ASSESSMENT OF THE STRUCTURAL INTEGRITY OF WATER RESERVOIR DAMS USING SEISMIC REFRACTION AND SURFACE WAVES METHODS

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ABSTRACT

Seismic methods, including refraction and surface wave techniques (both one- and two-dimensional), are widely used to assess the technical condition of water reservoir dams. These methods enable the mapping of soil structures and the evaluation of their stability. Among surface seismic waves, Rayleigh waves have gained significant application in geotechnical studies. These waves propagate near the surface, as illustrated in Figure 1.

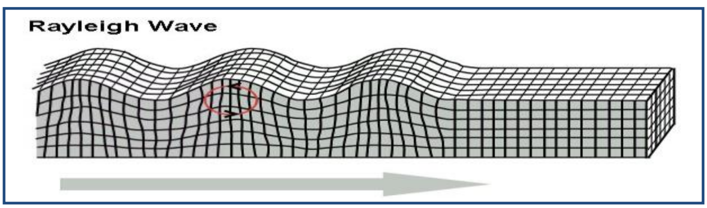

Fig.1: Rayleigh waves.

Rayleigh waves are commonly employed in geotechnics to characterize soil types. This approach relies on analyzing the dispersion of these waves, which are recorded in the field, and solving the associated inverse problem. The velocity values derived from these analyses provide insights into the geotechnical properties of the deposits, as outlined in "Eurocode 8" (Table 1).

Table 1. Characterization of soil according to (V_{S30}), based on

Soils	Geotechnical description	V_{S30} (m/s)
A	Very strong homogeneous deposits.	>800
B	Very thick gravel or slip deposits or very durable clays, characterized by a gradual improvement of mechanical properties with depth.	360÷800
C	Gravel deposits or moderately compressed sands or moderately durable clays.	180÷360
D	Deposits with a granular material, from uncompressed to slightly compressed, or with lightweight to medium toughness.	<180
E	Deposits consisting of alluvial layers with values of Vs similar to type C or D extending over a strong material base with Vs> 800m / s.	
S1	Deposits consisting of, or involving low-strength clay, high-grade plasticity (IP> 40) and water content.	<100
S2	Soil deposits that are exposed to liquefaction, clay or any other soil category that cannot be classified in the above types.	

"EUROCODE 8".

1. INTRODUCTION

The seismic waves were recorded using a "Geode 24-channel" instrument. Seismic recordings utilized seismographs capable of detecting both vertical and horizontal oscillations. Alongside field measurements, significant attention was given to the computer processing of the recorded data. Digital processing was performed using the "SeisImager/2D" and "SeisImager/SW" software packages. For result interpretation, geological data and surface observations were thoroughly integrated. The seismic data processing, conducted with SeisImager/2D and SeisImager/SW (MASW), is illustrated in Figure 2 (Roma 2003; Silo *et al.*, 2012; Silo *et al.*, 2016). By evaluating the velocities of longitudinal waves (Vp) and transverse waves (Vs), it was possible to map geological boundaries, identify slide planes, detect heterogeneities within layers, and determine the physical-mechanical parameters of the rocks constituting the geological layers.

2. MATERIALS AND METHODS

The following parameters were used during the recording of refracted and surface seismic waves: i) Recording schemes: Lengths of 34.5 m, 46 m, and 115 m, utilizing 24 vertical and horizontal seismographs arranged in a straight line., ii) Seismograph spacing: Distances of 1.5 m, 2 m, and 5 m, with shot points positioned at each seismograph, iii) Recording time: 0.5 seconds, 1.0 seconds, and 1.5 seconds, iv) Sampling time: 125 μs and 250 μs, v) Energy source: A 9 kg sledgehammer, vi) Trigger sensitivity: Set to medium, and vii) Signal amplification: Adjusted to enhance the seismic signal based on the distance between the shot point and the seismographs.

