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AN INVESTIGATION OF AN EXTERNAL IMPACT CONVERSION INTO THE STRAINED ROTATION INSIDE ANCIENT BOULDER STRUCTURES (SOLOVKY ISLANDS, WHITE SEA)

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Abstract. The experimental seismic study of ancient structures are discussed to find out constructive solutions forming and reasons of their high long-term stability against external impacts, including local non-catastrophic earthquakes. The theoretical background is based on the fact that any block media is capable to convert external deformational influence into the seismic radiation. One of the conversion processes is a strained rotation of blocks. The resulting seismic field contains eigen oscillations of the blocks and high-frequency signal generated at the blocks contacts. The experimental observations were performed with standard linear seismic sensors and direct rotational readout sensors. The experimentally observed response is compared with numerical models of the structure dynamics.

1 INTRODUCTION

The objective of the current investigation is to figure out the origin of the long-term high stability of some ancient buildings towards external impacts including local non-catastrophic earthquakes. This is done by studying the mechanic implemented in the structure of these buildings.

One of the methods found relies on construction formed by series of large monolith blocks with a characteristic dimension from 1/100 to 1/10 of the whole building. Glacial granite or basalt boulders are a construction material commonly used in Northern Europe. And the houses build with it proved to be the most durable towards both natural and anthropogenic influence including seismic. Despite the hard basic constructional material a large portion of the wall space belongs to gaps filled with mortar or brick masonry. This less rigid media allows the construction to adjust itself optimally to the load applied. One of the adjusting mechanisms is a strained rotation. Substantially, it is dominant at the external load processing by Earth crust blocks at platform areas [1] so that it can possibly contribute to the geodynamical stability of the platforms.

We performed seismic experiments on natural objects to probe a boulder masonwork impact processing mechanism. Several masonry types were studied with varying boulder size, mortar type and external load properties. Basic impact types were studied including gradual slow, series of pulses and a prolonged vibration of a combined nature, being a wind pulses with microseisms. The objects examined all belong to Solovetsky monastery. They are: a sea and a lake boulder dams and the famous fortification – White Tower. The striking feature of objects location especially dams is an absence of constant anthropogenic vibrations, which is rarely found on the planet nowadays. Additionally, the dam locations are uninhabited thus greatly simplifying the detection of the media response to an external impact.

2 EXPERIMENT DESCRIPTION

2.1 Methodology

A theory behind observations is based on the fact that any blocked media is capable to convert external deformational influence into the seismic radiation. One of the conversion processes is a strained rotation of blocks. The resulting seismic field contains eigenmodes of blocks and a high-frequency signal radiated by joints between blocks. Theoretically this mechanism decreases the strength of construction but preserves its integrity against external impacts. The purpose of the field experiment was to establish observation schemes and data processing techniques capable of the characteristic seismic signal identification and confirming this type of structural behavior.

The observations were performed with standard linear seismic sensors (seismological accelerometers CMG5T velocimeters CMG3TD by Guralp and Russian SM-3) and direct readout rotational sensors. The direct registration of the rotational modes was carried out with the help of special sensor installed side by side to the linear sensors, which measures angular velocities (or angular accelerations) in XY, XZ and YZ planes. The model of the sensor is METR-03 by R-sensors Co [2].

2.2 Solovky dams description

The big sea dam in Fig. 1 is built in XIX century and dams the channel between the two islands in White sea. It is 1.1 km long 10 m width and its height is 6 to 7 m while 2 m of these are always underwater. The boulders forming the dam are averagely 1 m in diameter and are bind with sand-clay mortar. The dam has zigzag shape because of the several factors. Firstly, the basement of the dam is partially a morainal ridge since a plenty of such ridges is found at islands shores, which are clearly seen from satellite picture in Fig. 1. These ridges are responsible for the curvatures at the dam ends. Secondarily, curvatures at the central part are considered to be the most appropriate for the water flow of sea currents in the channel. This suggestion has to be proved by calculations though the shape of the central part is a shape of the second oscillation mode of a slab fixed at sides. Passages for small ships are found at the central part. Besides the natural loads including thermal and tidal cycles, gales and erosion processes dams were barbarian treated in 30-s of XX century.

