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SPATIAL AUTOCORRELATION OF PASSIVE SURFACE WAVE DATA FOR ASSESSMENT OF AN EARTH DAM IN BRASÍLIA, BRAZIL

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ABSTRACT. Surface wave methods are commonly applied to engineering problems for S-wave velocity estimations. Conventional active Multichannel Analysis of Surface Waves (MASW) surveys for earth dam assessment suffer from limitations mainly associated to restrict depth of investigation and negative influences of near noise sources. In Brazil, the need to image around noisy sites over 30 m deep, which are non-ideal contexts for traditional active seismic data campaigns, is commonly in demand. We acquired ten minutes of ambient vibration data at the crest of a large earth dam in Brasília, Federal District. The Spatial Autocorrelation (SPAC) method was applied to develop a 2D S-wave model velocity using surface wave generated from passing vehicles on the adjacent road. A maximum depth of 42 m was achieved, and the model presented a S-wave velocity range from 274 m/s up to 713 m/s. The water level, foundation ground and possible low and high anomalous compaction zones were interpreted. Vs30 was found to vary from stiff to very dense soil along the profile, with higher values observed towards the left abutment.

Keywords: earth dam; SPAC; MAM; S-wave; ambient noise.

RESUMO. Métodos de onda de superfície são rotineiramente aplicados a problemas de engenharia para obtenção de estimativas de velocidade da onda S. A realização de levantamentos de Análise Multicanal de Ondas de Superfície (MASW) ativos convencionais para avaliação de barragens de terra sofrem limitações principalmente associadas à profundidade de investigação restrita e às influências negativas de fontes de ruído próximas. No Brasil, ocorre a necessidade de obter resultados em locais ruidosos com mais de 30 m de profundidade, que são contextos não ideais para as campanhas de sísmica ativa tradicionais. Dez minutos de dados de vibração ambiental foram registrados na crista de uma grande barragem de terra em Brasília, Distrito Federal. O método de Autocorrelação Espacial (SPAC) foi aplicado para desenvolver um modelo 2D da velocidade de onda S considerando ondas de superfície geradas a partir do tráfego de veículos na rodovia adjacente. Foi atingida uma profundidade máxima de 42 m e o modelo apresentou uma faixa de velocidade da onda S de 274 m/s a 713 m/s. Foram interpretados o nível freático, terreno de fundação e possíveis zonas anômalas de compactação baixa e mais elevada. Verificou-se que o Vs30 varia de solo rígido a muito denso ao longo do perfil, com valores mais altos observados em direção à ombreira esquerda.

Palavras-chave: barragem de terra; SPAC; MAM; onda S; ruído ambiental.

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INTRODUCTION

Surface wave methods are known for a significant demand in engineering problems for S-wave velocity (Vs) estimations. Vs can correlate with shear modulus (Sheriff & Geldart, 1995), thus being generally used as a satisfactory stiffness indicator. Park et al. (1999) developed the multichannel analysis of surface waves (MASW), probably the most popular surface wave method nowadays for near surface Vs estimation. The MASW method is applied along active seismic datasets, and a traditional survey relies on a controlled seismic source for wavefield generation registered by a linear spread of geophones in line with the energy source.

The field operation, level of cultural noise and depth of investigation are the most addressed aspects for consideration around active surveys. Many earth dams in Brazil present near cultural noise sources (e.g., heavy machinery work and vehicle traffic) and require over 30 m of investigation depth. Despite being less sensitive to noise sources when compared to methods that rely on body wave propagation, the accuracy of a dispersion curve obtained with the MASW method enhances with the removal of noise on ground roll data (Park et al., 1999). With active surveys, sledgehammer or weight drops rarely achieve penetration depths greater than 30 m (Foti et al., 2018), which suggests that it is not a self-sufficient approach for adequate Vs30 estimation (e.g. Hayashi et al., 2016).

Due to the limitations around active MASW, the use of ambient vibrations originating from natural or cultural sources for Vs estimation has gained a great deal of attention over the last years. The most traditional analysis for Vs estimation using ambient vibrations has been introduced by Aki (1957), which proposed the spatial autocorrelation (SPAC) method. This approach measures seismic phase velocity from ambient vibration data based on the variation with frequency of the autocorrelation coefficient (coherence) between two signals. From the SPAC method, Okada (2003) presented the microtremor array measurement (MAM) technique to estimate deep Vs variation. To this date, MAM has been applied in many studies for investigation over 30 m deep, such as geotechnical, environmental, and earthquake engineering (e.g., Eker et al., 2012; Hayashi et al., 2018; Moon et al., 2019; Zhang et al., 2019; Ku et al., 2021).

