SPECIAL ISSUE: "KAMCHATKA EARTHQUAKE M 8.8 ON JULY 29, 2025"

On the Features of the Kamchatka Earthquake on July 29, 2025 (The View of a Seismological Engineer)

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Abstract: The magnitude of the Kamchatka earthquake of July 29, 2025, was significantly higher than the estimated maximum possible earthquake in the region. At the same time, despite its high magnitude, the intensity of shaking in Petropavlovsk-Kamchatsky was significantly lower than predicted. This article explores one possible explanation for this phenomenon, which involves the nonlinear relationship between stress and deformation caused by seismic vibrations in the soil. The results of computer modeling of seismic processes in dispersed soils are presented. The calculations are based on assumptions about the properties of soils and the parameters of seismic impact. The obtained results have practical significance for seismic microzonation.

Keywords: Strong seismic event, nonlinear stress-strain relationship, computer modeling, hyperbolic dependence, seismic microzonation, Kamchatka megathrust earthquake

Citation: Aleshin A. S. (2026), On the Features of the Kamchatka Earthquake on July 29, 2025 (The View of a Seismological Engineer), *Russian Journal of Earth Sciences*, 26, ES2011, EDN: WKCCCG, https://doi.org/10.2205/2026es001121

RESEARCH ARTICLE

Received: February 2, 2026
Accepted: May 25, 2026
Published: July 1, 2026

1. Introduction

In the book [*The Seismic Concussion...*, 1979], the maximum possible earthquake off the Pacific coast of Kamchatka was estimated to be $K = 19$, where K is the Rautian energy class [*Rautian*, 1964]. The relationship between M and K was assumed to be in the form of the Gutenberg–Rautian relation: $K = 4 + 1.8M$. This implied that $M_{max} \leq 8.33$. In the fifty years that followed the publication of the book [*The Seismic Concussion...*, 1979], the magnitude of very strong earthquakes (megathrust earthquakes) was estimated using the Kanamori moment magnitude [*Kanamori*, 1977]. At the same time, the relationship between moment and "local" magnitudes is still a debated issue. The moment magnitude of the Kamchatka earthquake, July 29, 2025, was estimated to be 8.8 [*Chebrov*, 2025]. For this work, the relationship between both types of magnitudes is crucial, as one of the objectives is to compare the parameters of the Kamchatka earthquake with estimates based on the formulas in the Russian guidelines of detailed seismic zoning (SP 286.1325800.2016), which uses the M_s magnitude value.

For Kamchatka, this connection was established in the work [*Gusev and Melnikova*, 1990] quite a long time ago, but in the subsequent publication [*Abubakirov et al.*, 2018], the results of this work were considered "outdated". However, since no new relationship between M_W and local magnitudes (M_s or M_L) has been established, we consider it possible to use the results of the work [*Gusev and Melnikova*, 1990]. In fact, the measured moment magnitude M_W of the Kamchatka earthquake is estimated to be 8.8. Using the results of [*Gusev and Melnikova*, 1990] in the form of the graph shown in Figure 1, we can see that the value of M_s is approximately 0.34 less than $M_W = 8.8$, resulting in an estimate of $M_s = 8.46$. The hypocentral distance from the epicenter to Petropavlovsk-Kamchatsky is approximately 120 km.

This article is a continuation of the research on the Kamchatka earthquake of July 29, 2025, which was the subject of the previous work [*Aleshin and Maryatov*, 2026]. This

