SEISMIC REFRACTION ANALYSIS OF LANDSLIDES

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Abstract

Seismic refraction has proven a useful geophysical tool for investigating landslides. The velocity structure of a landslide mass, the depth to the failure surface, and the lateral extent of a landslide are variables that may be estimated using seismic refraction. Data obtained using refraction can aid in determining appropriate mitigation and maintenance practices involving landslides. One method used to interpret seismic refraction data, the General Reciprocal Method (GRM), calculates refractor depths using overlapping refraction arrival times from both forward and reverse shots. The GRM assumes a layered model and is effective when the velocity structure is relatively simple and refractors are gently dipping. However, the velocity structures of landslides are often complex, involving lateral variations in velocity, steeply dipping refractors, and diffractions from blocks within the landslide mass. Refraction tomography, another method of interpreting seismic refraction data, is capable of modeling these complex velocity structures. Using first arrival picks, refraction tomography develops a best-fit velocity model by iteratively comparing different velocity distributions with observed data. In one example, the GRM was effective in modeling a landslide with abrupt changes in the depth to the top of the lowermost velocity unit, interpreted to be bedrock. The apparent vertical displacements in the bedrock refractor may indicate the landslide is a deep-seated feature incorporating bedrock as well as surficial deposits. A survey of a different landslide identified a localized high velocity zone in the near surface indicative of a bedrock block within the slide mass. In another example, velocity models of a landslide generated using GRM and tomography indicate low-velocity slide material over a steeply dipping, concave, high velocity unit interpreted to be bedrock characteristic of a rotational failure. In all three examples, seismic refraction surveys and analyses of the data provided information integral to understanding and characterizing the landslides.

Introduction

Seismic refraction is a technique that has been used to investigate landslides since the early 1960's. Refraction surveys have been used to estimate depths to the failure surfaces and the lateral extent of landslides (Cummings and Clark, 1988; Palmer and Weisgarber, 1988; Bogoslovsky, 1977; Brooke, 1972; Carroll et al., 1972; Trantina, 1963). The basis of the interpretations is the difference in the physical properties of the sliding materials and the underlying undisturbed sediments or bedrock that result in different seismic velocities (Abramson *et al.*, 2002). In addition to delineating the extent of a slide mass, refraction surveys can also provide data pertinent to construction, rippability and earthwork factor (Stephens, 1978). Some advantages of refraction surveys in landslide investigations over other methods are the environment is not disturbed, the equipment is portable, and the technique is relatively inexpensive (McGuffy *et al.*, 1996). Intercept-time and reciprocal methods of interpreting refraction data can be used to model velocity structures of some landslides. These methods are most applicable to sites where subsurface layers dip less than approximately 20° and have nearly uniform velocities, for these methods assume a layered model and continuity of refractor surfaces across a profile. However, the velocity structures of landslides can be complex, making them difficult to accurately model using intercept-time and reciprocal methods. Lateral and vertical changes in velocity, steeply dipping and discontinuous refractors, and diffractions from blocks within the landslide mass are features commonly observed in refraction surveys of landslides. Refraction tomography, another method of interpreting seismic refraction data, uses a gridded, inversion technique to determine the velocity of individual 2-D blocks (pixels) within a profile as opposed to modeling velocities as layers. As a result, refraction tomography can, in some cases, more accurately model and provide better resolution of complex velocity structures.

One limitation of seismic refraction is the inability to discern the existence of certain beds or layers, referred to as hidden layers or blind zones, because of insufficient velocity contrast or layer thickness (Redpath, 1973). Another limitation of seismic refraction are incorrect depth calculations to certain layers where velocity reversals exist, i.e., where layer velocities do not increase with progressive depth (Redpath, 1973). A discussion of the strengths, weaknesses, and cost effectiveness of seismic refraction surveys is presented in Rucker (2000).

This paper presents three examples of processing techniques used by the California Department of Transportation for the characterization of landslides using seismic refraction. The three landslides discussed in this paper are located in the Coast Ranges of northern California, a region that receives high amounts of rainfall and is prone to landslide activity (Figure 1).