For Vs estimations, active surveys are generally associated with better resolution near surface (Asten & Hayashi, 2018; Foti et al., 2018). However, there are still few evaluations about the resolution of dispersion image to this date (Baglari et al., 2018). The main distinct advantage of passive methods is the potential to achieve penetration depths over 30 m with significantly shorter acquisition time and field effort. Therefore, there is a growing preference for the passive method over the active method if only one of the surveys can be executed (Hayashi et al., 2016; Asten & Hayashi, 2018). Considering this context, we acquired only seismic ambient vibration data and applied the SPAC method to obtain dispersion curves at the crest of the Paranoá dam, the largest dam of Brasília, the federal capital of Brazil. The goal of this study is to calculate a representative pseudo-2D S-wave velocity model of the dam, interpret the observable internal features from velocity contrasts, compute Vs30 values across the massif and evaluate general aspects of the passive analysis as a geophysical assessment methodology for earth dams.

Study area

The Paranoá dam (Fig. 1) is located east of Brasília, in the Federal District of Brazil. The area is composed of slates and quartzites from the Paranoá Group (Campos et al., 2013) and red-yellow Latosol and haplic soil (Reatto et al., 2004). The structure is a rockfill earth dam with a 600 m crest length. The massif is composed by clay soils, clean natural sands, upstream rockfills with quartzite rocks and sandstones, and vegetation covering downstream. The main access road to the site is the Estrada Parque do Contorno (EPCT - DF-001), which is partially built over the crest of the dam, resulting in a constant vehicle flow parallel to the study area.

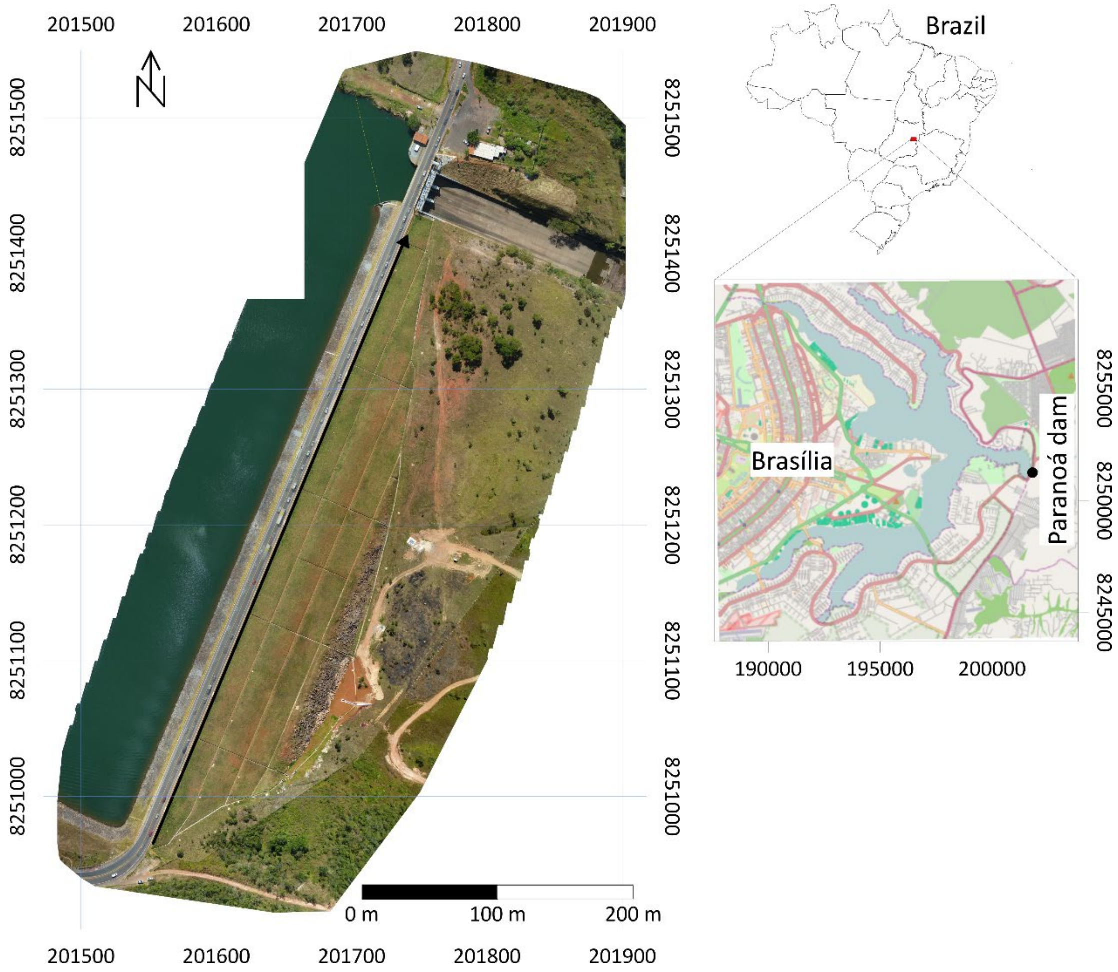

Figure 1 - Location map of the Paranoá dam with the acquired passive data profile (black line). The arrow indicates the direction of acquisition, pointing to the end of the profiles.

