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Damage assessment of water supply networks due to seismic events using vulnerability functions

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Professional paper

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The paper presents commonly used methodology for assessing damage of water supply networks after a seismic event. The methodology relies on deriving and applying so-called vulnerability function. An overview of the existing vulnerability functions is given together with parameters, primarily related to soil deformations, which are influencing the assessment. Also, a critical review of the possibility of their use is given. Finally, by using two approaches, the estimated number of damages, with associated repair costs, is given for the water supply network of the City of Petrinja after the earthquake on December 29, 2020. With a total of 3 800 new damages, it is estimated that the total repair costs are around HRK 28 million. The accuracy of these estimates should be verified after detailed collection and processing of relevant data in accordance with the given guidelines.

Key words:

earthquake, water supply network damage, vulnerability functions, soil deformation, City of Petrinja

Stručni rad

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Procjena oštećenja na vodoopskrbnim mrežama uslijed seizmičkih događaja primjenom funkcija ranjivosti

U radu se izlaže najčešće korištena metodologija procjene oštećenja nastalih na vodoopskrbnoj mreži nakon seizmičkog događaja, a koja se temelji na definiranju i primjeni takozvanih funkcija ranjivosti. Daje se pregled postojećih funkcija ranjivosti s navodom utjecajnih parametara, prije svega deformacija tla, te kritičkim osvrtom na mogućnost njihove primjene. U konačnici je primjenom dvaju pristupa procijenjen broj oštećenja i pripadnih materijalnih šteta na vodoopskrbnoj mreži vodovoda grada Petrinje nakon potresa 29. prosinca 2020. godine. S ukupno 3 800 novih oštećenja procjenjuje se da ukupna direktna materijalna šteta iznosi oko 28 milijuna kuna. Točnost navedenih procjena treba, sukladno s danim smjernicama, verificirati nakon detaljnog prikupljanja i obrade relevantnih podataka.

Ključne riječi:

potres, oštećenje vodoopskrbne mreže, funkcija ranjivosti, deformacije tla, grad Petrinja

1. Introduction

Damage to the water supply system following strong, large or devastating seismic events result in a reduction or complete loss of water supply. This also creates risks of indirect damages, for example, economic losses of water service providers due to the inability to supply water, economic losses in the economy due to the inability to implement water-dependent technological processes, the possible spread of waterborne diseases due to the lack of water quality, the inability to secure the quantities required for firefighting, etc. In addition to all that, the functioning of the water supply system is also a necessary condition for the survival of the environment affected by the earthquake.

In the domestic practice of designing water supply systems, the effects of a seismic event on the water supply network itself are usually not analyzed, although major, visually noticeable damage to it occurs after seismic events, but also some unnoticed, either in the form of cracks, longitudinal and shear separation of joints , i.e., differential displacements at the junction of pipes, fittings and water-supplying fittings, or some other mechanism of loss of function.

Damage to the water supply network due to a seismic event depend not only on the intensity of the seismic event, but also on the technical characteristics of the pipeline network and the nature of the surrounding ground, whereby, depending on the adopted methodology, the following are most often considered: pipeline age, pipe material, type of connection and sealing, pipeline diameter, construction technology, geomechanical characteristics of the surrounding ground, chemical aggressiveness of the surrounding ground, groundwater level, condition of the pipeline bed (storage), piepe supports on horizontal and vertical bends, penetrations on the walls of manholes and valve chambers and the construction of support blocks [1-7].

The most commonly used methodology for assessing damage to the water supply system is based on published scientific papers by authors who, using a larger or smaller volume of data related in particular to the type of pipe material and the corresponding type of connection and the diameter of the pipeline, have qualitatively and quantitatively analyzed the impacts of a seismic event on the occurrence of damage (cracks and/or leaks at connections) to the water supply network, mainly based on data following the seismic events in the United States and Japan [1-7].

It is important to note that this is only a damage assessment, since insight into the overall actual state of damage to the water supply system cannot be reliably determined due to the damage that remains unnoticed, as well as the fact that the state of damage of the water supply system before the seismic event is also not fully known.

In this paper, the most commonly used methodology will be presented, which exclusively refers to the assessment of damage to the pipeline, i.e., water supply network itself (including the assessment of damage to pipelines inside valve chambers and the assessment of damage to service connections) and as such it does not include other above-ground buildings of the water supply systems that can be visually inspected (such as water tanks, water intake buildings, pumping stations, etc.). In addition, an example of the application of the mentioned methodology to the assessment of damage to the water supply network for the water supply system of the city of Petrinja after the seismic event on December 29, 2020 will be given.

2. Methodology for assessing damage to water supply networks

2.1. General

The most common methodological procedure for assessing damage to the water supply network includes the application of individually developed "vulnerability functions" or the ones taken from the literature. The vulnerability function (also referred to as the "damage function" or the "fragility function") implies a methodology that uses an empirically determined equation to estimate the degree of damage or the probability of exceeding a limit state of the water supply network (e.g., allowable vertical pipe deformations). Usually, the vulnerability function expresses the number of damages (breaks and excessive deformations that do not enable the proper functioning of the pipeline and require rehabilitation, i.e., repair) per unit length of the pipeline network. In doing so, the vulnerability function establishes a functional relationship between the number of damages to the water supply network and the value of the ground excitation parameter due to a seismic event, most often through the Peak Ground Velocity (PGV), of the Peak Ground Acceleration (PGA) and the amount of permanent deformations (irreversible displacements) of the ground (abbr. PGD) [1-4].

The damage assessment methodology consists of two basic procedures that imply derivation, i.e., the definition of the vulnerability function itself and its application to the assessment of the resulting damages. In addition, the damage assessment through the application of the derived vulnerability function differs depending on the purpose of the analysis, i.e., the number of analyzed seismic scenarios, where as part of the anti-seismic design of the water supply network, several scenarios are considered (seismic events with different values of the ground excitation parameter), and the assessment of the resulting damage after a specific seismic event is carried out according to the measured parameters of the seismic excitation [5, 6].

Considering the characteristics of the water supply network foreseen by the project, by taking into account several seismic events, we try to evaluate the seismic resistance of the designed network by evaluating of the occurrence of damage. Thus, in case of insufficient resistance, different solutions are proposed in terms of the layout configuration of the routes that increase the safety and functionality of the water supply, or for the same layout configuration, different technical parameters of the network itself are considered (different pipe material, different wall thickness of the pipe material, different types of connections, different diameters, etc.).