Seismic data processing was carried out using the "SeisImager/2D" and "SeisImager/SW" software packages (MASW), as shown in Figure 2 (Roma 2003; Silo, 2005; Silo *et al*., 2012; Silo 2014; Silo *et al*., 2016). By analyzing the propagation velocities of longitudinal (Vp) and transverse (Vs) waves, geological boundaries, landslide planes, and various heterogeneities within layers were mapped. This process also enabled the evaluation and determination of the physical-mechanical properties of the rocks comprising the geological layers (see Table 1). Figure 3 presents the block diagram for processing refracted wave seismic data using the "SeisImager/2D" software package. This diagram illustrates the determination of first breaks of refracted waves for each seismic trace. Based on these first-break times, travel-time graphs for refracted waves were constructed, representing the time patterns recorded in the field. Further processing utilized inversion techniques to derive the lithological model and assess layer homogeneity according to seismic wave velocity values (refer to Table 1).

This methodology has proven to be highly effective and widely applicable for evaluating the structural integrity of dams and similar structures.

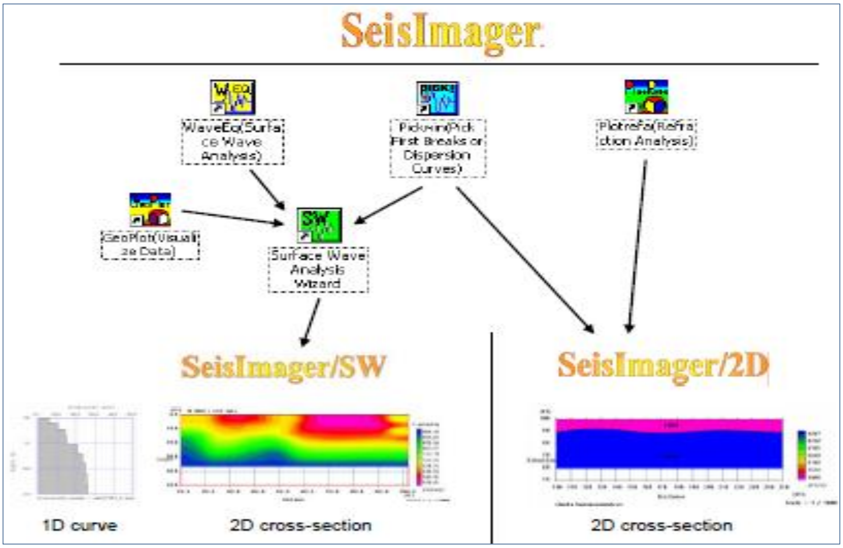

Fig.2: General block diagram of digital processing of refracted and surface seismic waves. ("SeisImager" software package).

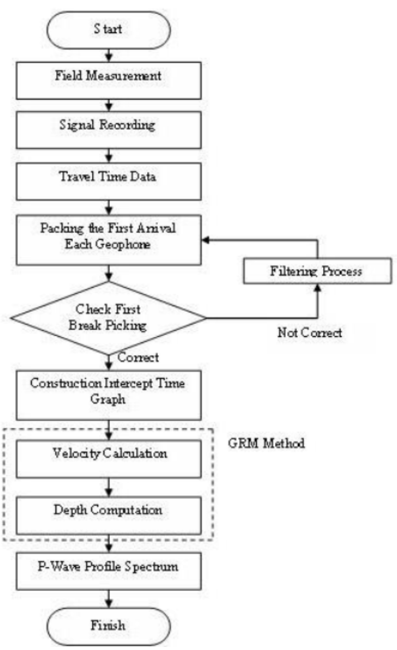

Fig. 3: Flow chart of refraction wave processing steps (SeisImager 2D).

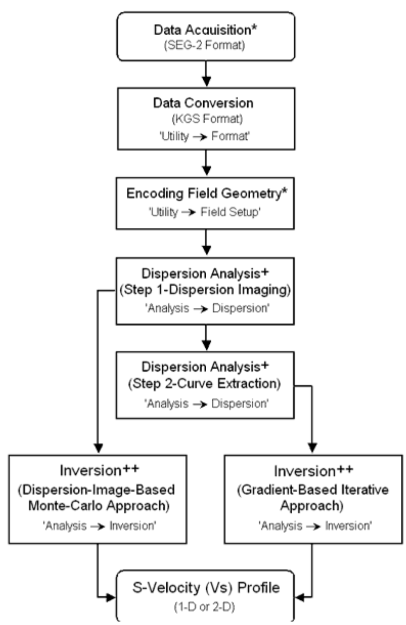

Fig.4: Flow chart of surface wave processing steps, (MASW).

