Application of seismic refraction tomography for detecting a hidden potential fault

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ABSTRACT

Seismic refraction technique is an increasingly useful geophysical tool for geotechnical studies in civil engineering work including the mapping of different soil formation of subsoil and detection of the bed rock. Additionally, wave velocity is a key parameter which correlates directly with significant geotechnical parameters of soils and rocks. Today, the evolution of the measurement technique in the field and the data processing allows to obtain tomographic images which increases its potential for applications to evaluate structuration of rock mass. This work describes the basic principles of seismic tomography and a case history of an application in civil works used to evaluate the foundation conditions of a site were a new structure for a spillway for the Gatun lake, north Panama, was projected. The study allowed to detect a destructured band sector in the bedrock which was covered by more modern sediments and vegetation just in the site of interest for the foundation of a project. The magnitude of the destructured bedrock forced to relocate the structure.

Keywords: Wave Velocity, Seismic Tomography, Material Characterization.

1. Introduction

The seismic refraction method is based on travelling of the elastic compression wave through geological media by using various sensors which are displayed equally spaced along a survey line. Elastic waves are generated at the ends and intermediate points by means of hammers, mass falls, guns, or even explosives for deep prospection. These waves are detected by sensors called geophones that measure the vibration velocity when the elastic wave reach the point where they are located. In general, 12, 24 or 48 geophones are usually displayed along the survey line. The spacing between geophones and length of the survey line depend on the required depth of exploration. As a roughly approximated rule, exploration depth ranges between 1/4 and 1/3 of the total length of the line. The signal captured by the geophones is conditioned (eg. Amplified and filtered) by a seismograph that also allows for displaying and recording the signals of all the geophones arranged along the lines. The time of arrival of the compression waves at each geophone is determined from the records and the space-time curves are then obtained. The analysis of these curves allow determine the seismic profile. The most common methods of interpretation of time-space curves are: intercept times, apparent velocities, wavefronts, delay times and the general reciprocal method (Sarria 1996; Redpath 1973; Kearey et al. 2002). Today, increasingly advances in sophisticated computational methods, allowed the development of tomographic processing algorithms of refraction. These algorithms allow to solve variations or velocity gradients in depth and lateral changes in highly variable sites such as due to the presence of voids, faults, karst for example. Tomographic images generally show gradual variations of wave velocities with depth oppositely to that obtained in the traditional interpretation methods where layers with different constant velocities are identified. The limitations of gradual velocity variations are discussed in elsewhere (Rucker 2002). In sedimentary environments where the propagation velocity increases with depth due to the change of confinement, the gradual variation of speed is more realistic than that obtained with a multi-layer model. The opposite can be understood in environments with sharp shifting such as sediment overlaying the bed rock or interlayers that occur due to the presence of water or stiff cemented soils.

The seismic refraction method has numerous applications in geotechnical engineering field including: the mapping of the stratigraphy of a site, determining the location of the bed rock and the water table, Evaluation of the degree of fracturing and weathering and of the rock, detection of geological faults and degree of compactness and cementation of sedimentary layers, the evaluation of dynamic soil parameters for use in seismic designs and more recently the determination of geotechnical parameters for foundation design. Probably the biggest limitation of seismic refraction is that requires that the stiffness of the layers increase in depth. The presence of any inclusion with lower stiffness can be misinterpreted.

This work describes an application of the tomographic technique used to evaluate the destructuration of a sedimentary bedrock (Tertiary Gatun Formation) due to a possibly hidden shear fault covered by more modern sediments and significant vegetation. The destructuration of the base rock, was difficult to be detect even by previous drill holes performed at the site. Such situation enhanced the significance of geophysics in the adequate geotechnical characterization of the site.

2. Geology

Fig. 1 and Fig. 2 show the location of the site close to the city of Colon, northwest of Panama, on the Atlantic coast side. The Isthmus of Panama is formed by the rigid block (often referred to as the micro plate Panama), located between the tectonic plates of Cocos and Nazca south, the Caribbean plate north and plaque South east America. It is part of the volcanic arc of Central America originated in the Miocene about 17 million years ago. The continuous movement of North America and South America, being at about 25 mm / year, is responsible for the internal deformation of the isthmus which translates into folds and interior faulting (Rockwell et al. 2010). The predominant directions of faults are parallel to the Panama Canal in the direction northwest-southeast and some direction Northeast-Southwest with high degree of dip (Pratt et al. 2003). Despite the complexity tectonism described, a very low actual seismic activity is recognized, although, such information creates a significant uncertainty in seismic risk assessment in Panama.

Figure. 1. Localization map of the sector of study.

