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Kinematic Seismic Isolation System with Magnetic Dampers

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Abstract

The aim of this study is to experimentally and theoretically investigate the behavior of a three-story fragment of a frame building constructed using the PGF-SIKF system—Prefabricated girderless frame with seismic-isolating kinematic foundations. Magnetic dampers are employed at the support level. The novelty of the research lies in the combination of a girderless frame with kinematic foundations and innovative magnetic dampers. The experimental research method involved loading the system with horizontal static force using a stationary winch, followed by the release of the load. Vibration measurements were recorded using a digital measurement system. The normative live load was simulated by applying additional static load. It was determined that the oscillation period varies between 1.8 and 2.1 seconds, depending on the amplitude of the impact. The dissipative characteristics of the seismic isolation system were obtained, with acceleration values during the testing phases ranging from 95 to 177 cm/s². The experimental results confirmed that the building fragment showed no visible damage. The logarithmic decrement of oscillations was found to range between 0.08 and 0.16. Theoretical studies involved calculations based on a sample of 14 real accelerograms, with parameters corresponding to the magnitudes of local earthquakes (M=6), the maximum magnitude expected in Shymkent. The main result is the reduction of seismic loads achieved by using kinematic foundations in the girderless frame system. It was established that, under 7-8 intensity seismic events, the average displacements at the foundation level will not exceed the experimental values.

Keywords: Seismic Isolation; Oscillation Period; Load Shedding; Oscillation Decrement; Dissipation; Results Processing; Damper.

1. Introduction

The idea of seismic isolation of buildings during earthquakes is one of the simplest and, at the same time, the most effective in the entire history of the development of earthquake-resistant construction. In the Republic of Kazakhstan, notable studies of kinematic foundations (hereinafter KF) are associated with the names of Cherepinsky & Lapin [1] and Cherepinsky [1, 2]. In 1966, he received copyright certificate No. 316817 for the design of a seismic isolating support. The first experimental studies of a residential large-panel house on the KF were carried out in Navoi in 1978 [2, 3]. In subsequent years [3, 4], dynamic tests of brick, large-block, frame-brick, and large-panel buildings on kinematic foundations up to 9 floors high were carried out in the cities of Almaty, Shymkent, Tynda, Navoi, Severo-Baikalsk, Petropavlovsk Kamchatsky, and Yuzhno-Sakhalinsk.

In 1989, on a nine-story large-panel building at KF and on a similar building only on strip foundations, stations of the engineering and seismometric service were installed. The result was a kind of testing ground for a comparative assessment of the reduction in seismic load because of the use of seismic isolating foundations [5, 6]. In addition, the

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specified building at the KF was tested immediately after construction using an inertial oscillation machine [4]. Consequently, its dynamic characteristics were determined.

During the earthquake of August 16, 2014 (earthquake source 41 km east of the city of Almaty and depth 5 km), instrumental records (accelerograms) were obtained on buildings with KF and strip foundations [6]. The intensity of the earthquake was 4-5 points. In terms of spectral accelerations, the seismic isolation effect was 2.4 times. To date, over 40 houses have been built in the city of Almaty on the KF, 1-2 in the city of Shymkent, and over 300 in the Russian Federation. As a result of experimental and theoretical studies, it was found that the use of the KF system makes it possible to reduce the calculated seismic loads by up to 2 times, reduce steel consumption by 5-7%, and the estimated cost of the building by 3-5% [7]. Quite a lot of buildings with kinematic foundations (KF) have been built in the city of Irkutsk. On August 27, 2008, a strong earthquake with a magnitude of MW = 6.2 occurred near Lake Baikal. In Irkutsk, the intensity of the earthquake was 6-7 points on the MSK 64 scale. A survey of residents who were in seismically insulated houses during the earthquake revealed that they did not even feel oscillations, unlike people in traditionally built buildings [8]. Unsecured objects fell into traditionally built buildings, and people experienced panic. An examination of seismically isolated buildings showed that no damage or cracks were found. A brief overview of the use of other types of seismic isolating structures in the Republic of Kazakhstan is given in [9].

In developed countries of the world, a lot of research has been carried out in the field of seismic isolating structures. Italy was one of the first countries in the world to use seismic isolating systems. The first earthquake-proof building (fire department in Naples) in Italy was built in 1981 [10, 11]. This is later than similar studies in the Republic of Kazakhstan. Over the past 40 years, a whole industry has developed in Italy for the production of various types of seismic isolation elements - the company “FIP Industriale”.

Calvi & Calvi [12] provides an overview of the different types of friction systems used in Europe. It is noted that friction-type seismic isolating systems appeared in Europe in the late 80s of the last century. Seismic isolation of this type is very effective and has fairly simple dynamics. Basically, Asian systems with friction connections are considered in Zhang & Ali [13]. This paper provides a detailed review of friction-based insulation systems in the light of numerical, analytical and experimental studies. Seismic isolating systems are used in significant quantities in the Russian Federation [14]. The first building with seismic isolation was built in 1959 - two houses in the city of Ashgabat. In 1970-1974, buildings were built using the seismic isolation system V.V. Nazina. Since the 80s, over 300 houses were built on the kinematic foundations of Cherepinsky [2], several buildings with seismic isolation by A.M. Kurzanov. Over 100 buildings with switchable connections by Ya.M. Eisenberg were built in Siberia and the Far East. More than 50 buildings using friction-type seismic isolation systems by L. Kilimnik were built in the Far East and Kyrgyzstan.

In the Republic of Turkey, by 2019, over 120 objects with seismic isolation elements were built [15]. It should be noted that many seismically isolated sites are hospitals with a large number of beds. That is, these are social facilities whose safety under conditions of strong seismic impact is a mandatory requirement of the developer. During the catastrophic earthquake of February 6, 2023, 5 seismically isolated hospitals were examined by specialists [16]. It was determined that 4 hospitals received virtually no damage and remained usable. One of the seismically isolated hospitals suffered significant damage due to the fact that the seismic isolation layer was practically pinched. This prevented the normal operation of the seismic isolation system.

Turkey has implemented a public-private partnership program aimed at the widespread construction of seismically isolated hospital buildings. Notably, in the city of Adana stands one of the world's largest earthquake-resistant hospitals [17]. This campus boasts a total bed capacity of 1,550, distributed among three hospital units: the main hospital with 1,300 beds, a physical therapy and rehabilitation hospital with 150 beds, and a high-security psychiatric hospital with 100 beds. The structural integrity of the campus is ensured by 1,512 base isolation rooms.