By evaluating the damage after a specific seismic event, it is attempted to determine the number of new damages, i.e., to gain insight into the extent of network damage by applying the derived susceptibility functions in order to evaluate the damage and plan remediation measures. The methodological approach described above for developing the vulnerability function implies successive:

- collection of basic technical data on the water supply (transport and supply) network, primarily on pipe materials, diameters, routes, age and other existing buildings on the routes of the analyzed water supply system,
- collection of parameters (*PGV*, *PGA*, *PGD*) of previous relevant seismic events and the related actual damage to the water supply network,
- statistical analysis of the influence of seismic excitation parameter values on the occurrence of the detected damage,
- defining vulnerability functions depending on "temporary" (*PGV* and *PGA*) and "long-term" (*PDG*) ground deformations, whereby the basic technical characteristics of the water supply network are put into a functional relationship with the ground deformation parameters,
- establishing the shape and parameters of the vulnerability functions for the technical characteristics for which statistical significance has been determined.

In each of the above steps, in addition to statistical methods, various graphical, computational or computer methods (e.g., hydraulic-mathematical modeling, application of GIS tools, neural networks, other data mining methods, etc.) and procedures are used, the application of which depends on the availability and quality of the relevant data. The damage assessment process consists of:

- estimates of the mean extent of damage, i.e., the specific (by length of the network) mean number (or median) of damages to the water supply network by vulnerability function through one or more scenarios of a seismic event, with an assessment of the extent of loss of utility function, and sometimes an assessment of the uncertainty in the estimate of the mean extent of damage (or median) damage with regard to the vulnerability functions used,
- estimates of the total damage to the water supply network, i.e., estimates of the cost of rehabilitating or replacing a portion of the water supply network, and sometimes estimates of the duration of the rehabilitation until the full functionality of the water supply network is established.

In doing so, it should be noted that the estimation of the time for the restoration of the water supply infrastructure depends at the same time on the state of damage to other public infrastructures, primarily that is related to the availability of electricity, telecommunication infrastructures and road damage, but also on the extent of damage suffered by legal entities closely related to the construction industry (e.g., availability of appropriate construction materials, availability of contractors with appropriate expertise, etc.), which directly affects the response time for reparing damage to the water supply network. Such a comprehensive damage assessment , as well as an evaluation of the time required to restore (rehabilitate) the water supply system, taking into account the influence of other closely related infrastructure systems, is often not possible due to the lack of all relevant data, but it is the subject of research in defining comprehensive methods for hazard assessment of natural disasters. At the same time, certain computer programs, such as *MAEViz* (developed by American research institutions *National Center for Supercomputing Applications* and *Mid-America Earthquake (MAE) Center*) and *UILLIS* (*Urban Infrastructure and Lifelines Interactions of Systems* (developed by an American research institution *Pacific Earthquake Engineering Research Center*) enable the modeling of such scenarios [7, 8].

2.2. Vulnerability functions of the water supply network

In general, damage to the water supply network due to a seismic event can be attributed to so-called temporary (short-term, i.e., transient) ground deformation and permanent ground deformation. Temporary deformations occur as a result of the propagation of different types of seismic waves, and pipeline damage correlates with the relative displacement between the ground and the pipeline, i.e., measured or estimated seismic parameters such as modified Mercalli intensity, *PGA*, *PGV*, peak ground displacement, i.e., spectra of ground response or spectrum of acceleration, velocity and displacement. Permanent ground deformation is most often reflected in the occurrence of landslides, faulting, subsidence and ground liquefaction [3, 9].

The relative proportion of these deformations determines which ground deformation has the predominant effect on pipeline damage. Temporary deformations generally cause much less stress and pipeline deformations. However, because they extend over a larger area, damage to pipelines due to these deformations can dominate (e.g., half of the damage to the water supply system in San Fernando, California, USA, in the 1971 earthquake was attributed to temporary deformations). Such damage is observed when pulsating peak ground velocities occur or when ground properties cause wave interference with resulting larger ground displacements, i.e., pipeline displacements [10].

Usually, for water supply networks damaged by seismic wave propagation, i.e., temporary deformations, it can be expected that 15-20 % of the damage will be in form of new cracks, and the rest in the form of leakage caused by differential movement at the connections between pipes, fittings and water-supplying fittings. Due to permanent deformations, it can be expected that 80-85 % of new damage will appear as cracks, and the as leakage at the connections. However, the above should be taken with a considerable margin, because some studies report different (some even equal) ratios in the occurrence of damage [11].

The empirical equation of the vulnerability function is usually defined on the basis of statistical processing of the data on the repairs carried out after the seismic event, primarily as a function of the length of the network (e.g., the number of repairs per km'), the connection method and the material of the water supply network, and the parameters of seismic excitation. They are often defined by a lognormal probability distribution function, although such a distribution may not always correspond normally to the actual situation. Other forms of vulnerability functions can be used to determine the probabilities of reaching or exceeding some undesirable state conditioned by the level of ground excitation [12, 13].

In 1975, Katayama et al. performed one of the earliest correlations between seismic parameters, specifically PGA and pipeline damage, and did not distinguish between damage caused by temporary and permanent ground deformation [14]. Between 1981 and 1983, Eguchi et al. correlated the degree of pipeline damage with Mercalli intensity levels and recommended that only damage from seismic wave propagation be evaluated. Furthermore, their vulnerability functions were developed for cast iron and welded steel pipes. Also, under the assumption that joint failures will prevail, it is also assumed that asbestos-cement pipelines and welded steel pipelines will exhibit a similar levels of damage as gray cast iron pipelines [15, 16].

In 1989, Barenberg proposed that pipeline damage should be correlated with temporary ground deformations in a low-intensity earthquake zone, specifically peak horizontal ground velocity, and correlated with permanent deformations in an earthquake zone with pronounced permanent deformations, i.e., visible surface faulting, liquefaction and other resulting phenomena [17]. In 1993, O'Rourke and Ayala extended Barenberg's results with larger profile pipelines (DN 500 - DN 1800) made of gray cast iron, asbestos cement pipelines and reinforced concrete (steel cylinder) pipelines. These studies were also adopted in 1999 by the *Federal Emergency Management Agency* (*FEMA*) within the *Methodology for Estimating Potential Losses from Disasters* (*HAZUS*) as a method for estimating damages caused by earthquakes [18].

