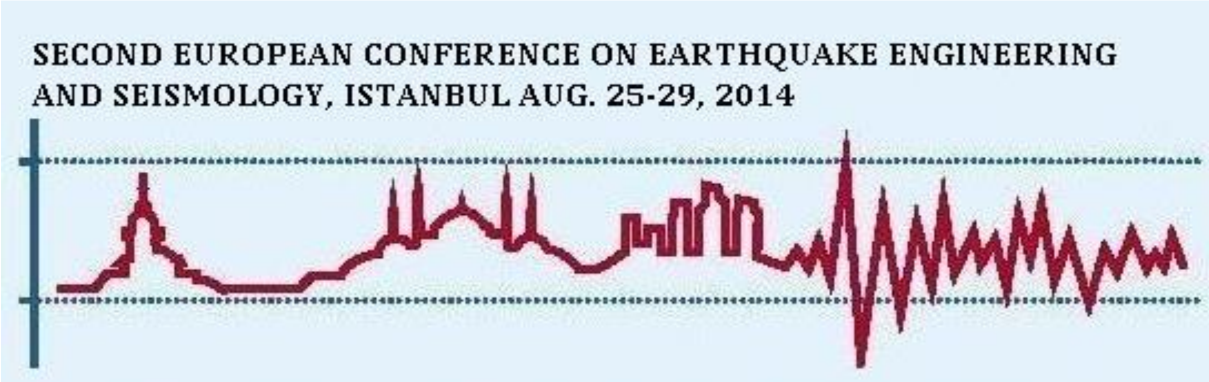

NEW SEISMIC METHODS FOR THE HISTORICAL CONSTRUCTIONS DIAGNOSTICS

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ABSTRACT

At the article on an example of inspection of an architectural monuments possibility of use of seismometric supervision for restoration problems is shown. The method of measurements is simple and economic. The conclusion about a condition of building object is given by comparison of values of own frequencies and forms of fluctuations on natural measurements and calculations. This allows you to build a real computational model of the object and estimate the parameters of concentration zones of pressure.

INTRODUCTION

Many historical buildings are susceptible to the destruction by natural means, first being the aging of the construction itself. To probe and identify such flaws in construction we developed a new seismic method. It is based on the measurements done at natural objects compared with computer simulation. The resulting data is processed via analysis of the spatial distribution of amplitudes and phases of building’s eigenfrequency oscillations and is supplemented with the study of soil properties (structure, velocity) by the engineering seismic prospecting (Yudahin et al., 2009*)*. The construction state defines the real shape of characteristic (eigenfrequency) oscillations. Such oscillations are measured simply by observation of constantly present microseisms with the subsequent identification of eigenfrequencies in the power spectrum, their amplitude and phase. It is convenient to estimate relative amplitude i.e. amplitude in the point divided to amplitude in stationary point measured at the same time. The next step is the creation of a computer model provides shapes of eigenfrequency oscillations similar to these of the inspected building. The modified parameters are the construction materials and the way of soil anchoring. The resulting model becomes the basis for a reconstruction arrangement.

The soil properties of a model are defined by the data of engineering seismic prospecting. In most cases the weaken zones of a construction are directly related to deficiencies in the foundation soil. This defines the importance of soil investigation procedure.

The values of a construction eigenfrequencies are directly related to the construction material properties, the construction scheme itself, basement type and the way it anchors with the soil. This implies that seismic methods have to be included into the procedure of historical buildings inspection. Seismic measurements take few hours and are performed for important structural points. These data

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are used to obtain a dynamic image of an object via the calculation of the spatial distribution of amplitudes and phases of seismic characteristic eigenfrequencies.

Seismic equipment type is of a great significance. The right choice is the broadband high dynamic range sensor. Velocity meters and accelerometers CMG-6TD, CMG-5T by Guralp fit well to the engineering seismic surveys since they are simple in operation and do not weight much. However, the plotting of real forms of oscillations requires the simultaneous recording of no less than three components (X, Y, and Z) to a single logger. The best solution is analog velocity meter coupled to a specially designed logging device, which is capable of less than 5 μs synchronization. That is required to obtain phases of oscillations.

The basic method used to form a real building computer model is a comparison of the real and simulated spatial distribution of eigenfrequency-oscillation amplitudes and phases at each component (X, Y, and Z). The properties of building are defined by architectural measurements, visual identification of defects and by implementation of soil anchoring according to soil properties obtained in engineering seismic prospecting.

The experimental values of eigenfrequency oscillations are considered as a reference one. The next step is a correction of model properties by matching of oscillation shapes and the experimental ones. This is achieved by the variation of construction material properties and by modifications of a construction scheme by means of cracks and weakening joints introduction. At the point when the correlation of the model and experiment becomes no less than 0.9 and the error is less than the measurement precision the model is considered to be adequate and its properties are treated as the real ones.

The procedure of historical buildings state diagnostics includes **three stages**.

Stage one is a formation of the simulation model that reproduces the experimental data.

Stage two is a creation of the simulation model of a building after the future reconstruction.

The final stage is an estimation of the correctness of the reconstruction. It is performed via analysis of tension map generated in the simulation of the model from stage two. This allows an identification of the correct route and effective methods for the historical building reconstruction.

Several applications of the seismometric method are given.

