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Modern sediment characteristics of Cua Dat Hydroelectric Reservoir based on high-resolution seismic data

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ABSTRACT

The Cua Dat Reservoir is located on the Chu River, in Thuong Xuan District, Thanh Hoa Province, Vietnam. It was constructed to serve the Cua Dat Hydroelectric Power Plant with a designed capacity of 97 MW. After 10 years of operation (2010–2023), the water accumulation process has formed a modern sediment layer with its own characteristics. High-resolution seismic survey work was carried out using the EdgeTech 3400 Sub-bottom Profiler equipment within the reservoir area of the Cua Dat Hydroelectric project, covering over 40 km of survey lines. The processed results and data analysis have revealed fundamental features of the terrain and modern sediment characteristics within the reservoir area. The study indicates that sediment materials in the area upstream of the dam consist mainly of coarse materials (sand, gravel, etc.) deposited in a medium to weak hydraulic environment with short cycles and very low deposition rates, frequently re-settled due to hydraulic dynamics. The weak cohesion of the sediment materials often causes localized surface slumping phenomena with significant amplitudes, extending up to several meters, disrupting the equilibrium trend of sedimentation and leading to an accumulation of sediment towards the dam intake culvert. These observations provide insights into the dynamics of the reservoir surface sediment environment, while also demonstrating that current reservoir operation and exploitation conditions can ensure the longevity and safety as per the design of the Cua Dat Hydroelectric project.

Keywords: Modern sediment, Cua Dat Hydroelectric Reservoir, high-resolution seismic.

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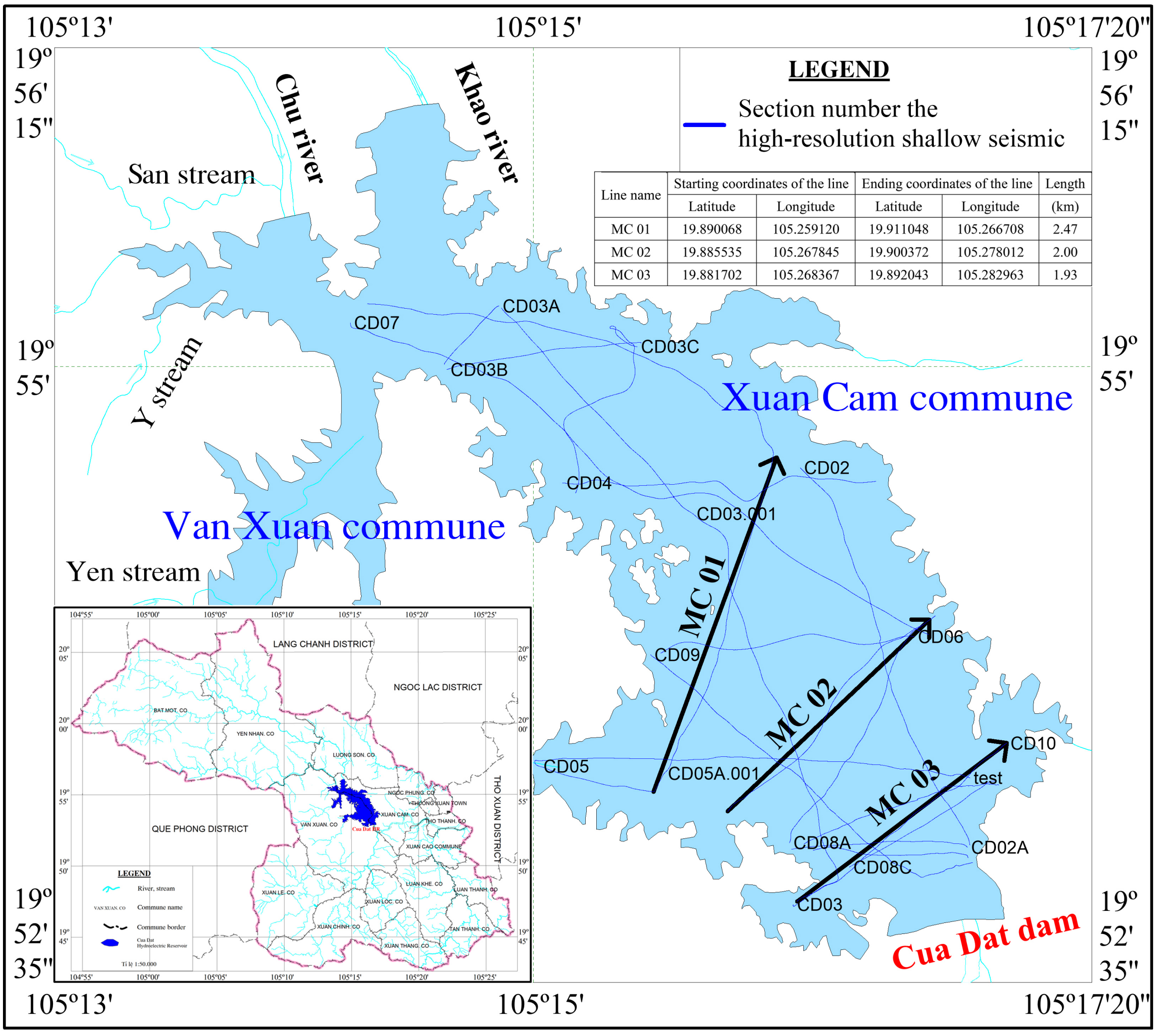
INTRODUCTION

