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ORIGINAL RESEARCH ARTICLE

Non-destructive integrity assessment of roller-compacted concrete dams using multi-channel analysis of surface waves: A case study of the Se San 4 Hydropower Dam, Vietnam

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Abstract

The structural integrity of hydropower dams is paramount for sustainable energy production and downstream safety. Traditional inspection methods, such as core drilling, are destructive, localized, and often fail to capture the spatial heterogeneity within the concrete. This study evaluates the efficacy of the multi-channel analysis of surface waves (MASW) method—a non-destructive seismic technique—for assessing the stiffness and identifying potential defects within the Se San 4 Hydropower Dam in Gia Lai, Vietnam. We conducted MASW surveys along two strategic profiles: the dam crest surface and the internal inspection tunnel. By inverting Rayleigh wave dispersion curves, we derived two-dimensional shear wave velocity (V_s) profiles and subsequently calculated shear modulus (G) distributions to map the stiffness of conventional vibrated concrete (CVC) and roller-compacted concrete (RCC) layers. The results reveal a distinct stratification in the dam body. The surface survey identified a top layer of CVC/asphalt with V_s ranging from 1,500 to 2,500 m/s, overlying a stiffer RCC layer exhibiting V_s values between 2,500 and 4,000 m/s. Conversely, the tunnel survey recorded significantly higher velocities in the RCC core (4,000–5,500 m/s), reflecting better confinement and material quality at depth. Crucially, the study detected specific low-velocity anomalies ($V_s < 2{,}000$ m/s) and reduced stiffness zones at depths of 17–30 m along the survey lines. These anomalies may indicate areas of potential water seepage, variable concrete density, or natural construction lift joints inherent to the RCC layering process. This research demonstrates that MASW is a rapid and cost-effective tool for the periodic structural integrity monitoring of large-scale hydraulic structures, providing critical baseline data for maintenance and risk mitigation in tropical operating environments.

Keywords: Dam safety; Multi-channel analysis of surface waves; Non-destructive testing; Roller-compacted concrete; Shear wave velocity

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1. Introduction

Hydropower remains a cornerstone of renewable energy strategies globally, particularly in Southeast Asia, where river systems provide abundant kinetic energy.[1,2] In Vietnam, hydropower is a critical component of national energy security, with the Se San River cascade serving as a primary contributor to the electrical grid.[1,2] Since the commissioning of the first major dams in the 1990s, the country has developed a dense network of over 40 large-scale and hundreds of small-to-medium-scale hydropower plants.[1,2] However, as this infrastructure ages, the imperative for rigorous, periodic structural integrity monitoring becomes undeniable.[1,2] The structural failure of a dam can lead to catastrophic downstream flooding, economic paralysis, and loss of life. Therefore, ensuring the geotechnical stability and structural integrity of dam bodies, particularly those constructed with roller-compacted concrete (RCC), is a priority for operators and regulatory bodies.[1-3]

The primary challenge in dam maintenance lies in detecting internal defects before they manifest as external failures.[1-3] Common pathologies in concrete gravity dams include cracking due to thermal stresses, honeycombing from poor compaction, and, distinctively, water seepage, which can leach cementitious material and degrade structural stiffness over time.[1] Extensive research has been conducted to model and analyze the failure modes, seismic response, and structural integrity of gravity dams using numerical methods such as the finite element method[4-6] and the extended finite element method.[3,7,8] These studies emphasize that accurate material properties, such as stiffness and density, are critical for reliable safety assessments.[9]

Traditionally, engineers have relied on invasive methods such as borehole coring to assess material quality.[10] While coring provides high-fidelity samples, it is destructive, expensive, time-consuming, and provides data only at discrete points.[10] Consequently, there is a pressing need for non-destructive testing methods.[10] Geophysical methods have emerged as powerful alternatives. Techniques such as electrical resistivity tomography are widely used to map moisture and leakage in earth and concrete structures.[10-13] Other studies have employed combined geophysical surveys for comprehensive site characterization.[14,15]

