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Dynamic-geophysical tests of the technical condition and earthquake-resistance of historical buildings

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Abstract:

The object of research is historical structures, assessment of their technical condition and seismic resistance. Historical buildings are at great risk of destruction not only due to aging and wear of structures, but also due to the impact of dynamic and static loads of natural and man-made impacts, the intensity of wear can significantly increase and the building can become unsafe. The most dangerous are dynamic loads associated with vibration impact on structures from the passage of heavy vehicles and impacts from earthquakes. To assess the technical condition of historical buildings required a reliable non-destructive method of natural oscillations for assessing the degree of their wear and seismic resistance. That is, the method of researching historical structures should be non-destructive. It is proposed to use new non-destructive dynamic-geophysical method based on background microseismic vibrations of soil construction system for the integral assessment the technical condition and earthquake-resistance of historical buildings. **The result** of non-destructive studies by the method of dynamic-geophysical testing of historical structures will be an assessment of their technical condition and seismic resistance.

1 Introduction

Destructive and non-destructive methods are applied to assess the technical condition of soil construction system. Non-destructive methods for assessing the state of structural elements of buildings include: visual, geodesic, ultrasonic, electromagnetic methods, sclerometry, control of crack opening width using gypsum and glass beacons etc [1]. Using these methods, local parameters of strength, flaws in geometry (rolls, subsidence, deflections), and the thickness of load-bearing structures at controlled points are obtained. Based on the obtained data of local values: geometry, strength, cross-sections, state of the structural design and possible loads, verification calculations are performed. In most cases, verification calculations for assessing the load-bearing capacity of structures and soils are performed separately, that is, the joint operation of the soil construction system and its reaction to loads are not taken into account. With the advent of modern calculation methods implemented in various complexes of engineering analysis programs, calculations for assessing the stress-strain state of structural systems of buildings can be performed taking into account the properties of soils at the base of the structure. However, the accuracy of the calculations will depend on the accuracy and completeness of the data obtained on the state of the soil and the structural system of the building. The integral three-dimensional assessment of the object, physical, mechanical and dynamic characteristics of the soil massif is a very difficult and complex task. To create reliable three-dimensional numerical models of the soil construction system, it is necessary to have detailed data on the parameters: strength, geometry, defects of the soil-structure system and loads, which, as a rule, is not implemented in practice [2], [3]. The only way that provides a reliable integral assessment of the reaction of structures and the soil construction system to an external dynamic load is full-scale tests. Considering a structure in the form of a finite element model with the properties of a real object and placing measuring sensors along the structure and soil base, one can test the structure-soil system to external influences and get its system response to a given load.

The most difficult task is to assess the seismic resistance of structures. Test methods are used to record the response of a structure to the specified test load. In modern conditions this is done on seismic stands or seismic platforms, but such tests cannot be performed for real objects. Tests are performed using vibrators, which are installed directly on the structure, however, due to the enormous power of the vibrators and the need to create resonant vibrations, this test method becomes destructive and unsuitable for protected historical objects [4]–[6].

To solve this problem, it is proposed to use a non-destructive method of dynamic-geophysical testing, in the implementation of which the dynamic parameters of the soil-structure system are determined under conditions of background microseismic effects or under the influence of weak impulse loads. Impulse loads can be created by impacts of a soft load at the top of the structure, or by impulse going through the ground, created when a heavy truck passes through an obstacle.

Speaking about surveys and tests of historical buildings, it should be noted that they have special, often non-standard design solutions and require a special approach when assessing their technical condition. To determine the most appropriate method for assessing the technical condition of historical structures, it is necessary to take into account the features of the design solutions that were used to increase the seismic resistance of the structure. For example, the builders of ancient and medieval buildings built them on the hills and used special foundations. To protect against earthquakes, soil conditions were taken into account and special design solutions were created to reduce the seismic effect on the soil construction system [7].

For example, technical solutions, when for the seismic protection of structures, slotted screens were equipped and multilayer or special configuration foundations were used, which made it possible to reduce the seismic effect on the structure., fig. 1 и 2 [8]–[10]. The Kalyan minaret, built in 1127 in the seismic region of Central Asia (Bukhara), has not been critically damaged due to its earthquake-resistant foundation and special design.