1. Preobrazenskaya hotel (XIXth century) in Solovetsky Monastery, Arkhangelsk region, Russia.

The hotel is a memorial and is a three-floored construction built in a simple rectangular shape with two small annexes on the backside (Fig.1a). The plan is also symmetrical relatively to the main entrance and represents a system of corridors along the long side of the building with rooms on both sides of corridors. The simplicity of construction scheme makes this building a good object for the method verification and the need for reconstruction was a good reason to conduct a research.

The present state of the hotel is quite bad: floor beams are partially missing and walls are cracked. The possibility of bearing structures reinforcement is a key question on the way to reconstruction. The second important task is to define the deformational properties of weathered brick-rough-stone walls with mortar. Laboratory studies were unable to give integral characteristics like effective hardness that defines stress-strain state and it is reflected in shapes of characteristic eigenfrequency oscillations.

Calculation model.

The main problems in the formation of the model were related to definition of material properties of walls and floors and to the anchoring properties of the building (fig.1b). A large (0.5 m cell size) and a small (0.25 m cell size) grid were used to make finite elements representation of the building. The cell size turned to be of a minor importance as it was shown by further calculations.

Young’s modulus E and density of materials ρ were varied next. A severe state of the quarry stone ribbon fundament and soil basement leads to a visually detectable inhomogeneous immersion. This fact complicates the calculation and was omitted during the first iteration. Averaged values were used for dynamical picture acquisition due to experimental error (10%) and incomplete understanding of parameters interaction. The most intensive oscillations are for the second form and were chosen for the first iteration of modeling. Calculations were performed for a set of major parameters (Table 1) and the results were compared to an experimental data.

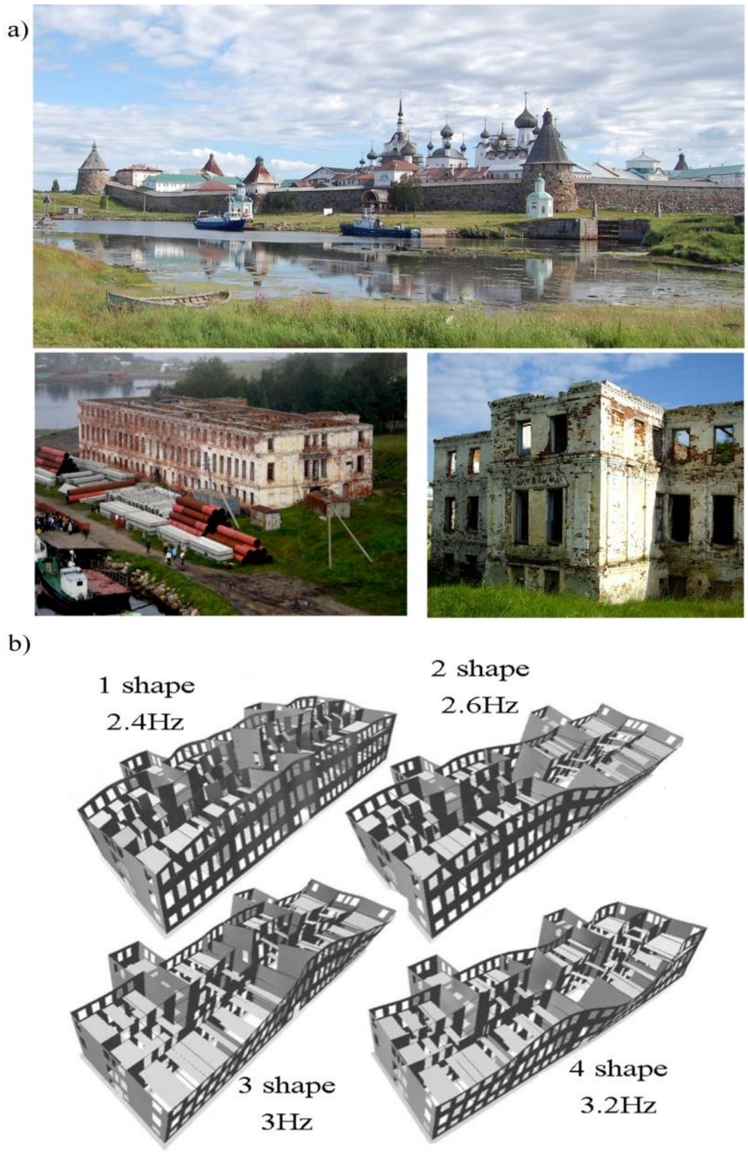

Figure 1. Diagnostics of the historical building - Preobrazenskaya hotel, Solovetsky Monastery: a) – Solovetsky Monastery (Arkhangelsk region, Russia), Preobrazenskaya hotel; b) – simulated shapes of eigenfrequency oscillations

Table 1. Parameters used in calculations for the model of Preobrazenskaya hotel

Model index	Walls		Floors		Eigenfrequency of the second form oscillations, Hz
	E_c, kN/m^2	ρ, ton/m^3	E_n, kN/m^2	ρ, ton/m^3	
A	299200	1.8	3×10^6	2.2	8.13
Б	299200	1.8	3×10^7	2.2	6.39
В	192000	2.2	3×10^6	2.2	6.28
1	336000	2.2	$2{,}9\times10^6$	2.2	2.38
2	533550	2.2	$2{,}9\times10^6$	2.2	2.90
3	375000	2.2	$2{,}9\times10^7$	2.2	2.95

Experimental seismometer setup consisted of one unmovable sensor (correlation detector) while the other sensors moved along the building. This layout allows joining the datasets acquired in various time moments. Sensors record all three components (Z, X, Y) but the most informative data is extracted from the horizontal components, parallel and perpendicular to the façade. The measurement points were chosen on the façade, corner sections and key dynamical points (Yudahin et al., 2009).

