NON-DESTRUCTIVE INVESTIGATION ON SMALL EARTH DAMS USING GEOPHYSICAL METHODS: SEISMIC SURFACE WAVE MULTICHANNEL ANALYSIS (MASW) AND S-WAVE REFRACTION SEISMIC METHODS

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ABSTRACT. The application of non-destructive methods of investigation in dams, such as refractive seismic analysis and multichannel surface wave analysis (MASW) are increasingly effective from the point of choosing the best dam site, as well as in the phases of construction and maintenance of the structure. Considering that the objective of the use of the geophysical surveys in the dam structure is to detect the internal flow of fluids, to detect the presence of voids and/or craters, to find possible fracture zones and to identify variations in the saturation level of the massif, characteristics related to the permeability and directly linked to the stability of the dam, the geophysical methods stand out as excellent tools because, unlike probes, for example, they can cover a large area of study quickly and with a good cost effectiveness. This paper aims to present the results of the correlation between the multichannel surface seismic wave analysis (MASW) method and the S wave seismic refraction method in two small earth dams in the countryside of the State of São Paulo, Brazil, more precisely in the cities of Cordeirópolis and Ipeúna. The main goal was to obtain the depths of the rocky top and the saturated / unsaturated zone of the earth dams using seismic tests under conditions of lack of information about the construction of the dam. The application of geophysical methods in dams that do not previously have important information (presence of drainage blanket, vertical / horizontal filters, for example) proves to be a very interesting non-destructive investigation technique.

Keywords: geophysics in dams, MASW, seismic refraction, dam investigation.

RESUMO. A aplicação de métodos não destrutivos de investigação em barragens, como o método da sísmica de refração e a análise multicanal de ondas de superfície (MASW), são cada vez mais eficazes desde a fase de escolha do melhor local para a instalação da barragem, bem como nas fases da construção e manutenção da estrutura. Considerando que o objetivo do uso dos ensaios geofísicos na estrutura da barragem busca detectar o fluxo interno de fluidos, observar a presença de vazios e/ou crateras, encontrar possíveis zonas de fratura e identificar variações no nível de saturação do maciço, características relacionadas à permeabilidade e diretamente ligada à estabilidade da barragem, os métodos geofísicos se destacam como excelentes ferramentas, pois, ao contrário das sondagens, por exemplo, podem cobrir uma grande área de estudo com rapidez e economia. Este trabalho tem como objetivo apresentar os resultados da correlação entre o método de análise multicanal de ondas sísmicas de superfície (MASW) e o método sísmico de refração com ondas S em duas pequenas barragens de terra no interior do Estado de São Paulo, mais precisamente nas cidades de Cordeirópolis e Ipeúna. O objetivo principal foi o de obter as profundidades do topo rochoso e da zona saturada/insaturada das barragens de terra fazendo uso de ensaios sísmicos em condições de ausência de informações a respeito da construção do barramento. A aplicação de métodos geofísicos em barragens que não possuem previamente informações importantes (presença de tapete drenante, filtros verticais/horizontais, por exemplo) mostra-se como uma técnica de investigação não destrutiva bastante interessante.

Palavras-chave: geofísica em barragens, MASW, sísmica de refração, investigação em barragens.

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INTRODUCTION

The development and use of dams began thousands of years ago. In Brazil, according to data from the Agência Nacional de Águas (ANA - National Water Agency) as of 2013, 13,529 dams were registered throughout the country. Among these, large dams, which drew attention due to the recent accidents, are only 371. Therefore, the great majority of the national dams are of medium or small size.

The first projects of dams were constructed empirically, that is, without great engineering techniques and little scientific knowledge, with the intention of damming a material, initially water, through the construction of a blockage in transversal position to the main flow of a river, mainly with material near the construction site, creating an artificial reservoir for water accumulation. With the advancement of knowledge on Dams Engineering, the dams reached larger sizes and the uses became varied, such as dams for electric power generation (Brazil’s main energy source), embankments or dams for industrial waste storage, fish farming, leisure and mining tailings dams, added to the classic and pioneering use for irrigation (Duarte, 2008).

