliding systems by identifying subtle impedance contrasts. Full elastic wave inversion and unstructured meshing with SRT have enabled detailed simulations of sliding areas [6], [7], [8]. Additionally, the Finite Element Method (FEM) is used for modeling in areas with complex and severe topography terrain, enabling the analysis of wave propagation [9]. These findings are often cross-validated with Electrical Resistivity Tomography (ERT), reinforcing the reliability of the geophysical interpretations [10].

2. METHODOLOGY

This section outlines the forward and inverse modeling algorithms specifically tailored for 2D SRT. Delaunay triangulation is employed for discretizing the subsurface model domain. This approach is particularly effective for accurately reconstructing geological features in challenging terrain characterized by rugged topography and intricate source geometries.

2.1. Forward Modeling

The fundamental role of forward modeling in geophysics is to predict theoretical data based on a known subsurface model and seismic sources. In this study, a finite element framework is utilized to compute synthetic seismic responses, such as apparent velocity, from predefined subsurface velocity distributions. The general relationship between the subsurface model and observed data can be expressed as:

$$d_{obs} = F(m) + n \quad (1)$$

Here, F represents the forward modeling operator, which maps the subsurface model m (a vector of seismic velocities) to the predicted data d. The observed data dobs comprises the true data and noise n. This problem is generally well-posed, ensuring a unique theoretical solution for a given model [11].

The governing equation for 2D SRT forward modeling is the Eikonal equation, which describes the travel time T of seismic first-arrival waves. This equation accounts for seismic velocity $v(\mathrm{x.z})$ variations in the horizontal (x) and depth (z) directions. This equation is foundational for computing travel times in the spatial domain and can be expressed as:

$$(\frac{\partial T}{\partial x})^2 + (\frac{\partial T}{\partial Z})^2 = ((\frac{1}{v(\mathrm{x.z})}))^2 \quad (2)$$

While the Eikonal equation is used for spatial-domain travel-time modeling, the Helmholtz equation is leveraged in the wavenumber domain to compute synthetic seismic wavefields. This wavefield computation is then used to derive travel times, complementing the Eikonal equation approach and ensuring consistency with the overall synthetic response generation [12], [13], [14].

For 2D SRT, where subsurface properties are assumed constant in the y-direction, a cosine Fourier transform is applied to convert the spatial-domain equations into the wavenumber domain. This transformation significantly enhances computational efficiency. The resulting wavenumber-domain solutions are then converted back to the spatial domain to derive measurable quantities like apparent velocity. For horizontally layered subsurface models, a zeroth-order Hankel transform is employed to convert the velocity kernel into apparent velocity, aligning with the SRT field survey setup (Operto et al., 2007).

2.2. Inverse Modeling

Inverse modeling in SRT aims to estimate subsurface seismic velocities from measured seismic travel time data. Unlike forward problems, inverse problems are inherently ill-posed, nonlinear, and sensitive to geological noise and measurement errors. The input data for SRT inversion consists of seismic first-arrival travel times, from which the apparent velocity distribution is derived. Due to the non-uniqueness of inverse solutions, regularization techniques and optimization methods are essential to ensure stable and accurate results. Numerical techniques, such as the FEM, are commonly employed to solve the governing equations for SRT data inversion [15].

The evolution of geophysical inverse modeling has prioritized robust computational methods to resolve complex geological structures. Early theoretical work highlighted the importance of defining clear objective functions for discrete inverse problems [16], leading to advanced criteria that enhance model reliability even with inconsistent data [17]. Specific advancements in SRT have seen the development of direct inversion methods for characterizing subsurface velocity structures, followed by iterative schemes for refining 2D velocity models [18], [19]. The integration of migration and reflection tomography has further improved SRT's ability to map complex geological boundaries, proving critical for landslide investigations [20].

To address the non-uniqueness and instability of the inverse problem, a regularization term is added to the objective function, which is minimized during the inversion process. This function balances fitting the observed data with maintaining model smoothness or simplicity. The general form of the regularized objective function is:

$$\phi = \|(d_{obs} - F(m))\|_2^2 + \lambda\|R(m)\|_2^2 \quad (3)$$

Here, d_{obs} is the observed data, $F(m)$ is the calculated data from the forward model, m is the model parameter vector (seismic velocities), $R(m)$ is a regularization operator (e.g., a smoothness constraint), and λ is the regularization parameter. This term is crucial for managing large, complex datasets inherent in landslide applications [21].

