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RESEARCH ARTICLE

ASSESSMENT OF SEISMIC RISK AND RELIABILITY BASED ON THE RESULTS OF PASSPORTIZATION

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Abstract. *In the city of Almaty, a complete certification of the housing stock of multi-apartment buildings was carried out for the first time. A total of over 10 thousand buildings were inspected. The structure of the housing stock was revealed, with groups of buildings identified based on design solutions and reliability assessment. Based on the certification results, quantitative assessments of the failure probability values for various types of buildings were obtained for the first time. Formulas for assessing the quantitative value of seismic risk were obtained. The results of seismic vulnerability assessment using the classification of buildings according to the European macroseismic scale EMS-98 and the seismic scale MSK-64(K) used in the Republic of Kazakhstan are presented. The obtained results are compared. The number of multi-story residential buildings of various design types located on tectonic faults was identified. Based on global statistical data, the number of people killed in a design earthquake was assessed. An integral assessment of the reliability (probability of failure-free operation) of the multi-story housing stock of Almaty was obtained. It was shown that the demolition of non-earthquake-resistant wooden buildings will increase the overall reliability of a group of multi-story residential buildings by almost 15%. It has been established that the most dangerous buildings are those with external load-bearing walls and an internal frame; buildings with load-bearing walls made of brickwork and precast reinforced concrete floors; buildings with a height of 2 or more floors with load-bearing walls made of brickwork and wooden floors; single-storey buildings with load-bearing walls made of brickwork. The results of the quantitative assessment of seismic risk values can be used to develop rational urban development schemes and economic assessment of the territory used.*

Keywords: *passportization, risk, building, losses, reliability, repeatability, vulnerability, tectonic faults.*

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ҒЫЛЫМИ МАҚАЛА

ПАСПОРТТАУ НӘТИЖЕЛЕРІ БОЙЫНША СЕЙСМИКАЛЫҚ ТӘУЕКЕЛ МЕН СЕНІМДІЛІКТІ БАҒАЛАУ

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Аңдатпа. *Алматы қаласында алғаш рет көппәтерлі ғимараттардың тұрғын үй қорына толық төлқұжаттау жүргізілді. Барлығы 10 мыңнан астам ғимарат зерттелді. Конструктивті шешімдер мен сенімділікті бағалау бойынша ғимараттар топтарын бөле отырып тұрғын үй қорының құрылымы анықталды. Төлқұжаттау нәтижелері бойынша алғаш рет ғимараттардың әртүрлі типтері үшін ақау пайда болу ықтималдығының сандық бағалары алынды. Сейсмикалық тәуекелдің сандық мәнін бағалауға арналған формулалар алынды. Қазақстан Республикасында қолданылатын EMS-98 еуропалық макросейсмикалық шкаласы және MSK-64(K) сейсмикалық шкаласы бойынша ғимараттардың жіктемесін пайдалана отырып, сейсмикалық осалдықты бағалау нәтижелері келтірілді. Алынған нәтижелерді салыстыру орындалды. Тектоникалық жарықтарда орналасқан әртүрлі конструктивтік типтегі көп қабатты тұрғын үйлердің саны анықталды. Статистикалық әлемдік деректер негізінде есептелген жер сілкінісі кезінде қаза тапқандар санын бағалау жүргізілді. Алматы қаласының көпқабатты тұрғын үй қорының сенімділігінің (ақаусыз жұмыс істеу ықтималдығына) интегралды бағалауы алынды. Сейсмикаға төзімді емес ағаш ғимараттарды бұзу көп қабатты тұрғын ғимараттар тобының жалпы сенімділігін 15%-ға арттыратыны көрсетілген. Ең қауіптісі сыртқы күш түсетін қабырғалары мен ішкі жақтауы бар ғимараттар; кірпіш қалаудан жасалған күш түсетін қабырғалары және құрама темірбетон жабындары бар ғимараттар; кірпіш қалаудан жасалған күш түсетін қабырғалары мен ағаш жабындары бар биіктігі 2 немесе одан да көп қабатты ғимараттар; кірпіш қалаудан жасалған күш түсетін қабырғалары бар бір қабатты ғимараттар. Ал сейсмикалық тәуекел шамаларын сандық бағалау нәтижелері ұтымды қала құрылысы, пайдаланылатын аумақты экономикалық бағалау схемаларын әзірлеу үшін пайдаланылуы мүмкін.*

Түйін сөздер: *төлқұжаттау, тәуекел, ғимарат, шығындар, сенімділік, қайталану, осалдық, тектоникалық жарықтар*.

