INFLUENCE OF VIBRATIONAL IMPACTS ON THE BELL TOWERS AND THE PROBLEM OF SAFETY

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Abstract. *Due to reconstruction and restoration of the original guise of the landmarked buildings the investigators are facing the problems of assessing possible adverse consequences of such sorts of work in the recent years. The most problematic are the works requiring dismantling of the bearing and fencing structures built into original scheme. This article gives consideration to the ways of solving a problem of ensuring safety of buildings and structures in use provided their operating conditions have changed (e.g. the assessment of possible consequences of bells installation on the steeples of St. Isaac's Cathedral is presented). The measurements of vibrations with simultaneous assessment of robustness and bearing capability of the brickwork have shown that the vibrational impact of chimes of heavy bells cannot adversely affect the bearing structures of the bell towers. However, there is always a risk of such adverse effect on the structure of the bell tower and stability of soils at its base. A danger emerges not because of significant settlements, but rather due to irregularity owing to inhomogeneity of soil. The obtained assessments of settlements show that they cannot be ignored and it is reasonable to perform an annual leveling check of settlements of foundation or base of the bell tower It is offered, therefore, to carry out investigation before the beginning of reconstruction using the structure model, which makes it possible to give consideration to the impact of «new» loads to exclude any possible emergency situation at the objects being reconstructed.*

Keywords

Bell tower, cyclic strain-induced creep, dynamic monitoring, safety of buildings and structures, vibrations, vibrational impact, vibrodiagnostics.

1. Introduction

The most problematic are the works requiring dismantling of the bearing and fencing structures built into original scheme. Kroonstad Naval Cathedral, building of the church of Transfiguration of Jesus and other significant historical buildings have become the examples of such sort of objects for Saint Petersburg. The builders and architects have succeeded to successfully solve these complex problems using the up-to-date methods of technical diagnostics and calculation by means of three-dimensional finite-element models [1], [2].

Another type of works implies a revival of ensembles of bells on the steeples [3], [4]. In order to assess possible adverse consequences of these actions, it is necessary to take into account not only the new load emerging in the structures not being used for direct purpose for long, but the possible consequences of vibrational impact on the soils of bases of structures. A group of researchers (including one of the authors of this article) under the leadership of I.V. Sitnikov from the research-and-development center No.26 of the Ministry of Defense of the Russian Federation together with the specialists of Saint-Petersburg Railway Engineering and Transportation University have conducted measurements of vibrations caused by the chimes of the bell tower of St. Isaac's Cathedral (Saint Petersburg) and analyzed the possible consequences thereof within a period of 2013-2015.

The measurements of vibrations with simultaneous determination of the robustness of brickwork of the bearing structures of steeples have been performed in two stages: in November-December 2015 in the course of installation of a big ten-ton polylinear bell on the north-eastern steeple and in December 2016 after installation of 17-ton bell on the north-western steeple of St. Isaac's Cathedral (Fig. 1).

Fig. 1: Process of installation of 17-ton bell.

The bell weighing 17-tons has been cast at Anisimov Voronezh bell foundry according to the intact drawings of 1845. The author of the drawings is Auguste Ricard de Montferrand, the architect, the builder of St. Isaac's Cathedral. The bell has been decorated with five medallions with the bas-reliefs of emperors: Peter the Great, Alexander I, Nikolai I, Pavel I and Catherine the Great.

2. Results

The acquired results have been analysed and compared with the existing requirements of standards with a view to exceedance of actual loads [5], [6], [7], [8].

In case of necessity of assessing consequences of vibrational load impact on the bearing structures the dynamic parameters thereof have been determined in the way of:

- obtaining pulsed implementations of identified resonance peaks for every free vibration mode by means of inverse Fourier transformation,
- identification and graphical representation of various waveforms.

The vibrations have been recorded «under load» in the process of chiming.

The dynamic parameters of the «beams-bearing structures of bell tower» system have been determined by analyzing the structures response to the pulsed load. The obtained frequencies and waveforms have been analyzed, response spectra determined and values of accelerations and velocities in the targeted range of frequencies (up to 50 Hz). The diagrams of measurements at the structures of the north-western bell tower, where the vibrations have been registered and the brickwork probed, are shown in Fig. 2 (north-west).

