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Comparative Assessment of Tectonic Waves affecting the Hydropower Plants in Făgăraş-Câmpulung Seismic Area

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Abstract

In order to assess the seismic risk of the energy infrastructure on the Făgăraş-Câmpulung seismic area, the accelerations of seismic vibrations produced by 7 earthquakes were measured (in two distinct locations, with different morphostructural characteristics of the soil) and compared. Thus, were analysed 3 subcrustal earthquakes, with epicentres in Vrancea area, a crustal earthquake with epicentre in Făgăraş-Câmpulung seismic area (approximately 30 km from the measurement locations), 2 crustal earthquakes and a subcrustal earthquake with epicentres located at a longer distance (over 650 km) from the measurement locations. Following the data processing, it was found that the intensity of local vibrations produced by the analysed earthquakes is determined by the earthquake intensity, by the distance between epicentre and measurement point and by the geological layers morphological structure in the epicentre-measurement direction. The measurements showed that the mountains in the seismic waves direction, especially those generated by crustal earthquakes (with hypocentre h<10km), produce a significant attenuation of the measured vibrations. Based on measurement results and their analysis, it is considered that the energy infrastructure on the Făgăraş-Câmpulung seismic area presents an appreciable seismic risk. Thus, the earthquakes in the Făgăraş-Câmpulung seismic area can cause significant damage: the subcrustal earthquakes of Mw> 7.2 with epicentres in the Vrancea seismic area on large scale, and surface earthquakes, near the epicentre zone, on limited areas. Therefore, in order to ensure the safety of the hydroelectric dams, with high risk in operation, it is necessary to have them constructed and maintained so as to withstand vibrations with accelerations of at least 3.5-4 m/s^2.

Keywords: earthquake, seismic waves, warning systems, hydropower plants, energy security

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1. Introduction

In the perspective of sustainable development, ensuring the operational security of energy infrastructures - such as natural gas networks, electricity networks, power plants (especially thermo, hydro and nuclear) - is a priority issue, of significant importance and with practical and economic implications.

Due to their specificity, the energy infrastructure objectives have a high risk in operation. In the event of natural disasters, such as major earthquakes, the energy infrastructure is often damaged, leading to a significant increase in material damage and human casualties - as reported following the Fukushima (Japan) nuclear power plant disaster [1]-[3].

It is worth mentioning that major seismic events affect not only the safety of nuclear power plants, but also other high-risk energy facilities such as pressure boilers of thermo power plants, dams of hydro power plants, pipelines in gas networks, overhead power lines etc.

More intense seismic vibrations of about 1.5 m/s^2, are causing the damage of pipelines in gas networks [4] - both metallic [5] (especially those affected by corrosion [6]-[8]) and those made of polymeric material [9]. Demolition of buildings following earthquakes is inevitably accompanied by damage to the gas installation, which leads to uncontrolled gas leaks followed by explosions and devastating fires, thus increasing property damage and human casualties [10].

On the other hand, major earthquakes often cause poles demolition (mainly those affected by corrosion [11]-[14]) of the overhead power lines and/or conductors break. Thus, there is a major risk of fire (ignition of flammable materials due to short circuits of conductors) and / or electric shock when touching fallen conductors [15].

Several seismic areas have been identified in Romania [16]:

Vrancea subcrustal area located in the Curvature Carpathians is characterized by a relatively high seismic activity. In this area there are frequent earthquakes with Mw greater than 6, with hypocentre at intermediate depths (h = 60-200 km). The significant seismic events reported in the 19th century were:

10.26.1802, h = 150 km, Mw = 8.2;
11.26.1829, h = 150 km, Mw = 7.3;
01.23.1838, h = 150 km, Mw = 7.5;
08.17.1893, h = 100 km, Mw = 7.1;
08.31.1894, h = 130 km, Mw = 7.1.

The significant seismic events reported in the twentieth century were:

10.06.1908, h = 125 km, Mw = 7.1;
11.10.1940, h = 150 km, Mw = 7.4;
09.07.1945, h = 80 km, Mw = 6.8;
03.04.1977, h = 94 km, Mw = 7.2;
08.30.1986, h = 131 km, Mw = 7.1;
05.31.1990, h = 86.9 km, Mw = 6.9–7.