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НАУЧНАЯ СТАТЬЯ

ОЦЕНКА СЕЙСМИЧЕСКОГО РИСКА И НАДЕЖНОСТИ ПО РЕЗУЛЬТАТАМ ПАСПОРТИЗАЦИИ

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Аннотация. *В городе Алматы впервые проведена полная паспортизация жилого фонда многоквартирных зданий. Всего было обследовано свыше 10 тысяч зданий. Выявлена структура жилого фонда с выделением групп зданий по конструктивным решениям и оценки надежности. По результатам паспортизации впервые получены количественные оценки величин вероятности отказа для различных типов зданий. Получены формулы для оценки количественного значения сейсмического риска. Приведены результаты оценки сейсмической уязвимости с использованием классификации зданий по Европейской макросейсмической шкале EMS-98 и сейсмической шкалы MSK-64(K), применяемой в Республике Казахстан. Выполнено сопоставление полученных результатов. Выявлено количество многоэтажных жилых зданий различных конструктивных типов, расположенных на тектонических разломах. На основе статистических мировых данных проведена оценка количества погибших при расчетном землетрясении. Получена интегральная оценка надежности (вероятности безотказной работы) многоэтажного жилого фонда города Алматы. Показано, что снос не сейсмостойких деревянных зданий увеличит общую надежность группы многоэтажных жилых зданий почти на 15%. Установлено, что наиболее опасными являются здания с наружными несущими стенами и внутренним каркасом; здания с несущими стенами из кирпичной кладки и сборными железобетонными перекрытиями; здания высотой в 2 и более этажей с несущими стенами из кирпичной кладки и деревянными перекрытиями; одноэтажные здания с несущими стенами из кирпичной кладки. В результаты количественной оценки величин сейсмического риска могут быть использованы для разработки схем рационального градостроительства, экономической оценки используемой территории.*

Ключевые слова: *паспортизация, риск, здание, потери, надежность, повторяемость, уязвимость, тектонические разломы.*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу Қазақстан Республикасы Ғылым және жоғары білім министрлігі Ғылым комитетінің ИРН AP23485057 "Тектоникалық ақауларды паспорттау және есепке алу нәтижелері бойынша көп қабатты үйлер үшін тәуекелді статистикалық бағалау" гранттық қаржыландыру шеңберінде жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось в рамках грантового финансирования Комитета науки Министерства науки и высшего образования Республики Казахстан ИРН AP23485057 "Статистическая оценка риска для многоэтажных жилых домов по результатам паспортизации и учета тектонических разломов".

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

1 INTRODUCTION

The districts of the Almaty metropolis constitute the most seismically active area in Central Asia. Over the past 140 years, three strong earthquakes with magnitudes of 7 – 8 have occurred here: the Verny earthquake of 1887, the Chilik earthquake of 1889, and the Kebin (Kemin) earthquake of 1911. The current population of Almaty is about 2.0 million people, and including the suburbs, about 2.5 million. The background seismicity of the city's territory, according to the MSK-64(K) scale, is 9 points. According to the old seismic zoning map, there are extensive ten-point zones composed of soft and loose soils. The entire central part of the city is literally located on tectonic faults, some of which may be seismogenic. According to the Seismic Zoning Map of the Republic of Kazakhstan, the median peak ground acceleration is 0.38 g for a recurrence period of once in 475 years and 0.73 g for a recurrence period of once in 2,475 years (g – acceleration of gravity). Since December 12, 2019, the Republic of Kazakhstan has adopted a new construction regulatory framework based on Eurocode, which provides a probabilistic description of seismic hazard parameters and formalizes the concept of risk to a significant degree.