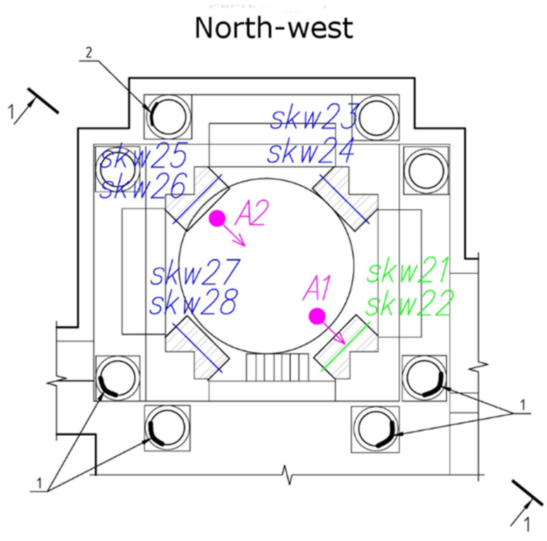

Fig. 2: Diagram of installing sensors for measuring vibrations and through probing (a 1 and a 2 – accelerometers, skw 21, 22, 23, 24, 25, 26, 27, 28 – places of brickwork probing). Digits 1 and 2 in figure designate granite columns restored in the course of general repair of the cathedral.

Results of frequency response analysis of vibrations in Fig. 3 and 4.

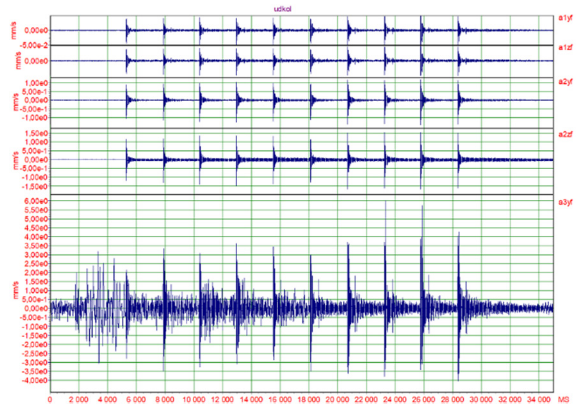

Fig. 3: Fragment of recording response to chimes of 17-ton bell.

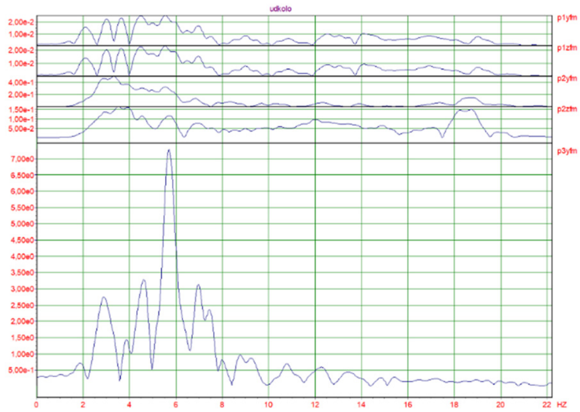

Fig. 4: Spectra of response to chimes of 17-ton bell (short section).

The measurement sensors have been arranged on the bearing structures. The numbers of sensors are shown along the right-hand vertical axis, and time in milliseconds is shown along horizontal axis, m/s^2 – along the left-hand vertical axis.

The maximum registered velocity at sensors A 3 and A 4 (metal structures) amounted to 3 mm/s, and at sensors A 1 and A 2 (at brick pillars) – 1.5 mm/s. In this case displacements amounted to not more than 15 µm at the metal frame and 2.1 µm – in the brickwork (Fig. 5).

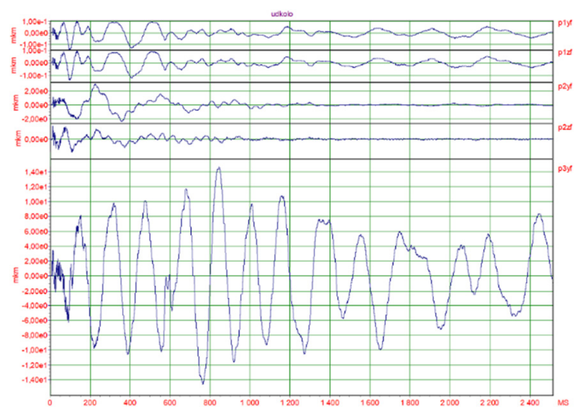

Fig. 5: Records of displacements during chimes of 17-ton bell.