In the 21st century, so far, there has been only one major event, namely:

10.27.2004, h = 98.6 km, Mw = 6.0.

It is found that in the 19th and 20th centuries there were 5-6 major seismic events (Mw ≥ 7) while in the 21st century, until now, only one event with Mw = 6.0. This suggests the imminence / high probability that a major earthquake with Mw≥ 7 will occur in this area in the near future. A feature of intermediate depth earthquakes is that they can cause significant material damage, even at distances of 3-400 km from the epicentre, and are felt by the population within a radius of even over 500km.

The Predobrogean area located on the Sfântul Gheorghe fault is characterized by a moderate seismicity. It is interesting to note that the seismic activity in this area was activated especially after the earthquake of Mw = 7.2 from Vrancea in 1977. Thus, starting with 1980, the following earthquakes were recorded in this area:

09.11.1980, h = 20 km, Mw = 4.2 - hypocentre near Galati;

11.13.1981, h = 4 km, Mw = 5.1 - hypocentre near Tulcea;

09.03.2004, Mw = 5.1 - hypocentre near Tulcea;

05.07.2008, h = 5 km, Mw = 5 - 5.2 - hypocentre in the Black Sea, North-East of Sulina;

10.22.2005, h = 190 km, Mw = 4.5 - hypocentre near Galati;

09.29.2013, h = 5 km, Mw = 4.0 - hypocentre near Galati.

It is noted that the hypocentre of the earthquakes with Mw ≤ 5.2 recorded in this area varies widely, between 4 km and 190 km.

Făgăraş-Câmpulung area - is located at the contact between the Moesic Platform and the orogen of the Southern Carpathians. It is characterized by moderate earthquakes with hypocentre at depths of approximately 10 km. The significant events recorded in this area were:

10.26.1550, h = 10 km, Mw = 6.5;
08.10.1590, h = 10 km, Mw = 6.5;
12.07.1746, h = 10 km, Mw = 5.9;
12.08.1793, h = 10 km, Mw = 6.2;
02.19.1832, h = 10 km, Mw = 5.6;
10.26.1916, h = 10 km, Mw = 6.4;
04.18.1919, h = 10 km, Mw = 4.1.

Unlike the Banat, Crişana-Maramureş, Danube area, Bârlad Depression and Transylvania Depression, Făgăras - Câmpulung area is the one with the most intense crustal earthquakes in Romania (Mw ≤ 6.5). Crustal earthquakes with hypocentre at depths of up to 20 km, although usually of relatively low intensity, can cause localized material damage (usually in small areas, within a radius of 10-30 km from the epicentre). This happens especially when the epicentre is located in densely populated areas (such as the Banloc-Romania event that took place on 07.12.1991, Mw = 5.6, h = 11 km, or recently, the representative earthquake of Mw = 6.4 from 12.29.2020 that took place at 11:19:54.37 in Croatia [11]).

Considering the above-mentioned aspects, it is found that the energy infrastructure (hydro power plants dams, thermo power plants pressure boilers, nuclear power plants, overhead power lines, gas networks [17]-[19] etc.) in Romania, especially those located in the crustal (surface) seismic areas and those in the propagation range of seismic waves generated by the subcrustal deep earthquakes (produced in the Vrancea area), are exposed to a significant seismic risk.

In order to predict seismic events, there are many concerns worldwide for monitoring the evolution of earthquake precursor data [20], such as: radon concentration [21]-[30], anomalies in the radio waves propagation [31]-[33], groundwater levels [34]-[36] etc. The current state of knowledge does not provide an accurate prediction of the occurrence time and the intensity of earthquakes.

In order to prevent material damage and human casualties following major earthquakes, warning systems have been developed that generate messages of imminent seismic risk [37]-[48]. These messages are generated following the analysis of the produced earthquakes characteristics (intensity, hypocentre, epicentre, etc.) and are transmitted in the affected territory by telecommunication systems faster than the speed of seismic wave propagation. In order to increase the efficiency of these systems, the movement speed and the amplitude attenuation of the seismic wave in various directions in the areas of interest have to be known.

In the Făgăraș-Câmpulung crustal seismic area, there are several objectives with high-risk in operation, such as over 10 hydropower plants on the Olt River defile, hydropower plants on the Argeş River - Vidraru and downstream, etc. These objectives are also in the influence area of the Vrancea subcrustal seismic zone.