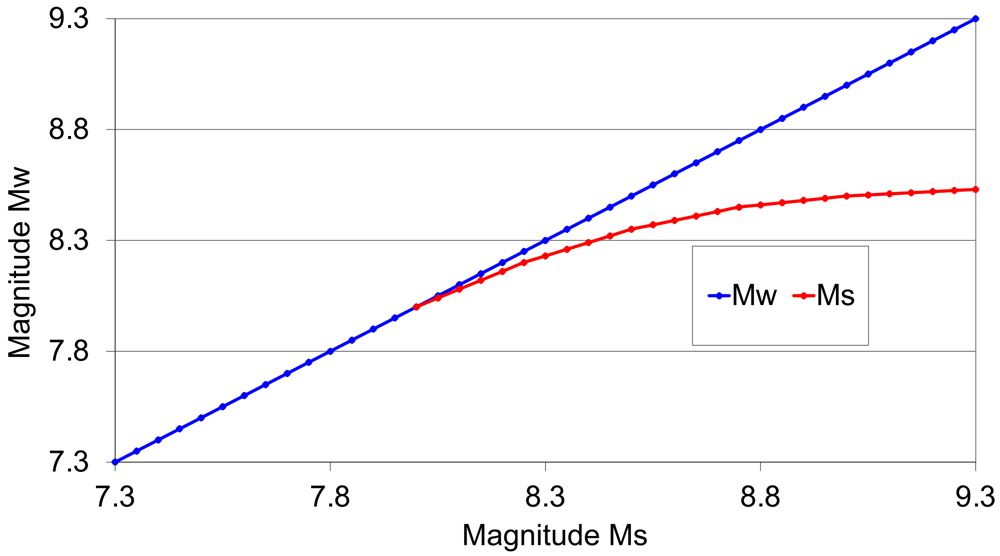

Figure 1. The comparison of magnitudes M_W and M_s (based on work [*Gusev and Melnikova*, 1990]).

study differs from the previous one in at least three ways. Firstly, it highlights a miscalculation in the estimation of the maximum possible magnitude of an earthquake in the Kamchatka region and provides some insights into the reasons for this miscalculation. Secondly, the study continued to examine another unexpected phenomenon: despite the very high magnitude of this earthquake, its effects were relatively weaker than expected for such magnitude and distance values. Finally, the calculations used accelerograms of the Kamchatka earthquake.

2. Materials and Methods

Parameters of the Kamchatka Earthquake and Their Compliance with Regulatory Estimates. Accelerograms characterizing the parameters of vibrations from the Kamchatka earthquake on the surface of rocky soils at two points (PET and SPZ stations) in the territory of Petropavlovsk-Kamchatsky are shown in Figures 2 and 3.

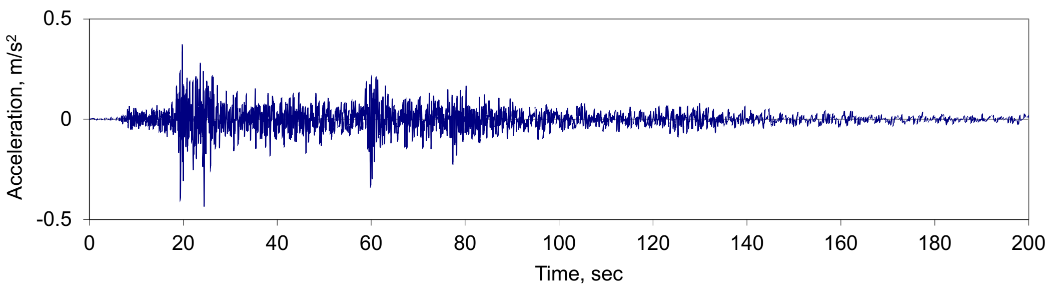

Figure 2. Accelerogram of Kamchatka earthquake on PET station.

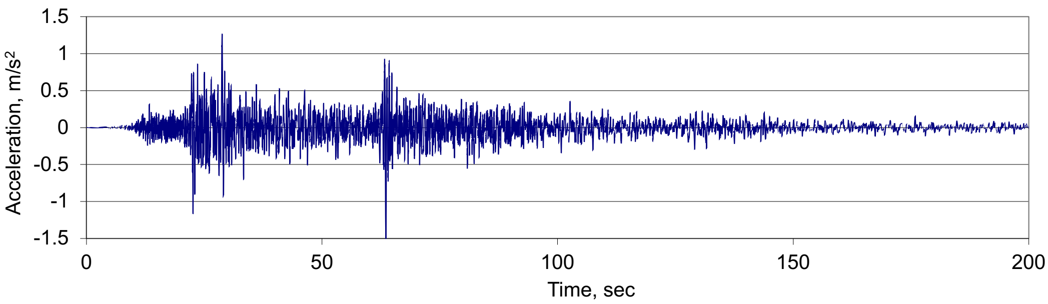

Figure 3. Accelerogram of Kamchatka earthquake on SPZ station.