The general stratigraphy of the sector of interest has been extensively described by Jones (1950) and Woodring (1957) which mainly consist on Miocene and Holocene deposits overlaying the Pre-Tertiary volcanic formations. The deepest sedimentary deposit is the Gatun Formation. This Formation is composed of alternating sequences of sandstone, siltstone, conglomerate and marine peats. It is gray-green in color, with a gentle dip to the northwest. This Formation contains macro and micro fossils in very good condition of preservation. It has an estimated maximum thickness of about 500 m with an approximate elevation of +100 m in southern Limon Bay and reduces its elevation below sea level to the Caribbean coast. The Chagres Formation over the Gatun Formation, consists of massive sandstone, siltstone being a whitish calcareous, bioclastic formation, with coral fragments and marine fossils, slightly fractured and slightly altered and some element found on its base identified as Toro limestone. The colluvium sediments that covers toe of the hills are originated from destructured falling fragments of the Gatun and Chagres formations at higher elevations.

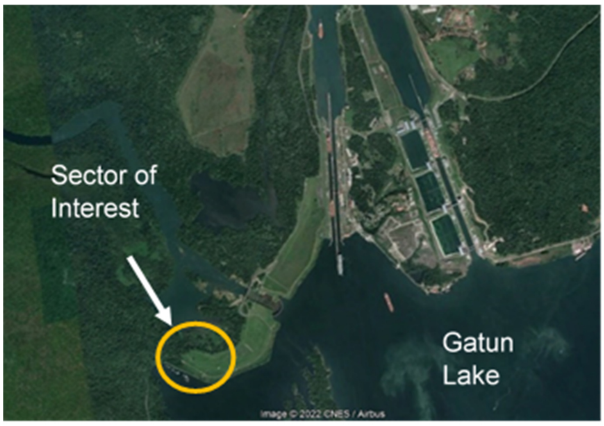

Figure. 2. Location of the sector of interest in this work on the left margin of Gatun dam.

In sedimentary rock where diagenetic processes (causing structure lithification) have taken place at high pressures, as in the case of the Gatún formation, the effect of release in the confining pressure (either by sampling or excavation) may cause its destructuration in the form of microfissures (hair cracks). A decrease in water content (dessication) tends to accelerate and magnify this microfissuring process. Besides, when the material is saturated in an unconfined condition, residual stresses in the formation relax and also cause massive fractures in the sample reducing shear strength, elastic module and wave propagation velocity.

Fig. 3 shows this effect on a Gatun sample corresponding a depth of about 25 m. After being immersed for 24 hs, Fractures develop following predominantly horizontal planes, which probably correspond to the direction of the bedding planes.

Figure 3. Cracking effect on a sample from the Gatún formation, which results from saturation.

3. Works performed

The geophysical study was carried out as part of a program required for evaluating the geotechnical conditions for the foundation of a second set of spillways on the left margin of the Gatun Dam. The geotechnical program included geophysical studies and drilling. The geophysical studies consisted of four parallel seismic profiles 250 m each using the refraction technique. Three of the seismic profiles were placed along the axis of the spillway and one line across it. For this work, a Geode 24 device from Geometrics was used. Each of the survey lines was performed using a total of 24 geophones with separations 5 m. The geophones were fixed to the soil by means of inserts of 8 cm in length. For each seismic line, 5 shots were made at both ends, at the quarters and at the centre. The energization for each shooting at each point was made using a pressurized gas gun system. This system allowed to increase the impact energy with respect to a manually driven mass and therefore increase the penetration depth (no explosives were allowed to be used at the site). Fig. 4 displays a picture of the gas cannon described here.

Figure. 4. Gas gun used in this work.

Field records obtained were processed and interpreted using the computer programs Plotrefa, and Pickwin of Geometrics. For the data processing the following steps were used:

a) Detailed study of the records: Records were studied signal by signal, in order to assess the quality of them and consistency.

b) Processing Records: The raw signals obtained were filtered in bandwidth sensors, in order to remove line noise, odd measurements.

c) Detection of Arrivals: From the records processed, the arrival times of the compression waves were determined. The detection of these points was initially performed by the computer program Pickwin and thereafter checked manually.

d) Obtaining seismic profiles: From the analysis of the space-time curves, the cross sections were obtained. For this operation, the processing software Plotrefa from Geometrics was used. The program uses the routine of least squares minimization in order to approximate the time model calculated with that measured in the field.

e) Interpretation of Seismic Profile: The seismic profile was interpreted using a program that allows generic images tracing dividing lines and signs.

4. Results

The tomography that results of the processing the central seismic section is shown on Fig. 5. Similar results were obtained for the others sections. The seismic tomography obtained presented a mean square error RMS lower than the desirable limit of 5%. Table 1 shows the correlation obtained between p-velocities and soil formation condition obtained from boreholes.

The tomography shows a profile of increasing wave velocity with depth. it is observer a surface layer with low p-velocities (less than 700 m/s) which correspond to destructured and sedimentary materials. This layer can be associated to colluvial deposits, originated from the destructuration of the Toro and principally the Gatún formation.