Examples of such structures are the Kalyan minaret, the antique Parthenon temple in Athens, the Ai-Sophia temple in Istanbul, the Geghard temple and the antique temple in Garni in the Republic of Armenia, the ancient mausoleum in the Islamic Republic of Iran and other historical buildings.

When constructing structures, builders took into account the terrain, ground conditions, understanding the wave nature of seismic impacts, they created special design solutions that reduce the wave effect of earthquakes. They paid special attention to the geometry of structures and terrain, using the rigid and pliable properties of structures and soils. For historical buildings erected on the hills, an obvious connection is visible between the proportions of the structures by their length, width and height and the proportions of the hills on which they were built.

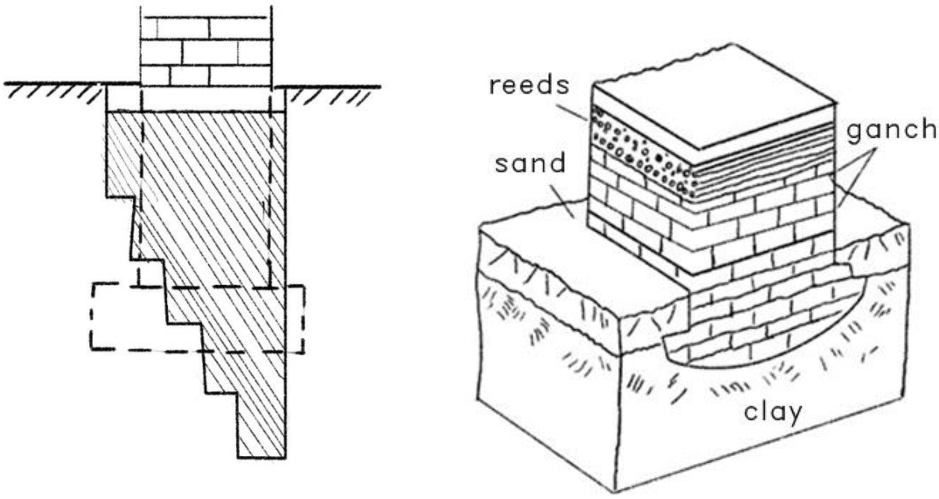

Fig. 1 - Seismic resistant structural solutions of the foundations of ancient temples in Central Asia.

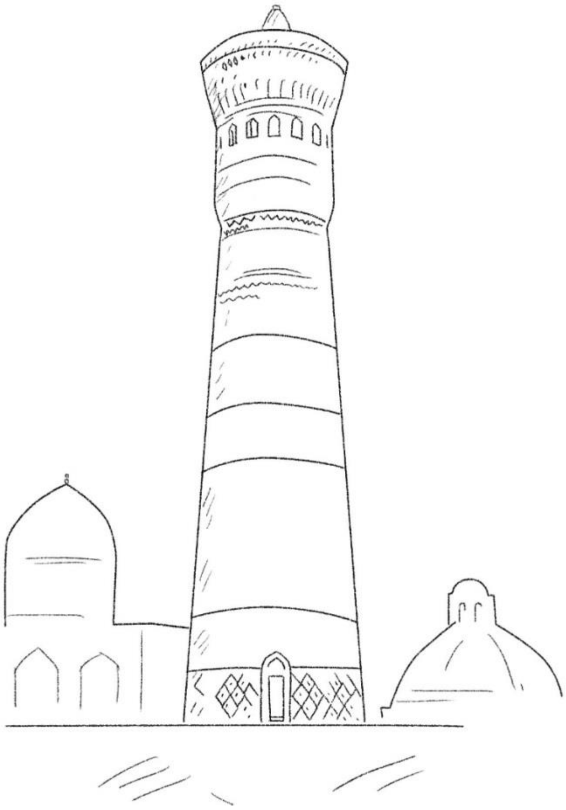

Fig. 2- An example of an earthquake-resistant high structure in Central Asia is the Kalyan minaret, built in 1127 in the city of Bukhara.

Fig. 3 - The ancient mausoleum of the 14th century of the famous Iranian Sufi Abu Garladani in the Islamic Republic of Iran in Isfahan. (Original photo made by one of the authors)

An example of such an ancient building, where the architect understood the oscillatory connection of the structures of the building, is the mausoleum of the 14th century in Iran. In Fig. 3 it can be seen that the minarets of the mausoleum have expansion joints.

