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Railway infrastructure in earthquake affected areas

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Research Paper

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In the case o seismic impact on rail infrastructure, even small deformations or damage to track structure can compromise safe operation of rail traffic. Damage can affect track substructure or permanent way of the track, but also the electrification system and safety-signalling devices. Ballast prism will suffer damage in case of greater intensity earthquakes, resulting in the reduction of lateral and longitudinal resistance of track structure. Earthquake action may also cause derailment of moving rail vehicles. Operation of rail vehicles also causes certain levels of vibrations, and so an analysis of subsequent effects of rail traffic.

Key words:
earthquake, rail infrastructure, damage, traffic safety, vibrations, tram

Prethodno priopćenje

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Tračnička infrastruktura u potresom pogođenim područjima

U slučaju djelovanja potresa na tračničku infrastrukturu, čak i male deformacije ili oštećenja kolosijeka mogu ugroziti sigurnost odvijanja tračničkog prometa. Oštećenja mogu biti prisutna na donjem odnosno gornjem ustroju kolosijeka, ali i na sustavu elektrifikacije te signalno sigurnosnim uređajima. Kod potresa jačeg intenziteta dolazi do oštećenja zastorne prizme koja za posljedicu imaju smanjenje bočnog i uzdužnog otpora kolosijeka. Djelovanje potresa stvara i opasnost od iskliznuća tračničkog vozila koje je u pokretu. Prometovanje tračničkih vozila također izaziva određene razine vibracija te je u ovom radu dan prikaz analize naknadnog djelovanja vibracija tračničkog prometa na građevine stradale u potresu 22. ožujka 2020. u Gradu Zagrebu.

Ključne riječi:
potres, tračnička infrastruktura, oštećenja, sigurnost prometa, vibracije, tramvaj

Vorherige Mitteilung

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Schieneninfrastruktur in erdbebengefährdeten Gebieten

Im Falle der Einwirkung eines Erdbebens auf die Schieneninfrastruktur können bereits kleine Verformungen oder Schäden am Gleis die Sicherheit des Schienenverkehrs gefährden. Schäden können am Bahnober- oder Bahnunterbau, aber auch am Elektrifizierungssystem und an den Vorrichtungen für Zugsicherung/Signalgebung auftreten. Bei Erdbeben höherer Intensität wird das Schotterprisma beschädigt, was zu einem verringerten seitlichen und längslaufenden Widerstand des Gleises führt. Durch die Auswirkungen des Erdbebens besteht auch die Gefahr des Entgleisens fahrender Schienenfahrzeuge. Schienenfahrzeuge verursachen während der Fahrt auch bestimmte Vibrationsniveaus, und diese Arbeit enthält eine Analyse der nachträglichen Auswirkungen von Vibrationen des Schienenverkehrs auf Gebäude, die durch das Erdbeben am 22. März 2020 in der Stadt Zagreb beschädigt wurden.

Schlüsselwörter:
Erdbeben, Schieneninfrastruktur, Schäden, Verkehrssicherheit, Vibration, Straßenbahn

1. Introduction

Earthquake engineering is an interdisciplinary area aimed at designing and analysing structures that are capable of responding to destructive seismic action. The primary focus of earthquake engineering is on high-rise structures, but no lesser significance is given to infrastructure facilities which must also be designed to withstand seismic action when located in seismically active areas. Rail infrastructure is characterised by a very high precision in construction process and small tolerances, which alone shows how important it is to identify earthquake-caused displacements and deformations that may prove harmful to the trains in motion. Due to railway track geometry limitations, longitudinal grade in particular, rail track is very often constructed on viaducts or bridges that form an integral part of rail infrastructure, and that also must be resistant to destructive earthquake action, so that rail traffic can promptly resume after an earthquake event.

If we observe rail system as a source of vibrations, then we also have to consider its influence on the surrounding structures, especially those that have already been damaged as a result of seismic action. In effect, rail infrastructure in interaction with oftentimes very heavy rail vehicles generates vibrations that can cause, unless properly controlled, the effect that can be similar to a lower-intensity earthquake. That is why it is necessary to analyse the condition of rail infrastructure and its capacity to absorb vibrations and transfer them to the surrounding structures and facilities.

