ASSESSMENT OF THE STRESS-STRAIN STATE OF STRENGTHENED BUILDINGS IN SEISMIC REGIONS TAKING INTO ACCOUNT SOIL DYNAMIC PARAMETERS

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Abstract: *The main objective of the article is to assess the stress-strain state of building structures under seismic action taking into account the dynamic characteristics of the soils. As well as an assessment of the effectiveness of strengthening method of masonry building based on the Time History Analysis of the bearing capacity of structures.*

During the study a real existing masonry building is chosen. The building is modeled with the Lira-SAPR computer software with usage of the proposed strengthening method. Then, with the help of full-scale tests, the geophysical characteristics have been determined, as well as the prevailing period of the soil. Based on the existing engineering-geological and obtained by us geophysical data, the synthetic accelerogram corresponding to the masonry building soils have been chosen. The Time History Analysis of the building structures under seismic action have been carried out using previously obtained accelerogram, where the results have been compared with the standard Response Spectral method. And, finally, based on a comparison of various methods for assessing the bearing capacity, the effectiveness of building strengthening has been evaluated. The results of this study can assist the structural engineer in making better decisions for future design decisions.

Keywords: *seismic impact, soil dynamic parameters, structural system, stress-strain state, strengthening, masonry building.*

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Introduction

There are many different calculation methods for analysis of stress-strain state of building structures, as well as for assessing the bearing capacity of structures. The main method for computation of buildings is the Response Spectral method. This method depends on the soil category. Time History Analysis directly depends not only on the soil category, but also on the period, since the accelerogram includes all parameters that depend on the dynamic characteristics of soils. One of the main difficulties in the calculation is the selection of the correct accelerograms for the calculation of buildings. Until now, various countries of the world use a different approach when choosing these accelerograms. For a correct assessment of the bearing capacity of structures, it is necessary to set such accelerograms that correspond to the construction site under consideration.

Therefore, one of the main parameters influencing on bearing capacity of buildings and structures and the stress-strain state of their structures during seismic action, is the subsoil of the building. Usually, for assessment of the bearing capacity of the subsoil they are limited to engineering and geological studies of the soil. But in special cases it is also necessary to have the geophysical characteristics of soils. In some building codes it is necessary to compare the periods of the building and the soil. The structural system of a multistory building according to building codes of Armenia[1] should be chosen so that the conditions $T_1 > 1.3T_0$ or $1.3T_1 < T_0$ are met, where T_0 is predominant period of the ground, and T_1 is the first mode free oscillations

[1] HHSHN 20-04-2020. Yerkrasharjadimackun shinararutyun. Nakhagtsman normer, Yerevan, 2020 (in Armenian).

period of the structures. At the same time, it is necessary to compute the structures with implementation of accelerograms, taking into account the subsoil dynamic characteristics.

Among numerous problems of modern urban development, the problem of strengthening, retrofitting and reconstruction of existing buildings and constructions in current construction takes one of leading places. Issues are very actual as the majority of different types of buildings constructed in Republic of Armenia are not satisfying requirements of operating building codes[2,3,4] [1]. With the global scientific and technological advance of the recent years the earthquake resisting building code of the RA have undergone to certain changes, as a result of which the buildings and constructions erected years ago do not meet the current demands of operating building codes. The current demands of seismic code have been made strict, so the bearing systems of the many public and civil buildings, erected in the period of the USSR, are subject for strengthening and reconstruction.

The main goal of the research work presented herein, is the investigation of structural behavior in action of static and dynamic loads of the existing college building with masonry walls by FEM analyses taking into account soil dynamic parameters, as well as an assessment of the effectiveness of strengthening building structures based on the analysis of the bearing capacity of structures. The building's structures were designed in the years 1970-1980 in accordance with the structural concepts of that period. It was designed for earthquake loads, according to the provision of old codes, much lower than those require by current code.