There are two minarets on the portal of the mausoleum, if a person swings one of the minarets from the inside, then at the same time a neighboring minaret starts to swing with it and a bell rings on it. This example shows that the ancient masters knew and used the secrets of resonant oscillations. It is believed that the mausoleum was built from sandstone and feldspar according to the project of Al-Amili, a famous artist at the court of Shah Abbas 1.

The ancient builders apparently understood how mass, strength, geometry and cross-section of structures affect the rigidity, load-bearing capacity and seismic resistance of structures. They created constructive solutions for the soil-construction system, allowing to reduce the seismic effect on structures transmitted through the soil [11], [12].

Thus, it can be argued that most of the historical structures, that have survived in our time, are located on hills or uplands and have strong rocky soils at the base. This indicates that at the stage of the project, serious surveys were carried out to identify the properties of the soil massif.

The purpose of the research is to show the possibility of using a non-destructive integral method of dynamic geophysical testing to assess the technical condition and seismic resistance of historical structures, taking into account the influence of soils at their base.

To achieve this goal, it is necessary to solve the following tasks:

- Compare non-destructive methods of control of structures;
- Show the relationship between the square of the frequency of a structure and its rigidity;
- Show the empirical relationship between the geometry of the structure and its design feature;
- Show the criteria for categorizing structures of various designs;
- Show how to assess the technical condition of the structure by changing the frequency of natural oscillations.
- Show how to calculate the seismic resistance of a structure, taking into account the influence of soil vibrations at their base;
- Give examples of calculations of the technical condition and seismic resistance of historical structures.

2 Methods

On the basis of 30 years of experimental research, the authors established that the dynamic parameters of the structure depend on geometric parameters, strength characteristics of construction materials, design, construction mass and construction quality.

In order not to collapse, structures must reliably combine all these parameters. In a structural design, the parameter that combines properties of geometry and strength is rigidity. It is possible to assess the rigidity of a structural system through the parameters of its vibration, since they depend on its size, mass and rigidity.

Such connection between the square wave frequency, length, mass and rigidity can be seen from the solution of the differential equation describing the oscillations of a beam of length l [13]–[15]:

$$f_1^2 = \frac{\pi^4 EJ}{l^4 m} \quad (1)$$

f_1 is beam oscillation frequency, Hz;

l is length of the beam, m;

m is linear mass of a beam, kg/m;

E is modulus of elasticity, N/m2;

J is moment of inertia of the beam section, m^4.

On the basis of empirical data, the authors established a connection between geometry, design, and the oscillation frequency of structures. To determine the standard value of the oscillation for an intact structure, the authors propose the following connection:

$$f_i = \frac{\sqrt{gL_i}}{kH} \quad (2)$$

L_i is length of the side of the structure in the horizontal plane along which the oscillation period is determined, m

H is height, m;

k is Coefficient for the block building, equal to 0.3;

g is acceleration of gravity, m/s^2.

Comparing the frequencies of natural oscillation of structures with periods of oscillation of soil masses, one can see that the smaller the difference between the frequencies of oscillations of soils and structures, the greater the likelihood of damage to the structure due to the resonance effect. A criterion characterizing the degree of damage to the structure, it is proposed to use a relative value, which shows the degree of reduction of the standard value of the square of the frequency of natural oscillations, relative to the measured value of the square of the frequency of oscillations:

$$\vartriangle EJ_i = \left(\frac{[f_i^2] - f_i^2}{[f_i^2]}\right) * 100\% \quad (3)$$

Where:

$[f_i^2]$ is the square of the standard value of the frequency of natural vibrations of the structure in the directions X, Y, Z;

${f_i}^2$ is squared frequency of natural oscillation of the structure in the directions X, Y, Z, measured during the test;

ΔEJ_i is relative decrease in the rigidity of the structure.

From the formula (3), having obtained the percentage reduction in stiffness, according to table No. 3 we can determine the category of the technical condition of the structure.

3 Results and Discussion

Applying formula (2), it is possible as an example for comparative analysis to calculate the oscillation frequencies of some historical buildings and hills at their base. To calculate the period of oscillation of the hills, a correction was made to formula (2), taking into account the greater mass of the hill relative to the mass of the structure. Let us consider examples of dynamic parameters for various historical structures and their soil foundations, obtained by calculations and experimentally.

Table 1. The oscillation frequencies of historical buildings and the hills at their base, obtained by calculation.