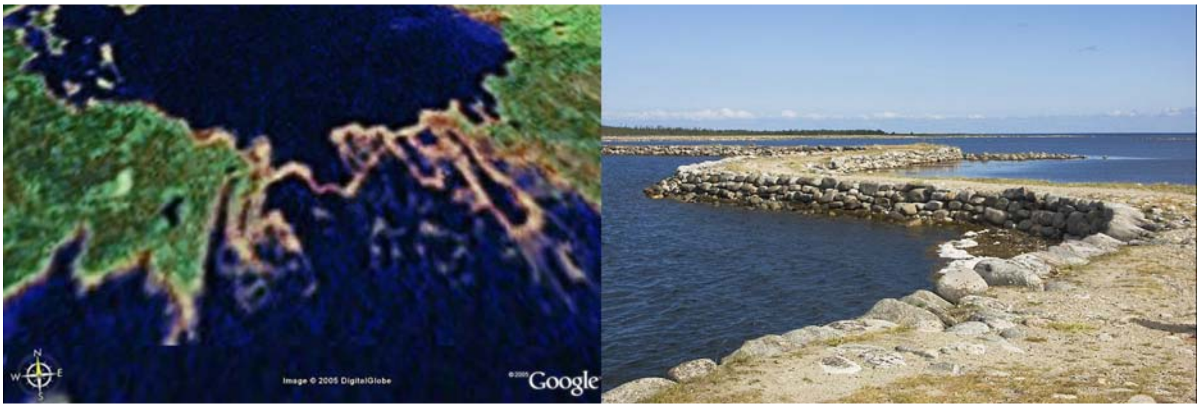

Figure 1. A satellite view (to the left) and a photo (to the right) of the big sea dam at Solovky Islands

The small (lake) dam is placed in an interconnected system of internal lakes of the Bolshoy Solovetsky Island. The dam serves as a backing wall (a shore part substantially) for a remote lake thus enclosing the system. The dam is 225 m length the width and height are both of 4 m. The same composition based on morainal boulders 1 m size is bonded with sand-clay mortar. We performed seismic prospecting profile along the dam. The results of data processing reveal two boundaries, first one is related to dam-bottom boundary and the second (13 m depth) is ascribed to a bedrock.

2.3 Observation of the blocked media response to external impacts: pulses

To understand the possible mechanism responsible for the external load processing two “clean” experiments were carried out during two field seasons in 2008-2009 with the same shot points. Several stations with three-component accelerometers CMG-5T Guralp were placed in several points at the dam ridge (2008, 2009) and few additionally aside in 2009. The pulses were generated to probe the structure with a 20-80 Hz frequency impact with 100 and 10 pulses series in 2008 and 100 pulses in 2009. The record was maintained after the pulses till the batteries got empty.

Frequency-time plots are presented in Fig. 2 along components: Z, transversely ($\perp$) and parallel (II) to the dam at points 1, 2 and 3 (2008). The pulse series is clearly observed at 500 s. The higher microseisms level of 30-40 Hz is present in the parallel component in respect to the transversal one. Notably this raised level is seen before and after pulses. This could be a result of the dam being fixed at edges in a shore. During 2008 and 2009 aftershot measurements the curves elevated at higher frequencies (>30 Hz). This change varies across horizontal components – the high-frequency radiation transversely is lower than the radiation along the dam. This effect reproduces in 2008 and in 2009. Additionally a maximum at low frequencies is detected in all components. Its position shifts with years is 2.5 Hz in 2008 and