Materials and Methods

Initial data for the masonry building

The building of the State Agricultural College named after G. Aghajanyan, located at 5 Student Street, Nor Geghi community, Kotayk region, RA, has been selected for the project (Fig. 1).

Fig. 1. *General and interior views of the building*

College building is a four-storey building with load bearing stone walls. It has a complex outline, about 51.5x16.5m axial dimensions in the plan. The standard floor height of the building is 3.2m (floor height was observed from floor to floor). The building has two staircases inside. The solution of the structural system of the building is given with 4 longitudinal and connecting transverse walls of stone structures, with partial reinforeced concrete frames in the internal longitudinal walls, with horizontal hard disks of the midfloor slabs and the roof slab. The axial distances of the longitudinal walls of building are 6.4m, 3.3m and 6.4m, respectively, and the transverse walls are installed at a distance of 17.0m (Fig. 2).

[2]HHSHN 20-04-2020. Yerkrasharjadimackun shinararutyun. Nakhagtsman normer, Yerevan, 2020 (in Armenian).

[3]HHSHN 20.06-2014, Shenkeri yev karrutsvatskneri verakarrutsum, verakangnum yev uzheghatsum. Himnakan druytner, Yerevan, 2014 (in Armenian).

[4]HHSHN 52-01-2021, Betone yev yerkatbetone karrutsvatskner. Nakhagtsman normer, Yerevan, 2021 (in Armenian).

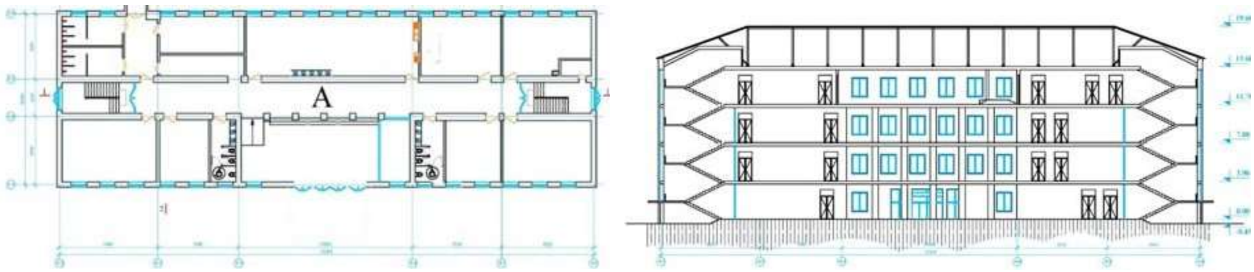


Fig. 2. *The first floor plan and section of the uilding*

The observation of the side facade of the building shows that there are beam foundations made of rubble masonry with basalt stones. The walls are made of "Midis" type load bearing stone walls using tuff stones and lime mortar, 55cm thick. External walls are made of dressed tuff stones. The partial reinforced concrete frame used in the internal longitudinal walls is made of in-situ reinforced concrete, the columns have a square cross section of 40x40cm, they are plastered with mortar. Some of the columns are plastered to a 50cm diameter circle. The beams of the internal reinforced concrete frames have a rectangular section with 50x60cm. Slabs are made of hollow core reinforced concrete panels and the part of fourth floor slab is made of in-situ reinforced concrete. The staircases consist of prefabricated reinforced concrete stairs, which rely on steel stringers. The roof is multi-sloped with external drainage system and it is constructed with timber rafter system as well as covered by steel profile sheeting.

