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Assessment of the technical condition of the Sukhumi Lighthouse, Abkhazia using passive seismic standing waves method

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ABSTRACT

The results of a geophysical survey of the technical condition of the lighthouse are presented. The stress–strain state, the residual resource, the tension of the fastening cables, the fixation of piles in the ground (rigid/non-rigid), and the immersion depth of the historical study object, the Sukhumi Lighthouse built in 1861 were determined. The passive seismic standing method based on the extraction of the natural vibrations of the object from noise records, as well as the tapping method, based on the recording of a reflected seismic wave passing along the structure were used to solve the above problems.

1. Introduction

Sukhumi Lighthouse was constructed in 1861 on the territory of Abkhazia and is one of the oldest lighthouses located on the Black Sea coast. In the field of examining engineering structures for stability and defects, objects of historical heritage are of interest. Such structures, on the one hand, are of cultural and historical value, and on the other, due to age, they are often in poor technical condition, have a large number of defects, or are not safe for operation at all. For these reasons, it is impossible to use destructive methods, for example, seismic with an excited source or sampling of structural material.

When surveying buildings, the photogrammetry method based on the use of optical systems is often used. Most often, it is used to create a 2D or 3D computer model of an object on which the survey results are applied by other methods. Photogrammetry is combined with thermal methods [2,4,7], microwave spectroscopy [3], georadar [7] and others. This method is also used to analyze the subsidence of buildings [2], documentation of damages, cracks for their further analysis [5], to monitor changes in the slope of buildings using drone technologies [6] to monitor changes in the slope of buildings using drone technologies [1,8]. Thus, this method can be used to examine buildings for the presence of deformations, and displacements, to create 2D and 3D models of objects. Relating to non-destructive methods, photogrammetry, however, is limited to the examination of only the surface of structures.

One of the reasons for the degradation of building materials is the penetration of moisture with possible subsequent deposition of salts, the problem is especially relevant for old wooden and stone structures. For the corresponding survey, a thermography method based on measuring and mapping the temperatures of the surfaces of buildings is common. The method has been successfully used to examine basalt pillars [4], internal, external walls and roof of the castle in Calvello, Italy [9], stone church [10], a Roman stone bridge [11] and others [7,12]. Like photogrammetry, the method is non-destructive and also has a small measurement depth, limited by the near-surface part.

Another common method of inspecting buildings for defects of different natures is georadar. It is based on the emission of an electromagnetic wave into the medium, followed by the recording of the signal reflected from the media section. The method is used to determine cavities, cracks [13,15], determination of zones saturated with water [11,14]. The resolution of the ground-penetrating radar decreases as the depth of profiling increases, and any metal parts lead to distortion of the data obtained, nevertheless, the method is more often used when examining the technical condition of buildings of historical value.

In this study, the technical tasks set (below) are solved using the method of passive seismic based on the extraction of standing waves from noise recordings, as well as with the help of tapping, which is based on the excitation of seismic waves in a building using an artificial source,

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Fig. 1. Baikal – 1 recorder and sensor – (yellow). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

followed by the recording of reflected waves.

The purpose of the study is to assess the technical condition, in particular, to assess the anchoring stability of the Sukhumi lighthouse. At the same time, a number of engineering and geological tasks were solved:

- Determination of the immersion depth of piles;
- Determination of the fixation of piles in the ground (rigid/non-rigid);
- Determination of the stress–strain state of the structure;
- Determination of cable tension;
- Determination of the residual resource by natural vibrations.

The applied method was invented in the early 21 century and currently is not widely used. In this regard, the method was not applied to many types of engineering structures. In the presented work, for the first time, an attempt is made to survey the lighthouse using the passive seismic method. The structure has a circular section, which can lead to a specific distribution of modes. We consider gained experienced useful for specialists who use this method and will help the further development of this technology. The social significance of the work is to warn people operating the building about its emergency condition, issue a recommendation either to stop using the building or to repair/strengthen it.

2. Methods and equipment used

2.1. Research technique using the passive seismic standing waves method

All passive seismic measurements were made using Baikal-1 recorders and sensors with a natural frequency of 5 Hz, recording transverse, longitudinal and vertical vibrations (Fig. 1.).

2.1.1. Profile and area measurements

The method is based on recording acoustic vibrations records of an object, in the absence of a controlled artificial source of vibrations. The natural frequencies are distinguished from the obtained recordings, at which the natural vibrations are formed in the form of standing waves. Since each object has a set of natural frequencies and a characteristic distribution of standing waves, their change may indicate the appearance of defects, loss of seismic stability, etc.

