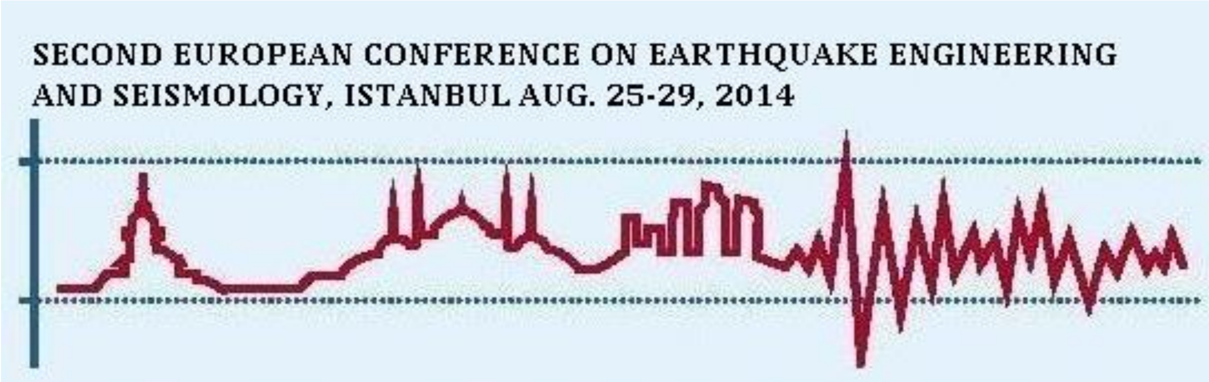

SEISMIC ENGINEERING INVESTIGATION OF HYDROPOWER STATION DAMS

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ABSTRACT

This paper presents new methods of seismic monitoring hydropower station’s dams on two experimental examples. The first one is an observation of construction characteristic (eigenfrequency) oscillations induced by ever-present background microseisms and by wind pulses. The second one is a seismic scanning of a dam body performed with hydropower machinery vibrations.

INTRODUCTION

Construction state survey is a basis for safety during operation and reconstruction. Traditional methods (for example, building code (STO 70238424.27.140.032-2009)) include a visual inspection followed with measurement of of the crack size and disclosure, horizontal and vertical displacement and a laboratory study of construction materials. Strategic complexes like hydropower stations (HPS) in addition to inspections after accidents and earthquakes ((STO 70238424.27.140.032-2009) for 5-score quake) are constantly monitored by geodesic means and by methods that inspect strain-stress state (SS), engineering seismology, etc. The latter ones allow to detect defects that cannot be found visually yet and additionally can be used to create a computer simulation model of a complex. This model is used to estimate the safety of the construction.

According to Russian practice of seismic engineering monitoring of hydrotechnic objects (approved in 1980s) the number of low-sensitivity seismometers is placed in the body and board-sides of a dam. The low sensitivity is determined by high level of technogenic microseisms, the hardware and analyze methods of that time. Since then a large shift happened in seismometry - digital data acquisition permits a wide-band and high dynamic range (above 130 dB (The remote logger of seismic signals, 2013)) registration followed by a multitude of data processing techniques. These possibilities served as a basis for creation of new seismic methods that unite several different methods of inspection.

It is well-known that the integrity of a construction relies heavily on the ground soil properties. We developed an experimental complex utilizing seismometric tools for investigation of large structures. It is based on a comparison of experimentally obtained data with simulation results and allows us to understand the very nature of a defect. It is noteworthy that all measurements are performed with a single set of equipment.

A modern HPS monitoring systems should be capable of:

- dam state survey
- geological and geophysical monitoring of the dam area.

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The latter is required for the forecasting of possible seismic dangers and for the triggering of alert systems if any are coming (aftershocks, landslides, etc.).

Two examples of the experimental methods application are given. The first one is an observation of construction characteristic eigenfrequency oscillations, which are induced by ever-present background microseisms and by wind pulses. The second one is a seismic scanning of a dam body performed with hydropower machinery vibrations. Considering that some HPS are running non-stop the monitoring can be also performed persistently. The technogenic signals that are used in our technique propagate to a long distance so that a direct measurement can be performed several kilometers from HPS. Moreover, the use of the special equipment and signal processing allows the detection to be performed up to 120 km away from HPS (Kapustian, Yudakhin, 2007).

The survey of Gunib HPS (Dagestan, Russia) was performed with dam characteristic vibrations. The work was done in Dagestan on Sulak cascade of the HPS. Dagestan is known as one of the most seismic hazard region because of often earthquakes, landslides, rockfalls, floods, etc. The last devastating earthquake happened in 1970. Considering the population and industry density the possible disaster in Dagestan can bring the most destruction compared to any other region of Russia. The strong rains over the Kara-Koisu river in 2009 resulted in the rise of water level at the entrance of Gunib HPS. The body of the dam endured the increased pressure and prevented the massive disaster. However the flood did not pass without the consequences leaving several structural damages in the body of the dam and the connecting bridge supports.

