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Prediction of the Seismic Manifestations of Vrancea Earthquakes in Moscow

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Abstract—According to the normative maps of the General Seismic Zoning in the Russian Federation, OSR-97, the Moscow metropolitan area is situated within the 5 point seismic zone. Of highest hazard priority for tall buildings in Moscow are the low-frequency vibrations proceeding from the deep sources of strong earthquakes that occur in the East Carpathians (the Vrancea zone, Romania) at a distance of approximately 1350 km from Moscow. Accelerations of the ground vibrations in Moscow are found from the analysis of seismic signals produced by $Mw = 5.0$ to $Mw = 7.4$ Vrancea earthquakes and recorded at the Moskva seismic station. Extrapolation of the parameters of the weak and moderate earthquakes towards stronger seismic events provides an estimate for the maximum expected horizontal accelerations of $A_{hor} = 2.3$ cm/s^2 in case of the $Mw = 8.0$ Vrancea earthquake. The synthetic accelerogram of the maximum possible effect on the benchmark soils of Moscow is calculated. The displacements of the ground are multidimensional and not necessarily oriented strictly towards the seismic source. These inferences suggest that the MSK-64 macroseismic scale be corrected and the Construction Norms and Regulations, SNIP II-7-81*, be updated with regard to the hazard assessment of low-frequency seismic effects of 5 point and weaker seismic events including those caused by distant earthquakes.

Key words: prediction of seismic hazard, seismic manifestations in Moscow, synthetic accelerogram

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INTRODUCTION

In 1991–1997, during the construction of the general seismic zoning maps for the territory of the Russian Federation (OSR-97) at the Schmidt Institute of Physics of the Earth, Russian Academy of Sciences, particular attention was given to the study of seismic effects shown in the Moscow metropolitan area. Both close and remote sources of strong earthquakes including those in the East Carpathians (the Vrancea zone, Romania) were considered [Ulomov and Shumilina, 1999a; 1999b].

In view of the high-rise building construction that has been taking place in Moscow, I resumed these studies in 2002–2003 and proceeded in 2007–2008 purposefully to prepare the normative high-rise building design documentation. It was expected, in particular, that long-lasting low-frequency vibrations, even hardly distinguishable on the Earth's surface, as well as the resonance phenomena in the soil and at building sites, can substantially affect their reaction [Ulomov, 2007; 2008; Ulomov et al., 2007].

Thrice, during only the last 70 years, the Moscow region experienced quite perceptible seismic effects caused by strong earthquakes in the Vrancea zone: in 1940, 1977, and 1986. The moment magnitudes Mw of these events were 7.7, 7.4, and 7.1, respectively. Noticeable vibrations on the top floors of buildings were also felt in 1990 during the Vrancea earthquake with $Mw = 6.9$. Had it been only a little stronger, the 2004 Vrancea event with $Mw = 5.9$ would also not have remained unnoticed by Muscovites. At the same time, its seismograms digitally recorded in 2004 at the Moskva Central seismic station proved the most informative and were used in our calculations of the maximum possible seismic effect in Moscow.

It is also important that until our works in 2007–2008, all the precedent domestic assessments of seismic effect on buildings in European Russia were based on the incorrectly "renormalized" accelerogram of the March 4, 1977 Vrancea earthquake, recorded 484 km southwest of the epicenter at the NIS seismic station in Serbia. The original digital accelerogram of the NIS station, which had suffered "renormalization" from the domestic hydraulic engineers, had been then artificially "extrapolated" by them northeastwards, up to a distance of 1400 km. Later on, this falsification had entered the seismic safety calculations of even highly critical buildings such as nuclear power stations. In this form, incorrectly, it entered into the first normative document for high-rise construction in Moscow [*Temporary* ..., 2006].

Figures 1 and 2 display the original and the faked accelerograms. The same configuration of the original of the accelerogram recorded at the NIS seismic station and its exact copy with distorted scales across the coordinate

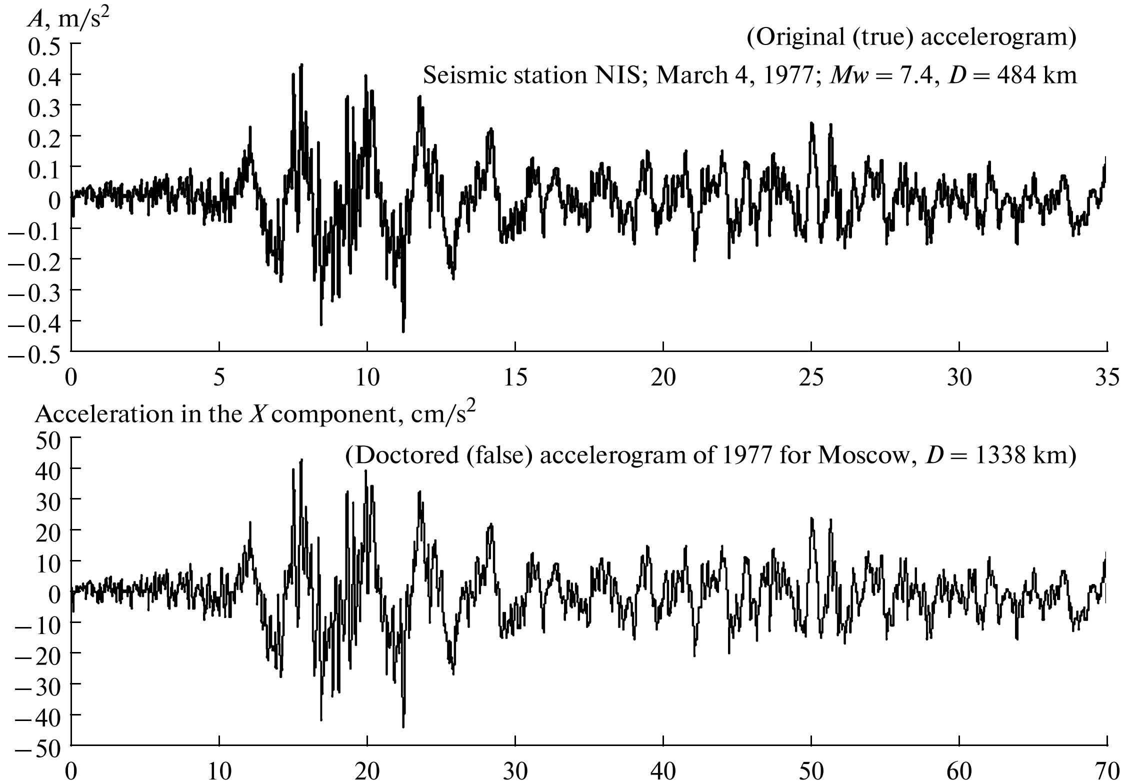

Fig. 1. Original accelerogram of horizontal shocks recorded at the NIS seismic station (Serbia) for the earthquake of March 04, 1977 with $Mw = 7.4$ is presented at the top. Horizontal and vertical peak accelerations are 0.444 m/s^2 and 0.214 m/s^2, respectively. The same accelerogram with the artificially changed scale across the X-axis is presented at the bottom. In this form, it was used for a long time as a synthesized accelerogram, including application in the design of nuclear plants in the European part of the country.

axes, allegedly obtained in the territory of Moscow (below), is distinctly visible in Figs. 1 and 2.

As it is clear, in the "renormalization" of the real accelerogram, the authors left unchanged the nominal values along the Y-axis, despite the fact that the epicentral distance to Moscow was three times as large as the distance from the epicenter to the NIS seismic station. The scale along the X-axis has been, meanwhile, arbitrarily zoomed in by a factor of two. As a result, peak ground accelerations (PGA) with an amplitude as high as nearly 40 cm/s^2 were artificially doctored to the Moscow recording of the $Mw = 7.4$ earthquake in the Vrancea zone, which corresponds to almost 6-points on the MSK-64 scale seismic intensity. As it will be shown below, the values of accelerations obtained in our study proved 20 times smaller in magnitude even for the maximum possible Vrancea earthquake as intense as $Mw = 8.0$.

In the "renormalization", also the substantial changes in the shape of the record, which appear at a distance from the epicenter and reflect the corresponding traveltime curves of different wave modes, were also disregarded.

MACROSEISMIC MANIFESTATIONS WITHIN MOSCOW

According to the official normative maps of General Seismic Zoning of the Russian Federation, OSR-97, the intensity of the maximum possible seismic shaking on the average soils (the soils of the second category according to SNIP II-7-81*) of Moscow corresponds to 5 point seismicity on the MSK-64 macroseismic scale, with a probability of 99% for this seismic level not being exceeded during a 50-year-long time interval [*Seismic* ..., 1999; Ulomov and Shumilina, 1999a; 1999b].

Until the OSR-97 maps had been compiled, the site of Moscow was traditionally considered a seismically safe area, although quite perceptible seismic effects caused by remote strong earthquakes were still known. First of all, this relates to the Vrancea source zone in the East Carpathians (Fig. 2). Soil vibrations of 2–3 points caused by the strong earthquakes occurring in the western part of Central Asia, in the North Caucasus and in the Crimea, are also observed in Moscow. A recent event felt on the top floors of buildings in Moscow was the earthquake of December 6, 2000 that occurred in West Turkmenistan.