Among seismic techniques, the multi-channel analysis of surface waves (MASW) technique has gained prominence over the last two decades following the pioneering work of Park *et al.*[16] Originally developed for shallow soil characterization and shear wave velocity (V_s) estimation[17,18], MASW provides a direct proxy for material stiffness. Existing literature highlights the versatility of MASW in various geotechnical applications, including soil liquefaction assessment[19], karst and fracture detection[20], landslide characterization[21], and hydrological studies.[22] Specifically, regarding hydraulic structures, MASW has been successfully applied to assess the integrity of levees and embankments.[23-25] Numerous researchers have utilized surface waves to detect defects, seepage zones, and characterize materials in earth dams.[26-33]

In the context of concrete dams, recent studies have demonstrated the capability of seismic methods to characterize the concrete body and identify weak zones.[34,35] In Vietnam, recent efforts have begun to apply MASW for geotechnical parameters and foundation design[36,37], but its application to RCC dams remains under-documented.

This study addresses this gap by applying the MASW technique to the Se San 4 Hydropower Dam. We aim to achieve three primary objectives: (i) to determine the *in situ* V_s distribution of the dam body; (ii) to differentiate the elastic properties of the protective conventional vibrated concrete (CVC) layer and the internal RCC core; and (iii) to identify and spatially delineate anomalous low-velocity zones to inform potential maintenance interventions.

2. Materials and methods

2.1. Site description and geological setting

The study focused on the Se San 4 Hydropower Dam, located in Ia O Commune, Gia Lai Province, within the Central Highlands of Vietnam. The Se San River, a major tributary of the Mekong, flows through a geologically complex region. The dam itself is a gravity structure primarily composed of RCC with a crest width of 10 m, a structural height of 74.13 m, and a total reservoir volume of approximately 893 million m^3. Key technical specifications are summarized in Table 1.

Figure 1A illustrates the study area and the location of the geotechnical investigation. The geological profile derived from core samples (Figure 1B) revealed a stratified composition: a thin overlay of high-density asphalt concrete (approximately 0.1 m thick), followed by a layer of light gray, firm CVC extending to a depth of roughly 0.7–1.0 m. Below this lies the massive RCC body, characterized by dark gray, stiff concrete. Density measurements from core samples indicate an average density (ρ) of 2.32 g/cm^3 for the CVC/transition layers and 2.45 g/cm^3 for the deeper RCC material.

2.2. Theoretical background of multi-channel analysis of surface waves

The MASW method is based on the analysis of the dispersion properties of Rayleigh waves (ground roll). In a vertically heterogeneous medium, Rayleigh waves of different frequencies penetrate to different depths; generally, lower frequencies travel deeper and propagate at velocities influenced by deeper materials.[16] This frequency-

Table 1. Summary of the key geotechnical and structural properties of the Se San 4 Dam

Properties	Description
Dam height	74.13 m
Crest width	10 m
Dam length	850 m
Total reservoir volume	893.106 million m^3
Type of dam	Gravity concrete dam constructed using roller-compacted concrete technology
Average water level	36 m
Power plant type	Open type

dependent velocity relationship is known as dispersion.

We conducted the geophysical survey along two distinct profiles to capture the variation in concrete quality at different structural elevations (Figure 1B): Line 1 (dam surface), surveyed along the crest of the dam to assess the upper CVC and RCC layers, and Line 2 (dam tunnel), surveyed inside Tunnel No. 190 to investigate the internal core integrity deep within the dam body. Conducting MASW surveys inside a confined gallery presented significant acoustic challenges.

Figure 2A provides a schematic diagram of the acquisition setup, and Figure 2B and 2C presents photographs documenting the actual field conditions on the dam surface and inside the inspection tunnel. Data acquisition utilized a specialized land-streamer configuration adapted for concrete surfaces. We employed a 24-channel seismograph (Model MAE-X820S, M.A.E, Italy) coupled with 4.5 Hz vertical component geophones (Seis Tech, China). The choice of 4.5 Hz geophones was crucial for capturing the low-frequency components required to image depths up to 30 m.[22] The detailed acquisition parameters are listed in Table 2.