The subduction type of the earthquake is confirmed by the presence of several sharp peaks on the record, due to the braking of the process of breaking through obstacles. The peak accelerations are equal to 0.4 m/s^2 and 1.5 m/s^2, respectively. It should also be noted that the given values of peak accelerations refer to peaks that differ in time: in the first case (PET), approximately 24 s, and in the second case (SPZ), 63.5 s. Let us evaluate how well the obtained data correspond to the values determined by the ratios given in the regulatory document SP 286.1325800.2016. To assess the peak accelerations in Petropavlovsk-Kamchatsky, we first determine which of the three zones – the focal zone, the near zone, or the far zone relative to the rupture plane – the city falls into. The size of the focal zone, R_0, is determined by the equation $\lg R_0 = 0.33M_s - 1.51$. With $M_s = 8.46$, $R_0 = 19$ km. The boundary between the far and near zones is located at a distance R_1 from the focal point, which is determined by the equation $\lg R_1 = 0.33M_s - 0.61$. At $M_s = 8.46$, $R_1 = 152$ km. Thus, we determined that the territory of Petropavlovsk-Kamchatsky was in the near zone relative to the earthquake focus. In the near zone, the value of peak accelerations PGA in m/s^2 is determined by the ratio $\lg \mathrm{PGA} = 0.209M_s - 0.633\lg R - 0.156$, where R is the distance from the focus to the object, in this case to the city of Petropavlovsk-Kamchatsky. Substituting $M_s = 8.46$ and $R = 120$ km, we obtain PGA = 1.98 m/s^2. It should also be noted that in the near zone, according to SP 286.1325800.2016, accelerations do not depend on the type of movement or the soil category.

Thus, only the peak accelerations at the SPZ station more or less correspond to the regulatory parameters. At the PET station, the accelerations are significantly lower than the regulatory values. Calculations show that this cannot be explained by the difference in the seismic stiffness of the rock formations on which the accelerometers at the two stations are installed. The reason for the significant amplitude differences seems to be a difference in the directional characteristics due to the differences in the terrain at both stations: the SPZ station is located on a nearly horizontal surface, while the PET station is located on a fairly steep (about 20°) slope. This fact may be the subject of further research, but for now, it is sufficient to mention it and return to the main topic of this article.

The predominant oscillation period for an earthquake with magnitude M and hypocentral distance R, if we do not take into account the type of displacement and the speed of seismic waves in the focal zone, is determined by the expression [*Chebrov*, 2025]: $\lg T = 0.15M_s + 0.25\lg R - 1.9$. Substituting $M_s = 8.46$ and $R = 120$, we obtain $T = 0.77$ s.

The duration of seismic vibrations τ (s) in the near zone on medium soils is estimated by the equation $\lg \tau = 0.15M_s + 0.5\lg R_1 - 1.05$, where R_1 is the distance to the boundary between the near and far zones. In our case, $M_s = 8.46$ and $R_1 = 152$ km. Substituting these values into the expression for determining the duration, we obtain $\tau = 20$ s. As can be seen from Figures 2 and 3, the corresponding duration of the Kamchatka earthquake is slightly longer than 40 seconds.

To check the compliance of the obtained estimates with the regulatory requirements, we use the expression for seismic intensity in terms of PGA values and the duration of seismic vibrations: $I = 2.5\lg \mathrm{PGA}(\mathrm{cm/s^2}) + 1.25\lg \tau\ (\mathrm{s}) + 1.05$. Substituting PGA = 198 cm/s^2 and $\tau = 20$ s into this expression, we obtain $I = 8.42$. Let us compare this value with the estimates obtained by the macroseismic field formulas in two variants: (a) with coefficients for Kamchatka and (b) with average values of coefficients. In the first case, $I = 1.5M_s + 2.5 - 2.6\lg R - 0.0087 \cdot R$, when $M_s = 8.46$ and $R = 120$ are substituted, we obtain $I = 8.68$. The difference between this value and the value obtained from the parameters of the Kamchatka earthquake is $8.68 - 8.42 = 0.26$ points. Interestingly, the calculation using the formula with average parameters yielded a closer value of $I = 8.41$, which is almost identical to $I = 8.42$.