№	Name of structure	The length of the structure (x), m	The width of the structure (y), m	Construction height (h), m	Oscillation frequency along the X axis (fx), Hz	Oscillation frequency along the Y axis (fy), Hz	Oscillation frequency along the Z axis (fz), Hz
1	Santa Maria del Suffragio, L'Aquila in L'Aquila in the Republic of Italy	22	17	15.4	3.125	2.78	1.43
2	The prevailing period of natural oscillation of soils in the city of L'Aquila (obtained experimentally)				3.3-2	13.89	12.5-2

Table 2. Oscillation frequencies of structures obtained experimentally by the authors.

№	Name of structure	The length of the structure (x), m	The width of the structure (y), m	Construction height (h), m	Oscillation frequency along the X axis (fx), Hz	Oscillation frequency along the Y axis (fy), Hz	Oscillation frequency along the Z axis (fz), Hz
1	Temple of St. John in Leon, Republic of Nicaragua	25	23	9.7, (19.55)*	[7.143], 4.167	[4.76], 3	[3.3], 3.85
2	Buddhist temple in	12.87	12.3	14	3.356	3.23	2.38

	Nepal						
3	The predominant period of the natural oscillations of the hill on which the temple was erected				6.41	5.62	1.2
4	Armenian Apostolic Church of the monastery complex in the village of Geghard of the Republic of Armenia	13.3	10.77	22.7			

* The brackets indicate the height of the bell tower. The square brackets indicate the normative values of periods of natural oscillations of structures.

For example, let's consider assessment of seismic resistance of the Armenian Apostolic Church of the monastery complex in the village. Geghard of the Republic of Armenia (see Fig. 4-7).

Fig.4 - Armenian Apostolic Church of the monastery complex in Geghard of the Republic of Armenia. (Original photo made by one of the authors)

The construction consists of two blocks erected on a rock massif. The walls of the structure are made of natural stone. Stone vaulted ceilings.

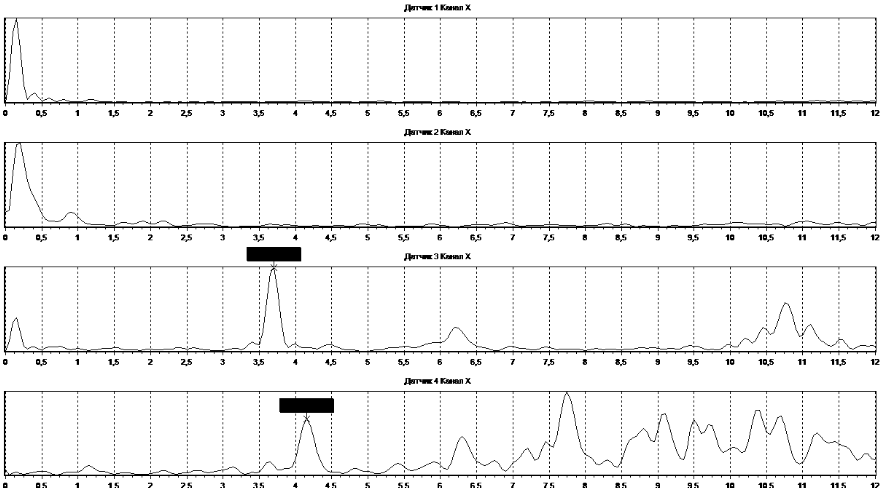

Fig. 5 - An example of the spectrum of the natural oscillations (1 sensor - soil, 2 - the zero level of the building, 3 - the bell tower of the church, 4 - the cornice of the opening in the altar of the church) along the X axis.