The recording geometry utilized a fixed receiver spacing (dx) of 1.5 m, resulting in a total spread length of 34.5 m per shot gather (Table 2). The seismic source was a 10 kg sledgehammer impacting a metal striker plate, with a source offset (X) of 3 m from the first geophone. Figure 3 illustrates the geometric relationship between the sledgehammer source, the land-streamer receiver array, and the seismograph. For every shot, the seismograph recorded 250 ms of data at a sampling interval of 0.5 ms. This high sampling rate ensures the resolution of high-frequency surface waves typical of stiff concrete media. The source and receiver arrays were moved in 3 m increments along the profile (roll-along technique) to build a continuous subsurface image.

2.3. Data processing and inversion

We processed the raw field data (SEG-2 format) using the licensed ParkSEIS software package (version 2.0). The processing workflow followed these specific steps: (i) preprocessing to remove noisy traces; (ii) dispersion imaging to convert time–space data into frequency-phase velocity domain; (iii) curve extraction to pick the fundamental mode dispersion curve; (iv) inversion to determine the one-dimensional V_s profile; and (v) two-dimensional (2D) interpolation to generate continuous cross-sections.

To mitigate the acoustic noise and signal reverberation commonly encountered in confined tunnel environments (Line 2), spatial filtering and careful muting of air-waves (which travel at approximately 340 m/s) and body waves were meticulously applied during the preprocessing phase. By focusing the dispersion analysis on the high-amplitude, low-frequency, and low-velocity coherent energy band, the software successfully isolated the fundamental mode of the Rayleigh waves from the tunnel wall reflections. While the signal-to-noise ratio in the tunnel was inherently lower than on the open dam crest, the robust stacking of multi-channel data ensured high-quality dispersion curve extraction. Figure 4 illustrates this workflow, showing a typical seismic record, the extracted dispersion curve, and the resulting one-dimensional V_s profile.

2.4. Calculation of shear modulus

To directly assess the material stiffness, we converted the inverted V_s profiles into G profiles using the dynamic elasticity relationship as described in similar geotechnical studies[17,38] (**Equation 1**):

$$G = \rho \times V_s^2 \tag{1}$$

where ρ is the material density (g/cm^3) and V_s is the shear wave velocity (m/s). We applied the density values of 2.32 g/cm^3 for the upper CVC layers and 2.45 g/cm^3 for the RCC layers, as determined from the physical core samples. This conversion allows for a more engineering-centric interpretation of the dam's condition, as G represents the material's resistance to shear deformation. All stiffness values are consistently reported in Megapascals (MPa).