The subsurface model is discretized using Delaunay triangular meshing (DT). This unstructured mesh design supports the FEM by assuming uniform properties within each cell, allowing for an accurate representation of complex geology. The quality of the mesh is evaluated using a parameter that relates a triangle’s area to the squared sum of its edge lengths [22].

3. SEISMIC SIMULATION OF LANDSLIDE MODEL

This section details the development of a synthetic subsurface model specifically designed to replicate the topographical and geophysical characteristics of a landslide environment for SRT simulation. This synthetic model serves as a controlled environment to generate realistic seismic data, which is crucial for testing inversion algorithms and evaluating the overall methodology. The model's geometry and material properties are carefully defined to represent the subsurface architecture of a typical landslide. A simplified schematic of a landslide and th related components of it are depicted on Fig. 1.

The synthetic model is conceptualized as a multi-layered structure extending to a depth of 120 meters, facilitating a comprehensive characterization of potential sliding surfaces. Three distinct geological layers are considered, each assigned a unique seismic velocity to represent varying material compositions and consolidation levels. Table 1, for example, would typically present these predefined seismic velocity values for each layer.

The initial geological model, which forms the basis for the simulation, is constructed by defining specific polygonal regions for each layer, reflecting expected subsurface stratigraphy. This includes defining key boundaries and the overall slope morphology, as shown in the primary geometry of the synthetic SRT model (Figure 2a). The underlying numerical mesh, which discretizes this geological model for computational analysis, is then generated. This mesh, an unstructured triangular grid, is optimized for finite element modeling, allowing for accurate representation of complex geological features (Figure 2b). The quality of this mesh is rigorously evaluated to ensure numerical stability and accuracy during the forward modeling process, with metrics like minimum, maximum, and mean quality typically assessed (Figure 2c).

For the SRT simulation, a network of seismic sources and receivers is strategically positioned across the simulated topographic terrain. The Python code defines three distinct layers with assigned seismic velocities detailed in Table 1.

Table. 1. Geophysical Descriptions of the Synthetic Landslide Model.

Layer	Resistivity (Ωm)	V_p (m/s)	Material
First layer	150	500	Alluvium + Conglomerate + Tuff
Second layer	50	1700	Alluvium
Third layer	350	3000	tuff

These velocities are clipped to a predefined range (500 to 3000 m/s) to ensure realistic physical parameters. The spatial distribution of these assigned velocities across the discretized mesh, along with the simulated sensor locations, constitutes the synthetic 2D landslide velocity model used for simulation (Figure 2d).

Following the setup of the synthetic velocity model and sensor configuration, the forward modeling process computes the theoretical first-arrival travel times for seismic waves propagating through this defined subsurface. These synthetic travel times are then used as the "observed" data for the subsequent inverse modeling.