Further examples of hospital complex behavior can be found in the United States and China [18]. By 2020, New Zealand had constructed over 119 seismically isolated facilities [19], predominantly employing rubber-metal supports. Among these is a hospital covering an area of 7000 m^2, featuring a 23-story high-rise building. Seismic isolation has been widely recognized as an effective measure against earthquake damage. Traditionally, seismically isolated structures have tended to be relatively rigid. However, in the past two decades, alternative options for seismic isolating kinematic foundations have emerged, including those suitable for "flexible" buildings [20-22], characterized by longer periods of oscillation.

Recent studies highlight the use of various types of geotechnical seismic isolation systems [23]. The seismically isolated structure is surrounded by a layer composed of different geomaterials, such as silicate-soil mixtures, cement-soil mixtures, bitumen-soil mixtures, and rubber-soil mixtures. This layer acts as a damping barrier screen, reducing the intensity of seismic impact.

A significant body of research focuses on the application of different types of damping devices. In Lan et al. [24], the problem of optimal placement of 8 sets of viscous dampers on a steel frame is addressed. The results provide solutions for optimal damper placement in the design of frame structures.

Viscoelastic dampers are employed [25] to reduce the amplitude of structural oscillations across a wide frequency range of 0.1 to 25 Hz. A review by Fujii & Shioda [26] of international literature on passive damping systems examines 196 publications on various frictional, metallic, and viscous dampers. The review emphasizes that while all types of dampers are effective, the selection of devices for specific structures should consider economic feasibility. It proposes a classification of 23 types of damping devices. However, magnetic dampers are not included in this classification, highlighting the novelty of the research presented in this study. Fujii & Shioda [27] proposes using a steel damper column as an energy-dissipating element in reinforced concrete frame buildings. The efficiency of this damping system is evaluated using an energy-based approach, with examples of its application in 8- and 16-story frame buildings.

At the 18th World Conference on Seismic Isolation (18WCSI), held in Antalya, Turkey, from November 6 to 10, 2023, the latest developments, new concepts, and innovative applications related to seismic isolation, energy dissipation, and active vibration control in structures were discussed. Theoretical and experimental studies on various types of seismic isolation systems were presented, including structures with rubber-metal bearings and bearings with dry friction elements. Numerous types of damping systems were proposed, but magnetic dampers were not mentioned as a means of reducing seismic loads.

This study contributes to the body of knowledge on the use of new types of magnetic dampers in earthquake-resistant construction.

This study addresses the following issues:

- Experimental study of the dynamic characteristics of a three-story girderless frame on kinematic foundations with magnetic dampers.
- Analysis of the behavior of a dynamic model of a building fragment under the influence of real accelerograms, a sample of which was formed based on seismological information about the expected parameters of the earthquake source for the city of Shymkent.
- Present conclusions about the applicability of the proposed design solution for a kinematic-type seismic isolation system with magnetic dampers.
- Visual inspection of girderless frame structures after each loading stage.
- Present conclusions on the applicability of the proposed kinematic seismic isolation system with magnetic dampers based on experimental and theoretical studies.

Previously, such problems had not been solved.

2. Research Methodology

In 2014, a new variant of kinematic foundation was introduced through the Republic of Kazakhstan Patent No. 31353, titled "Seismic isolating kinematic foundation." Constructed from reinforced concrete of at least B-40 grade, this variant features a circular cross-section with a widened heel, also circular, and a spherical supporting surface. The operational principle remains consistent: during seismic activity, the foundation rolls atop the foundation slab. The resulting inertial force, generated by its weight, restores the building to its original position.

Subsequently, in June 2018, the Republic of Kazakhstan Patent No. 34202 was granted for the "Seismic isolating foundation" equipped with a magnetic damper. This innovation is integrated into the Seismic isolating kinematic foundation (SIKF) utilizing the PGF-SIKF technology, specifically on a 3-story segment. The magnetic damper consists of a search magnet with a 125 mm diameter, capable of exerting a magnetic force of 600 kg. Additionally, a project has been devised for a magnetic damper featuring a magnetic thrust of 3000 kg, intended for buildings with nine floors and above. Its purpose is to mitigate oscillations induced by strong winds, hurricanes, and both natural and anthropogenic factors, thereby enhancing system damping.

The experimental segment analyzed in this article encompasses the PGF-SIKF system, comprised of a vertical structure denoted as PGF, per Invention Patent No. 32274 titled "Prefabricated girderless structure 2 in 1." This structure features a cross-section measuring 400x400 mm and a floor height of 3 meters, with three above-column slabs, each 250 mm thick, arranged within a column grid of 6x7.2 meters. The inter-column slabs, resting upon the above-column slabs, possess a thickness of 240 mm, while the central and cantilever slabs are supported by the inter-column slabs, as specified in Invention Patent No. 34412 titled "Circular hollow-core slab of off-form concreting." The assembly of these structures adhered to the methodologies outlined in Invention Patents No. 33269 and No. 39137 EAPO, describing the "Method for the construction of prefabricated girderless frames of buildings with SIKF." Additionally, the connection between slabs followed the guidelines delineated in Invention Patent No. 31945, addressing the "Connecting prefabricated floor slabs of frame girderless buildings in seismic areas."

The PGF-SIKF system is characterized by its absence of crossbars and stiffening diaphragms, alongside the inclusion of voids in the slabs. These design features collectively reduce the building's weight, consequently minimizing seismic forces, shortening construction duration, and lowering housing costs.

Located in the vicinity of Shymkent, along the shores of Lake Kolken-Ata, an experimental structure was erected resembling a 3-story segment utilizing the PGF-SIKF system, titled "Prefabricated girderless frame with seismic isolating kinematic foundations." The foundation's height from the base plate to the washer measures 2630 mm, with plan dimensions of the fragment spanning 6×7.2 meters. Following structural evaluations revealing no damage, plans are underway to finalize the construction of the building fragment as outlined in the working design: a "3-story hotel-type sanatorium". In the future, it is planned to build a 3-story family-type sanatorium on the site of the steel frame model for testing. A photograph of the foundations is shown in Figure 1. The fragment is loaded with a payload of 400 kg/m2 for a total of 280 tons. Accordingly, the load on one kinematic support is 70 tons.

Figure 1. Fragment of a 3-story building with payloads

2.1. Experimental Methods

Given that the system in question is a long-period structure, it was decided to test the building fragment by applying horizontal static load using a stationary winch, followed by the release of the load. This testing method is considered classical and, for instance, was used in the early 2000s to test the airport building in Almaty. Figure 2 shows the layout of instruments and channel numbers. 3 sets of instruments were used: the eight-channel RSM-8 measurement system, a set of Aistov mechanical gauges with dial indicators, and three strain gauges.