Seismic effects from the Vrancea earthquakes of 1940, 1977, and 1986 in Moscow were felt as events of magnitude 4 at the street level and even stronger on the 14th–

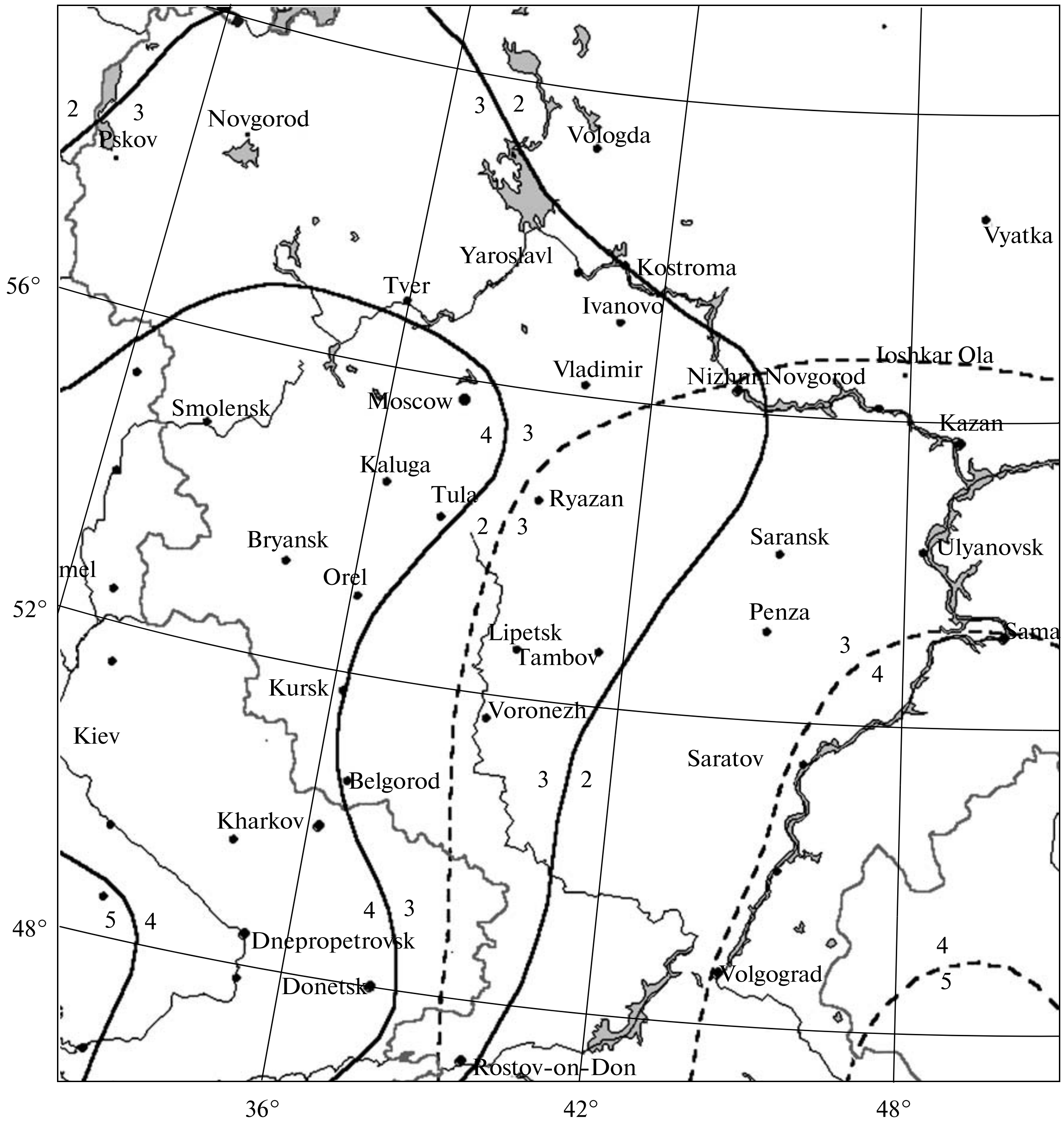

Fig. 2. Diagram of isoseits for the strongest far earthquakes felt in Moscow (composed by V.I. Ulomov, according to the data of I.V. Anan'in, A.V. Drumya, A.A. Nikonov, G.L. Golinskii and others). Solid lines are the isoseists of the $Mw = 7.4$ Vrancea earthquake of 1977 with; dotted lines are the isoseists of the $Mw = 8.0$ Krasnovodsk earthquake of 1895 (West of Turkmenia). Intensity (points) in the zones where the shocks were perceived are indicated by numbers.

18th floors of high-rise buildings. Thus, the Vrancea earthquake of March 4, 1977 caused noticeable damages such as small cracks at the joints of walls and ceilings on the 24th floor of reinforced concrete frame buildings in the southwest Moscow. It was also reported that the spire at the top of the Moscow State University building on Vorob'evy gory swung with an amplitude of up to two meters.

The relatively recent seismic events of this kind, during which the shocks on the top floors of tall buildings in Moscow reached an intensity of 3–4 MSK, were the earthquakes in the Vrancea zone of May 30 and 31, 1990.

The Vrancea region located on the southeastern bend of the mountain structure of the Carpathians in Romania is one of the most active seismic areas of Europe. The source region is an almost vertical lithospheric slab submerged to a depth up to 180 km and deeper. The largest seismic sources are located very compactly within a depth range of 80–160 km, occupying an area 30×60 km^2 wide in a plane.

The mechanism of rock motion in the source of the $Mw = 5.9$ Vrancea earthquake of October 27, 2004 determined from the signs of the first arrivals of the *P*-waves is depicted in Fig. 3. Such a mechanism is also typical of the

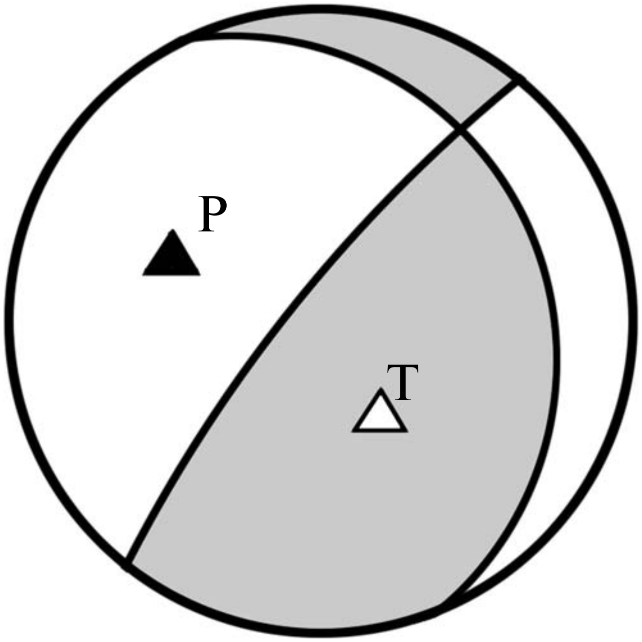

Fig. 3. Focal mechanism of the earthquake of October 27, 2004 with $Mw = 6.9$ in the Vrancea zone, according to the data of Harvard SMT catalog. The footprints of the compression (P) and tension (T) axes on the lower hemisphere of stereographic projection are indicated by triangles, and the traces of nodal planes are marked by arcs.

other strong seismic events at these depths within this zone. However, distributions of the focal mechanisms of weaker earthquakes is usually less regular, because these events are associated with the discharge of elastic stress via secondary faults more chaotically distributed in space.

As shown in the works [Drumya et al., 2006], the source motion patterns of the earthquakes of 1977, 1986, and 1990, determined by different methods, show good agreement with each other. Both possible rupture planes have a northeastern strike, which agree with the strike of the region of numerous aftershocks and practically coincide with the isoseist elongation towards Moscow. One of the rupture planes is steep, and the other, flatter. The slips along these planes are represented by overthrust with a small shear component. The axis of tensile stress (T) is almost vertical, the axis of compressing stress (pressure tension) (P) is near-horizontal and is oriented northwest.

Strong Vrancea earthquakes are accompanied by destructive effect shown not only within the Romanian territory but also in the adjacent European countries.

Recent studies of Romanian seismologists exposed the specific character of the Vrancea earthquakes, featuring, on the one hand, a higher rate of rupturing in the buried sources as compared to the intracrustal sources, and, on the other hand, high stress drop upon the slip of rocks in the seismic source. Calculations were carried out for two typical sources at a depth of $h = 90$ km (moment magnitude $Mw = 7.4$) and at a depth of $h = 150$ km ($Mw = 7.7$). For the deeper source, the attenuation of the seismic effect from the epicentral distance proved appreciably lower at longer distances, and the opposite, at shorter distances.

The first source corresponds to the earthquake of March 4, 1977, which occurred in the upper part of the Vrancea region. The second source is related with the earthquake of November 10, 1940 with the hypocenter at a depth of 150 km. The rock slip mechanisms in these sources proved similar. The values of peak ground acceleration (PGA), velocity (V), and displacement (D) of soil in Bucharest, which is especially subjected to earthquakes in the Vrancea zone, were:

1977: PGA = 0.23 g, $V_{max} = 27$ cm/s, $D_{max} = 18$ cm;

1940: PGA = 0.52 g, $V_{max} = 105$ cm/s, $D_{max} = 42$ cm.

In Bucharest, 35 high-rise buildings collapsed almost completely during the earthquake of 1977. More than 1500 fatalities occurred. Another two Romanian cities located approximately 200 km apart from the epicentral region were also destroyed.

Thus, the elongation of the Vrancea earthquakes isoseists towards Moscow is due to relatively weak seismic attenuation and the Vrancea seismic zone orientation close to this direction. The vast areas that experience seismic shocks are explained by the deep source location of these earthquakes relating to the so-called intermediate depths range.

Fig. 4 displays the seismic setting within the source region located at a depth of 60–180 km in the Vrancea zone. The succession of the large earthquakes that have occurred and are predicted to occur, which can be perceived in Moscow, is shown. The table illustrating the average repeatability of seismic events with different magnitudes is also given.

As regards the expected seismic effect in the site of Moscow, it is necessary to remember that the seismic situation in the city is getting worse and worse from year to year [*Moscow*..., 1997]. The reason for the increase in the seismic vulnerability of the city is the water-table elevation implying the aquifer rises to a depth of less than 3 meters, as well as karst caving and suffosion processes.

THE ASSESSMENT OF SEISMIC HAZARD BASED ON OSR-97 MAPS

The ambiguity persisting in the natural conditions and fluctuations in the seismic setting of a territory make a probabilistic approach the only acceptable tool in the assessment of seismic hazard. In other words, a risk will always persist but it must be properly evaluated and minimized. This is the underlying concept set in the normative maps of the regionalization of seismic risk on the territory of the Russian Federation, OSR-97. These maps were included in 2000 in the Construction norms and regulations (SNIP II-7-81*) *Building in seismically active regions* [*Construction* ..., 2000]. The probabilistic approach makes it possible to assess the seismic hazard for objects of different risk classes and life spans.

