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SPECIAL APPROACHES OF ENGINEERING-GEOPHYSICAL OPERATIONS AT HIGH LEVEL OF INDUSTRIAL NOISE

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ABSTRACT: The capabilities of the complex of seismic methods, which are suitable for inspecting of large strategic objects are presented. In this paper next tasks for the dam investigation and the upper part of the section of its area were considered: probing of the construction state of the dam; characterization of the dam connection to the river banks; identification of possible tears in the proximity of a day surface; identification of possible soil state changes that are caused by technogenic-originating impact or geologic processes.

Keywords: Passive seismic methods, strategic objects, upper part of the geological section.

INTRODUCTION

The introduction of the paper should explain the nature of the problem, previous work, purpose, and the contribution of the paper. Disturbances in the founding soils are responsible for the majority of accidents at hydro power stations (HPS), high-rise buildings, railroad banks and other relevant constructions [1]. To estimate the conditions of them and foundation soil,it is necessary to have the information about structure state and velocity properties of the ground in the upper part of the section (UPS). Geophysical methods provide the required dataset and a wide variety of modifications is available: the engineering-geophysical probing of construction sites, the soil state monitoring and the construction state monitoring.

UPS probing in cities or industrial zones is often complicated by vibrations or by the construction loads, which cause an artificial alteration of the UPS leading to an inhomogeneity of the geological media or by the temporal drift of the physical properties of mountain rocks. Other contributing factors are: artificial vibrations, strong electromagnetic noise, compact development, asphalt, etc. Traditional methods proved to be ineffective under these circumstances.

The efficacy of the UPS probing can be amplified by new geophysical technologies that combine various techniques. Passive seismic and microseismic methods are gaining relevancy [2-4] as a) the technology behind the signal acquisition and processing advances, b) they do not require a dedicated signal source and c) they are cheap and accessible.

The term “microseism observations” covers a variety of techniques that is based on the analysis of waveforms with different frequencies and genesis (seismic emission, industrial vibrations, surfave waves,...).

We develop new approaches of the UPS analysis by extracting "beneficial" signal from technogenic microseisms. The wavefield at the site can be processed in parallel in this manner to tackle principally different data with the use of different extracted signals. An approach is tested at Song Tranh-2 HPS dam (Central Vietnam, operating since 2011) and the reported results serve as an illustration of the developed microseism observation and processing techniques.

DESCRIPTION OF THE RESEARCH OBJECT

Concrete dam Song Tranh-2 is situated in Central Vietnam in Quang Nam province. It is 80 meters high and 640 meters wide, the crossection is triangle-like with inner galleries (fig. 1a). The deterioration of the constructed state of the dam is visible with the naked eye, including different kinks in the dam's body (fig. 1b) [5].