The first to consider is the integrity of the dam structure. According to the Russian codes, one way is to compare the observed and calculated vibration properties. The important task of a survey is to build the simulation model that reflects the changes, which occurred in the dam construction during exploitation. The early models were simple and could reproduce only the major properties of a construction. Modern simulation programs are capable of detailed calculation of the model. This is essential for reconstruction works, when the model should be as close to the reality as possible. The model constructed for Gunib HPS is a good example.

Gunib HPS (Fig.1) is placed on Kara-Koisu river in a complicated topographic and geologic situation. The narrow canyon, the bedrock in canyon sides and large amount of silt in the river were all the premises to the arc concrete solution of the dam body. The length along the ridge is 58.74 m, height – 73.70 m and the width across the ridge is 4.5 m. The transport bridge is connected with the dam.

Figure 1. Gunib HPS, Dagestan, Russia

The following procedure was used to obtain real eigenfrequency oscillation parameters, which are the one of the most important values that describe construction dynamics. Velocimeters CM-3KB

(Russia) and accelerometers CMG-5T (UK, Guralp) were placed along profiles on the dam ridge and in gallery: 11 measurement points for each profile. The power spectra are plotted in Fig.2 accordingly to the measurement scheme and data processing algorithm. Additionally, the coherence function was calculated for spatial points because the eigenfrequency oscillations are represented by standing wave unlike the induced ones (Yudakhin, Kapustian, Antonovskaya, 2011).

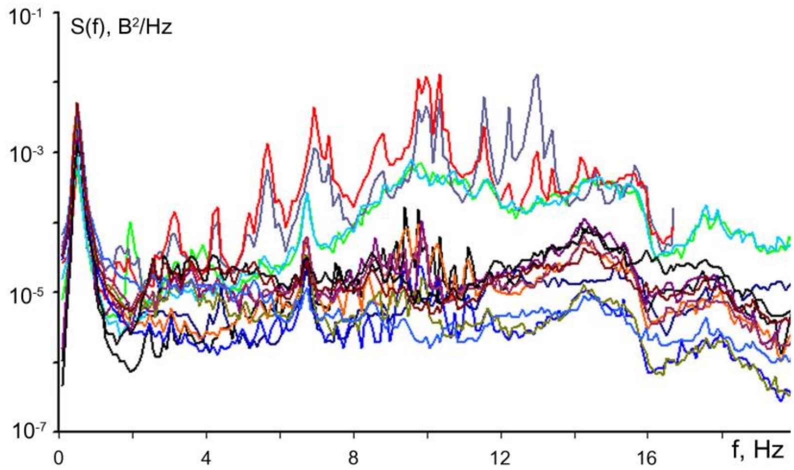

Figure 2. Power spectra of horizontal radial components (along the river flow) of vibrations recorded on dam body – on the ridge and in the gallery (curve colors correspond to registration points)

The combined analysis of power spectra and coherence reveals the following (Yudakhin et al., 2011):

- A maximum with the central frequency of 0.47 Hz in a low-frequency domain (Fig.2.) that dominates in power.

- A set of peaks (3.6, 4.3, 6.7, 9.9, 11.5 Hz) that correspond to eigenfrequency oscillations in a high-frequency domain.

- Peaks at other frequencies are drifting in frequency in the set of measurements points thus are not characteristic eigenfrequencies for the dam.

- Peaks at 6.25 and 12.5 Hz, which correspond to the main and doubled rotation frequencies of turbines, are absent because at that time machines were turned off due to low intake water level.

High frequency definition power spectra in 0.1-1 Hz range show the fine structure of low-frequency peak – it consists of 0.47 and 0.53 peaks. Additionally, the intensity ration of these two peaks varies across the dam. This is an evidence of a superposition of two forms of characteristic eigenfrequency oscillations. We consider the 0.47 Hz to be the main form since it dominates in power.

The variation amplitude-distance curves across measured profiles were plotted basing on absolute values and vibration phases. This corresponds to real forms of characteristic eigenfrequency oscillations. Results for the main form, which corresponds to radial shifts in a horizontal plane (along the river flow), are shown in Fig.3.

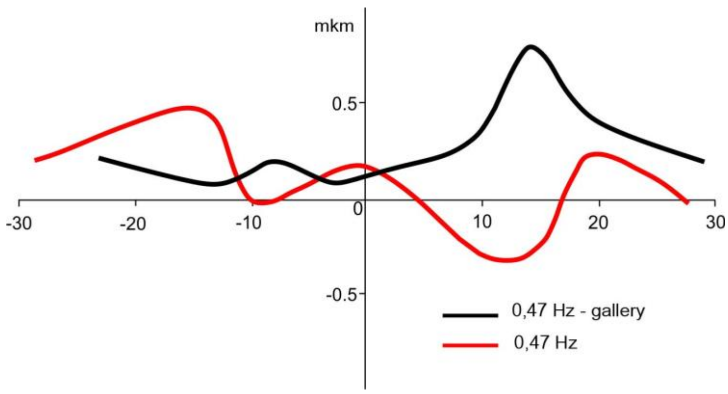

Figure 3. Experimentally determined horizontal radial oscillation shifts (in micrometers) of points on arc-shaped Gunib HPS (at ridge and gallery levels) at frequency of 0.47 Hz

Several **features** are to be considered when analyzing characteristic oscillations of the dam:

A. Curves are not symmetrical relative to an axis that lies through the center of the dam – in left and right parts.

B. Characteristic eigenfrequencies are distributed inhomogeneous on the frequency scale – there are close values for different forms.