Figure 4 presents the block diagram of seismic information processing for surface waves using the "SeisImager/SW" and "SurfSeis/2" (MASW) software packages. This software transforms the wave data from the time domain into the "phase velocity–frequency" field, enabling the calculation of the dispersion curve (Figure 5) (Silo *et al*., 2016; Silo and Bushati 2017; Silo *et al*., 2018; 2019).

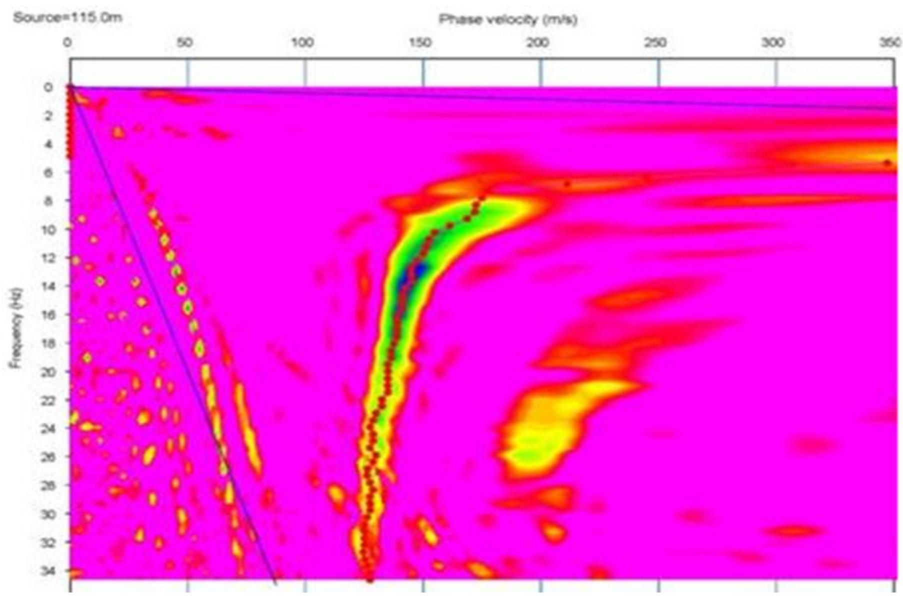

Fig. 5: Representation of "Phase Velocity - Frequency" spectrum, (Dispersion curve) taken from software SeisImager/SW, according to Fig.2.

To perform the inversion, an initial model consisting of 10 to 15 layers is used. The inversion process involves multiple iterations, refining the model until the error between the initial model and the field measurements is minimized in the least-squares sense. After completing the inversion, the resulting velocity model is presented in either 1D or 2D format (Figure 2).

3. RESULTS AND DISCUSSIONS
Bunavi reservoir dam, Vlora

The Bunavi reservoir dam is located in the Municipality of Vlora, approximately 6.6 km north of the City of Vlora. The dam stands 21 m high, stretches 190 m in length, and is oriented NE-SW. It is situated on siltstone clays from the Lower Pliocene ($N_{21}h$), with its shoulders supported by this formation. The dam was constructed using soil sourced from its vicinity. Notably, the left shoulder of the dam shows signs of being affected by sliding phenomena.

To assess its stability, two seismic profiles were conducted using refracted and surface seismic wave methods. One profile, 115 m in length, was taken along the dam axis, while the other, 46 m in length, was taken across the axis (Figure 6). The processing results are presented in Figures (7-9).

Fig.6: Placement of seismic profiles in the dam of the Bunavisa reservoir. Seismic profiles are in red. Electrometric profiles are in blue.