High-resolution seismic survey (HRSS) plays a crucial role in studying the environment of lakes, especially when a comprehensive understanding of the geological characteristics of the lake bed, water quality, and other environmental factors within the reservoir is desired. HRSS can determine small details on the lake or sea floor, including sediment layers with thicknesses of only a few tens of centimeters. Additionally, it can provide detailed information about the geological structure from the lakebed surface to a depth of 100 m below the lakebed surface, aiding in understanding geological features. The results obtained from interpreting HRSS data can be utilized to construct geological models for predicting the trends of sediment accumulation and development in the future and help understand sediments' the origin and formation processes, contributing to improving resource management efficiency and reservoir environmental protection. In Vietnam, sedimentation in reservoirs has been a subject of scientific interest [1–3]. However, the HRSS method has yet to be addressed, even though globally, it has proven effective in assessing sedimentation levels in hydroelectric reservoirs [4–6] and in the topographic mapping of lake beds [7, 8].



Line name	Starting coordinates of the line		Ending coordinates of the line		Length
	Latitude	Longitude	Latitude	Longitude	(km)
MC 01	19.890068	105.259120	19.911048	105.266708	2.47
MC 02	19.885535	105.267845	19.900372	105.278012	2.00
MC 03	19.881702	105.268367	19.892043	105.282963	1.93

Figure 1. Location of Cua Dat reservoir and the survey lines of the High-Resolution Seismic Profiles (HRSP) in the reservoir area

In this study, the authors collected high-resolution seismic data collection in the reservoir area of the Cua Dat Hydroelectric in Thanh Hoa Province (Figure 1). The study results serve to assess the status and the origin of modern sedimentary formations in the research area. By providing detailed information about the geological environment of the reservoir sediments, our findings can assist local authorities and project management units in making informed decisions about the exploitation and operation of the Cua Dat water reservoir.

STUDY AREA

The Cua Dat Hydroelectric Reservoir is part of a hydropower complex constructed on the Chu River, with construction starting in February 2004 and completion in November 2010. The main plant of the Cua Dat Hydroelectric Power Plant is located in Cua Dat Village, Van Xuan Commune, Thuong Xuan District, Thanh Hoa Province, Vietnam (Fig. 1). The reservoir is approximately 17 km upstream from the Bai Thuong Dam. With a capacity of nearly 1.5 billion cubic meters, the reservoir plays a crucial role in flood control for the downstream area, ensuring sufficient irrigation water for over 86 thousand hectares of agricultural land and meeting the water demands for industrial and domestic purposes.

Additionally, the reservoir contributes to reducing salinity in the lower Chu River and collaborates with the Cua Dat Hydroelectric Power Plant, which has two commercial generating units with a total capacity of 97 MW. This power plant supplements the national power grid with an average output of around 430 million kWh annually [9, 10]. After more than 10 years of operation, the geological environment of the reservoir area and the downstream Chu River has changed due to variations in hydrological regimes, dynamic flow forces, and geological processes such as sedimentation, deposition, and erosion. These changes have led to unique characteristics in the geological environment of the reservoir area and the downstream Chu River region.