C. Non-zero shifts are observed at an edge of the dam, which is impossible if the dam was rigidly fixed. For example, this behavior can be seen for the point at the gallery 30 m to the right from central axis despite this point is outside the dam body. This testifies of some sort of shore mass attached to the dam that participates in vibrations.

D. The comparison of forms of the ridge and gallery shifts exhibits both similarities (of forms at small segments) and significant discrepancies (Fig.3.) up to opposite phases in a point. The latter can be possible if the bend deformation in a vertical plane (parallel to the dam facade) takes place.

In order to interpret these peculiarities simulations were performed.

A model of Gunib HPS is composed of 3D elements with a rib size of approx. 1 m in accordance with the blueprints. Specific details were omitted (gallery, spillway, technical devices) to understand the basic patterns while thermal (deformational) joints were included as an essential element for the dam dynamics. The measurements were performed in winter and maximal opening of thermal joints is expected along with dynamical isolation of various chains of the dam structure especially in the upper part of it.

In this model deformational joints of parts of the dam are emulated by links with varied rigidness with length of ~0.15 m. Several modeling parameters were adjusted: anchoring to banks, deformation joint cross-sections, water load profiles, soil coefficient, external mass at rigid/flexible anchoring and other. Characteristic eigenfrequency oscillation forms were calculated for each model and compared with data in measurement points.

Calculation analyses reveal several things (Fig.4). The main factor responsible for changes of the dam eigenfrequency is the bank anchoring, while water level is of minor importance. The attachment of external mass leads to a) lower frequency: first from is reduced by 50% if ends are anchored, while partial anchoring reduces frequency by only 15%, b) all model variations adjustments the result and is being small for first oscillation forms and growing up to 100% for higher forms. This altogether proves that the method based on characteristic oscillations is very effective for the dam safety monitoring.

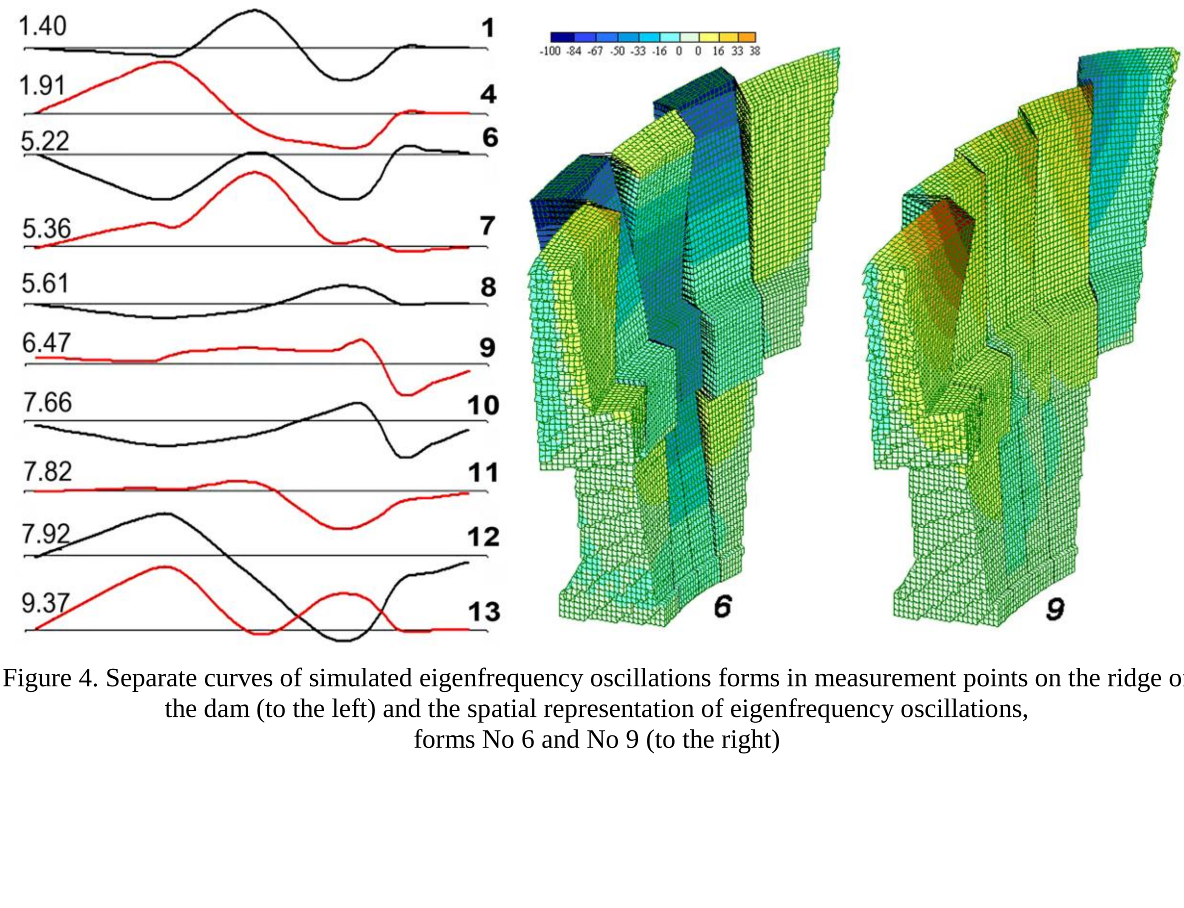

Figure 4. Separate curves of simulated eigenfrequency oscillations forms in measurement points on the ridge of the dam (to the left) and the spatial representation of eigenfrequency oscillations, forms No 6 and No 9 (to the right)