An ARR seismic motion monitoring system is in operation near the Vidraru dam. The acquired data are sent for processing to the national seismic dispatcher.

Recently, in Râmnicu Vâlcea, Romania was designed [49], built (near the storage reservoir from Râmnicu Vâlcea) [50] and put into operation [15], [51] a complex system for earthquake warning based on local assessment of seismic events **RMGV**. The system is equipped with an accelerometer, mounted in a 50 m deep borehole (to avoid the influences of surface vibrations, such as car traffic, railways, etc.), that monitors the intensity of local seismic movements caused by earthquakes with various epicentres. The system acquires both local intensity of seismic movements and evolution of radon concentration data [50].

Given these considerations, the purpose of the paper is to assess the seismic waves produced by earthquakes in the territory and recorded at RMGV, compared to records from ARR.

2. Data acquisition

With the equipment from **RMGV** [50], [51] were measured and recorded the accelerations of seismic shocks produced by 7 seismic events (earthquakes with different epicentres E1 - E7, according to Figure 1.). In comparison, the same seismic events were recorded in the **ARR** mounted near the Vidraru hydropower plant dam (approx. 50 m from the eastern end), to approximately 25.5 km North-East of the **RMGV** location.

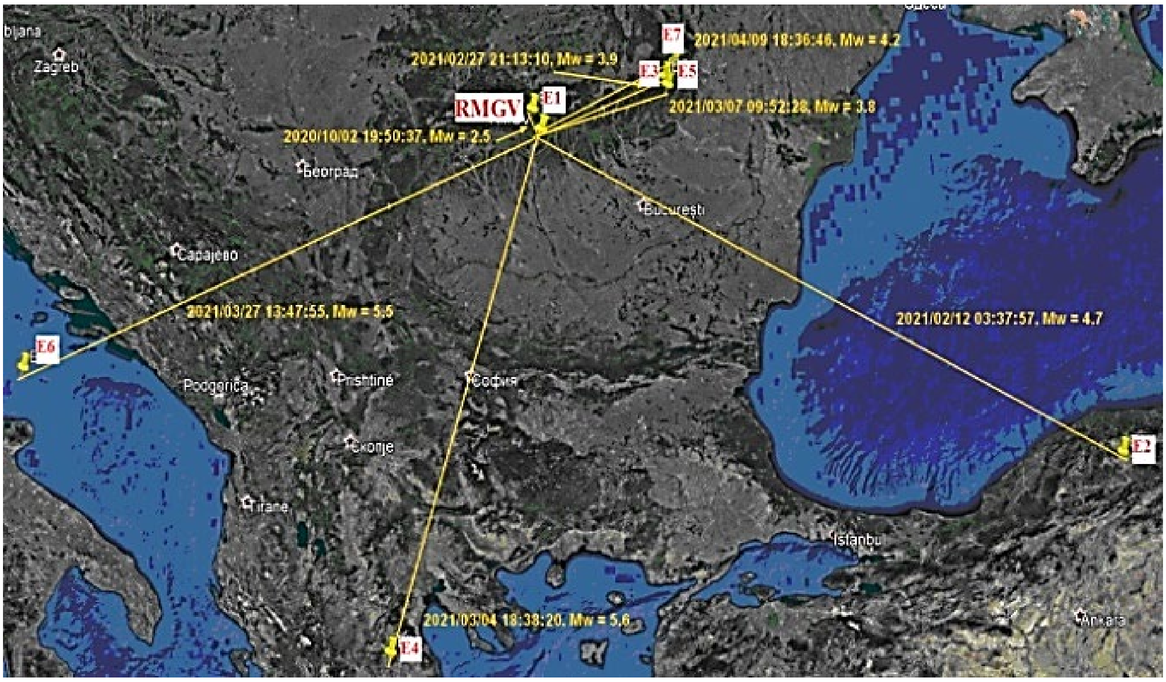

Figure 1. Geographical distribution of epicentres E1 - E7 of earthquakes measured using RMGV located in Râmnicu Vâlcea

The analysis of Figure 1 shows that the epicentres of the seven investigated earthquakes were located as follows: 1 in Făgăraș-Câmpulung seismic area, 3 in Vrancea subcrustal area, 1 in northern Turkey, 1 in central mainland Greece and one in the Adriatic Sea.