DATA AND METHODS

Data utilized

In June 2022, the author's team conducted measurements of over 40 km of high-resolution seismic profiles in the reservoir area of the Cua Dat Hydroelectric. The data quality of the seismic profiles met the requirements of the research objectives. For this paper, three seismic cross-sections (MC01, MC02, MC03) were selected for analysis to elucidate the characteristics of modern sedimentary formations in the research area based on the seismic reflection facies (Figure 1).

High-resolution seismic method

The high-resolution seismic survey system includes an acoustic source, a system of receivers to capture signals reflected from the subsurface geological environment, and the conversion of these signals into seismic cross-sections. The seismic cross-sections represent continuous-time profiles vertically beneath the survey vessel's trajectory, with the vertical axis depicting two-way travel time and the horizontal axis indicating the survey vessel's position on the water. Acoustic reflection signals contain valuable information regarding the elastic wave field, such as reflection coefficients, acoustic impedance, wave velocity, amplitude, signal frequency, etc., linked through phase axes to determine acoustic reflection boundaries, representing geological boundaries with density variations [11].

For the research objective of characterizing modern sedimentary formations, which often have shallow depths, the high-resolution sub-bottom profiler system, EdgeTech 3400 Sub-Bottom Profiler (Fig. 2), was chosen for implementation. The EdgeTech 3400 Sub-Bottom Portable System is a frequency-modulated, broadband terrain and sub-bottom profiling equipment capable of collecting high-resolution data on the subsurface in inundated areas (oceans, rivers, lakes, etc.). The system comprises a towfish, signal cable, and a central control processing unit with EdgeTech's Discover 3400 software for data collection and processing. The towfish can be towed behind the vessel or mounted on its side, nearly eliminating secondary pulses (bubble pulses) and emitting sharp, nearly half-cycle ideal pulses, allowing for a 6–10 cm vertical resolution. The penetration depth in most sand or mud layers generally ranges from 6 m to 80 m and may be deeper for finer sediment layers [12].

Pre-installed control programs on the computer carry out the entire operation of the seismic equipment. This program directly oversees the measurement, recording, wave representation, and selection of relevant measurement parameters at the site. The collected data are integrated with the Global Positioning System (GPS) or Differential GPS (DGPS) to ensure navigation and determine the positions of measurement points along the profile.

The dedicated data processing software REFLEXW ver. 6.0 is used for data processing. The survey data are processed to convert the acquired data into the most realistic image possible, reflecting detailed structures beneath the surface. The processing involves several algorithms using computer language for data, aiming to increase signal-to-noise ratio and data resolution, typically including the following steps: a) Amplitude correction to restore the amplitudes of seismic signals attenuated during transmission and reflected from geological objects; b) Frequency filtering to eliminate irrelevant frequency components, enhancing signal-to-noise ratio; and c) Seismic attribute analysis to determine quantified values obtained through measurement, calculation, or inference from seismic data [13–16].

Signal receiver - transmitter EdgeTech 3400 | Tow Cable | Central processor system EdgeTech 3400

Figure 2. Sub-bottom Profiler 3400 equipment system

RESULTS

Processing of seismic data

Figure 3 represents the raw seismic profile (MC01) on the top and the results obtained after several processing steps on the bottom. For this specific case, amplitude correction and frequency filtering steps can be omitted because the study target has shallow depth, and the frequency spectrum characteristics of this type of equipment are concentrated within a narrow range, resulting in relatively homogeneous frequency signals. Therefore, the focus is solely on the seismic attribute analysis step to clarify the characteristics of thin-surfaced sedimentary formations formed during the operation of the hydroelectric reservoir. The applied algorithms include wave summation, inverse filtering, scattering noise reduction, industrial frequency component removal, amplitude spectrum stacking, energy spectrum, etc. Additionally, some features of graphic tools are also utilized to enhance the visual effects of the data.

The processing results indicate that the initial reflected signals often have wavelet shapes extending to less than 10 ms, covering subsequent reflected signals and hindering the tracking of the reflection wave field and the boundaries of reflections from thin layers. After processing, the reflected wave phases have become more concentrated and sharper, allowing for a more detailed observation of the acoustic wave field. From these processing results, it is possible to distinguish reflection boundaries with thicknesses down to a few tens of centimeters. Additionally, preliminary sedimentary material distribution characteristics can be identified based on differences in reflection coefficients, reflection intensities, continuity of reflection signals, etc. (Figs. 4, 5).