The analysis of resulting calculation oscillation forms gives the following:

- Form profile curves are mostly non-symmetrical relatively to the central axis of the dam; this coincides with experimental **feature A**. The cause is asymmetry of the model that includes asymmetric banks. Additionally, thermal joints significantly influence the oscillation forms and block movement – directions of shift can reverse when passing from one to another (Fig.4). This reflects in the asymmetry of the form curves and coincides with experimentally observed oscillations. The absence of symmetry in simulations is a significant proof of its correctness.
- A set of simulated eigenfrequencies is a group of narrow spaced values (Fig.4), thus correlating with experimental **feature B**.
- **The feature C** – non-zero shifts – is observed if the anchoring is flexible. However, significant shifts can be observed even if the anchoring is rigid. This is attributed to the rotation of sections (form No 9 in Fig.4).
- The shifts of the upper ridge and the gallery can be reverse to each other (form No 6 in Fig.4). This explains the experimental **feature D**. The possible explanation is a presence of a bending deformation in the vertical plane parallel to the dam façade.

Hence, all experimentally observed shift-form features receive an adequate explanation by the theoretical model thus proving the trustworthiness of the data acquired.

Notably, the described models of the dam form a basis for more complicated model. It requires not only the inclusion of constructional peculiarities but also the addition of geology data (acquired during the construction of the dam) and the results of detailed visual and seismometric investigation of the dam-to-banks junction points.

The next part concerns an application of mechanical vibrations that are generated by HPS to the investigation and monitoring of the dam. A program named “Vibrational sounding of the Earth” was found in 1980s and contained the basic principle we use – the principal possibility of registration of a very weak signal at a large distance to its source.

1. The sounding (scanning) of the dam body was performed on Chirjurt HPS (Dagestan, Russia). The hydropower turbines generate two frequencies, the one at 3.125 Hz is the main rotation and another is a doubling of it – 6.25 Hz. The scheme of seismic scanning is given in Fig.5.

Frequencies and amplitudes of vibrations generated by HPS machines vary considerably because the dam is ground-piled one. Amplitudes of technogenic signals presented in Fig.6 are measured with two horizontal seismometers (e – along the dam, n – normal to the dam) and the vertical one. The curves for different components at 6.25 Hz are similar, while at 3.125 the variation is considerable. The likeliness of the curves may mean that waves are of different nature for 6.25 Hz oscillations while at 3.125 all waves are of a single type. To check this a polarization analysis was carried out in an intermediate point 0.5 km from the machinery and in a point at the ridge – Fig.7.

Trajectory analysis of points shows that a transversal wave is emitted at 3.125 Hz and is enhanced by surface Rayleigh wave. A mix of P- and S- waves is emitted at 6.25 Hz. This is confirmed by amplitude profile in Fig.6.

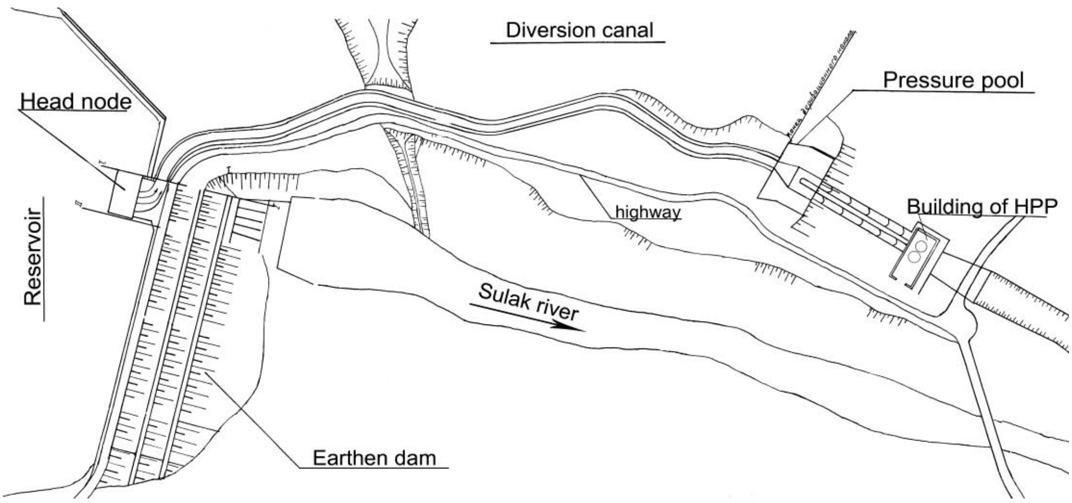

Figure 5. The scheme of seismic scanning of Chirjurt HPS (Dagestan, Russia) by vibrations of HPS turbines