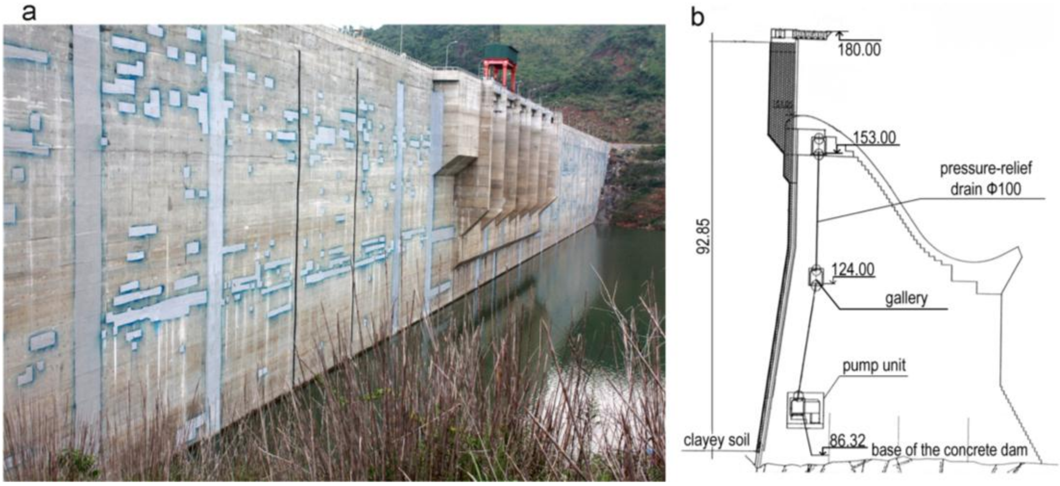


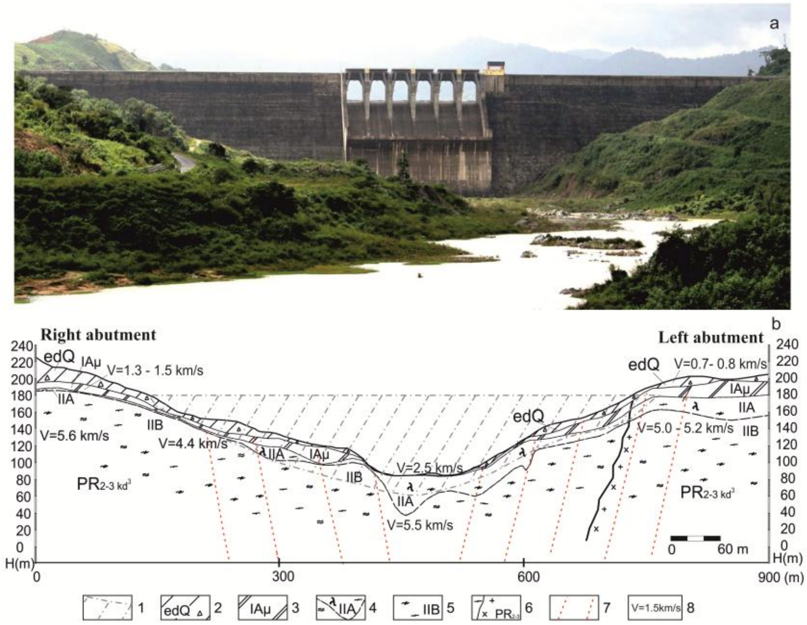
Fig. 1. The concrete dam Song Tranh-2: a- a view from the water head of the dam after the reconstruction, b- a schematic cross-section of the dam

Engineering, geologic and geophysical characteristics of the investigated area

The general information on the founding soils (fig. 2) was obtained before construction in an engineering-geological study and was kindly provided by our Vietnamese colleagues from Institute of Geophysics, VAST. The riverbed is inside the grabenoid structure, whose sides contain plentiful cracks oriented towards the center of the graben. The upper part of the section consists of quaternary sediments (edQ) with clay, sand, gravel, the weathered rocks and (IA1, IA2) cracked rocks of the basement (IIA) are located below. The rocks of the basement (IIB, $PR_{2\text{-}3}$) are represented by: gneisses, amphibolites, shales, gabbros, diorites, migmatites, granites,...

The area around the dam is geologically complex and exhibits geodynamic activity in a form of frequent earthquakes with variable magnitude [6]. Both sides of the river plain are crossed by north-east and north-west cracks (along the river flow). The direction of the rock cracking azimuth (160-170^{o}) is visible for both regional and local zones (fig. 3). Notably, small cracks are close to vertical meaning that they can transmit fluids to the depth activating geodynamic processes of induced seismicity. A similar behavior was observed at Nurek HPS [7] and is generally well-known.

After an M=4.7 earthquake the water level at the dam was brought down to the minimum. The subsequent visual inspection revealed zones of the excessive durability loss: cracks (fig. 4a) and areas with an elevated filtration of water into the dam galleries (fig. 4b). The latter is aggravated by concrete defects all across the reservoir side surface of the dam (water head of the dam, fig. 1b). The defects are concentrated in the lower part often forming extended zones.