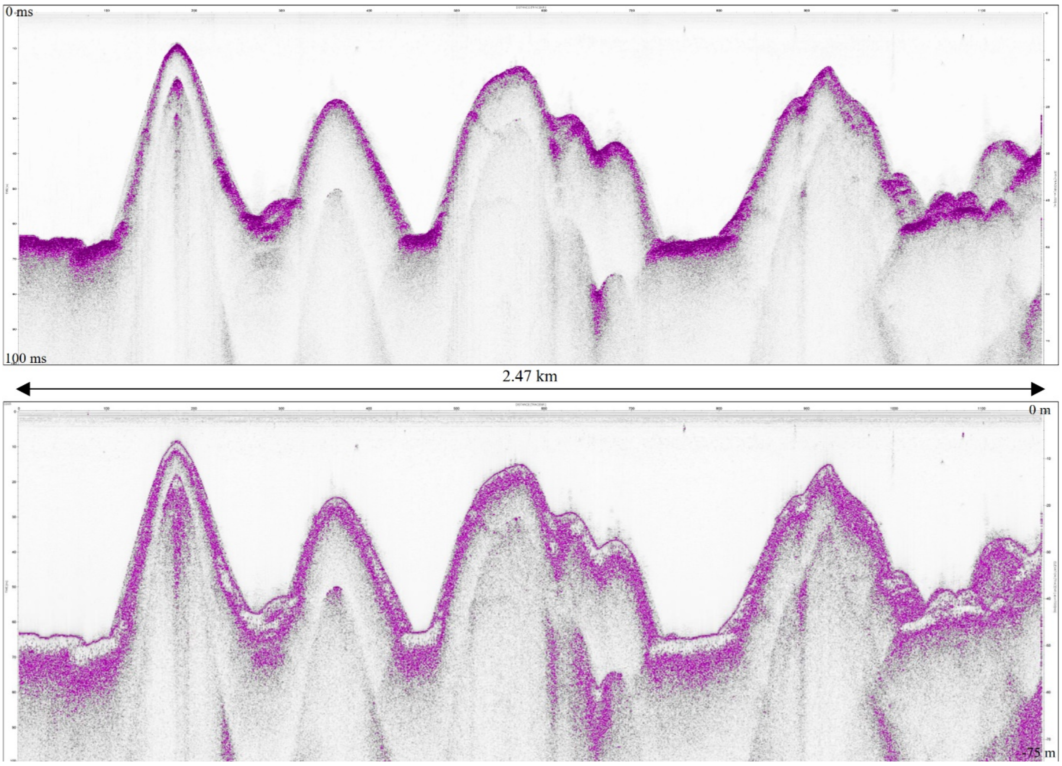


Figure 3. Cross-section of HRSP MC01 before (top) and after processing (bottom) - Viewing position according to Figure 1