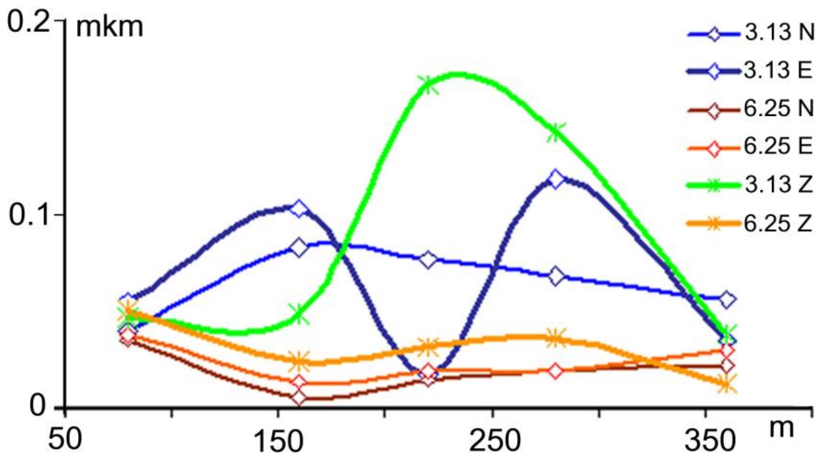

Figure 6. Distribution of technogenic signals amplitudes along the profile of Chirjurt HPS dam

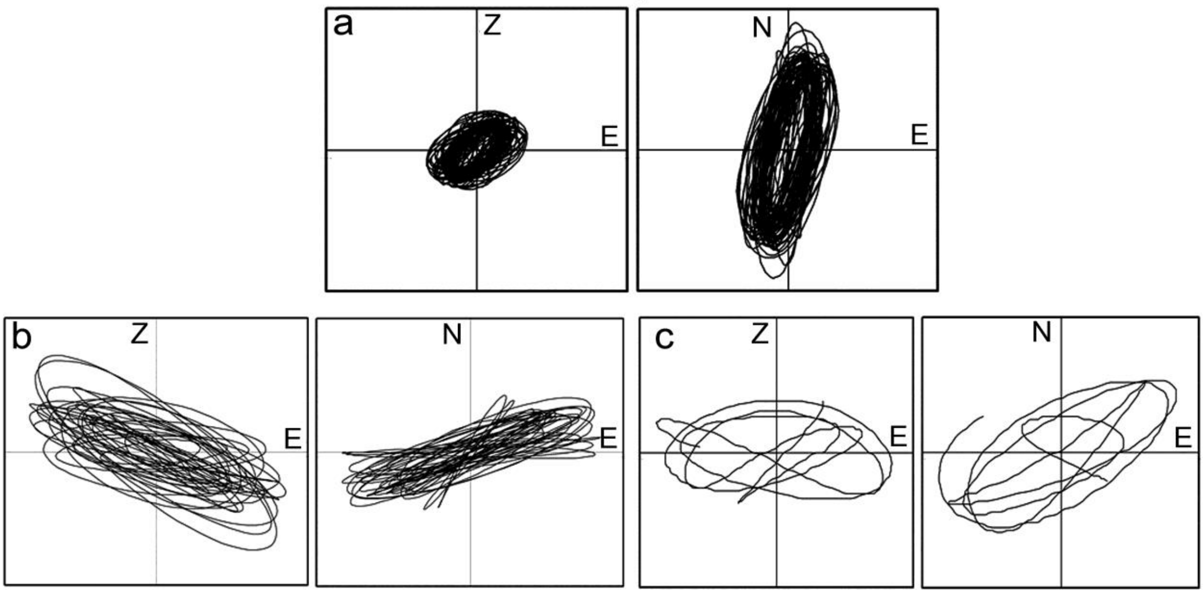

Figure 7. Trajectory for 6.25 Hz oscillations, distance 0.5 km (a) and trajectory for 3.125 Hz oscillations, distances 0.5 km (b) and 4 km (c) from HPS machinery plotted in vertical and perpendicular to the beam (to the left) and horizontal (to the right) planes

This result is important for seismic scanning because S-waves are sensitive to filtration, which leads to the S-wave decreasing. Rayleigh waves, however, receive larger amplitude when the velocity gets lowered. This leads us to conclusion that such technogenic signals are a good instrument for detection of fluids filtrating inside the dam body. Component “e” in Fig.6 is preferred by S-wave and exhibits a sudden drop at 220 m, which corresponds to the dam center. The component “z” is preferred by Rayleigh waves and at this point experiences a maximum. Thus in the given cross-section both increased water presence and small cavities caused by suffusion are present. This is possible if the filtration of water through the dam is increased.

This result undeniably needs a more thorough confirmation and a comparison with filtration monitoring data. However, the possibility presented is worth looking at as it can be the way of safety control system improvement considering the low cost and good technological capability of it. It is relevant for safety because of the several causes leading to dam destruction:

- A loss of static balance of the dam lower prism,
- Suffusion into the dam basement,
- Suffusion into the dam body.
- A breach of fluid through waterproof anti-filtration units in the dam,
- An earthquake above the threshold the dam was designed,

- Terrorist attack.