3. Analyses and interpretations

The results of the comparative **RMGV** and **ARR** recordings of the seismic event E1 (crustal earthquake produced on 10.02.2020 at 19:50:37, intensity of Mw = 2.5 with hypocentre at 6 km depth and epicentre near Brezoi – 26.53 km N-NW from RMGV location and 32.32 km West from ARR location) are shown in Figure 2.

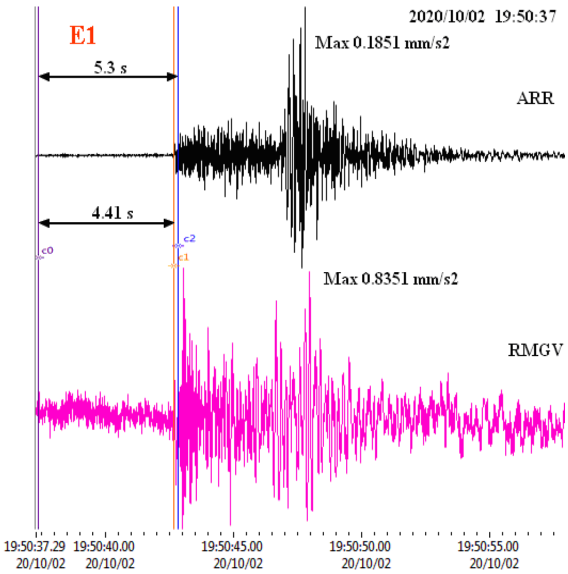

Figure 2. Comparative recording of seismic vibrations produced by the crustal earthquake E1 - Mw = 2.5, h = 6 km, epicentre at Long = 24.2268° / Lat = 45.3196°

Figure 2 shows that the maximum value of acceleration recorded by **RMGV** (26.53 km from the epicentre) was 0.8351 mm/s^2 - approximatelty 4.5 times higher than the value recorded by **ARR** (32.32 km from the epicentre). It is also noted that the time required by the seismic wave to reach the **RMGV** was only 4.41 seconds, while to reach the **ARR** was 5.3 seconds. Related to the distances between the epicentre and the locations of the measurement points, the seismic wave speed is of 6.17 km/s in the RMGV case and of 6.2 km/s in the ARR case.

The results of the comparative **RMGV** and **ARR** recordings of the seismic event E2 (crustal earthquake produced on 02.12.2021 at 03:37:57, intensity of Mw = 4.7 with hypocentre at 7 km depth and epicentre in northern Turkey – 857.39 km N-E from RMGV location and 854.69 km S-E ARR location) are shown in Figure 3.

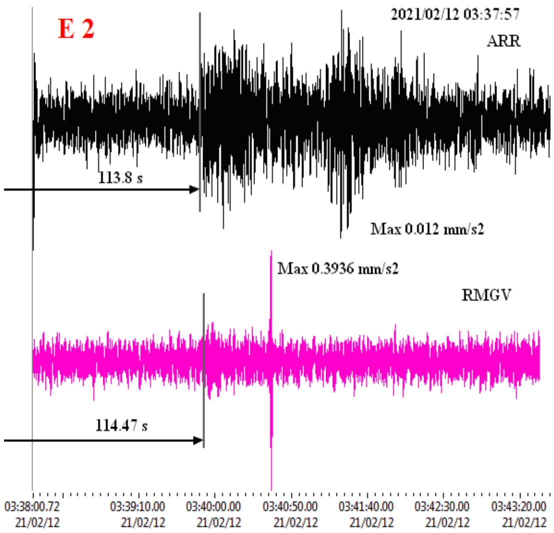

Figure 3. Comparative recording of seismic vibrations produced by the crustal earthquake E2 - Mw=4.7, h=7 km, epicentre at Long = 33.7258 °/ Lat = 41.4636°

Figure 3 shows that the maximum value of the acceleration recorded at **RMGV** (857.39 km from the epicentre) was 0.3936 mm/s^2, approximately 33 times higher than that recorded at **ARR** (854.69 km from the epicentre). This significant difference between the recorded accelerations can be explained by the fact that the route from the earthquake epicentre to **ARR** passes through the Iezer, Leaota and Bucegi mountains, whose morphogeological structure produces a significant attenuation of surface seismic waves, while the route to **RMGV** does not pass through significant mountains.

