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Seismic isolation of hospital buildings

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Abstract. This paper illustrates an analytical investigation of the vibration parameters of buildings on sliding seismic isolation bearings with elastic limiters of the relative displacement. The installation scheme of sliding bearings and elastic limiters for the separate unit of a 4 storey hospital building with brick walls is designed. The analysis of the vibrations of the hospital building is conducted for harmonic base excitation.

Keywords: earthquake; building; foundation; seismic isolation bearings; rubber limiter; horizontal oscillations; accelerations; dynamic response.

1. Introduction

The development of constructive schemes, aimed at lowering the probability of damages of strategic buildings during strong earthquakes, is one of the major problems for the scientists involved in seismic risk mitigation. It is especially important to provide suitable safety to hospital and school buildings. The destruction of this type of buildings may result in the loss of a great number of people and the loss of valuable equipment. One of the perspective ways to reduce the horizontal seismic influence during strong earthquakes is the installation, between the foundation and the superstructure, of seismic isolation sliding bearings with elastic limiters to the horizontal displacement. In such seismic isolation bearings, anti-frictional linings with low friction coefficient are installed.

In buildings with anti-seismic sliding bearings the base accelerations is transferred to a rigid body, until the seismic force does not overcome the dry friction force of the anti-frictional linings. As the horizontal action increases, the foundation begins sliding with respect to the structure.

On the shaking table at the Kyrgyz State University of Construction, Transportation and Architecture (KSUCTA), many experimental studies of the dynamic response of buildings models with sliding bearings and elastic limiters of relative horizontal displacement were conducted. The most effectively seismic protection system works with anti-frictional linings in two layers: fluorocarbon-4 and polished steel, with rubber dampers as elastic limiters. Experimental studies show that at harmonic vibrations of the shaking table with high accelerations a non-stop process of sliding models takes place.

In this paper an analytical investigation of the vibration parameters under horizontal harmonic vibrations of foundation is persecuted.

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2. Mathematical model

The stiffness of the building is much higher than the stiffness of the rubber dampers, so at this stage of investigations the building is considered as a rigid mass *m*. When sliding, under high accelerations of the foundation, only the force of dry sliding friction and the elastic reaction of the limiters with stiffness coefficient K_1 act on the mass *m*. The design scheme is given in Fig. 1.

The non-linear equation of motion of the mass *m* with dry friction is:

$$m\ddot{x} + F \cdot Sign(\dot{x} - \dot{x}_0) + K_1(x - x_0) = 0 \quad (1)$$

where x_0, $\dot{x}_0$ - displacement and velocity of the foundation; x, $\dot{x}$, $\ddot{x}$ - displacement, velocity and acceleration of the mass *m*; *F* - force of dry friction; Sign - unit function with sign of argument.

The Coulomb's law at a constant coefficient of sliding friction f_s defines the force *F*

$$F = m \cdot g \cdot f_s \quad (2)$$

where *g* - gravity acceleration.

The experimental dynamic investigations were conducted at harmonic vibrations on a large shaking table under the law:

$$x_0 = A_0 \sin \omega t \quad (3)$$

where A_0 - amplitude and ω - angular vibration frequency

Den-Gartor (1960) shows that the vibration in a mode of stable sliding the dry friction can be substituted with an equivalent viscous friction with coefficient of damping α_1 found from the conditions of equivalent work, estimated on the friction force for one period of vibration. It is defined for each mode of vibration by the formula:

$$\alpha_1 = \frac{4 \cdot F}{\pi \omega A_0} \quad (4)$$

The design scheme with viscous friction is given in Fig. 2. A linear equation of the mass motion *m* with viscous friction is given by:

$$m\ddot{x} + \alpha_1(\dot{x} - \dot{x}_0) + K_1(x - x_0) = 0$$

$$m\ddot{x} + \alpha_1 + \dot{x} + K_1 x = \alpha_1 \dot{x}_0 + K_1 x \quad (5)$$