1- Dam, 2- edQ: Boundary of bottom deluvial-eluvial layer: brown dark, red brown clay, loam, with 20-30% gravel, pebble of quartz and souce rock; 3- IAμ: Zone of completed weathered rock: Upper part is brown dark, yellow darrk clay, loam, loamy sand, with gravel pebble (15-40%). Lower part is piece pebble, clay, loam; 4- IIA λ: Zone of fractured rock: Gneiss, amphibolite, schist, gabbro, gabbro amphibolite, granodiorite, diorite. Rock is strongly fractured, with calcium or quartz at joint , medium hard to very hard; 5- IIB: Zone of relatively intact rock: Gneiss, amphibolite, schist, gabbro, gabbro amphibolite, granodiorite, diorite. Rock is weakly fractured, with quartz or calcium at joint, medium hard to very hard; 6-Geological boundaries; 7-Faults; 8- Speeds of P-waves, km/s

Fig. 2. Song Tranh-2 view from the downstream water of the dam (a) and the geological-geophysical cross-section along the dam (b)

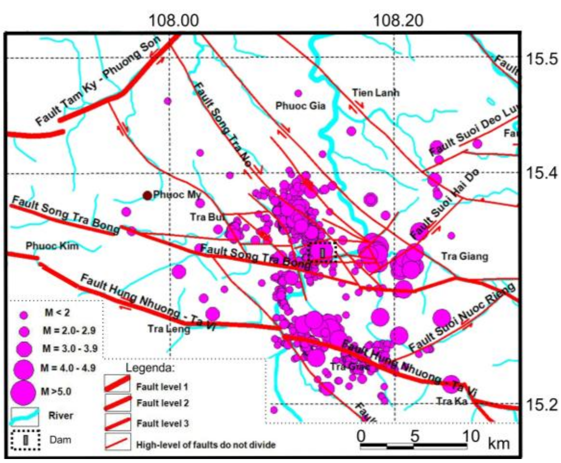


Fig. 3. The map of seismic activity in the region of the dam in 2011-2012

Fig. 4. Visual inspection results: a- a crack with water pouring through, b- water filtration inside the dam

The design of Song Tranh-2 is tailored to withstand earthquakes up to M= 5.5. The calculated seismic impact response, which was used for design, shows that:

All parts of the dam are moving when exposed to vibration especially the upper part (upper third of the dam) and thus the most damage is expected to happen in it;

The founding soils are also susceptible to vibrations.

The latter implies that an inspection of the soil state should be conducted regularly after the construction was over. Complex seismic inspections during the field seasons of 2012 and 2013 covered both dam and its foundation soils.

SEISMIC EQUIPMENT AND OBSERVATION SCHEME

For investigation in 2012 we used equipment that belongs to Institute of Geophysics VAST and includes 4 analog seismometer complexes CMG-40T by Guralp (Great Britain) and a registration device SAMTAC-801H (Japan). The frequency range is 0.1 to 50 Hz and the dynamic range is 130 dB. Time reference is based on GPS except for inter-dam measurements, which used internal clock synchronization. In 2013 a new set of equipment included 7 sets of digital seismometers CMG-6TD by Guralp. We made several successive profile measurements: along the dam's ridge and then along the first, second and third galleries. Each profile had an immobile reference station in the center of the dam [5].

For microseism recordings in the area of the dam we used with the same set of equipment. A long measurement profile (2012, fig. 5a) is parallel to the dam's foundation and lies 250 m from it. Fig. 5b contains the scheme for the detailed measurements of the banks in 2013. The interval between measurement points in the close area of the dam is 20-30 m, then 40-50 m and reaches 100 m for the most distant point. The choice of such placement was dictated by the equipment placement conditions.