The first four types can take a great advantage of the presented method based on scanning with technogenic vibrations of HPS.

2. Another possibility to survey a dam is a combination of a scanning with technogenic vibrations and a study of its base soils by microseisms registration and surface waves analysis. An example is given by an investigation performed for the concrete gravitational dam Song Tranh-2 (Vietnam) – Fig.8. The base of the dam is granite-gneiss with cracks. The dam is designed to withstand earthquakes with M=5.5 (Ngô Thị Lư, Rogozhin, 2008).

The investigation was carried twice with one year interval – in November of 2012 and 2013. The vibrations generated by the HPS machinery 3 km from the dam are used as a probing sounding signal for scanning. A set of measurement points with a reference station at the ridge of the dam were covered successively. Soils of the basement were investigated by seismic Rayleigh waves probing (MMZ, a modification of method (Gorbatikov, 2006)) with the same set of equipment as was used for dam scanning.

Turbine vibrations manifest themselves distinctively in the microseisms power spectra as two peaks at 3.125 and 4.6 Hz (Fig.9). Signal at 3.125 Hz was chosen as a main frequency for the dam scanning. The peak amplitudes at all points vary with time. However, normalization to the reference point (A_i / A_0) eliminates the time dependence leaving spatial distribution of amplitude field.

Figure 8. The Song Tranh-2 HPS (Vietnam) view from the the lower afterbay and a cross-section of the dam

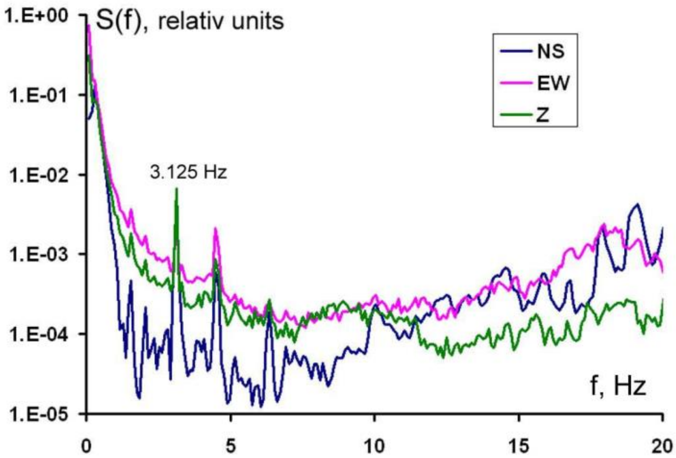

Figure 9. Typical microseism power spectra

Turbine vibrations vary slightly in frequency and the wavelength of the seismic signal correspondingly. It is important that the reference point and survey points are spaced with distances comparable with the wavelength so that the frequency and wavelength drift do not impact the amplitude ratio notably. This prevents the distortion of the relative amplitudes distribution and that is why the reference point was placed on the construction.

Fig.10 shows the spatial distributions of relative amplitudes at 3.125 Hz frequency. The wave types of the technogenic vibrations that were used for the scanning were not studied thoroughly and it is hard to relate the displacement velocities values in the dam body with deformations. Nevertheless, a homogeneous spatial picture corresponds to a homogeneously durable material and anomalies correspond to zones with material properties altered. A bright anomaly in the left part of the dam (Fig.10a, 2012) was proved to coincide with a visually found (Fig.11a) wet area with lowered durability. Some few zones seem to appear in the central part of the dam (blue spots in Fig.10a). Results of the study in 2013 (Fig.10b) confirm previous findings with a bright anomaly in left part – an inspection of the dam reveals the corresponding zone with lower durability. Additionally, the whole body of the dam exhibits a general loss in durability. The filtration level has raised resulting in visible water currents (Fig.11b).

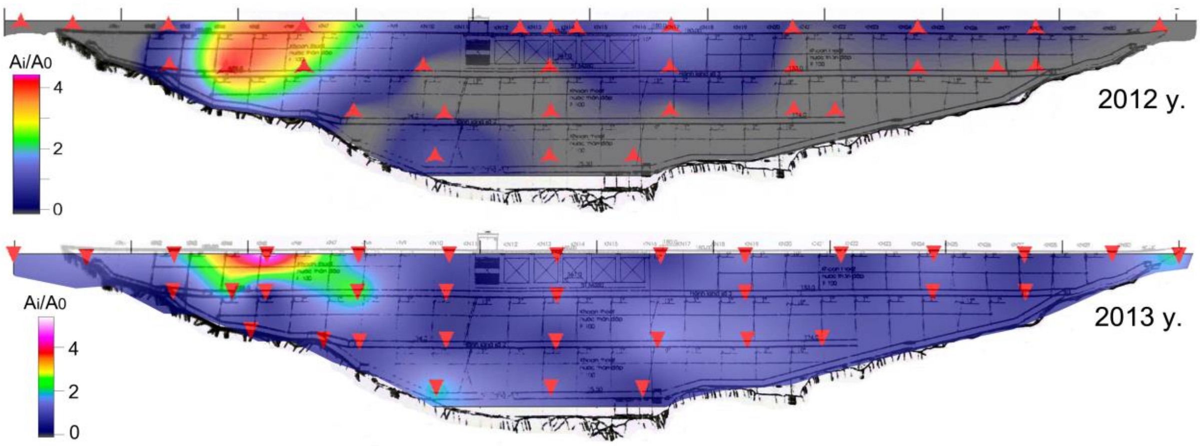

Figure 10. The results of dam body sounding with the vibration generated by HPS machinery. Yellow-red area marks an anomaly zone related to the lowered durability zone