At the same time, by substituting the values of PGA and the duration of the Kamchatka earthquake into the above formula, we obtain an intensity value of $I = 8.49$, which is almost identical to the standard values. In general, the applicability of the formulas in SP 286.1325800.2016 for determining the parameters of megathrust earthquakes with a magnitude of approximately $M = 9$ and a complex focal structure may require further investigation. Let's compare these estimates with the estimates based on the general seismic zonation (GSZ) maps and the seismic microzonation data for the territory of Petropavlovsk-Kamchatsky [*Ershov*, 1977]. According to the regulatory GSZ-2015 maps, presented in Seismic building design code SP 14.13330.2018, for recurrence periods of 500 years or more, the territory of Petropavlovsk-Kamchatsky is characterized by an intensity of IX or more points for medium soil conditions of the 2nd category. Buildings and structures in Petropavlovsk-Kamchatsky were designed for this intensity. It is a good thing that the damage from such a powerful earthquake was relatively small, but why was the intensity of the oscillation from such a powerful earthquake lower than the normative estimates? The answer to this question was provided in the previous article [*Aleshin and Maryatov*, 2026], which examined the behavior of dispersed soils under strong seismic impact. In this article, we will further explore the details of this research using the recorded data from the Kamchatka earthquake.

Experimental Technique. Studying the behavior of dispersed soils under strong earthquakes in natural conditions is a task very unlikely due to the impossibility to accurately predict the time and place of a future strong earthquake. For this reason, the study of the behavior of dispersed soils under the influence of strong seismic events in this work was carried out by the method of computer modeling using the program `NERANew` [*Bardet and Tobita*, 2001].

First of all, a sufficiently realistic model of the soil stratum was set, i.e., corresponding to the conditions of Petropavlovsk-Kamchatsky. This model is a refinement of the models given in [*Shteinberg et al.*, 1975], due to a more detailed account of the physical properties of the very upper part of the geological section. The model of the soil stratum is made up of a set of several layers of dispersed soils with a thickness of 49 m, underlain by a rock half-space. It is important to note that it was on these soils that the vibrations from the earthquake of November 24, 1971, were most intense in the city [*Shteinberg et al.*, 1975]. In addition to the elastic properties, represented by the corresponding values of density ρ in t/m^3 and the speed of transverse waves V_s in m/s for each layer, this model also takes into account the plastic properties of the soils, which are particularly evident under high stresses caused by strong seismic forces. Plasticity in soils is defined as the ability to irreversibly change shape and size under the influence of stress. Above the elasticity threshold, soils enter the stage of plastic deformation. At this stage, two types of phenomena occur: the elastic shear modulus of the soil decreases significantly, resulting in a degradation of the shear modulus, and the attenuation of elastic vibrations as they pass through the soil mass increases dramatically due to the development of dislocations in the soil. In other words, the vibrations are damped.

Both of these phenomena are described using the reference strain value γ_a in hyperbolic expressions [*Ishihara*, 1996]. The degradation of the shear modulus G/G_0 is described by the expression $G/G_0 = (1+\gamma_a/\gamma_r)^{-1}$. The formula for the damping coefficient D is more complex:

$$D = \frac{4}{\pi}\cdot\left[1+\frac{1}{\gamma_a/\gamma_r}\right]\cdot\left[1-\frac{\ln(1+\gamma_a/\gamma_r)}{\gamma_a/\gamma_r}\right]-\frac{2}{\pi}.$$

Due to the differences in the parameters, these general expressions lead to different dependencies for different types of soil, which is taken into account in the `NERANew` program using the nonlinearity index: 0 for rocky soils, 1 for clays, 2 for sands, and 3 for coarse-grained soils (such as gravel).

The type of graphs of degradation of shear modules and damping curves for three types of dispersed soils is shown in Figures 4 and 5. Special attention should be paid to the difference in the behavior of the graphs of degradation of modules and damping for cohesive soils (clays and sands) and gravel. This nature of the graphs is due to the fact that the inertial forces acting on the particles of coarse-grained (pebble, gravel, and pyroclastic) soil under seismic effects significantly exceed the forces of adhesion between them. At the same time, clay particles, which are relatively small in mass, have a huge cohesive energy due to the large role of surface effects and the relative weakness of inertial forces.

In this regard, sands occupy an intermediate position between clays and gravel. This sheds light on the role of the connection between dispersed soil particles and the nature of nonlinear processes under strong seismic impacts. The parameters of the soil model used in this article are listed in Table 1.