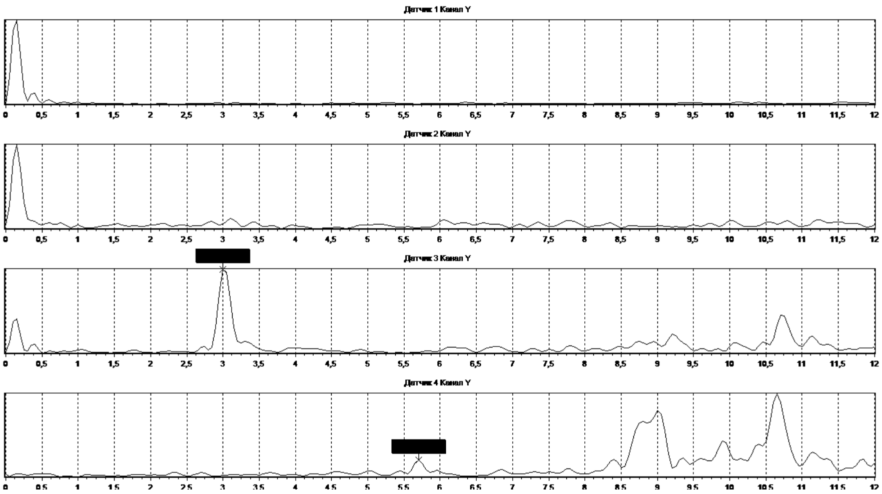

Fig. 6 - An example of the spectrum of the natural oscillations (1 sensor - soil, 2 - the zero level of the building, 3 - the bell tower of the church, 4 - the cornice of the opening in the altar of the church) along the Y axis.

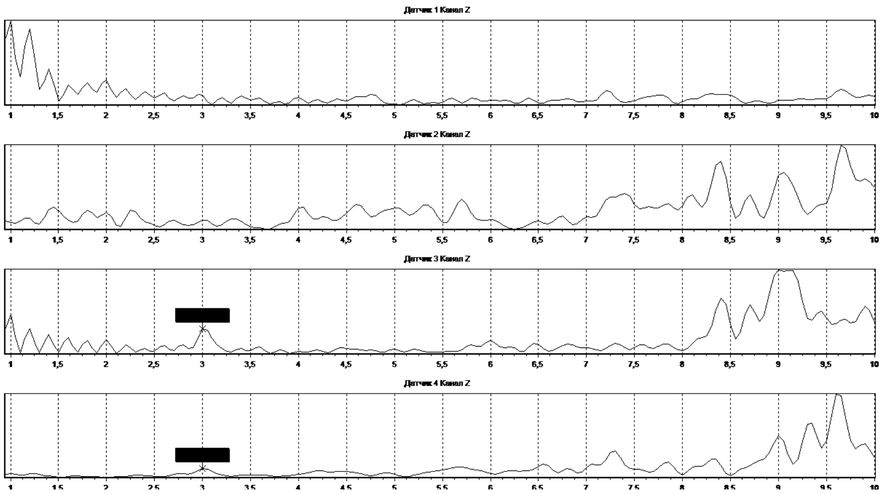

Fig. 7 - An example of the spectrum of the natural oscillations (1 sensor - soil, 2 - the zero level of the building, 3 - the bell tower of the church, 4 - the cornice of the opening in the altar of the church) along the Z axis.

During dynamic tests of the soil-structure system, microseismic effects of soil on the building were recorded. To register seismic pulses, a multichannel seismic measuring complex with five threecomponent acceleration sensors was used. The first sensor was installed at the base of the building and on the ground, the rest in the building in accordance with the test scheme. The calculated values of the natural oscillation of the building were determined taking into account their spatial dimensions and structural design:

Table 3. Standard values of the natural frequencies of the church

№ of the block	[Fx]	[Fy]	[Fz]
2	2.4	2.4	3.14
1	1.1	1.2	5.6

A spectral analysis of the data obtained as a result of dynamic tests shows that the frequencies of natural oscillations of the blocks along the first tone along the X, Y, Z axes have the following values:

Table 4. Data of dynamic geophysical tests of the church.

№ of the block	F_x, Hz	F_y, Hz	F_z, Hz
2	3.5	2.1	2.0
1	2.6	2.7	2.75

The stiffness deficit along the X, Y and Z axes of the building is determined by comparing the calculated and experimental data:

$$\triangle f_x\% = (\frac{[f_{1x}^2] - f_{1x}^2}{[f_{1x}^2]})*100\% = 65.96\%$$

$$\triangle f_y\% = (\frac{[f_{1y}^2] - f_{1y}^2}{[f_{1y}^2]})*100\% = 58.38\%$$

$$\triangle f_z\% = (\frac{[f_{1z}^2] - f_{1z}^2}{[f_{1z}^2]})*100\% = -48.22\%$$