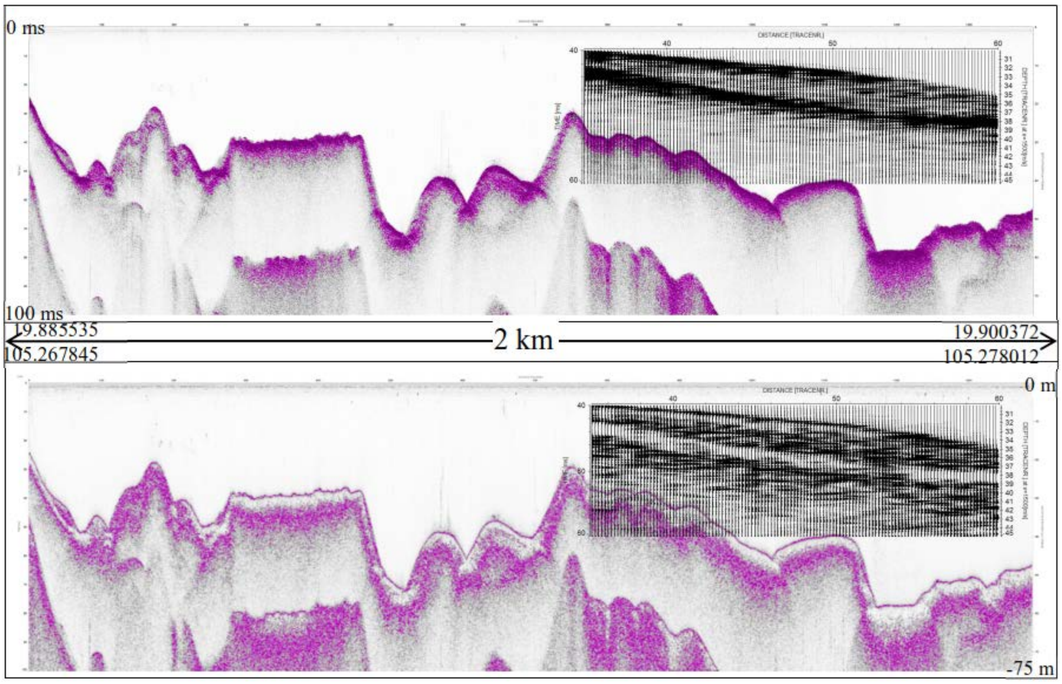


Figure 4. Cross-section of HRSP MC02 before (top) and after processing (bottom) - Viewing position according to Figure 1

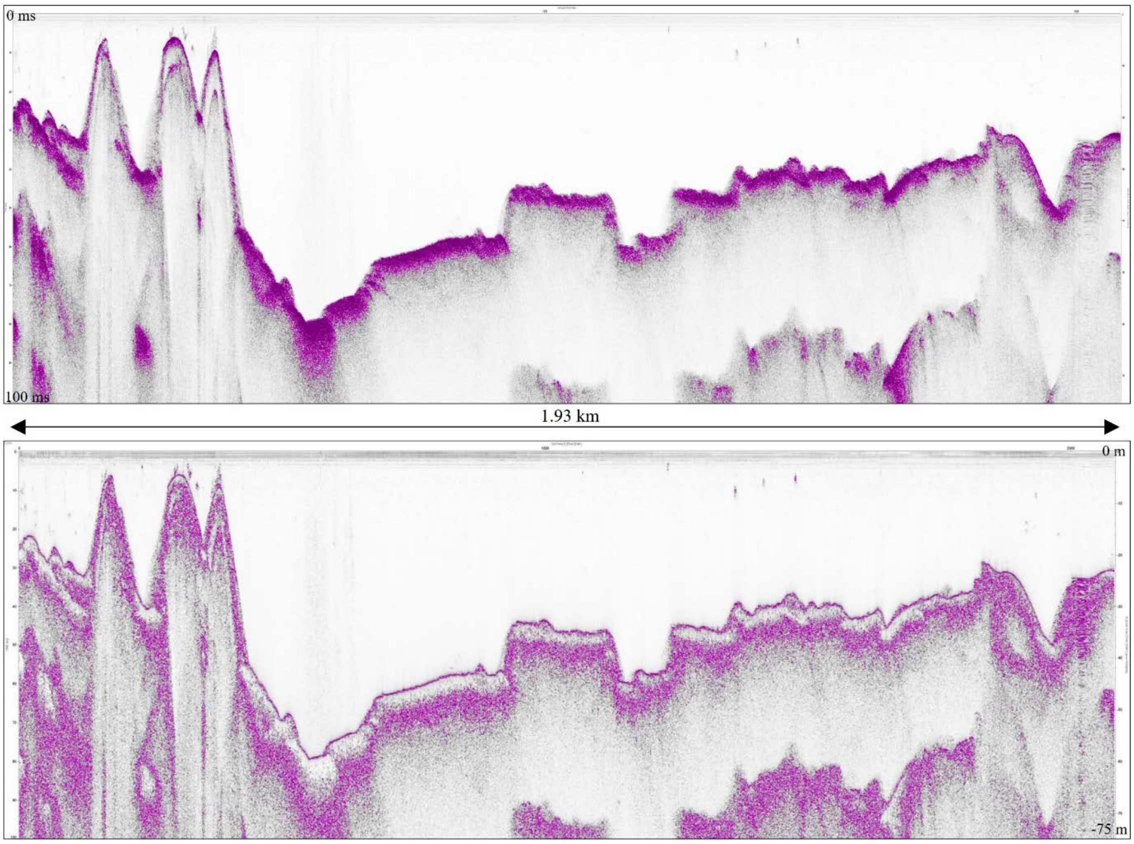


Figure 5. Cross-section of HRSP MC03 before (top) and after processing (bottom) - Viewing position according to Figure 1

Terrain features and characteristics of modern sediments in the study area

Terrain features

On the seismic profiles, a strong topographic variation in the reservoir area is evident, with the deepest point reaching up to 65 m of water depth, interspersed with dome-shaped hills that sometimes emerge above the water surface (Figure 6).