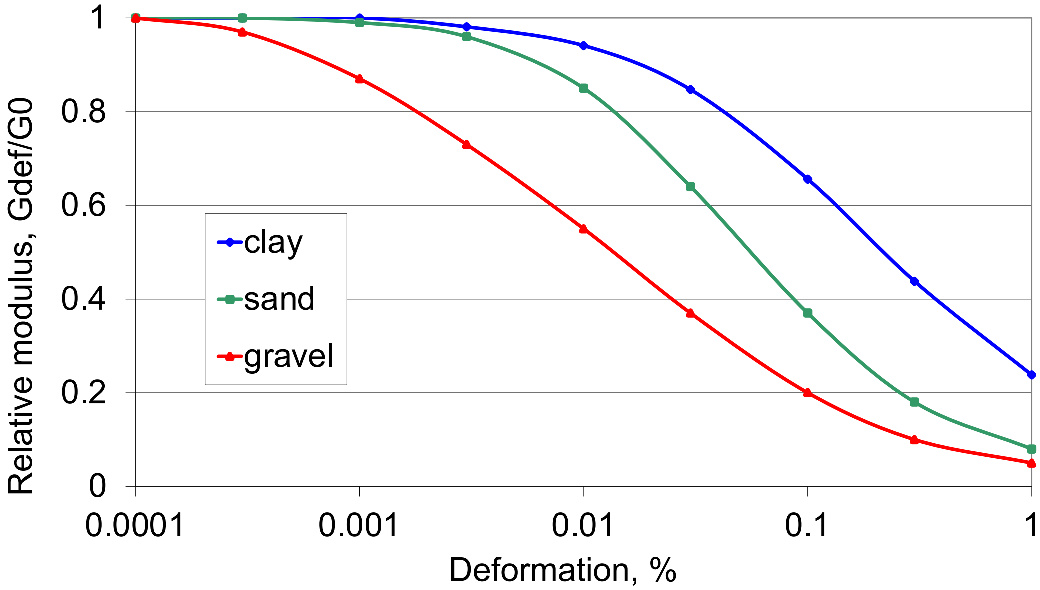

Figure 4. Graphs of module degradation.

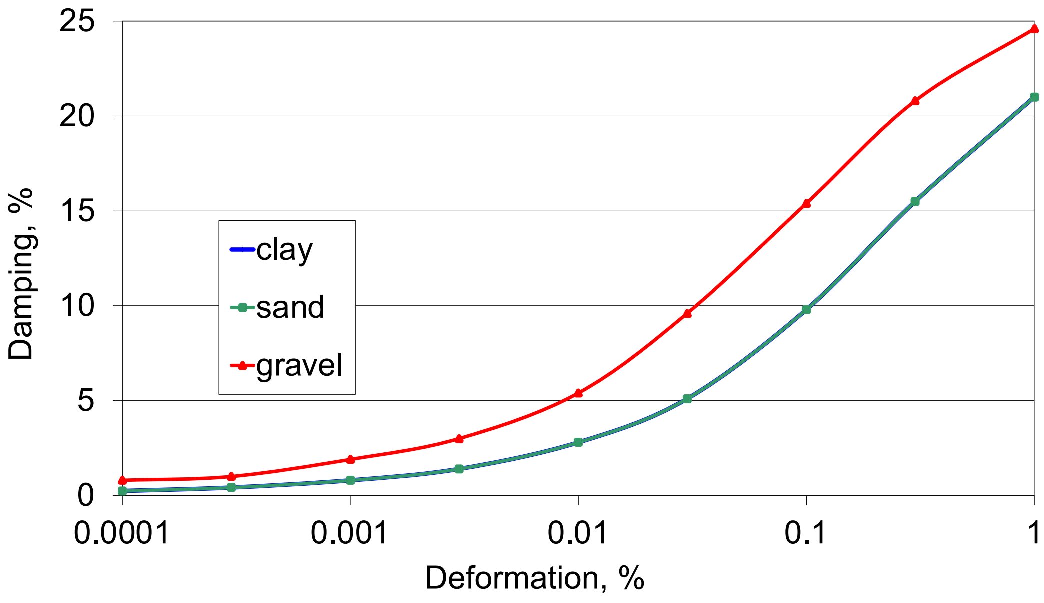

Figure 5. Damping curves.

As can be seen from Table 1, with the exception of the uppermost (no more than 6 m) part of the section, the soil stratum is dominated by coarse-grained (in this case, pyroclastic) material with the inclusion of shale and andesite fragments, which belongs to the 3rd type of stress-strain relationship. Pyroclastic soils also have a relatively high density of more than 2 t/m^3. The layer of loose dispersed rocks is underlain by micaceous-siliceous and sandy-clayey shales with increased (more than 2000 $t \cdot m^{-2} \cdot s^{-1}$) seismic rigidity relative to dispersed soils. The roof of these rocks is the initial seismic impact.