A stiffness deficit was found along the Y and Z axes; a stiffness deficit was not found along the X axis. The permissible acceleration value or seismic resistance can be determined using the value of the period of natural vibrations obtained from the test results and the value of the permissible roll or displacement value.The values of displacements and rolls are easily connected with each other, by the following dependency:

$$\triangle d = i * h \tag{3}$$

Where
i is the maximum permissible roll;
h is the height of the object.
To calculate the value of acceleration A through the displacement Δd, we apply the relation

$$A = \frac{4\pi^2 \triangle d}{k_0 k_1 k_\varphi \beta(T) T^2} \tag{4}$$

Where
Δd is maximum permissible displacement of the structure [16];
k_0 is coefficient taking into account the peculiarity of the constructive solution and the degree of its responsibility K0 [17];
k_1 is coefficient taking into account permissible damage k_1 [18];
k_φ is coefficient taking into account the dissipative properties of the structure, k_φ [19];
β (T) is the dynamic coefficient of the structure [20];
T is period of natural vibrations of the structure.

On the basis of calculation and experimental data, authors found that a decrease in stiffness of more than 30% leads to a decrease in the category of technical condition and seismic resistance, see table. No. 3 and the formula (4). Using the obtained dynamic parameters in the example, the permissible maximum accelerations that the structure can withstand under seismic effects along the X, Y, and Z axes were calculated.

Table 5. Assessment of earthquake resistance and deficiency of earthquake resistance of building blocks:

№ block	Ax, m / s2	Ay, m / s2	Az, m / s2	Earthquake resistance deficit, m / s2
2	2.9	2.2	2	2.3
1	3	3.2	3.4	1.3

Table 6. The percentage reduction in stiffness (squared frequency of the natural oscillation of the structure) depending on the category of technical condition [7].

Type of construction	The percentage of relative decrease in the rigidity of the structure in its various conditions			
	weak	medium	strong	full
low-rising brick building (one, two floors)	22-33	33-55	55-78	78-100
Multi-storey brick building (three floors or more)	20-30	30-50	50-75	75-100
Wooden houses	20-27	27-40	40-67	67-100

The highest damage to the structure is expected at close values of the frequencies of natural oscillations of the soil base and structure. To exclude resonance phenomena in the soil-structure system, a condition must be fulfilled under which the oscillations created by the soil massifs should be 60% or more different from the oscillations of the structure.

An example of insufficient rigidity to absorb a resonant seismic load is the collapse of a dome structure in the city of Aquilla in the province of Abruzzo in Italy after the impact of a catastrophic earthquake in 2009. For the Church of Santa Maria del Suffraggio in the city of Aquila in the Republic Italy, the ratio between the periods of construction and soil is 1-1.6, which is less than 2 and corresponds to the resonant state, this apparently contributed to the collapse of the dome. From the traces of seismic waves on the pavement, it can be established that the waves moved parallel to the facade of the temple (in the direction of the X axis) and the direction of the collapse of the dome coincided (or opposite) with the direction of the waves.

Fig. 8 - Church of Santa Maria del Suffraggio in Aquilla, damaged after the seismic impact of the earthquake in 2009. (Original photo made by one of the authors)

When examining and testing historical structures, non-destructive control methods are required that do not violate the integrity of the structure and its serviceability, while taking into account the effect of the soil mass at the base of the structure. The currently applied non-destructive testing methods solve local problems [21], [22] and cannot give a reliable assessment of the technical condition of the entire soil-structure system. In contrast to these methods, using the method of dynamic-geophysical testing, an integral assessment of the technical condition [23]–[26] and seismic resistance of the entire soil-structure system is obtained.

Comparison of non-destructive methods of inspection (Table 7) shows that an integral assessment of the soil construction system can only be given by the method of dynamic-geophysical tests.

Table 7. Comparison of non-destructive methods of inspection and testing of structures

№	Control test methods	Instruments	What controls	Labor intensity Cost Efficiency	Result for the soil construction system
1	Visual method	Camera, ruler, caliper, measuring tape, probes	Visible defects	time-consuming; average price; not effective	Local. Unable to retrieve latent defect data. Impossible to evaluate soils
2	Strength method	Ultrasonic and Impact Strength Measuring Instruments	Strength	time-consuming; average price; medium effective	Local
3	Geodetic method	Theodolite, level, tacheometer, roulette	Banks, inclines, deflections	time-consuming average price medium effective	Local and integral
4	Geophysical method	Georadar, seismic prospecting complex «LAKOLIT»	Structure and physic-mechanical properties of soil	time-consuming; high price; effective on soils and individual structures	Local
5	Dynamic geophysical method	HARDWARE AND SOFTWARE SYSTEM «STRUNA»	Rigidity of buildings and structures	little laborious; low price; effective	integral