The results of the comparative **RMGV** and **ARR** recordings of the seismic event E3 - subcrustal earthquake produced in Vrancea area (174.18 km E-NE from **RMGV** location and 149.16 km E-NE from **ARR** location) on 02.27.2021 at 21:13:10, intensity of Mw = 3.9 with hypocentre h = 126 km - are shown in Figure 4.

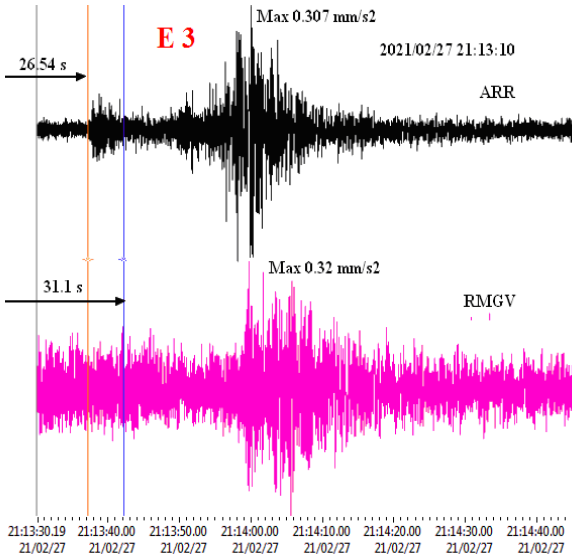

Figure 4. Comparative recording of seismic vibrations produced by the subcrustal earthquake E3 - Mw=3.9, h=126 km, epicentre at Long = 26.4979°/ Lat = 45.5578°

The analysis of Figure 4 shows that the maximum value of acceleration recorded at **RMGV** (174.18 km from the epicentre) was 0.32 mm/s^2 - approximately equal to 0.307 mm/s^2 recorded at **ARR** (149.16 km from the epicentre). Seismic wave propagation time was of 31.1 seconds at **RMGV** and 26.54 seconds at **ARR**.

The results of the comparative **RMGV** and **ARR** recordings of the seismic event E4 - crustal earthquake produced in mainland Greece (620.66 km S-SW from **RMGV** location and 650.45 km S-SW from **ARR** location) on 03.04.2021 at 18:38:20, intensity of Mw = 5.6 with hypocentre h = 5 km - are shown in Figure 5.

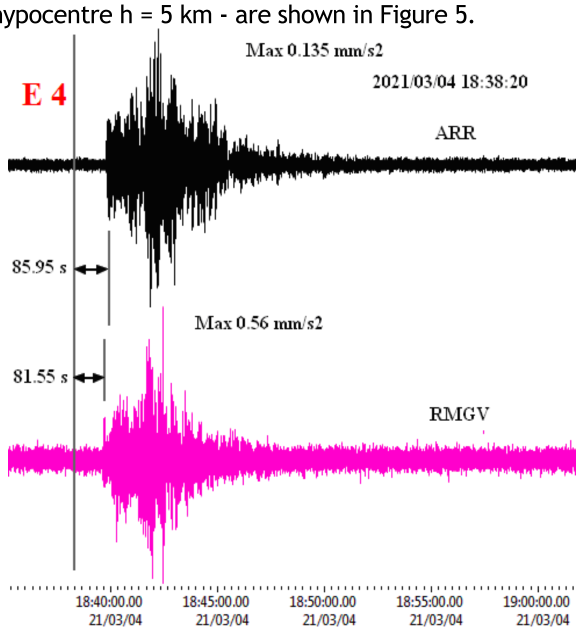

Figure 5. Comparative recording of seismic vibrations produced by the crustal earthquake E4 - Mw=5.6, h=5 km, epicentre at Long = 22.0892° / Lat = 39.7741°

Figure 5 shows that the maximum value of acceleration recorded at **RMGV** (620.66 km from the epicentre) was of 0.56 mm/s^2 - approximately 3.6 times higher than the value recorded at **ARR** (650.45 km from the epicentre). Also, the seismic wave needed 81.55 seconds to reach the **RMGV** location and 85.95 s to reach to **ARR**. Related to the distances between the epicentre and the locations of the measurement points, the seismic wave speed is of 7.61 km/s in the RMGV case and of 7.57 km/s in the ARR case.