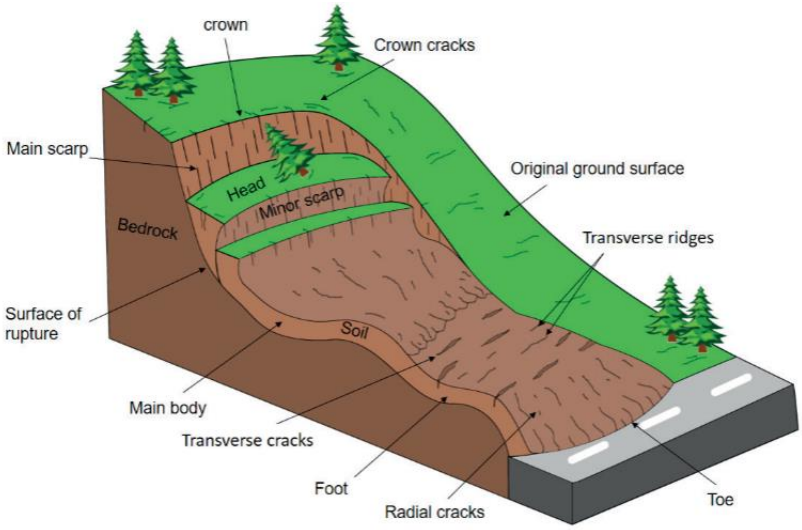
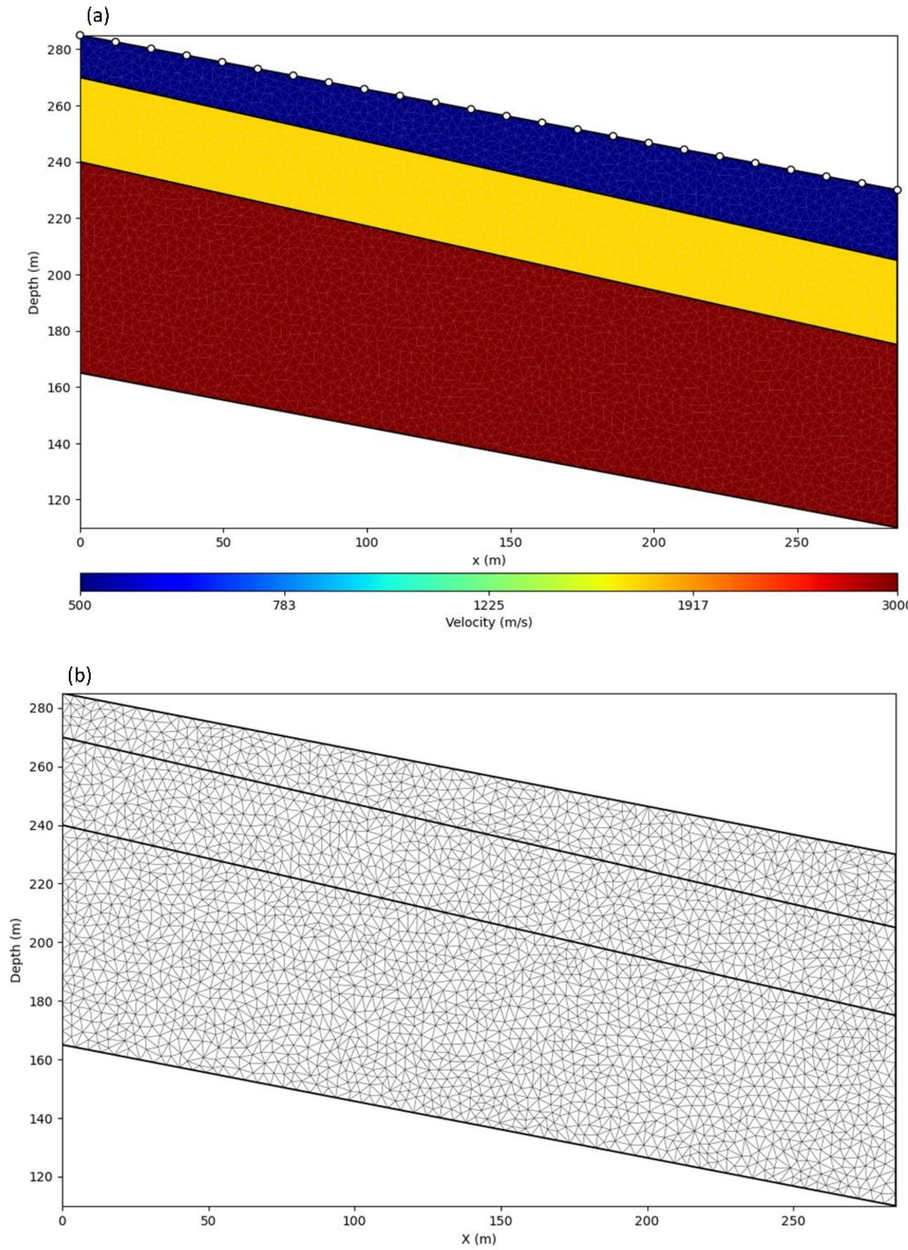


Fig. 1. A 2D Simplified Schematic of a Landslide [8].