Table 1. Parameters of the soil layer model

No	Type	h, m	ρ, t/m^3	V_s, m/s
1	2	2.3	1.9	250
2	1	3.5	1.5	380
3	3	9	2.09	280
4	3	9.6	2.22	410
5	3	9.2	2.21	335
6	3	15.4	2.05	450
7	0	∞	2.3	1000

The 2025 Kamchatka earthquake record on the SPZ station was used as the initial input, as it best matches the regulatory estimates. It should also be noted that the mechanisms mentioned above, such as degradation of elastic modules and damping, have different effects on the response parameters: the first increases the amplitude of accelerations, while the second reduces the accelerations. Only an experiment can fully assess the combined impact of both mechanisms.

3. Results and Discussion

The results of the model experiment on passing the initial seismic effects with changing peak accelerations through the model of the soil stratum are shown in Figure 6, where the red line shows the values of peak accelerations at the output of the model, and the blue line displays the amplitude of peak accelerations of the oscillations coming to the model. It is obvious that there are two regions in the graph of Figure 6: in the first region, at lower values, the peak response accelerations exceed the peak excitation accelerations, while in the second region, starting from approximately 0.1g, the growth of the peak response accelerations slows down, and starting from 0.3g, the peak response accelerations become less than the peak excitation accelerations.

This behavior of accelerations at the output of the model is a consequence of the nonlinear relationship between stresses and strains. If the properties of the soil did not change with the increase in stresses in the falling seismic wave, then the two graphs would not intersect, differing by a certain amount that characterizes the influence of the soil layer on the increase in seismic intensity.

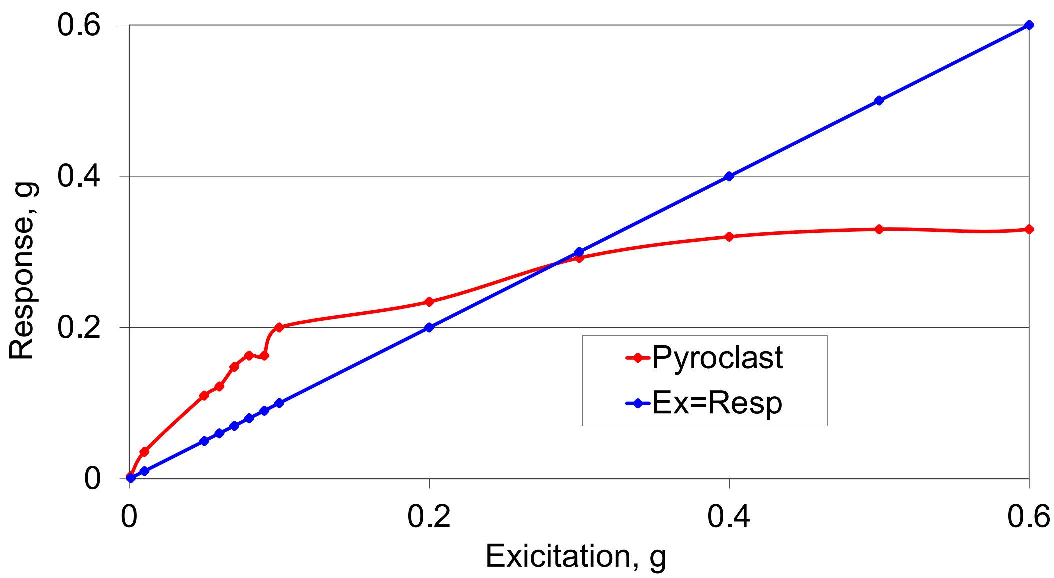

Figure 6. The result of the model experiment.

In a nonlinear model, everything is quite different, as we described above. Let's see how this affects the increments of seismic intensity. The ratio of the acceleration of vibrations that passed through the soil model to the acceleration of vibrations that entered the soil model corresponds to the increments of seismic intensity according to the formula: $\Delta I = 3.3\lg(A_{\mathrm{imp}}/A_{\mathrm{in}})$. The coefficient of 3.3 corresponds to the MSK-64 scale [*Medvedev*, 1968], according to which a doubling of the acceleration ratio corresponds to an increase in seismic intensity by 1 point. In order to show the dependence of intensity increments on small peak accelerations, the data are presented as a logarithm of accelerations on the abscissa. This graph, obtained for two types of soil – clays and pyroclastic material, is shown in Figure 7.