The results of the comparative **RMGV** and **ARR** recordings of the seismic event E5 - subcrustal earthquake produced in Vrancea area (174.23 km E-NE from **RMGV** location and 146.09 km E-NE from **ARR** location) on 03.07.2021 at 09:52:28, intensity of Mw = 3.8 with hypocentre h = 145 km - are shown in Figure 6.

The analysis of Figure 6 shows that the maximum value of acceleration recorded at **RMGV** (174.23 km from the epicentre) was of 0.0874 mm/s^2 - approximately 5.8 times higher than the value recorded at **ARR** (146.09 km from the epicentre). The seismic wave propagation time was of 31.46 s in the **RMGV** case, and of 27.99 s in the **ARR** case.

The results of the comparative **RMGV** and **ARR** recordings of the seismic event E6 - crustal earthquake produced in Adriatic Sea (748.62 km S-W from **RMGV** location and 774.26 km S-W from **ARR** location) on 03.27.2021 at 13:47:55, intensity of Mw = 5.5, h = 5 km - are shown in Figure 7.

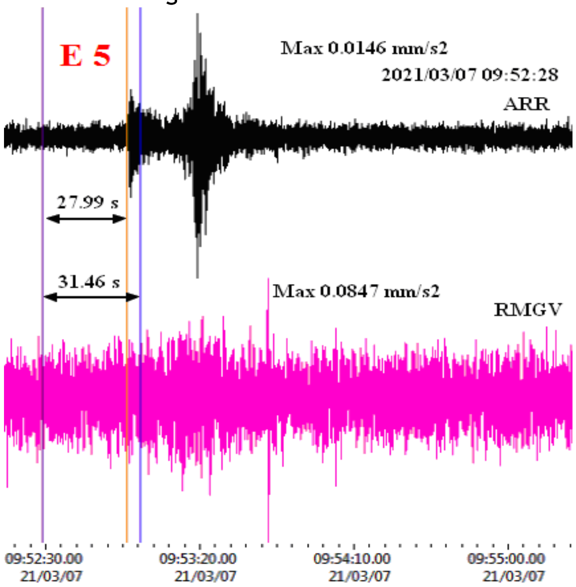

Figure 6. Comparative recording of seismic vibrations produced by the subcrustal earthquake E5 – Mw=3.8, h=145 km, epicentre at Long = 26.4583° / Lat = 45.6390°

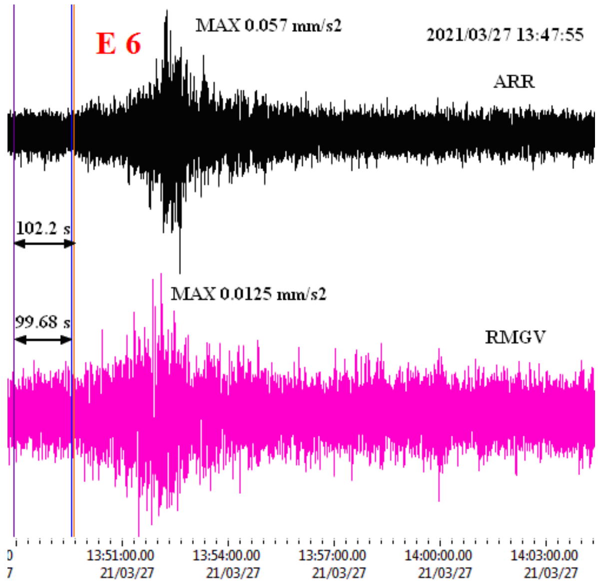

Figure 7. Comparative recording of seismic vibrations produced by the crustal earthquake E6 – Mw=5.5, h=5 km, epicentre at Long = 15.8924° / Lat = 42.3951°

The analysis of Figure 7 shows that the maximum value of the acceleration recorded at **RMGV** (748.63 km from the epicentre) was 0.0125 mm/s^2 of approximately 4.5 times lower than that recorded at **ARR** (774.26 km from the epicentre).

Seismic wave propagation times were 99.68 seconds at **RMGV** and 102.2 seconds at **ARR**.