For seismic exploration work in the region we employed 24-channel stations «Geode» [8]. Horizontal and vertical seismic receivers recorded seismic P and S waves. 8 kg sledgehammer strikes on the steel plate, which was aligned at 45^o crosswise to the profile direction, generated probing waves. The conditions for the profile laying for the right and left banks of the dam define the measurement scheme (fig. 6). Spacings between channels are 1, 2, 3, and 5 m and the corresponding profile lengths are 24, 48, 72 and 120 m. Signal were processed with RadExPro+ [9] and ZondST2d [10] software suites with the support from Geosignal Ltd [11].

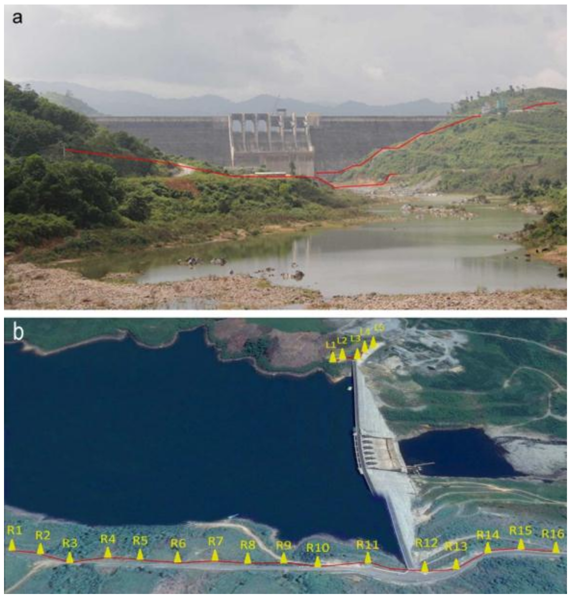


Fig. 5. Profile schemes for the microseism registration near the dam in a) 2012 and b) 2013

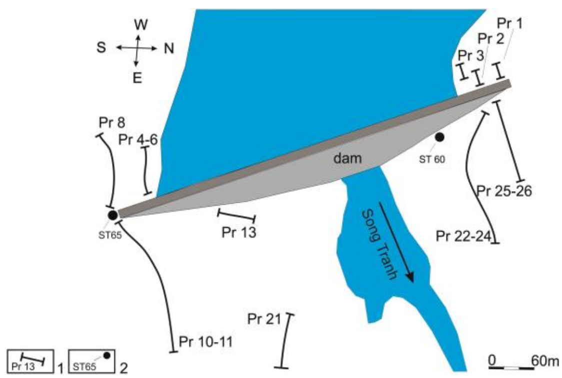


Fig. 6. Seismic survey profile disposition relative to the dam

INSPECTION METHODS

We pursued several tasks for the dam investigation and the UPS of its area:

Probing of the construction state of the dam;

Characterization of the dam connection to the river banks;

Identification of possible tears in the proximity of a day surface;

Identification of possible soil state changes that are caused by technogenic-originating impact or geologic processes.

For this time a combination of passive and active seismic methods was used in order to maximally exploit the wavefield for the characterization of the system formed by the structure and founding soils. Passive seismic methods utilize ever-present microseisms and enable the reconnaissance with small number of movable channels of an object of interest and its territory [12-14]. Then, for detailed studies of the anomalous areas identified in reconnaissance, it is preferable to use seismic methods based on the use of special source of excitation signals (so-called active seismic methods such as shallow seismics methods). Though, there is a passive method based on the seismic interferometry [2, 4] that reaches the same detail level by having more measurement points, it is inferior compared to active ones in terms of observation technology. Another advantage of passive methods is the relative simplicity of wavefield monitoring [7].