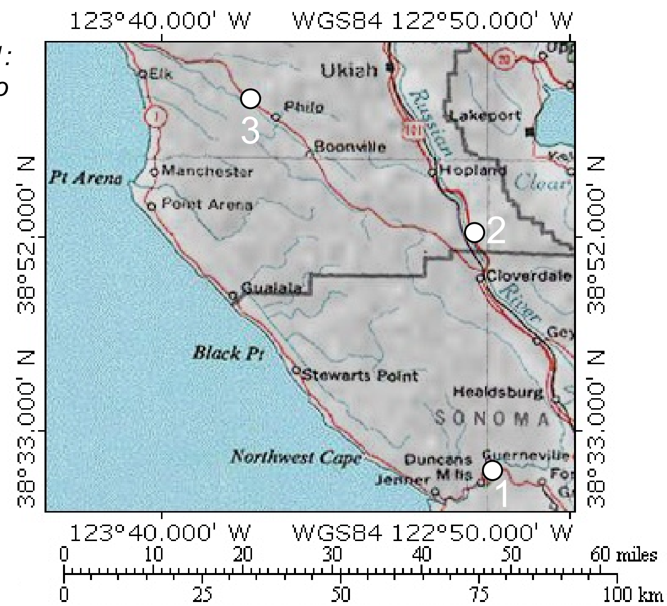

Figure 1. Maps showing landslide locations. 1: Monte Rio slide 2: Cloverdale slide 3: Navarro River Slide. Maps courtesy of Mapquest.com and TOPO software.

General Reciprocal Method of Interpretation

The Generalized Reciprocal Method (GRM) calculates refractor depths for each geophone location using overlapping refraction arrival times from both forward and reverse shots, warranting multiple shots along a profile. Multiple shotpoints along a survey profile permit interpretations of changing interface depths and layer velocities (Rucker, 2000). The GRM assumes a layered model and assumes continuity of refractor surfaces across a profile. The GRM is most effective when the velocity structure is relatively simple and refractors are gently dipping (<20°). The GRM method relies on data from both forward and reverse shots, and on the selection of an optimum XY value. XY is defined as the distance of separation, measured at the surface, where forward and reverse seismic waves originate from the same point on the refractor. Two variations of the GRM analysis can be used: the approximate velocity (AP) and the average velocity (AV) methods. The approximate velocity method is relatively insensitive to optimum XY selection. However, this method requires that every refractor above the target be defined. In contrast, the average velocity method is very sensitive to optimum XY selection. The average velocity method, however, does not require that every refractor above the target be known. Where refraction data are insufficient for GRM interpretation, the refractor can be modeled using the more traditional intercept-time method of interpretation (ITM), though with comparatively reduced accuracy. A complete explanation of the GRM is given in Palmer (1980).

Analysis of a Landslide Using GRM

A seismic refraction survey was conducted on a landslide with recurrent movement along State Route 16 near Monte Rio, CA to aid in characterizing the landslide (Figure 2). The landslide is located on a sloping (~20°) forested hillslope adjacent to the Russian River. The survey profile (MR-1) was 72.0 meters in length and was oriented across the slide mass.

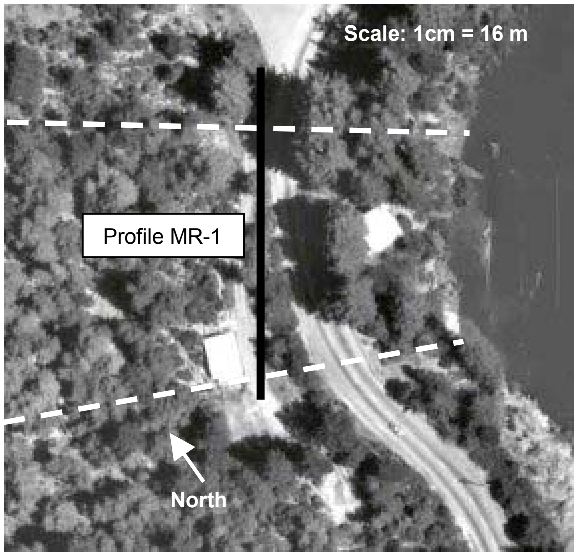

Figure 2. Aerial photo showing approximate location of Monte Rio landslide (dashed white line) and seismic refraction profile MR-1 (solid black line).