MATERIAL AND METHODS

Spatial autocorrelation (SPAC)

The MAM technique uses the SPAC method to analyze the signal complex coherency between multiple observations in an array of receivers, independently of source location. Coherency is the similarity between all possible pairs of geophones, and generally, as receiver separation increases, coherency decreases.

The SPAC function represents the variation of the coherency with frequency between two signals, and is given by

$$\mathrm{SPAC}(r,\omega)=\frac{1}{2\pi}\int_{\varphi=0}^{\varphi=2\pi}\mathrm{Re}\big(\mathrm{COH}(r,\varphi,\omega)\big)d\varphi = J_0\left(\frac{\omega}{c(\omega)}r\right) \quad (1)$$

where r is the distance between two receivers of a 2D isotropic array (e.g., a circle or a triangle), φ is their direction in relation to a central receiver, COH is the complex coherency of observed data, $c(\omega)$ is the phase velocity at an angular frequency ω, and J_0 is the Bessel function. The left term in Eq. (1) can be calculated from observed ambient vibration and relates to calculating coherency for two receivers with a separation r and direction φ and averaging the complex coherency. Phase velocity is calculated by the comparison of the left term and the Bessel function, the right term in Eq. (1), by changing the phase velocity $c(\omega)$. The velocity that minimizes the error can be considered as the phase velocity at ω. Equation (1) is valid for isotropic arrays, but also appliable for an anisotropic array observing ambient vibration propagating equally from all directions (Hayashi, 2008).

Comparison of SPAC with other passive array methods

Surface wave methods based on ambient vibrations for Vs estimation consist in array analysis with multiple receivers. Besides SPAC, two other popular array analyses are the frequency-wavenumber (f-k) beamforming and seismic interferometry (SI).

With the f-k method (Horike, 1985), ambient vibrations are processed in the frequency-wavenumber domain using spectral estimation methods. Dominant source direction is favorable for f–k, but a dominant ambient vibration direction can add bias into SPAC estimates (Foti et al., 2018). Flores-Estrella et al. (2001) obtained more consistent results with SPAC regarding the expectations from geological conditions in comparison with the f-k method. Claprood & Asten (2008) concluded that SPAC gives information over a wider range of frequencies than f-k, which enhances the interpretation at higher frequencies, allowing a better characterization of shallow layers. As a general understanding, f-k tends to overestimate phase velocity, a potentially hazardous aspect, while SPAC tends to underestimate it (Claprood & Asten, 2008; Asten & Hayashi, 2018).

SI is a relatively new approach to retrieve the Green’s functions from the crosscorrelation of ambient vibrations (Wapenaar, 2004). The method has been vastly used in global seismology to obtain velocity models at a crustal scale from passive data and measurement of group velocity (often addressed as ambient noise tomography). Although the use of SI for shallow phase velocity calculation for engineering purposes is gaining more attention over the last few years (e.g., Cheng et al., 2015; Olivier et al., 2018), it can be considered a relatively new topic of research still in development phase (Asten & Hayashi, 2018). Tsai & Moschetti (2010) presented an explicit comparison of the two approaches and pointed that the SPAC theory in the frequency domain is equivalent to the crosscorrelation theory used in SI in time domain if vibrations are assumed to come from all directions equally.

Ambient vibrations

Surface waves suffer much less energy decay with propagation distance than body waves. This means that, far away from the source position, most of the seismic energy is carried out through surface waves, and far-field ambient vibrations are mainly composed of surface waves (Foti et al., 2018).

SPAC uses ambient vibrations originated from natural (e.g., ocean wave action at coastlines and microseisms) or cultural sources (e.g., vehicle traffic, vibrations from construction or other machineries). Usually, low frequencies are created by large-scale events, while high frequencies come from local sources, generally related to human activities. The term “ambient noise” in passive surveys is judged to be inappropriate by some authors. Foti et al. (2018) relate “noise” with effects that are not directly associated to wave propagation (e.g., instrumental self-noise, weather actions on the receiver and bad coupling with the ground) and wave propagation features that are not usable for analysis (e.g., body wave components), while “signal” is surface waves originating from distant sources.

The ideal vibration sources for SPAC are steady signals without strong changes in amplitude. The fundamental assumption is that the vibration wavefront is planar and isotropic (comes from all directions), making it independent of source positions. Passive methods in general may face difficulties in areas where the level of ambient vibrations is very low, while a higher success chance occurs in environments that have a good level of ambient vibrations with a reasonable degree of isotropy (Hayashi & Craig, 2017; Foti et al., 2018). In such cases, coherent vibrations dominated by surface wave can be recorded, and reliable results can be obtained with a limited number of receivers and a relatively short recording time window (Foti et al., 2018).