Engineering-seismic technique

Drives and pump stations produce a signal that fits well for transmission of the dam body and UPS [5]. The foundation of the seismic transmission was laid in 1980s during the "Vibrational transmission of Earth" project as the possibility of weak harmonic signal registration at a point distant from the source was proved by Nikolaev (1999) [15]. To utilize vibrations from industrial machines as this kind of signal one has to identify them by calculating power spectra with the correct frequency resolution and averaging in the vicinity of the machine. At a distance of tens of kilometers from the source, it is necessary to apply an additional tracking filter with reliance on power network [7]. In our case the distance to operating power machinery reaches 1 km. Vibrations of an industrial origin are clearly manifest themselves as 3,125 and 4.6 GHz peaks (fig. 7), thus we chose them to perform the transmission.

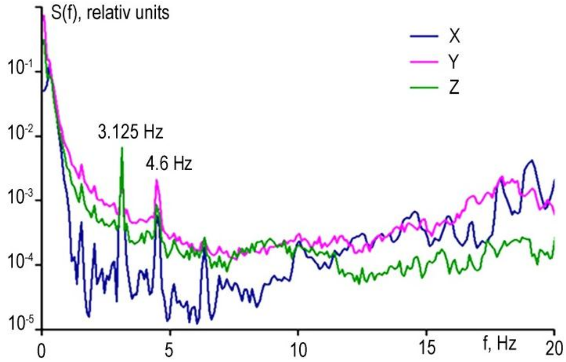


Fig. 7. Typical power spectra of microseisms

The procedure of signal identification and segregation from the microseismic field along with the registering signal amplitude mapping are thoroughly described in [7]. One thing should be noted, though. The peak amplitudes of the analyzed signal change with time but the ratio of amplitudes at the registration and at the reference point (A_i/A_0) does not, thus time variation can be ruled out leaving the spatial distribution of amplitudes undistorted. It is important to keep the distance between the reference and measurement points to be comparable to the wavelength of the signal, so in the case of frequency (wavelength) drift the error of an amplitude ratios stays minimal. If these precautions are taken, the cumulative distortion of the spatial distribution of relative amplitudes is non-crucial. This is why we placed the reference point for the construction inspection at the structure and on the soil for the soil study.

Microseismic probing method

The description of the microseismic probing method (MPM) along with examples is given in [16]. The technique is based on the interpretation of the surface Rayleigh waves that are present in microseisms. The value of the amplitude of a surface wave depends on structure propagation velocity with low velocities having in high amplitude and vice versa. An interpretation of the Rayleigh wave package at different frequencies provides the information about velocities at various depths. Substantially, LFMP targets the near-vertical inhomogeneities. The method has been adopted to fit various goals and special software was developed for data processing in the field [14, 17].

Temporal autocorrelation functions

This method allows studying periodical signals, their correlation and their likeness at different time intervals. It is based on the temporal signal correlation, which is estimated by calculating time-dependent autocorrelation function:

$$\Psi\ \tau = \int_{-\infty}^{\infty} f\ t\ f^{*}\ t-\tau\ dt \qquad (1)$$

Where *f(t)* is a seismogram; τ is time shift and * is a complex conjugation. This function characterizes the similarity of the signal to its own copy shifted by τ. The function local maxima correspond to phase-matches, while the minima mark signals in the counter-phase.

In this article we present the transmission properties of the dam and its zones in contact with geologic media obtained with the analysis of autocorrelation functions of the seismic noise along the right and left banks.

Multichannel surface wave analysis

This method is described in the pioneering works [18-20 and is developed in [21]. It analyzes dispersion properties of the surface waves and produces one-dimensional velocity models of the geologic media along linear seismic survey profiles. The core of the multichannel surface wave analysis technique is a wave-spectra (f-k) signal processing with the consecutive summarization across all channels [22, 23].