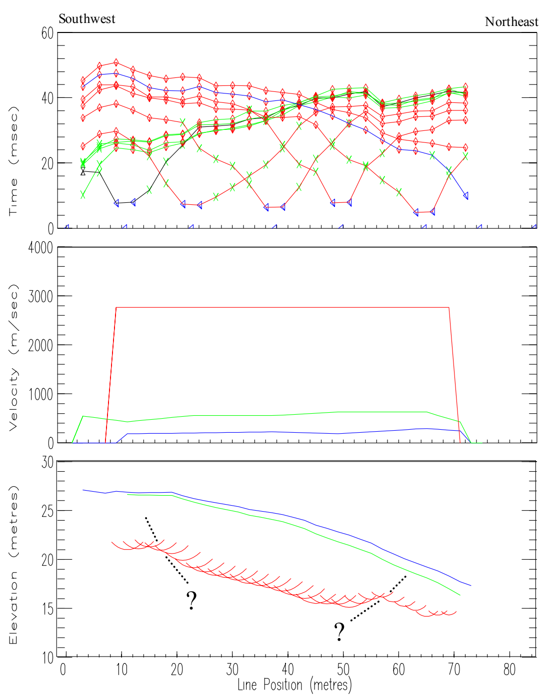

Figure 3. Travel time curves, velocity model, and depth section for profile MR-1. Queried dotted lines on depth section denote location of inferred offsets in bedrock refractor.

Figure 3 shows compiled travel time curves, a velocity model, and a depth section for profile MR-1. Three velocity layers were detected in profile MR-1: 1) a relatively thin uppermost layer with an average velocity of 230 m/s 2) an intermediate layer with an average velocity of 560 m/s 3) a lower layer of unknown thickness with an average velocity of 2800 m/s. Based on correlation with logs from exploratory borings, the upper refractor in profile MR-1 likely represents a contact between fill and soil and a thicker underlying layer composed of weathered fluvial deposits and shale/pebble conglomerate. The lower refractor in profile MR-1, modeled using the GRM, marks the top of the lowest layer and appears to correspond to the top of a graywacke unit. (The upper refractor was modeled using the intercept-time method of interpretation because refraction data provided insufficient refractor coverage for GRM interpretation.)

The most prominent features detected in profile MR-1 are the offsets in arrival times and resulting changes in depth to the top of the bedrock refractor at approximately 18 meters and 54 meters. The offsets correspond to the mapped edges of the landslide mass at the ground surface. The apparent vertical displacements in the bedrock refractor may indicate the landslide is a deep-seated feature incorporating bedrock as well as surficial deposits. Although the survey did not detect the failure surface within the bedrock, it was able to define what is interpreted to be the edges of the slide mass at the bedrock refractor and aid in characterizing the slide as a deep-seated feature.

Refraction Tomography

The GRM assumes continuity of refractor surfaces across a profile. Where this assumption is not valid, as is often the case with landslides, refraction tomography can provide better results. Tomography is a technique where measurements are made of energy that has propagated through a medium. The received character of the energy is then used to infer the properties of the medium through which it propagated (Stewart, 1991). Several tomographic techniques have been applied to seismic first arrival travel time data

(Pullammanappallil and Louie, 1994; Ammon and Vidale, 1993; Simmons and Backus, 1992; Vasudevan et al., 1991; Olsen, 1989). Tomographic techniques develop best-fit velocity models by iteratively comparing different velocity structures with observed data to a degree of resolution specified by the modeler. Greater resolution, however, does not imply improved accuracy. The tomographic analyses presented in this paper used a simulated annealing procedure, where a controlled Monte-Carlo inversion is used to develop a globally optimized velocity model of the subsurface (Pullammanappallil and Louie, 1994). The method uses only first arrival time data and profile geometry as input. No initial assumptions of velocity structure or layering are required. As such, the method is easily applied and is well suited for investigation of areas dominated by complex shallow structure, significant velocity gradients and variable topography. Another advantage of tomography is the minimum curve raypath in the inversion defines a maximum depth of investigation whereas only estimates of the investigation depth are possible using more traditional methods. In cases where insufficient data exist, any tomographic inversion may generate false models. Therefore, as with the GRM, multiple shotpoints along a survey profile provides greater data coverage for analysis and aids in generating a more accurate model.