The main defects of the building

The building with its structural-planning solutions does not comply with the requirements of earthquake resistant construction codes applied in RA related to the buildings with bearing stone walls, moreover, it is worth mentioning that there were no anti-seismic measures taken in the structural system of the building. The distances between the transverse walls in the structural system of the building considerably exceed the requirements of current codes, for this type masonry the permissible size is 6m. The some of transverse bearing walls in transverse direction is not located on the full width of the building (they are interrupted). In the transverse walls of the building there are openings which are too big in size. Slab panels are installed closely to each other, without anti seismic belts. The width of the piers of external bearing walls and of corner parts is considerably smaller than the values required by earthquake resistant construction codes, for this type masonry the width of piers should be not less than 2m and for the piers of corner parts the required width is 2.3m. The number of floors does not meet the requirements of the current codes, for schools and colleges it can be no more than three. Overall, the building is in a sufficient condition in case of static impact, and in case of an earthquake weaker than the designed one. The building condition is insufficient according to operating earthquake resistant construction building code. In order to provide enough strength and stiffness for the building and to minimize the possible damages and decay in the structure in case of seismic impact, it is necessary to provide a completely new structural system for the building. The new structural system should be designed so that it entirely gets the possible seismic load [1-12].

Some features for strengthening of masonry buildings in RA

According to operating codes it's permitted to increase the level of seismic resistance in buildings instead of the strengthening. The quantitative value of “Increment the seismic resistance” is the coefficient Ks ($0.5 < Ks < 1$) that is equal to $Ks = \sum S / \sum Sn$, where $\sum S$ is the sum of seismic forces at the upper level of the basis (Seismic Base Shear) that is resisted by a building as a result of strengthening (“Increment of seismic resistance), $\sum Sn$ is the sum of seismic forces at the same level that is determined by calculation according to operating codes.

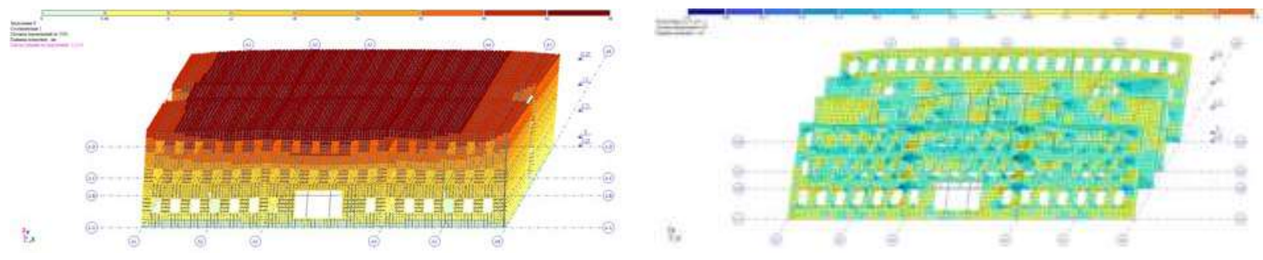
Modeling of multi-story masonry building by software and analysis of the stress-strain state of the masonry structures without strengthening

The building has been modelled under seismic actions by operating building codes having in mind the existing bearing system (without top floor), with deficiencies of the structural system and real soil parameters.

Initial data:

1. The calculations are made to increase the level of seismicity (for three floors bearing system, Ks = 0.5).
2. The calculations of the building are made by Lira SAPR 2017 software. The building is calculated as a 3D model, from vertical loads and seismic impact, in the direction of the digital and letter axes of the building [9-11].
3. The characteristics of the materials of bearing structures in the FEM model:
   - concrete B25 (strength of compression 25 MPa),
   - heavy concrete, average density R = 2500 kg/m^3, modulus of elasticity E_b = 3060000 t/m^2,
   - stone walls "Midis", modulus of elasticity E = 96000 t/m^2, average density R = 1760 kg/m^3.
4. The general parameters for calculation from seismic impact:
   - seismic zone (0.3g) – 2,
   - soil category – II, soil conditions coefficient – K_0 = 1,
   - building and structure permissible damage coefficient – K_1 = 0.6.
5. The calculation is made with the following loads:
   - Load 1 - self weight of the bearing structures,
   - Load 2 – dead load,
   - Load 3 – live long term load,
   - Load 4 – live short term load,
   - Load 5 – seismic impact in the longitudinal direction for the determination of the stresses,
   - Load 6 – seismic impact in the transverse direction for the determination of the stresses,
   - Load 7 – seismic impact in the vertical direction for the determination of the stresses.
6. As the results of the calculation are presented: period of oscillation, displacements and storey drifts, main tensile stresses in the "Midis" type walls (Fig. 3).