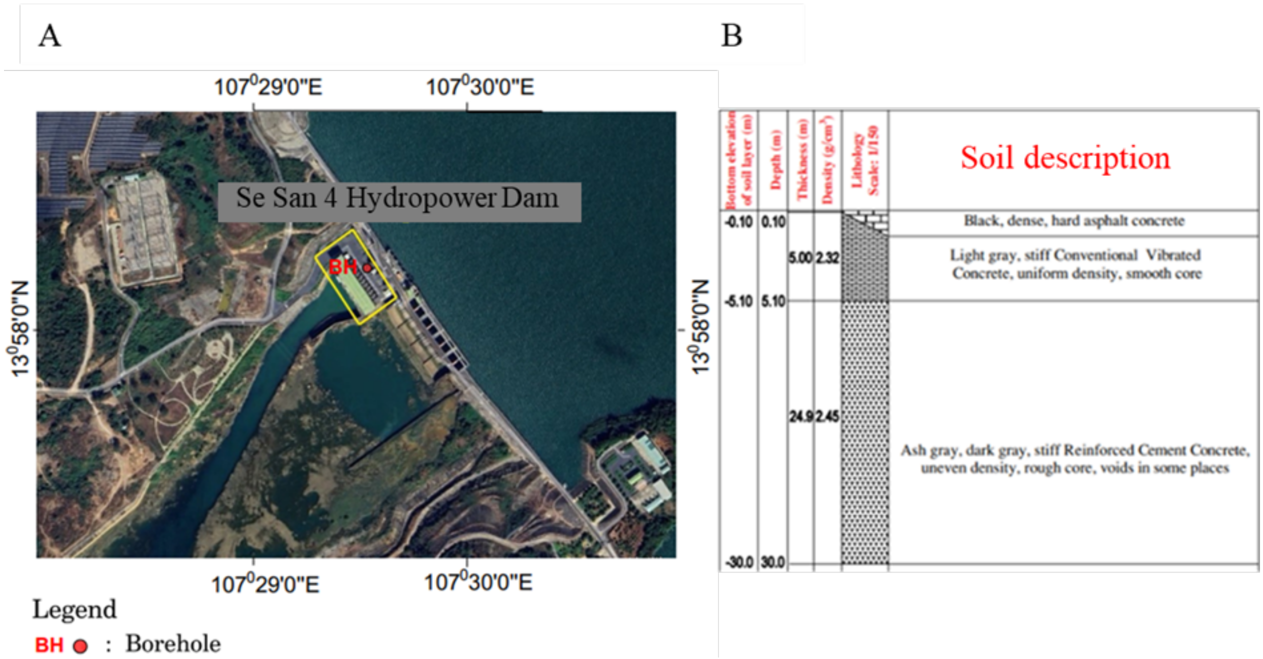

Figure 1. Se San 4 Hydropower Dam details. (A) Location map of the Se San 4 Hydropower Dam showing the specific study area and the location of the geological borehole (left) and (B) the geological borehole log from the study area, detailing the stratigraphy of asphalt concrete, conventional vibrated concrete, and roller-compacted concrete.