In 1992, based on data analysis of four earthquakes, Honegger and Eguchi defined the influence of permanent ground deformation on the occurance of damage to the water supply network, whereby through the deformation behavior of the pipe material, rigid (gray cast iron, concrete, asbestos cement) and elastic pipes (nodular cast iron, polyvinyl chloride, steel), were taken into account [19].

In their papers from 1998, Toprak and O'Rourke, based on the processing of a large number of seismic data and almost 12,000 km of water supply network in the Los Angeles area, determined the most statistically significant correlations between the number of damages and the peak horizontal velocity of the ground. The equations were developed primarily for damage to gray cast iron pipelines, although a limited comparison with damage for other types of pipe materials has also been made. They also took into account the influence of the diameter, so the equations were grouped for diameters ≤ DN 600, i.e., for diameters > DN 600 [20].

In 1999 and 2000, authors O'Rourke and Jeon defined individual vulnerability functions for gray cast iron, nodular cast (ductile) iron, asbestos cement and steel pipelines. Their equations, in addition to PGV, also take into account the diameter of the pipe, i.e., the influence of the diameter on the occurrence of damage [21].

In 2001, Eidinger, J. proposed two vulnerability functions: one for the influence of the passage of seismic waves and the other for the influence of permanent ground deformation on the occurance of new damage to the network. The mentioned vulnerability functions are given for the average number of damages per 100 [m] of the water supply network for different pipe materials and small (≤ DN 300) and large (≥ DN 400) diameters [22].

As part of the risk reduction project for municipal and transportation systems due to natural hazards, *The American Lifelines Alliance* (*ALA*), American *National Institute of Building Sciences* by downloading Eidinger's results and analyzing the data of seismic events from the USA, Japan and Mexico, developed vulnerability functions in dependence of peak ground velocity, permanent ground deformation, pipe material, diameter and ground corrosivity. These vulnerability functions are also used by a computer program *HAZUS-MH,* which is commonly used in the USA for such assessments. At the same time, manufacturers recommend the developed vulnerability functions when the technical data on pipe material, connection method, diameter, corrosion condition, etc. are not known.

Pineda and Ordaz, by analyzing the data of seismic events for the water supply system of Mexico City in 2003, concluded that *PGV* overestimates the number of damages for earthquakes of magnitude 8 and below, and they proposed a correcting parameter PGV^2/PGA [23].

In 2004, O'Rourke and Deyoe investigated the differences between the vulnerability functions developed by *FEMA* (*HAZUS*) and other authors, where they concluded that the most significant differences are the result of the used data sets related to the type of seismic wave, specifically the differences between the influence of secondary (transverse waves in which ground particles oscillate perpendicular to the direction of wave propagation) and Rayleigh waves (where particles move in a vertical plane, along an elliptical path opposite to the direction of seismic wave propagation) [24].

In 2014, O'Rourke et al. defined vulnerability functions for the median repairs required per 1 [km] of asbestos-cement and cast-iron pipes exposed to temporary ground deformation, depending on the mean of the two peak horizontal ground velocities of all relevant measurements [25].

Halfaya et al. proposed a vulnerability index for the water supply network based on the extension of any vulnerability function with correction coefficients that take into account pipe diameters from DN <75 to DN >1100, different types of materials and associated types of connections, and the existence of ground liquefaction [2]. In 2020, Lee et al. proposed an extended ALA method with additional coefficients that considered the type of pipe material, pipe diameter, installation conditions and the presence of ground liquefaction [26].

Comparing the damage rating of the listed most commonly used vulnerability functions with respect to temporary ground deformations, the relationship shown in Figure 1 is obtained.

From the attached diagram, it can be seen that the two vulnerability functions (according to Pineda and Ordaz and O'Rourke and Deyoe for Rayleigh waves) differ considerably in their estimates already for initial values of *PGV*, while the vulnerability function according to Toprak predicts extremely high damage values for higher values of *PGV*. Other vulnerability functions in the largest range of values for *PGV* obtain relatively similar levels of damage, which implies greater certainty in damage estimates when it is not possible to define vulnerability functions for a specific water supply system.

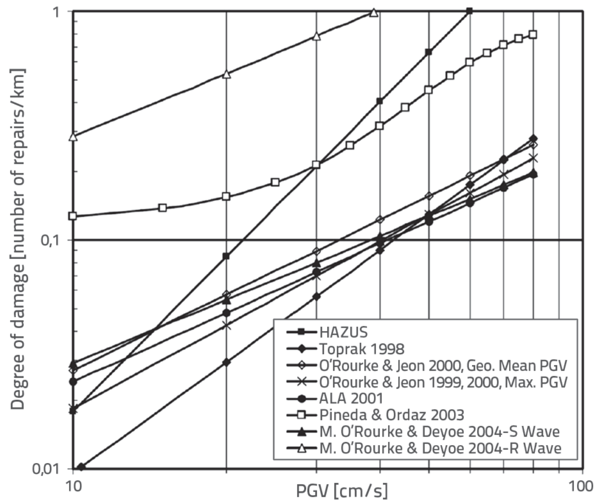

Figure 1. Graphic representation of the relative comparison of the number of damages on the water supply network according to the most commonly used vulnerability functions [10]

2.3. The possibility of applying the exposed vulnerability functions in case of seismic events in the service area of the public water supply system of the city of Petrinja

The presented vulnerability functions are primarily derived for specific seismic events, i.e., specific magnitudes, local geographic/geologic/geotechnical conditions, as well as specific technical characteristics of the water supply system, and cannot be used uncritically to assess damage for each seismic event. It is important to emphasize that the available information regarding the exposed vulnerability functions was limited mainly in terms of the relatively small number of analyzed earthquakes and associated damage to the water supply network, and the presence of measured seismic parameters.

Establishing a correlation between the number of damages, i.e., number of required repairs and estimated seismic parameters, such as intensity according to the Mercalli-Cancani-Sieberg (abbr. MCS) scale, involves considerable uncertainty. In accordance to the MCS scale, intensity is a subjective measure of a seismic event, as well as the scope in regards to the area where a certain intensity, which is also a result of a subjective judgment, is noticed. Therefore, vulnerability functions with inherent uncertainties resulting from estimating the magnitude of the intensity and the extent of the area covered by a single intensity value are not considered here.