3 Hz in 2009. In frequency-time plots in Fig. 2b this maximum is seen as a stable narrow line with stable frequency.

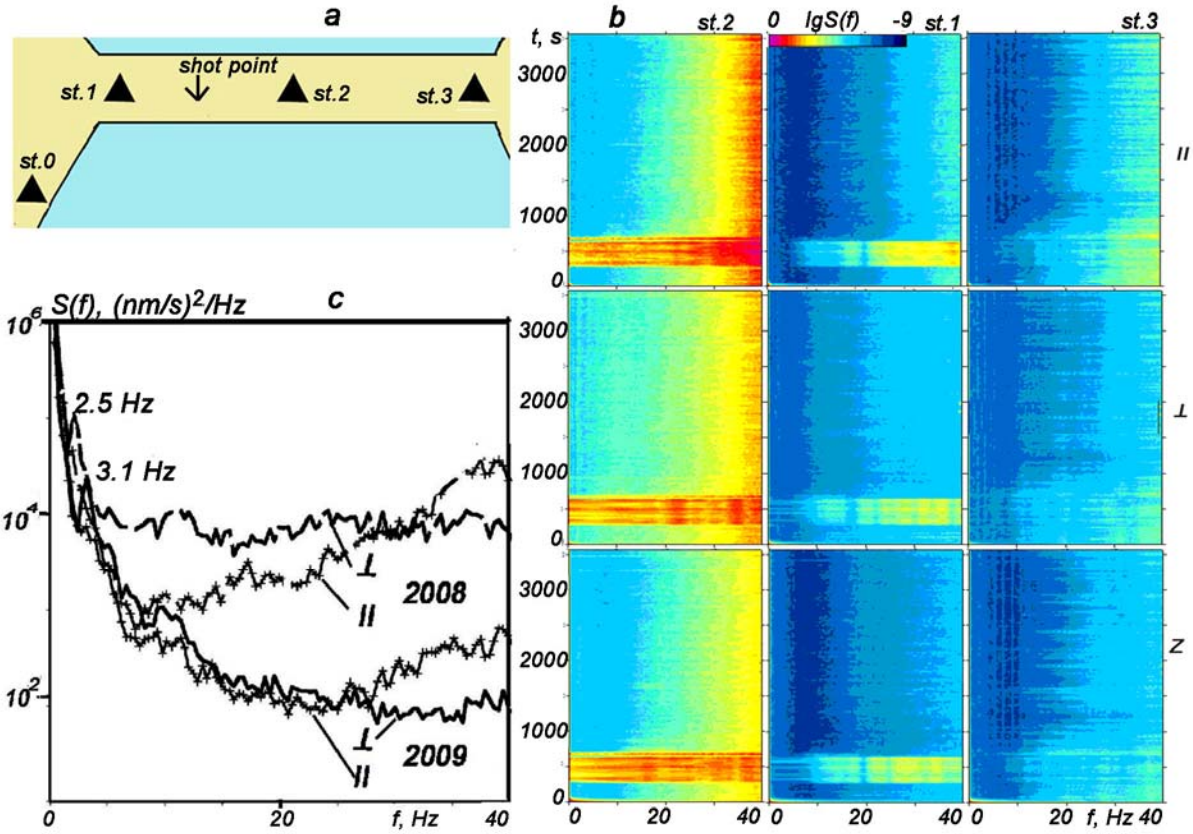

Figure 2. The shot impact experiment at the lake dam: ***a*** – the measurement scheme, ***b*** – microseism frequency-time plots for observations: Z, perpendicular (⊥) and parallel (II) to the dam directions, ***c*** - microseism power spectra observed in 2008 and 2009.

The observation of such a signal in an uninhabited region is very strange especially it being present at the dam with no sign of it outside. These all factors are the witness this peak to be an eigenfrequency of the dam. Given dam's geometry, ground bonding at bottom and along its sides, construction material (torn rubble stone) and the mortar type (the weakest one) the finite element model was constructed to estimate eigenfrequency of a slab similar to the dam. The low-frequency amplitude values are schematically shown in Fig. 3 for observation points along the dam. The first form oscillations fit the experimental data by the frequency and amplitude ration for points. The shift from 2.5 to 3 Hz in 2008-2009 is explained simply by a rainy summer in 2008 and thus a mortar being more elastic compared to the dry summer of 2009. The rigid mortar corresponds to a rigid construction with higher eigenfrequency.

The amplitude ratio of low (2-3 Hz) to high (~36 Hz) frequency signals varies considerably from parallel to transverse the dam (Fig. 2c). Low-frequency signals dominate at the transverse component and high-frequency – along it. These two directions will be mentioned further as "basic" for the respective signal frequencies – Fig. 3a. First oscillation mode is well seen on the low-frequency amplitudes envelope. The maximal high-frequency radiation is directed perpendicularly. Additionally the maxima for the both vibration types is detected at the center of the dam.