The tops of these domes occasionally exhibit signs of erosion and flattening at a depth of around 30 m and are mainly concentrated near the dam body. This phenomenon can be explained by this being the area with the largest water accumulation, supplying the hydroelectric dam with significant water flow that regularly passes through and converges towards the dam gate, leading to continuous erosion and flattening of the elevated landforms, especially during the dry season (Figure 7).

In the deepest part of the reservoir (beyond 60 m), V-shaped (W-shaped) and U-shaped depressions are commonly observed, characteristic of riverbed terrain or small streams before the reservoir's formation. The V-shaped (W-shaped) depressions have one or both relatively gentle slopes, serving as locations for accumulating sedimentary materials from the upstream and the eroded material from the slopes above, distributed at an average depth of 30–45 m. In many observed locations, there is evidence of accumulated deposits from different stages (Figure 8). On the other hand, U-shaped depressions are distributed at greater depths, with two relatively steeper slopes affected by sub-flows from the upstream, causing redeposition and smoothing of the bottom terrain (Figure 9).

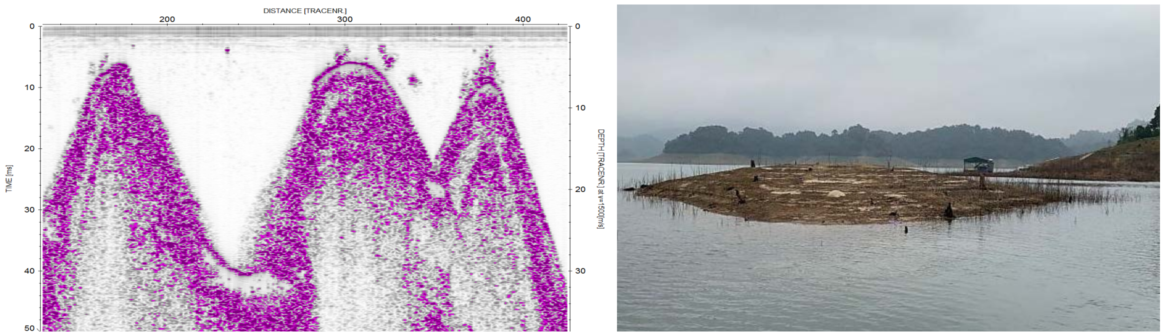


Figure 6. Submerged hill terrain type on cross-section MC02 (left) and above water surface (right)

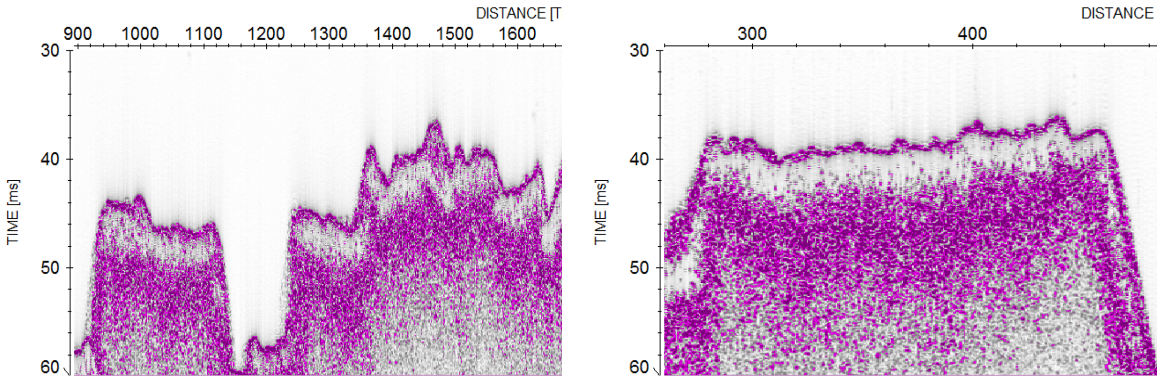


Figure 7. Flat-bottom terrain type on cross-section MC02 (left) and MC03 (right)