Figure 11. Photos of visual inspection inside the dam (3rd floor, N-E direction) in 2012 (a) and 2013 (b)

The calculation of seismic impacts performed during the design of the dam gives following results (Fig.12):

- All parts of the dam are moving especially the upper part (1/3 of the height). This means that the most amount of damage is expected to happen there.

- Not only the body participates in vibrations but the ground soil too. This fact implies that the grounds are to be investigated thoroughly and are changed since the dam construction.

Microseismic investigation (MMZ) of the upper layer of the crust (Fig.13a) reveal contrast nearvertical inhomogeneities. The nature of these is related to the regional fractured tectonics and to the fissured mountain rock, which was noted at the engineering study before construction stage (Fig.13b).

Heavily fissured area is in south-eastern shore - right side of the dam. The position of inhomogeneities and the direction of cracks indicate the presence of systematic behavior of fractures in this region. This may be a result of the block geodynamic activity. All these data indicate that a monitoring system should be installed on Song Tranh-2 dam.

Thus, the highly fractured zone in founding grounds in the right part of the dam leads to variation of stress-strained state of the dam. Fig.14 shows schematically the possible development for deformations, which are similar to a well-known example of a beam deformation. The base of the right shore is susceptible to immersion and causes coulisses-like systems of cracks in the dam on the other side.

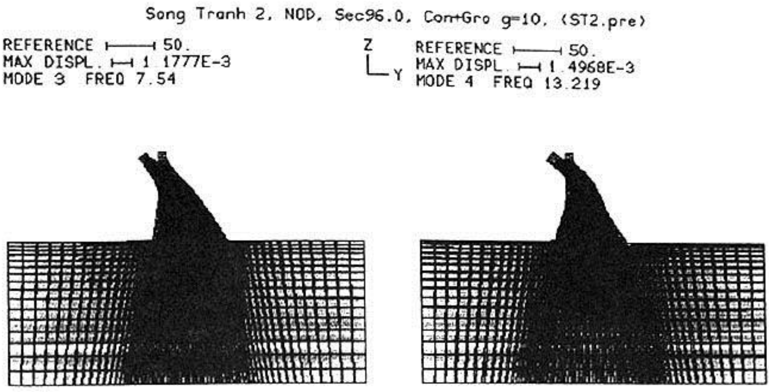

Figure 12. Simulation models for Song Tramh-2 dam oscillations at characteristic frequencies, earthquake impact