According to camputations the oscillations period values of the first mode are: by the axis X – T_1 = 0.246s, by the axis Y – T_1 = 0.481s:



a) *b)*

Fig. 3. *a) - Displacements and storey drifts from seismic impact by the axis Y,*
b) - The main tensile stresses from seismic impact by the axis X

Maximum storey drift Δy, max = 17.10mm > [Δ] = H/600 = 3750/520 = 7.2mm. For dressed stones and "Midis" type masonwork the maximum value of permissible storey drift is h/600. The main tensile stresses in the masonwork is σρ = 91.9 t/m^2 > [σρ] = 20.0 t/m^2 (Table 9, point 4a, RABC IV-13.01-96 Stone-reinforced stone structures). The calculations have shown that the condition is not met.

Modeling and analysis of the stress-strain state of the building with strengthenings

To increase the level of seismic resistance, it is planned to demolish the fourth floor, increase the cross-section of the columns, reinforce the load-bearing walls with shotcrete and add new monolithic reinforced concrete walls and frames in the transverse direction, dismantle the staircase and build a new one on site from in-situ reinforced concrete, reinforce the floor slabs with a reinforced concrete layer 50mm thick. The strengthened plan for the building is shown in Figs. 4-5 [1].

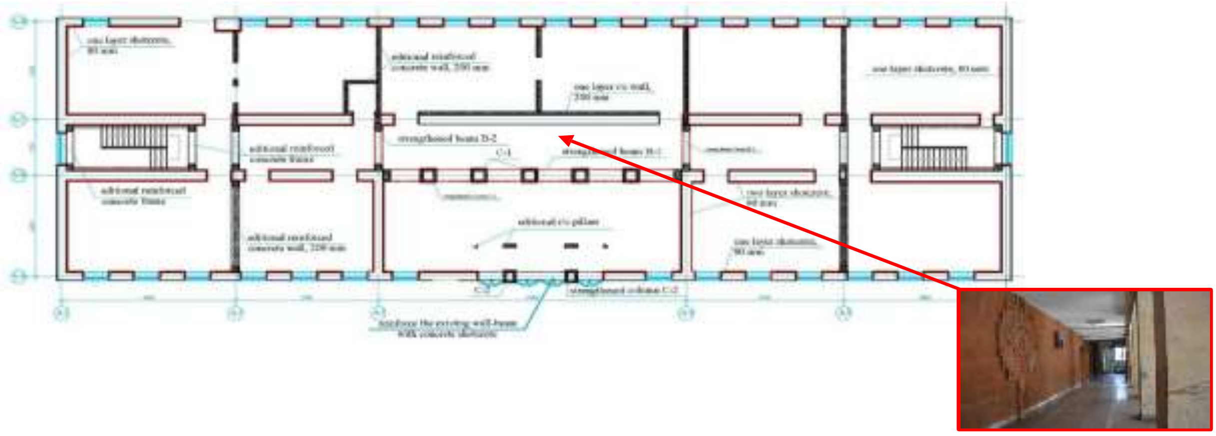


Fig. 4. *The strengthened plan for the building and interior view*

Initial data:

1. The calculations are made to increase the level of seismicity (for three floors bearing system, Ks = 0.5).
2. The calculations of the building are made by Lira SAPR 2017 software. The building is calculated as a 3D model, from vertical loads and seismic impact, in the direction of the digital and letter axes of the building [9-11].
3. The characteristics of the materials of bearing structures in the FEM model:
   - concrete B25 (strength of compression 25 MPa),
   - heavy concrete, average density R = 2500 kg/m^3, modulus of elasticity E_b = 3060000 t/m^2,
   - one-layer shotcrete (strength of compression 25 MPa), thickness 8cm, average density R = 2100 kg/m^3, modulus of elasticity E_b = 2240000 t/m^2,
   - two-layer shotcrete B25 (strength of compression 25 MPa), thickness 6cm, average density R = 2100 kg/m^3, modulus of elasticity E_b = 2240000 t/m^2,
   - stone walls “Midis”, modulus of elasticity E = 96000 t/m^2, average density R = 1760 kg/m^3.
4. The general parameters for calculation from seismic impact:
   - seismic zone (0.3g) – 2,
   - soil category – II, soil conditions coefficient – K_0 = 1,
   - building and structure permissible damage coefficient – K_1 = 0.6.
5. The calculation is made with the following loads:
   - Load 1 - self weight of the bearing structures,
   - Load 2 – dead load,
   - Load 3 – live long term load,
   - Load 4 – live short term load,
   - Load 5 – seismic impact in the longitudinal direction for the determination of the stresses,
   - Load 6 – seismic impact in the transverse direction for the determination of the stresses,
   - Load 7 – seismic impact in the vertical direction for the determination of the stresses.
7. As the results of the calculation are presented: period of oscillation, displacements and storey drifts, main tensile stresses in the “Midis” type walls (Fig. 6-7).

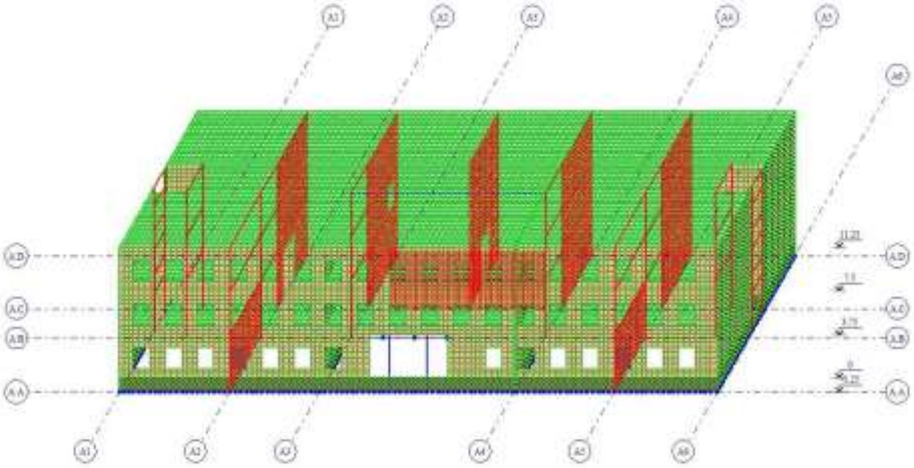
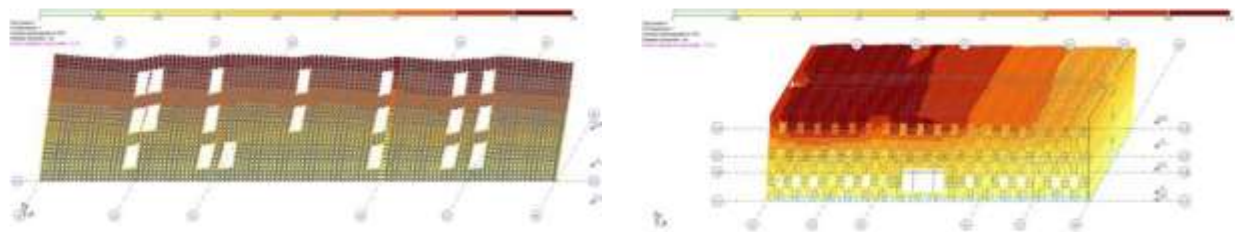