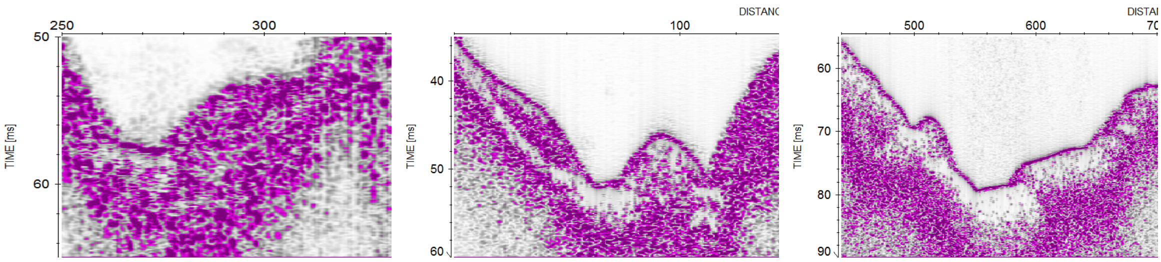


Figure 8. V-shaped (W-shaped) terrain type with accumulated sediment materials over multiple stages on cross-sections MC01, MC02, and MC03 (from left to right)

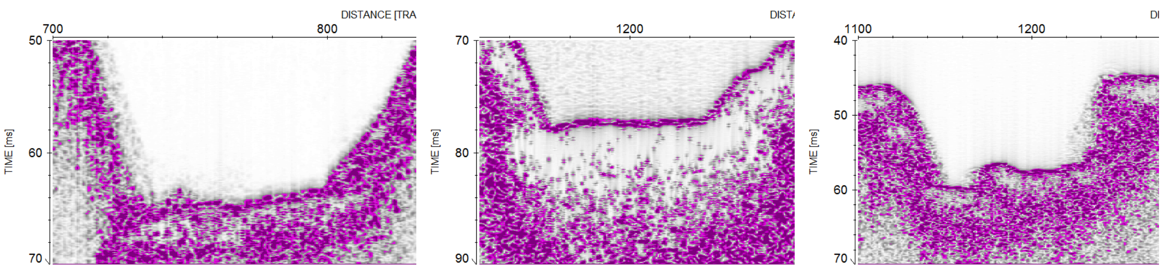


Figure 9. U-shaped terrain type with a flat bottom due to redeposition on cross-sections MC01, MC02, and MC03 (from left to right)

Sedimentary characteristics

Based on the acoustic reflection wavefield characteristics on the seismic profiles, along with direct observations from the dam walls on both sides of the Cua Dat Dam (Figures 8–10), the sediments in the Cua Dat Reservoir can be classified into the following types:

a) Highly selective sediments, characterized by weak intensity reflection wavefields, no clear layering, often distributed in thin layers (less than 1 meter) on the slopes of steep walls or forming bottom layers in topographic depressions (Type ‘a’). This type represents highly weathered sediment materials, low cohesion, and exposure to strong dynamic environmental influences, leading to frequent gravitational redeposition.

b) Mound-shaped sediments, characterized by a concentrated structure, piled high with reflection wavefields of average amplitude. Internal reflection boundaries are not distinctly visible, though they exist at varying degrees (Type ‘b’). This type represents chaotic sedimentary materials transported to accumulation locations in a high potential or dynamic energy environment in different stages, where fine particle components have been partially transported by fluid flow to other locations.