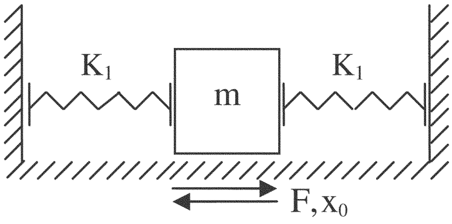

Fig. 1 Design scheme with dry friction

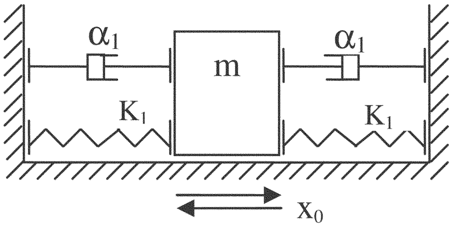

Fig. 2 Design scheme with viscous friction

Eq. (5), of forced vibration, shows that the sources of motion of the mass m at sliding are the force of friction $\alpha_1 \dot{x}_0$ and the elastic reaction of limiter $K_1 x$. The singular solution of Eq. (5) at harmonic vibrations is the following:

$$x = A_1 \mathrm{Sin}(\omega t - \varphi_1) \tag{6}$$

with A_1 - amplitude of displacement of the mass m and φ_1 - shear phase defined by the formula:

$$A_1 = A_0 \sqrt{\frac{K_1^2 + \alpha_1^2 \omega^2}{(K_1 - m\omega^2)^2 + \alpha_1^2 \omega^2}} \tag{7}$$

$$tg\varphi_1 = \frac{\alpha_1 \cdot m\omega^3}{K_1(K_1 - m\omega^2) + \alpha_1^2 \omega^2} \tag{8}$$

The velocity $\dot{x}_0$ and the acceleration $\ddot{x}_0$ of the foundation are respectively equal to:

$$\dot{x}_0 = A_0 \omega \cos \omega t \text{ and } \ddot{x}_0 = -A_0 \omega^2 \sin \omega t \tag{9}$$

The velocity $\dot{x}$ and the acceleration $\ddot{x}$ of the mass m are:

$$\dot{x} = A_1 \omega \cos(\omega t - \varphi_1) \text{ and } \ddot{x} = -A_1 \omega^2 \sin(\omega t - \varphi_1) \tag{10}$$

For the assessment of the effectiveness of the system with anti-seismic sliding bearings a coefficient of seismic isolation γ is introduced. It is equal to the ratio of acceleration amplitude of the foundation and acceleration amplitude of the mass m:

$$\gamma = \frac{A_0 \omega^2}{A_1 \omega^2} = \frac{A_0}{A_1} \tag{11}$$

i.e., at harmonic vibrations the coefficient of seismic isolation is equal to the ratio of displacement amplitude of the foundation A_0 and the displacement amplitude of the rigid mass A_1. It is defined for each frequency of excitation.

Den-Gartor (1960) and Biderman (1980) show that, under harmonic excitation, systems with dry friction undergo vibration if the amplitude of the disturbing force P_0 is higher than the force of friction:

$$P_0 > \frac{4}{\pi}F \tag{12}$$

In the harmonic case:

$$P_0 = -mA_0\omega^2 \sin\omega t \tag{13}$$

Using Eqs. (2), (12) and (13) the stable sliding in the systems with dry friction at harmonic vibrations appears if

$$A_0\omega^2 > \frac{4}{\pi} f_s \cdot g \tag{14}$$

In sliding bearings with anti-friction layers made from the fluorocarbon polumer-4 and polished stainless steel f_s may remain from 0.04 to 0.11, since it depends only on normal pressure, velocity of sliding etc. Under the conditions of experimental investigation of the models, its magnitude is varying from 0.08 to 0.11. In further calculations its magnitude is taken at the level of 0.11 and in accordance with formula (14) the established sliding movement is realized under the acceleration amplitudes of the foundation $A_0\omega^2$>137.5 cm/s^2. At the lower level of accelerations, the model follows the acceleration of the foundation.

The results achieved by the proposed methodology are compared with the results of tests on the available shaking table. The amplitudes of displacements, velocities and accelerations were assessed. Fig. 3 gives experimental and analytical values of displacement amplitudes A_1 of the mass m, at the amplitudes A_0 and frequency f, of the shaking table vibration when spring limiters are mounted. In Fig. 4 the same results are given for rubber limiters. The rubber limiters were installed with backlash exceeding the double displacement amplitude of the shaking table, therefore when calculating the vibration parameters of the model the value of stiffness of the rubber dampers put to zero. The calculated values of amplitude displacements, velocities and accelerations of the mass m are close to the values obtained during the experiments. This allows concluding that the proposed methodology can be used to calculate the dynamic reactions of buildings with anti-seismic sliding bearings, and rubber limiters of the horizontal displacement, for harmonic vibrations of the foundation.