Currently, dams can be classified in different ways, depending on the type of retention structure used (land, rockfill, gravity and mixed, for example), depending on the generation system (base or tip generation plants, reversible mills or tides) and materials used in its construction processes (geomaterials, concrete, synthetic materials and civil construction steel). Due to lower costs, simpler construction techniques and large soil presence, earth dams are the most common type of small dams (Cullen, 1964). According to data from Bulletin 99 of the International Commission on Large Dams (ICOLD), due to the ease of construction and use of less robust techniques, landfill dams account for approximately 45% of the accidents due to foundation problems, such as piping of the dam body (28%) or erosion of the foundation (17%).

In Brazil, recent cases of tailings dam rupture have gained prominence due to natural, social and economic disasters. In 2015, a tailings dam in Mariana - MG from the Samarco mining company burst, dumping 62 million m³ of tailings in areas as far as 100 km from the dam (IBAMA, 2015). In the beginning of 2019, an iron ore tailings dam of the mining company Vale burst in Brumadinho - MG, dumping 12 million m³, causing hundreds of deaths and environmental losses in an area of 2.6 million square meters.

Despite being a minority (approximately ten thousand dams of the total of two hundred thousand), the medium and large dams have the largest contribution of resources for geotechnical research and the elaboration of technical projects. For that reason, a more detailed study of the small dams is mandatory, not only because they are more common, but also because they are easier to study and the knowledge acquired can also be used in larger dams.

Another alarming problem refers to the lack of data on the conditions of Brazil’s dams. The National Dams Safety Policy (PNSB), issued in 2010, presented a lack of data in its latest report, as the following: dam height, potential damage rating and reservoir capacity. The data about these topics were not contained in several reports sent to the National Water Agency (ANA). There is a clear need for investments in techniques that could help in the management of dam safety levels and, more than that, to employ methods that can help in the investigation of the conditions of the dams, in a scenario which there isn’t any previous information since many of the dams are abandoned.

The geophysical methods, for instance, can be a tool with a low-cost benefit ratio, concerning both installation and construction of the dam. It can also be applied in the phase of maintenance and monitoring of the safety level of the dam through time, since the integration of different geophysical methods can assist in the detection of internal flows and / or weaknesses developing or formed in the dam structure, for example.

The seismic study presented here is only part of a larger project for the use of geophysical methods in small-scale dams, other methods such as electrical tomography (Camarero & Moreira, 2017) and self-potential (Guireli Netto, 2017) have already been performed in dams. The objective was to perform two non-destructive geophysical investigation methods that allowed to better identify the physical characteristics of the materials that compose the dam body, as well as to identify the bedrock under which the dam was constructed, since these data were not available.

This paper targets the use of MASW (Multi-channel Analysis of Surface Waves) and S-wave seismic refraction, making a comparison between both methods of analysis of the behavior of the shear wave in subsurface and the consequence on the physical integrity of two land dams located in the cities of Ipêu and Cordeirópolis, both in the interior of the State of São Paulo, Brazil.

THE PHYSICAL INTEGRITY OF DAMS AND THE AID OF GEOPHYSICAL METHODS

Until the mid-nineteenth century, the construction of dams had an empirical basis, taking into account a technique that resulted in cross sections of high volumes, since they followed the idea of reservoir containment by the dam mass (Bretas et al., 2010).

Almost at the end of the nineteenth century, the first
works in this area were published, being the first the famous “A manual of applied mechanics” by Rankine & Miller, 1898. However, the focus on intensifying dam safety development occurred only in 1979, during the International Congress of Large Dams in New Delhi (ICOLD, 1995). In other words, dam safety is a relatively recent issue that has been developing since the last quarter of the twentieth century. According to Lou (1981), the reasons that can lead to the rupture of a dam can be divided into two groups: causes of human and non-human origin.

The first group includes deficiencies and errors in the construction and / or design and improper location of the dam. The geophysical methods can help in the characterization of the lithologies present in the area, seeking to assist in choosing the most suitable location for the construction of the dam, but this is not the focus of this investigation.

This study aims to put a spotlight on the second group, which addresses problems in landfill dams, such as overtopping, internal erosion in the dam body (piping) and / or foundations problems, landslides and earthquakes.

According to data from the 2014 Dam Safety Report issued by the National Water Agency (ANA), the main causes of ruptures of earth dams are: events of internal erosion in the body of the dam (piping), instability of slopes and overtopping. The latter occurs when the dammed water level is higher than the ridge level, that is, it overflows. Generally, the result is the collapse of the dam body. The instability of the slope can be generated by several factors varying according to the material used in the construction of the dam. When it comes to earth dams, poor compaction of the material can cause increased infiltration and elevation of the water table, compromising the structure of the dam.