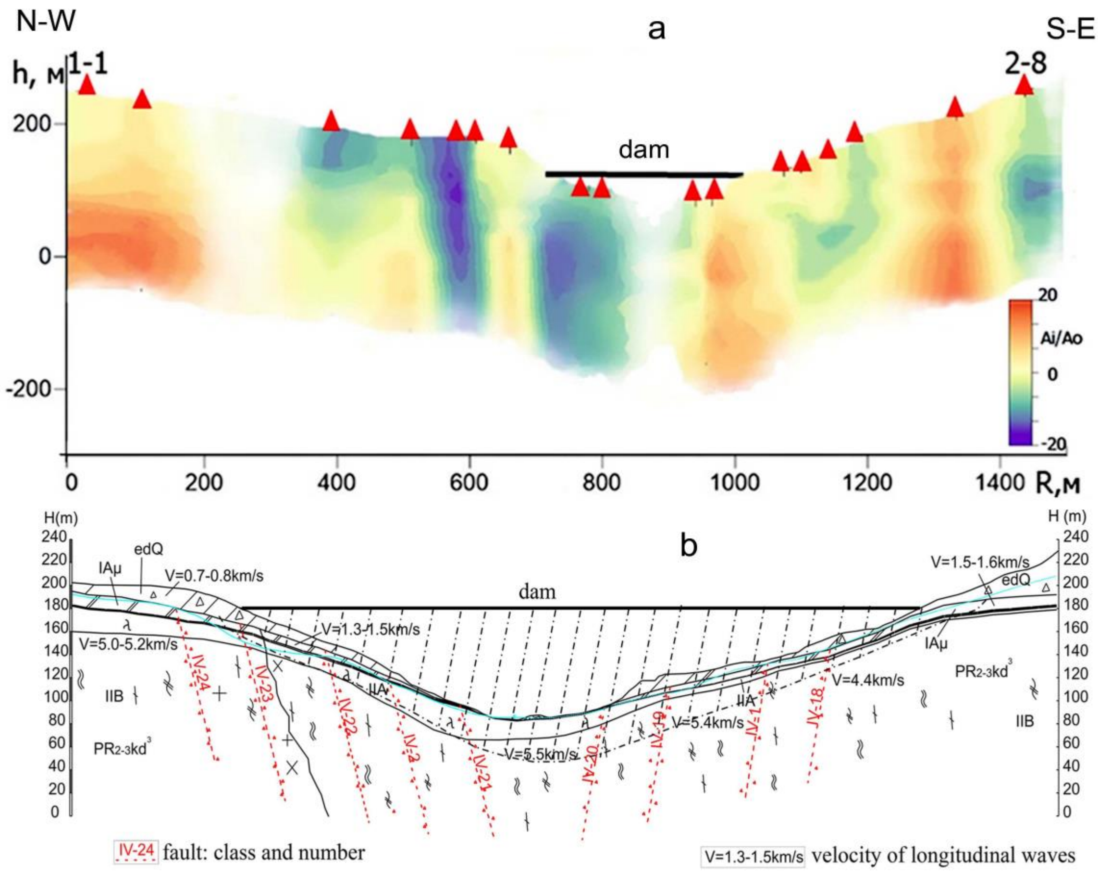

Figure 13. The results of geologic studies: a – MMZ cross-section along the profile that shows the velocity differentiation in upper crust. Large values of Ai/A0 correspond to low velocities, i.e. to weaker soil; b – results of geologic studies of the Song Tranh-2 dam soil

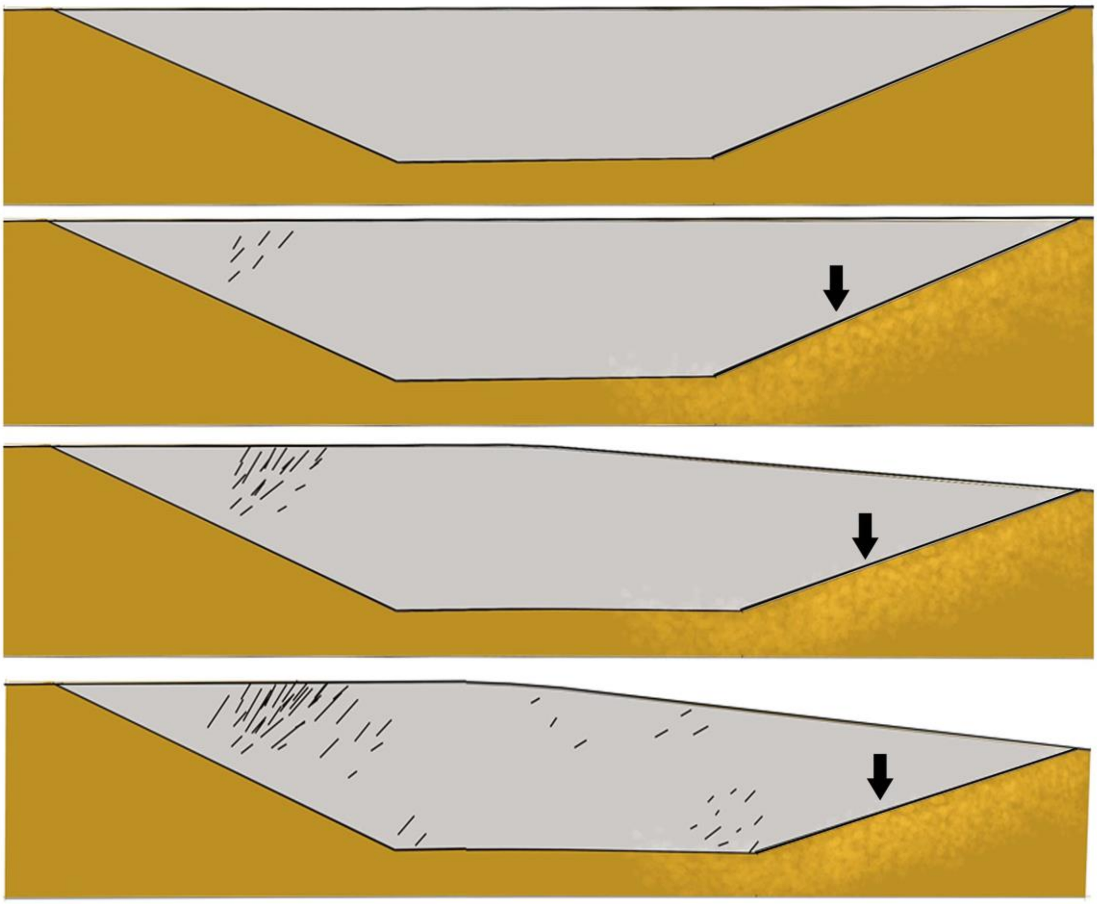

Figure 14. Principal scheme of weakened zones formation in the Song Tranh-2 dam

CONCLUSIONS

A modern system of seismometric monitoring of HPS dams should include various types of seismic surveys capable of the following:

- Detection of anomalies in a dam body by monitoring of the spatial distribution of vibration fields induced by external technogenic sources and of the characteristic oscillations. A comparison of anomalies in dam body with inhomogeneities in soils and construction model can help to detect the reason of construction defects appearance.
- Preventing emergency situations of natural and technogenic nature in early stages of their development.

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