The first building inventory in Almaty was carried out in the late 1990s under the supervision of Academician T.Zh. Zhunusov. Recommendations for building inventory were developed, and the central part of the city was surveyed. The first seismic risk assessments for Almaty were discussed at an international expert meeting held in the city on October 22-25, 1996. It was noted that, in the event of a 9-point earthquake in the Almaty region, depending on the season and time of day, up to 75 thousand people could be killed and up to 300 thousand injured. This initiated the development of the Program for the Protection of the Population of Almaty from Earthquakes (**Lobodryga & Shardarbek, 2001; Lobodryga, 2015**).

The second building inventory – a sample survey of multi-apartment residential buildings in Almaty – was carried out in 2008 within the framework of the "Study on Seismic Risk Management in the City of Almaty, Republic of Kazakhstan" under the auspices of the Japan International Cooperation Agency (JICA). The survey showed that at least 30% of multi-apartment residential buildings were non-seismic-resistant. In works **(Lapin & Erzhanov, 2016; Lapin & Erzhanov, 2017; Aldakhov, 2019)** the problems of assessing seismic risk levels for facilities in Kazakhstan and Almaty began to be considered from the standpoint of risk theory.

2 LITERATURE REVIEW

The third certification was carried out in 2017-2018 on the basis of an agreement between the State Institution "Department of Architecture and Urban Development of Almaty" and JSC "Kazakh Research and Design Institute of Construction and Architecture" (JSC KazNIISA) **(Tuleev et al., 2018; Shokbarov, 2020)**.

The results are presented in **Table 1**. These results are, as it were, experimental data on assessing the seismic resistance of the housing stock of a specific territory.

It should be noted that during the certification, a large number of photographs were obtained for all types of buildings.

It should be noted that for the first time, when examining all buildings, the practice of shooting the objects being examined from drones was implemented. Photographic materials on shooting the objects being examined from various angles are stored for each object. **Figure 1-2** show photographs of some non-earthquake-resistant buildings.

The structure of the housing stock in any settlement, including the city of Almaty, is crucial information for assessing the levels of reliability and seismic risk for a given city or metropolis.

Based on the results of the building inventory conducted in 2017-2018 **(Lobodryga & Shardarbek, 2001)**, the complete structure of the housing stock is presented in **Table 3** (multifamily residential buildings). The risk of failure is shown in **Tables 4, 5**.

The first significant result was obtained: as a result of additional inspections of multistory residential buildings, the proportion of non-seismic-resistant buildings decreased from 33.32% to

25.90%. The explanation is fairly straightforward: modern multistory residential complexes were constructed using monolithic structural solutions.

The second significant result was that only buildings with a steel frame in Almaty can be unequivocally classified as seismic-resistant. All other building types have non-zero probabilities of failure, which applies even to relatively seismic-resistant large-panel buildings. **Figure 1** shows an example of a non-seismic-resistant large-panel building

Table 1
The structure of the housing stock of the city of Almaty - apartment buildings (2017-2018)

№	Design solution	Number of buildings	Number of non-earthquake-resistant buildings	Index of non-earthquake-resistant buildings, %	Main types of non-earthquake-resistant buildings
1	Large-panel	2658	33	1,242%	Buildings with a first flexible or brick floor
2	Brick	1607	1594	99,07%	Two-story buildings with wooden floors, four-story buildings of the 60s
3	Frame	1847	59	3,195%	Individual objects
4	Monolithic	1420	27	1,902%	Single objects
5	Wooden	627	627	100%	Two-story frame-reed with a service life of over 50 years
6	Metal-frame	12	–	–	–
	Total	8171	2340	33,32%	

Figure 1 – Large-panel building with a flexible first floor, Mynbayev str.47 (author’s material)

Figure 2 – Brick building, Shcherbakov str.16 (author’s material)

Table 2
Results of the passportization of residential multi-storey residential buildings (MSRB) in 2024

Series of multi-storey residential buildings	Quantity	Non-earthquake-resistant buildings
IPkar	300	195
IPmon	1402	-
158	2	-
1Кз-464-AS	1	-
1Кз-464DS	4	-
308	2	-
69	1	-
VP	3	-
VT	2	-
IP kir	36	36
IPder	7	7
IPmetal	6	-
Reed panel frame buildings	5	5
СЖКУ (SZHKU)	2	-
СЖКУ-9 (SZHKU-9)	1	-
No buildings	3	3
total:	1777	246