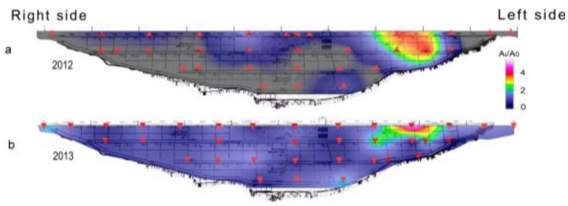
Shallow seismics methods

This paper demonstrates various applications of shallow seismics, including reflection and refraction wave methods. The methods are based on the use of different types of seismic waves characterized by different modes of propagation. The common feature of all these methods is their sensitivity to spatial changes of seismic velocities in the subsurface. Analyzing the seismic data acquired at the surface, one can estimate the subsurface velocity distribution and map the corresponding structural features. For this purpose, each method implements its specific acquisition and processing techniques [24]. Methods were used to identify a) non-homogeneous areas and b) correlation losses at the refracting borders in the dam area.

RESULT ANALYSIS

Engineering-seismic method

Fig. 8 contains spatial distributions of the relative amplitudes at 3.125 Hz for signals recorded in two sessions. Authors did not study types of the waves that constitute technogenic vibrations and which were used for the transmission studies. Therefore, it is hard to relate the values obtained with velocities in the dam's media and additional deformations as well. Nevertheless, the homogeneous spatial distribution corresponds to the material with homogeneous sturdiness while anomalies mark zones with altered media.

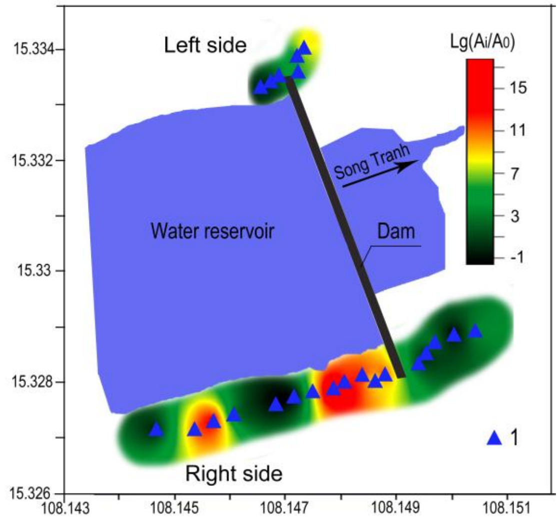


a) 2012 year; b) 2013 year

Fig. 8. The results of dam body sounding with the vibration caused by hydropower machine. Yellow-red area marks an anomaly zone related to the weak zone

The left side of the dam had a bright anomaly in 2012 (fig. 8a), which corresponds to an area with decreased durability. The visual inspection reveals wet walls and water leaks. Some areas in the central part are starting to degrade (blue spots in fig. 8a). In 2013 these observations were confirmed (fig. 8b): The left anomaly persisted and the dam exhibited the general loss of durability.

The 3.125 Hz vibration is a probing signal for vertical component. The signal's amplitude was normalized to the reference point and is presented as logarithm (fig. 9).



1) microseism recording points

Fig. 9. Vertical component (Z) of the dam area probing with 3.125 Hz signal

Temporal autocorrelation functions

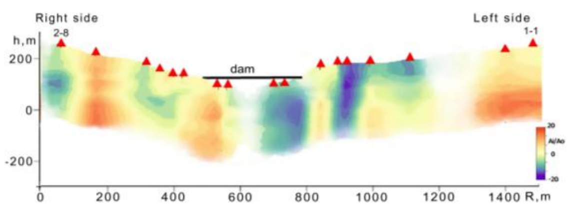
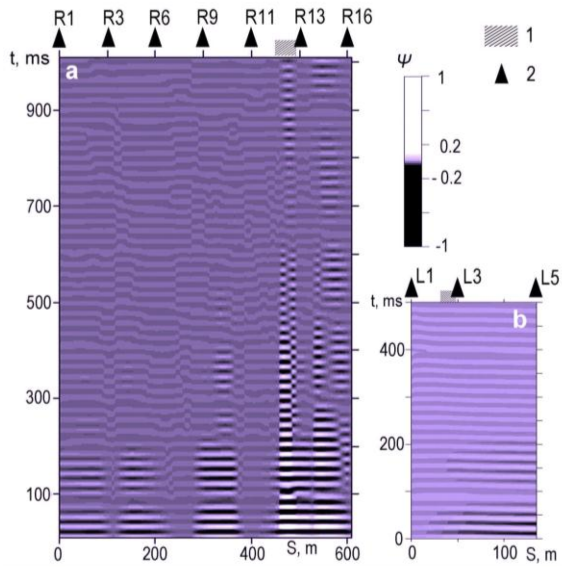