Data acquisition

A passive survey was executed along a profile downstream of the Paranoá dam in September 2020 at the crest of the massif. Using four Geode seismographs (Geometrics) of 24 channels each, ambient vibrations were registered by a 475 m long linear array of 96 vertical 14 Hz geophones (Geospace), spaced every 5 m. We acquired 20 continuous SEG2 waveform files with a time length of 32 seconds each, totaling 640 seconds (approximately 10 minutes) of data acquisition period, a sufficient interval pointed by Hayashi (2008) for SPAC analysis. A sampling frequency of 500 Hz was used, summing 16,000 samples per trace (one sample every 2 ms).

Data processing

For editing the waveform files, we used Pickwin from the SeisImager/SW package. From all 20 raw passive datafiles with 96 traces each, 24 sequential traces were extracted from the original vibration sections every 10 m and saved into new SEG2 files. After the “roll along” trimming processes, a total of 740 waveform files were generated (20 files of 32 s of observed ambient vibration by a 115 m long linear array of receivers). Park et al. (2001) and Xia et al. (2004) reported that the longer the geophone spread, the higher the resolution of the dispersion image. The goal of this approach is to obtain a pseudo-2D Vs model from the interpolation of horizontal aligned 1D models at every 10 m along the survey line which was addressed as Two-dimensional Linear Array Microtremor Survey (2D-LAMS) by Kita et al. (2011).

As for calculation and inversion of dispersion curves obtained from ambient vibration data, we used WaveEq, also from the SeisImager/SW package. For each set of passive data at every 10 m along the survey profile (Fig. 2A), complex coherencies were calculated for every receiver pair. The real parts with the same spacing were averaged in frequency domain, and the separation between each pair of receivers was plotted against their coherency as a function of frequency (Fig. 2B). Coherencies were finally compared with the Bessel function, where the match between coherencies and the Bessel function provided phase velocity information, used to develop the dispersion image (Fig. 2C).

For inversion of an observed dispersion curve (Fig. 2C), an initial model based only around the fundamental mode of vibration was constructed by one-third wavelength transformation (e.g., Hayashi, 2008) in terms of apparent depth and Rayleigh wave velocity. The non-linear least squares method was used for model fitting (Xia et al., 1999). The number of layers was fixed as 15 and only Vs were modified throughout the inversion iterations, while density and P-wave velocity were changed based on empirical relations (Ludwig et al., 1970; Kitsunezaki at al., 1990). The theoretical dispersion curves were calculated with a matrix method (Saito & Kabasawa, 1993). The iterative process recalculated Vs until a best fit with low RMS error was obtained between the observed and calculated phase velocities (Fig. 2D). Finally, a 1D Vs model in depth was plotted (Fig. 2E).

The average Vs down to 30 m (Vs30) is a popular parameter of geotechnical interest. Vs measurements with surface wave methods are generally presented as a layered format. From the obtained 1D Vs models, all respective Vs30 values were calculated after the International Building Code IBC-2000 (Paz & Leigh, 2004), as

$$Vs30=\frac{\sum d_i}{\sum \frac{d_i}{Vs_i}} \qquad (2)$$

where d_i and Vs_i are the thickness and the S-wave velocity of the i^{th} layer of the model, respectively.

RESULTS AND DISCUSSION

Observable frequency range

Figure 3 shows the frequency spectrum for every 32 seconds of ambient vibration records observed by the 96 in line receivers spread. The registered cultural vibrations at the site present a frequency content mainly between 8 Hz and 30 Hz. Vehicle-related vibrations are generally dominant at 2-30 Hz (Coward et al., 2003). As the survey happened during daytime, it is reasonable to consider that the main sources of signal were moving vehicles.