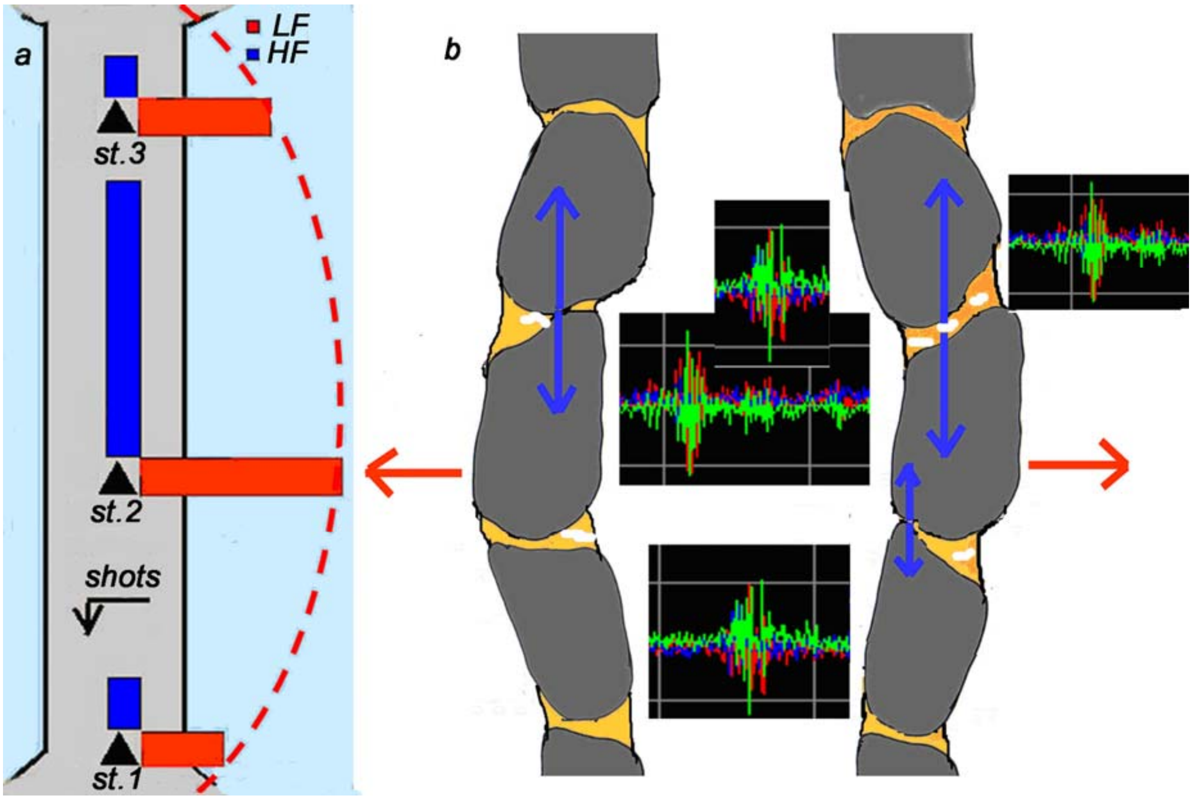

Figure 3. The transformation of low-frequency eigenmode oscillations into high-frequency microseisms: ***a*** – an experimental scheme with sensors positions and amplitudes of dominant oscillations, ***b*** – the scheme of the transformation mechanism based on boulder steering at dam eigenmode oscillations (*red arrows*) and on micropulse formation at the boundaries of the boulders, *insets* – typical micro pulses waveforms along all 3 seismic components.

In order to understand these peculiarities let us consider the following model describing the processes taking place in the dam's centre (Fig. 3b). Some of the boulders move when the first mode oscillations take place. This deviation is larger for central ones than for the boulders at edges. The resulting "hooking" between the sides of boulders during the strained rotation leads to the microscopic defects formation in bonding material, e.g. micro cracks. The series of high-frequency pulse is witness of this mechanism created by the intense low-frequency oscillations. An example is shown in Fig. 3b. It is known that shearing deformation result in the seismic radiation propagating transversely to the deformation direction [3], which is indeed in the case.

The following mechanism occupies some time required to process an external influence. Fig. 4 shows the amplitude-time plots of both high- and low-frequency signals at the components on both (⊥ and II) horizontal directions at point 2 in the center of the dam. The local minima ("calm") appears in all curves few minutes after the shot. Then it is followed by a rise of the amplitudes reaching the level higher than before shocks. The duration of such specific "excitations" reaches 1.5 to 2 hours.

The series of intervals with magnitude surges are present with an important one at 40 min after shocks – Fig. 4. The time shift between magnitude curves of low- ($\boldsymbol{A_{LF}}$) and high-frequency ($\boldsymbol{A_{HF}}$) oscillations is the important fact. The rise of $\boldsymbol{A_{HF}}$ takes place at high $\boldsymbol{A_{LF}}$ values and the decrease of $\boldsymbol{A_{LF}}$ at high values of $\boldsymbol{A_{HF}}$ correspondingly. These peculiarities can be explained by a non-controversial model. It relies on construction eigenfrequency oscillations, which are caused by microseisms or wind pulses, being present at all times. The batch of shot impacts including some matching boulder's eigenfrequency (40 Hz according to [1]) assisted severely the reorganization of the bonds between blocks. This resulted in a “calm” and in followed dam rocking resulting from the new bond structure. The strongest force affects boulders and mortar at high amplitude oscillations, especially in the centre of the dam. This is the case when the considered transformation mechanism of low-frequency oscillations into high-frequency radiation can take place. Thus presence of high-frequency component points at the crack formation. The bond between boulders weakens due to defects in mortar resulting in the dam oscillation damping.