Comparison of a GRM and SeisOpt Model

A seismic refraction survey was conducted on a hummocky, sloping surface of a landslide along Interstate 101 near Cloverdale, California. The purpose of the survey was to define the velocity structure beneath the proposed alignment of a drainage trench to define depth to rock, assess excavation potential, and identify features that could impact construction. The survey profile (C-1) was 60 meters in length and was recorded along the long axis of the landslide (Figure 4). Gravel to cobble-sized clasts of shale and graywacke in a predominantly clay matrix were observed in the slide mass. Large boulders of indurated graywacke were exposed immediately south of the profile.

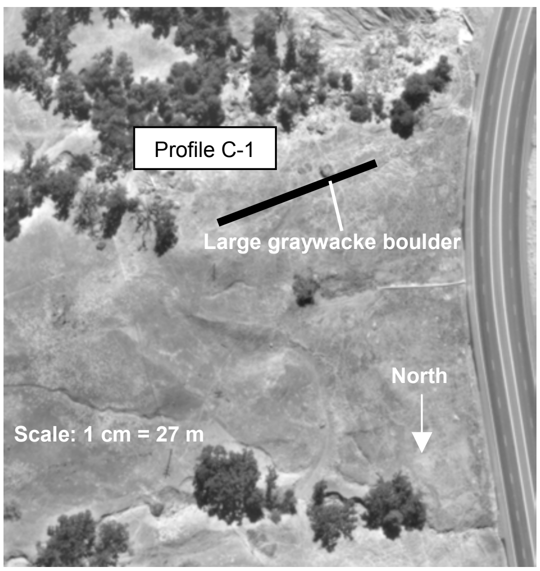

Figure 4. Aerial photo showing approximate location of seismic refraction profile C-1.

Figure 5 shows compiled travel time curves, a velocity model, and a depth section for profile C-1 generated using the GRM. Three velocity layers were modeled along profile C-1. The upper refractor in the depth section was modeled using the intercept-time method of interpretation because refraction data provided insufficient refractor coverage for the GRM. The lower refractor was modeled using the GRM. The velocity model for profile C-1 (Figure 5) indicates a velocity increase in layer three from 1560 meters per second (m/s) to 2415 m/s at approximately 38 meters. The GRM does not model the higher velocity zone as a separate layer and the depth section model for layer three is slightly shallower in the vicinity of the higher

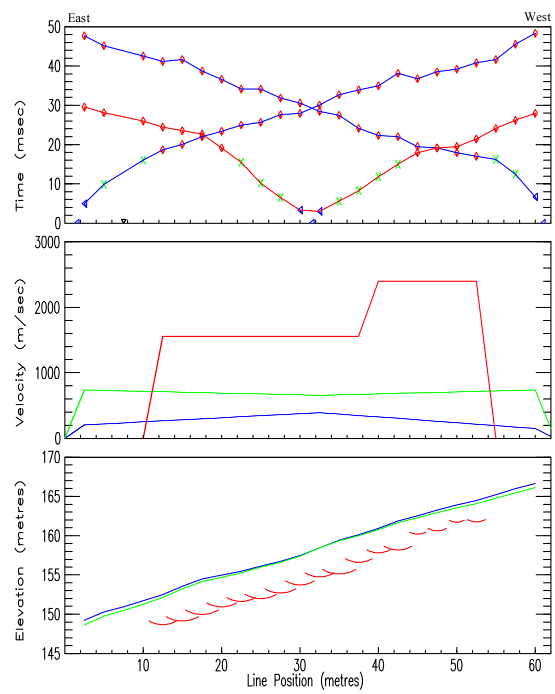

Figure 5. Travel time curves, velocity model, and depth section for profile C-1.

velocity zone. The tomogram (velocity model) and hit count plot for profile C-1 generated using the tomographic inversion are shown in Figure 6. The tomogram differs from traditional velocity models in that velocities are presented by pixel rather than by layer. A single high-velocity zone is indicated, below 160 meters and between positions 46 and 58 meters. The hit count plot shows the number of seismic rays crossing each pixel. More evenly distributed hits and higher hits per cell are positively correlated with improved accuracy in the model. Hit counts show that, except for a small region near a dead geophone at 8 meters, empty pixels exist only as isolated, random cells, indicating adequate ray coverage throughout the profile, despite the relative coarseness of shot points (only three in this case).