The regressive erosion process from downstream to upstream into the body of an earth dam can result in its rupture, developing a pipe capable of carrying soil particles by the mass, resulting in an unrestrained flow. In homogeneous dams, (only compacted soil without the presence of an impermeable central core) this type of process is more recurrent.

Recent accidents in dams draw attention to the need for investment in further studies, in addition to the development of new dam monitoring and inspection techniques. The use of associated geophysical methods, as proposed by the present study, can be an alternative that will bring positive results, such as the use of the self-potential (classically used in dams), electrical and seismic methods. Therefore, applied geophysics is shown as a non-destructive method of evaluating the physical integrity of dams, both in the construction phase of the work and also as a mechanism to follow the development of the dam during its lifetime, certainly increasing the dam’s levels of security.

APPLICATION OF THE MASW AND SEISMIC REFRACTION METHOD IN DAMS

The seismic refraction method is much more consolidated in the applied geophysics community than the multichannel surface wave analysis (MASW) method. However, the use of the S wave in the refraction method is not commonly applied. The application of both methods presented in this study in dams is a little more difficult to find, making it interesting to disseminate the results. Works involving the use of seismic refraction applied to dams are mostly related to the study of the depth of the dam foundation, as shown by Dutta (1984).

Recently, Herzig (2003) presented the application of shallow seismic to obtain subsurface structural information that subsidized a dam construction project. On the aforementioned report, the possibility of applying seismic methods at both the phase of investigation, prior to dam construction, and during the maintenance and inspection phases was made clear.

Another important work was developed by Teixeira (2013), concerning the application of various geophysical methods in dams, such as electrical tomography, ground penetrating radar (GPR) and seismic refraction methods, seeking to analyze the physical integrity of dams.

As for the object being discussed on this paper, the Multichannel Surface Wave Analysis (MASW) method has been increasingly implemented and accepted by the geophysics community over the years, a good part of this study is mainly applied to understanding the material compaction and variations of the thickness of the lithological layers, as shown by the works of Karray et al. (2010) and Eikmeier (2014).

GEOGRAPHICAL AND GEOLOGICAL LOCATION OF THE STUDY AREA

The area subject to this study is located in the interior of the Brazilian State of São Paulo, in Brazil, in the cities of Cordeirópolis and Ipeúna, and it includes two small earth dams. The first one is 69 meters long and approximately 6 meters wide in ridge, being used for irrigation of sugarcane crops; the second one is 86 meters long and approximately 5 meters wide and is used for fish farming (Fig. 1).

Both dams do not have the construction projects. However, it is believed that the dams were constructed by compaction of alteration soils existing near the construction sites, without the presence of vertical or horizontal filters in their bodies. This type of construction, quite simple and requiring relatively low investment has been mainly used in Brazil for small dams.
The reasons for choosing these dams were not random, they had already performed geophysical surveys in their areas: electrical tomography (Camarero & Moreira, 2017) and self-potential (SP) (Guireli Netto, 2017). The electrical one indicated both a possible internal erosion (piping) event in the dam located in Cordeirópolis and a process of water saturation / infiltration in the structure of the dam located in Ipeúna. The knowledge of these data facilitates the interpretation of the seismic refraction data. Another good point is that, even though they have the same construction technique (a homogeneous dam consisting of a single compacted material), the Cordeirópolis and Ipeúna dams have local geology with different characteristics (degree of compaction and different electrical resistivities, for instance), which could result in distinct S-wave velocities. Such set of characteristics would favor the application of the method on the dams.

The study area is geologically inserted in the Paraná Sedimentary Basin and has a sedimentary fill composed of siliciclastic materials with intrusion of a basaltic lava flow, quite expressive throughout the region of the study. The following geological formations of the Paraná Sedimentary Basin occur in the region: Itararé Group, Tatuí, Irati, Corumbataí, Pirambóia, Serra Geral and Botucatu Formations. However, this work will focus only on the Itararé Group and the Serra Geral Formation, which are lithostratigraphic units present in the Cordeirópolis and Ipeúna areas, respectively.

The Serra Geral Formation in the area is represented by a clayey lateritic soil with a reddish-brown coloration, characteristic of the alteration of basic rocks. The altered basalt blocks occur frequently in the region and around the dam of the city of Cordeirópolis – SP (Fig. 2a). Geological mapping in the region indicates that rivers are running over basalt spills (Morenghi, 2007).