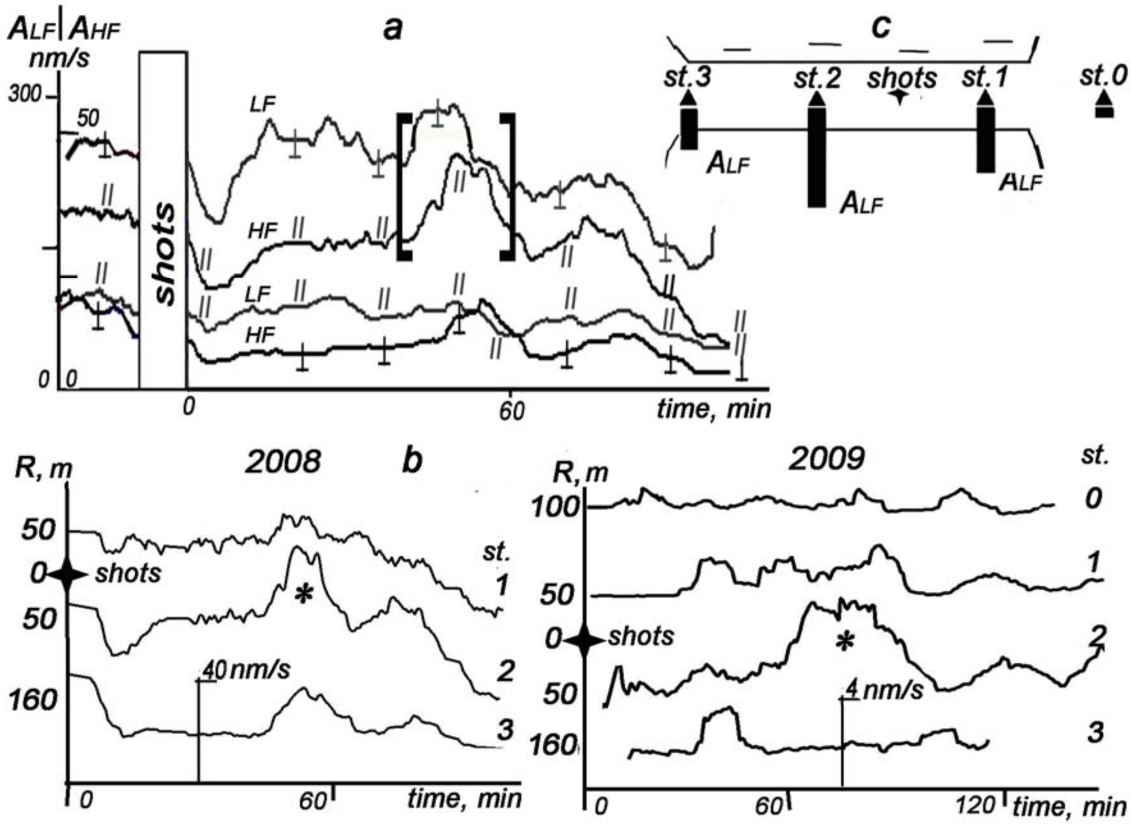

Figure 4. The lake dam experiment: ***a*** – time behavior of high- and low- frequency amplitudes along axis parallel (II) and perpendicular (⊥) to the dam at point 2 in 2008, ***b*** – time behavior of high-frequency amplitudes after shots at various points in 2008 and 2009 (curves sorted by the distance from shot point and asterisks mark anomalous surges), ***c*** – an experimental scheme with amplitudes of the dam eigenmode oscillations.

A surprisingly time and spatial signal reproducibility is seen from the analysis of data obtained at all points during several years of study. The main trends are: high- and low-frequency resonance oscillations and their amplitude ratio, seismic radiation anisotropy (across and along the dam) and finally the maximum shot response at the center of the dam. Another important feature is the reproduction of time evolution peculiarities shown at Fig. 4: the radiation “calm” (low-frequency especially) followed with an anomalous surge long time (40 min in 2008 and 70 min in 2009) after the shot. The possible situation following these is a sort of an oscillation “reorganization” resulting in time evolution at different points being similar.

An analogous experiment with a shot impact carried out on a larger sea dam doesn’t contradict qualitatively the former one. An abrupt surge of the amplitude-time evolution is detected at the center of both dams. This effect relates to an increase of the local strained deformed state at the observation points. The eigenfrequency oscillations are the cause at the small dam appearing as a 2 Hz peak in power spectrum. The cause for the sea dam is a strain concentrator, which is an ark in the dam body build to allow a passage for small ships.

Let us estimate the seismic conversion efficiency of an impact into response. Given $\sigma \sim$, v - being an amplitude of displacement velocity and considering that response and impact have similar frequencies and an amount of phases, we get $\boldsymbol{v}_{response} / \boldsymbol{v}_{impact} \approx 4*10^{-8}$ m/s / $4*10^{-6}$ m/s=0,01 with an efficiency of 1%. This very value of 1-2% was obtained in an additional experiment with a sea dam, which is described further. Since only up to 10% of an impact enters the solid the total efficiency is of an order of 0.1%. These values were obtained in our experiment with an "intermediate chain", which is a resonance dam excitation at low frequencies i.e. with a nonlinear impact transformation.