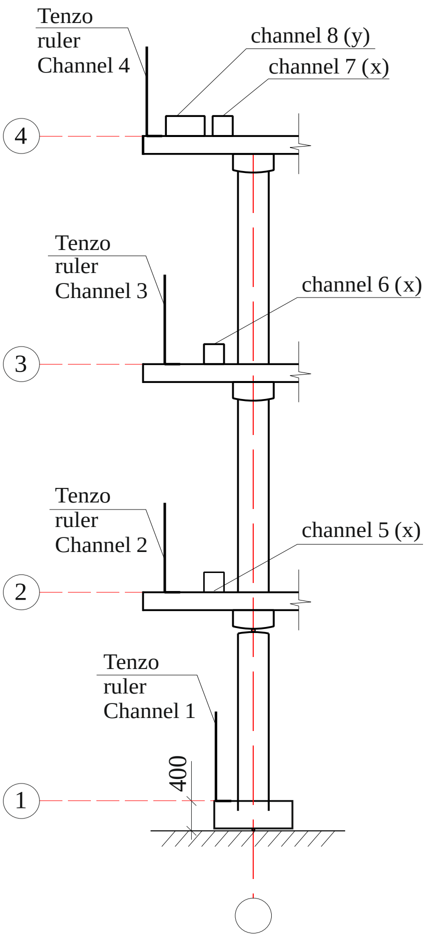

Figure 2. Arrangement of instruments

The RSM-8 system is an eight-channel digital measurement complex equipped with AT105 digital accelerometers. These accelerometers can record accelerations up to 4g across a wide frequency range. The load was applied using a powerful winch, followed by the rupture of a calibrated steel insert. After the release, the three-story building fragment underwent free damped oscillations. Measurements included inter-story displacements, accelerations, and logarithmic decrements of oscillations. Additionally, a nonlinear deformation diagram was constructed and subsequently used for calculations based on real accelerograms. The structural integrity of the building fragment was assessed by inspecting for visible damage to the load-bearing elements.

2.2. Theoretical Methods

The seismicity of the city of Shymkent and its surrounding areas is associated with the activity of the Chulinsk seismic-generating zone. Shymkent is located directly within this zone. The consolidated foundation of the area consists of carbonate-terrigenous formations, with the thickness of the Earth's crust not exceeding 40 km. Earthquakes with magnitudes of up to 6.0 are predicted along the Chulinsk fault within this consolidated foundation.

To determine the response parameters of the building fragment (a girderless frame with kinematic foundations and magnetic dampers), a dataset of 14 accelerograms was compiled. The sample was based on Californian earthquakes, including events with magnitudes between 5.3 and 6.6, and hypocentral distances from 6 to 64 km. The accelerograms are used without normalization, as previous studies have shown that normalization distorts the frequency composition of seismic events. The average horizontal component value is 207.3 cm/s², corresponding to an intensity level 8 earthquake on the MSK-64(K) scale. The difference between the median and obtained acceleration values does not exceed 10%. The standard peak ground acceleration (PGA) for this dataset is 60.0 cm/s², with a coefficient of variation of 0.29. The accelerograms were digitized with a step of 0.02 seconds, and the files are provided in text format.

A software module was developed in MATLAB to integrate nonlinear differential equations. The deformation diagram was constructed based on the results of the experimental studies. Statistical processing was then performed using MATLAB, where the sample mean, median, standard deviation, and variance of peak acceleration, velocity, and displacement values were calculated. Finally, the theoretical results were compared with the corresponding experimental characteristics.

3. Results

The tests were conducted in 2 stages with varying levels of horizontal loads. The horizontal forces were measured using dynamometers. After each stage of testing, a visual inspection of the load-bearing structures of the building fragment was carried out. No damage was observed.

Figures 3 to 5 show instrumental recordings of accelerograms in millivolts obtained as a result of tightening the winch at the 1st stage of the test, and Figures 6 to 8 - at the 2nd stage. Figures 3 to 5 show 3 sections of acceleration increase due to turning the winch off and on. The oscillations exhibit a highly non-stationary nature.