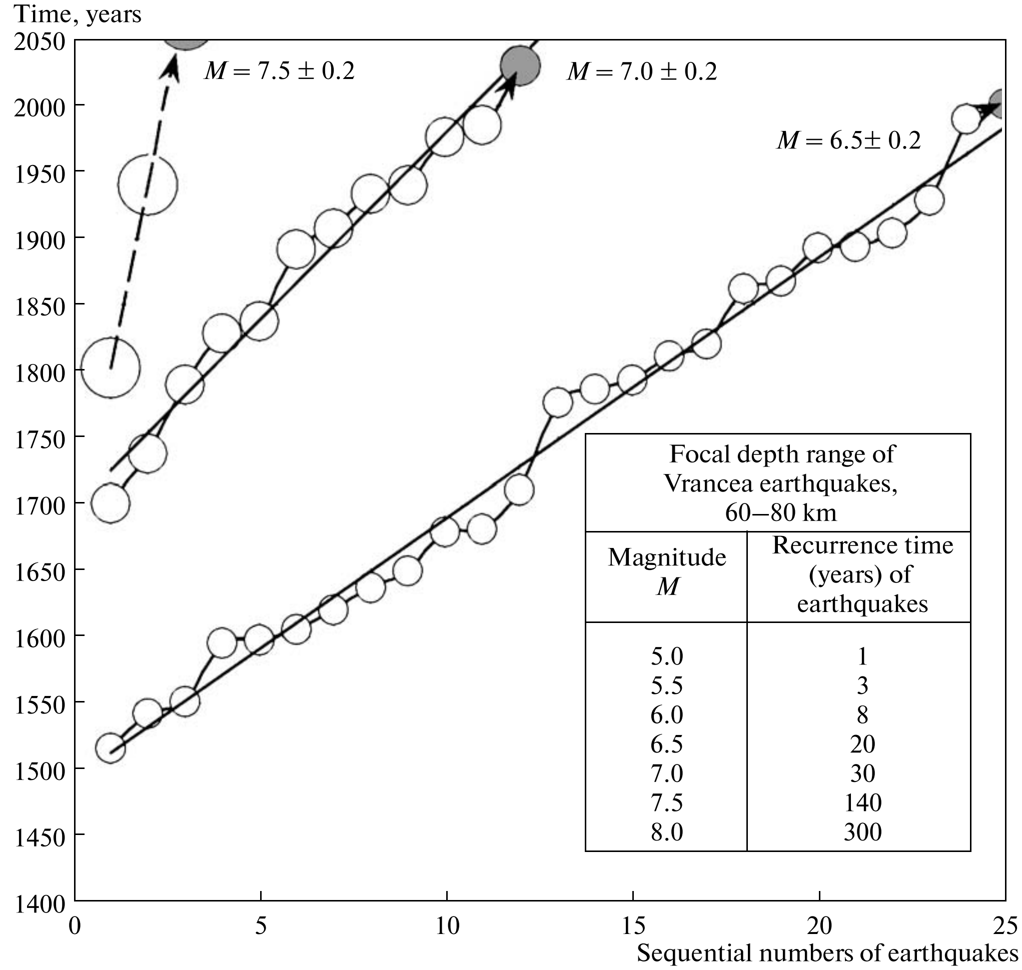

Fig. 4. Seismic setting in the Vrancea focal zone at a depth of 60–180 km. The succession is shown of the occurred (open circles) and predicted (grey circles) strong earthquakes in the Vrancea zone with magnitudes higher than 6.5 ± 0.2.

The OSR-97 maps (A, B, C), included in SNIP II-7-81* (Construction norms and regulations), are intended for civilian and industrial engineering. The seismic hazard estimation is executed at three levels reflecting the calculated intensity of seismic shocks in terms of magnitudes on the MSK-64 scale, which are expected on average soils (the soils of category II, according to SNIP II-7-81*) with a given probability, during a particular time interval. For instance, the OSR-97A map corresponds to a 10% risk of the occurrence and possible excess (or a 90% probability of not exceeding) over the specified seismic intensity during 50-year-long time intervals. This map is used in the mass construction of residential, public, and industrial buildings. The OSR-97B and OSR-97C maps correspond to 5%- and 1%-risks of exceeding (or 95% and 99% probabilities of not exceeding) the limits that are intended for the design and construction of the higher and highest class critical objects including high-rise buildings. These three maps correspond to a 500-, 1000- and 5000-year recurrence of the seismic effect in any geographical point within the zones delineated in the maps. For the extremely critical construction objects such as nuclear power stations, the OSR-97D map corresponding to a recurrence period of $T = 10\,000$ years was built. This map has been also included in the relevant building regulations.

The OSR-97 maps provided for the first time a complete seismic zoning for the entire territory of the country including territories of low-active platforms and shelves of the internal and marginal seas.

Moscow is situated at the center of the East European platform, which is characterized by relatively weak seismicity and very rarely occurring local earthquakes with a intensity 6-MSK in the epicenter. Such phenomena were observed, for example, in Almetevsk (earthquakes in 1914 and 1986), Elabuga (1851, 1989), Vyatka (1897), Syktyvkar (1939), Verkhnii Ustyug (1829), Kaliningrad (2004), and others. Seismic events of similar intensity hit the Central Urals, the Cis-Ural, Azov and Volga regions, and the Voronezh massif. On the Kola Peninsula and in the adjacent territory even stronger seismic events were detected (the White Sea, Kandalaksha, 1626).

Together with these seismic events in the European part of the country, as it has been already mentioned

Table 1. Evaluation of seismic effect in the territory of Moscow for different recurrence time of shocks and quality of the medium

Recurrence period T, years	Map series	Intensity I for different quality factor Q of geological medium	
		Q_1	Q_2
100	–	<3	3.2
250	–	<3	3.6
500	OSR-97A	<3	3.8
1000	OSR-97B	<3	4.2
2500	–	3.4	4.4
5000	OSR-97C	4.1	4.6
10000	OSR-97D	4.6	5.0

above, vibrations produced by strong earthquakes occurring in the adjacent regions are also felt . Northwest Russia is affected by the Scandinavia earthquakes (Norway, 1817), and the South by the strong earthquakes of the Caspian basin (Turkmenistan, 1895, 2000), Caucasus (Spitak, Armenia, 1988), and Crimea (Yalta, 1927).

The OSR-97 maps, depending on the time interval considered (500, 1000, 5000 and 10 000 years), noticeably change not only their rating levels, but the seismic patterns as well. The longer the period of the "expectation" of a seismic event, the more serious the relevant seismic hazard may prove. And vice versa, the seismic zones shrink with a decrease in the duration of the "expectation" period. As evident in the fragment of the OSR-97C map (Fig. 5), representing the average recurrence of seismic effects in any geographical point once per 5000 years, the nearest 6 points zone to Moscow is approximately 120 km distant from downtown and overlaps only the eastern part of the Moscow region.

Table 1 presents the results of calculations for different seismic recurrence intervals in Moscow in accordance with the two accepted quality parameters Q_1 and Q_2 of a geological medium [Gusev and Shumilina, 1999]. The Q_1 quantity, corresponding to predominantly intracrustal seismicity, was applied in OSR-97 for the whole territory of North Eurasia, and the Q_2 quantity was introduced especially for calculating seismic attenuation along the trace from the deep sources in the Vrancea zone to the East European platform, including Moscow. The grounds for the introduction of the increased quality parameter, Q_2, was, on the one hand, a decrease in seismic attenuation of the distance from the epicenter, as found by Romanian seismologists and, on the other hand, the northeastern elongation of the observed isoseists and seismic effects observed on the territory of Moscow.

Simultaneously, for the same periods of recurrent seismicity of different intensity, probabilistic analysis of seismic hazard in the site of Moscow was carried out (Fig. 6). The equation given in Fig. 6 for the approximating straight line (exponent) makes it possible to calculate the shock intensity in Moscow for any given period of seismic recurrence, including estimates in fractions of points. The latter can be used for microseismic zoning in cases when the site soil effects are also estimated in fractional increments to the initial point.

As it is evident from Table 1 and Fig. 6, even for the interval of the longest recurrence, T = 10000 years (OSR-97D map), the expected seismic effect should not exceed 5 points on the soils of category II.

Thus, the set of OSR-97 maps for Moscow provides a quite reliable estimate of the "initial" seismic effect of magnitude 5 with the probability of it being exceeded not higher than 1.0–0.5% (OSR-97C and OSR-97D maps).

Together with the probabilistic assessment of the seismic hazard, I also carried out deterministic calculations of the seismic effect intensity in Moscow. I used the scenario sources of Vrancea earthquakes with magnitudes Mw ~7.0, 7.5, and 8.0 in the form of areas with appropriate sizes and similar orientation corresponding to the real source patterns (see Fig. 3). Calculations were carried out in accordance with the same method as applied in the construction of the OSR-97 maps [Ulomov and Shumilina, 1999b]. However, in this case, the seismic effect was not considered in relation to any particular source and the estimates were, hence, deterministic, i.e., with no allowance for the seismic specificity of the Vrancea zone. The estimated shock intensity related to the average soil conditions and also did not exceed seismic intensity of 5 points, including the case of maximum possible seismic event with magnitude Mw = 8.0.

THE ASSESSMENT OF SEISMIC EFFECTS BASED ON INSTRUMENTAL OBSERVATIONS

In 2002–2003, I analyzed the seismograms of the Moskva Central seismic station in order to gain an idea of the intensity and the spectral composition of shocks caused in the territory of Moscow by the strongest earthquakes in the Vrancea zone in 1977, 1986, and 1990. Together with this, I have, for the first time, carried out the spectral analysis of weaker seismic events imperceptible in Moscow, which were digitally recorded in recent years at the Moskva and Obninsk seismic stations. The general idea was to explore the possibilities for extrapolating the parameters of weak earthquake records towards the strongest seismic events. This approach was a certain modification to the technique suggested in [Aptikaev and Erteleva, 2002]. However, in our case the accelerograms were selected from a single distinctly localized source region in Vrancea zone rather than those showing a certain similarity but selected from different source zones . This approach improves the quality of the selected accelerograms and increases the reliability of their quantitative analysis.