(a)
Depth (m)
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Velocity (m/s)
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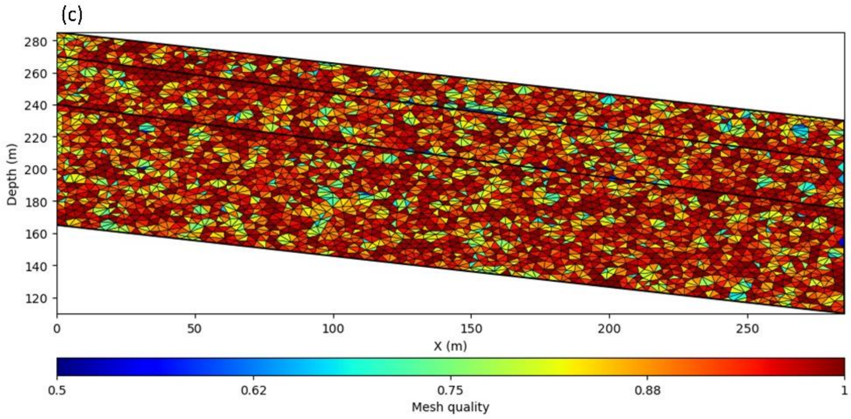
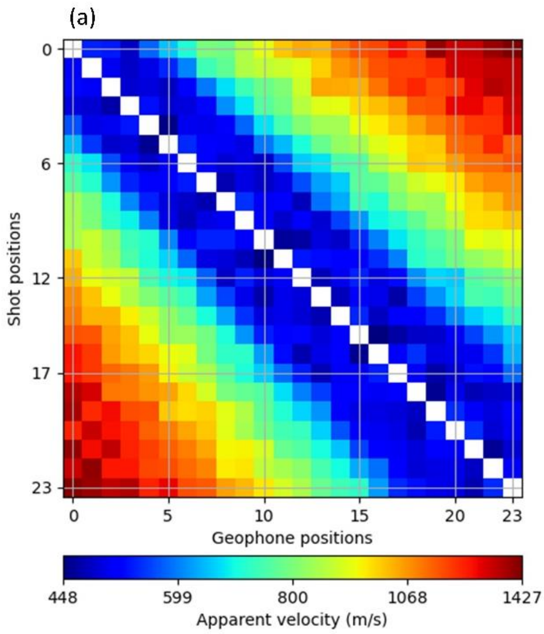


Fig. 2. Synthetic 2D Landslide Velocity Model Simulation Components. (a) Assigned seismic velocity distribution with simulated sensor locations; (b) Unstructured triangular finite element mesh; (c) Analysis of mesh quality.

4. RESULTS AND DISCUSSION

This section presents the outcomes of the synthetic SRT simulation, focusing on the generated travel time data and its characteristics. The synthetic data, derived from the established subsurface velocity model (as described in Section 3), serves as a crucial input for subsequent inverse modeling. Figure 3 illustrates the simulated seismic responses: Figure 3a displays the comprehensive travel time data matrix, showing the relationship between shot and geophone positions, while Figure 3b presents the hodograms of the first-arrival picks, which are essential for understanding wave propagation patterns and for the inversion process. These visualizations provide fundamental insights into how seismic waves would propagate through the simulated landslide environment.



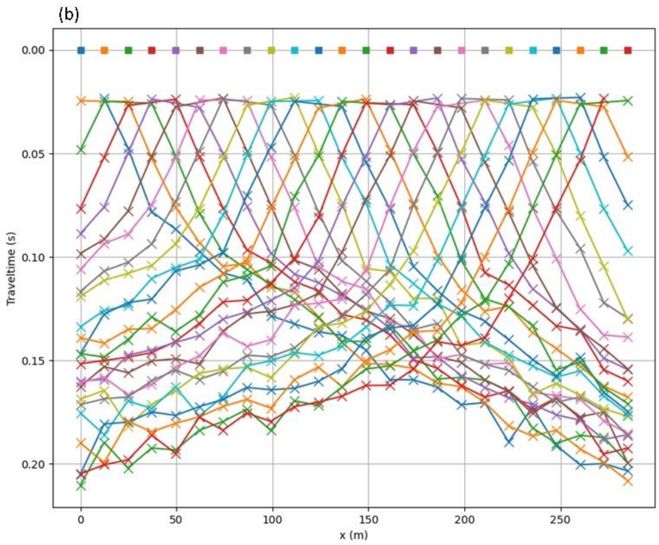
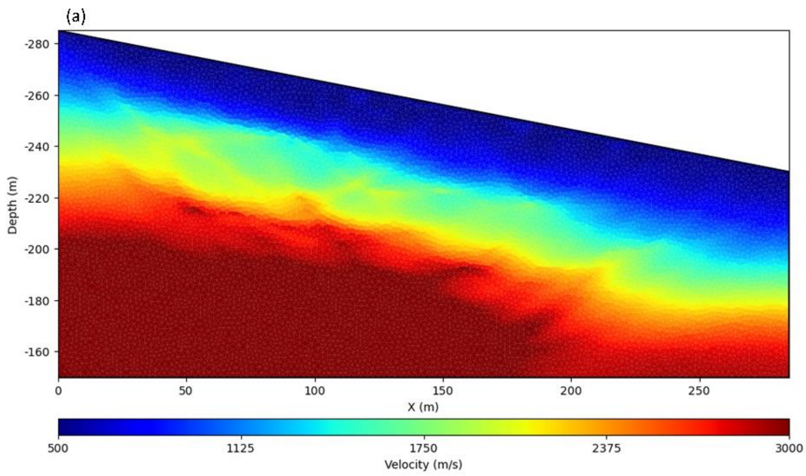