The results of the comparative records from **RMGV** and **ARR** of the E7 seismic event - subcrustal earthquake produced in the Vrancea area (193.57 km E-NE of **RMGV**, respectively 164.01 km E-NE of **ARR**) on 04/09/2021 at 18:36:46 of Mw = 4.2 intensity with hypocentre at the depth of h = 77 km are shown in Figure 8.

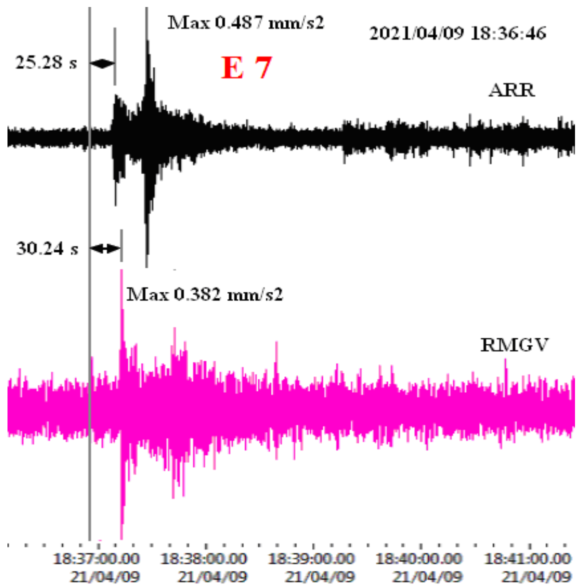

Figure 8. Comparative recording of seismic vibrations produced by the E7 subcrustal earthquake - Mw = 4.2, h = 77 km, epicentre at Long = 26.6292°/ Lat = 45.7916°.

The analysis of Figure 8 shows that the maximum value of the acceleration recorded at **RMGV** (193.57 km from the epicentre) was 0.382 mm/s^2. At **ARR** the maximum value of the recorded acceleration was 0.487 mm/s^2. Seismic wave propagation times were 30.24 seconds at **RMGV** and 25.28 seconds at **ARR**.

Table 1 summarizes the characteristic data of the seismic events analysed in the RMGV and ARR locations.

The analysis of the Table 1 shows that the vibrations recorded after crustal earthquakes (excepting the E6 with epicentre in the Adriatic Sea) are higher at **RMGV** than at **ARR** - the biggest difference among the measured values was in the case of E2 (with epicentre at distances practically identical from the measurement points) when at **RMGV** the maximum measured acceleration was approximately 33 times higher than at **ARR**.

It is noted that in the case of the E1 crustal earthquake, with epicentre at only 26.53 km, in **RMGV** produced significant vibrations of 0.8351 mm/s^2, which indicates that the crustal earthquakes with Mw>5 with the epicentre in the Făgăras - Câmpulung area present a significant risk for energy infrastructure in the Olt River Defile.

Table 1. Comparative characteristic data of the analysed seismic events

Even	Epicentre					RMGV (Long: 24.377087 Lat: 45.10753)					ARR (Long: 24.6332 at: 45.3657)				
	Date Time	Mw	Long	Lat	Depth *h* [Km]	Distance [km]	Azimuth [degrees]	Δ t [sec]	Speed [km/s]	Max Acceleration [mm/s^2]	Distance [km]	Azimuth [degrees]	Δ t [sec]	Speed [km/s]	Max Acceleration [mm/s^2]
E 1	2020/10/02 19:50:37	2.5	24.2268	45.3196	6	26.53	153.39	4.41	6.17	0.8351	32.32	80.79	5.3	6.20	0.1851
E 2	2021/02/12 03:37:57	4.7	33.7258	41.4636	7	857.39	301.42	114.47	7.49	0.3936	854.69	303.52	113.80	7.51	0.012
E 3	2021/02/27 21:13:10	3.9	26.4979	45.5578	126	174.18	253.93	31.1	6.91	0.3206	149.16	262.62	26.54	7.36	0.307
E 4	2021/03/04 18:38:20	5.6	22.0892	39.7741	5	620.66	16.47	81.55	7.61	0.5602	650.45	17.54	85.95	7.57	0.153
E 5	2021/03/07 09:52:28	3.8	26.4583	45.6390	145	174.23	250.71	31.46	7.21	0.0847	146.09	258.77	27.99	7.35	0.0146
E 6	2021/03/27 13:47:55	5.5	15.8924	42.3951	5	748.62	63.23	99.68	7.51	0.0125	774.26	61.88	102.22	7.57	0.057
E 7	2021/04/09 18:36:46	4.2	26.6292	45.7916	77	193.57	247.53	30.24	6.89	0.3820	164.01	253.29	25.28	7.17	0.487