Among the different recorded seismic parameters, the most statistically significant correlations were found for horizontal ground peak velocities, *PGV*, due to the occurrence of axial deformation in the ground due to the propagation of seismic waves, whereby, depending on the resulting relative displacement between the pipeline and the surrounding ground, the pipeline itself also gets deformed. It is important to note that different authors define *PGV* in different ways. *PGV* is defined as the larger of the two horizontal velocity components recorded during the earthquake, and also as the geometric mean of the largest horizontal velocity components, and as the largest single recorded horizontal velocity value.

The main reason why is *PGV* a better indicator of pipeline damage compared to *PGA* is its relationship to ground deformation. *PGV* shows a better ground response than *PGA* when considerd as a function of time, making it more acceptable for deterministic models. Therefore, *PGV* is the most commonly used seismic parameter for evaluating damage to water supply networks due to seismic activity, so for the evaluation of damage in the specific area, only vulnerability functions that include an evaluation based on *PGV* will be analyzed.

Other relevant parameters that should be taken into account, and which most often figure in the derived vulnerability functions, refer to the type of pipe material, the type of connection and the pipe diameters. Namely, certain vulnerability functions, especially those developed within *ALA* and *HAZUS* methods (the method by O'Rourke and Ayala from 1993), take into account the damage assessment based on these criteria [2, 18, 20, 21, 22, 25]. For other relevant parameters, such as age, i.e., the physical condition of the water supply network, ground properties (mechanical and chemical), pressure conditions, etc., corresponding individual vulnerability functions exist, however, adequate data is not available for the considered area, so such vulnerability functions will not even be considered.

On the other hand, in the last twenty years the construction of new, as well as the rehabilitation or reconstruction of existing water supply networks was based on the use of plastic pipe materials, mostly polyethylene (PE), and high-density polyethylene (PEHD), which is slowly taking precedence over poly(vinyl-chloride) (PVC). To date, there is no empirical evidence on the seismic performance of plastic PE pipes in water supply systems, but limited experience shows good results in gas distribution systems. Limited tests of PE pipes under pressure showed that the deformation capacities before rupture exceed the nominal values by 25 % for tensile and 10 % for compressive stress, which indicates a relatively favorable seismic robustness [7, 27]. Also, only a few studies on the impact of seismic events evaluated the seismic resistance to damage of PE pipes in comparison to other pipe materials, where it was determined that the degree of damage for PE is < 0.5 [1/km], and for example for nodular cast iron it is 1.0 [1/km], steel 2.4-2.6 [1/km], PVC 2.6 [1/km], gray cast iron 3.3 [1/km] and 4.5 for asbestos cement [1/ km] [7, 27]. However, some give other ratios.

Furthermore, PE is not susceptible to corrosion, but there are some concerns about the health effects of long-term use. Therefore, any recommendation for the use of PE pipes in areas prone to seismic activity should follow the determination of the actual effect of long-term use of polyethylene as a pipe material on human health.

The aforementioned *ALA*, *HAZUS* and the Honegger-Eguchi method are also methods for assessing damage to municipal buildings, gas pipelines, oil pipelines and water supply networks, which are recommended by the European Commission for the systematic analysis of the seismic vulnerability and risk of municipal buildings, taking into account the interactions between different components and systems (e.g., the transportation system) according to the documents *Systemic Seismic Vulnerability and Risk Analysis for Buildings, Lifeline Networks and Infrastructures Safety Gain* [28], and according to the document *Guidelines for deriving seismic fragility functions of elements at risk: Buildings, lifelines, transportation networks and critical facilities* derived from the research scientific project SYNER-G [28, 29]. For the assessment of damage to oil pipelines, the application of the *ALA* method is recommended, while for the assessment of damage to water supply networks the *HAZUS* and the Honegger - Eguchi methods are recommended.

The aforementioned scientific project developed an innovative methodological framework for assessing physical as well as socioeconomic seismic vulnerability and risk at the urban scale. The built environment is modeled according to a detailed taxonomy devided into the following categories: buildings, transportation and utility networks, and critical structures. Each category has several types of components and subsystems, and the developed framework integrates all aspects, from hazard assessment, to the assessment of the vulnerability of components, subsystems and systems, as well as the socioeconomic impacts of earthquakes, taking into account the uncertainties of the quantitative simulation scheme and modeling the interaction between systems.

In conclusion, it can be said that for the considered area, according to the available data presented previously and the recommendations of the European Commission, *ALA* and *HAZUS* methods as well as the Honegger-Eguchi damage assessment method can be used, which will be explained in more detail here.

2.3.1. ALA method

Vulnerability functions according to *ALA* methods are defined by equations (1) and (2):

$$R_p = K_1 \cdot 0{,}002416 \cdot PGV \tag{1}$$

$$R_t = K_2 \cdot 2{,}5831 \cdot PGD^{0{,}309} \tag{2}$$

where: R_p is the average number of damages due to temporary ground deformations per 1 [km] of the water supply network, R_t is the average number of damages due to permanent ground deformations per 1 [km] of the water supply network, *PGV* peak horizontal ground velocity in [cm/s], *PGD* permanent ground movement after the earthquake in [m], K_1 and K_2 are coefficients that take into account the type of pipe material, connections, ground corrosivity and pipe diameter (Table 1).