The analysis of amplitude of vibrations and spectra of oscillations of the system shows that the maximum values of acceleration and velocity in the range of frequencies posing a danger to the bearing structures (up to 50 Hz) do not exceed the values at the walls − up to 2.0 m/s^2, at that, the vibration velocity of the brick pillars does not exceed 0.9 mm/s, while the displacement is up to 2.5 µm.

The maximum registered velocity has amounted to 10 mm/s. In this case the displacements have not exceeded 15 µm at the metal frame and up to 1 µm – in the brickwork.

The values of accelerations from vibrations occurring during bell tower usage are lower than it is permitted by GOST sanitary standards (2010) for office premises for the steeple structures [5].

Apparently, it is difficult to expect any considerable vibrations at the structure base with the registered values of vibrations and displacements at the bell tower structures close to the attachment points of suspensions.

The settlements of the buildings foundations in weak soils reach 2 mm/year according to data of SN (1997) and TSN (2004) [6], [7] under working conditions at the vibration velocities about 400 µm/s, while light damages of old buildings, separation of limewash, chipping of small pieces of plaster are possible at the vibration level of 1,200 µm/s.

The analysis of requirements of GOST (2007) [8] has made it possible to set a threshold value of vibrational impact on the soil ground by the velocity of oscillations of 73 dB or 225 µm/s. In case this level is exceeded it will be necessary to carry out special engineering measures to reduce vibration negative consequences for maintaining the bearing capabilities of soils, reliable and trouble-free operation of engineering structures and provision of people’s optimal vital activities. Even though, no registrations of soil oscillations at the base have been carried out while investigating vibrational oscillations of the bell tower during chimes, it is apparent that the actual values of velocities and displacements are significantly below the threshold value of vibrational impact, which can adversely affect the soil ground [9], [10], [3].

The effect of the bell tower resonance swinging is not observed during multiple chimes, since the frequencies of clappers swinging and the natural frequency bending oscillations of the bell tower differ significantly.

The maximum oscillations in the course of regular work of bells occur in the steel frame structures. However, the pulse transmitted to the suspension beam and further to the bell tower is quite insignificant. The measurements of vibratory oscillations have shown that the maximum values of velocity and acceleration in the range of frequencies posing a danger to the bearing structures (up to 50 Hz) do not exceed the values at the walls − up to 2.0 m/s^2, at that, the vibration velocity of the brick pillars does not exceed 0.9 mm/s, while the displacements are up to 2.5 µm.

In our case, when investigating the north-western steeple of St. Isaac's Cathedral, the maximum velocities of oscillations, maximum displacements and the values of frequency of spectral maximum for horizontal oscillations in the north-western direction obtained at different steeple levels when ringing the bells have been measured. Using experimental data, it is also possible to build a dependence of amplitude of oscillations on elevation points. The acquired full-scale data can be described as a parabolic dependence proving the bending character of oscillations [11].

Nevertheless, in the course of bell swinging the vibration levels at frequencies normally about 2 Hz may cause significant destruction [12]. One can say that a potential danger of vibratory oscillations provoked by the chimes of heavy bells remains for the bearing soil capability. This adverse impact sets in because of uneven settlement, when the soil becomes substantially non-uniform by its properties.

It is also important to involve a theory of cyclic strain-induced creep for assessing and calculating soil settlements. According to formula:

$$S = \alpha\sqrt{t} \, , \tag{1}$$

where, S − settlements in mm, a − intensity of cyclic strain-induced creep, t − time in minutes. It equals $10^{-2} \div 10^{-1}$ mm / $\sqrt{\text{min.}}$ for marshy soils with soil-bearing load of about 2 kg/cm^2 (such soil-bearing load is produced by the weight of the north-western steeple, including the cathedral base used for supporting it). This implies that the settlements can amount to 0.5 ÷ 0.05 mm during half an hour of chimes. In case of repeated impacts the settlements will get recommenced and summarized. A danger emerges not because of significant settlements, but rather due to irregularity owing to inhomogeneity of soil [13], [14], [15]. The obtained assessments of settlements show that they cannot be ignored and it is reasonable to perform an annual leveling check of settlements of foundation or base of the bell tower.

3. Conclusion

The effect of St. Isaac's Cathedral bell tower resonance swinging is not observed during multiple chimes, since the frequencies of clappers swinging and the natural frequency bending oscillations of the bell tower differ significantly. It is important to take into consideration that the process of foundation settlement corresponds to quite a durable change, therefore, it is necessary to establish an instrumental monitoring and take the due engineering decisions for soils stabilization.

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