The advantage of this method is that it is non-destructive and can be used even if points are of limited access.

The results of the simulation are:

- Elastic modulus for walls (E_c) and floors (E_n) strongly influence the value of characteristic frequency, E_c especially. 50% increase of E_c (models A and B) results in the same change as a tenfold increase of E_n (model A and B).

- Model 2 gives the frequencies and oscillation profile form that is closest to the experimental ones.

The visual inspection of construction materials seems to be consistent with parameters in model 2. Cracks were introduced into calculation in attempt to achieve better coincidence with experimental curve but the results did not change considerably. The results, however, prove that simple seismic observations can be enough to make a good estimate of the construction material properties.

Hotel founding soils were studied with seismic prospecting and georadar scanning. The data obtained are compared with ones aquired by drilling of engineering geological bores (Technical report, 2006). Seismic prospecting data when compared with results of georadar and drilling reveal inhomogeneous funding soil layering with distinctive watered zones. This leads to a conclusion that the natural proccess responsible for most deformations are soil-based, such as freezing swell, suffusion and sagging.

A group of prominent peaks is present in the seismic power spectra (Fig.2). A peak can be assigned to eigenfrequency oscillation if it confirms several conditions. Firstly, it should be present in all observations. Secondly, it should not be a multiple of 50 Hz (this is related to electric machines vibrations). Also the amplitude of the peak should be maximal on the horizontal component normal to a wall, first amplitude from raises with the observation point height, time evolution follows the wind pulses pattern (Seismological studies 2011). This holds true for the constructions in a good state, while for damaged ones the first criteria does not have to be met by a peak to be eigenfrequency characteristic.

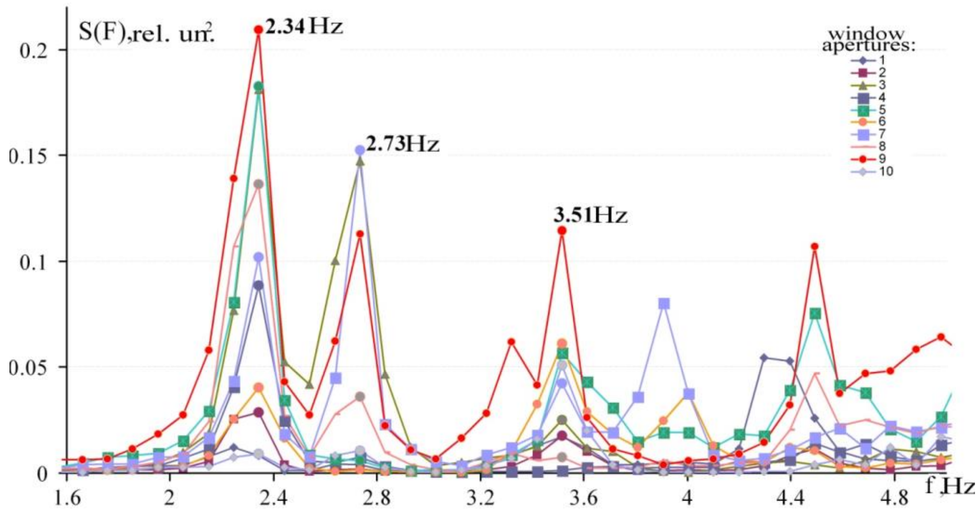

Figure 2. Microseisms power spectra in several parts (window apertures) of the hotel

According to the obtained eigenfrequency values the building can be represented as a set of blocks each having a separate behavior. The nature of eigenfrequency value floating in a damaged building is related to the semi-independent movement of blocks connected with flexible (or non-linear) joints. The eigenfrequencies with close values form a group and a spectrum can have several such groups separated with lengthy segments. Generally, the more a construction is damaged the wider is a maximum in the experimental data because it is composed of the many thin peaks each being an eigenfrequency form.

Thus we consider the main maximum frequency value may move according the measurement position. The record length limits the precision of frequency determination so that the band 2.34 to 3.51 Hz is considered.

Another part of the data processing is a calculation of coherence function (or coherence spectrum) as:

$$K(f) = \left|S_{ij}(f)\right| / \sqrt{S_{ii}(f) \cdot S_{jj}(f)} \qquad (1)$$

where *i,j* indicate the observation points, $|S_{ij}(f)|$ – is an averaged cross-correlation spectrum, $S_{ii}(f)$, $S_{jj}(f)$ – power spectra.

The coherence indicates the degree of correlation of oscillation processes in space (recording points in our case) and allows drawing a conclusion of the possible link between phases of the oscillations. Facade recordings have a coherence plot (Fig. 3) with lines indicating a correlation of coherence maxima (actually a standing waves monitoring). It is clear that the left block of the building shows the coherence values 0.44 - 0.62 for oscillation eigenfrequency at 3.125 Hz. A peak at 2.73 Hz has lower coherence value 0.27 - 0.48. The last fact is indications of these oscillations participate in superposition, though they are weak and are masked by microseisms more than intensive eigenfrequencies. Notably, the coherence peaks correlation results in a so called "dashed field", which in analogy with seismic prospecting practice is a signature of fractured media.