Fig. 5. *The new bearing system of the building with additional elements*

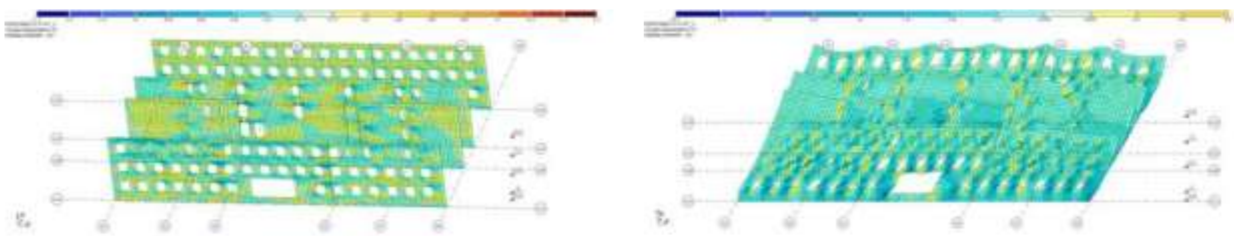
According to camputations the oscillations period values of the first mode are: by the axis X – $T_1 = 0.099$s, by the axis Y – $T_1 = 0.14$s. As the calculation results show, the oscillations period values decreased by 2.5 times. For buildings and structures with largely uniform distribution of rigidities and masses along the height, if the oscillations period value of the first mode is $T_1 < 0.4$s only the first oscillation mode is considered[5].



a) *b)*

Fig. 6. *a)- Storey drifts from seismic impact by the axis X,*
b) - Storey drifts from seismic impact by the axis Y

Maximum storey drift Δx, max = 0.70mm < [Δ] = H/600 = 3750/520 = 7.2mm. Maximum storey drift Δy, max = 2.10mm < [Δ] = H/600 = 3750/520 = 7.2mm. For dressed stones and "Midis" type masonwork the maximum value of permissible storey drift is h/600. The calculations have shown that the condition is met.



a) *b)*

Fig. 7. *a) - Storey drifts from seismic impact by the axis X,*
b) - Storey drifts from seismic impact by the axis Y

[5]HHSHN 20.04-2020, Yerkrasharzhadimatskun shinararutyun. Nakhagtsman normer, Yerevan, 2020 (in Armenian).

The main tensile stresses in the masonwork in ***longitudinal direction walls*** is σρ=17.5 t/m^2 < [σρ]=20.0 t/m^2 (seismic impact by the axis X), σρ = 6.35 t/m^2 < [σρ] = 13.0 t/m^2 (seismic impact by the axis Y), (Table 9, point 4a, RABC IV-13.01-96 Stone-reinforced stone structures).

The results of the calculations show that the new bearing system developed for the building satisfies all the requirements of the seismic building codes. We can note that the strengthening project can be developed based on the proposed bearing system.

Synthetic accelerograms for structural analysis

According to archival data the Nor Geghi community of the RA is located on the right bank of the Hrazdan River, in the southern part of the Yeghvard Plateau, in the geological structure of which columnar andesite-basalts of the Lower Quaternary age play the main role. Andesite-basalts are fine-grained, porous and fissured, which on the territory of the plateau plane are covered with deluvial and eluvial deposits of the Upper Quaternary age, represented by sandy loam and loam, with a content of andesite-basalt fragments of 20–40%. Their thickness varies about 10m, sometimes reaches 30m.

According to the specified characteristics, the type of soil in terms of seismicity belongs to the 2nd category, what was accepted in the calculations of buildings. An instrumental determination of the geotechnical parameters of the soil was carried out to check the accuracy and efficiency of the work performed. For geotechnical investigation fieldwork were used Multichannel Surface Wave Analysis (MASW) method. It is evaluating ground stiffness by measuring shear-wave velocity (Vs) of subsurface in the most common depth range of 0-30 meters. This method accepted in the seismic building code of Armenia. MASW first measures seismic surface waves generated from various types of seismic sources - such as sledge hammer, analyzes the propagation velocities of those surface waves, and then finally deduces shear-wave velocity (Vs) variations below the surveyed area that is most responsible for the analyzed propagation velocity pattern of surface waves. Shear-wave velocity (Vs) is one of the elastic constants and closely related to Young's and shear moduli. Under most circumstances, Vs is a direct indicator of the ground strength (stiffness) and therefore commonly used to derive load-bearing capacity.