1.1. Earthquake effect on railway infrastructure

Registered frequencies of seismic waves range from 0.1 to 30 Hz, with waves of higher frequency having greater acceleration but relatively small amplitudes, while lower-frequency waves have smaller acceleration, but greater amplitudes [1]. In railway traffic, vibrations caused by seismic waves can cause derailment, damage to track structure, soil liquefaction, and landslides. Rail transport ranks among the most significant infrastructure segments in all countries, which is why it is highly important to keep it vital and functional. It must be fast, safe, comfortable and resilient in any weather conditions, and also in the case of natural disasters. Considering that safe operation of rail traffic is primarily dependent on geometrical properties of track, such as track gauge and superelevation, it of utmost importance to maintain the initial track geometry even after big natural disasters such as earthquakes [2]. Damage that will occur on a railway structure due to seismic action is directly related to the peak ground acceleration. As the response to seismic activity and damage mechanism greatly vary in rail infrastructure components (embankments, tracks, bridges, stations), the level of damage will also differ to a great extent [3]. The sensitivity of railway track is directly related to the properties of soil on which the track lies [3]. When considering seismic action, embankments present a much greater danger compared to cuttings and, in such case, the embankment slope stability is the most significant parameter [4]. Natural frequency of railway embankments varies from 1 to 10 Hz. If compared with the earthquake frequency that can vary between 0.1 and 10 Hz, depending on an earthquake, it can be seen that the propagation of seismic waves through or around rail embankments can cause embankment resonance, which will in turn result in embankment displacement [4]. In addition, soil liquefaction very frequently occurs on road or railway embankments as a result of seismic action. Liquefaction in foundation layers can cause damage to all structures situated above that level, and rail tracks are highly sensitive to such damage [5]. In the case of rail embankments, horizontal displacement of soil must not exceed 5 cm as track surface deformations occur in case of greater displacements [6]. Figure 1 shows examples of track displacement after settlement of railway embankment caused by the 2011 Tohoku Earthquake in Japan.

The longitudinal track buckling increases with an increase in ground acceleration. When the acceleration is equal to 2 m/s^2, longitudinal buckling amounts to 0.07 mm. This increase is linear and the maximum value is attained at 10 m/s^2, when the buckling amounts to 0,35 mm. It can be seen that longitudinal buckling is negligible and that it does not cause any train operation problems. Lateral buckling also increases with an increase in acceleration. When the acceleration is 2 m/s^2, lateral buckling amounts to 20.35 mm, and at 10 m/s^2 lateral buckling is 101.80 mm. Ultimate value of lateral buckling is attained when ground acceleration is 4 m/s^2, when it amounts to 40.70 mm. At that point the operation of train traffic is no longer possible [2].

The influence of seismic load on the ballast bed was tested in [8, 9] using a shaking table. The shape of ballast bed at a frequency of 1 Hz, for accelerations ranging from 5 to 8 m/s^2, is shown in Figure 2. At an acceleration of 5 m/s^2 the shaking table, sleepers, and ballast bed vibrated together, which is why no change was registered on the ballast bed. At 6 m/s^2, some changes were observed at the ballast bed banks and slopes. At accelerations of 7 and 8 m/s^2, significant changes were noted between the vibration of sleepers and ballast bed, with significant damage to ballast bed at the slope and banks. The lateral resistance of ballast bed reduces with an increase in maximum acceleration. At an acceleration of 8 m/s^2, the lateral resistance was reduced

Figure 1. Example of embankment damage after earthquake event and reconstruction of the same embankment [7]