Figure (7a) clearly shows the soil configuration with depth. In the section from 12 to 42 m of Profile 2 (Figure 8a), which runs perpendicular to the dam axis, the sliding phenomenon is observed. The slide plane is located at a depth of 4 to 5 m, as confirmed by the velocity inversion shown in Figure (8b). Figure (9) presents the 2D velocity model of Profile 1, recorded with a horizontal seismograph. In the section from 0 to 40 m of this profile, bending of the dam's crown is observed, coinciding with the landslide that occurred on the outer slope near the left shoulder of the dam. Furthermore, it is evident that the soils forming the body of the dam do not exhibit homogeneous characteristics along its entire length. Toward the right shoulder, the soil properties appear to weaken.

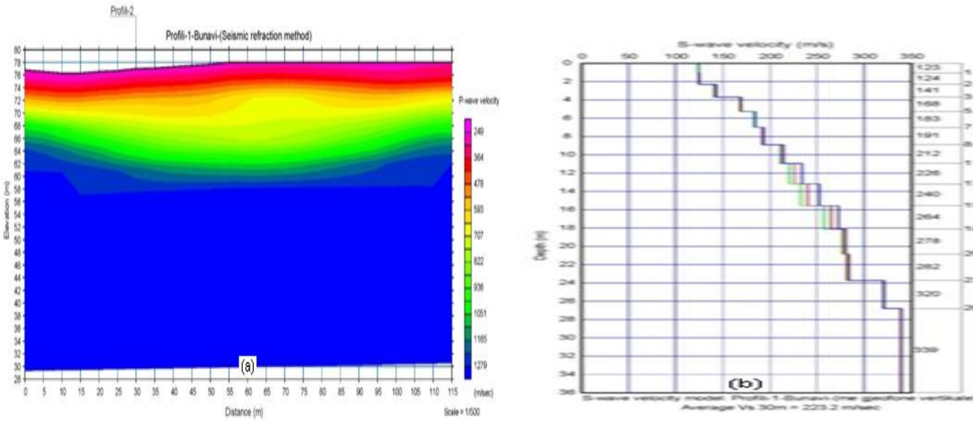

Fig.7: Seismic profile 1, Bunavi reservoir dam, Vlora. (a)- 2D velocity model, $V_P = f(h)$ according to refracted seismic waves.(b)- 1D velocity model, $Vs_{30} = f(h)$ according to surface seismic waves.

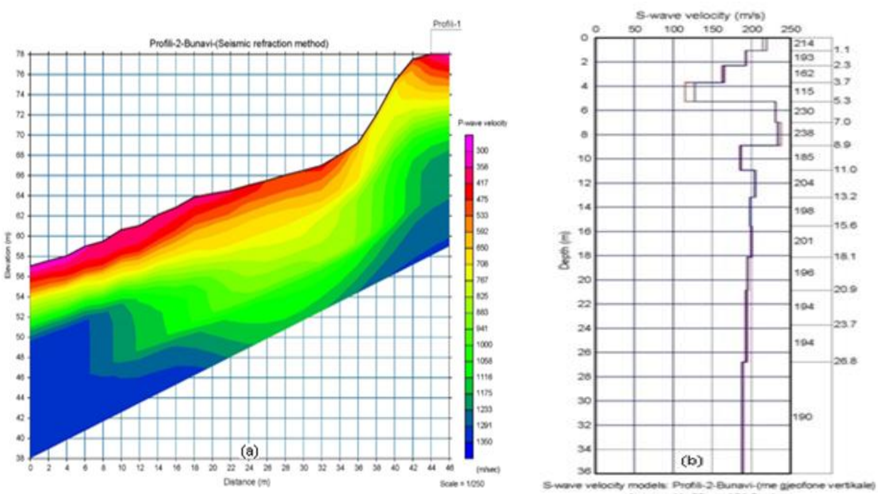

Fig. 8: Seismic profile 2, perpendicular to the Bunavi reservoir dam, Vlora. (a)- 2D velocity model, $V_P = f(h)$ according to refracted seismic waves. (b)- 1D velocity model, $Vs_{30} = f(h)$ according to surface seismic waves.