When carrying out measurements, a non-movable seismic vibration recorder was used as a reference, and several movable recorders were used along the measuring profile/area. All sensors were installed on the surface of the object. The reference sensor was used at the processing stage to normalize the noise recording level of the portable sensor, removing differences in noise traces caused by the level of external

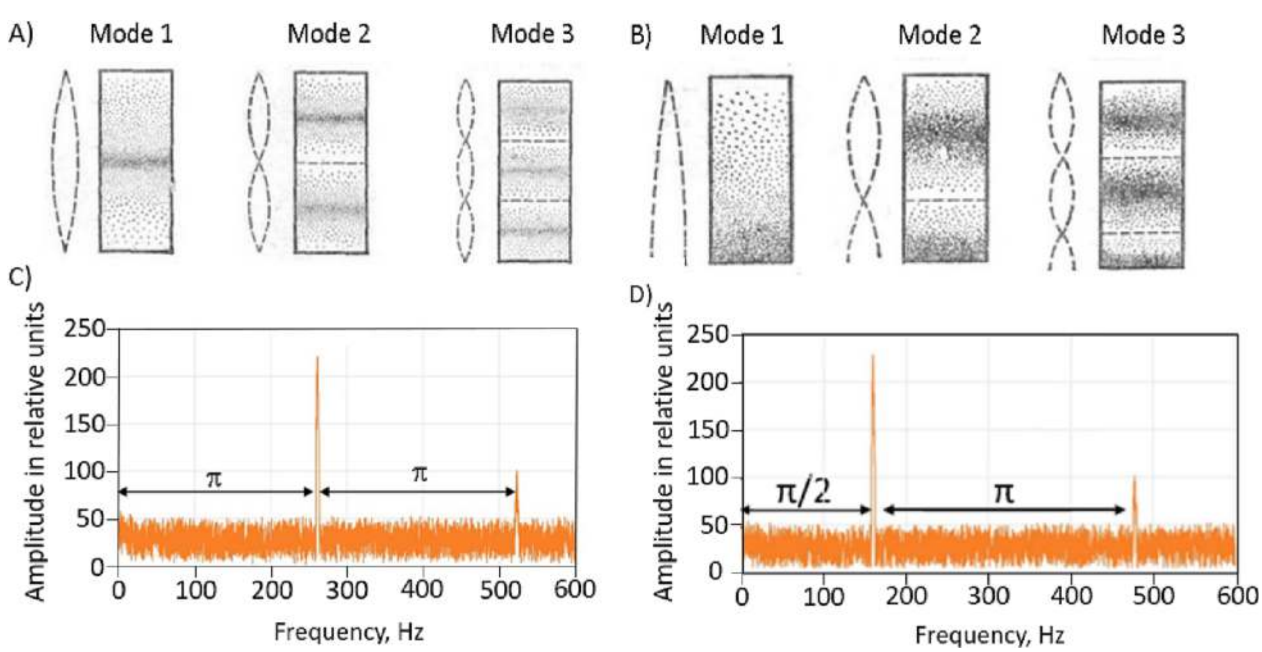

Fig. 2. A, B) Shapes of the first three vibration modes for rigidly fixated and non-rigidly fixated piles, respectively; C, D) are generalized amplitude spectra for rigid and non-rigid supports, respectively. The case of vertical vibrations.

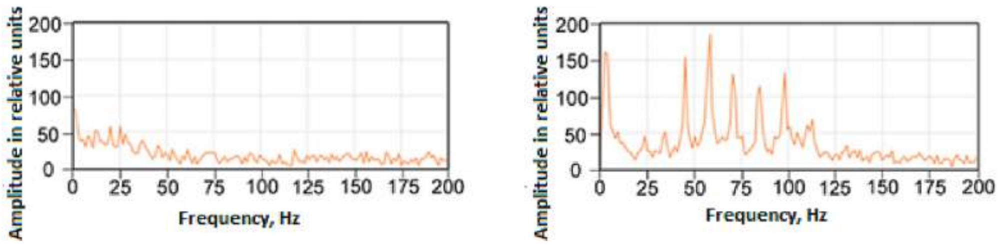

Fig. 3. A) Generalized amplitude spectrum of horizontal vibrations of a rigidly fixated pile; B) Generalized amplitude spectrum of horizontal vibrations in the case of non-rigid fixation of one of the ends of the pile.

noise. The recording was made by accumulation, i.e. for a period of time sufficient for the accumulation of a useful signal exceeding the interference and fluctuations caused by traveling waves.