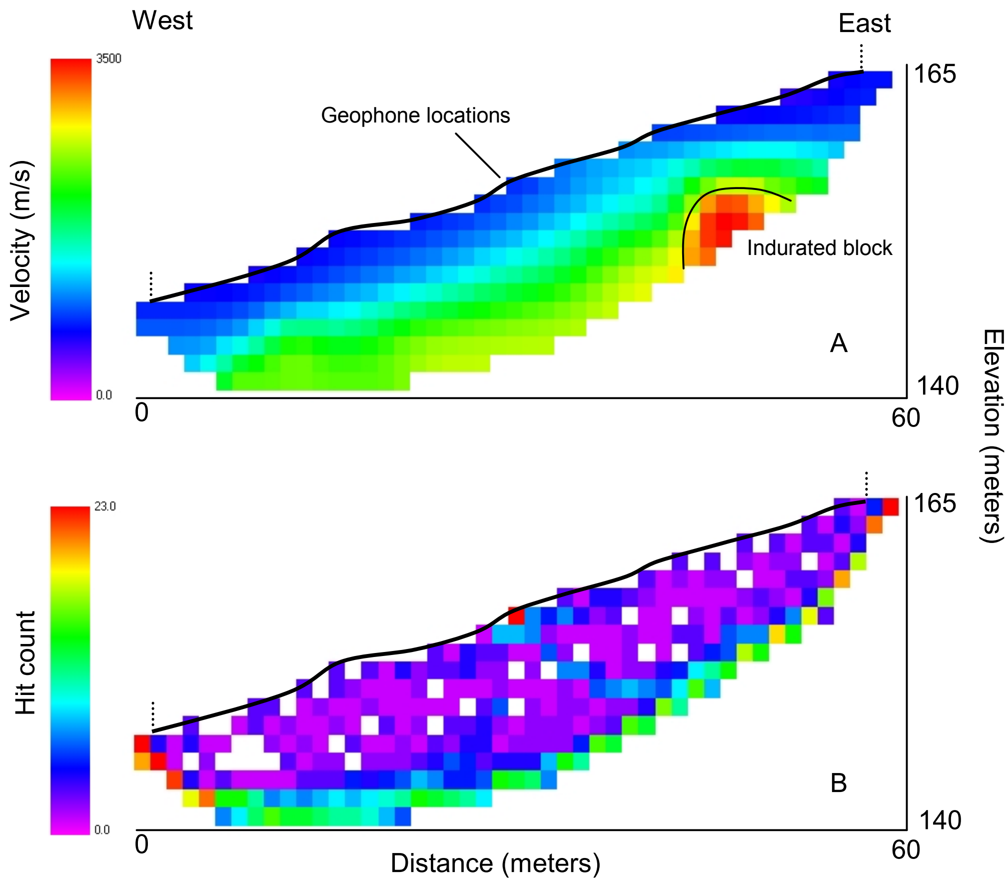

Figure 6. Tomogram (A) and hit count plot (B) for profile C-1.

Similarities were noted on both models, with greater detail apparent in the tomogram. The tomographic model resolves the velocity structure of the slide mass in greater detail than the model generated using the GRM. The high velocity zone detected in the velocity model shown in Figure 5 is modeled as a discrete zone in the tomographic model (Figure 6) and is interpreted to be a block within the landslide mass characteristic of the Franciscan Complex. The Franciscan complex is a regional scale geologic terrain typified by competent bedrock blocks within matrices of sheared, soil-like material. In this example, the refraction survey was useful for constructability evaluation. Based on the refraction models and velocities, the upper several meters along the profile appear rippable. The tomographic model was effective in identifying a localized high velocity zone indicative of a indurated block in the near surface which will likely require blasting for excavation.