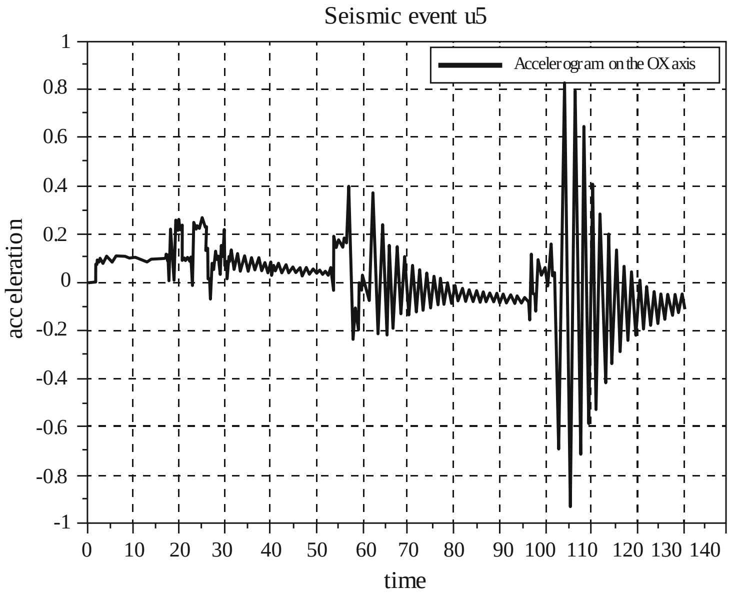

Figure 3. Original recording channel 5, recording stage 1

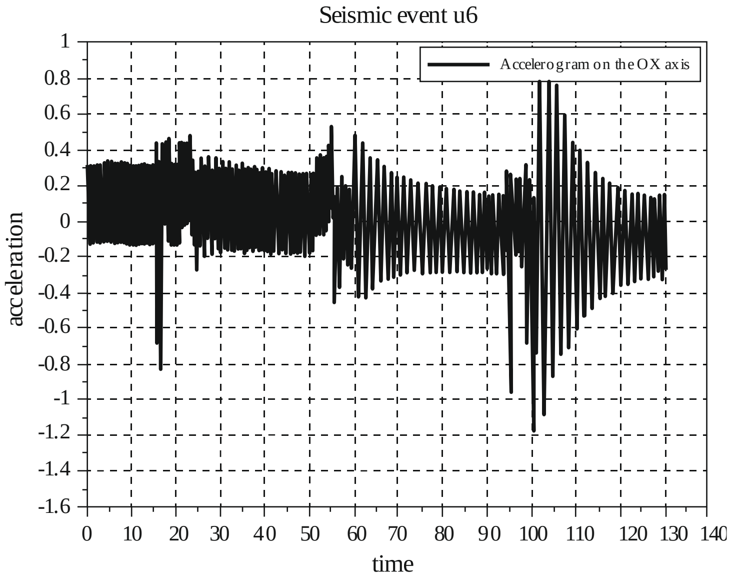

Figure 4. Original recording channel 6, recording stage 1

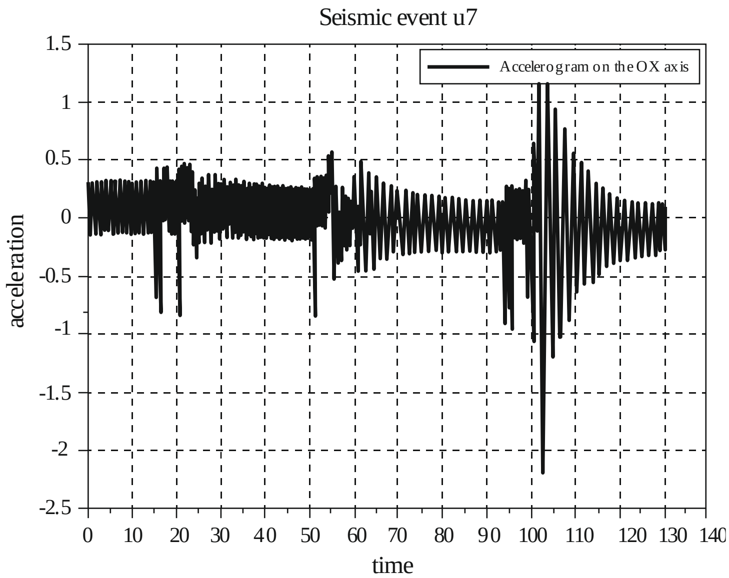

Figure 5. Original recording channel 7, recording stage 1

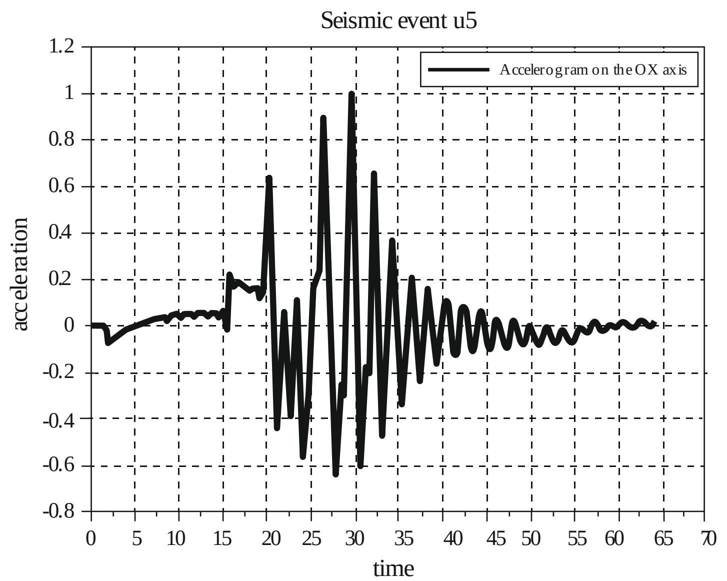

Figure 6. Original recording channel 5, recording stage 2

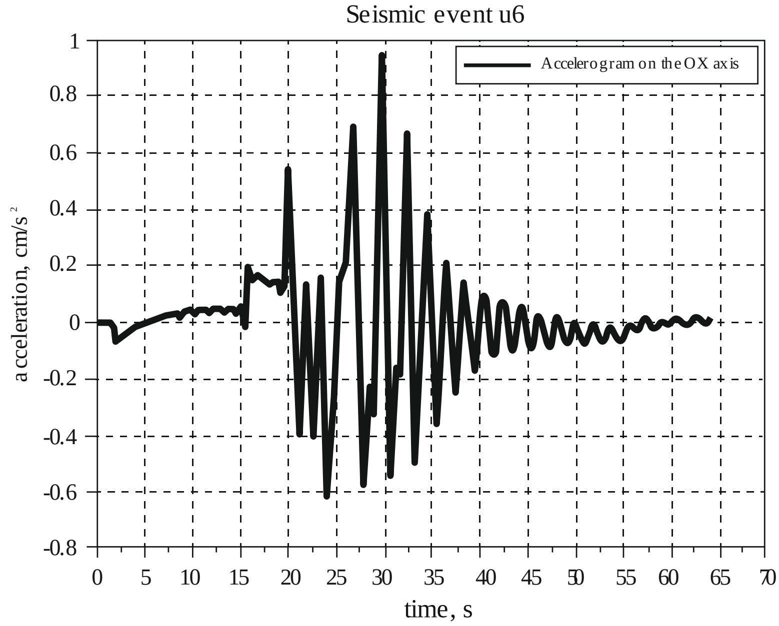

Figure 7. Original recording channel 6, recording stage 2

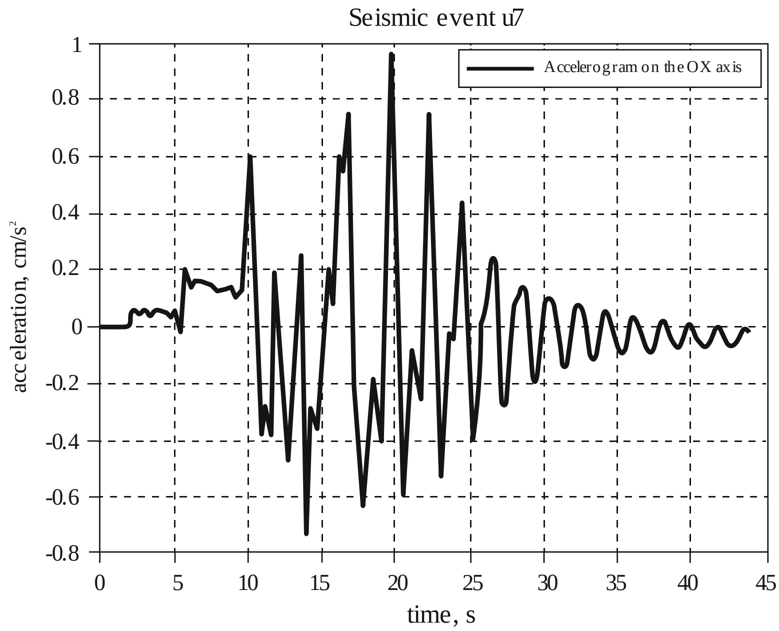

Figure 8. Original recording channel 7, recording stage 2

Channel 1 is a digital sensor installed directly on the foundation body. Channels 2 and 5 are sensors located at the first-floor level, Channels 3 and 6 are positioned at the second-floor level, and Channels 4 and 7 are at the third-floor level. Each figure indicates the channel number, allowing the identification of the recording location for each instrumental measurement (Figure 2).