Processing algorithm:

1. Removal of separately recorded coherent spurious noise from noise profile records;
2. Normalization of the level of noise amplitudes of the moving sensor to the level of the reference one for each measurement for each fragment;
3. Splitting noise records into blocks of 8192-time fragments;
4. Fourier transform for each block and averaging of the obtained amplitude spectra by summing them;
5. Construction of amplitude-frequency distribution maps on the studied area or profile.

The interpretation is based on the analysis of the frequency response maps obtained at the last stage, as well as on the generalized spectrum obtained from the maps by summing at each measurement point.

2.1.2. Single measurements

In addition to profile and area measurements, it is possible to apply the technique on the supports of objects using a single recorder mounted on the end of the pile protruding from the ground. According to the modes of standing vibrations recorded at one of the ends, one can judge if it is rigidly fixated in the ground or not.

The lighthouse is anchored on piles, which, according to their geometry are elongated parts. Let's consider their vertical and horizontal vibrations in different cases of anchoring in the foundation (Fig. 2).

If the pile is rigidly fixated at the top and bottom, or when it is not fixated at all, then the first three modes of vertical vibrations (vibrations along the pile) will look like in Fig. 2A. At the rigidly fixated ends, the vibrations will be minimal, and on the generalized spectrum, the peaks of the amplitudes of the accumulated signal will be at a distance of π from each other (Fig. 2C). Horizontal vibrations (across the pile) will be minimal, the generalized spectrum will look like in Fig. 3A.

In the case of a pile rigidly fixated at only one end, the vertical vibrations will look like in Fig. 2B, with a minimum amplitude at the rigidly fixated end and a maximum at the loose end. An example of the first two modes of standing waves on reflected ones in the generalized spectrum is shown in Fig. 2D. In this case, horizontal vibrations near the loose end form quasi-regular peaks in the generalized spectrum (Fig. 3B).

2.2. Active seismic measurements

The method of tapping was used in this study, in which an artificial source of seismic waves is used, a single pulse generated by a hammer blow. A single oscillation sensor placed on the surface of the pile was used, from the recording of which a reflected wave signal is extracted from the geometric boundaries of the object and its defects. The main application of the method is to determine the depths of supports/piles and their defects. This is done at a known speed in the material and the time of arrival of the signal (reflected wave) to the sensor.

Fig. 4. A set of measuring equipment "Spectrum 4.3".

During the measurements, the Spectrum 4.3 equipment was used (Fig. 4), which is a set of a hammer, an oscillation sensor, and a tablet with software that allows for primary processing.

3. Study object

The study object was the Sukhumi Lighthouse, built in 1861 on the Black Sea coast (Fig. 5). Since its construction, the structure has lost stability, tilted, and is supported by 6 stretched cables. In addition to the cables, the lighthouse rests on 8 piles. The height of the object is about 35 m.

4. Research results

4.1. Profile measurements using passive seismic standing waves method

The measurement profile was stretched along the entire height of the lighthouse, the recorders were located on a spiral staircase, a total of 14

Fig. 5. Sukhumi Lighthouse.

measurement points (Fig. 6). The measurement frequency was 500 Hz, and the signal accumulation time at each point was 5 min. An amplitude-frequency response was constructed, which reflects the expected waveforms with peaks of amplitudes located at the top of the lighthouse. At the same modes, an increase in the amplitude with respect to height is observed. In addition, intermediate modes are observed, the nature of which is difficult to establish. Since the amplitude of these vibrations is comparable to the amplitudes of the fundamental modes, it is most likely that the obtained intermediate modes are not associated with any defect, but are modes of other vibrations, for example, torsional ones.