Fig. 3. Simulated SRT Data. (a) Synthetic travel time data matrix showing recorded arrival times between various shot and geophone positions; (b) Hodograms illustrating the first-arrival seismic wave picks from the simulated data.

Following the generation of synthetic data, the core of the analysis involves the inverse modeling process to reconstruct the subsurface velocity structure. This crucial step aims to estimate the true velocity distribution from the simulated first-arrival travel times. The inversion algorithm iteratively refines the model parameters until an optimal fit between the observed and predicted data is achieved, while also incorporating regularization to ensure a geologically plausible solution. Figure 4 comprehensively visualizes the outcomes of this inversion: Figure 4a presents the inverted 2D seismic velocity model, highlighting the reconstructed subsurface velocity distribution; Figure 4b augments this model by displaying the calculated ray paths, offering insight into the subsurface coverage and data sampling; and Figure 4c further refines this by showing the ray paths overlaid on the inversion coverage, which indicates areas of reliable velocity estimation based on ray density. These results demonstrate the ability of the SRT method to accurately delineate subsurface layers and potential landslide-related features.



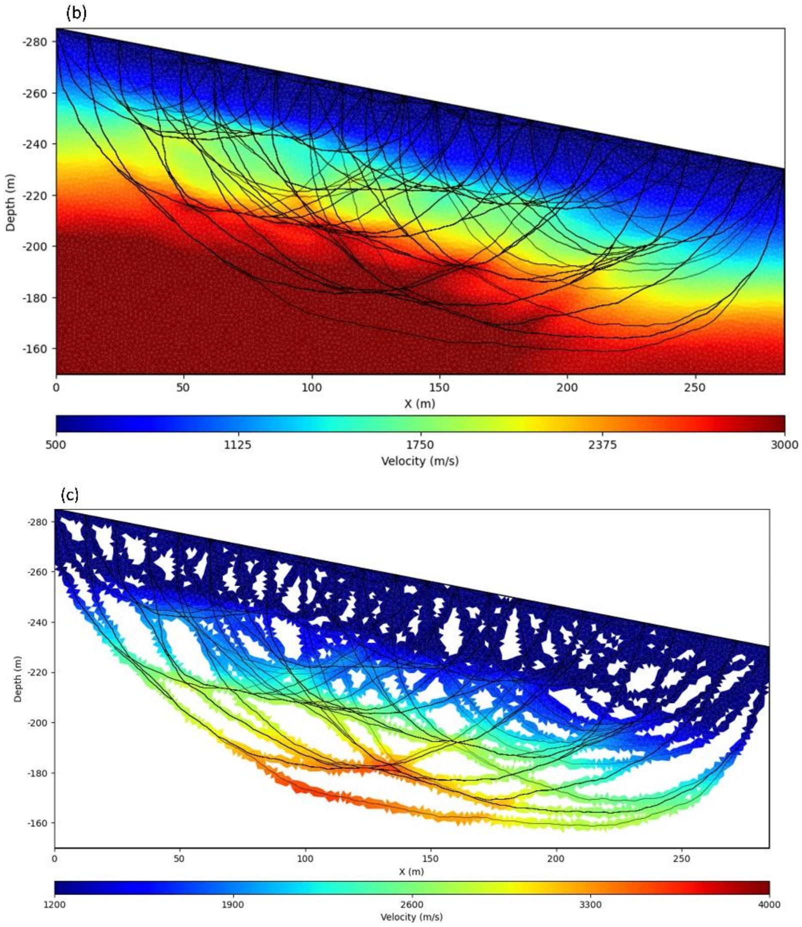


Fig. 4. Results of the SRT Inversion. (a) Reconstructed 2D subsurface seismic velocity model; (b) Inverted velocity model overlaid with the calculated seismic ray paths; (c) Ray paths displayed on the standardized inversion coverage map, indicating areas of reliable velocity estimation.

The accuracy and reliability of the inversion process are further validated by analyzing the fit between the observed (synthetic) data and the model-predicted responses. Figure 5 illustrates this crucial comparison: Figure 5a displays the predicted travel time data matrix, which is the forward-modeled response based on the inverted velocity model. This matrix should ideally closely resemble the input synthetic data shown earlier. Furthermore, Figure 5b provides a detailed misfit plot, visually quantifying the discrepancies between the observed and predicted travel times. A good fit, indicated by minimal scatter around the diagonal, confirms the convergence of the inversion and the robustness of the derived subsurface velocity structure.

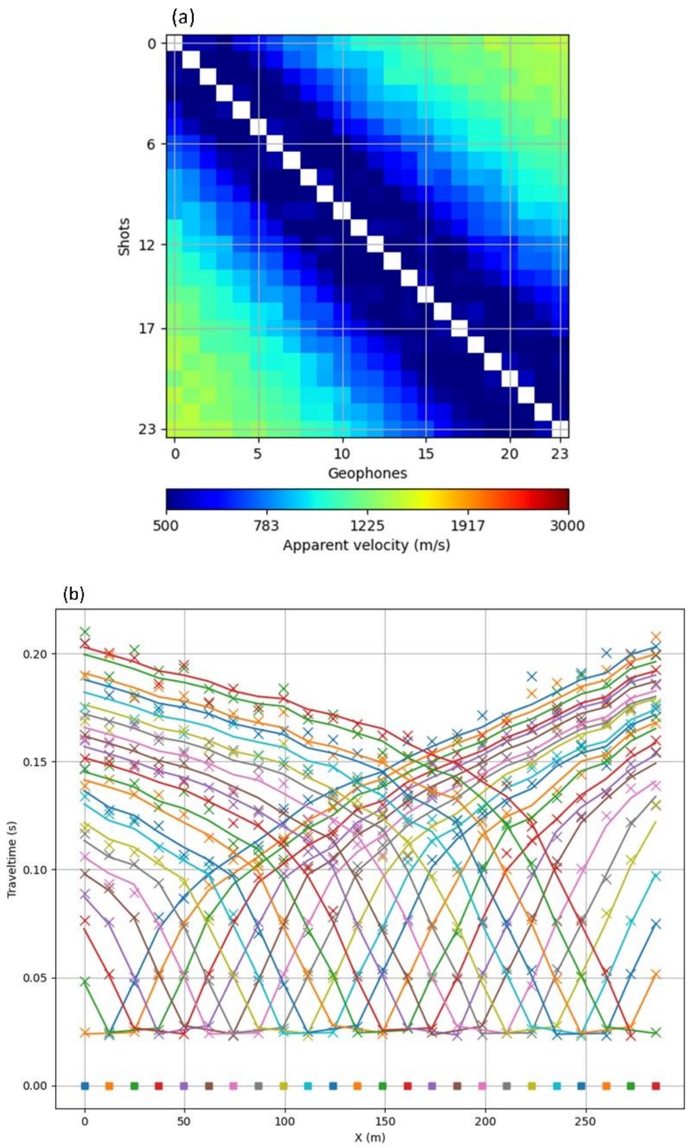


Fig. 5. Assessment of Inversion Fit and Data Misfit. (a) Predicted synthetic travel time data matrix derived from the inverted velocity model; (b) Misfit plot illustrating the agreement between observed and predicted travel times.