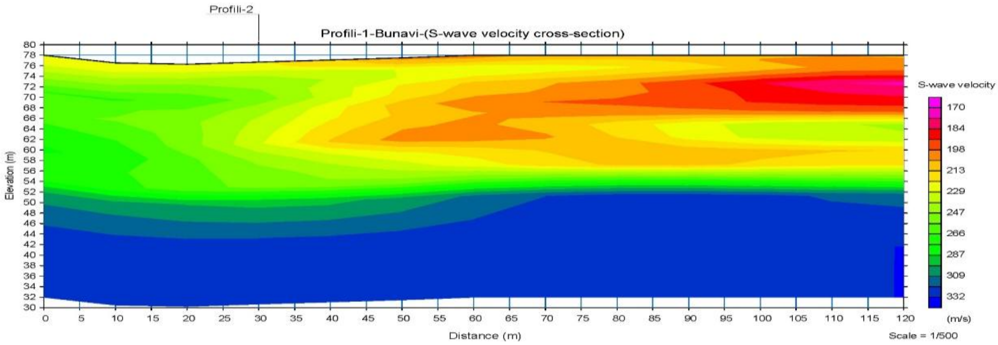

Fig.9: 2D velocity model according to surface seismic waves Vs = f(h). Seismic profile 1, acquired with horizontal geophones.

Libofsha reservoir dam, Fier

The Libofsha reservoir dam is located in the Municipality of Fier, approximately 2 km east of the center of the village of Libofsha. It is 270 m long, 19.4 m high, and oriented NW-SE. The dam was constructed using soil sourced from the surrounding area. To assess its stability and identify damaged areas, three seismic profiles were conducted using the method of refracted and surface waves. Two profiles were aligned along the dam axis, each measuring 115 m, while the third profile was perpendicular to the dam axis and 34.5 m in length (Figure 10). The results obtained from the digital processing of the field measurements are presented below.

Fig. 10: Seismic profile placement in the Libofsha reservoir dam.

The 2D seismic profiles of refracted waves, shown in Figures (11a) and (12a), clearly reveal the soil configuration. The 1D vertical profiles of transverse wave velocity (Vs) indicate a gradual compaction of the soil with depth, as seen in Figures (11b) and (12b). In seismic Profile 3, which is perpendicular to the dam axis, the configuration of the layers and the shape of the landslide affecting the dam are clearly visible (Figure 13a). The landslide extends to a depth of 6 m, as shown in Figure (13b). Figure (14) presents the tomographic representations of Profiles 1 and 2, derived from surface seismic waves recorded with horizontal geophones. These data demonstrate that the soils forming the dam body are inhomogeneous.

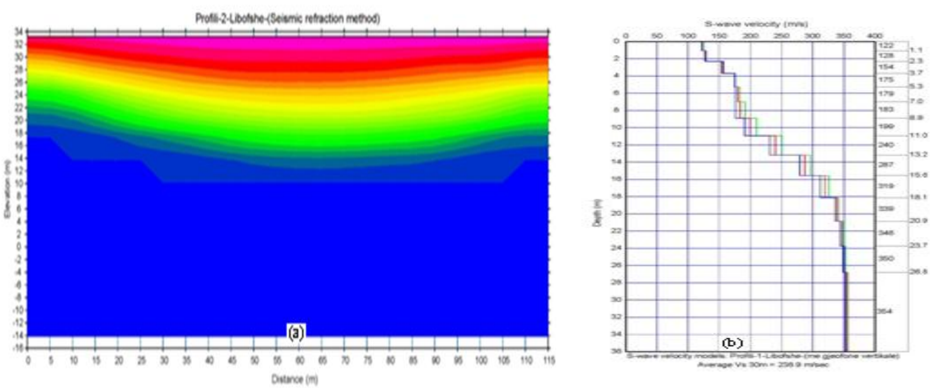

Fig.11: Seismic profile 2, Libofsha reservoir dam, Fieri.