One of the indicators of the physical state of the structure is the residual resource, defined as the total operating time of the object from the moment of monitoring its technical condition to the transition to the limit state [[16]]. The bending stiffness of an engineering structure can be characterized by the flexural rigidity of dangerous sections of load-bearing structural elements, while there is a relationship between the bending stiffness and the natural frequency spectrum (1). Then the wear and tear can be determined by the formula (2):

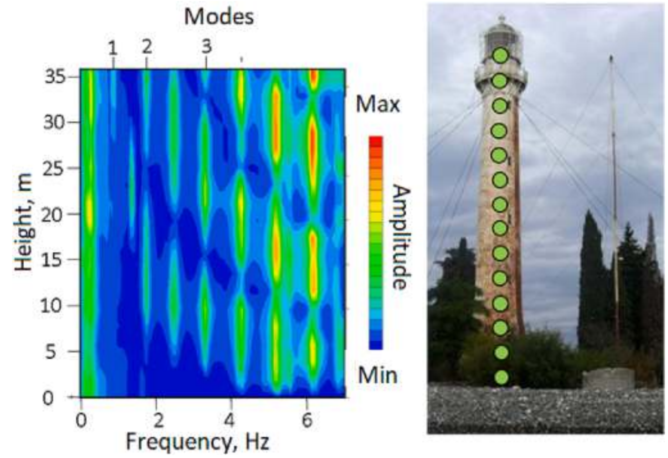

Fig. 6. On the left: A photo of the lighthouse and measuring points (highlighted in green); on the right: Frequency-amplitude distribution along the pendulum. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

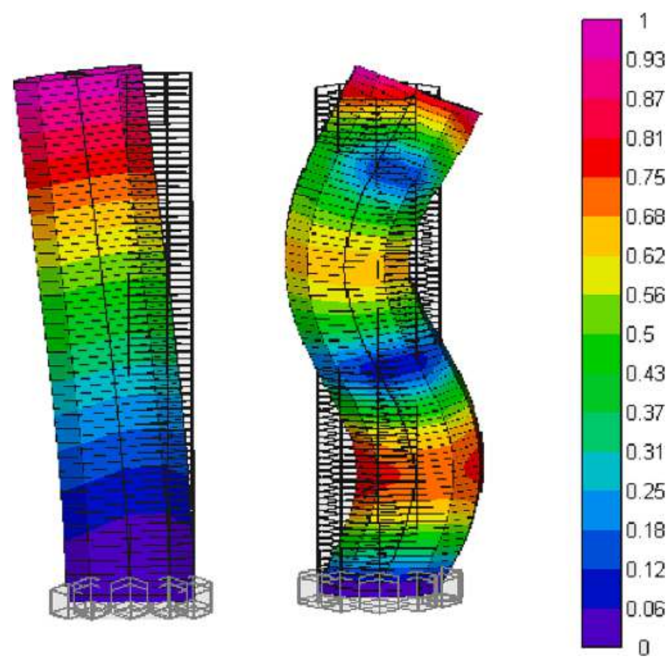

Fig. 7. Lighthouse vibration modes obtained by finite element simulation.

$$B = EJ = \frac{\alpha_i^{\,4}\omega_i^{\,2}}{H^4 m} \tag{1}$$

B – bending stiffness; E – elastic modulus; J – the moment of inertia of the normal section.

ω_i– natural frequency of i mode; α_i – frequency coefficient that depends on the elastic properties of the reference section; H – the height of the structure; m – linear weight.

$$\xi = \frac{B^t - B^{t+\Delta t}}{B^t} * 100\%, \tag{2}$$

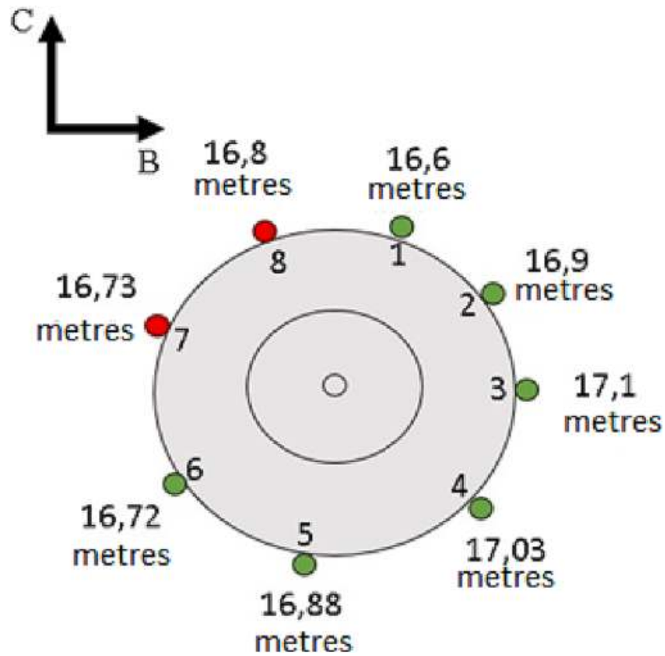

Fig. 8. The immersion depth of the piles and the degree of their anchoring (floating piles are highlighted in red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
The immersion depth and the nature of the anchoring of piles.