Before 1999, only analog recording of earthquakes was available at the Moskva Central seismic station. The data were recorded on photo paper; and therefore I had

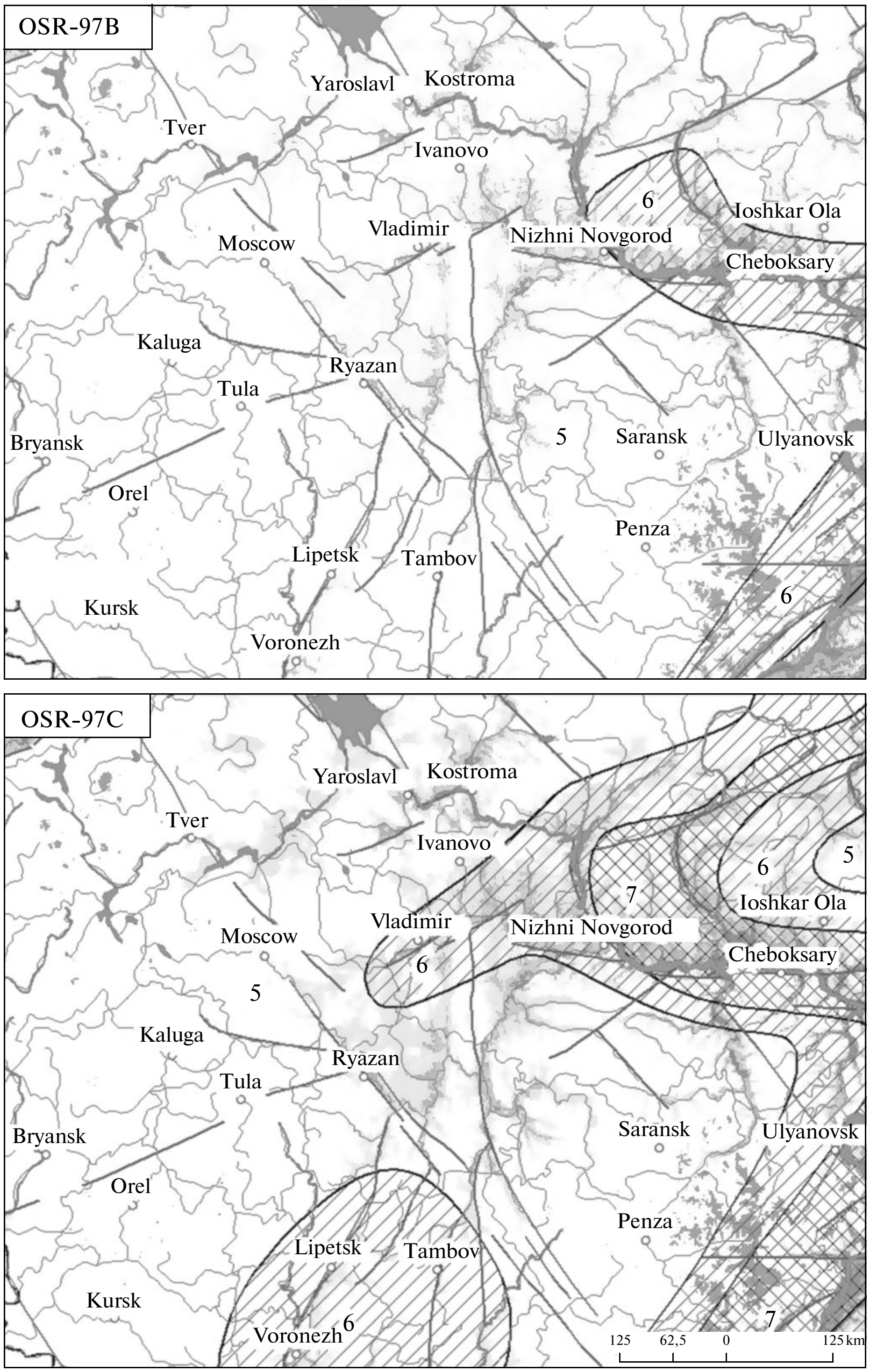

Fig. 5. Fragments of the maps of the general seismic risk regionalization for the territory of the Russian Federation, OSR-97B and OSR-97C, characterizing the maximum possible seismic effect with probability 95% and 99% of its non-excess for 50 years. Different shading displays the 6- and 7-magnitude zones of seismic intensity; location of tectonic faults is shown by black segments.

to manually digitize the seismograms of the three earthquakes mentioned above. Moreover, due to the fact that at high amplitudes even the instrumentation with intentionally lowered sensitivity went off scale, it proved possible to digitize only the vertical (i.e., not the most intense) component of the three-component record. However, for the strongest Vrancea earthquake of March 4, 1977, only the initial part of the vertical component record was

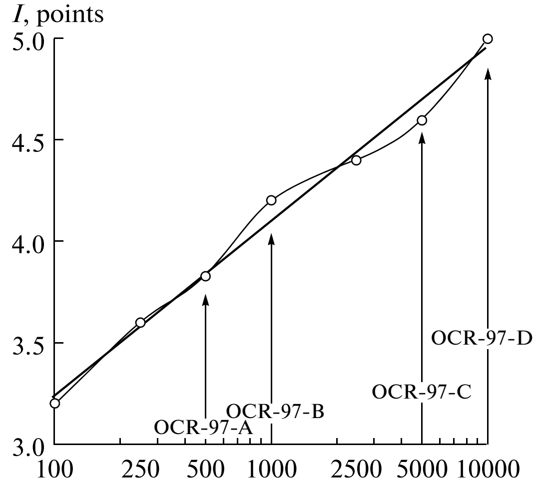

Fig. 6. Probabilistic analysis of seismic hazard in the territory of Moscow on the basis of the electronic database of OSR-97. The point values of intensity are calculated for periods 100, 250, 500, 1000, 2500, 5000 and 10000 years. Estimates by corresponding maps OSR-97 are indicated by arrows. The approximating straight line (exponent) allows calculation of the shock intensity for any given recurrence period of the seismic effect.

digitized (Fig. 7). As shown below, this record was hardly suitable for analysis at all.

The work was implemented in two stages. The first one, as already mentioned, covered the period of 2002–2003. These studies were conducted by V.I. Ulomov (principal investigator), I.V. Gorbunova, L.S. Shumilina, and N.S. Medvedeva (Institute of Physics of the Earth, Russian Academy of Sciences), and V.D. Feofilaktov and V.F. Babkina (Geophysical Service of the Russian Academy of Sciences). The second stage (2007–2008) of the research was to a considerable degree motivated by interest in the largest (for the past 17 years) Vrancea earthquake of October 27, 2004 with magnitude of $Mw = 5.9$. At the Moskva Central seismic station, a digital record of such a strong event has been obtained for the first time. A.A. Gusev (Institute of Volcanology and Seismology, Far East Division, Russian Academy of Sciences) and O.V. Pavlenko (Institute of Physics of the Earth, Russian Academy of Sciences) were involved in this part of the research. The results of their work are complied into a separate paper, *Scenario Earthquakes for Evaluating the*

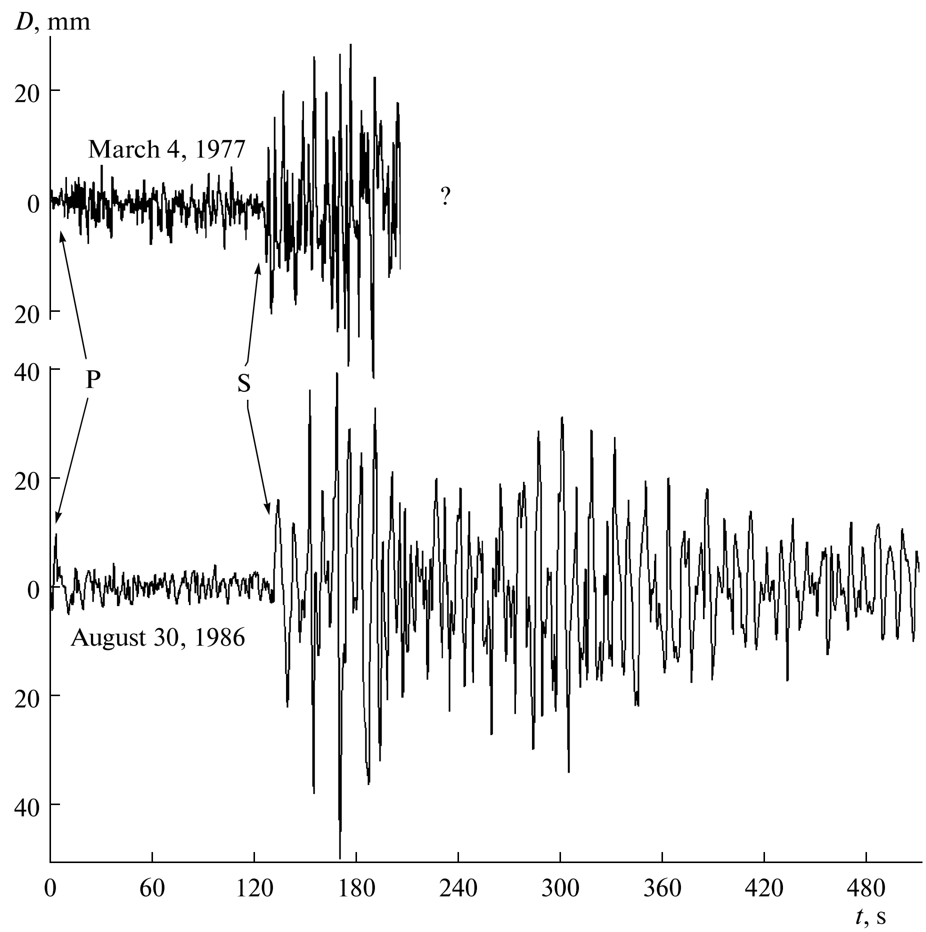

Fig. 7. Digitized sections of the vertical components of analog records obtained at the Moskva seismic station for the earthquakes in the Vrancea zone of March 4, 1977 with $Mw = 7.4$, and of August 30, 1986 with $Mw = 7.1$ felt in Moscow.

Table 2. Catalog of the earthquakes in the Vrancea zone used in the analysis of seismic hazards in Moscow

Date of earthquake	Moment magnitude, *Mw*
Analog seismograms	
March 4, 1977	7.4
August 30, 1986	7.1
May 30, 1990	6.9
May 31, 1990	6.1
Digital seismograms	
April 28, 1999	5.4
May 24, 2001	5.3
June 20, 2001	5.2
November 30, 2002	5.1
September 27, 2004	5.2
October 27, 2004	5.9
May 14, 2005	5.2
June 18, 2005	5.0
December 13, 2005	5.2

Seismic Loads in Moscow: Parameters and Model Movements of the Ground.

Table 2 shows a list of the earthquakes used in our analysis. Events of 1977, 1986, and 1990 felt in Moscow were recorded by analog instrumentation, and less strong events of 1999–2005, by digital implementation.

The record of the earthquake of 1986 looks the most complete. The duration of rather intense variations in the vertical component exceeds 8 minutes (Fig. 8). However, in the record of the earthquake of 1977, the more or less readable section of the record hardly reaches three minutes. It proved possible to digitize only the vertical component in seismograms of the earthquakes of 1977, 1986, and 1990 that were recorded on photographic paper, therefore this very component was assumed as the basis for the comparison between strong and weak earthquakes.