2.4 Blocked media response to an external impact: smooth loads

Several types of smooth loads affecting constructions are present: tectonic deformational waves, air pressure changes and short thermal cycles. Usually the properties of time evolution of slow processes are unknown thus complicating the task of the response evaluation. We consider the load processing is carried out by blocks vibrations resulting in a flow of micro-pulses as in the previously described experiment. Basing on this assumption an observation aim is to detect change in statistics of such a flow and to compare of the change to the impact that causes it. A Guttenberg-Richter law suits this task. This law can be applied not only to earthquakes but also to pulses of microevents [4].

According to the observation technique 3 seismic components (X, Y, Z) are recorded in a wide frequency band (0.5-30 Hz). Important is that events are very weak and are masked by the noise. The flow of superweak events emitted by the media allows one to obtain an amount of pulses sufficient for statistical analysis (thousands) in a short time range (3 hours in observation point). The data analysis procedure is a main feature of the method as well as the construction of Guttenberg-Richter law plot, which characterizes seismicity in 1-3 km vicinity around the observation point. Analysis are based on calculation of the coherence function for different components of a seismic signal in an observation point $\boldsymbol{\kappa}_{ij}(\boldsymbol{f})$:

$$\kappa_{ij}(f) = \frac{|S_{ij}(f)|}{\sqrt{S_{ii}(f)\cdot S_{jj}(f)}},$$

where i, j are pairs of (Z, X, Y) components, f - frequency , $S_{ii}(f)$ and $S_{jj}(f)$ - power spectra for the i and j component respectively and $|S_{ij}(f)|$ is a averaged mutual spectrum for the i, j components couple. The coherence function is virtually a correlation coefficient for each frequency component of a signal.

It is easy to show that $\kappa_{ij}(f)$ is equal to 0 if the seismic noise is collected from the entire media volume. In the frequency band of a signal source coherence function is $0 < \kappa_{ij}(f) \le 1$ if the preferential direction is present to the source within media or on its surface. Thus, a coherence function calculation allows picking out signals emitted from the compact volume. In addition, it permits not only suppressing of signals from large volume sources (e.g. surface microseisms) but also of signals generated by the moving transport. Comparison of $\kappa_{ij}(f)$ for component pairs in a horizontal plane with $\kappa_{ij}(f)$ estimation in vertical planes allows elimination of signal sources on the surface.

It's possible to calculate the set of $\kappa_{ij}(f)$ estimated for consecutive time intervals and to obtain the distribution (histograms) of $\kappa_{ij}(f)$. Let us consider that a microseism level is identical in different points of an observation area or that levels are easily compared. Then for very weak events (signal-to-noise ratio $\boldsymbol{S / N} \ll 1$) it is possible to use this distribution of $\boldsymbol{\kappa_{ij}(f)}$ as a Guttenberg-Richter plot in the vicinity of an observation point.

For the sea dam the main influence is the water level raising and lowering due to the sea tide, and a load estimation gives 0.1 bars (12 h tide period). Seismic measurements were put on hold during the phase of the tide when the water level had achieved its maximum and started to decrease. Hence, the load was alternating during the registration. Typical power spectra and a part of measured microseismic signal are shown in Fig. 5. Several micro-events, which are clearly distinguishable on the Z and Y components, are marked. The main frequency of these events is equal 40 Hz approximately. This fact is reflected in a local maxima present on the spectra for all components. Suffice to say, according to [1] this frequency is an eigenfrequency for vibrations of blocks with the characteristic dimension of 1 m. The seismic signal in a frequency band of 45-55 Hz is the most intense for the X ($\perp$) component of microseisms. Thus, this radiation can be produced by processes caused by the water level change taking into account that the tide influence direction and X component coincides. There are maxima present at higher frequencies on Z and Y components and partly on X component (>60 Hz). Presence of such maxima can be attributed to a boulder “stirring” caused by the tide.