On the other hand, the Itararé Group in the region of the dam located in Ipeúna – SP has a different lithology than the Cordeirópolis area. In this case, outcrops are formed composed of clayey diamictites with granules up to 4 cm, as well as light gray colored siltstones (Fig. 2b). The outcrops found in the region of the Ipeúna dam (clayey diamictites with granules of different dimensions), are typical of the influence of glacial processes. According to Zaine (1994), the sediments of the Itararé Group are found in the basal unit of the permo-carboniferous sequence of the Paraná Basin, outcropping at the base of the stratigraphic column in the bottom areas of river valleys in the region of the study area.
MATERIALS AND METHODS

The availability of the dam construction project would be very positive and could bring important insight in the interpretation of the data, such as the precise location of the spillways, the existence or not of waterproofing material in the central part of the dam body, lithological variations in the composition of the chosen material and the presence or absence of vertical and/or horizontal filters, for example.

However, dam design data were not available, which made the interpretation process much more difficult. It is worth mentioning that with the construction project and prior knowledge of the material of the dam body it would have been possible to carry out simulations in a dedicated software in order to have an idea of the model to be found in the field.

The geophysical data acquisition performed in this work utilized the following seismic methods: Multichannel Analysis of Surface Waves - MASW and S-wave seismic refraction at the crest of the dams.

The use of seismic methods prior to the construction of a dam is interesting, since it is a work of great impact and requires high levels of safety. The precise determination of the dynamic elastic parameters of the massif (since the reservoir is not static) (P) and shear (S) modulus in this case are necessary and possible to obtain through the propagation velocities of the compressional (P) and shear (S) seismic waves (Taioli, 1999; Pasquet et al., 2015).

Both methods provide the S-wave velocity mapping in depth. The process of data acquisition is very similar among the methods (Gandolfo, 2011) (Fig. 3). Thus, the joint use of the methods become interesting since the same arrangement is used. Furthermore, the comparison of both methods increases the safety in making affirmations about the depth of the lithological contacts, for example.

Multichannel analysis of surface waves (MASW)

The MASW (Multichannel Analysis of Surface Waves) method has as principle the extraction of a dispersion curve from a double Fourier transformation of multi-channel recordings. Those recordings receive the surface waves generated by a seismic source (Xia et al., 2000). The method is performed through the spectral analysis of the surface waves generated by a seismic source, generating a layer model in terms of Vs (shear wave velocity) (Turesson, 2007).

Figure 2 - a) Outcropping of altered basalt blocks, typical of the Serra Geral Formation. b) Outflow of diamictite, characteristic of the Itararé Group near the Ipeúna dam, with granule detail. Source: Guireli Netto, 2017.
It is advisable to use the MASW method together with other methods, especially other seismic methods: cross-hole geophysical testing and, as shown by this work, refractive seismic method, aiming to operate with shallow areas (up to 10 meters) due to the frequencies used by the method (between 4 and 50 Hz). The main use of this seismic method is the characterization of alteration of soils and the evaluation of compaction techniques of soils and pavements.

The understanding of the dispersive character of surface waves in stratified media, for example in order to infer variations in the elastic properties of the subsurface, is of great importance in engineering geology, since the velocity of the S waves is directly related to the degree of rigidity of the subsurface material and is practically insensitive to the saturation of the earthy mass. This characteristic made the use of the method in this study more interesting, since as mentioned before, the data of electroresistivity and self-potential pointed to a possible water infiltration in the body of the dam in some points. The same applies to the study of the physical integrity of dams, considering that poorly consolidated materials would have lower values of Vs, and materials with a lower degree of alteration, such as a sound rock, would have higher values of Vs and, therefore, higher values of stiffness.

Another feature of the MASW method that was expected to be referred to is the depth of the method. Since it is a suitable method to analyze the behavior of the S wave at shallow depths, it was expected to obtain reliable data at depths of around 10 meters. It is clear that depending on the conditions of compaction, porosity, degree of saturation and
rigidity of the material, the penetration capacity of the S waves increase, also increasing the reach levels of the method.

The operation of the method is not very complex, being carried out in three steps: data acquisition, extraction of the dispersion curve and inversion of the dispersion curve to obtain 1D profile of S wave velocities (Vs) (Fig. 4).