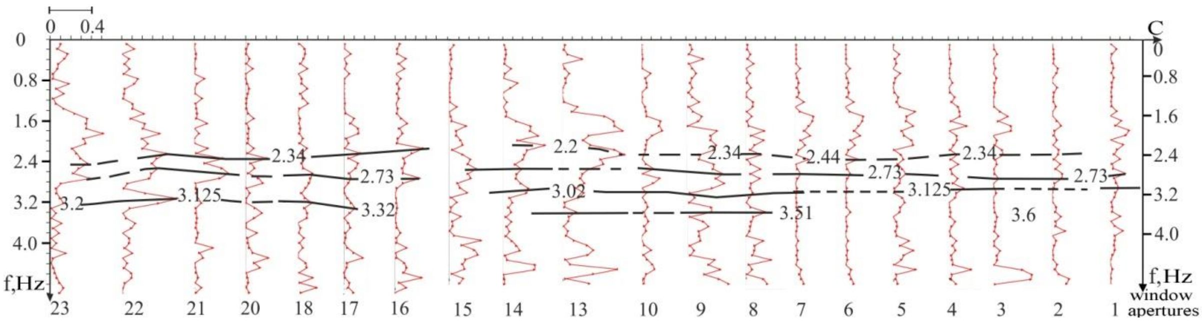

Figure 3. Coherence and eigenfrequencies. Dashed lines are coherence peaks correlation

So, the coherence analysis is an additional verification channel of experimental data processing conclusions. We analyze coherence function using quantitative and qualitative criteria but we do not perform coherence filtering.

The second important parameter needed for the oscillation profile determination is the phase ratio for records in different points. GPS-synchronized autonomous recorders GSR-24 do not give the required precision and the data for the phase ratio calculations was obtained from velocity-meters, which were placed on windowsills of three windows and synchronized as three channels of KBS-station. The distribution of amplitudes across the facade is plotted (Fig. 4) for selected frequencies and the phase ratios taken into account. Despite the fluctuations, the second form oscillation profile is dominating. Thus the experimental curve of the hotel oscillation form is acquired.

Comparison of the calculation and the experiemental results. The set of calculated and experiemntal eigenfrequency f values and amplitude profiles was chosen to be a basis for the collation. The precision of frequency determination in short recordings (20-30 minutes) is limited by 0.05 Hz and the amplitude has a 20-30 % error. Another source of error is an insufficient sensor site position (hardness of windowsill and well-junction with construction). It is reasonable to assume that the maximum observed is represented not by a single form but rather by a superposition of a set of forms with similar frequency values. The amplitude calculation in the 2.4-3.3 Hz band corresponds to frequencies of forms No 1 to No 5.

A best experimental fitting superposition of oscillations was calculated basing on dominating maxima frequencies, though the "weightening" coefficient (0 to 1) for amplitudes superposition depends on the dominating frequency. The possible cracks are assumed to strongly influence on the corresponding form presence. Almost perfect set of calculated and experimental results is achieved this way as shown in Fig. 4. The deviation for windows 5 and 3 are possibly due to an insufficient sensors fastening. Lower part of Fig. 4 shows which forms were included into superposition in every point. First form appear in many points of the left wing and is absent in the right wing. This is attributed to a difference in wall to basement caused by weathering.