Tomographic and GRM Model of a Landslide with a Complex Velocity Structure

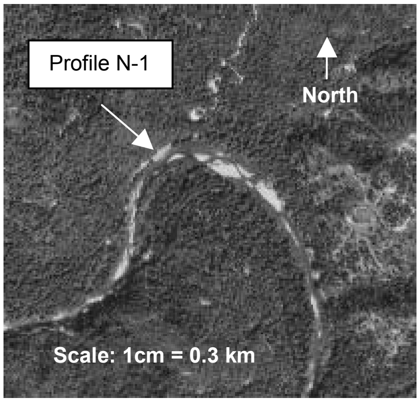

Figure 7. Aerial photo showing approximate location of seismic refraction profile N-1.

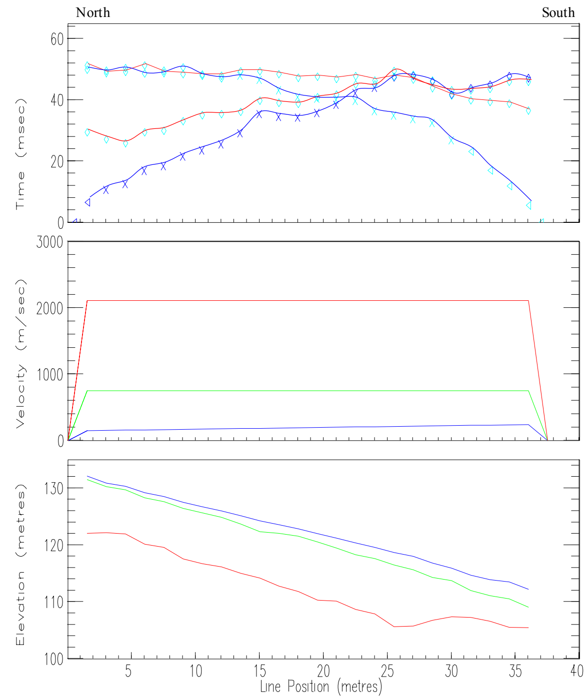

Figure 8. Travel time curves, velocity model, and depth section for profile N-1.

A seismic refraction survey for a landslide along State Route 128 in Mendocino County was located on a steep hillslope adjacent to the Navarro River. The survey profile (N-1) was 36 meters in length and was recorded along the long axis of the slide mass (Figure 7). Interpretation of the survey results used both GRM and tomographic analyses.

Figure 8 shows compiled travel time curves, a velocity model, and a GRM depth section for profile N-1. The travel time curves show erratic arrival times indicative of diffractions from features within the landslide mass and a complex velocity structure. The erratic arrival times present problems when processing the data using the GRM and in turn decreases confidence in resulting models.

The tomogram (velocity model) and hit count plot for profile N-1 are shown in Figure 9. The hit count plot indicates two zones where there is no ray coverage. The zones are centered at approximately 16 meters and 47 meters and are associated with the offset shots. However, the lack of data at these locations does not significantly effect the interpretation of the velocity model, which focused on the shallower features and the region bounded by the actual geophone locations. The