2.3.2. HAZUS (O'Rourke and Ayala) method

With this method for assessing damage caused by temporary ground deformations, R_p [1/km], the vulnerability function is used; equation (3):

$$R_p = K_3 \cdot 0{,}0001 \cdot PGV^{2{,}25} \tag{3}$$

where: *PGV* is the peak horizontal ground velocity in [cm/s], and K_3 a coefficient which depends on the deformation behavior of the pipe

Table 1. Values of coefficients K_1 and K_2 according to Eidinger with additions according to other authors [22, 27, 29]

Material	Connection	Ground	Diametar	K_1	K_2
Gray casting	cement	All grounds	≤ DN 300	1.0	1.0
	cement	corrosive	≤ DN 300	1.4	1.0
	cement	non-corrosive	≤ DN 300	0.7	1.0
	rubber seal	All grounds	≤ DN 300	0.8	0.8
	mechanical couplings	All grounds	≤ DN 300	0.7	0.7
Steel	Sealed fold	All grounds	≤ DN 300	0.6	0.15
	Sealed fold	corrosive	≤ DN 300	0.9	0.15
	Sealed fold	non-corrosive	≤ DN 300	0.3	
	Sealed fold	All grounds	≥ DN 400	0.15	0.15
	rubber seal	All grounds	≤ DN 300	0.7	0.7
	Bolted joint	All grounds	≤ DN 300	1.3	
	rivets	All grounds	≤ DN 300	1.3	
Asbestos cement	cement	All grounds	≤ DN 300	1.0	1.0
	rubber seal	All grounds	≤ DN 300	0.8	0.8
Reinforced concrete (steel cylinder)	Sealed fold	All grounds	≥ DN 400	0.7	0.6
	cement	All grounds	≥ DN 400	1.0	1.0
	rubber seal	All grounds	≥ DN 400	0.8	0.7
PVC	rubber seal	All grounds	≤ DN 300	0.5	0.8
Nodular cast iron (ductile)	rubber seal	All grounds	≤ DN 300	0.5	0.5

Table 2. Data of the seismic measuring stations of the City of Zagreb with the values of the corrected parameters *PGA*, *PGV* and *PGD* based on the accelerometer record for the ML=6.2 magnitude seismic event of December 29, 2020. (website of the seismological service at the Geophysical Department of the Faculty of Science, https://www.pmf.unizg.hr/geof/seizmoloska_sluzba/potresi_kod_petrinje_2020, visited on February 12, 2021)

Measuring station	Latitude j [°N]	Longitude l [°E]	Elevation [km]	Epicentral distance [km]	Component of the record (direction of ground movement) up-down (Z), north-south (N)	PGA_{corr} [cm/s²]	PGV_{corr} [cm/s]	PGD_{corr} [cm]
Zagreb 1	45.777	15.993	0.1	45.462	Z	45.482	2.160	0.859
					N	93.358	7.792	2.768
					E	79.973	**8.490**	**4.214**
Zagreb 2	45.827	15.987	0.179	50.775	Z	57.450	2.664	0.796
					N	97.696	5.240	1.791
					E	106.458	**6.399**	**2.954**
Zagreb 3	45.914	16.103	0.264	57.795	Z	122.490	3.574	0.664
					N	243.165	**9.586**	1.021
					E	162.763	6.072	0.937
Zagreb 4	45.808	15.999	0.115	48.503	Z	42.681	2.427	0.862
					N	124.275	5.960	2.309
					E	95.777	**6.234**	**2.870**
Zagreb 5	45.811	15.879	0.122	52.754	Z	36.999	1.743	0.500
					N	112.538	6.728	1.372
					E	127.554	**7.483**	**2.508**
Zagreb 6	45.907	15.968	0.994	59.654	Z	19.697	1.244	0.549
					N	38.826	1.776	0.797
					E	27.842	2.340	1.247

material, which receives a value of 1.0 [1] for rigid pipe materials (gray cast iron, concrete, asbestos cement) and 0.3 [1] for elastic pipe materials (nodular cast iron, polyvinyl chloride, steel).

2.3.3. Honegger - Eguchi method

This method is used to assess damages caused by permanent ground deformations, R_t [1/km], according to equation (4):

$$R_t = K_3 \cdot 7{,}821 \cdot PGD^{0{,}56} \tag{4}$$

where *PGD* is permanent ground movement after the earthquake in [cm], and the coefficient K_3 takes on values as in the *HAZUS* method.

3. Seismic excitation parameters in the service area of the public water supply system of the city of Petrinja

For the preparation of this paper, reports on earthquakes, that occurred on December 28 and 29, 2020, and were published by the seismological service at the Geophysics Department of the Faculty of Science (abbr. PMF) of the University of Zagreb were used.
The values of the seismic excitation parameters were recorded at the location of the Čerkezovac monitoring station (Figure 2) and on the accelerometers of six monitoring stations located in the city of Zagreb. The values of maximum horizontal accelerations and velocities in the epicenter of the earthquake and in the cities of Petrinja, Sisak and Glina were not recorded because there are no measuring stations in the mentioned areas. The distances of the mentioned monitoring stations from the epicenter of the seismic events in the area are listed in Table 2.

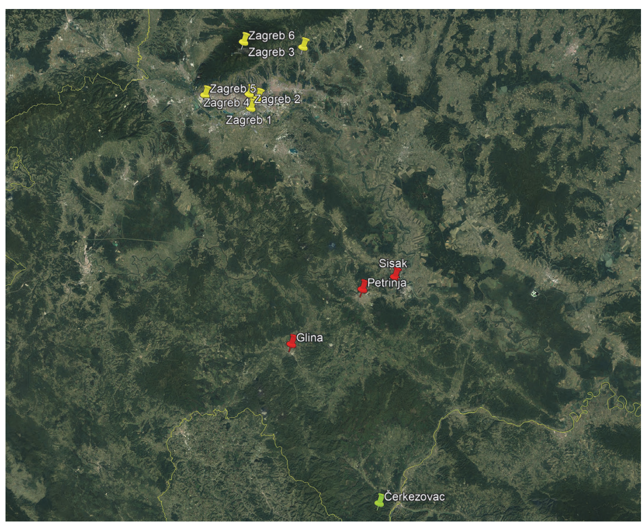

Figure 2. The location of the monitoring station Čerkezovac in relation to the city of Zagreb and the analyzed area of the city of Petrinja

The measured values of the earthquake of December 29, 2020, i.e., earthquake of magnitude 6.2, were used to create an assessment of the damage to the water supply system. All the data collected at the monitoring stations were processed for each component to create a report by the Geophysical Department of the Faculty of Science, and finally, in order to eliminate mistakes in the record and errors in the monitoring itself, the final corrected records of the values of the highest accelerations, (*PGAcorr*), velocities (*PGVcorr*) and displacements (*PGDcorr*) which are all shown in Table 2, were created. In the rest of the text, these corrected values will be referred to as *PGA*, *PGV* and *PGD*.