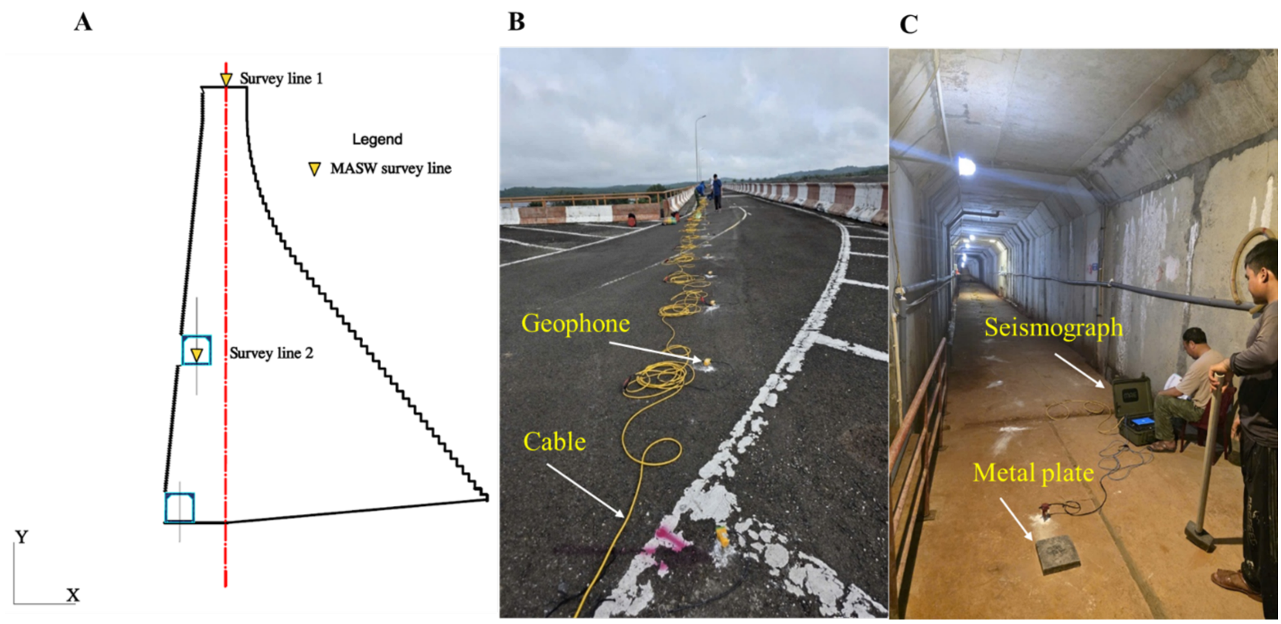

Figure 2. Schematic representation of the two multi-channel analysis of surface waves (MASW) survey profiles. (A) Line 1 (dam surface) and Line 2 (Dam Tunnel No. 190). Photographs of the field data acquisition process: (B) the land-streamer array deployed on the dam surface, and (C) the acquisition inside the dam inspection tunnel showing the confined space environment.

Table 2. Data acquisition parameters utilized for the two-dimensional multi-channel analysis of surface waves survey

Parameters	Description
Seismic source	10 kg sledgehammer
Receiver spacing	1.5 m
Sampling interval	0.5 ms
Recording time	250 ms
Recording format	SEG
Receiver	4.5 Hz (Seis Tech)
Cable	CPS24
Seismograph	MAE-X820S
Source–receiver moving distance	3 m

3. Results

3.1. Shear wave velocity distribution

The processed MASW data yielded high-resolution 2D velocity tomograms for both the dam surface and the tunnel, revealing significant structural details. To facilitate intuitive visual comparison of material stiffness across different structural elevations, the color scales (min/max values) for both the surface and tunnel profiles were standardized.

3.1.1. Dam surface profile (Line 1)

The 2D V_s profile obtained from the dam surface (Figure 5A) illustrated a clear two-layer system. The uppermost layer (0–5 m) exhibited V_s in the range of 1,500 to 2,000 m/s, corresponding to the asphalt facing and CVC. Below this, from depths of 5 m down to 30 m, the velocity increased significantly to a range of 2,500–4,000 m/s, representing the main RCC dam body.

3.1.2. Dam tunnel profile (Line 2)

The results from the tunnel survey (Figure 5B) indicate even higher material stiffness. The core RCC material exhibited extremely high velocities ranging from 4,000 to 5,500 m/s. This increase compared to the surface line can be attributed to the higher confinement stress deep within the dam body. These values (4,000–5,500 m/s) align exceptionally well with published values for high-quality RCC dams globally,[13,14] validating that the core of the Se San 4 dam is in excellent structural condition.

3.2. Identification of low-velocity anomalies

A critical finding was the detection of distinct low-velocity zones within the generally competent concrete mass. In the tunnel profile (Figure 5B), specifically at distances between 17 m and 30 m along the profile, we observed localized zones where V_s drops significantly (V_s < 2,000 m/s). These anomalies likely correspond to areas of lower density, segregation of aggregates, or the presence of micro-cracking.

3.3. Stiffness characterization

The shear modulus (G) profiles (Figure 6) amplify the contrast observed in the velocity data. On the dam surface (Figure 6A), the stiffness of the top layer ranged from 5,000 to 9,000 MPa, while the underlying RCC ranged from 15,000 to 40,000 MPa. In the tunnel (Figure 6B), stiffness values reached 40,000 to 75,000 MPa. The sharp gradient in G values at the boundary of the low-velocity zones suggests a material interface where stress concentrations could occur.

4. Discussion

The application of MASW at the Se San 4 Hydropower Dam demonstrates that surface wave methods are highly effective for characterizing large concrete bodies. The velocity values obtained (V_s > 2,500 m/s for RCC) align well with international standards for high-quality mass concrete.[24,25] The ability to distinguish the transition from CVC to RCC non-invasively validates the method's resolution.

The identification of the anomalous low-velocity zones at depths of 17–30 m requires careful interpretation. From a geophysical perspective, a significant drop in V_s and stiffness typically corresponds to areas of lower density, segregation of aggregates, micro-cracking, or potential water seepage.[11] However, in the specific context of RCC dam construction, these heterogeneities are often a natural result of the RCC layering process. RCC dams are built in continuous horizontal lifts, and the interfaces between these lifts (construction joints) can exhibit slightly lower stiffness and higher porosity compared to the mass of the compacted layer itself.[25,27] Therefore, the observed low-velocity zones might represent planned variations in the concrete mix design at those elevations or specific lift joints rather than critical structural defects.