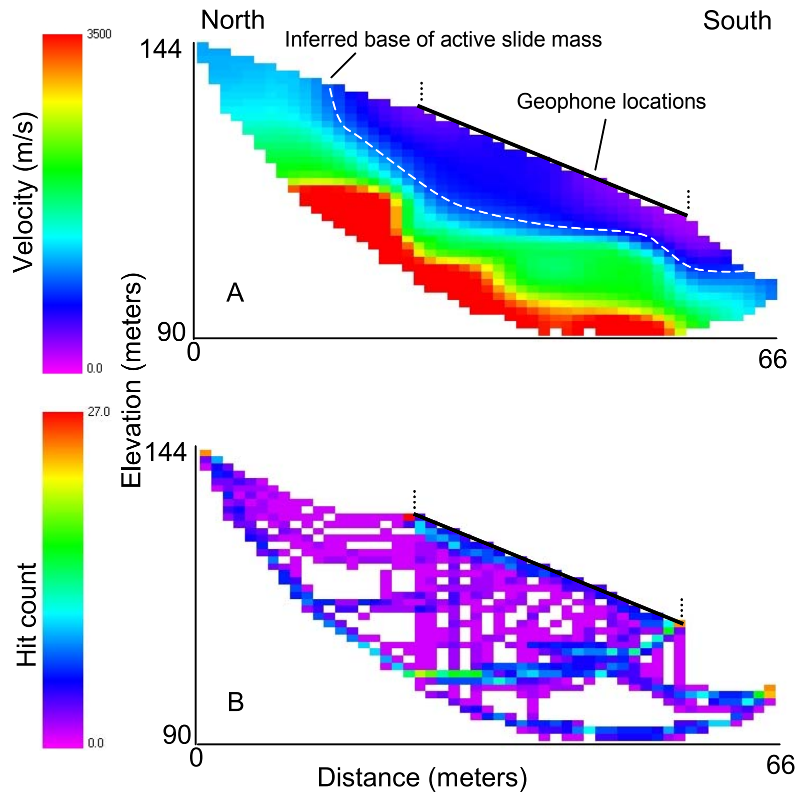

Figure 9. Tomogram (A) showing location of inferred base of active slide mass and hit count plot (B) for profile N-1.

velocity model essentially shows low-velocity slide material overlying a concave, higher velocity layer. The high-velocity material at the base of the profile is interpreted to represent bedrock and dips southeastward toward the river. The velocity distribution supports an arcuate slide mass characteristic of a rotational landslide. The undulating surface of what is interpreted to represent the bedrock refractor (the green to red zone in Figure 9) may be an indication that fracturing and displacement extends into the bedrock. In this example, the GRM model oversimplified the velocity structure of the landslide. The tomographic model however, is interpreted to provide better resolution of the complex velocity structure and possibly indicates the active slide is a rotational feature. Based on the tomogram and field observations, the active slide mass is interpreted to be superimposed on a larger slide, with fracturing and displacement extending into bedrock.

Summary

Seismic refraction is a useful geophysical tool for investigating landslides. The velocity structure, depth to the failure surface, and lateral extent of a landslide are variables that can be estimated from analyses of seismic refraction data. Rippability and earthwork factor, variables important in planning excavations, can also be estimated. Seismic refraction equipment is portable, relatively inexpensive, and non-destructive. The technique does not work well, however, where velocity contrasts between layers are subtle, velocity layers are thin, and where velocity reversals exist.

The General Reciprocal Method (GRM), one method used to interpret seismic refraction data, assumes a layered model and is effective when the velocity structure is relatively simple and refractors are gently dipping (<20°). However, the velocity structures of landslides can be complex, making them difficult to model using reciprocal methods. Refraction tomography, another method of interpreting seismic refraction data, is well suited for investigation of areas dominated by complex shallow structure, velocity gradients, and variable topography. Regardless of the technique used to interpret the data, multiple shotpoints along the survey profile provide greater data coverage and potentially more accurate models. Where insufficient data coverage exists, the GRM cannot be performed and tomographic analyses may produce unrealistic models. It is prudent to perform both reciprocal methods as well as tomographic analyses, as the different models can compliment one another and when in agreement, increase confidence in the interpretation.

A refraction survey of a landslide adjacent to the Russian River near Monte Rio, California identified apparent vertical displacements in the bedrock refractor coincident with the mapped edges of the landslide. The apparent vertical displacements in the bedrock refractor may indicate the landslide is a deep-seated feature incorporating bedrock as well as surficial deposits. A localized high velocity zone, indicative of a resistant block within a slide mass was identified in refraction survey of a landslide along Interstate 101 near Cloverdale, California. The velocity distribution of a landslide along the Navarro River can be explained by a rotational slide superimposed on a larger landslide with fracturing and displacement extending into bedrock. In all three examples, seismic refraction surveys and analyses of the data aided in characterizing the landslides and provided information important in determining appropriate mitigation and maintenance measures.

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