Mainly, the movement speed and the seismic wave attenuation are determined by the morphological structure of the geological layers which they cross. In this context, the differences in speeds and accelerations recorded at **RMGV** and **ARR** can also be explained by the significant geological differences of their locations. At **ARR**, the vibration transducer is mounted in the crystalline rocks on the western slope of the Ghiţu Mountains, unlike the **RMGV** system, where the transducer is placed in the Olt River bed, in the Getic Subcarpathians depression.

5. Conclusions

In order to assess the seismic risk of the energy infrastructure in the Făgăraş-Câmpulung seismic area, the vibration intensities produced by 7 earthquakes were measured. The measurements were made comparatively in two locations with different morphostructural characteristics of the soil - one near the North Râmnicu Vâlcea hydropower plant (with the vibration transducer mounted in a well drilled at 50 m depth, at about 100 m near the storage reservoir), the other in the rocks at the end east of the Vidraru dam.

By data processing from 7 seismic events with different epicentres and characteristics (a 2.5 Mw crustal earthquake with hypocentre h = 6 km and epicentre at only 26.53 km from the measuring point in Râmnicu Vâlcea, produced in the Făgăraş-Câmpulung seismic area, 3 subcrustal earthquakes of 3.9 Mw with h = 126 km, 3.8 Mw with h = 145 km and 4.2 Mw with h = 77 km with epicentres in the Vrancea seismic area, 3 crustal earthquakes with distant epicentres: 4.7 Mw and h = 7 km with epicentre in northern Turkey at over 850 km, 5.6 Mw and h = 5 km with epicentre in mainland Greece at over 650km and 5.5 Mw and h = 5km with epicentre in the Adriatic at over 740km) it was found that:

- the seismic waves speeds were between 6.17 km/s and 7.61 km/s;
- the registered accelerations between 0.012 m/s^2 and 0.8351 m/s^2 are determined by the analysed earthquake intensity and by the morphostructural characteristics of the soil in the epicentre direction;
- for the same earthquake, the maximum difference between the registered accelerations values in two measurement points was in the case of the crustal earthquake with epicentre in northern Turkey (at over 850 km), when at Râmnicu Vâlcea was measured 0.3936 m/s^2 and at Vidraru only 0.012 m/s^2. This difference is explained by the shielding effect of the Iezer, Leaota and Bucegi mountains located in the Vidraru-epicentre direction;
- the significant difference between the registered accelerations values in two

measurement points was also in the case of the crustal earthquake with epicentre in the Făgăraş-Câmpulung seismic area, at which, at similar distances from the epicentre (26.53km, respectively 32.32 km), the acceleration measured at Vidraru was approximately 4.5 times lower than the one from Râmnicu Vâlcea, a fact that can be explained by the attenuation due to the Frunţii and Cozia Mountains located on the epicentre-Vidraru direction;

- in case of subcrustal earthquakes with hypocentres between 77 km and 145 km (comparable to the epicentre-measurement point distances) and epicentre in the Vrancea seismic area, the maximum accelerations recorded in these two locations were approximately equal.

Based on the undertaken investigations, results and analyses, it is considered that the energy infrastructure in the Făgăraş-Câmpulung seismic area presents an appreciable seismic risk. Thus, the earthquakes in the Făgăraş-Câmpulung seismic area can cause significant damage: the subcrustal earthquakes of Mw> 7.2 with epicentres in the Vrancea seismic area on large scale, and surface earthquakes, near the epicentre zone, on limited areas. Therefore, in order to ensure the safety of the hydroelectric dams, with high risk in operation, it is necessary to have them constructed and maintained so as to withstand vibrations with accelerations of at least 3.5-4 m/s^2.

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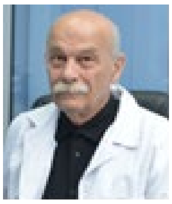

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