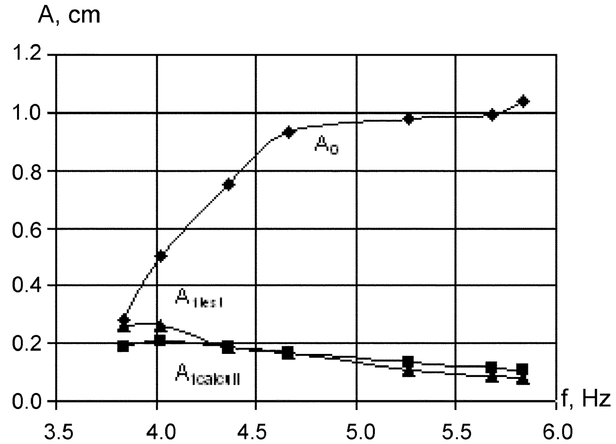

Fig. 3 Displacement amplitude during the test of a rigid model with spring limiters

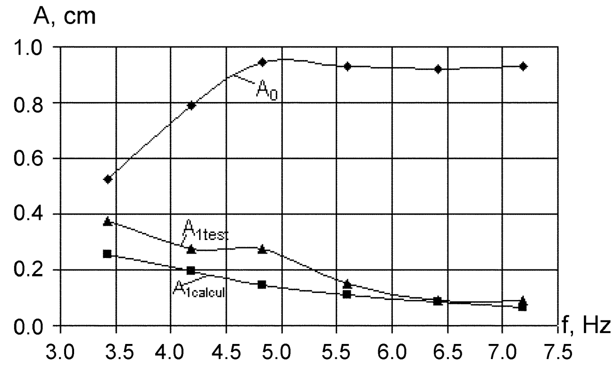

Fig. 4 Displacement amplitude during the test of a rigid model with rubber limiters

3. Dynamic response of a rigid model of hospital building

The application highlights the issue of seismic isolation of a typical hospital building for 100 beds with a clinic designed for 150 visits per working day. It is a 4 storied building with brick walls and assembled strip foundation of reinforced concrete slabs. Intermediate floors and roofs are realized with reinforced concrete slabs. The upper fourth floor is for technical purposes. The overall dimensions of the building are: length 105.55 m, width 104.5 m, height 13.05 m (top level 12 m, ground level -1.05 m). The building consists of six blocks separated by anti-seismic joints.

The block of maternity hospital building (width 14.4 m and length 48 m) was selected for the dynamic investigations. Under the walls of the building were anti-seismic bearings are meant to be installed, a reinforced concrete grillage must be arranged (height 55 cm). According to the grillage height the ground level would change to -1.6 m, and the entire height of the building block would be 13.6 m. The weight of the building *G*, including all the loads of the intermediate floors and the roofs, calculated in accordance with the standards of Russia and Kyrgyzstan, is: $G = 48996$ kN.