At the Čerkezovac measuring station, the highest value of the *PGA* on the surface was recorded for the east-west component at the level of 0.5 [m/s^2], i.e., about 5 % of the acceleration due to gravity, which is several times lower than the acceleration recorded in the area of the city of Zagreb (Zagreb 3 measuring station with the *PGA* of 2.4 [m/s^2]).

As it is generally true for the spatial distribution of the above values that they decrease with distance from the epicenter, it can be assumed that the peak values of *PGA* and *PGV* in the observed area, closer to the epicenter, were higher than the measured ones. Namely, there is a large number of studies on the influence of the epicenter distance on the reduction of the intensity of the seismic event according to which for an average distance of 50 [km], as in the observed case, a decrease in intensity by 2 to 3 degrees can be expected, depending on the authors, i.e., the investigated seismic events [30, 31]. Furthermore, according to the reports of the Croatian Geological Institute and the Geophysical Department of the Faculty of Science, the intensity of the earthquake of December 29, 2020, was at the epicenter between VIII and IX level of the MCS scale, and at the same time for Zagreb the intensity was evaluated and calculated with the value VI. This was also confirmed in the reports of the static inspections of the buildings, which were done afterwards, and according to which near the epicenter of the earthquake family houses with constructed retaining walls suffered irreparable damage.

Given that the authors of this paper do not have available data on the spatial distribution of ground types in the analyzed area and its influence on the propagation and deformation of seismic waves, on the basis of which the values could be determined with greater certainty *PGV* and *PGD* for that area, the maximum recorded, i.e., measured value of six measuring stations in the Zagreb area will be used in the evaluation. In doing so, a doubled value will be taken into account, assuming that higher values of *PGV* and *PGD* are needed for the subject area which reflects higher intensity values in that area. The above does not necessarily correspond to the actual event, i.e., it cannot be confirmed by relevant measurements. However, based on published work that has analyzed the relationship between peak ground acceleration and intensity, it is assumed that there is at least a double difference in *PGA* value for intensity differences of two to three degrees [32-34].

Under such a calculation assumption, it can be considered that the damage to the water supply network corresponds to the lower and upper limit of damage, i.e., conservative assessment and assessment of the largest number of damages. Such an approach was chosen in order to recognise the range of the possible number of damages and to give as realistic an estimate as possible. Given the above, the damage assessment will be based on the highest recorded value of *PGV* of 9.6 [cm/s] and the assumed value of 19.2 [cm/s], i.e., at the highest recorded value of *PGD* of 4.2 [cm], i.e., 8.4 [cm].

4. Assessment of damage to the existing water supply network of the public water supply system of the city of Petrinja

This chapter provides an assessment of the number of damages to the existing, i.e., build, water supply network of the water supply system of the city of Petrinja, including the municipality of Lekenik, in accordance with the established appropriate vulnerability functions according to the highest measured values of seismic excitation parameters, *PGV* and *PGD*, at measuring stations in the area of the city of Zagreb, tables 3, 5 and 7, but also according to assumed values of *PGV* and *PGD* in the considered area itself, tables 4, 6, and 8. Results related to the evaluation of the number of damages on the existing water supply network according to the assumed values of *PGV* and *PGD* in the considered area, are marked with an asterisk (*) next to the name of the damage evaluation method. In the above

Table 3. The evaluation of the number of damages to the water supply network of the public water supply system of the city of Petrinja and the municipality of Lekenik due to temporary and permanent deformations of the ground according to ALA method for the highest measured values of *PGV* and *PGD*

Materijal	Duljina [km]	*ALA*					
		K_1 [1]	K_2 [1]	R_p [1/km]	R_t [1/km]	R_p [1]	R_t [1]
Polietilen visoke gustoće (PEHD)	210.5	0.5	0.8	0.012	3.266	2	688
Polivinil-klorid (PVC)	38.1	0.5	0.8	0.012	3.266	0	124
Azbestcement (AC)	50.5	1.0	1.0	0.023	4.083	1	206
Lijevano željezo – sivi lijev (SL)	21.8	0.8	0.8	0.019	3.266	0	71
Lijevano željezo – nodularni lijev (NL)	20.0	0.5	0.5	0.012	2.041	0	41
					∑ =	**3**	**1 130**

Table 4. The evaluation of the number of damages to the water supply network of the public water supply system of the city of Petrinja and the municipality of Lekenik due to temporary and permanent deformations of the ground according to the *ALA* method for estimated values of *PGV* and *PGD* in the studied area

Material	Length [km]	*ALA**					
		K_1 [1]	K_2 [1]	R_p [1/km]	R_t [1/km]	R_p [1]	R_t [1]
High density polyethylene (PEHD)	210.5	0.5	0.8	0.023	3.756	5	791
Polyvinyl chloride (PVC)	38.1	0.5	0.8	0.023	3.756	1	143
Asbestos cement (AC)	50.5	1.0	1.0	0.046	4.695	2	237
Cast iron - gray cast iron (SL)	21.8	0.8	0.8	0.037	3.756	1	82
Cast iron - nodular cast (ductile) iron (NL)	20.0	0.5	0.5	0.023	2.347	0	47
					∑ =	**9**	**1 299**

tables, the estimation of the number of damages is given according to the type of pipe material and the corresponding lengths of the water supply network.

For *ALA* method, the coefficients K_1 and K_2 for PEHD pipelines were taken with regard to the values used by other authors investigating the effects of seismic events on the occurance of damage to water supply pipelines, which practically correspond to the values of the coefficients for PVC. Although the *ALA* method is used according to the recommendations of the European Commission documents, for the evaluation of damage to oil and gas pipelines, it was used here to see the range of the possible number of damages, because according to the American guidelines, i.e., recommendations, the method is used for the evaluation ofdamage to water supply networks.

Evaluation of the number of damages using assumed values for *PGV* and *PGA* that are twice as large relative to the measured values, shows that an increase in the number of damages, in relation to a conservative estimate, can be expected equally for "rigid" and "elastic" pipelines, and that twice the assumed values for *PGV* and *PGD* have a smaller effect on increasing the total number of damages. It can be seen that the difference in the number of damages was obtained on the basis of assumed values of *PGV* and *PGD*, compared to the same measured values, which is about 15 %.