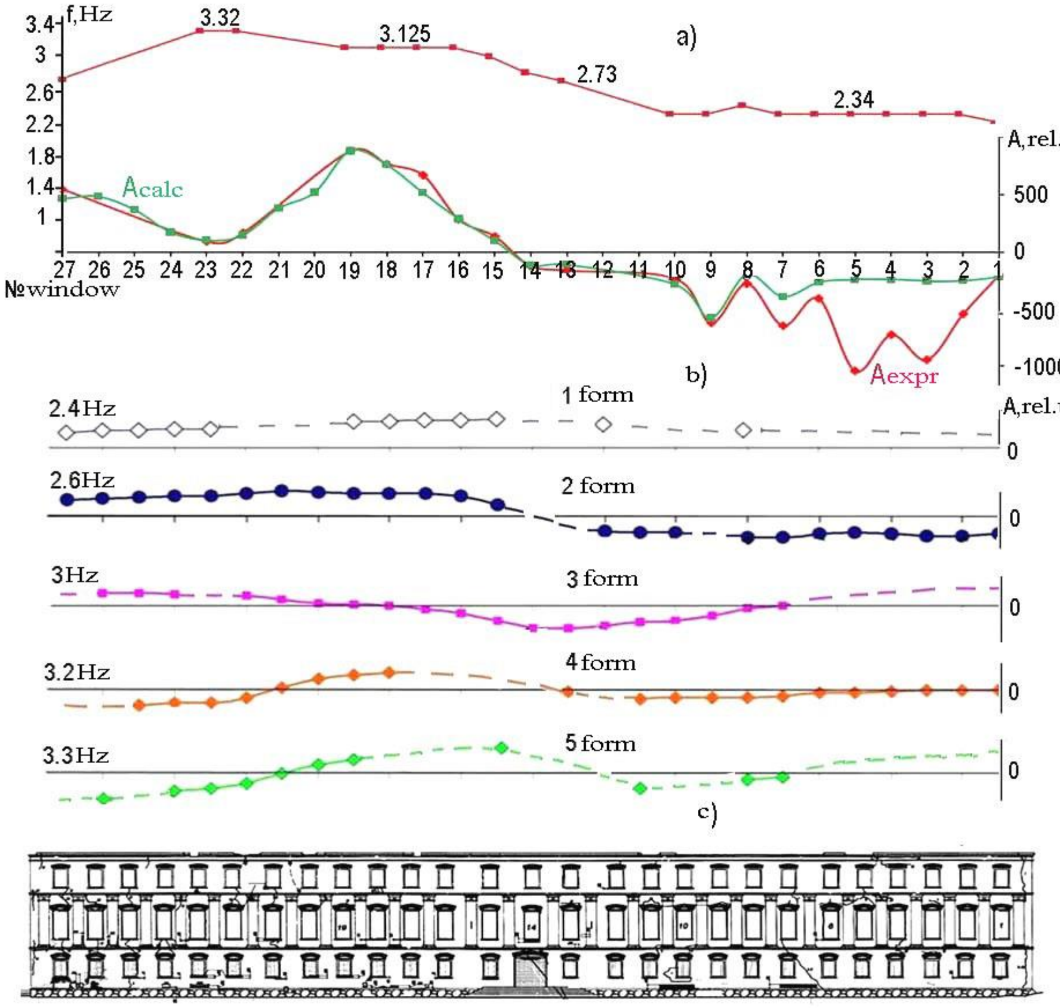

Figure 4. Results of experiemntal study of the Preobrazenskaja hotel: a) maxima frequency plot (upper part), experimental and calculated amplitude profiles of eigenfrequency oscillations at various measurement points, b) the calculated values of amplitudes of oscillation forms, c) hotel facade

Second form of eigenfrequency oscillations is present almost everywhere thus proving in a first approximation to the correctness of assumed oscillation model. The coincidence of the experiment and calculation (Fig.5a) is achieved by the variation of fitting parameter – elastic modulus (E) of the brickwork. Fig. 6 contains calculated compression stress.

A new model is developed (Fig. 5b) that incorporate all reconstructions (like floor reconstruction) and the static-stress calculation is performed on it. The main constriction strains are plotted for the reconstruction model in Fig. 7. The values at tension concentrations are compared to the material ultimate strength (R), which is determined on the basis of code SNiP II-22-81. This gives an estimate whether the reconstruction choice is sufficient for construction safety. Young's modulus was experimentally found to be $E=84000\ ton/m^2$ and the ultimate strength $R=280\ ton/m^2$. The calculation result for the reconstruction model with only floors insertion shows the maximum constriction stress in a spot reaching $R_p=150\ ton/m^2$ (Fig. 7). Therefore, the structure is sufficiently sturdy and does not need other fortification efforts.

Hence, the seismometric monitoring allows to conduct a complex survey of a construction technical state. The method we present can be used to create a building simulation model that reproduces well properties of the real construction. The correctness of the model is achieved via comparison of an experimental data and by regulation fitting parameters unless the maximum correlation is achieved.

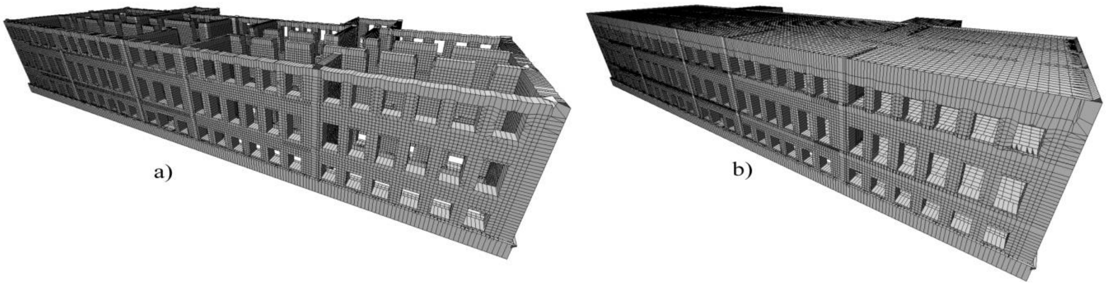

Figure 5. The calculation model for the hotel for the a) basic and b) reconstructed state

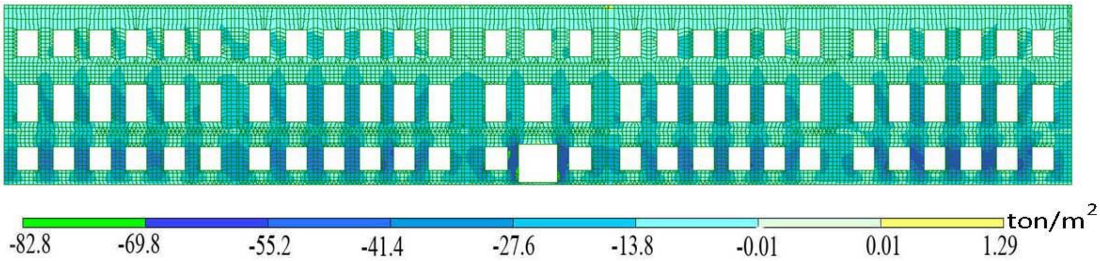

Figure 6. Main vertical compression stress (ton/m^2) as a function of permanent load on a basic model. Constriction resistance scale (ton/m^2) is given in the lower part