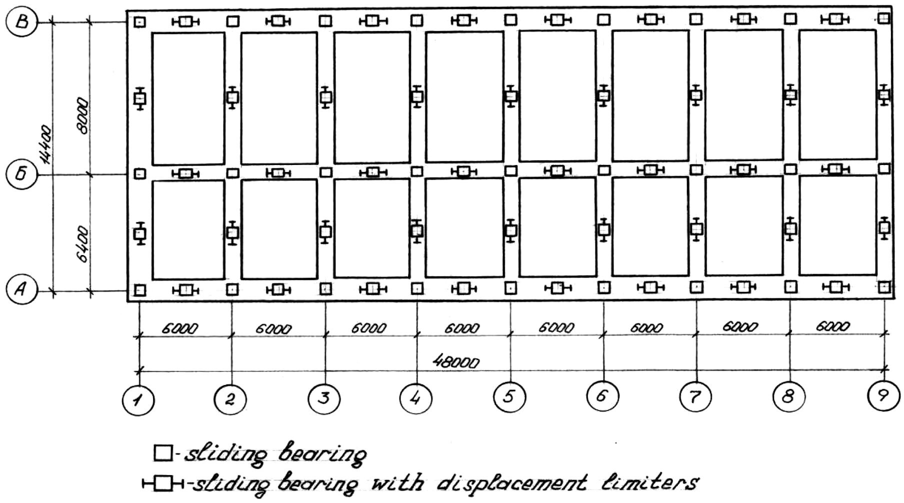

Fig. 5 Installation scheme of seismic isolation bearings

There are 3 longitudinal and 9 cross walls in the block. It is supposed in this work to install between the grillage and the foundation 51 sliding bearings under the wall crossover points, 24 sliding bearings aligned with elastic displacement limiters under the longitudinal walls and 18 sliding bearings aligned with elastic limiters under the cross walls. The installation scheme of the anti-seismic bearings is shown in Fig. 5. It is recommended to install antifriction layers, made of fluorocarbon polymer-4 and polished stainless steel plates, in the sliding bearings.

The rubber dampers are the elastic limiters, with the following dimensions: width 194 mm, length 240 mm, height 125 mm. Those dampers were installed in already erected three-storied buildings with anti-seismic bearings in Bishkek. Horizontal stiffness of such dampers is K_1 = 6.03 kN/cm. The cross-direction horizontal stiffness of all dampers is 108 kN/cm, while in the longitudinal direction is 145kN/cm.

At the KSUCTA an investigation of the dynamic response of the rigid model of the maternity hospital building block under harmonic base vibration was conducted. It is known that base acceleration during strong earthquakes may reach high values up to: 180 cm/s^2, 400 cm/s^2 and 900 cm/s^2, with magnitude of 7.8 and 9 points respectively (Zhunusov and Kurekeev 1998). The amplitudes of the base accelerations considered during the tests varied with a sinusoidal law from 137 cm/s^2 up to 900 cm/s^2, while the amplitudes of the displacement A_0 varied from 0.06 cm to 14.2 cm. The frequency range was chosen from 0.6 Hz to 10 Hz (periods 0.2s to 2s). The design of the vibrations parameters of the rigid model are given in Table 1.

The vibration parameters of a rigid building model will change in the following range: acceleration amplitudes from 97.48 cm/s^2 to 138.36 cm/s^2, shear phase 0.793-1.507 rad. Their value raises as the base displacement amplitude increases and sensibly do not depend upon the vibration frequency. The amplitude of displacement of the rigid model A_1 increases from 0.03 cm to 11.38 cm as the vibration frequency decreases and the base displacement and acceleration amplitudes increase (Fig. 6). The maximum absolute value of displacement of the rigid building model with respect to the base is reduced from 11.33 cm to 0.052 cm as the frequency of vibration, the amplitudes of displacement and the base acceleration increase (Fig. 7). The maximum value $[x - x_0]_{max}$ = 11.33 cm was obtained with f = 0.5 Hz and A_0 = 14.2 cm. The maximum elastic reaction of the rubber dampers was $R_1 = K_1[x - x_0]_{max}$ = 1222 kN, considerably lower than the force of friction F = 5390 kN. From this remarks it can be concluded that under the considered excitation natural vibration did not appear in the system (rigid model, elastic limiters and foundation). The natural frequency of such system (Fig. 1) is equal to:

$$P = \sqrt{\frac{K_1}{m}} \tag{15}$$

For the building under study P = 1.471 s^{-1}, f = 0,234 Hz and T = 4.27s. The forced vibrations were imposed with frequencies that exceeded the natural frequency of the system and, as a result, the resonance does not appear. In order to make the sliding of the system take place in the field of resonance frequency, the displacement amplitudes of base must be more than 60 cm. Such amplitudes under the period of base vibration T = 4s were not observed during earthquakes.

The buildings with seismic isolation erected in Bishkek have rubber dampers installed with backlash in the direction of movement. In hospital buildings, the rubber dampers also need to be installed with backlash. Then under relative displacement within the backlash limits K_1 = 0 and fundamental frequency P = 0, i.e., the natural period growth to infinity. It is possible to regulate the natural frequency of vibration of the system by changing its stiffness and number of rubber dampers in order to avoid the resonance vibrations.