While MASW successfully indicates these anomalies, determining whether immediate intervention is needed requires corroborating evidence. Integrating these findings with visual inspection logs from the tunnel, data from embedded piezometers, or electrical resistivity tomography surveys would definitively confirm if active water seepage is occurring along these joints, consistent with multi-method approaches suggested in literature.[14] Currently, the extremely high overall stiffness of the core suggests the dam is highly stable, and these localized heterogeneities

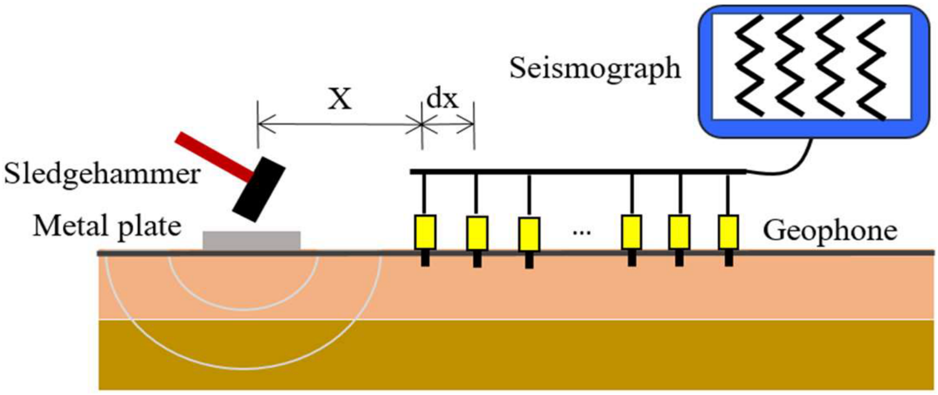

Figure 3. Schematic diagram of the multi-channel analysis of surface waves data acquisition setup, illustrating the geometric relationship between the sledgehammer source, the land-streamer receiver array, and the seismograph. Image was created using Microsoft PowerPoint.