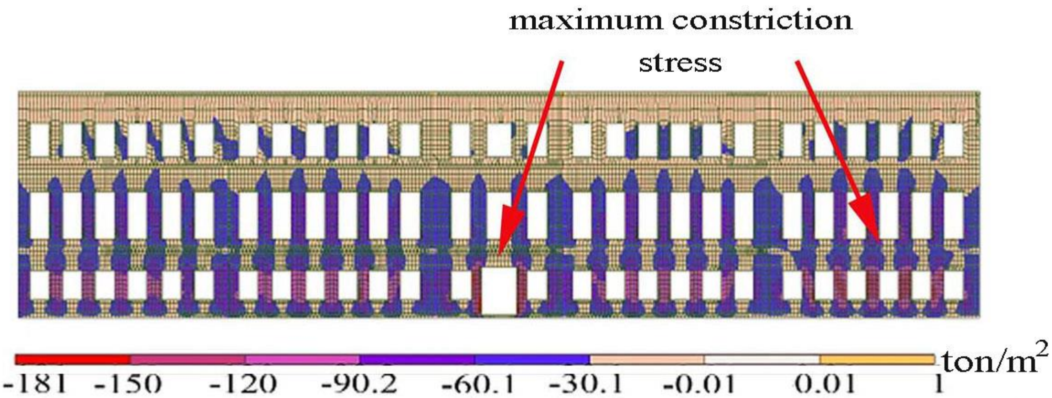

Figure 7. Main vertical compression stress (ton/m^2) as a function of permanent load on a reconstructed model. Constriction resistance scale (ton/m^2) is given in the lower part

2. Another example of the seismometric technique in use is an investigation of the **southern wall of Spaso-Prilutskij monastery (Vologda, Russia)** – Fig. 8a. The purpose of the study was to estimate the impact of vibrations caused on the wall by the neighbouring railway and to find the cause of its damages.

The monastery was found in 1371 and in the current state the southern wall is damaged and is careened inside along visible cracks, which are close to towers (Fig.8b). Five controforces present to support the wall and are in poor condition too. 170 m separate the southern wall from the Nothern Railway and Vologda river flows across the western wall. The vibrations caused by passing trains are tangible without any devices and are especially strong near the southern wall.

Accelerometers and velocity-meters were used to measure eigenfrequency oscillations and a possible vibration impact from the railway. The measurements were conducted in the upper gallery including entrances to towers, in lower embrasures and on the ground. Three axis (X, Y, Z) were one vertical and two horizontal parallel and normal to the wall (Kapustian et al., 2012). The wall length is 140 m and the sensor spacing was roughly 3.5 m equal to embrasure spacing.

According to the eigenfrequency oscillations analysis procedure (Kapustian et al., 2012), (Yudahin et al., 2009) phases and amplitudes are calculated in each observational point and the experimental forms profile are shown in Fig. 9. Eigenfrequency oscillations form analysis shows the strongest shifts occur at 3.5 Hz and the most jagged form shape is in the left part of the plot (embrasures 20-35). The latter indicates that the right part is in better condition compared to the left one. The cracks between the wall and towers does not reach the basement as the shifts of the first two forms are embrasures No 1 and No 35 negligible and confirmed by visual study - crack not reaching the basement.

Figure 8. The southern wall of Spaso-Prilutskij monastery as observed from a) the railway side and b) from monastery courtyard

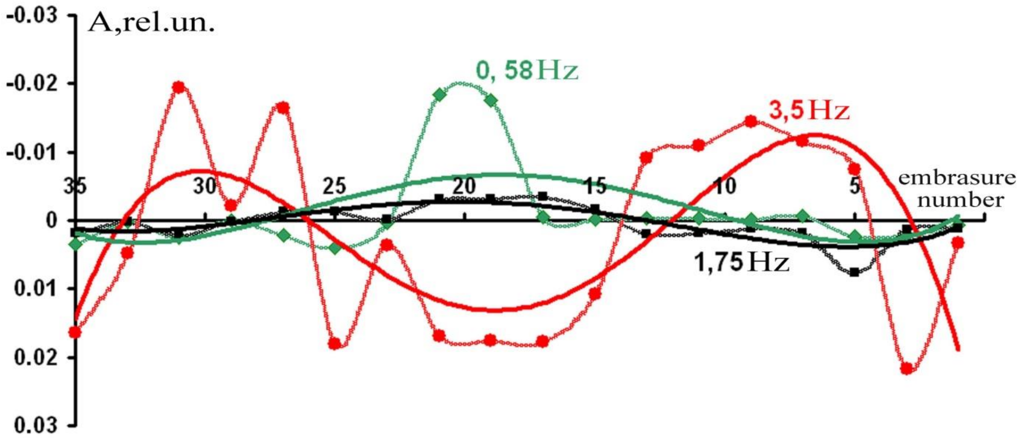

Figure 9. Experimental oscillation forms at eigenfrequencies 0.58, 1.75 and 3.5 Hz. Dash-dotted line is experimental profile, continuous line is a polynomial smoothening. Shift are given as a function of the embrasure number with 0 marking the tower closest to the river

The frequency for the first form is 0.58 Hz (green curve in Fig. 9) and the amplitude maximum correlates with the construction weakening by the large Central gate in the wall filled with brickwork nowadays. These form profiles are primary for the choice of a theoretical model.

The seismic prospecting method was applied to founding soils. The obtained seismic signal was processed by RadExPpo and ZondST2D software. The resulting vertical cross-sections of velocity distribution for each profile-line both on outer and inner parts of the wall are given in Fig. 10.

The first discontinuity along the outer side is clearly tilted towards the river and separates the technogenic layer (velocities below 500 m/s) from loamy sand. This loamy sand is expected to include clay soils: loam (salad color in Fig. 10) with inhomogeneous clay layers (velocities above 1500 m/s). Clay soils have a tendency to expand when freezing, which can be responsible for the wall damage. The zone highlighted (70-100 m along the profile) is supposed to present in the inner courtyard up to the refectory, where also the freezing expansion-caused damage is found. The velocity parameters of founding soils are used in calculation model of the wall anchoring.