Fig. 10. Geologic study results: a) LFMP cross-section along the generalized profile (1 and 2), that represents the velocity differentiation in the upper crust. High values of A_i/A_0 correspond to low velocities, i.e. to the weakest media in the dam foundation

Given that the dam is a source of the quasi-coherent signal in the temporal area, therefore the temporal autocorrelation functions for seismograms at various distances from the dam provide some information about the geologic structure. Transmission properties of the dam in fig. 11 are acquired by processing seismic noise recorded along the right and left side profiles (fig. 5b).



1) dam area, 2) numbered microseisms recording points

Fig. 11. Autocorrelation function values for a) right and b) left sides according to the scheme in fig. 5

Autocorrelation function for the left side has small correlation coefficient compared to the right side, implying that the left side has no specific signal source. Stable signal source is visible in the UPS only in the right side (fig. 11a) and the correlation drops with distance from the right side.

This is because the dam-structure contact zone has better transmission properties compared to other areas. This, in turn, signals a breach in the dam integrity at the right side contact zone.

Results of the multichannel surface wave analysis

We calculated 2D velocity models by inverting dispersion curves for profiles: PR13-21 (right side) and PR22-24 (left side) as in fig. 6. Low-velocity slab (c.a. 200 m/s) of transversal waves is up to 5 m deep in the right side and extends to 180-200 m from the dam with the depth reaching 15 m (fig. 12). Low-velocity zone in the left side exists only in a surface layer. Despite the velocity cross-section of the right side being more detailed due to higher profile count, it has more mosaic-like structure compared to the left side. Low-velocity zones might relate to the water-saturated soils. Generally, the right side has higher density rarefaction and is thus less stable.

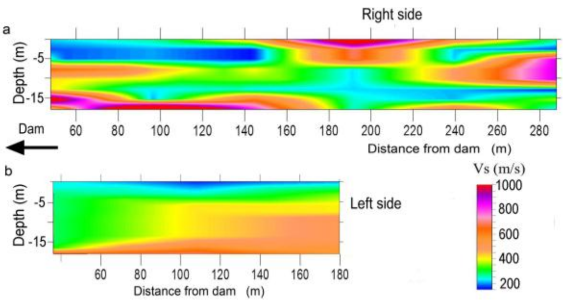


Fig. 12. Velocity cross-sections obtained by inverting dispersion curves for surface waves for a) right and b) left sides, according to the scheme in fig. 6

Results of the engineering seismic exploration work

We identified faults zones in the foundation rocks that are 20-40 m deep (profiles PR4-PR10 from the reservoir side and PR9-PR21 downhill from the dam). Average velocities of the longitudinal waves in Quaternary sediments (up to 10 m) vary in the range from: 200 - 600 m/s to 1000-1300 m/s (fig. 12a) in the foundation rock. The boundary velocity along the layer of weathered and fractured rocks of amphibolites, gneisses varies in the range of 1410 to 2030 m/s, and in the top layer of the foundation rocks: 4430-5030 m/s.

Left side has fault areas too (profiles PR1-PR3, the reservoir side, and PR22-PR26). Average longitudinal wave velocity in Quaternary sediments is 518-650 m/s, layer thickness is 4-6 m and the averaged boundary velocity along the refracting border of cracked and withered foundation rocks is 2270 m/s. The average velocity before the second refracting boundary (between cracked (IA1, IA2) and withered (IIA) foundation rocks from the undamaged foundation (IIB, PR_{2-3})) is 900-1350 m/s (fig. 13a). The upper limit along the second refracting border is 6160 m/s. Second layer is 17-24 m thick. Therefore, velocity properties of grounds are different for the sides of the dam. The right side has low-velocity grounds especially in the contact zone due to fracture of ground structures, thus it is less stable towards loads.