Figure 9 illustrates an example of the original three-component records at the Moskva and Obninsk seismic stations of the Vrancea earthquake of April 28, 1999 with $Mw = 5.4$. While processing the digital seismograms of weak shocks, I considered two groups of waves: longitudinal P(pressure) and S + L combining the transverse (S, shear) and surface (L, Love) waves.

Deconvolution of the observed seismograms was carried out taking into account the parameters and amplitude-frequency response of the recording instrumentation.

The spectral densities of the ground acceleration, calculated for the modulus of the Fourier spectrum and plotted for the vertical components of three-component records, are shown in Fig. 10. For a clearer representation, the plots are smoothed in a rectangular window with a width of 0.025 Hz. For the purposes of spectral analysis I selected longest possible time series in the groups of P and S + L-waves. For the P-waves, I chose an interval from the first arrival to the S-wave arrival, and for the S + L-waves, from the arrival of the *S*-waves to the end of the surface waves, i.e., almost to the noise level.

I did not conduct the transition from the Fourier spectra to the response spectra used in the practice of construction engineering, and did not construct any plots of dynamic response factors except for a single case, shown below as an example (Fig. 12).

A noteworthy feature in Fig. 10 is the similarity in the patterns of spectral density for all seismic events considered, both strong and weak, within a wide range of magnitudes *Mw* from 5.1 to 7.4. This again emphasizes the urgency for the thorough analysis of recent digital records in Moscow even for faint but numerous seismic manifestations of the Vrancea earthquakes. This also offers new possibilities for updating the engineering solutions.

An intense low-frequency component of seismic vibrations that is especially hazardous for high-rise building sites is easily detectable. At the same time, it must be also recognized that the results of seismic measurements are not quite reliable in the low frequency range (periods of 10 s and longer).

Figure 11 illustrates three projections (the east–west, the north–south, and the vertical) of the digital accelerogram of the ground motion under the Moskva seismic station during the strong earthquake in the Vrancea zone on October 27, 2004 with a magnitude of $Mw = 5.9$ and a focal depth of about 100 km. A fragment of the vertical component of the accelerogram of the March 4, 1977 earthquake perceived everywhere in Moscow, is presented at the bottom of this figure on the same horizontal but reduced vertical scale. This is the single fragment available for the analysis.

Comparing the amplitudes of accelerations in the corresponding fragments of the records of 1977 and 2004, I can find, at the first approximation, that the maximum accelerations on the benchmark soil (accepted as the soil beneath the Moskva Central seismic station at a depth of 4 m from the Earth's surface), did not considerably exceed 1 cm/s^2 in 1977 [Ulomov, 2008]. At first, such low values of accelerations raised doubts as to their feasibility, not only among designers and house builders, but also among some seismologists. However, as it will be

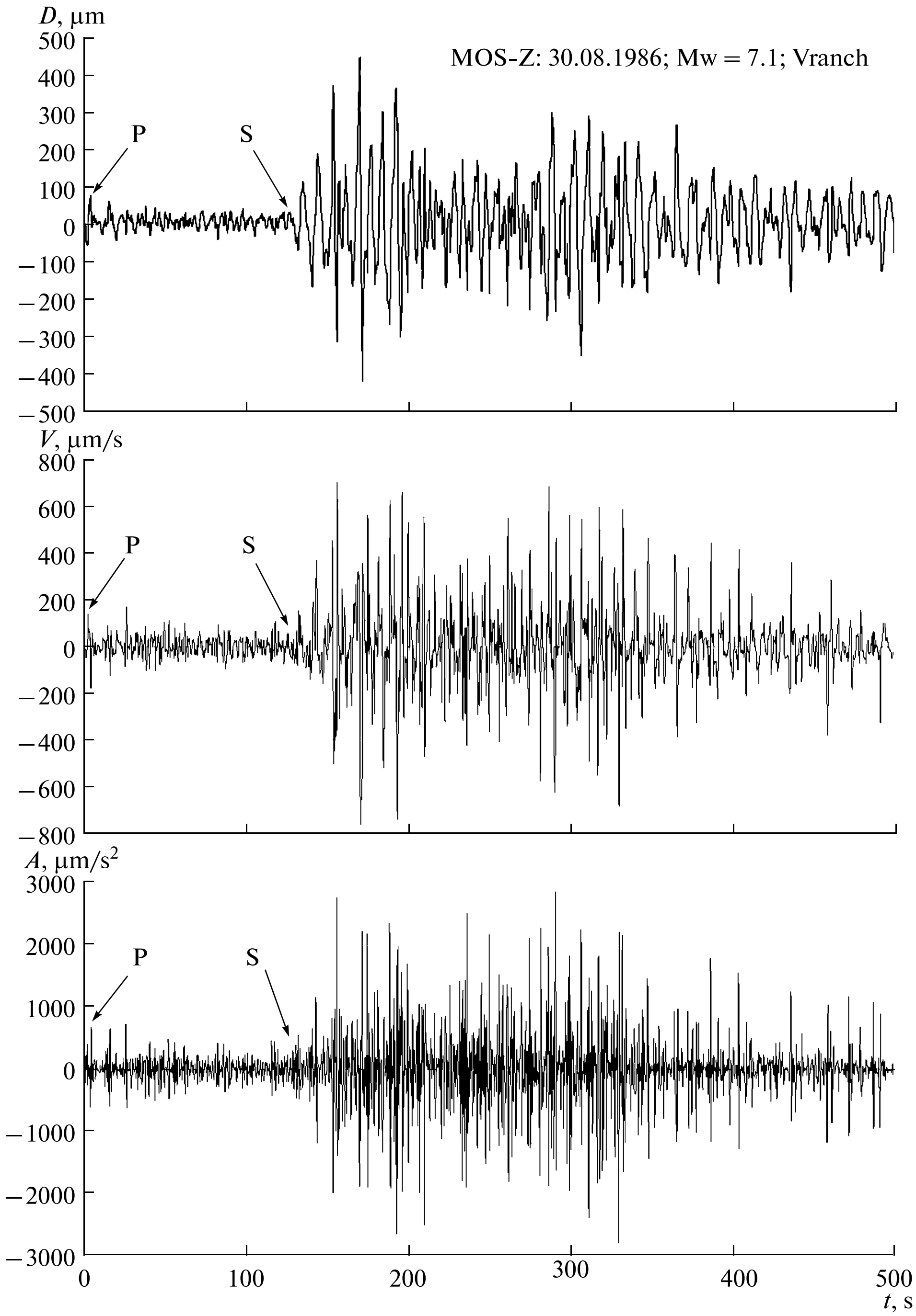

Fig. 8. Displacements (*D*), velocities (*V*) and accelerations (*A*) determined from the vertical component of the analog record of the Vrancea earthquake of August 30, 1986 in the zone with $Mw = 7.1$, recorded at the Moskva seismic station. The time of arrival of longitudinal (P) and transverse (S) waves at the Moskva station are marked by arrows.

shown below, the accelerations of the same order were confirmed by new calculations and constructions. These inferences were supported also by other researchers, including those who previously doubted our results.

The comparison between the plots of the dynamic-response factor (Fig. 12), constructed according to the vertical component of the P-waves accelerogram for the earthquake of 2004 (*1*), and according to its fragment (*2*) equal in duration to the available part of the record for the earthquake of 1977, shows a considerable loss in useful information, regarding the low-frequency component of seismic vibrations on the record of the earthquake of

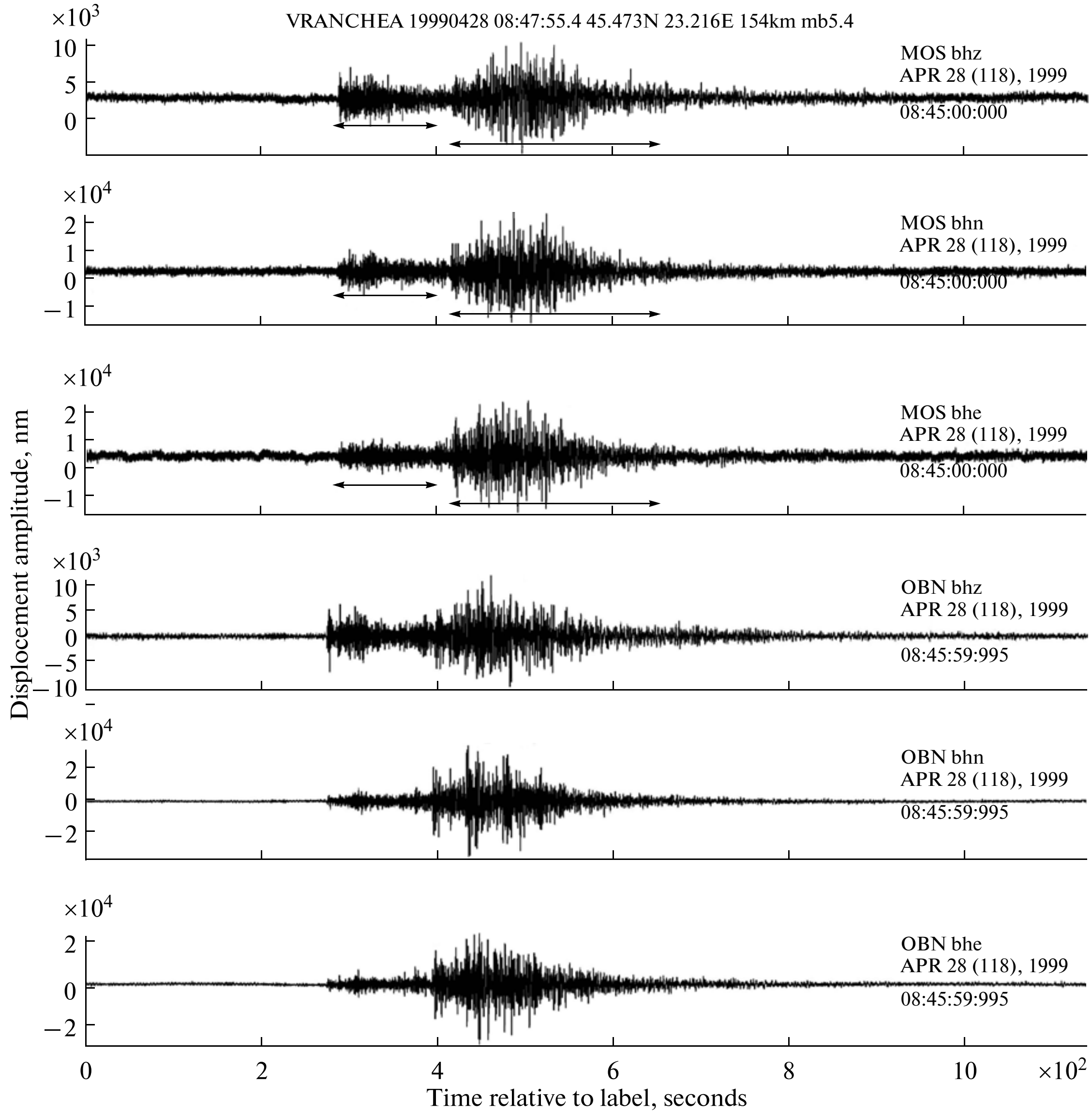

Fig. 9. Example of records of the earthquake of April 28, 1999 in the Vrancea zone with $Mw = 5.4$ carried out by the Moskva (at the top) and Obninsk seismic stations (with permission of the Geophysical Service of the Russian Academy of Sciences). The groups of P and S + L waves analyzed are marked by double arrows.