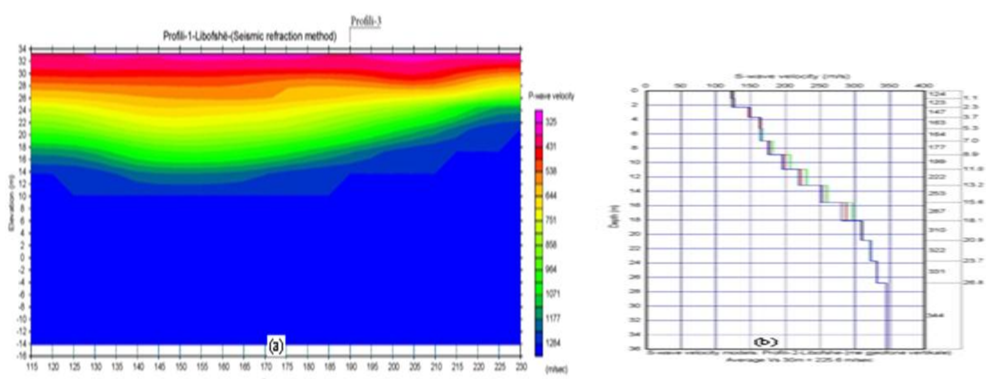

Fig.12: Seismic profile 1, Libofsha reservoir dam, Fieri. (a)- 2D velocity model, VP = f(h) according to refracted seismic waves. (b)- 1D velocity model, Vs30 = f(h) according to surface seismic waves.

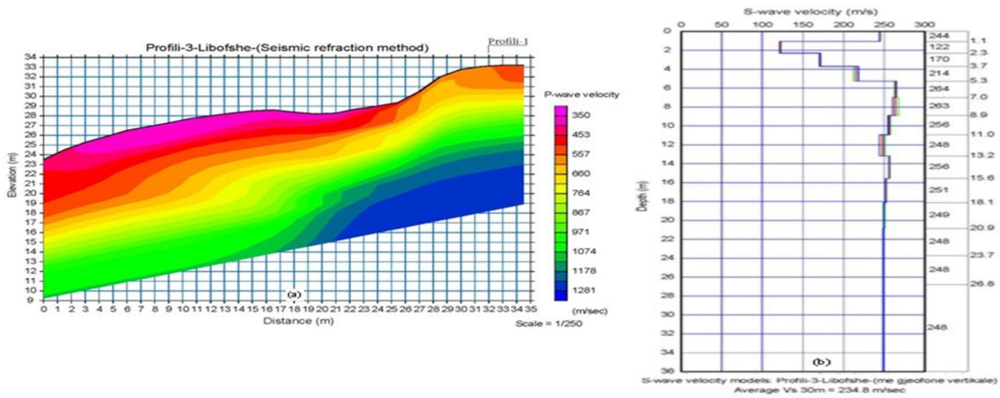

Fig.13: Seismic profile 3, Libofsha reservoir dam, Fieri.(a)- 2D velocity model, VP = f(h) according to refracted seismic waves.(b)- 1D velocity model, Vs30 = f(h) according to surface seismic waves.

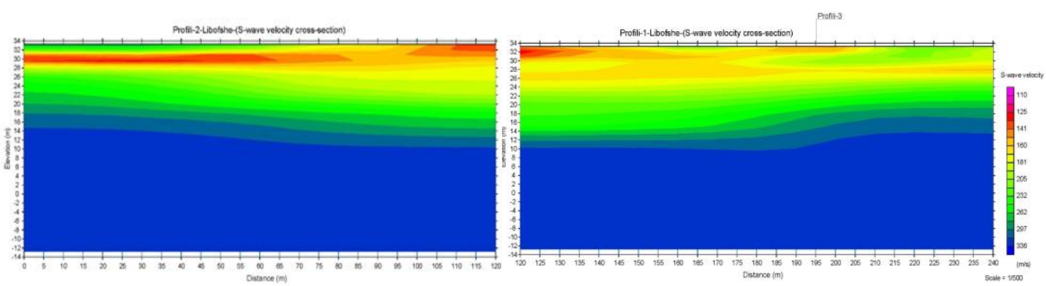

Fig. 14: Seismic profile (1+2), Libofsha reservoir dam, Fieri, recorded with horizontal geophones.2D velocity model according to surface seismic waves Vs = f(h). The soils that build the body of dam are inhomogenous.