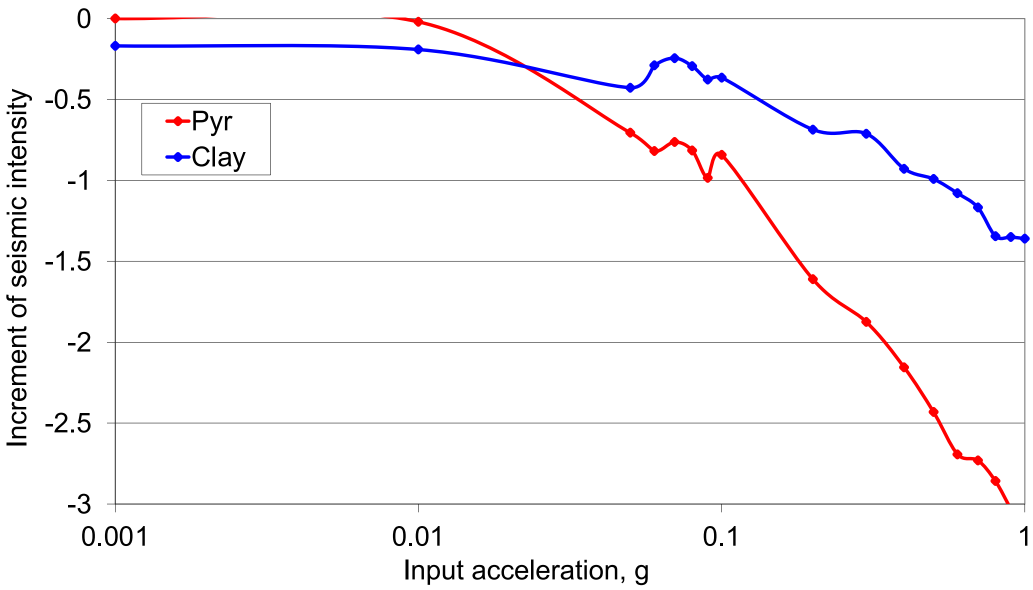

Figure 7. Dependence of the increment of seismic intensity on the logarithm of peak accelerations of the exciting pulse.

From the graph, it can be seen that at low accelerations (approximately 0.01g), the increment of intensity for both types of soil remains constant. As the accelerations increase, the slope of the graph for pyroclastic soils begins to decrease, while for clays, the constant increment remains until the acceleration reaches approximately 0.1g, which corresponds to an intensity of approximately VII points. The wave-like behavior of the graphs (Figures 6 and 7) may be due to the presence of sharp pulses in the initial accelerogram. However, this does not affect the main results of the model experiment.

The results obtained indicate that the decrease in the intensity of seismic vibrations during the Kamchatka earthquake in July 2025 was significantly influenced by the presence of pyroclastic material in the soil layer. This suggests that the properties of the soil layer formed by the Kamchatka volcanoes played a crucial role in preventing damage during the earthquake.

4. Conclusion

The results of the model experiment are of great practical importance for seismic microzonation, which can be summarized in the following conclusions.

1. The magnitude of the Kamchatka earthquake in July 2025 significantly exceeded previous estimates. The reasons for this situation are noted.
2. In the complex tectonic and geomorphological structure of the territory of Petropavlovsk-Kamchatsky, there is a significant difference in the acceleration amplitudes on rocky soils at nearby locations. An assumption has been made about the possible cause of this phenomenon, which needs further verification.

3. With a relatively large magnitude of the Kamchatka earthquake, the intensity of shaking in the territory of Petropavlovsk-Kamchatsky was relatively low, about 1.5 points lower than expected.
4. The observed decrease in peak accelerations during strong (more than VII points) seismic impacts is due to the presence of a loose cover of dispersed pyroclastic rocks in the territory of Petropavlovsk-Kamchatsky, formed by the action of nearby volcanoes.
5. The magnitude of the intensity reduction during strong seismic impacts depends on the size of the soil particles, decreasing sequentially from coarse-grained (gruss and gravel) to sandy and clayey.
6. The noted factors were the reason that buildings and structures designed according to the standards calculated for linear properties of the soil were able to withstand the effects of earthquakes of very large magnitude.

Acknowledgments. The author expresses his gratitude to D. V. Chebrov for the kindly provided accelerograms of the Kamchatka earthquake.

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