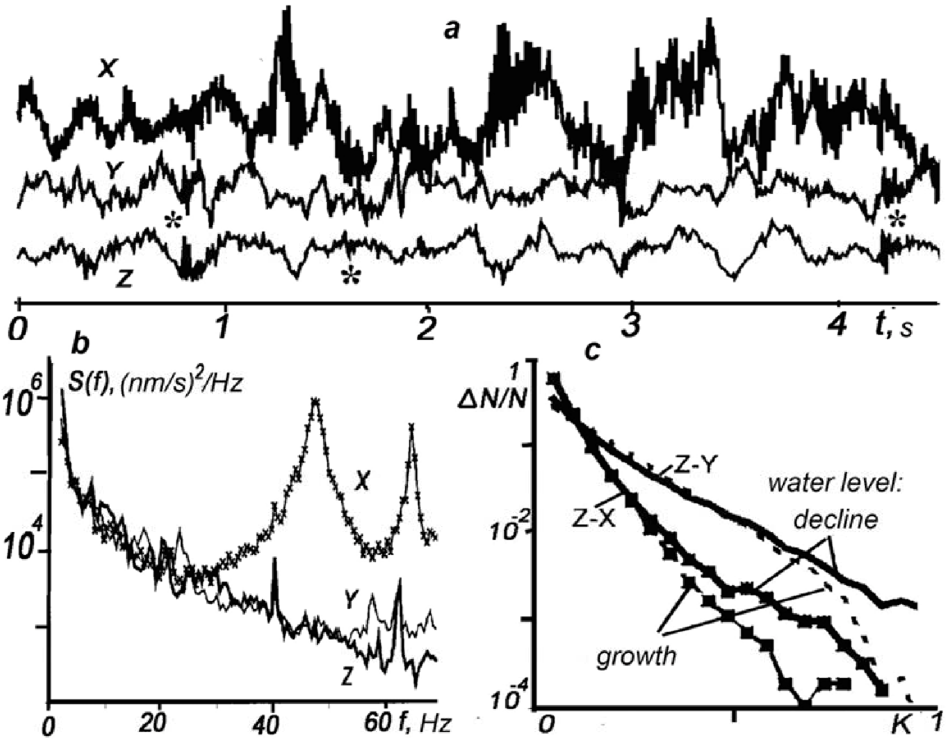

Figure5. The microseismic field at the sea dam: ***a*** – an example of a three-component signal recording with micropulses (*), ***b*** – the typical power spectra for Z, X and Y components, ***c*** – coherence diagrams (histograms) corresponding to the phases of sea tide.

We calculated coherence functions for different pairs of components in the time interval sliding along the record. Using these values, we plot in Fig. 5c histograms with separation between intervals of the water level rising and lowering. Curves are close to straight lines which additionally confirms their analogy with Guttenberg-Richter plots. The comparison of the curves reveals that the sequence of curve slopes follows changes of the water level mostly in the dam cross-section plane. A comparison for different cross-sections (Z-X, Z-Y) reveals the difference, which implies that the methodic is sensitive not only to a value influence but also to its direction. These all supports the strained rotation assumed as the major mechanism of external load processing by the media.

Basing on a concept of processes occurring during straitened rotation of blocks one can estimate the value of the tension decrease during a seismic radiation [1]: $\Delta\sigma = \boldsymbol{v}_0 \boldsymbol{NG} / \boldsymbol{L}\pi \boldsymbol{f}$, v_0 is the maximum amplitude of pulses, $\boldsymbol{N}$ =5 - number of phases in a pulse, L – the typical block dimension. Given $\boldsymbol{v}_0 \approx 100$ nm/s, $\boldsymbol{G}$ =$2\cdot10^{10}$ Pa (granite), $\boldsymbol{L}$ =1 m and f =40 Hz we obtain $\Delta\sigma \approx 100$ Pa=10^{-3} bars. Considering the influence load (≈0.1 bars) it's possible to estimate that 1% from the active load is lost in a form of high-frequency microseism signals.

2.5 Block media response to external impact: long-term impact

All the constructions studied earlier were composed of rigid blocks with weak bonds between them – granite boulders with a clay-sand mortar. Let us consider the building with strong bonds. It is a tower of Solovetsky monastery (XVI century). It has a round shape and is built from boulders with a brick-calcic filling – Fig.6. The characteristic oscillations caused by microseisms and wind pulses were studied. Both linear and rotation sensors were used with placement positions at gun slots of the 4^{th} floor and at the ground. In a horizontal plane the observation components were aligned along the radius and the tangent.