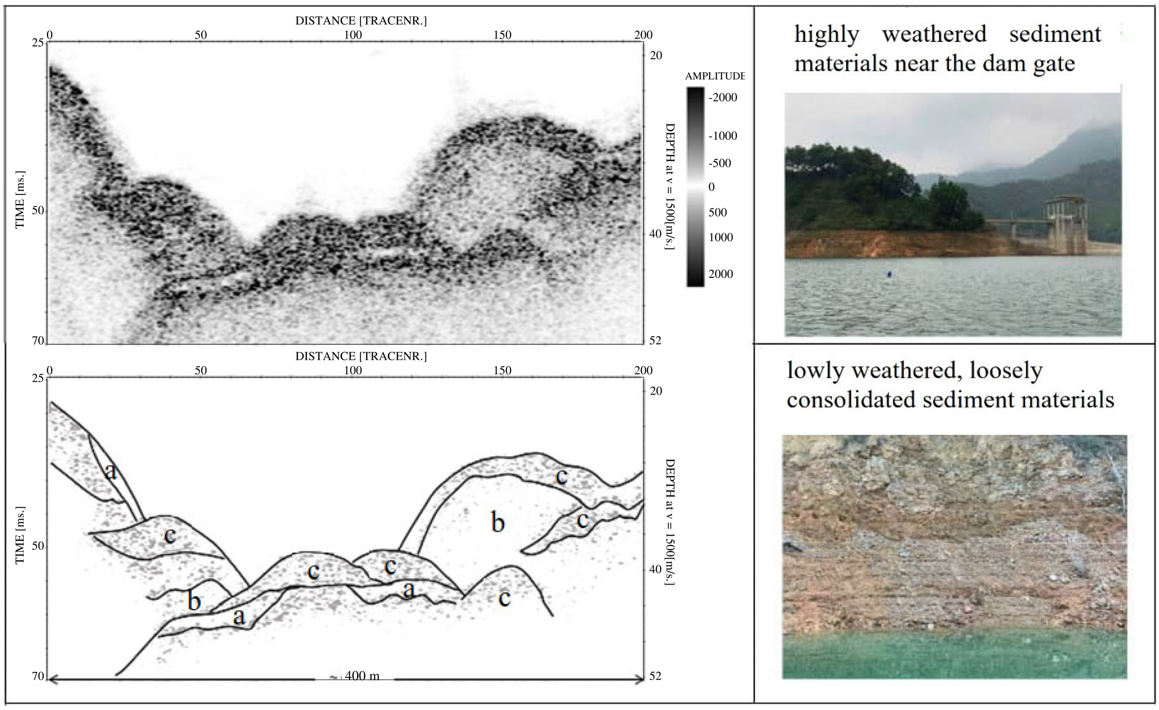


Figure 10. Sectional excerpt from MC01 and the main acoustic reflection boundaries

c) Coarse fragmented sediments, often forming shell layers on top of the ‘b’ type sediment layers, featuring relatively high amplitude reflection wavefields with strong scattering. This type represents incompletely weathered sediment materials with particle sizes from coarse to very coarse (boulders, debris, gravel) equal to or larger than the wavelength of the acoustic source (Type ‘c’). These materials are less likely to be transported from afar but are primarily formed in situ through erosion and sliding processes from the slopes.

From the research results and the analysis presented above, the formation and development of modern sediments in the Cua Dat Reservoir can be described as follows: Since its inception, the reservoir has maintained a thin layer of sediment, partially leveling the depressions, undergoing gravitational redeposition and topographic variation compensation into the depressions. Subsequently, this layer is overlaid by mixed weathered materials eroded from the slopes and brought down from the upstream, forming mound-shaped terrains on the reservoir bottom. This process occurs irregularly and depends on the hydrological regime during seasonal and yearly fluctuations. The tops of these terrains are directly impacted by erosion, especially near the dam gate, resulting in continuous erosion, scouring, and the transport of fine particle components while leaving coarse particle components. However, initial assessments suggest that the weathered sediment cover layers on the reservoir banks exhibit relatively strong cohesion, minimizing the significant transport of eroded material into the current reservoir.

CONCLUSION AND RECOMMENDATIONS

Conclusion

Based on the thickness of loosely consolidated sediment layers, the sedimentation and accumulation within the Cua Dat Hydroelectric Reservoir after more than 10 years of operation and exploitation are considered insignificant. With the current operational, exploitation, and reservoir protection procedures, it is possible to ensure the longevity and efficiency of the Cua Dat Hydroelectric Reservoir according to its original design and purpose.

The high-resolution seismic method has demonstrated significant advantages in sediment studies within submerged areas, especially under survey conditions that demand high accuracy, reliability, and considerably lower costs than other traditional research methods.

Recommendations

There are over 3,000 hydroelectric and irrigation reservoirs across the country, many of which have existed for several years and have yet to be thoroughly studied or assessed for their current status. It is essential to conduct in-depth, interdisciplinary research on these reservoirs to develop reasonable maintenance measures, particularly in climate change and the increasing rapid environmental and geological changes. Continuing such research is crucial to ensuring energy security, disaster prevention, and mitigation and contributing to the nation's sustainability goals, focusing on green and sustainable growth.

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