4. CONCLUSIONS

The methodology used in this study combines seismic refraction and surface wave analysis (MASW) to assess the Bunavi and Libofsha reservoir dams. Seismic refraction is typically conducted with vertical geophones to accurately measure P-wave velocities (Vp), as shown in SeisImager/2D (Figure [2]), which provides information about compressional wave travel through the subsurface. In this study, horizontal geophones are used for surface wave (Rayleigh wave) analysis, which are more suitable for detecting shear waves (Vs) and are widely employed in studying the heterogeneities of subsurface layers. The integration of results from digital processing of both refracted seismic waves and surface seismic waves allows for an accurate interpretation of the structural integrity of the dams. The MASW method is appropriately applied in this study. Horizontal geophones are ideal for measuring surface waves, which are used to derive shear wave velocity (Vs) profiles. The software SeisImager/SW (Figure 2) is used to generate accurate models for this purpose. Seismic methods of refracted and surface waves, both in one and two dimensions, are widely applied to evaluate the technical condition of dams, particularly for analyzing the structure and stability of soils.

For the Bunavisa reservoir dam, Figure (7a) clearly shows the soil configuration with depth. Between the 12 m and 42 m marks on Profile-2 (Figure 8a), which was taken across the dam axis, the sliding phenomenon is observed. The slip plane varies between depths of 4 to 5 m, as also confirmed by the velocity inversion in Figure (8b). Figure (9) shows the 2D velocity model of Profile-1, recorded with a horizontal seismograph. Between 0 and 40 m along this profile, bending of the dam crown is observed, corresponding to the landslide that occurred on the outer slope near the left shoulder of the dam. Furthermore, the soils forming the dam body are not homogeneous along its entire length, with the soil characteristics weakening toward the right shoulder.

For the Libofsha reservoir dam, the 2D seismic profiles of refracted waves (Figures 11a 12a) clearly show the soil configuration. The vertical 1D profiles of shear wave velocity (Vs) with depth indicate a gradual compaction of the soils, as seen in Figures (11b) and (12b). In seismic Profile-3, taken across the dam axis, the layer configuration and the shape of the landslide affecting the dam are clearly observed (Figure 13a). The landslide extends to a depth of 6 m, as also confirmed by the velocity inversion in Figure (13b). Figure (14) presents the tomographic images of Profiles-1 and 2, based on surface seismic waves recorded with a horizontal seismograph. These data highlight the inhomogeneities of the soils that form the dam body.

REFERENCES

Roma V. 2003.Soil properties and site characterization through Rayleigh waves, deformation characteristics of geomaterials. IS Lyon, September 2003.

Silo E. 2013. Evaluation of geotechnical characteristics of soils through seismic surface waves for the "Ashta Hydropower Plant", Albania". 7th Congress of Bakan Geophysical Society, Tirana, Albania 7-10 October 2013.

Silo E. 2014. Application of seismic methods of refracted and reflected waves in civil engineering, (Disertacion-2014), bib. F.GJ.M. Tirana.

Silo E. 2018. Seismic refracted and surface waves used to studying landslides. 1st Western Balkan Conference on GIS, Mine Surveying, Geodesy and Geomatics, Tirana, Albania 3-4 October 2018. Proceedings ISBN: 978-9928-07-599-4.

Silo E. 2019. Application of Seismic methods in the evaluation of geodynamic phenomena of water reservoirs, XVIII-th Balkan Mineral Processing Congress 23-26 Maj 2019, Durrës Albania, ISBN 978-9928-05-264-***3***

Silo E. Silo V. 2016. Seismic surface waves and their application in civil engineering, library of Faculty Geology and Mining Tirana, Albania, ISBN: 978-9928-4303-2-8, p.224.

Silo V. 2005. Digital processing of seismic data, (v.2), library of Faculty Geology and Mining Tirana, Albania, ISBN: 99943-877-9-0, pages 163.

Silo V, Bushati S. 2017. Bazat teorike dhe zbatime të metodave sizmike dhe gravimetrike, (bib. Akademia e Shkencave Tiranë, ISBN 978-9928-237-24-8).

Silo V, Bushati S, Silo E. 2012. Applied geophysics in the Earth sciences. Library of Faculty Geology and Mining Tirana, Albania, ISBN: 978-9928-4096-5-2, pages 560.

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