In practice, surface wave registrations (MASW) were carried out with the help of an Italian-made digital seismic station PASI GEA24.

In the upper layers of the engineering-geological section, the dynamic characteristics of the ground were interpreted as the mean velocity of transverse waves Vs30. The values of the velocities of shear waves are obtained on the basis of four tests (Vs1 = 827.8 m/s, Vs2 = 837.6 m/s, Vs3 = 716.6 m/s, Vs3 = 755.0 m/s). The shear waves' average velocity of the studied area's ground is 700 < Vs < 840 m/s, according to HHSHN 20.04-2020 heterogeneous ground substrate soils correspond to soil category II.

According to the results of experimental data from the database of open accelerograms accepted for the software, a suitable accelerogram was selected for further calculations. Directory DBN_ACCEL contains eight sets of three-component synthesized accelerograms. Every file of accelerogram has a *.txt extension and is an ordinary text file. The file contains an array of acceleration values (m/s^2).

Table 1. Parameters of three-component synthesized accelerograms

Name of accelerogram file	Range of prevailing periods Tpr, s	Amplitude of max acceleration A, m/s^2	Step of discretization Ät, s	Number of points N	Time of accelerogram
Vb1r	0.1 - 0.3	1.485	0.0125	10500	131.2375
Vb1t	0.1 - 0.3	1.298	0.0125	10500	131.2375
Vb1z	0.1 - 0.3	0.972	0.0125	10500	131.237
vb1_mod29	Vb1r + Vb1t + Vb1z		0.0125	310500	131.237

The results of the calculations show that the calculation with the selected accelerogram gives a more accurate picture of the stress-strain state of the bearing system of the building. At the same time, it should be noted that it is desirable to make calculations with several different accelerograms, given that they narrowly describe the possible expected earthquakes.

Results and Discussion

Below (Table 2) the values for the main dynamic parameters of the building performed by different models is showed.

Table 2. The main dynamic parameters of the building performed by different models

	Total masses (t)	Base Shear		Displacement		Storey drift		Tensile stresses			
		Px (t)	Py (t)	X (mm)	Y (mm)	Δx (mm)	Δy (mm)	LW by X (t/m^2)	LW by Y (t/m^2)	TW by X (t/m^2)	TW by Y (t/m^2)
Model 1 without strengthening	6602.5	2135	1995	12.0	48.0	4.1	17.1	91.9	82.4	74.5	262.0
Model 1 with strengthening	7657.3	1730	1815	1.9	4.6	0.7	2.1	17.5	6.35	5.07	20.3
Model 1 by accelerogram	7635.5	1780	1525	7.08	3.74	2.36	1.25	21.6	23.4	11.3	38.7

Comparative analysis shows that the results of the spectral analysis meet all the requirements of the operating building codes, but when calculations were made by the accelerogram the values of main tensile stresses in some parts of the masonwork can exceed the allowable values by about two times. Therefore, in order to increase the efficiency of the structural projects, it is necessary to make a calculation with at least three suitable accelerograms.

Conclusion

The correct choice of the method for analysis the stress strain state of the bearing structures, taking into account geotechnical investigation of the soils, will make it possible to more accurately assess the stress-strain state of building structures. In this case, the structural project will also be effective.

In the case of building strengthening, before developing the project of increasement the level of buildings seismic resistance it is often necessary to understand whether it is economically profitable to strengthen the building or it will be effective to build a new one. In general, when the cost of strengthening project exceeds 70% of the new construction, it is more expedient to build a new one.

The method presented in the work can be used to easily assess the geotechnical parameters of the soil without drilling, on the basis of which, using FEM analysis, it is possible to determine the expediency of strengthening the structures. Based on the results of the work, we can say that the parameters determined by the MASW method match the actual data for the investigation of the stress-strain state of the building structures, so the above method will allow to get rid of drilling work at the initial stage of the project, saving money and time.

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