The results obtained on the basis of the applied methods of damage assessment due to temporary ground deformations show that no significant damage to the water supply network shouis expected due to the passage of seismic waves, i.e., that temporary ground deformations have an extremely small impact on the total number of damages to the existing water supply network. The obtained results show a lower number of damages than the expected literature values of the influence of temporary deformations on the occurance of the number of damages. However, such a result can be attributed to the fact that the majority of the existing water supply network consist of pipe materials, which, according to the applied damage assessment methods, are considered elastic and thus respond better to temporary ground deformations.

Namely, on that water supply system, the largest part of the existing water supply network was built from PE pipes, which, according to the value of the coefficient K_3 have three times higher seismic resistance than gray cast iron or asbestos cement pipes. Additionally, the estimates given here are based solely on the previously adopted vulnerability functions. However, a more detailed evaluation of the effects of the propagation of seismic waves on new damages should follow detailed spatial processing of the measured seismic parameters of ground excitation in relation to the type of ground, the

Table 5. The evaluation of the number of damages to the water supply network of the public water supply system of the city of Petrinja and the municipality of Lekenik due to temporary ground deformations (passage of seismic waves) according to *HAZUS* (O'Rourke and Ayala) method for the highest measured values *of* *PGV*

Material	Length [km]	*HAZUS* (O'Rourke - Ayala)		
		K_3 [1]	R_p [1/km]	R_p [1]
PEHD	210.5	0.3	0.005	1
PVC	38.1	0.3	0.005	0
AC	50.5	1.0	0.016	1
L.Ž (SL)	21.8	1.0	0.016	0
L.Ž. (NL)	20.0	0.3	0.005	0
			∑ =	**2**

Table 6. The evaluation of the number of damages to the water supply network of the public water supply system of the city of Petrinja and the municipality of Lekenik due to temporary ground deformations (passage of seismic waves) according to *HAZUS* (O'Rourke and Ayala) method for estimated values of *PGV* in that area

Material	Length [km]	*HAZUS* (O'Rourke - Ayala)*		
		K_3 [1]	R_p [1/km]	R_p [1]
PEHD	210.5	0.3	0.023	5
PVC	38.1	0.3	0.023	1
AC	50.5	1.0	0.077	4
L.Ž (SL)	21.8	1.0	0.077	2
L.Ž. (NL)	20.0	0.3	0.023	0
			∑ =	**12**

Table 7. The evaluation of the number of damages to the water supply network of the public water supply system of the city of Petrinja and the municipality of Lekenik due to permanent ground deformations according to the Honegger - Eguchi method for the highest measured values of *PGD*

Material	Length [km]	Honneger - Eguchi		
		K_3 [1]	R_t [1/km]	R_t [1]
PEHD	210.5	0.3	5.241	1103
PVC	38.1	0.3	5.241	199
AC	50.5	1.0	17.470	882
L.Ž (SL)	21.8	1.0	17.470	380
L.Ž. (NL)	20.0	0.3	5.241	105
			∑ =	**2,670**

Table 8. The evalaution of the number of damages to the water supply network of the public water supply system of the city of Petrinja and the municipality of Lekenik due to permanent ground deformations according to the Honegger - Eguchi method for estimated values of *PGD* in the observed area

Material	Length [km]	Honneger - Eguchi*		
		K_3 [1]	R_t [1/km]	R_t [1]
PEHD	210.5	0.3	7.726	1627
PVC	38.1	0.3	7.726	294
AC	50.5	1.0	25.755	1300
L.Ž (SL)	21.8	1.0	25.755	560
L.Ž. (NL)	20.0	0.3	7.726	155
			∑ =	**3,936**

actual damage mechanism of pipes and connections, and according to the types of pipe materials. At the time of writing this paper, such an approach could not be applied due to the lack of relevant data, and primarily due to the lack of field research on the actual number of damages to the water supply network of the entire water supply system. Recommendations for the collection of data for the preparation of future relevant assessments of damage due to seismic events are given in the conclusion of this paper.

Based on the evaulation of the number of new damages according to the Honegger-Eguchi method, it can be stated that permanent ground deformations caused most of the damages to the water supply network in question. At the same time, taking into account the conservative approach with the highest measured ground deformation values, it is estimated that about 2,600 new damages occurred to the water supply network, of which the author estimates that about 85-90 % are due to interventions requiring earthworks. Namely, it is estimated that approximately 10-15 % of the damage can be repaired directly using valve chamber or other chambers such as regulation shafts, flow metering chambers, etc. An evaluation of the expected forms of rehabilitation is given later in the text.

Taking into account the spatial increase of the values of the seismic excitation parameters, i.e., the *PGD*, according to the epicenter of the analyzed seismic event, an increase of about 50 % in the number of damages to the water supply network can be expected compared to the conservative estimate.

Additionally, unlike the *ALA* method, the Honegger - Eguchi method shows a significantly higher response in increasing the number of damages for increasing values of *PGD*, which is in line with expectations. Namely, it is known that there is a logarithmic relationship between the two values of earthquake magnitude, so that with each increase in magnitude, multiple times greater amounts of elastic earthquake energy are released, which ultimately leads to an increase in damage to the pipeline network.

On the other hand, the range of all values between the analyzed methods shows that the difference between the expected number of damages to the water supply network can be greater than 350 %, i.e., the most conservative estimate according to *ALA* method results in about 1,100 new damages after the analyzed earthquake, while the upper limit of expected damages is about 4,000. Taking into account the level of damage to the water supply network before the earthquake, according to which water losses, depending on the success of the implementation of loss reduction activities, amounted to between 60 % (immediately before the earthquake) and 75 % of the affected quantities (immediately after the earthquake), as well as the fact that the analyzed earthquake of December 29 was preceded on December 28 by another significant earthquake of magnitude 5.0 with the epicenter near the city of Petrinja, and on the same day by two earthquakes of magnitude 4.7 and 4.1, it is reasonable to assume that the totality of seismic events resulted in the number of damages tending towards the upper limit of the performed assessments. Additionally, as the guidelines of the European Commission were adopted in the preparation of this work, the number of damages according to a conservative estimation that corresponds to the *ALA* method was not considered any further.