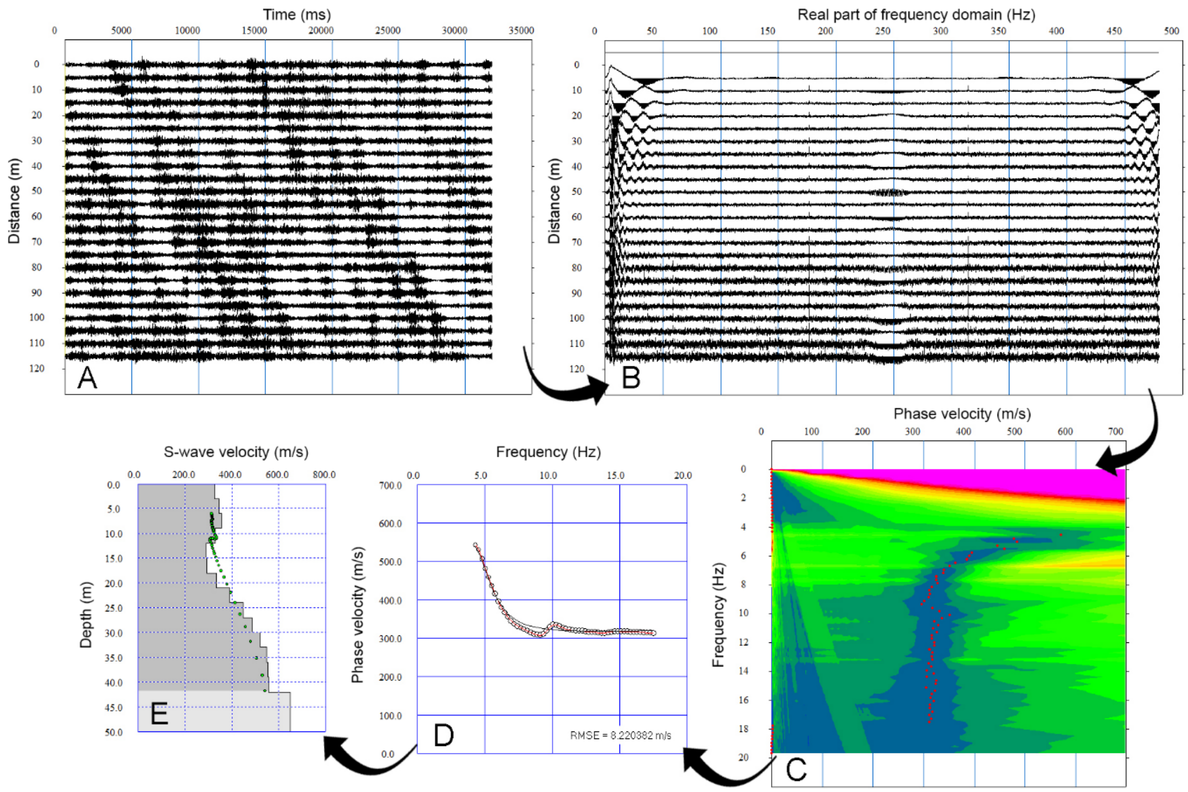

Figure 2 - Processing flow with the SPAC method. A) 32-second record out of the 10-minute continuous data acquisition; B) Plot of the separation between each pair of geophones against their coherence as a function of frequency; C) the obtained phase velocity image; D) the observed and calculated dispersion curves; E) the resulting 1D Vs profile after a non-linear least squares inversion.