1977, whereas this is just that information, which is most important for calculations of seismic impacts upon high-rise objects. The same is also evident in Fig. 10, where the low-frequency part of the plot of the spectral density for the earthquake of 1977 is noticeably lower compared to the weaker earthquake of 1986.

Therefore, and also because of the deficiency of the record of 1977, further calculations of the seismic effect in Moscow were carried out by means of comparison between digital accelerograms of moderate and weak earthquakes with the vertical component record of the earthquake of 1986.

SEISMIC EFFECTS IN MOSCOW CAUSED BY THE MAXIMUM POSSIBLE EARTHQUAKE IN THE VRANCEA ZONE

Presented in Table 3 are the basic parameters of the Vrancea earthquakes with different magnitudes, which were used for estimating the measured and for calculating the predicted accelerations. As seen from the Table, for all digital records the value of acceleration for all three components are determined: the vertical (Z) and the two horizontal (EW, NS). The rightmost column presents the values of the full vector of horizontal accelerations (A_{hor}). The bottom row of the Table relates to the predicted earthquake with $Mw = 8.0$.

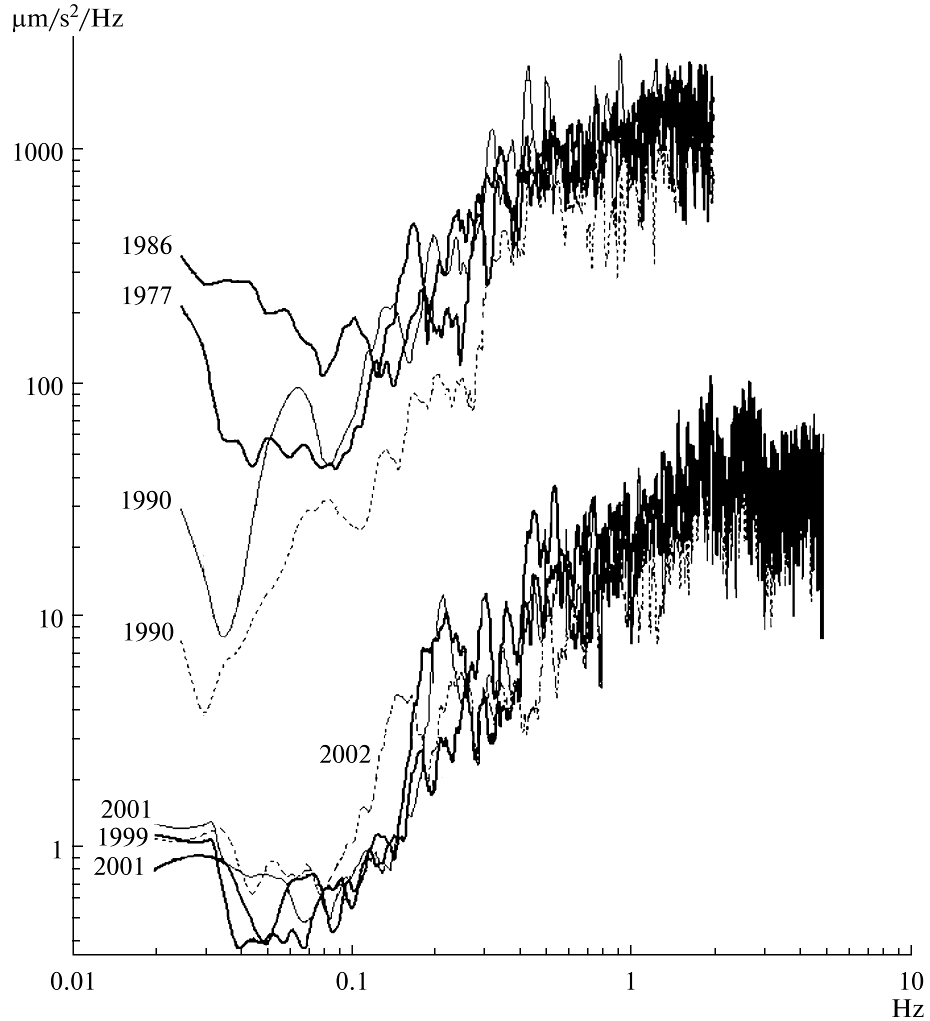

Fig. 10. Spectral density of ground accelerations in the P waves beneath of the Moskva seismic station. The dates of earthquakes in the Vrancea zone are indicated by numbers.

Table 3. Basic parameters of the seismic effect caused by Vrancea earthquakes

Date	H, km	Mw	X, km	A_Z, cm/s^2	A_{EW}, cm/s^2	A_{NS}, cm/s^2	A_{hor}, cm/s^2
March 4, 1977	108	7.4	1338	–	–	–	(1.0)
August 30, 1986	137	7.1	1382	0.08	–	–	0.312
April 28, 1999	156	5.4	1365	0.005	0.018	0.018	0.025
May 24, 2001	129	5.3	1335	0.007	0.014	0.017	0.022
October 27, 2004	96	5.9	1317	0.022	0.063	0.059	0.086
June 18, 2005	139	5.0	1321	0.004	0.007	0.005	0.009
Prediction (2100 ?)	150	8.0	1350	0.8	2.3	2.2	2.3

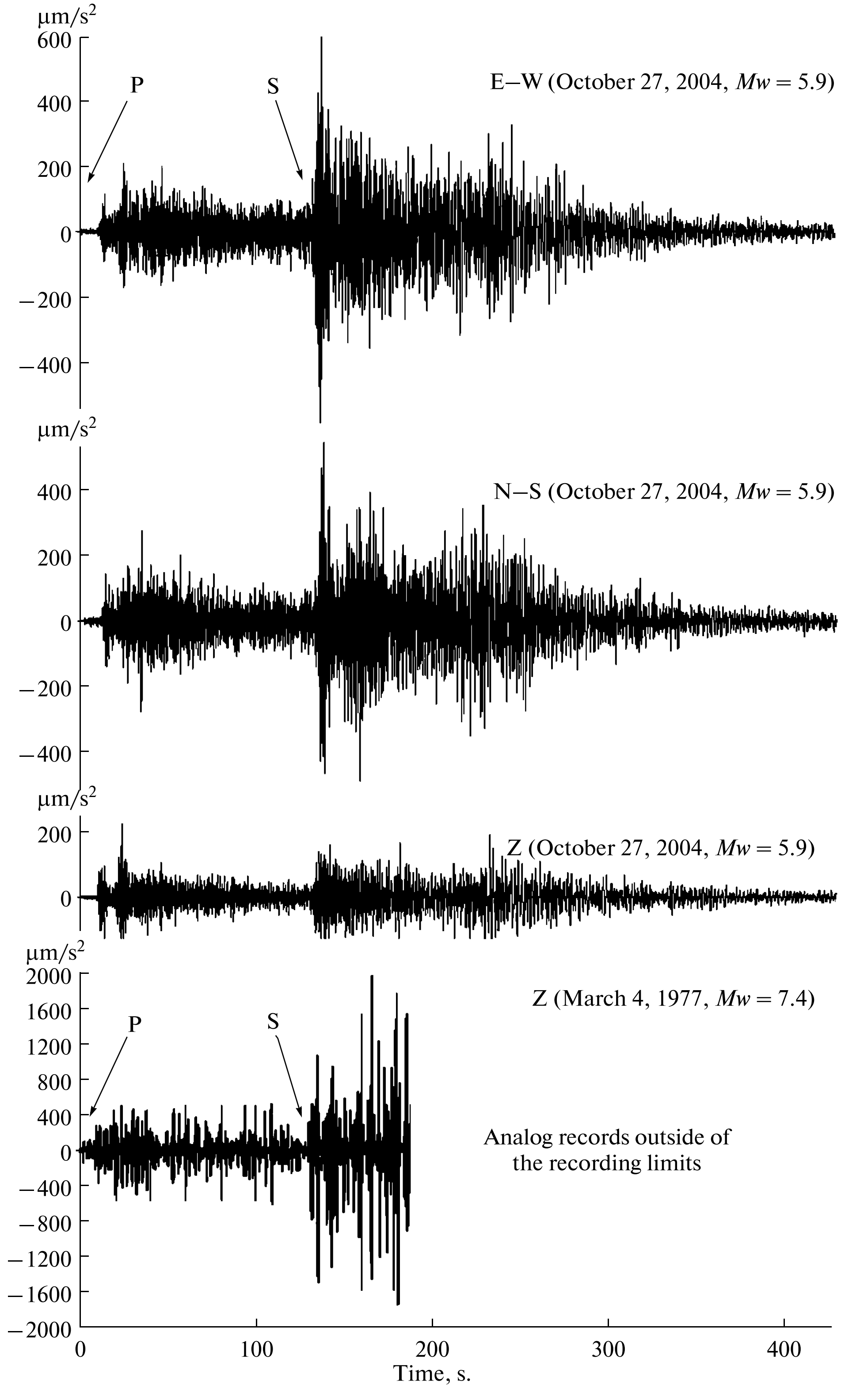

Fig. 11. Digital three-component accelerogram of the movement of ground beneath the Moskva seismic station during the earthquake of October 27, 2004 in the Vrancea zone (the magnitude $Mw = 5.9$) and the fragment of partly digitized vertical component of the accelerogram of the earthquake of March 4, 1977 with $Mw = 7.4$ (at the bottom). The time of arrival of longitudinal (P) and transverse (S) seismic waves at the Moskva seismic station are indicated.