To further evaluate the inversion's robustness and the structural integrity of the reconstructed model, the properties of the inverted mesh are examined. Figure 6 provides insights into the mesh used for the inversion: Figure 6a displays the refined mesh structure that underlies the inverted velocity model, showing how the computational grid adapts to resolve the subsurface features. Complementing this, Figure 6b presents the quality assessment of this inverted mesh, ensuring that the discretization maintains high standards necessary for accurate and stable geophysical interpretations. These visualizations confirm the computational foundation upon which the final velocity model is built, assuring the reliability of the detailed subsurface characterization.

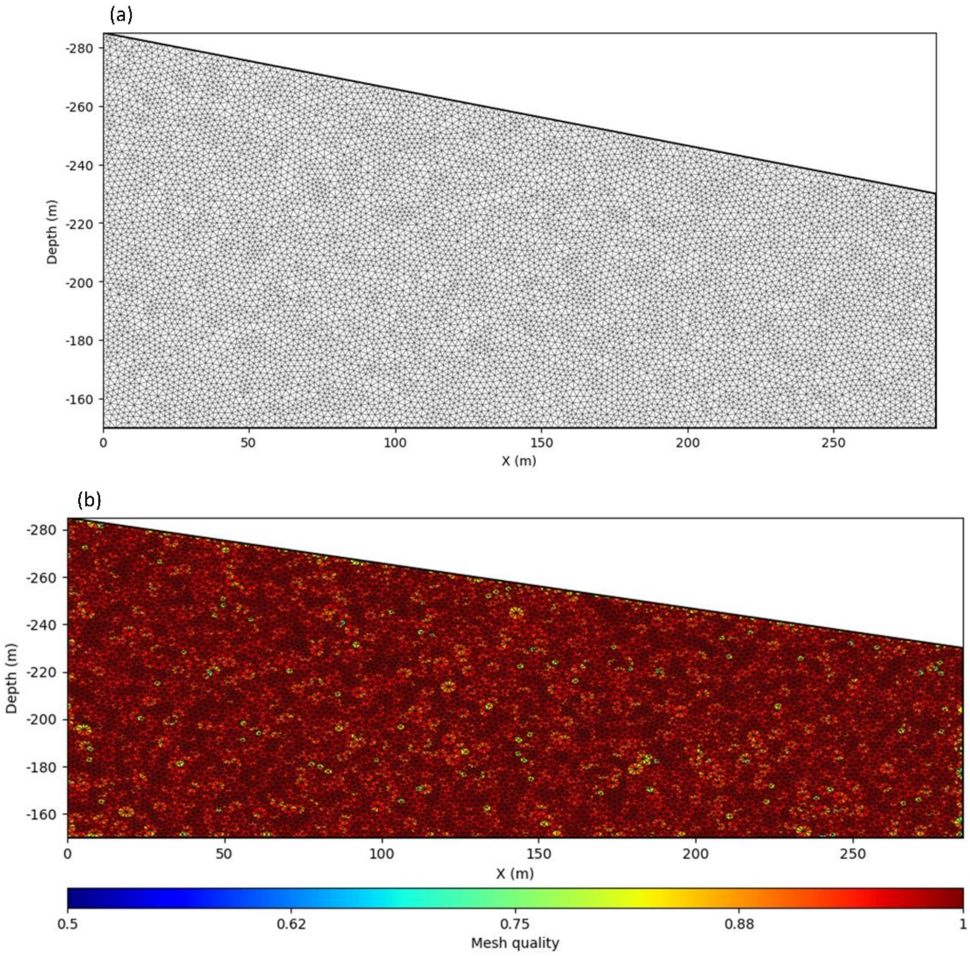


Fig. 6. Characteristics of the Inverted SRT Mesh. (a) The refined mesh structure used for the inversion process; (b) Quality assessment of the inverted mesh.

5. CONCLUSION

This study successfully demonstrated the utility of SRT for characterizing complex landslide environments through detailed synthetic modeling and inversion. A robust methodological framework is established, from generating a realistic 2D subsurface velocity model and simulating seismic data to performing accurate inversion to reconstruct the geological structure. The analysis of synthetic travel times and subsequent inversion results, including the clear delineation of velocity contrasts and ray path coverage, validates SRT's capability to effectively map subsurface features relevant to slope stability. This approach confirms the potential of integrated geophysical simulations to enhance our understanding of landslide dynamics, offering a powerful tool for reliable subsurface characterization crucial for informed geohazard assessment and mitigation strategies.

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