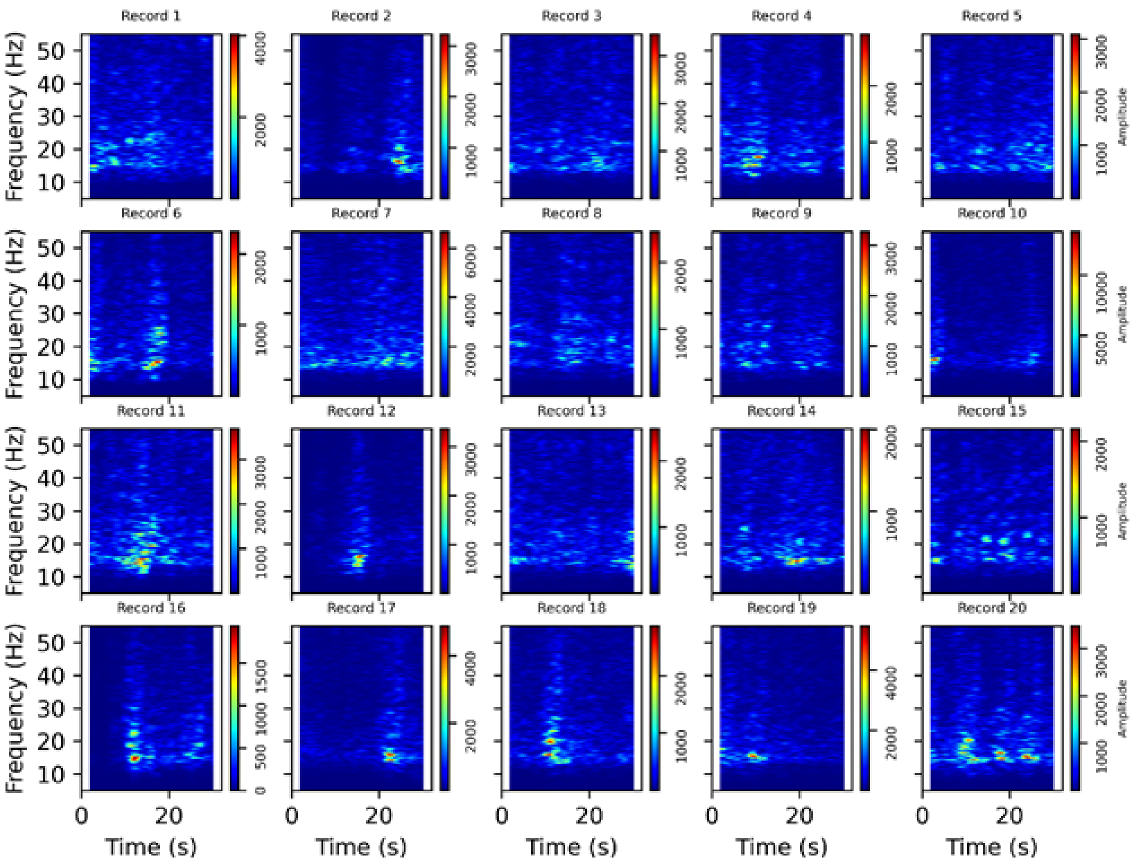

Figure 3 - Frequency spectrogram of all 32-second records of the 10-minute continuous data acquisition. The arrow indicates the direction of acquisition, pointing to the end of the profiles.

For MASW, Park et al. (2002) found that the lower-frequency limits of higher-frequency geophones of 10 Hz and 40 Hz were not limited by their natural frequencies for dispersion imaging. Similarly here, using 14 Hz geophones, we observe reliable phase velocities down to about 4 Hz, far below the instrument natural frequency. Figure 4 shows the observed dispersion curves during data processing, with phase velocity data from 4 Hz up to 18 Hz.

S-wave velocity model and Vs30

Figure 5A shows the obtained pseudo-2D velocity model. Low velocity values are presented in reddish color tones, while higher velocities are in blueish color tones. Vs ranges from 274 m/s up to 713 m/s. The maximum depth of 42 m is observed around the center of the section. At the edges, Vs changes are only imaged down to approximately 20 m. This is likely due to a smaller content of observable phase velocities at lower frequency intervals around these positions. The black triangles show the horizontal position of each 1D Vs profile obtained after data inversion, separated every 10 m (a total of 37 velocity profiles). The first and last 1D Vs profiles are at 57.5 m and 417.5 m, respectively.

The white dashed line marks the interpreted water level. It is found to vary from 6 m down to 13 m deep. A water saturated soil usually presents an increase in P-wave velocity and a decrease in S-wave velocity (Baechle et al., 2009; Kassab & Weller, 2015; Konstantaki et al., 2016; Foti et al., 2018). This is caused due to the decrease in the shear modulus of materials when water is present (Baechle et al., 2009). Low Vs near the surface between 57.5-100 m and 320-370 m may be related to lower soil compaction, marked as light pink. Likewise, high velocity anomalies near surface are pointed as higher compaction zones. At the center of the dam crest, the foundation ground is expected at a depth of approximately 48 m (CEB, 2020). The obtained velocities can be correlated to the stiff clay soil, which usually ranges approximately from 200 m/s up to 600 m/s (Foti et al., 2018). The black dashed line marks the Vs contrast of 600 m/s as a possible transition zone between the clay soil and the quartzite foundation.

Figure 5B shows the Vs30 distribution across the profile. After UBC (1997) site classification, the blue circles mark Vs30 related to stiff soil (180 m/s < Vs ≤ 360 m/s), and red circles mark Vs30 related to very dense soil (360 m/s < Vs ≤ 760 m/s). It is clear from the profile that higher Vs30 values are found towards the end of the acquisition line, closer to the dam spillway (left abutment).

The obtained velocity values are within the range of values found in other similar structures. Table 1 presents ranges of S-wave velocities obtained in other studies that used seismic methods to characterize earth dams.

Assumptions around the SPAC method

Some aspects must be considered when applying the SPAC method. The key assumptions, as described in many studies (e.g., Asten, 2006; Asten & Hayashi, 2018; Baglari et al., 2018; Foti et al., 2018), are: a) the study area can be sufficiently represented as a layered earth model; b) far-field Rayleigh waves are the main content of the vertical-component recorded ambient vibration data; and c) there is a spatial averaging of sources.

According to CEB (2020), the Paranoá dam is mostly composed of compacted clay soil, followed by a quarzitic foundation. Despite not being a layered earth, the studied site can be considered well represented with the SPAC method, since there are no expected sharp variations and the massif composition is considerably homogeneous.