Seismic refraction

The seismic refraction method is based on the assumption that when a seismic wave encounters changes in the elastic properties of the environment it is traveling through, such as a contact between layers of distinct lithologies, part of the energy is reflected, another part is refracted and one part of the energy is absorbed by its surroundings.

The refraction of a seismic wave, therefore, occurs when the seismic wave, after encountering and transposing a layer interface with distinct elastic composition materials, begins to propagate at a different velocity than before (Seimetz, 2012).

The angle at which the seismic wave strikes the interface will also influence the direction of wave propagation. The angle between the normal to the surface and the wave radius is called the angle of incidence. However, if the incidence is normal to the interface that separates the layers, there will be no change in the direction of propagation.

The seismic refraction method using the S wave is almost never used. However, it makes sense to use it in this study considering the objectives of this investigation (assessment of the stiffness and physical integrity of the earth dams) and that the MASW 1D / 2D test data also provides the velocities values of the S wave in depth in the profile format.

The seismic sledgehammer was used as a seismic wave source, since it was capable of reaching the desired depth levels in the investigation with this type of source. In addition, the seismic sledgehammer can generate the types of waves needed for the study, striking both directly on the ground and horizontally on the wooden trunk.

On the first day of collection, seismic data were collected at the dam located in Cordeirópolis in an acquisition line 86 meters long with spacing of 2 meters between the geophones. However, it was noticed that it was difficult to record the seismic waves in the geophones farther from the source. For that reason, it was decided to use a smaller spacing between the geophones in the data acquisition in Ipeúna, performing a seismic survey line of 69 meters with spacing of 1.5 meters between the geophones.

For the MASW method we employed minimum offsets of 4, 8, 12 and 16 meters in Cordeirópolis, while in Ipeúna the offsets were 3, 6, 9 and 12 meters.

RESULTS AND INTERPRETATIONS

In order to display the results and interpretations more clearly, we will first present the results of the dam located in Cordeirópolis – SP and then the data of the dam located in Ipeúna – SP. After that, we will make more comments and observations comparing the results in both dams, which have distinct characteristics.
The velocity of seismic wave propagation depends on the mechanical properties of the geological materials by which they are transmitted. Therefore, it was expected to find different results of propagation velocities of the $S$ waves on the studied dams, due to the presence of different lithologies.

The areas of study are located outside major urban centers in a rural area with low vehicle traffic. Therefore, it was understood on general terms that good quality and easily processed data was obtained, since it had only few sources that could generate noise. However, the dam structure itself, due to the movement of the reservoir water, could generate seismic waves that could hinder data acquisition.
Figure 6 shows seismogram at the 31-meter shooting position (the center of the array), where the first breaks of the refracted waves were extracted. The acquisition of the data is made from strokes of the mallet on the ground and the data will overlap to generate the visualized seismogram. The first break picks of all seismograms resulted in the graph: time x distance showed in Figure 7.

In the seismogram of Figure 6, as the “strike point” (point of the seismic source - region of the hammer strikes in the ground) was in the almost central region of the arrangement, it was possible to collect data in all 24 geophones of the arrangement that constituted the seismic base, even on geophones furthest from the source; therefore, it is a reliable determination of the arrival times of the S wave at these points. If this situation was not found during data acquisition in the field, in the pre-processing step, which consists of verifying the quality of the acquired data, controlling the influence of seismic noise, the ideal would be to start the data collection again, using this time an arrangement with smaller spacing between geophones. In the dam located in Ipeúna, it was noted that the seismic waves were not reaching the geophones furthest from the arrangement with spacing of 2 m between them, so it was decided to reduce the spacing to 1.5 m. The signal quality has improved considerably. This condition may have occurred due to the degree of compaction and/or saturation of the dam massif.

Figure 8 - Section 2D modeled S wave refraction obtained by tomographic inversion of the dam located in Cordeirópolis - SP.

Figure 9 - Dispersion image obtained from the MASW data and the extracted dispersion curve (base 1 of the seismic line).

Figure 10 - Analysis of the first 20 meters of section 2D of S-wave seismic refraction comparing with the values obtained by the MASW method at the dam located in Cordeirópolis – SP.
Before the study was carried out, we had the knowledge about the material that composed the body of the dam which were soil of alteration of basic rocks (basalts) compacted. So, it was expected to find a material with slightly smaller S wave velocities in the more superficial regions and higher values when it reached the rockfilled top, which in this case would be composed of basalt blocks, characteristic of the Serra Geral Formation.