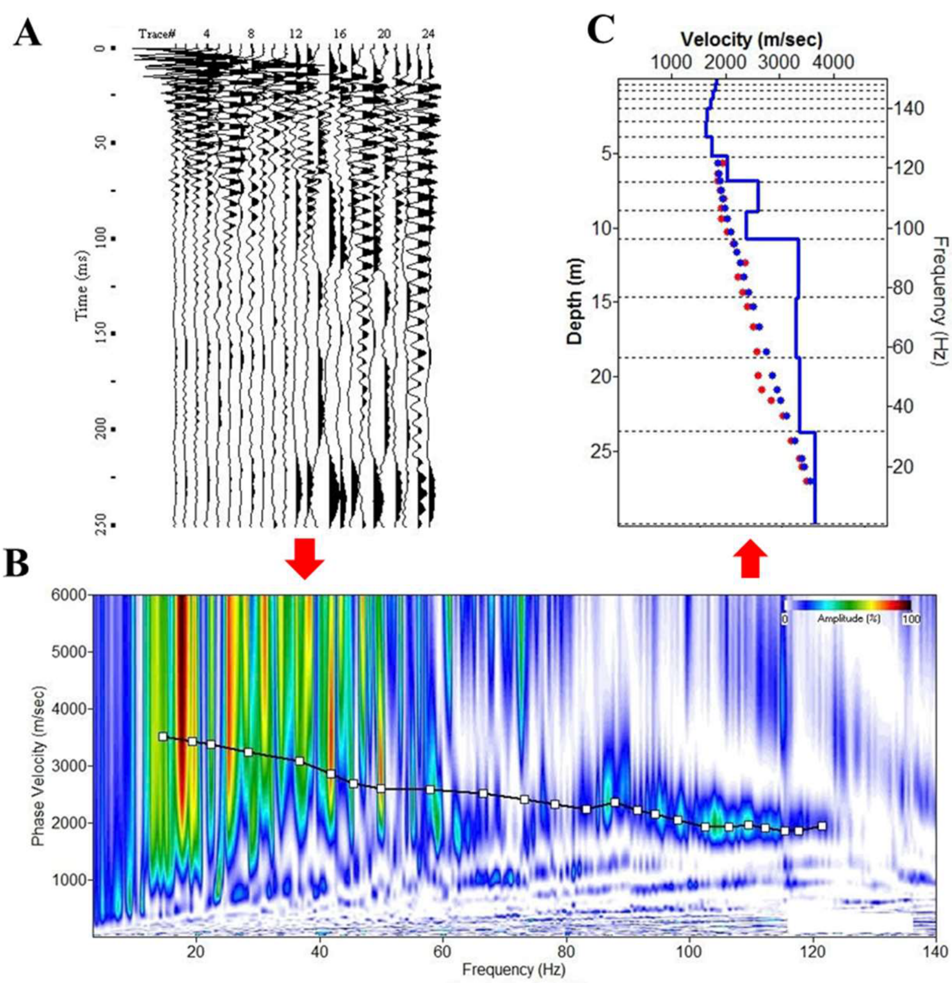

Figure 4. Typical data processing workflow. (A) Raw multi-channel seismic record (shot gather). (B) The generated dispersion image with the fundamental mode curve extracted (white dots). (C) The inverted one-dimensional shear wave velocity depth profile.

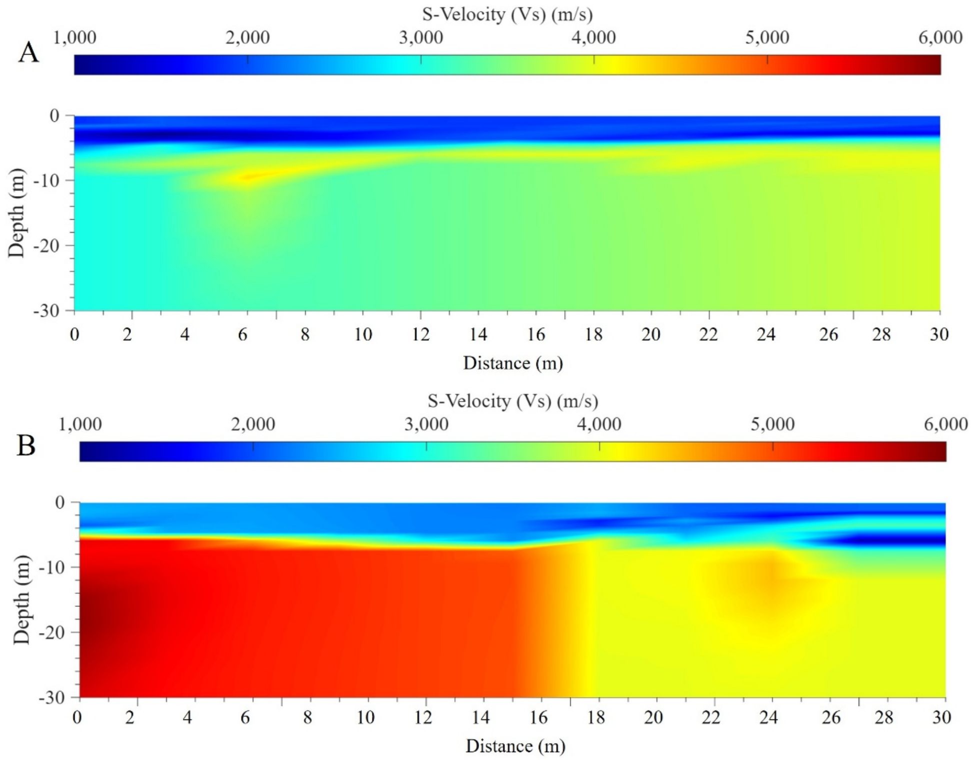

Figure 5. Two-dimensional shear wave velocity (V_s) tomograms obtained from two-dimensional interpolation. (A) Profile along the dam surface showing stratification. (B) Profile inside the dam tunnel revealing high-velocity core and low-velocity anomalies.