Considering the short distance between the receiver spread and the road (approximately 6 m) and the wavelengths of Rayleigh waves at 5 Hz and 10 Hz (around 100 m and 30 m, respectively), it is unlikely that a pair of receivers could properly record surface waves generated by a very near passing vehicle, specially at lower frequencies (larger wavelengths). This short distance may cause a distortion in phase velocity estimation for low frequency, known as the near-field effect. On the other hand, increasing the distance between source and receiver can raise attention to far-field effects. Considering the attenuation property of

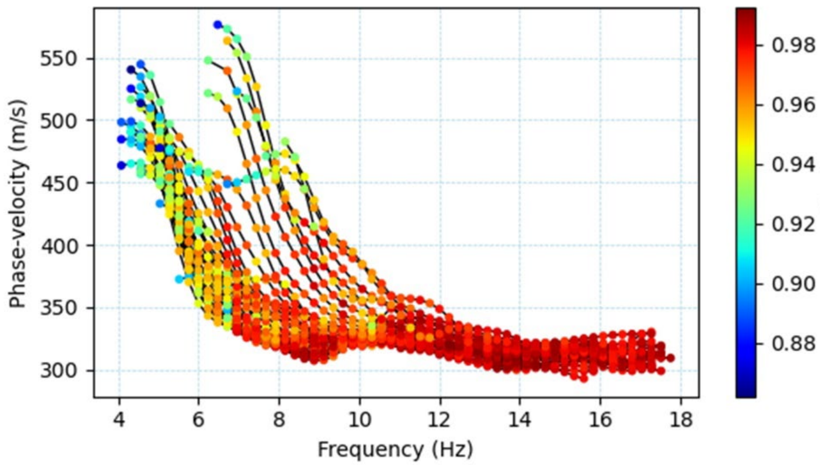

Figure 4 - The observed dispersion curves used for data inversion, obtained from the SPAC phase velocity images.

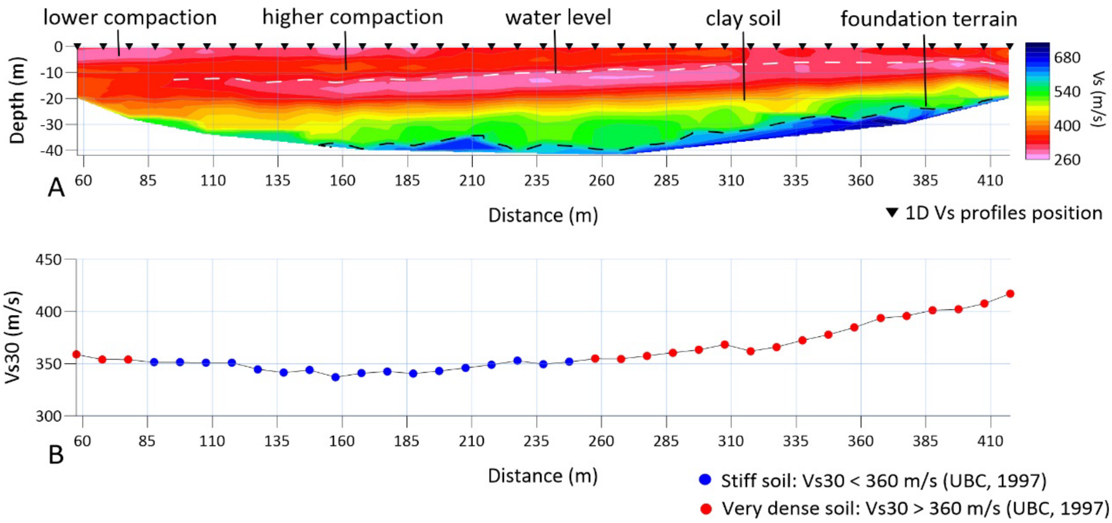

Figure 5 - A) The 2D velocity profile obtained after 1D Vs profile interpolation; B) Vs30 distribution across the profile, according to the reference UBC (1997) site classification.

Table 1 - Comparison of S-wave velocity values obtained in other works using seismic methods at earth dams.

Reference	Country	Methods	Vs (m/s)	Approximate maximum depth of investigation (m)
Kim et al. (2011)	South Korea	MASW	100-1480	30
Cardarelli et al. (2014)	Italy	SRT	120-300	9
Hayashi et al. (2014)	USA	MASW	120-350	16
Rahimi et al. (2019)	USA	MASW and FWI	100-2100	25
Guireli Netto et al. (2020)	Brazil	SRT and MASW	150-700	16
This study (2021)	Brazil	MAM (SPAC)	274-713	42

Note: MASW = Multichannel Analysis of Surface Waves; SRT = Seismic Refraction Tomography; FWI = Full Waveform Inversion; MAM (SPAC) = Microtremor Array Measurements (Spatial Autocorrelation).

higher-frequency components of Rayleigh waves, the recorded passive data at far receivers may contain wavefields generated from local sources, such as interference from dominant high frequency body waves (Baglari et al., 2018).