Pile number	Immersion depth, m	Rigid fixation/non-rigid fixation in the ground
1	16,6	Rigid
2	16,9	Rigid
3	17,1	Rigid
4	17,03	Rigid
5	16,88	Rigid
6	16,72	Rigid
7	16,73	Non-rigid
8	16,8	Non-rigid

B^t– initial bending stiffness of structural elements; $B^{t+\Delta t}$ – subsequent bending stiffness of structural elements; ξ – deterioration.

$$P = 1 - \xi \tag{3}$$

P– the residual resource of structure.

Using all the formulas above we get the following expression, which allows us to calculate the residual resource of structure using experimental and model natural frequencies:

$$P = \left(\frac{\omega^{t+\Delta t}}{\omega^t}\right)^2, \tag{4}$$

ω^t– initial natural frequency obtained from modeling; $\omega^{t+\Delta t}$ subsequent natural frequency obtained from the experiment.

Using the expression above (4) recorded natural frequencies of the structure are compared to natural frequencies obtained during the simulation of the object by the finite element method (Fig. 7.). The comparison showed that the residual resource of the beacon is 68%. It should be borne in mind that for accurate calculation, it is necessary to carry out measurements without the support of stabilizing cables. Without them, the residual resource of the object would be less and given that a deviation from the original values of natural frequencies by 50% makes the structure an emergency, it is not recommended to operate the lighthouse.

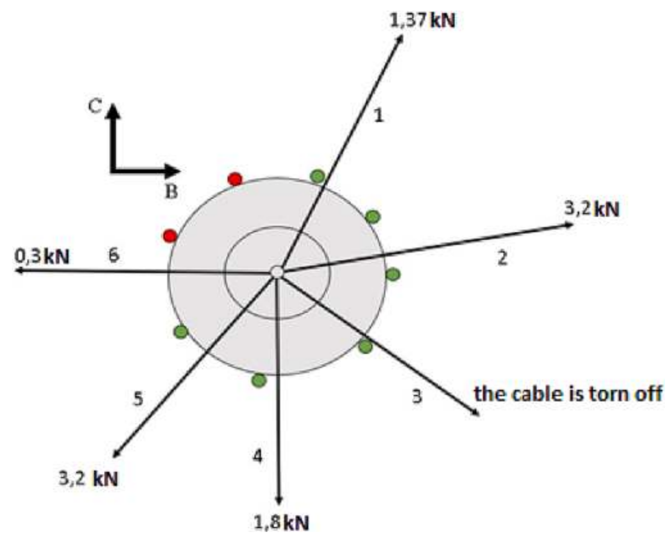

Fig. 9. The location and tension strength of the cables securing the lighthouse.

Table 2
The tension degree of the cables holding the structure.

Cable number	Tension force, kN
1	1,37
2	3,2
3	The cable is torn off
4	1,8
5	3,2
6	0,3

Table 3
Permissible load and breaking force for steel cables.

Diameter	Permissible cable load, kN	Breaking force, kN
2 mm	0,47	2,35
3 mm	1,06	5,29
4 mm	1,88	9,41
5 mm	2,94	14,7

4.2. Measurements on piles

When recording natural vibrations on piles, the measurement frequency was selected to be 500 Hz and the signal accumulation time was 3 min. The results are shown in Fig. 8 and Table 1.

Measurements by the passive seismic method showed that the 7th and 8th piles (numbered in the figure) are not rigidly fixed. This implies that the buried end of the pile vibrates, and therefore the structure loses its stability. Tapping, an active seismic method made it possible to determine the depth of the piles. The depths of the piles vary in a small range, but it is noteworthy that the greatest depth is the supports (3,4) located opposite those that have lost stability (7,8), which may indicate their immersion depth when part of the weight of the structure is transferred to them.