After the loads were reset, the values of the oscillation periods and decrements were determined on the attenuated sections of the instrumental recordings.

In the first stage of testing, sections of accelerograms up to 18 seconds in duration were used to determine the oscillation period and logarithmic decrement. In the second stage, accelerogram sections up to 50 seconds in duration were analyzed.

In Figures 9 to14, accelerograms of the free oscillation section are presented as a result after complete load removal and filtering of the accelerogram, as well as correction of the zero line. The values of maximum accelerations at the test stages are given (95-177 cm/s^2). It is obvious that there is a damped oscillatory process due to the inclusion of kinematic foundations in the work.

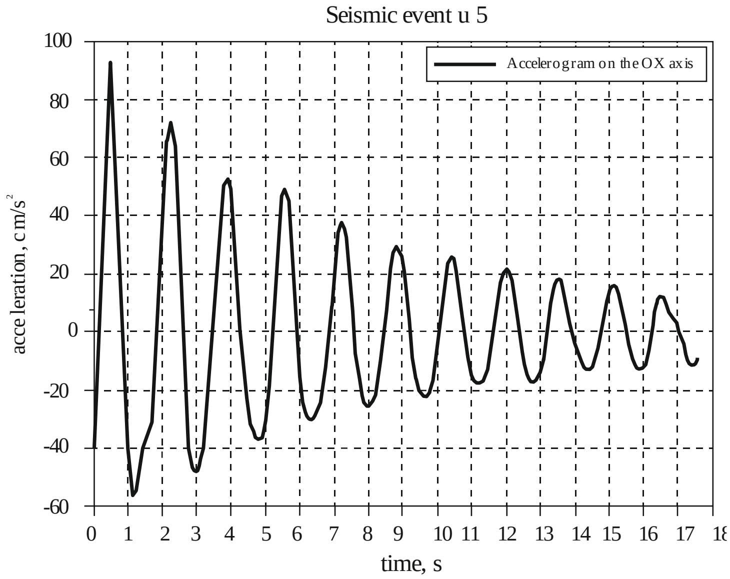

Figure 9. Free oscillations 5 channel, 1 stage, 95 cm/s²

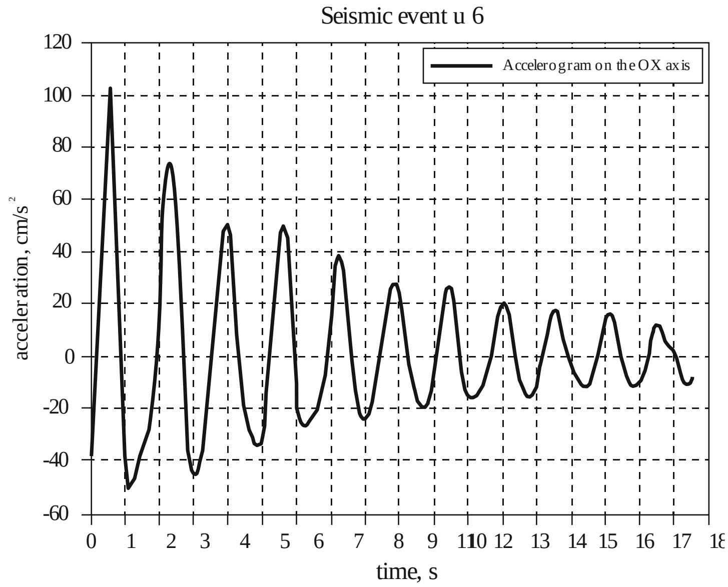

Figure 10. Free oscillations 6 channel, 1 stage, 103 cm/s²

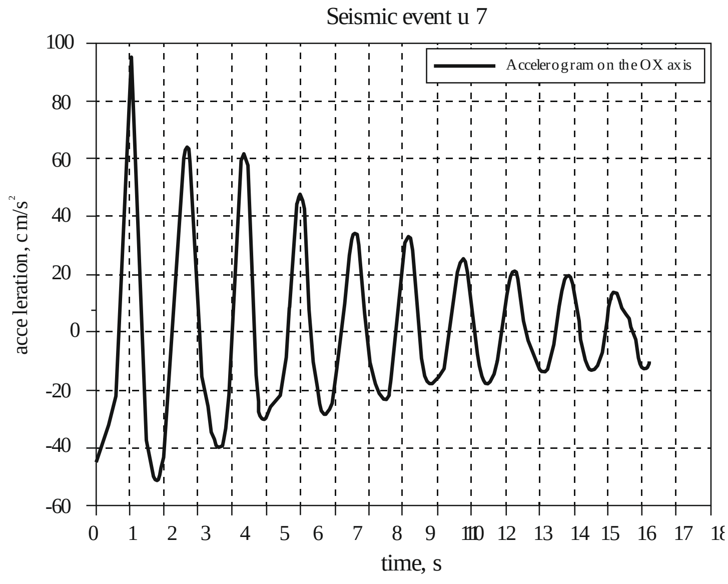

Figure 11. Free oscillations 7 channel, 1 stage, 96 cm/s²

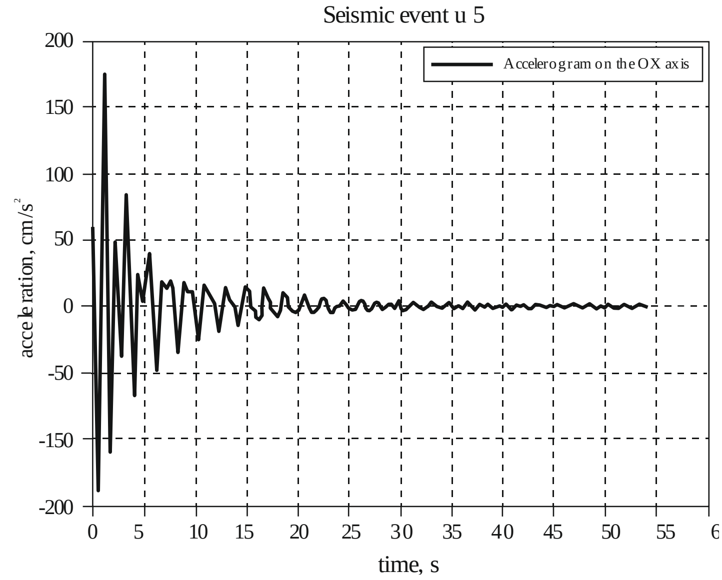

Figure 12. Free oscillations 5 channel, 2 stage, 177 cm/s²

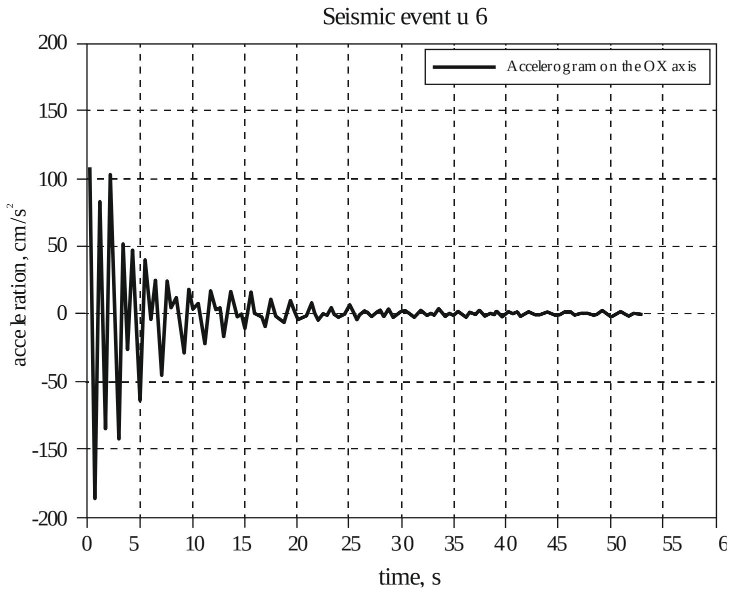

Figure 13. Free oscillations 6 channel, 2 stage, 177 cm/s²

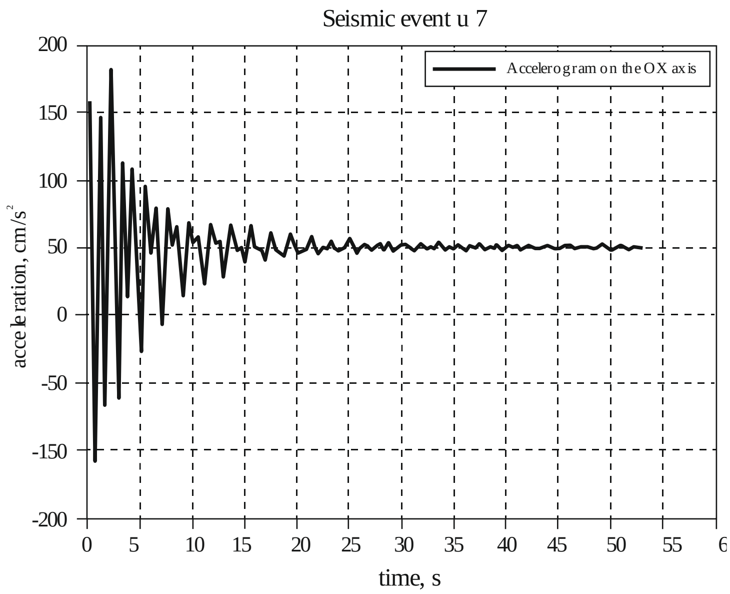

Figure 14. Free oscillations 7 channel, 2 stage, 162 cm/s²

Similar results were obtained for channels 5-7 at the 2nd stage of testing.

Tables 1 and 2 show the values of the maximum floor-to-floor movements obtained using Aistov's instruments, oscillation decrements, as well as periods of oscillations obtained from instrumental records after load shedding.

Table 1. Values of floor movements and decrements

№	Movements, cm	Decrement	Movements, cm	Decrement
1	1.0	0.08-0.1	12.5	0.11-0.15
2	4.3	0.05-0.11	11.0	0.15-0.16
3	4.75	0.11-0.13	13.75	0.12-0.18
	1 shedding		2 shedding	

Table 2. Periods of oscillations according to instrumental records

№	Oscillation period, s	Oscillation period, s
1	1.83	2.07
2	1.89	2.01
3	1.82	1.95
	1 shedding	2 shedding

The variance in oscillation periods between the two stages of the test approximates 13%, suggesting the presence of nonlinearity in the oscillatory process. The oscillation decrements, ranging from 0.1 to 0.18 across all channels and both loading stages, are within the expected range owing to the low-frequency characteristics of the seismic isolating system.