Table 3
Complete structure of the housing stock of the city of Almaty according to all passports - apartment buildings

№	Design solution	Number of buildings	Number of non-earthquake-resistant buildings	Index of non-earthquake-resistant buildings, %	Probabilities of failure risk
1	Large-panel	2666	33	1,238%	Buildings with a first flexible or brick floor, built in an economic way.
2	Brick	1645	1624	98,723%	Two-story buildings with wooden floors, four-story buildings of the 60s
3	Frame	2155	251	11,647%	Individual objects
4	Monolithic	2822	27	0,957%	Single objects
5	Wooden	639	639	100%	Two-story frame-reed with a service life of over 50 years
6	Metal-frame	18	–	–	–
7	Unfinished	3	3		
	Total	9948	2577	25,90%	

Table 4
Failure risk probabilities for different building types

№	Design solution	Number of buildings	Number of non-earthquake-resistant buildings	Index of non-earthquake-resistant buildings, %	Probabilities of failure risk
1	Large-panel	2666	33	1,238%	0.0124
2	Brick	1645	1624	98,723%	0.9872
3	Frame	2155	251	11,647%	0.1165
4	Monolithic	2822	27	0,957%	0.0096
5	Wooden	639	639	100%	1
6	Metal-frame	18	-	-	0
7	Unfinished	3	3		1
	Total	9948	2577	25,90%	

Table 5
Failure risk probabilities for different building types

№	Design solution	Probability of a building of this type	Probabilities of failure risk	Probabilities of risk of failure of buildings of this group
1	Large-panel	0.2680	0.0124	0.0033
2	Brick	0.1654	0.9872	0.1633
3	Frame	0.2166	0.1165	0.0252
4	Monolithic	0.2837	0.0096	0.0027
5	Wooden	0/0642	1	0/00642
6	Metal-frame	0/0018	0	0.0
7	Unfinished	0.00030	1	0.0030

3 MATERIALS AND METHODS

Below are the average values of economic damage U of buildings by groups of buildings according to the data of Khakimov Sh.A. **Figure 3**, which were obtained during the analysis of the consequences of strong earthquakes in Central and Middle Asia **(Khakimov & Nurtaev, 2003; Khakimov & Nurtaev, 2005; Khakimov, 2001)**. Note that here there is a connection between the earthquake score and the average damage in % of the initial cost.

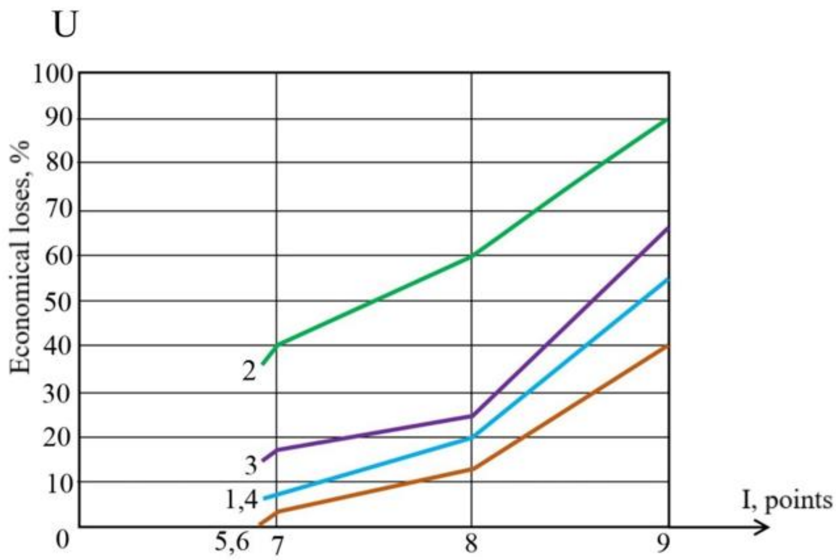

Figure 3 – Regression dependences of damage on the intensity of impact in points on a scale MSK-64 (K). (author's material)

Using the data in **Table 2** and the previous calculations, we can estimate the seismic risk R.