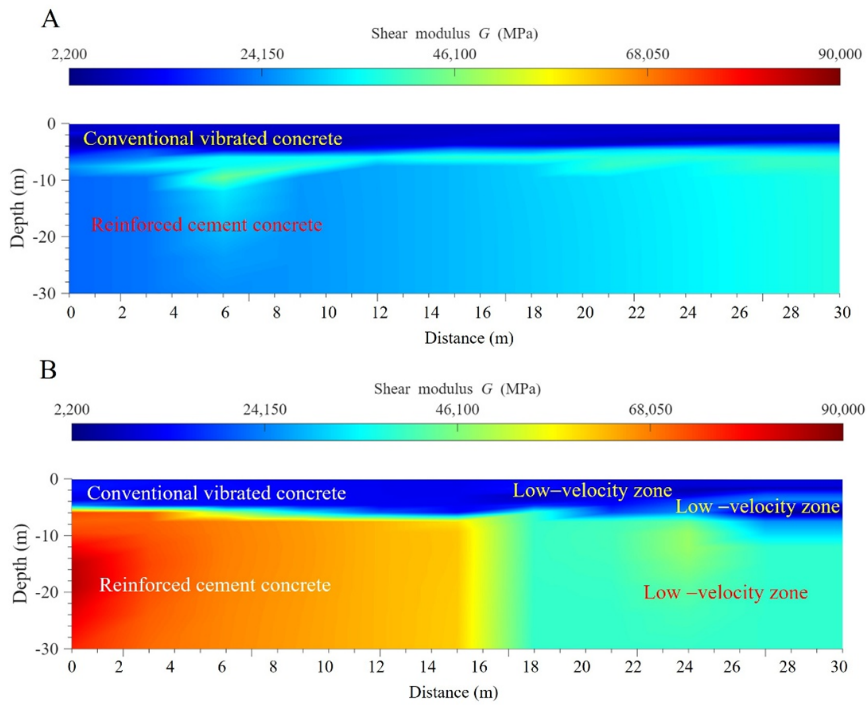

Figure 6. Two-dimensional shear modulus (G) stiffness profiles calculated from the velocity data. (A) Dam surface profile. (B) dam tunnel profile. Note the significant stiffness contrast in the deep roller-compacted concrete layers.

primarily serve as baseline data for future periodic health monitoring rather than indicators of imminent failure.

5. Conclusion

This study successfully employed the MASW technique to evaluate the geotechnical properties of the Se San 4 Hydropower Dam. The dam body comprises two distinct mechanical units. The protective CVC/asphalt layer exhibited V_s values of 1,500–2,500 m/s, while the internal RCC core demonstrated high structural competence with V_s values ranging from 2,500 m/s to over 4,000 m/s. The study-derived shear modulus profiles provided a quantitative assessment of concrete stiffness, confirming that the bulk of the dam meets high engineering standards. We identified specific zones of low seismic velocity and reduced stiffness, particularly along the tunnel survey line. In the context of RCC structures, these localized heterogeneities are interpreted as either natural construction lift joints inherent to the RCC layering process or areas of potential lower density/seepage, rather than immediate structural defects.

The MASW approach proved to be an efficient, non-destructive monitoring tool capable of providing continuous 2D visualization of internal conditions despite the acoustic challenges of a confined tunnel environment. The results establish a vital baseline for the ongoing structural integrity monitoring of the dam, guiding future targeted inspections.

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Conflict of interest

The authors declare they have no competing interests.

Author contributions

Conceptualization: All authors
Formal analysis: All authors
Investigation: Nguyen T. Vu
Methodology: Nguyen T. Vu
Writing–original draft: Nguyen N. K. Ngan
Writing–review & editing: All authors

Availability of data

Data is available from the corresponding author upon reasonable request.

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