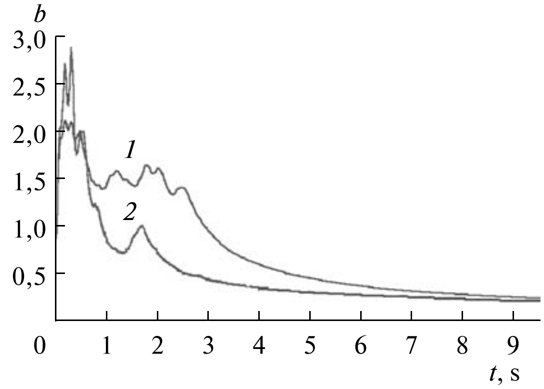

Fig. 12. Plots of dynamic-response factors obtained from the vertical component of the accelerogram of the earthquake of October 27, 2004 in the Vrancea zone (*1*) and from its fragment (*2*) with duration equal to the available part of the record of earthquake of 1977 (see Fig. 11). The loss of the low-frequency component of seismic vibrations is distinct.

For the earthquake of 1977 with $Mw = 7.4$, a tentative value of the full vector of accelerations is given in the parenthesis in the right-hand column of the table. For the earthquake of 1986, with $Mw = 7.1$, the accelerations $A_Z = 0.08$ cm/s^2 in the vertical component of the longitudinal waves turned out to be acceptable. Assuming the similarity between the seismograms of earthquakes with magnitudes 5.9 and 7.1, which seems quite reasonable for the large sources of the Vrancea zone, it is possible to compare the amplitude ratios for the accelerations A_Z for these two seismic events. Thus, taking $A_{hor}/A_Z = 3.9$ for the earthquake of 2004, I obtained $A_{hor} = 0.312$ cm/s^2 for the event of 1986.

The data of Table 3 are depicted in Fig. 13, where they were interpreted in two possible ways. The figure displays the dependence of the maximum horizontal accelerations A (cm/s^2) of the ground motions beneath the Moskva seismic station upon the magnitude Mw of the Vrancea earthquakes. The values of accelerations presented in Table 3 are shown by black dots. The approximation built according to all these data is depicted by the dotted line, and the dependence derived from the most confident values of accelerations (i.e., completely excluding the event of 1977, i.e., A_{hor} = 1.0 cm/s^2) is shown by the solid line. Accelerations of 2.3 cm/s^2 in the first case and of 1.7 cm/s^2 in the second case correspond to the predicted seismic event with $Mw = 8.0$.

The studies based on another approach for the estimation of the expected seismic impact were carried out by A.A. Gusev and O.V. Pavlenko. This work also showed that for the earthquake with magnitudeMw = 8.0 in the Vrancea zone, the accelerations of shocks in the site of Moscow will only slightly exceed 2 cm/s^2.

All these relatively low estimates of accelerations obtained for the seismic effects of the Vrancea earthquakes perceptible in Moscow, which raised doubts among designers and some seismologists, in the first approximation can be explained if we analyze Fig. 14, compiled with the use of the data from [Wald et al., 1999]. As is evident, although a sufficiently large (to one decimal order) scatter is seen in the observed values of accelerations corresponding to the seismic intensity I = 5 and higher, these data are still available for systematization and numerical analysis, which has been implemented in the work [Wald et al., 1999]. However, the parameters of weak seismic events (less than 5 point) and small accelerations (up to 10 cm/s^2), which are obviously insufficient

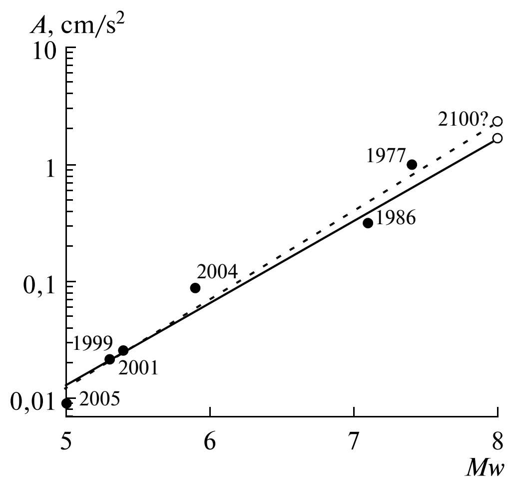

Fig. 13. Dependence of the maximum horizontal accelerations A (cm/s^2) of the displacements of ground beneath the Moskva seismic station on the magnitude Mw of earthquakes in the Vrancea zone. See explanations in the text.

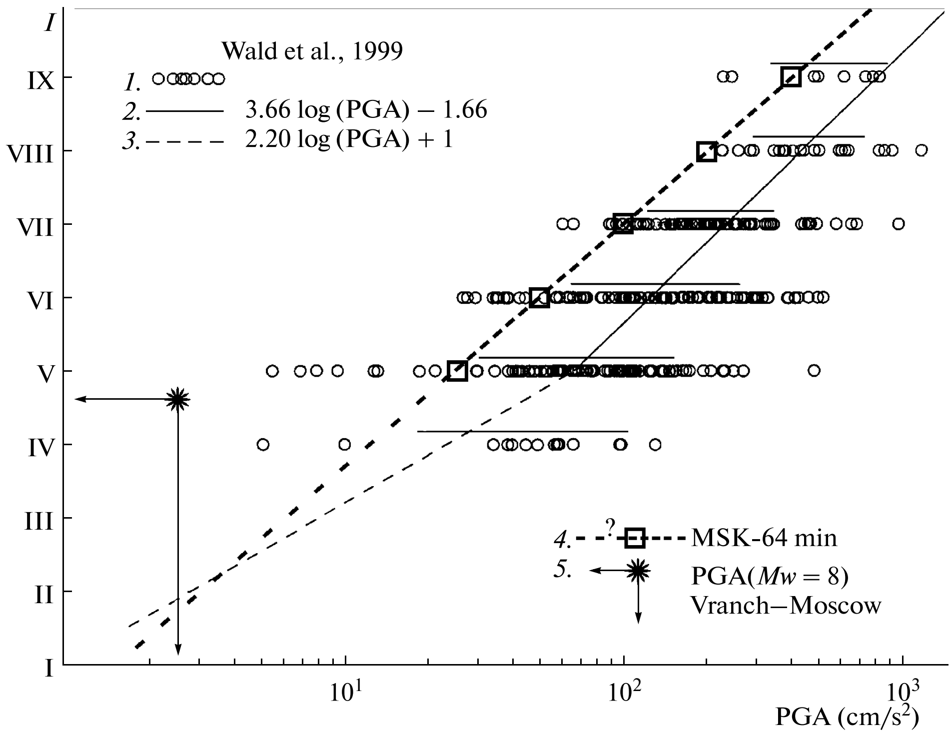

Fig. 14. Relationships between the seismic intensity (*I*, magnitudes) and peak accelerations (PGA); (*1*)–(*3*), according to the data [Wald et al., 1999], (*4*) the lower limit of accelerations on the MSK-64 scale, according to SNIP II-7-81* (Construction norms and regulations), (*5*) estimation of *I* and PGA ratio for the ground beneath the Moskva seismic station during the design-basis earthquake with $Mw = 8.0$ in the Vrancea zone.

to date, have not been systematized so far (the left lower corner in Fig. 14). At the same time, the scatter in both values may be indicative of the reliability of our obtained (seemingly underestimated) estimates for the peak accelerations PGA = 2.3 cm/s^2, corresponding to perceptible seismic shocks up to intensity 5 MSK.

The dotted line in the figure depicts the approximation and conditional extrapolation towards the lower seismic intensity of accelerations 100, 200, and 400 cm/s^2 suggested by SNIP II-7-81* (construction norms and regulations) as the minimum values for seismic events of 7, 8, and 9 points on the MSK-64 scale. It is also worth mentioning that the more reliable criterion for the assessment of seismic hazard, in the opinion of many researchers, is the vector velocity of vibrations of the ground at the bottom of building sites. Observations showed that, against the other parameters of seismic waves (displacement, acceleration, and others), the displacement velocity shows the best correlation with the extent of damages on the buildings.

Many researchers have noted the inconsistence that is sometimes encountered between instrumental and macroseismic data, as well as the necessity to take into account the duration of vibrations influencing the seismic effects [Aptikaev, 1999; Wald et al., 1999; Aptikaev and Erteleva, 2002; Ulomov, 2008; and others].

In summary, based on the high quality seismogram of the sufficiently strong ($Mw = 5.9$) Vrancea earthquake of October 27, 2004 recorded at the Moskva seismic station, it is possible to calculate the synthesized accelerogram for the grounds of category II in Moscow for the maximum possible assumed earthquake with $Mw = 8.0$ in the Vrancea zone. The accelerogram can be obtained by multiplying the digital record of accelerations caused by the event of 2004 (see Fig. 11) by the coefficient determined from the relationship between the maximum predicted value A_{hor}~2.3 cm/s^2 and the maximum amplitude of accelerations $A_{EW} = 0.063$ cm/s^2 in the horizontal component in 2004. This coefficient was 37. Thus synthesized accelerogram is presented in three projections (EW, NS, Z) in Fig. 15.

Figure 16 illustrates the trajectory of horizontal accelerations constructed by vector summation of the digital records of two horizontal components EW and NS. It is apparent that the maximum amplitude of the horizontal acceleration is close to $A_{hor} = 2.3$ cm/s^2 and exhibits latitudinal orientation but not the direction towards the earthquake source in the Vrancea zone located southwest of Moscow.