4 Conclusions

The following new scientific results were obtained:

1. A comparison of non-destructive methods for monitoring structures is given, it is determined that an integral assessment of a structure can be performed only by the method of dynamic geophysical tests;

2. The rationale for the use of the squared frequency of natural oscillations of the structure to assess its stiffness has been completed;

3. Empirical dependencies are given for assessing the standard values of the frequency of natural oscillations of structures, depending on their geometry and design;

4. The criteria for assessing the technical condition of structures by changing the square of the measured natural frequency of the structure relative to the standard square of the frequency of natural vibrations are given;

5. The dependence is given for assessing the seismic resistance of historical structures according to the dynamic parameters of structures and soil at its base;

6. Examples of assessing the deficiency of rigidity (technical condition) and seismic resistance of historical structures are given.

It can be concluded that as stated above, traditional survey methods do not make it possible to integrally assess the technical condition and seismic resistance of the "soil-structure" system, evaluate its dynamic and stiffness parameters, and obtain data on hidden system defects.

With the traditional approach, there is a high probability of missing hidden defects in structures and soils, errors in the development of the model due to the lack of data on strength measurements and section parameters.

The proposed non-destructive integral method of dynamic-geophysical tests is experimental, therefore, data on the technical condition of the structure and seismic resistance are obtained from the real data of the object with its real characteristics and existing defects. The reliability of the results obtained is confirmed by the operating data of the objects tested by the method of dynamic-geophysical testing, both in Russia and abroad.

Thus, the method of dynamic-geophysical testing can be used for both operational and detailed assessment and continuous monitoring of the category of the technical condition of historical structures, their seismic resistance and seismicity of the soil massif at the base of structures.

References

1. Ismail Ibrahim, K.M.H., Ibrahim, T.E. Effect of historical earthquakes on pre-stressed anchor tie back diaphragm wall and on near-by building. HBRC Journal. 2013. 9(1). Pp. 60–67. DOI:10.1016/j.hbrcj.2013.02.008.

2. Hoveidae, N., Fathi, A., Karimzadeh, S. Seismic damage assessment of a historic masonry building under simulated scenario earthquakes: A case study for Arge-Tabriz. Soil Dynamics and Earthquake Engineering. 2021. 147. Pp. 106732. DOI:10.1016/j.soildyn.2021.106732.

3. Saretta, Y., Sbrogiò, L., Valluzzi, M.R. Seismic response of masonry buildings in historical centres struck by the 2016 Central Italy earthquake. Calibration of a vulnerability model for strengthened conditions. Construction and Building Materials. 2021. 299. Pp. 123911. DOI:10.1016/j.conbuildmat.2021.123911.

4. Stepinac, M., Lourenço, P.B., Atalić, J., Kišiček, T., Uroš, M., Baniček, M., Šavor Novak, M. Damage classification of residential buildings in historical downtown after the ML5.5 earthquake in Zagreb, Croatia in 2020. International Journal of Disaster Risk Reduction. 2021. 56. Pp. 102140. DOI:10.1016/j.ijdrr.2021.102140.

5. Verdum, G., Bersch, J.D., Guerra, F.L., Socoloski, R.F., Giordani, C., Zucchetti, L., Masuero, A.B. Mortar coating degradation in historical buildings facades from Rio Grande do Sul – Brazil. Construction and Building Materials. 2021. 310. Pp. 125221. DOI:10.1016/j.conbuildmat.2021.125221.

6. Yasser, E.M., Rakha, T. A scoping review of non-destructive testing (NDT) techniques in building performance diagnostic inspections. Construction and Building Materials. 2020. 265. DOI:10.1016/j.conbuildmat.2020.120542.

7. Jiménez, B., Saloustros, S., Pelà, L. Seismic vulnerability index method for hybrid timber–masonry structures. Numerical calibration and application to the city of Valparaíso, Chile. Journal of Building Engineering. 2021. 44. Pp. 103185. DOI:10.1016/J.JOBE.2021.103185.

8. Iskhakov, Y., Klochko, A., Kudusov, A. Vibration testing of a monolithic reinforced concrete dome. Concrete and reinforced concrete. 1974. 5. Pp. 10–11.