In general, as the random source positions are not known, the closeness of sources are frequently neglected in passive surveys, with still no well stablished consensus to avoid near and far-field effects (Baglari et al., 2018; Foti et al., 2018). This is frequently the case for urbanized areas, like the Paranoá dam, where localized microtremor sources, passing vehicles and other general human activities can occur. However, there was a significant level of vehicle traffic along all the extension of the road during data acquisition, which makes the recorded ambient wave-field not related solely to close sources, but to far-field sources as well. Despite the nearness of sources (vehicle traffic) to receivers placed on sidewalks, Stephenson et al. (2009) presented credible Vs values with the SPAC method for a site characterization in lower Manhattan, New York City. Roberts & Asten (2008) reported that significant near source effects are unlikely to occur in real field scenarios, where a large number of sources, source directions and source distances are present.

An axiomatic assumption is that the SPAC method depends on spatial averaging of sources, either by multiple orientations of station separations or by an azimuthal distribution. As the ambient vibration wavefield might propagate from different and unknown directions, theoretically, a 2D isotropic receiver array, such as a circle or an equilateral triangle, is preferable for passive surveys (Foti et al., 2018). An isotropic array provides the same response regardless of the direction of the incoming wavefield and better ensures that velocities will be well estimated, even in the case of anisotropic vibrations (Hayashi & Craig 2017).

In practical terms, perfectly isotropic array configurations may be difficult to set up in the field. They may require an extensive open area, which is often not the case for many survey sites, and can be complex when using traditional recording systems that still rely on long spread cables. A linear array is the most practical alternative and can be considered as an option where logistical efficiency is required.

The assumption of homogeneous and isotropic distribution of the ambient vibration sources around the surveyed area or in-line with the array direction is needed when using a linear spread of receivers for SPAC (Foti et al., 2018). Hayashi & Kita (2010) showed, through a field experiment, that the linear array configuration can provide reliable phase velocities and almost identical dispersion curves as 2D array spreads when the propagation direction of the ambient vibration is distributed at a minimum range of 120º. Kita et al. (2011) employed a linear roll along acquisition of passive recording of ambient vibration to obtain a pseudo-2D Vs model. Hayashi et al. (2018) performed a comparison of dispersion curves calculated from passive records acquired using a linear array and a L-shaped array, obtaining similar dispersion trends.

For the survey line adjacent to the road of the Paranoá dam, the SPAC method assumes that passing vehicles generate Rayleigh wave signals over a wide azimuth angle. This means that passing vehicles on the south half of the road would generate seismic energy almost in line with receivers on the north half, removing most of the bias associated with wavefronts parallel to the linear array. In general, roadside passive surveys have been pointed as a practical alternative around the use of a conventional linear receiver array to obtain results with low overestimation of Vs values in comparison with conventional 2D arrays (usually less than 10%; Park et al., 2007).

CONCLUSIONS

We acquired ten minutes of ambient vibration data at the crest of the Paranoá dam in Brasília, Brazil. The SPAC method was applied for the development of 1D velocity models, and a subsequent 2D interpolated velocity model.

The main sources of signal were moving vehicles. The cultural vibrations at the site presented a frequency content mainly between 8

Hz and 30 Hz, a coherent range based on already reported values. We found that the lower-frequency limits of geophones of 14 Hz were not limited by their natural frequencies for dispersion imaging. Phase velocities down to 4 Hz and up to 18 Hz were observed. A maximum depth of 42 m was achieved, which suggests that higher frequency geophones, such as 14 Hz, can be used to obtain deeper results, suitable for Vs30 site classification.

The developed Vs model presented a velocity range from 274 m/s up to 713 m/s. The possible water level could be interpreted as a low velocity horizon from 6 m down to 13 m deep across the crest of the dam. Low and high Vs anomalies near the surface were marked as possible zones of lower and higher soil compaction, respectively. A Vs contrast of 600 m/s was interpreted as a possible transition zone from clay soil to the quartzite foundation. Vs30 was found to vary from stiff to very dense soil, with higher Vs30 values found towards the abutments.

The calculated S-wave velocities were found to be within the interval of already reported values in other similar structures, also obtained from seismic data analysis. However, we must point possible unknown effects around the use of the SPAC method, such as the dam geometry (not a layered earth), the possible biases associated with the close approach of sources, and the use of a linear array of receivers. There is still no forward guide to predict, without failure, passive survey parameters, such as the number of geophones, minimum and maximum offset distances or which array geometry is sufficient. Most of these variables are likely to be site specific when executing a field survey. Despite the uncertainties regarding the use of the SPAC method, the obtained results show that this passive surface wave analysis is a promising and time saving approach for investigating greater depths at noisier sites, such as large earth dams with a significant presence of human activities.

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