It's noteworthy that no visible damage to the load-bearing structures of the prefabricated girderless frame of the PGF-SIKF system was observed. Additionally, there were no instances of kinematic foundations colliding with oscillation limiters. Consequently, the incorporation of oscillation limiters within the scope of this experiment appears unnecessary.

Moreover, it's worth mentioning that the initial trial of a prefabricated girderless frame on kinematic foundations occurred within the former USSR. Furthermore, alternative methods for seismic isolation of such systems are conceivable [21]. Additionally, experimental investigations of buildings equipped with seismic isolation systems can employ oscillation methods to induce dynamic effects [28].

3.1. Calculations of Real Consequences

The experimental data do not provide a direct assessment of the behavior of the building fragment with the kinematic seismic isolation system, girderless frame, and magnetic dampers. Therefore, it is necessary to simulate the behavior of the building's dynamic model, constructed based on the experimental data, under real seismic impacts, taking into account local seismic characteristics. The city of Shymkent lies directly within a seismic-generating zone. The seismicity of the area is associated with the activity of the Chulinsk seismic-generating zone, where earthquakes with magnitudes of up to 6.0 are predicted. According to available seismological data, numerous earthquakes with an energy class of 9-12 have occurred along the Chulinsk fault [29, 30].

Shallow crustal earthquakes in this region typically exhibit a high-frequency nature and relatively short effective durations of seismic impact. (Effective duration refers to the duration of soil vibration with amplitude exceeding half of the maximum.) Consequently, employing seismic isolating systems with oscillation periods ranging from 1.8 to 2.1 seconds appears to be a highly effective strategy for mitigating seismic loads within this specific area.

A sample of real accelerograms has been compiled to analyze the building fragment's response to seismic impacts. Table 3 presents the accelerograms from the selected earthquakes of varying magnitudes, along with the corresponding maximum acceleration values, earthquake names, dates, and the hypocentral distance (R) from the recording location. The accelerograms must be used without normalization, as normalization can distort the frequency characteristics of seismic events. The average acceleration value of the horizontal components is 207 cm/s², corresponding to an intensity level 8 earthquake. Using these accelerograms, it is necessary to determine the possible response parameters of the building fragment.