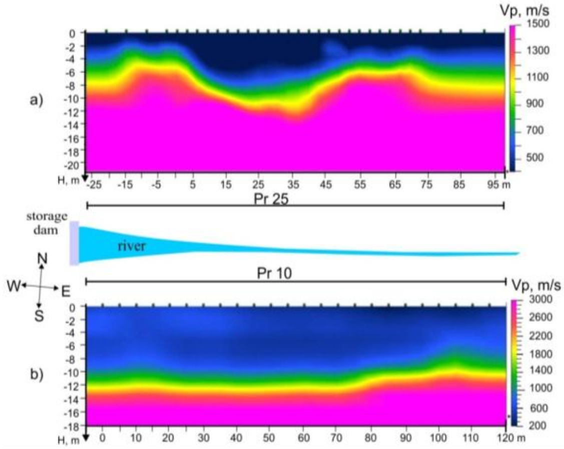
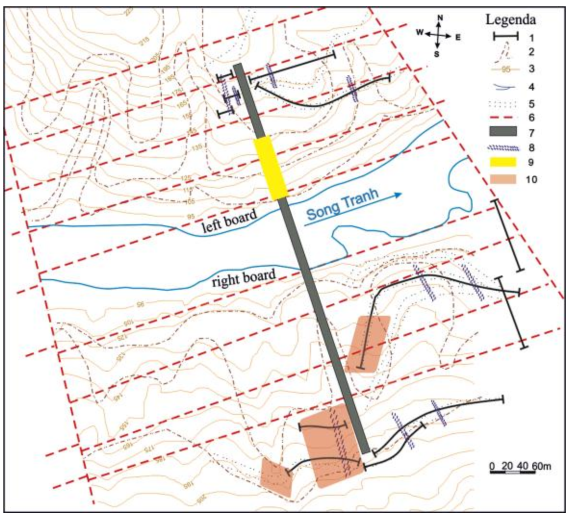


Fig. 13. Seismic survey results: deep seismic section of average longitudinal wave velocities along a) profile 25, left bank, b) profile 10, right bank

Combining methods



1- lines of seismic profiles; 2- ravine; 3- abs. elev. relief; 4- riverbed; 5- driveway; 6- tectonic faults; 7- the dam; 8- breaking. Anomalies: 9- in the dam body; 10- in the founding soils

Fig. 14. Inspection results of the dam and its area by a combination of methods

According to the tectonic map, both banks are permeated with numerous cracks of the north-eastern direction (in the direction of the Song Tranh-2 river) and the north-western direction. The detailed study reveals the following (fig. 14).

The right side is less stable than the left. As the reservoir fills up the stress-strain, state of the dam changes in the right part and the components appear in the north-western part that are characteristic of the console-type anchoring of the dam. Such strains can lead to cracking, which is indeed observed (yellow area in fig. 14). Thus even a simple representation of the structure of the dam leads to the good agreement between independent methods in that the weakened foundation leads to disruptions in the body of the dam.

CONCLUSION

We presented the capabilities of the complex of seismic methods, which are suitable for investigation of large strategic objects. The seismic field of Song Tranh-2 HPS dam was studied by a variety of techniques. The information on the state of the construction body, founding soils is promptly acquired as it is required for the countermeasures to be taken in time to ensure the safety of the operation. Experimental data is a key to the understanding of the nature of dam body deformations, which are mostly related to the state of the foundation. All necessary reconstructions can be designed timely if repeated surveys and the geodynamic monitoring of the region are performed according to the presented scheme.

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