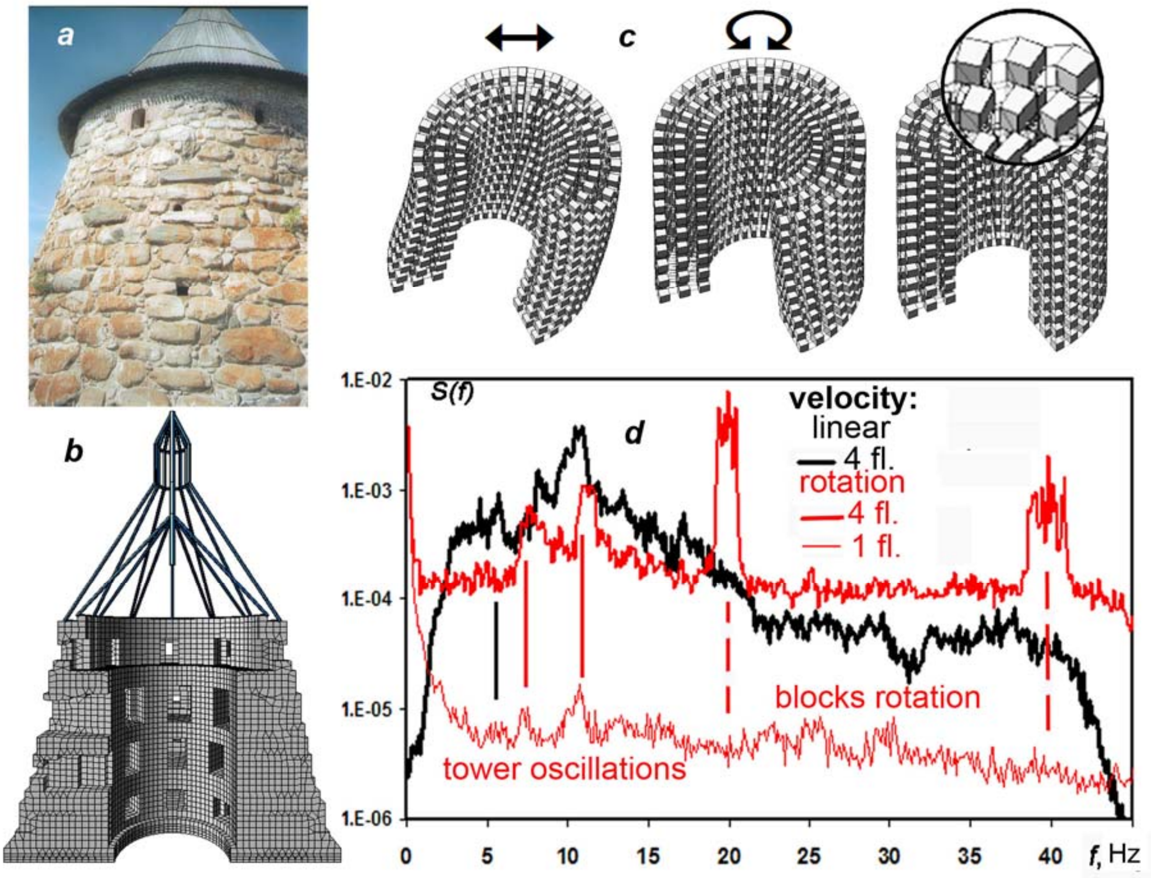

Figure 6. The seismometric study of Solovky tower operation: ***a*** - photo, ***b*** – a constructional scheme used in modeling, ***c*** – blocks movement during eigenmode oscillations, ***d*** – power spectra of linear and rotational sensors records at various points

The comparison of power spectra at different points and for different types of seismometers is shown in Fig. 6. Peaks are present, which correspond to the eigenfrequency oscillations of the building. A model was made (Fig. 6b) allowing a calculation of construction dynamics. The resulting data were the trajectories of various oscillation modes motion. The exampoles of these trajectories are shown in Fig. 6c. Thus, basing on the comparison between the calculation and experiment the spectra peaks were identified – Fig. 6d. The rotation of the whole tower appears in a rotation signal jointly with the rotation of the various parts of the tower. The 20 Hz peak on the spectra for a rotation around Z axis relates to the roof motion while the 40 Hz peak is attributed to the boulder rotation. Substantially, the peaks at these very frequencies are detected at the dams, which are composed of the similar boulders.

3 RESULTS

1. For all the tested structures the response typical for strained rotation was observed. For the sea dam the variation of the micro pulses flow was correlated with a growth/decline of the water level on the dam walls. The more complex mechanism was found for the lake dam. The artificial strikes produced eigenmode oscillations of the dam structure, which are associated with strained rotations of the blocks. If the amplitude of the eigenmode oscillations exceeds some threshold the high-frequency seismic radiation is produced. For the tower the strained rotations are also associated with the eigenmode oscillations.

2. The intensity of the signal, frequency and time behavior of the seismic radiation depends on the type of excitation, design of the structure and properties of the constructive materials. Some features of the response can be predicted *a priori* using numerical models.

3. All external impacts during the experimental study are very weak (the pressure variance ~ 100 Pa), but can be easily detected by seismometers including the rotational ones.

4 CONCLUSIONS

1. The theoretical concepts of the external impacts conversion by the block media by strained rotations mechanisms has been proven experimentally.

2. The long-term history of the ancient structures confirms the possibility to design the similar ones with very long time stability against non-catastrophic impacts.

3. A new method for the long-term processes (for example, tectonic) study using stationary seismic observations (including rotational measurements on the constructions of the blocks) can be developed.

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