Table 3. Sampling of earthquake accelerograms for calculations of a seismic isolating system in the region of the city of Shymkent

№	Accelerogram code	Earthquake, year, source parameters	Intensity, cm/s^2	Component
1	Aks27	Eureka,21/12/54 R=24, M=6.6	164.5	N11W
2	Aks28	Eureka,21/12/54 R=24, M=6.6	252.7	N79W
3	Aks74	Parkfield,27/06/66 R=6, M=5.3	264.3	N05W
4	Aks75	Parkfield,27/06/66 R=6, M=5.3	340.8	N85W
5	Aks71	Parkfield,27/06/66 R=9, M=5.3	236.6	N50W
6	Aks72	Parkfield,27/06/66 R=9, M=5.3	269.6	N40W
7	Aks115	Long Beach,10/03/33 R=27, M=6.3	192.7	SOUTH
8	Aks116	Long Beach,10/03/33 R=27, M=6.3	156.7	WEST
9	Aks118	Lower California,30/12/34 R=64, M=6.5	156.8	N00E
10	Aks119	Lower California,30/12/34 R=64, M=6.5	179.1	N90E
11	Aks48	Santa Barbara,30/06/41 R=16, M=5.9	233.8	N45W
12	Aks49	Santa Barbara,30/06/41 R=16, M=5.9	172.3	S45E
13	Aks112	Long Beach,10/03/33 R=53, M=6.3	130.6	N08E
14	Aks113	Long Beach,10/03/33 R=53, M=6.3	151.5	S82E

Table 4 shows the inflection points of the piecewise linear deformation diagram, taken from experimental data. The dynamic model of the building fragment is represented as a single-degree-of-freedom (SDOF) system. Fragment weight Q=2800 kN, logarithmic vibration decrement 0.18. The damping of oscillations is described using the simple Voigt hypothesis. A nonlinear differential equation describing the oscillation of a single-mass system is solved.

$$m\ddot{X} + \mu\dot{X} + R(X) = -m\ddot{X}_0 \quad (1)$$

where m is the mass equal to Q/g, g is the acceleration of free fall, R(X) is the piecewise linear experimental deformation diagram, μ is the coefficient of internal viscous friction, X is the horizontal movement, $\ddot{X}_0$ is the accelerogram of the seismic impact.

Table 4. Inflection points of the piecewise linear deformation diagram

X,cm	-17	-11	-4.3	0	4.3	11	17
R, kN	-550	-405	-307	0	307	405	550

Table 5 shows the results of calculations of the dynamic building model on the influence of real accelerograms from Table 3. The calculations were performed using the MATLAB mathematical package. The maximum kinematic parameters of the dynamic model of the building in the form of a single-mass nonlinear system are determined.

Table 5. Maximum building response parameters

Accelerogram	X, cm	$\dot{X}$, cm/s	$\ddot{X}$, cm/s²	R, kN
27	11.85	55.12	174.17	494.4
28	3.97	23.62	99.32	283.3
74	8.65	41.93	148.44	422.7
75	7.45	40.11	137.23	390.8
71	5.76	33.79	121.40	345.9
72	4.17	23.35	104.30	297.8
115	6.94	43.48	132.48	377.1
116	9.86	48.57	159.77	455.0
118	5.92	33.54	122.91	350.0
119	3.11	23.42	78.0	222.1
48	3.01	26.16	95.54	27.21
49	5.28	28.38	116.99	333.1
112	8.92	38.54	150.0	429.8
113	6.20	32.80	125.54	357.5

Analysis of Table 6 shows that the sample mean (estimate of the mathematical expectation) of the acceleration values differs by no more than 3% from the median value of the specified parameter. Therefore, approximately the law of distribution of acceleration values can be considered normal. Therefore, we apply the “three sigma” rule of mathematical statistics. The Three Sigma Rule states that about 68.26% of the values of a random variable are within one standard deviation of the mean, about 95.45% of the values are within two standard deviations, and about 99.7% of the values are within three standard deviations.

Table 6. Probabilistic characteristics of building response parameters

Accelerogram	X, cm	$\dot{X}$, cm/s	$\ddot{X}$, cm/s²	R, kN
Sample mean	6.50	32.8	126.01	335.8
median	6.06	35.20	123.23	353.8
standard	2.62	9.91	26.66	121.9
dispersion	6.88	98.21	710.84	1485.6

Therefore, taking into account the results of Table 6, with a probability of 68.26%, the acceleration value will not exceed 152.67 cm/s², with a probability of 95.45% - 179.33 cm/s². The difference from the experimental values at 95.45% security is less than 1%. Therefore, the predicted acceleration values correspond to the experimental data.

The magnitude of movements with a probability of 68.26% will not exceed 9.12 cm and with a probability of 95.45% - 11.74 cm. Movements at a probability of 95.45% are not higher than the experimental data when the load is released 13.75 cm. Here, too, the predicted values of displacement at the support level correspond to the experimental data. Thus, with the predicted intensity of earthquakes with magnitudes up to 6, the above reaction parameters of a seismically insulated building should be expected.

We also note that there are other methods for probabilistic assessment of the response parameters of seismically insulated buildings. For example, seismic impact can be modeled by stationary or non-stationary random processes, the parameters of which are taken based on the results of processing real accelerograms. Then digital modeling of a random process is performed [31], followed by determination of the building response parameters using.

4. Discussion of the Results

A comprehensive set of experimental and theoretical studies was conducted on the PGF-SIKF system (girderless frame on kinematic foundations with magnetic dampers). The system is protected by patents of the Republic of Kazakhstan. The experimental research determined the range of oscillation periods for the seismic isolation system, as well as the dissipative characteristics of the seismically isolated structure. In the theoretical studies, a sample of real accelerograms was selected, with the mean acceleration values corresponding to an intensity level of 8 on the MSK-64(K) scale, which is applied in Kazakhstan.

It is important to note that for the sample of 14 real accelerograms (Section 3.2), spectral characteristics were analyzed. It was found that high-frequency seismic impacts with predominant periods of 0.3–0.7 seconds are typical for the Chulinsk seismic-generating zone. Given that the oscillation periods for buildings using the PGF-SIKF system range from 1.83 to 2.07 seconds, resonance modes in real structures are deemed impossible. This makes it possible to effectively isolate such buildings under high-frequency seismic conditions. The results of this study will be useful for other countries expecting earthquakes with similar spectral characteristics.

The girderless frame was designed without additional seismic measures. As a result of the analysis of real seismic impacts, it was found that the kinematic seismic isolation system with magnetic dampers can reduce seismic loads by up to 4 times. Thus, the potential load reduction is comparable to that achieved by well-known seismic isolation systems with dry friction elements or rubber-metal bearings.