The choice of the calculation model. The basement parameters in the model were chosen simultaneously with the solution of a static problem. This allows estimating stress fields in the body of an object. The main load is the mass of the building. The congruence of calculated and experimental eigenfrequency values was a correctness criterion. Additionally the shift profiles for eigenfrequency oscillations are compared. The dynamical solution for vibration impact gives the amount of load that vibrations add to static stresses. The integral stress is compared with calculated material ultimate strength and the damage of vibration impact is estimated.

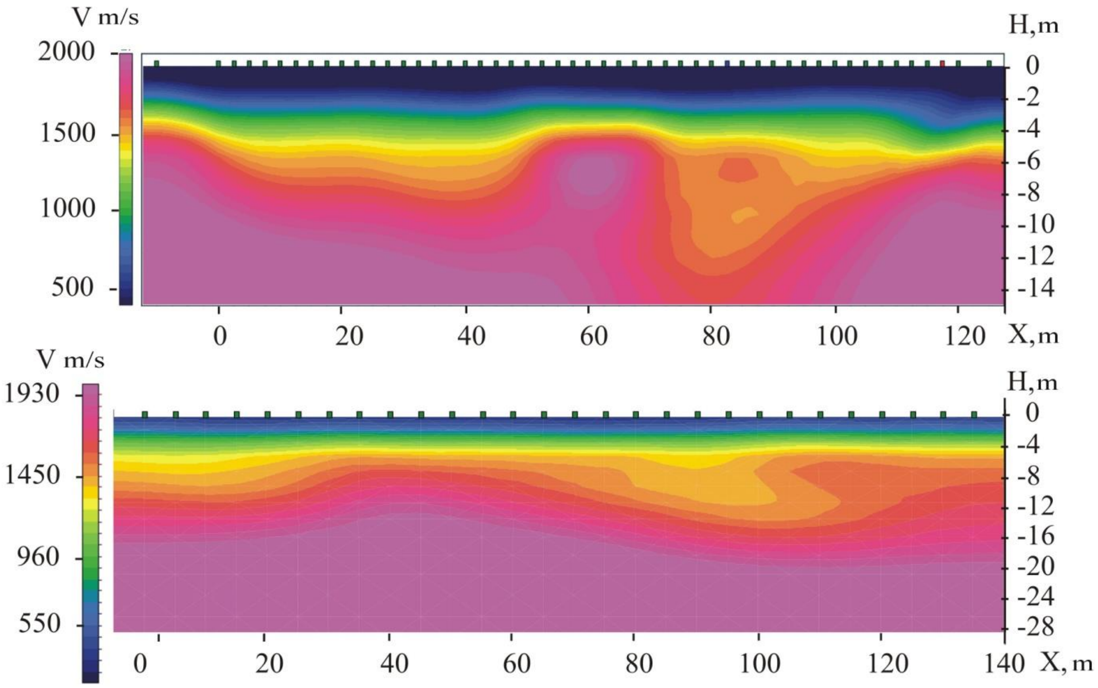

Figure 10. Vertical velocity cross-section of the soil along the profile for the a) outer and b) inner side of the wall

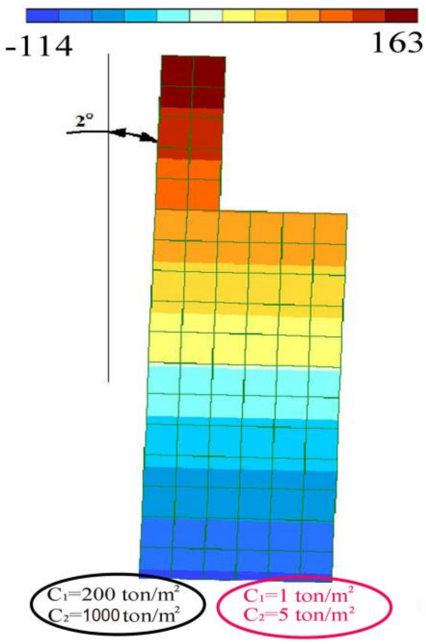

Figure 11. A solution of the static displacement problem with weakened soils

A model situation was constructed to solve the static wall model to reconstruct how it got to the modern state (Fig. 11). Relatively hard soils were assumed for outer part (C_1=200 ton/m^2, C_2=1000 ton/m^2) while the inner soil was weak (C_1=1 ton/m^2, C_2=5 ton/m^2). The solution is trustworthy as the wall was careened in the right direction significantly (2°) and the tangential stresses distribution (Fig. 11) explains the origin of cracks that are indeed present near the towers.

The static solution with towers included gives the deformation fields as shown in Fig. 12. The homogeneous soil model was assumed for the basement with elastic modulus E=17 MPa and Poisson coefficient ν=0.32. An elastic basement characterized according to Pasternak method by vertical and horizontal ductility coefficients:

$$C_1 = \frac{0.138 \cdot E}{1 - \nu^2} = 2.61 \text{ MPa} \tag{2}$$

$$C_2 = 2 \cdot C_1 = 5.23 \text{ MPa} \tag{3}$$

Analysis of static solution gives evidence of the cracks origin to be related to an insufficient bearing capacity of the fundaments. The river flood can unpredictably influence soil characteristics leading to the fundament weakening.