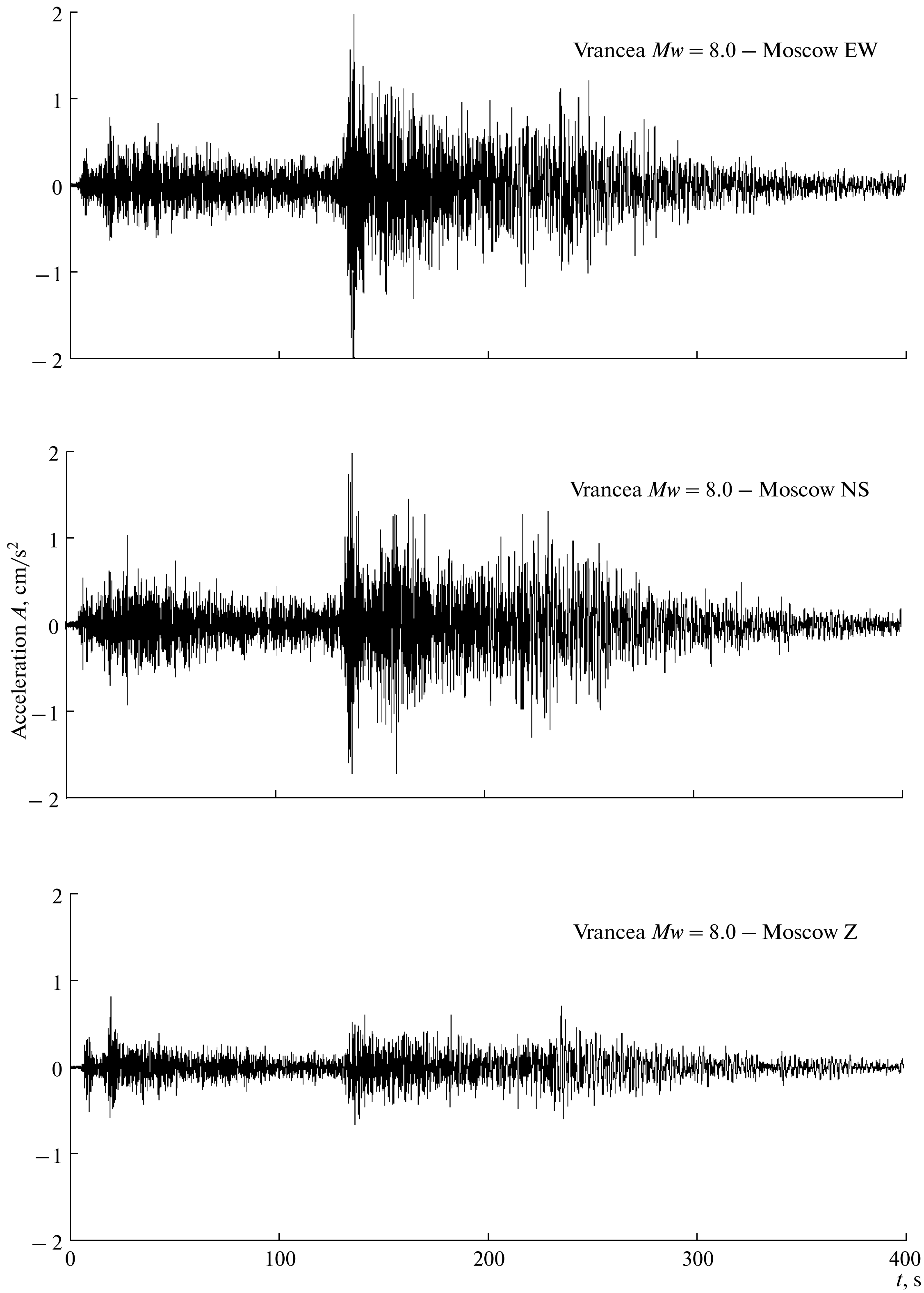

Fig. 15. Synthesized three-component accelerogram for the benchmark soil beneath the Moskva seismic station with the maximum possible earthquake in the Vrancea zone ($Mw = 8.0$).

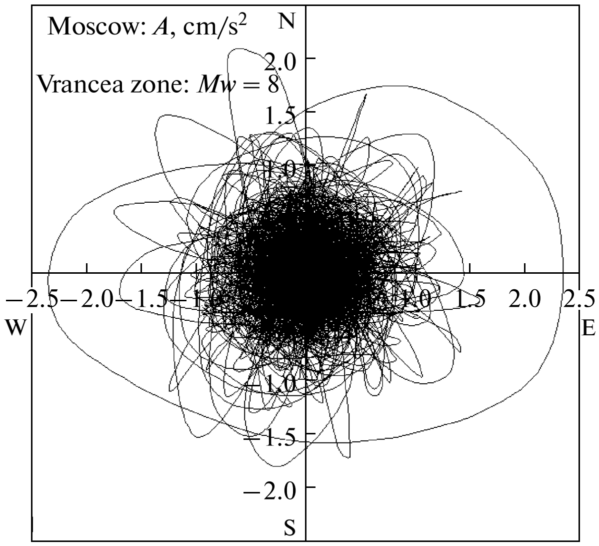

Fig. 16. Trajectory of the horizontal accelerations of the displacements of ground beneath the Moskva seismic station estimated by vector summation of digital records of two horizontal components (NS and EW), for the synthesized accelerogram of the earthquake in the Vrancea zone with $Mw = 8.0$.

Thus, the trajectory of the displacements of the ground during the earthquakes in the Vrancea zone is much more complex and more multidimensional but it is not polarized strictly in the direction towards the source of the shocks, as this is usually assumed by designers in calculations of dynamic loads on the buildings and constructions.

CONCLUSIONS

According to the normative maps of the general seismic zoning of the Russian Federation, OSR-97, the territory of Moscow is located within the 5-point seismic zone. Most hazardous for the high-rise buildings in Moscow are the low-frequency vibrations from the deep sources of strong earthquakes occurring in the East Carpathians (the Vrancea zone, Romania), which are approximately 1350 km distant from Moscow. The magnitude of maximum possible earthquakes in the Vrancea zone can reach $Mw = 8.0$, and their recurrence time amounts to 300–500 years.

Accelerations of the ground vibrations beneath the Moskva seismic station are determined by analyzing the records of the Vrancea earthquakes with different magnitudes (from $Mw = 5.0$ to $Mw = 7.4$). The ground beneath the Moskva seismic station was accepted as a benchmark soil. Extrapolation of the parameters of weak earthquakes towards the strong seismic events provided an estimate of the maximum horizontal accelerations $A_{hor} = 2.3$ cm/s^2 expected on the benchmark soil in case the $Mw = 8.0$ earthquake were to occur in the Vrancea zone.

The model (synthetic) accelerogram is calculated for the benchmark soil in Moscow for the largest Vrancea earthquake ($Mw = 8.0$). The maximum displacements of the ground are much more complex than those assumed earlier; and they are not oriented strictly in the direction of the seismic source, as this is usually assumed by designers when calculating the seismic stability of buildings and constructions.

Our research shows that the MSK-64 macroseismic scale should be corrected, and the construction norms, SNIP II-7-81* (construction norms and regulations), should be updated regarding the assessment of low-frequency seismic effects with intensity 5 MSK and weaker, including those caused by distant earthquakes.

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REFERENCES

1. F. F. Aptikaev, "The Problems of Elaboration of Seismic Scale of the New Generation," Vulkanol. Seismol., No. 4–5, 23–28 (1999).
2. F. F. Aptikaev and O. O. Erteleva, "Generation of Artificial Accelerograms by the Method of Scaling of Real Accelerograms," Fiz. Zemli, No. 7, 39–45 (2002).
3. A. V. Drumya, N. Ya. Stepanenko, and N. A. Simonova, "The Maximum Earthquakes of the Carpathian Region in the 18th–20th Century," Buletinul Institutului de Geofizica si Geologie al ASM, No. 1, 37–64 (2006).
4. A. A. Gusev and L. S. Shumilina, "Modeling of Correlation Rank–Magnitude–Distance on the Basis of Idea about the Incoherent Extensive Earthquake Source," Vulkanol. Seismol., No.4–5, 29–40 (1999).
5. *Moscow: Geology and City*, Ed. by V. I. Osipov and O. P. Medvedev (Joint Company "Moscow Textbooks and Cartography", Moscow, 1997) pp. 1–400.
6. *Seismic Zoning of the Territory of the Russian Federation. Map M 1 : 8000000 on the Four Sheets*, Ed. by V. N. Strakhov and V. I. Ulomov (OIFZ–RUSSIAN FEDERAL GEODESIC AND CARTOGRAPHIC SERVICE, Moscow, 2000).
7. *SNIP II-7-81* (Construction Norms and Regulations). Building in the Seismic Regions. State Committee on Questions of Architecture and Construction of the Russian Federation* (State Unitary Enterprise TsPP, Moscow, 2000) pp. 1–44 (Appendix with 10 maps).
8. *Tentative Recommendations on Specification of Loads and Impacts on the Multifunctional High-Rise Buildings and Complexes in Moscow—MDS 20-1 2006* (Federal

State Unitary Enterprise, Scientific Research Center "Building", Moscow, 2006).

9. V. I. Ulomov, "About Seismic Impacts on the High-Rise Buildings and Constructions in Moscow," Building Materials, Equipment, and Technologies of the 21st Century, No. 2, 109 (2008).
10. V. I. Ulomov, "Low-Frequency Seismic Impacts on the High-Rise Buildings in Moscow from the Distant Sources of Strong Earthquakes," in *Proceedings of the 5th International Conference–Exhibition "Contemporary Systems and the Means of Complex Safety and Fire-Prevention of the Objects of Building", November 21–22, 2007, Moscow* (The Center of New Construction Technologies, Materials and Equipment of Moskomarkhitektura, Moscow, 2007) pp. 1–8.
11. V. I. Ulomov, V. V. Sevost'yanov, I. G. Mindel, and B. A. Trifonov, "Estimation of Seismic Hazard for the High-Rise Buildings in Moscow," in *Contemporary High-Rise Building*, (State Unitary Enterprise "ITTS Moskomarkhitektura", Moscow, 2007) pp. 94–100.
12. V. I. Ulomov and L. S. Shumilina, in *Problems of the Seismic Zoning of the Territory of Russia* (All-Russian Scientific Research Institute of the Problems of Scientific and Technical Progress and Information in Building (VNIINTPI) of the State Committee on Questions of Architecture and Construction of the Russian Federation, Moscow, 1999a) pp. 1–56.
13. V. I. Ulomov and L. S. Shumilina, in *Set of Maps of the General Seismic Zoning of the Territory of the Russian Federation, OSR-97. Scale 1:8000000. Explanatory Note and the List of Cities and Populated Areas, Located in Earthquake-Hazard Regions* (Institute of Physics of the Earth, Russian Academy of Sciences (OIFZ), Moscow, 1999b) pp. 1–57.
14. D. J. Wald, V. Quitoriano, T. H. Heaton, and H. Kanamori, "Relationship between Peak Ground Acceleration, Peak Ground Velocity, and Modified Mercalli Intensity for Earthquakes in California," Earthquake Spectra, **15** (3) 557–564 (1999).