According to the regulatory documents of the Republic of Kazakhstan, the use of seismic isolation systems in civil construction is permitted, but the building height is limited to 19 floors. Healthcare facilities can be designed and built up to 5 floors. The use of kinematic seismic isolation systems with magnetic dampers can be widely adopted, making it a viable solution for mass implementation in earthquake-prone regions.

The obtained results of experimental and theoretical studies allow us to recommend this seismic isolation system with the upper part of the building in the form of a frameless frame (PGF-SIKF system) for use in the city of Shymkent and its environs on soils of type I or II according to seismic properties. To apply this system in other seismically hazardous areas, it is necessary to conduct research into the characteristics of local seismic impacts using computational analysis, such as, for example, in section 3.2.

Economic evaluations of the use of the PGF-SIKF system in residential construction were performed, yielding the following results:

- Selling price of kinematic supports for buildings up to 5 floors - $1500 per support;
- Selling price of kinematic supports for buildings up to 9 floors - $2000 per support;
- Selling price of kinematic supports for buildings up to 13 floors - $2500 per support;

The production cost of a kinematic support is up to 20% of its selling price.

The cost of constructing 1 m² of building space in Kazakhstan, excluding the cost of land, is no more than $700. This opens up opportunities for building affordable housing for low-income populations. The cost of magnetic dampers varies between $50 and $400. The findings from the experimental and theoretical studies will serve as the foundation and evidence base for the development of Special Technical Conditions (STU), which are required when designing buildings taller than 19 floors. Furthermore, these results will contribute to the development of new regulatory and technical documents on seismic isolation systems in the Republic of Kazakhstan.

It should be noted again that any seismic isolation system must be tied to regional seismic impacts. This point of view is already generally accepted. Therefore, the use of a seismic isolating system in the regions of Kazakhstan - the cities of Almaty, Ust-Kamenogorsk, Taldy-Korgan, etc. should be accompanied by the development or adjustment of appropriate seismic impact models.

In recent years, there has been a growing trend towards utilizing dynamic analysis models based on the dynamics of holonomic systems for kinematic-type systems [32, 33]. Such models certainly have their merit. In [34-36], attempts were made to construct mathematical models of seismic isolating systems of various types, utilizing the classical Lagrange equation of the 2nd kind. Specifically, the rotation angle of the kinematic support was considered as a generalized coordinate. The study focused on a structure with a rigid structural design, exemplified by a two-story residential building. Nonlinear differential equations of motion for buildings on kinematic supports were derived, and the feasibility of their linearization was assessed. Notably, for kinematic foundations with supports Cherepinsky [36] obtained an interesting result, establishing that the equations of motion for such supports are inherently nonlinear, making linearization impractical even within the realm of small oscillations.

Additionally, it is advisable for the initial constructed facility to incorporate a seismometric engineering service station to facilitate real-time monitoring of accelerations and displacements. For comparative analysis, it is recommended to conduct calculations for a three-story frame on kinematic foundations using software packages such as SAP2000, ETABS, FESPA, SOFISTIK, SCADA PRO, INDYAS, DRAIN-2DX, SeismoStuct, ADAPTIC, or RUAUMOKO 3D. For instance, LIRA CAD offers nonlinear finite elements FE 55 and an algorithm implementing the Pushover calculation method in its library. This approach enables comparison with the results of experimental research data, including oscillation periods and floor-by-floor accelerations, while conserving computational and resource expenses.

Various aspects of calculating seismically isolated systems pertinent to kinematic-type seismic isolation are elucidated in [37, 38]. Lapin et al. [39] outlines the main seismic isolation systems used in the Republic of Kazakhstan. The PGF-SIKF system is one of the latest developments in the field of seismic isolation structures. Further research is required to explore the potential application of such systems in areas with seismic intensity of 9 on the MSK-64 scale.

Kinematic foundations with magnetic dampers can be used for the seismic isolation of brick buildings and structures made of small-block materials, which face significant height limitations. However, these issues also require additional investigation.

5. Conclusions

- For the first time, PGF-SIKF seismic isolating system with magnetic dampers was tested, loaded with payloads corresponding to standard values.
- The value of the oscillation period of such a system after the static load is released is obtained. The magnitude of the oscillation period, depending on the amplitude of the impact, varies within 1.8-2.1 seconds. Accelerations varied throughout the test stages within the range of 95-177 cm/s^2. Thus, the seismic isolating system is nonlinear and low-frequency.
- The dissipative characteristics of the seismic isolating system were obtained. The fluctuation decrement values vary within 0.08-0.16, which is less than the standard values and seems insufficient. It is advisable to develop a design solution taking into account the possibility of increasing the damping of the system. It is also possible to increase the thrust of magnetic dampers.
- The maximum displacement values at floor levels for a three-story fragment with kinematic foundations are about 10-12 cm, and at support levels - up to 13.75 cm. The result was obtained using parallel operating electronic sensors and mechanical deflectometers with a clock indicator. Therefore, the obtained displacement values seem reliable.
- The relationship between the radius of curvature and the height of the kinematic foundation is chosen to be acceptable - as shown in Figures 5-6, the supports perform oscillatory movements. Otherwise, the kinematic support would be in an "indifferent" position.
- With the obtained displacement values, limiting the oscillation amplitudes using oscillation limiters seems unnecessary. The presence of a reinforced concrete oscillation limiter leads to the need to clear the gap from debris, accidentally falling fragments of building materials, etc. To prevent debris from getting into the vibration limiter, it is advisable to hermetically cover it with a soft material such as vapor barrier bundles.
- A fragment of a building was calculated using real accelerograms. With a probability of 68.26%, the acceleration value will not exceed 152.67 cm/s^2, with a probability of 95.45% - 179.33 cm/s^2. The magnitude of displacements with a probability of 68.26% will not exceed 9.12 cm and with a probability of 95.45% - 11.74 cm.
- The PGF-SIKF system is used for the construction of 3-story cottages on Lake Kolken-Ata in the village of AKSUABAD in the vicinity of the city of Shymkent.

6. Declarations

6.1. Author Contributions

Conceptualization, V.L., B.K, A.S., Y.S., and Y.A; methodology, V.L., B.K, A.S., Y.S., and Y.A.; investigation, writing—original draft preparation, V.L., B.K., and Y.A.; writing—review and editing, V.L., B.K., A.S., Y.S., and Y.A. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are contained within the article.

6.3. Funding

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6.4. Conflicts of Interest

The authors declare no conflict of interest.

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