The first analysis on the behavior of the S wave that could occur in the dam body, including being one of the reasons for the execution of the study, would be on regions indicating lower values of seismic wave propagation velocity, these spots could indicate possible regions where the material could be poorly compacted. This may be due to a compaction difference in the material of the dam body, in the construction step or during the operation resulting from the flow of large vehicles in the crest of the structure.

The interpretations of the results were proposed according to studies in the areas, which are well known and geologically mapped by researchers. Studies, such as those by Brandes et al. (2011), carried out using the same lithologies as in the present study, which obtained similar results and interpretations of seismic wave velocities, were also considered.

Figure 8 shows the propagation velocity in a section of the area. It is possible to perceive two pink spots on the 30 meter and 72-meter points, with S wave velocity values less than 100 m / s, identifying possible areas of weakness where the material would be badly compacted.

Another very clear point in the refraction section is the gradual but very remarkable change in the increase of the S-wave velocity at the depth of approximately 4.5 meters.

Figure 11 - Seismogram with the S wave register (marked with the pink line) obtained with shot 2 in the 26 meters position of base 1.

Figure 12 - Time curve x distance of the shots performed in the line of seismic acquisition of S-wave refraction in the dam located in Ipeuna – SP.
Such change occurs because at this point the rockfilled top was reached, and it is, as mentioned before, composed mostly of basalt blocks altered. The depth of 12 meters was established as a possible beginning of the presence of the rockfilled top, due to the increase in the values of Vs at this level. However, the Vs value were not as high according to what is expected for a basalt with little weathering action, according to data from Dias (2011), for example. Therefore, it is believed that it is an area with strong alteration of this basic rock.

The 2D refraction section of the S wave of the dam found in the city of Cordeirópolis – SP displays an anomaly between the points of 42 and 46 meters in the depth from 2 meters. It happens as a result from the presence of the concrete spillway of the dam in that point, which evidences the efficiency of the method in the investigation of important components of the subsurface of the dam structure, such as spillways and depth of the rockfilled top. The method is also thoroughly efficient in displaying characteristics for analysis of the physical integrity of the structure, such as problems in compacting the material in homogeneous dams, for example.

The extraction of the dispersion curve proved itself very difficult. The best result was with offset from base 1 and 16 meters away (Fig. 9). The generated curve causes certain difficulty in reading, since it can be either a first higher mode or the fundamental mode. After the inversion process, a S-wave velocity profile was generated in depth (as a gray column chart), shown below in Figure 10.

It is paramount to mention that the dispersion curve extraction step is quite delicate, and the process is highly dependent on the experience of the person interpreting the data, this doesn’t mean that the data is poor quality. Misinterpretation may compromise the entire outcome of the work. Poor quality data generates dispersion images which are not possible to extract the curve of dispersion. In none of the data acquisitions in the present study did this happened.

The positive point is that during the data acquisition process it was already possible to perform “primary data processing” and to view the dispersion images being generated, thus facilitating a first selection of quality data. And in the case of bad dispersion images, it was already possible to change the arrangement or the offset points, for example.

The first point that draws attention is the similarity between the S-wave velocity section derived from the seismic refraction data and the velocity profile derived from the MASW data. The velocities are quite close, varying between 150 and 180 m/s. The results of both methods were compared in Figure 10.

Lastly, another very clear point is that the S-wave velocity changes when the rockfilled top is found. Consistent with the refraction seismic data, the MASW data also gets a velocity increase (to 375 m/s) at 4.2 meters deep.

**IPEÚNA DAM**

Since the areas of study have different lithologies (sedimentary rocks x volcanic rocks), some changes in data quality were expected. In this case, one of the objectives of the research was to try to identify in which situation the operation of the MASW seismic method obtained better quality data.

In Figure 11, we have the seismogram of the acquisition line at the 26-meter shooting position, with the first picked
breaks of the refracted S waves (pink line). The first breaks picked from all the seismograms resulted in the graphs time x distance showed in Figure 12.

The S-wave velocity profile in the Ipeúna dam presents, for the near surface, higher values than the Cordeirópolis ones (between 300-350 m / s), probably because it is very compacted. It does not present regions with low values of Vs (possible indicative of poor compaction) (Fig. 13). The dam is inserted in an area with considerable flow of vehicles, situation which helps in the process of compaction.