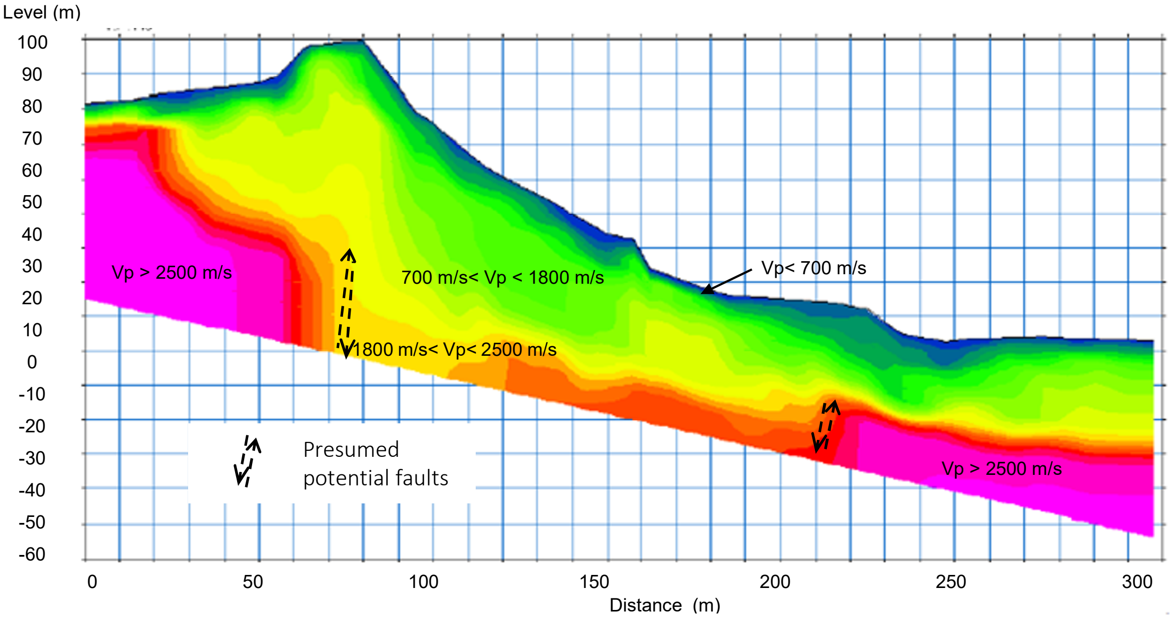

Fig. 5. Tomography obtained from the processing of the centre seismic refraction line performed in this work.

Table 1. Material description and related P-wave velocities

General Description	**Inferred Formation**	**Compression Velocity (m/s)**
Non-consolidated soils	Sediments or colluviums Nspt < 2	400 to 700
Slightly consolidated soils	Sediments or colluviums 2 < Nspt < 5	700 to 1000
Consolidated to highly consolidated soils	Sediments or colluviums 5 < Nspt < 10	1000 to 1800
Weathered or fractured rock	Gatún, weathered or fractured	1800 to 2500
Intact massive rock	Gatún, massive, Unweathered	2500 to 3200

On Fig. 5, it can be seen that the thickness of the top sedimentary stratum decreases from the higher elevations down (SW – NE direction). Velocities higher than 700 m/s were observed for in-site materials depending its different conditions respect to weathering and fracturing as described in the same Table 1. The p-wave velocity of the bedrock, corresponding to the Gatun Formation, ranges from 1800 m/s to 3000 m/s Propagation p-velocities between 1800 m/s and 2500 m/s are associated to the weathered and fractured rock. Propagation velocities greater than 2500 m/s are attributed to a rock in good structural condition.

According to this analysis, it can be observed in the tomographic image of Fig. 5, that there is a distinguishable structural discontinuity or band in the bedrock, which occurs between distances 50 m and 200 m, approximately, where the rock material seems to be destructured to larger depth.

The geometry of this discontinuity could be attributed to different mechanisms. These include the presence of a shear band (fault), where the relative movement of the blocks results in a band of unstructured material and also have caused sliding of materials from the top down to the toe of the slope as clearly seen. A more accurate identification of the mechanism explaining the discontinuity requires supplementary studies which exceeds the purpose of this study. Nevertheless, the results suggested the convenience to relocate the spillway.

5. Conclusions

This work presents the result of the seismic survey using the methodology of the seismic refraction tomography for data acquisition and processing. The main finding of the work is the tomographic image of the cross section presented on Fig. 5. From this result, the following conclusions can be summarized:

a) The geophysical method proposed to evaluate the site performed adequately attending the many difficulties that present topography and environmental conditions at the site.
b) The tomographic cross section allows to describe the variation with depth of the various layers associated to different compression wave velocities. The main refractor was that of the bedrock corresponding to the bedrock corresponding to the Gatun Formation.
c) The tomography image allows also to distinguish discontinuities in the bedrock that were related here to destructuration. This finding pushed the convenience to disregard the site for the project.
d) Further studies are required to evaluate the mechanism that may be responsible for the destructuration of the bedrock. Thus, there is enough data of structural faults with direction Northeast-Southwest observed in Panama.

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