Using the classical definition of risk as the product of the probability of failure Q and the value of the loss function **(Seismic Risk and Engineering Solutions, 1981)**.

$$R= QU, \quad (1)$$

where U is the damage from failure as a share of the initial cost of the object. Then, according to the data in **Table 2**, for the risk value we write

$$R=0.55 \cdot N_1Q_1U_1+N_2 \cdot Q_2U_2+N_3 \cdot Q_3U_3+0.55 \cdot N_4Q_4+0.40 \cdot N_5Q_5U_5 +0.40 \cdot N_6\, Q_6\, U_6, \quad (2)$$

where Ui – average damage to a building from *the i-th* group of buildings, *Ni* is the number of non-earthquake-resistant buildings in each group from **Table 2**. The values of *Qi* can be taken from **Table 2** for a particular value of repeatability.

Taking into account N_6=0, we will have a regression dependence

$$R=0.55 \cdot N_1Q_1U_1+N_2 \cdot Q_2U_2+N_3 \cdot Q_3U_3+0.55 \cdot N_4Q_4+0.40 \cdot N_5Q_5U_5 \quad (3)$$

By substituting the values of the average initial cost, it is possible to obtain a quantitative risk assessment.

Formula 3 is fairly simple and straightforward. If all old wooden buildings had been demolished in time, then N_5=0, and the damage value would decrease significantly. The same reasoning can be applied to any building group. The damage shares relative to the initial cost are taken from the works of Khakimov Sh.A.

It is clear that classical approaches to assessing building reliability as the probability of not reaching a specified damage level are also feasible for implementation **(Khakimov, 2001; Raizer, 2010; Seismic Risk and Engineering Solutions, 1981; Dzhinchvelashvili et al., 2018; Aizenberg, 1978; Aizenberg, 2004; Raizer, 2007; Tsipenyuk, 1987; Napetvaridze, 1985; Lapin, 1998)** and it is planned to use them in further research.

Let us discuss the presence of a correlation between seismic impact intensity and the degree of building damage. **Table 5** presents the degrees of damage for each building type at a given seismic intensity. The correlation coefficient was calculated using the MATLAB software package.

Table 6

Correlation coefficients between earthquake magnitude and damage extent

№	Design solution	7 points	8 points	9 points	Correlation coefficients
1	Large panel	7	20	55	0.9667
2	Brick	40	60	90	0.9934
3	Frame	18	25	65	0.9267
4	Monolithic	7	20	55	0.9667
5	Wooden	3	12	40	0.9588
6	Metal-frame	3	12	40	0.9588
7	Unfinished				

The correlation coefficient is quite high. Therefore, the assessment of the degree of damageability and loss appears to be reliable.

Example 1. Let us estimate the overall reliability W_0 of multi-storey residential buildings in the city of Almaty. According to **Table 5**, the probability of failure for the city's facilities is Q=0.2617. Therefore, the overall reliability is W_0 = 1-Q= 0.7383.

Example 2. How will the value of the total probability of failure-free operation of WO change under the condition of complete demolition of all wooden buildings **Table 5** (639 units).

The probability of failure for the group of wooden buildings will become equal to 1, and according to **Table 4**, Q=0,1975. Therefore, the overall reliability will be:

$$W_0=0{,}8025.$$

The change in overall reliability will amount to 8%, which is quite significant. The demolition of wooden buildings should therefore be carried out.

The expression for the risk values will then take the form

$$R=0.55 \cdot N_1Q_1U_1+N_2 \cdot Q_2U_2+N_3 \cdot Q_3U_3+0.55 \cdot N_4Q_4 \quad (4)$$

Example 3. How will the values of the total probability of failure-free operation W_0 change under the condition of total reinforcement of large-panel buildings in **Table 1** (33 units).

The probability of failure for the group of large-panel buildings will become equal to 0. Then, according to the results of **Table 5**, Q = 0,2584 and Q_0 = 0.26413:

$$W_0=0.7416$$

The change in overall reliability is about 1.0%, which is not significant. An obvious conclusion follows: reinforcing large-panel buildings in the city of Almaty should be the last priority.

Finally, we will obtain estimates for human losses in the event of a possible design-level earthquake. Such estimates were first obtained during the second certification of the city of Almaty.