Table 1 Vibration parameters of the rigid model of the hospital building

f Hz	T sec.	α_1 kN·s/cm	A_0 cm	A_1 cm	A_0' m/s	A_1' m/s	A_0'' m/s^2	A_1'' cm/s^2	γ -	φ_1 rad	$(x_0-x_1)_{max}$ cm	$k_1\,(x_0-x_1)_{max}$ kN	x_0 cm	x_1 cm
10	0.100	1820.26	0.06	0.3012	3.7699	1.8923	236.87	118.90	1.992	1.046	-0.0519	-5.6076	0.0519	-0.000028
		1092.15	0.1	0.0329	6.2832	2.0662	394.78	129.82	3.041	1.237	-0.0945	-10.2049	0.0944	-0.000052
		496.43	0.22	0.0344	13.8230	2.1610	858.53	135.78	6.397	1.417	-0.2174	-23.4807	0.2173	-0.00012
5	0.200	1092.15	0.2	0.1144	6.2832	3.5948	197.39	112.93	1.748	0.965	-0.1644	-17.7544	0.1640	-0.00036
		546.08	0.4	0.1317	12.5664	4.1386	394.78	130.02	3.036	1.241	-0.3785	-40.8796	0.3777	-0.00083
		273.04	0.8	0.1375	25.1327	4.3182	789.57	135.66	5.820	1.411	-0.7898	-85.3023	0.7881	-0.00117
4.5	0.222	1213.50	0.2	0.1306	5.6549	3.6913	159.89	104.37	1.532	0.863	-0.1519	-16.4078	0.1515	-0.00041
		485.40	0.5	0.1629	14.1371	4.6067	399.71	130.25	3.069	1.247	-0.4740	-51.1912	0.4727	-0.00128
		242.70	1	0.1698	28.2743	4.8024	799.44	135.78	5.888	1.416	-0.9882	-106.7198	0.9855	-0.00267
4.207	0.238	1298.02	0.2	0.1404	5.2867	3.7123	139.74	98.13	1.424	0.796	-0.1428	-15.4267	0.1424	-0.00044
		432.67	0.6	0.1874	15.8600	4.9534	419.23	130.93	3.202	1.263	-0.5718	-61.7499	0.5700	-0.00177
		207.68	1.25	0.1949	33.0417	5.1512	873.40	136.16	6.414	1.434	-1.2386	-133.7639	1.2347	-0.00383
4.179	0.239	1306.72	0.2	0.1414	5.2515	3.7125	137.89	97.48	1.415	0.789	-0.1419	-15.3251	0.1415	-0.00045
		435.57	0.6	0.1897	15.7545	4.9802	413.67	130.77	3.163	1.259	-0.5710	-61.6709	0.5692	-0.00179
		199.50	1.31	0.1977	34.3972	5.1901	903.18	136.28	6.627	1.440	-1.2991	-140.3009	1.2950	-0.00407
3.5	0.286	1040.15	0.3	0.2068	6.5973	4.5471	145.08	99.99	1.451	0.815	-0.2183	-23.5806	0.2174	-0.00098
		390.05	0.8	0.2688	17.5929	5.9114	386.88	130.00	2.976	1.241	-0.7569	-81.7428	0.7535	-0.00338
		167.77	1.86	0.2822	40.9035	6.2059	899.52	136.47	6.591	1.448	-1.8467	-199.4483	1.8385	-0.00826
3.315	0.302	823.64	0.4	0.2491	8.3315	5.1877	173.53	108.05	1.606	0.905	-0.3146	-33.9735	0.3130	-0.00157
		358.11	0.92	0.3008	19.1625	6.2658	399.13	130.51	3.058	1.252	-0.8738	-94.3698	0.8694	-0.00436
		158..39	2.08	0.3148	43.3238	6.5567	902.38	136.57	6.608	1.452	-2.0664	-223.1676	2.0561	-0.01030
2.5	0.400	753.21	0.58	0.4035	9.1106	6.3387	143.11	99.57	1.437	0.811	-0.4203	-45.3926	0.4166	-0.00368
		268.01	1.63	0.5313	25.6040	8.3454	402.19	131.09	3.068	1.264	-1.5547	-167.9045	1.5411	-0.01362
		119.69	3.65	0.5561	57.3341	8.7359	900.60	137.22	6.563	1.476	-3.6394	-393.0572	3.6075	-0.03190
2	0.5	626.23	0.87	0.6202	10.9579	7.7938	137.70	97.94	1.406	0.793	-0.6215	-67.1254	0.6130	-0.00851
		214.99	2.54	0.8340	31.9186	10.4802	401.10	131.70	3.046	1.277	-2.4327	-262.7343	2.3994	-0.03331
		95.80	5.7	0.8753	71.6283	10.9989	900.11	138.22	6.512	1.507	-5.7111	-616.8038	5.6329	-0.07820
1	1	312.94	3.49	2.5368	21.9283	15.9389	137.78	100.15	1.376	0.813	-2.5400	-274.3228	2.4009	-0.13913
		107.71	10.1	3.5046	63.7115	22.0203	400.31	138.36	2.893	1.381	-10.0834	-1089.0096	9.5311	-0.55231
0.66667	1.5	207.11	7.91	5.9672	33.1334	24.9955	138.79	104.70	1.326	0.849	-5.9816	-646.0099	5.2444	-0.73717
0.5	2.000	153.82	14.2	11.3810	44.6106	35.7544	140.15	112.33	1.248	0.893	-11.3296	-1223.5914	8.8473	-2.48225