At the same time, it is important to point out that all new damage is not exclusively related to cracks in the water supply network. All the damages that occur on it are taken into account, including differential displacements at the connection point , minor cracks that result in background leaks that are difficult to detect with regular acoustic methods (due to the intensity of the leaks, they do not have to have an economic justification for carrying out rehabilitation), damages to service connections and damages inside the valve chambers. Therefore, it can be stated that after the earthquake on December 29, 2020, about 3,800 new damages to the existing water supply network occurred.

Of the stated number of damages, bearing in mind the conclusions from the field insights into the types of damage to the buildings of the water supply system and taking into account the collected information from the public water supplier on the interventional repairs to the water supply system, it is estimated that about 90 % of the damages (3,420 damages) require rehabilitation that includes earthworks, i.e., excavation to access the damage, and that about 10 % of the damages (380 damages) can be repaired within the existing valve chambers in the form of by repairing cracks, displacement

Table 9. Distribution of the estimated number of damages to the water supply network of the public water supply system of the city of Petrinja and the municipality of Lekenik with an estimate of the total cost of rehabilitation

Damage category	Damage number	Estimate of the unit cost of rehabilitation [kn] (1 EUR ≈ 7,5 kn)	Total estimated cost of rehabilitation [kn] (1 EUR ≈ 7,5 kn)
Supply and transport pipelines	1 163	8 000	9 302 400
Minor damage to the network (background leaks)	205	/	/
Valve chambers with the possibility of rehabilitation	114	8 000	912 000
Valve chambers without the possibility of rehabilitation - construction of new chambers with equipment	38	80 000	3 040 000
Service connections	2 280	6 500	14 820 000
∑ =	**3 800**		**28 074 400**

or replacement of plumbing fixtures and fittings. In addition, it is estimated that about 40 % of all damage is due to damage to supply and transit pipelines and related valve chambers (a total of 1,520 damages, of which 1,368 were on the network and 152 were valve chamber damages), and that about 60 % of the damage (2,280 damages) is due to service connections. Furthermore, it is estimated that 15 % of the damage to the supply and transit pipelines (205 minor damages) corresponds to the occurrence of small (background) leaks for which there is currently no economic justification for making repairs. Also, it is estimated that about 10 % of the damage to the network is due to damage to the valve chambers (152 damages), of which 25 % of the damaged valve chambers will be out of order and will require a completely new construction (38 damages), and 75 % of damaged valve chambers can be repaired within the chamber (114 damages). The systematization of damage with the associated damage rating is shown in Table 9.

Certain verification of the above estimates can be found in the number of reports of failures in the water supply system after the earthquake from December 29. Namely, in the days that followed the earthquake, employees of the water service supplier (Privreda d.o.o., Petrinja) received numerousreports of damaged water supply networks (visible even from the surface of the field) and a large number of reports of damage to service connections. The number of damage reports was such that it exceeded the capacities that can be recorded by the supplier, so the recording was briefly interrupted.

It should be noted that the damage assessment was given solely for the purpose of applying the previously presented methodology and refers exclusively to individual point damages of the water supply (supply and transit) network due to the seismic event at the end of 2020. Therefore, the assessment does not include damage to other related buildings of the water supply system (e.g., water intakes, hydrotechnical galleries, pumping stations, etc.) that were also damaged during those earthquakes, and it does not include the reconstruction or rehabilitation of those sections of the network on which a subsequent inspection coupled with prior knowledge of the state of damage concluded that there is need for complete rehabilitation or reconstruction.

5. Conclusion

By applying the so-called vulnerability functions, an assessment of the damage and related damage to the water supply network, with the associated valve chambers and service connections, of the water supply system of the city of Petrinja after the earthquake on December 29, 2020, was carried out. By applying vulnerability functions, the number of damages is estimated based on temporary and permanent deformations of the ground caused by a seismic event, whereby as an influential parameter in relation to the technical characteristics of the water supply network, the type of pipe material is taken into account. Taking into account the measured parameters of seismic excitation at measuring stations in the city of Zagreb, as well as based on previous research on the estimated value of ground deformations in the considered area, it is estimated that after the analyzed seismic event, about 3,800 new damages occurred with a total damage amounting to HRK 28 million. The estimates given here should be understood as the best possible empirically based estimates of damages, where there is a certain degree of uncertainty related to not taking into account, i.e., partial consideration (the result of statistical processing of derived vulnerability functions) and other relevant technical characteristics of the water supply network and the fact that the detailed state of damage of the water supply network before the analyzed seismic event was unknown.

With this in mind, the stated estimates of the number of new damages to the water supply network should be verified in an iterative process according to the processing of data from field research, upon locating and repairing cracks in the water supply network, and spatial processing of seismic excitation parameters (PGV and PGA). All collected data should later be systematized with regard to the type of pipe material, type of connections and other relevant technical parameters such as diameter, age, type of pipe connections, type of material of valve chambers and the method of penetration (passage) of pipes on the chambers, types and aggressiveness of ground, geomechanical ground characteristics, groundwater level, etc.

Therefore, it is necessary to carry out detailed geomechanical investigations of the ground in that area in order to determine the accuracy of the methods used to evaluate the number of damages for that area, i.e., determine whether other ground deformations should be taken into account. At the same time, it is extremely important to collect relevant data for each repair which was done, i.e., to evaluate the damaged location, as well as to gather data related to a detailed description (with a photo) of the observed damage and the location of the damage, the method of repair, the duration of the repair, as well as the estimated and actual cost of the repair.

In addition to the mentioned technical parameters, and related to the conditions of the pipeline bed, it is necessary to examine in more detail the effects of the presence of concrete support blocks during earthquakes. Namely, it is not a rare case that the support blocks despite being designed at the places of horizontal and vertical changes in the direction of the pipeline routes are not actually built, so with the loss of adequate support, the resulting force of hydrodynamic and hydrostatic action is directly transferred to the connections at the places of changes in the direction of the routes. This increases the possibility of damage to such connections and is especially evident when the ground shakes due to a seismic event. Therefore, it is necessary to determine whether a sufficient number of support blocks can increase the general seismic resistance of the water supply network and at the same time reduce the vulnerability of pipelines.

Upon obtaining a result of the aforementioned analyses, ultimately, vulnerability functions for a specific water supply system should be also derived, which will be used with a greater degree of certainty to determine any and all possible damage that can occur in any future seismic event or to test different scenarios for determining the earthquake resistance of the water supply system at the time it is being designed.

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