Another difference between the results of the two dams refers to the level of the saturated / unsaturated zone. In the dam located in Ipeúna, the level of the saturated zone was established at approximately 5 meters referring to the S wave velocity (Vs) of 550 m/s. This difference in Vs can be explained due to the different lithologies and degrees of compaction of the material in the dam’s bodies. In the dam located in Ipeúna, the material was more compacted, therefore it was expected to find higher values of Vs in this area.

The analysis that we highlight is the one referred on the point of 42 meters, where there is an anomaly from the depth of 3 meters to, approximately, 8 meters. Precisely in this region, the spillway of the dam cuts its body transversely. As well as in the dam located in Cordeirópolis – SP, the presence of spillways resulted in interference in the velocity of the S wave, being even possible to trace the spillway depth in the case of the Cordeirópolis.

Another observation refers to the depth of approximately 9 meters, where the S wave velocities increase to values of 900 m / s, probably due to the presence of the bedrock. It is worth highlighting the difference of the S wave velocity values among the dams, justifying the choice of distinct lithologies to perform the methods and to better understand the S wave behavior in volcanic rocks x sedimentary rocks.

The velocity of wave S (Vs) at the Ipeúna dam are higher than those obtained at the Cordeirópolis dam due to the lithological composition. While in Cordeirópolis dam the material is basically basic rock alteration soil, in the Ipeúna dam the material used is siltstone, this explains the differences in values.

Upon analyzing the results of the MASW method in the dam located in Ipeúna, the best quality dispersion images were obtained employing 3 and 6 meter of minimum offset, however in the frequencies from 10 Hz it became difficult to precisely trace the dispersion curve (Fig. 14).

The first point that is highlighted is the decrease of Vs near the depth of 3 meters. Since it is an unusual behavior, the processing was carried out in two different softwares (Geopsy and SeisImager) in order to solve the doubts regarding a possible data processing problem. However, the same result was found in both processes. Therefore, the issue is believed to be related to the material that is more fragmented and has a lower degree of compaction at this location.
The depth of 7 and 8 meters shows an increase of Vs up to 375 m/s, quite compatible with the values found by the seismic refraction method. Both results were illustrated in the same image to better present the data (Fig. 15).

Finally, comparing the behavior of the application of the MASW method in the two dams, one can perceive a greater depth in the dam in Ipeúna. It is believed that better compaction of the material of the dam body has aided in better penetration of the S-wave in deeper layers.

CONCLUSIONS

The recent cases of bursts on tailings dams in Brazil have drawn a lot of attention because of the power of destruction, causing irreparable social, human and environmental damages. Thus, the need to develop new techniques or use several methods together in order to improve the understanding of the behavior of the dams and raise the levels of safety of the work is very clear.

For that reason, the development of this project in small dams is crucial, since the use of associated geophysical methods culminated in a very satisfactory result, determining the depth of the bedrock and also recording possible zones of bad compaction of the material that composes the body of the dam and the delimitation of layers of different lithologies.

The use of the MASW method in dams is not very common in Brazil, so the work becomes important since it shows that it is possible to obtain data about the dam body through the use of the method. It is also worth noting that the study is aimed at small earth dams, that is, with small depths of investigation, making the MASW method viable. In other circumstances, where more depth of research is needed, the method would not be the best option.

Due to the fact that it is a study in an area which didn’t have the data of the construction project of the dam, the work gains prominence, since it will be essential in the cases of abandoned dams or with data shortages, these being often the reality of some dams in Brazil. Another interesting point about the application of the MASW method and the seismic refraction, and also from obtaining the subsurface S-wave velocity prior to the dam installation is the dynamic stiffness module ($G_{max}$) provided by the data of Vs and soil density, being it a fundamental parameter for a work of this type (Park & Kishida, 2018).

Another advantage of the joint interaction of both seismic methods relates to the arrangement. Since they have the same arrangement, it facilitates field data acquisition, requiring only the change in seismic wave generation, since the multichannel method uses surface waves while the S wave uses seismic refraction.

The seismic methods of MASW and S wave data refraction in this work can be associated with data of electroresistivity, self-potential (SP) and ground penetrating radar (GPR), for example, to obtain a more detailed understanding of the dam behavior, defining a presence of zones of weakness and water percolation areas.

**Figure 15** - Analysis of the first 20 meters of section 2D of refraction seismic with S wave comparing with the values obtained by the MASW method in the dam located in Ipeúna-SP.
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