9. Todorov, E.I. Nondestructive Testing and Evaluation. Encyclopedia of Materials: Metals and Alloys. 2022. Pp. 168–192. DOI:10.1016/B978-0-12-819726-4.00145-9.

10. Nsengiyumva, W., Zhong, S., Lin, J., Zhang, Q., Zhong, J., Huang, Y. Advances, limitations and prospects of nondestructive testing and evaluation of thick composites and sandwich structures: A state-of-the-art review. Composite Structures. 2021. 256. Pp. 112951. DOI:10.1016/J.COMPSTRUCT.2020.112951.

11. Lupășteanu, V., Lupășteanu, R., Chingălată, C. Condition assessment of buildings in Romania: A proposed method and case study. Journal of Building Engineering. 2022. 47. Pp. 103814. DOI:10.1016/J.JOBE.2021.103814. URL: https://linkinghub.elsevier.com/retrieve/pii/S2352710221016727 (date of application: 1.02.2022).

12. Palagala, V.Y., Singhal, V. Structural score to quantify the vulnerability for quick seismic assessment of RC framed buildings in India. Engineering Structures. 2021. 243. Pp. 112659. DOI:10.1016/J.ENGSTRUCT.2021.112659.

13. Methodology for assessing and certifying the engineering safety of buildings and structures. Moscow. Moscow, VNII GOChS, 2003.

14. Panovko, Y. Foundations of Applied Vibration and Impact Theory. Leningrad, Mechanical engineering, 2010.

15. Li, S.Q., Liu, H.B., Chen, Y.S. Vulnerability models of brick and wood structures considering empirical seismic damage observations. Structures. 2021. 34. Pp. 2544–2565. DOI:10.1016/J.ISTRUC.2021.09.023.

16. Işık, N., Halifeoğlu, F.M., İpek, S. Nondestructive testing techniques to evaluate the structural damage of historical city walls. Construction and Building Materials. 2020. 253. Pp. 119228. DOI:10.1016/J.CONBUILDMAT.2020.119228.

17. Pallarés, F.J., Betti, M., Bartoli, G., Pallarés, L. Structural health monitoring (SHM) and Nondestructive testing (NDT) of slender masonry structures: A practical review. Construction and Building Materials. 2021. 297. Pp. 123768. DOI:10.1016/J.CONBUILDMAT.2021.123768.

18. Mouhine, M., Hilali, E. Seismic vulnerability for irregular reinforced concrete buildings with consideration of site effects. Materials Today: Proceedings. 2022. DOI:10.1016/J.MATPR.2022.01.038. URL: https://linkinghub.elsevier.com/retrieve/pii/S2214785322000657 (date of application: 1.02.2022).

19. Timoshenko, S., Jang, D., Yiver, Y. Fluctuations in engineering. Moscow, URSS, 2006. 475 p.

20. Akatev, V., Nigmetov, G., Nigmetov, T. Influence of extent of reinforcing of the ferroconcrete beams on its amplitude-frequency characteristic. TECHNICAL SCIENCES. 2015. № 3. Pp. 10–14.

21. Nigmetov, G., Rybakov, A., Savinov, A., Nigmetov, T. Modern Approaches to Assessing the Risk of Structural Collapse. Civil SecurityTechnology. 2018. 15(2). Pp. 26–29.

22. Grube, G.-R., Kutschmar, A. Gert-Rainer Grube, Aribert Kutschmar: Structures from the Romanesque to the present. A picture manual. 4th editio . Berlin, Huss-Medien / Verlag Bauwesen, 2004. 239 p. ISBN:3-345-00817-3.

23. Kirikov, B. Selected pages of the history of earthquake-resistant construction. Moscow, Science, 1993. 344 p. ISBN:5-03-002994-X.

24. Kirikov, B. Ancient and Newest Eartquakke Resistant Structures. Moscow, Mir Publishing House, 1990. 72 p. ISBN:5-02-006041-0.

25. Nigmetov, G., Akatev, V., Savinov, A., Nigmetov, T. Estimation of seismic resistance of buildings by the dynamic-geophysical method, taking into account the peculiarity of the interaction of the seismic wave with the “soil-construction” system. Structural Mechanics and Analysis of Constructions. 2018. 1. Pp. 24–30.

26. The use of elastic oscillations of different wavelengths to evaluate the dynamic parameters of buildings and structures and assess the strength of materials of the building construction Savin S., Tsakalidis V.

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