4.3. Measurements on cables

To obtain a more complete picture of the stability of the structure, the tensions on the cables were measured using K-B-12 T strain gauges. The results are shown in Fig. 9 and Table 2. The sum of tension forces on the southwestern side (cables 4,5,6, numbered in Fig. 9) exceeds the sum of tension forces on the northeastern side by 23%. Table 3 shows the values of the permissible load and breaking force for steel cables of different diameters. The lighthouse is secured with cables with a

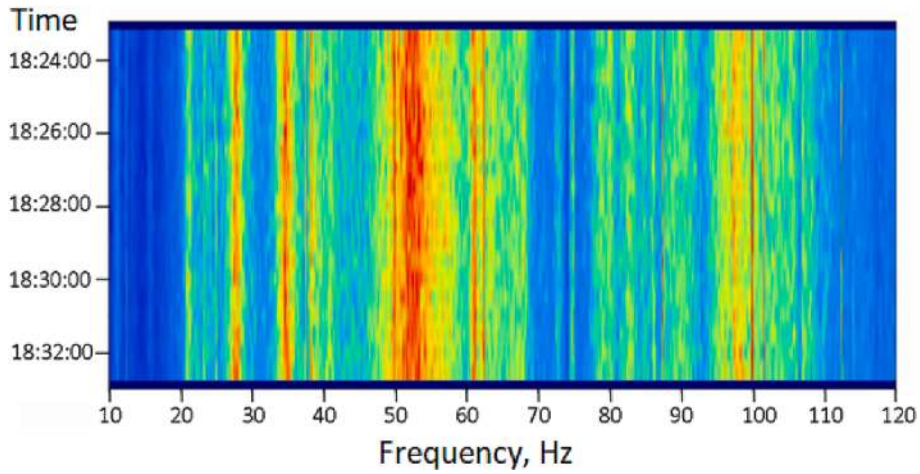

Fig. 10. Seismogram of seismic vibrations.

diameter of 5 mm and according to Table 3, the load on 2 cables (2 and 5) exceeds the permissible values. A break, however, is not expected. Cable No. 3 was torn off, most likely due to reaching the ultimate strength. From this one can conclude that the structure is inclined in a north-westerly direction. And given the poor anchoring of the piles on this side, the following picture is obtained: due to unknown reasons, two piles (7 and 8) were either initially poorly fixated in the ground or lost their rigid fixation. The structure was reinforced with tensioned cables, but the tension force, which was supposed to compensate for the slope of the structure to the northwest, exceeded the breaking force of cable No. 3. Furthermore, deterioration in the stability of the lighthouse and its inclination to the northwest is expected.

5. Further research

Since the structure is unstable, and there are no forces keeping the lighthouse from further tilting, it is proposed to conduct monitoring to prevent an emergency situation, the fall of the structure. This can be implemented using several installed seismic sensors that continuously record the vibrations of the object. An example of a recording of another structure's vibrations is shown on the seismogram (Fig. 10). When the state of the lighthouse changes, the values of its natural frequencies are expected to change, which are represented on the seismogram by continuous bands of high amplitudes (highlighted in red). Detection of changes in the values of natural vibration frequencies will prevent the moment of collapse of the structure.

6. Conclusions

In this work, a set of methods was tested for solving several problems of engineering-geological problems. The depth of the piles was determined using an active seismic method using the Spectrum 4.3 equipment. The residual resource and the nature of the anchoring of the piles were determined by the method of passive seismic which is based on the extraction of standing waves from noise recordings. The tension of the cables was determined using K-B-12 T strain gauges. The listed set of procedures makes it possible to characterize the stress–strain state of a structure.

Based on the survey results, it can be concluded that the building is tilted to the northwest, as the root cause is assumed to be poor anchoring of the corresponding piles. They tried to compensate for the loss of stability with cables stretched in all directions except for the direction of the fall of the structure. However, one of the cables located on the side opposite to the inclination of the structure was torn due to a load exceeding the breaking force value. In addition to problems with the stability of the structure, no major defects were found along the lighthouse itself. The residual resource of the building is 68%, but as mentioned above, this value should be determined without tensioned cables i.e., the actual residual resource is less than the determined one. Considering that the value of the residual resource equal to 50% is considered emergency, and there are prerequisites for further loss of stability, the operation of the lighthouse is not recommended. To monitor the condition of the structure, it is recommended to install a monitoring a set of several seismic vibration sensors, which will allow warning of an emergency by changing the natural frequencies.

The disadvantages of the study include the imperfection of the equipment, namely the use of sensors with a natural frequency of 5 Hz. This is reflected in the results in the appearance of standing waves that do not relate to the real vibrations of the object. Such a feature should be compensated by the interpreter's understanding of possible vibration patterns for a particular object.

This set of methods and related equipment is recommended by the authors for assessing the technical condition of such structures.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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None.

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