4 RESULTS AND DISCUSSION

There are various methods for predicting losses. It appears that all these methods are rather imperfect, with deviations reaching several hundred percent. Therefore, the statistical assessment confirmed during the 1988 Spitak earthquake **(Khachiyan, 2018)** seems well justified. According to global statistical data, the number of fatalities in earthquakes for developing countries can be estimated as follows.

In cities of developing countries:

For an 8-point earthquake on the MSK and ESC scales, on average, 0.5% of the population dies, and 2% are injured.

For a severe 9-point earthquake, on average, 5% of the population dies, and 20% sustain serious injuries.

Assuming that the total population of Almaty, including temporary residents, is 2.5 million people, the number of fatalities in an 8-point earthquake would average 12,500 people, with 50,000 injured.

In a 9-point earthquake, the fatalities would amount to 125,000, with up to 500,000 injured.

It should be emphasized that these are average estimates. The latter estimate correlates well with expert assessments from 1996, when the city's population was around 1.1 million.

This is a realistic assessment. After all, Almaty has a fairly extensive history of earthquake-resistant construction – about 60 years. The seismic construction standards are quite strict.

As a result of the passportization, the buildings were examined in terms of a macroseismic assessment according to the EMS-98 scale **(Rashid et al., 2023)**. Residential buildings were classified by type and plasticity class. They were then assigned to six vulnerability classes according to EMS-98. The degree of structural damage is assessed from slight damage to complete collapse, within a range of five levels. The expected mean damage was correlated with various seismic intensities and peak ground acceleration (PGA) values. The probability of damage was assessed for recurrence intervals of once in 475 years and once in 2,475 years.

The results of the EMS-98 assessment correspond to the conclusions of this article obtained using the MSK-64 seismic intensity scale. For masonry-walled and wooden buildings, the mean damage is very high for both earthquake recurrence intervals. The expected mean damage for reinforced concrete and precast reinforced concrete buildings with medium plasticity is rather moderate.

Buildings with steel frames will have an insignificant level of damage. This is a rare case where two methods of seismic risk assessment were applied using empirical passportization data.

5 CONCLUSIONS

1. At present, as a result of the building certification process for the city of Almaty, objective information has been obtained on the seismic resistance of six groups of multi-apartment residential buildings. This data makes it possible to carry out a quantitative assessment of seismic risk values.
2. The most hazardous are buildings with external load-bearing walls and an internal frame; buildings with load-bearing walls of brick masonry and precast reinforced concrete floors; buildings

two or more stories high with load-bearing brick masonry walls and wooden floors; one-story buildings with load-bearing brick masonry walls and wooden beam floors with normal masonry bond strength of less than 120 kPa (1.2 kg/cm²); as well as wooden buildings constructed in the 1950s without seismic-resistant measures.

3. Within the framework of the phenomenological approach, values of failure probability have been obtained for the six groups of buildings. Formulas have been derived from the quantitative assessment of seismic risk values.

4. The results of the certification indicate insufficient seismic resistance of buildings with load-bearing brick walls, 99% of which were found to be non-seismic-resistant. The seismic resistance of such buildings can be ensured only by using various types of seismic isolation systems or by the widespread application of energy-absorbing elements. JSC KazNIISA has extensive experience in applying various types of seismic isolation systems. Only the use of such systems will make it possible to prevent mass casualties and the loss of material assets. It should be remembered that in 1911 the Kemin earthquake had a magnitude of 8.2, was of a seismic disaster nature, and was felt over an area of 2 million square kilometers.

5. The results of the quantitative assessment of seismic risk values can be used for the development of schemes for the rational use of land resources, rational urban planning, economic evaluation of the utilized territory, and for providing information support for various works related to assessing the seismic hazard of the environment.

6. Research should be continued in the areas of the influence on building reliability of the following factors: quality of surveys, design, materials, and construction; technical condition, physical deterioration, specific features of operation, presence of vibration loads, and level of engineering protection.

7. Based on the results of the 2017-2018 certification, adjustments should be made to the certification card, taking into account both the experience gained and the experience of other EAEU countries. Particular attention should be paid to modern foreign studies on determining seismic risk values.

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