The dynamic deformation caused by the real accelerogram (train motion) is presented in Fig. 13. The most dangerous direction appears to be across the Y axis (normal to the wall). The loads caused by passing train are small and the maximal shift is 10 μ and is in the middle of the wall. Induced stresses in the wall (Fig. 14) are in the range of 10^{-2}-10^{-3} N/m^2. This value is much below the load caused by the mass of the wall and any static temporal loads. This all clearly demonstrates that the vibration generated by passing train cannot be responsible for the wall destruction.

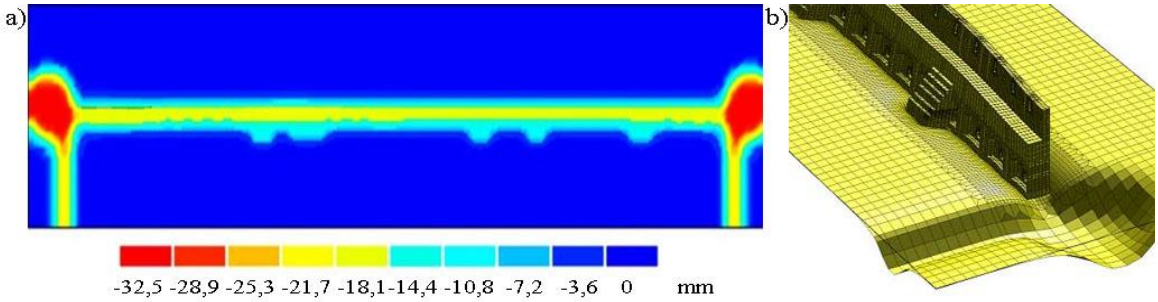

Figure 12. Deformation by the detailed wall model with towers: a) deformation values, b) 3D soil scheme

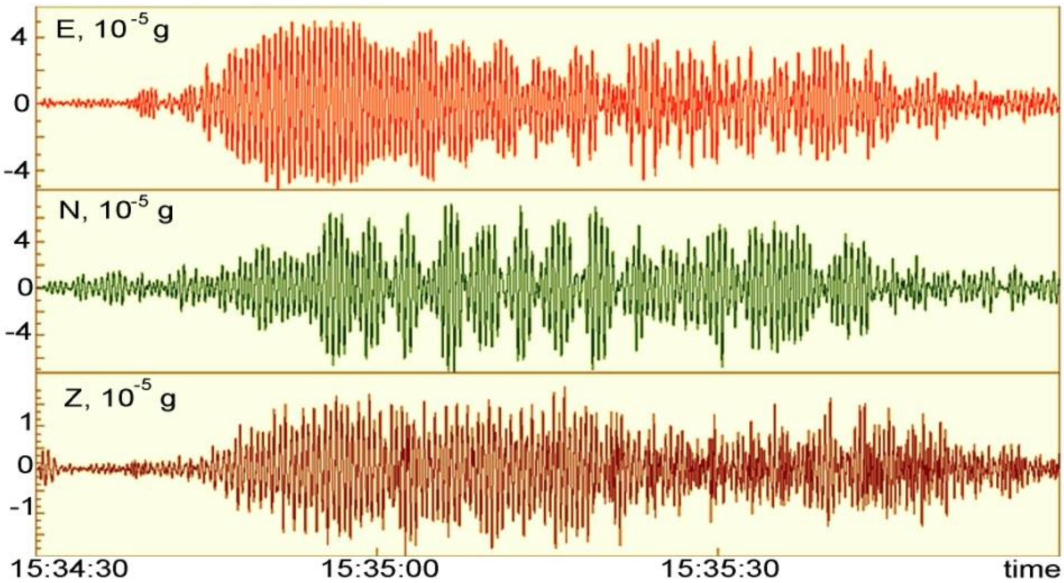

Figure 13. Passing train accelerogram for the directions: across the wall (top), normal to the wall (center) and vertical (bottom)

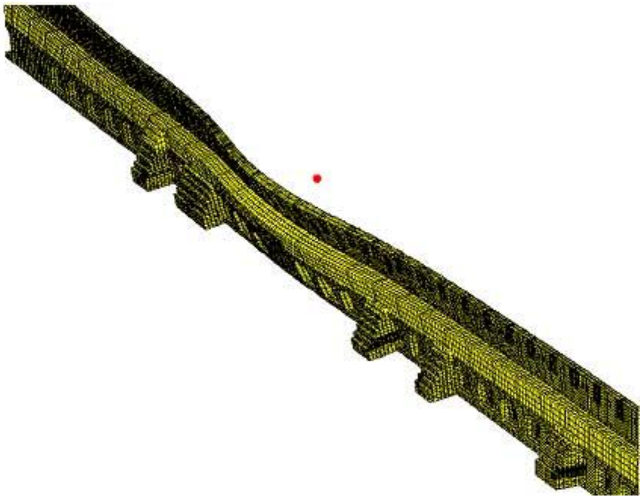

Figure 14. Dynamic shifts caused by the passing train (wall's mass is not included)

CONCLUSIONS

The wall is in unsatisfactory construction state and needs urgent repairs. The main source of cracks, horizontal shift and careen are caused by the founding soils. Thus, the fundament should be studied in detail and fortified. Additionally a soil fortification is recommended. The vibrations generated by the railway are found to be not responsible for the damages even if the long-time exposure takes place. Hence, the vibration isolation is not necessary.
Several examples are given for the engineering seismic technique applications. The results obtained by this method provide the important information of the construction state, external factors impact on it and thus the possible ways of reconstruction.

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