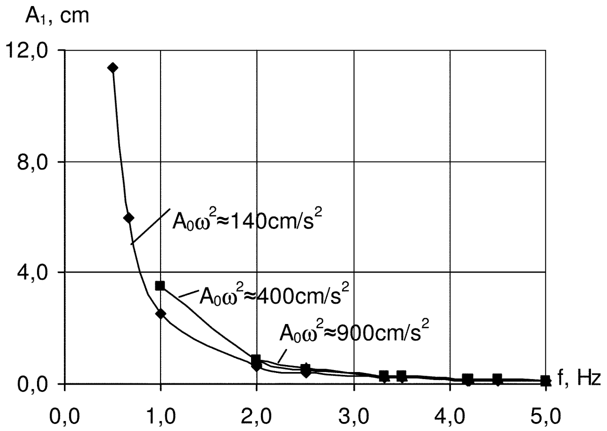

Fig. 6 Displacement amplitude A_1 of a hospital rigid model

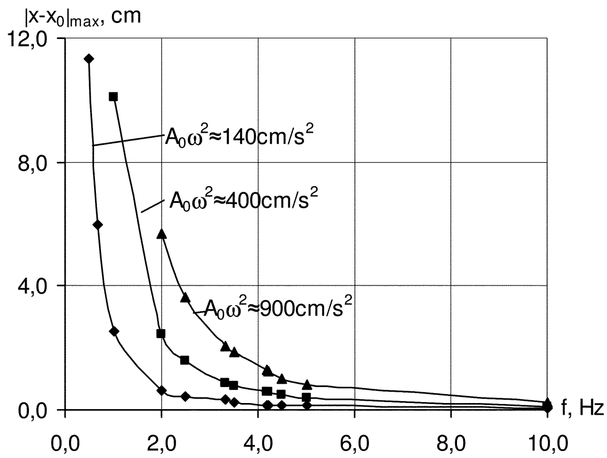

Fig. 7 Graphic of maximum relative displacement $[x - x_0]_{max}$

Coefficient of seismic isolation increased from 1.248 to 6.627 accordingly with the increase of foundation acceleration amplitude.

4. Conclusions

The analysis of the rigid model of a hospital building with anti-seismic sliding bearings and rubber limiters of relative displacement has shown that in the field of possible harmonic vibrations of the ground during strong earthquakes with periods of vibration up to 2.0 s and displacement up to 14.02 cm with amplitudes of acceleration from 137 cm/s^2 to 900 cm/s:

- the response acceleration is less than 139 cm/s^2;
- the maximum displacement of the system is 11.4 cm;
- the elastic reaction of rubber dampers is less than the forces of friction in sliding bearings.

Acknowledgements

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References

Biderman, V. L. (1980), Theory of Mechanical Vibrations, -M.: Higher School.
Den-Gartor, Dj. P. (1960), Mechanical Vibration.-M.: Nauka.
Zhunusov, T. Zh., Kurekeev, A. K., *et al*. (1998), "Standard for seismic danger assessment based on instrumental measurements, construction norms of Kazakhstan", SNPK B.1-3-98, Almaty.

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