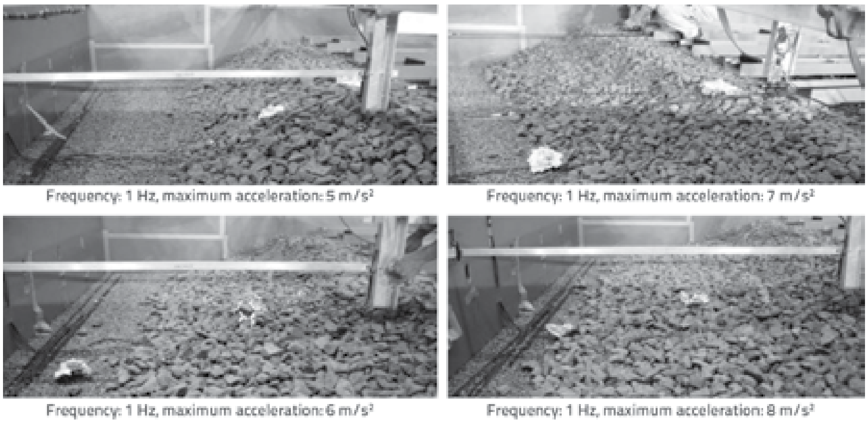

Figure 2. Damage to ballast bed at various acceleration values [8]

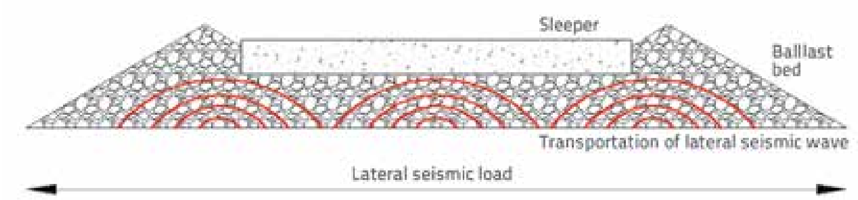

Figure 3. Propagation of lateral seismic wave through ballast bed during earthquake [10]

Table 1. Contact forces at various sleeper displacement values [10]

Sleeper displacement [mm]	**Before earthquake** [N]		**After earthquake** [N]	
	Maximum	**Average**	**Maximum**	**Average**
1	654.4	13.5	429.8	10.1
2	696.1	14.1	441.8	10.3
3	715.1	14.5	460.5	10.4
4	785.3	14.7	475.6	10.4
5	870.4	14.8	512.6	10.5
6	815.6	15.1	535.3	10.5
7	811	15.5	575.3	10.7
8	992.9	15.7	603.9	10.9
9	955	15.8	673.6	11.2
10	1010	16.1	785.3	11.4

by 15 %, while no reduction was noted at accelerations of up to 7 m/s^2. It was observed that there is no significant difference in the tendency of the ballast bed lateral resistance reduction at difference frequencies. In the light of the above findings, it can be concluded that the shape of ballast bed and lateral resistance depend only slightly on the frequencies ranging from 1 to 10 Hz. At usual earthquake strengths, damage to ballast bed occurs at an acceleration of 6 m/s^2 or more, and lateral resistance begins to reduce at an acceleration of 7.5 m/s^2.

In their paper [10], Qing Jing et al. used the discrete element method to simulate the influence of earthquake action on sleepers and ballast bed. Figure 3 shows propagation of seismic waves through the ballast bed during the earthquake. A displacement and redistribution of ballast bed material occurs during the earthquake, which results in a weak contact between material particles and in the change of force chain. The maximum and average contact force also reduces, which is why the well compacted ballast bed becomes loose. In addition, the change in force chain occurs in the ballast bed banks, which is accompanied by sliding of the ballast bed material, and relative displacements between sleepers and ballast bed particles. As banks are extremely significant for maintaining proper stability of the track, it is very important to bring ballast bed to an appropriate condition after a seismic event [10]. Changes occur at the contact between the ballast bed material and sleepers.

The friction between ballast bed particles is a very significant parameter when considering lateral resistance of sleepers, and vibration effects. It has been established that reduction in lateral resistance also compromises track stability in the case of ballast bed particles that are not angular and that have a smaller friction coefficient, because lateral resistance values are below limit values specified in standards [10].

The effect the earthquake load has on the track, that is on the ballast bed, at straight parts of the track and in curves, is analysed in [11]. After the seismic load was applied, the lateral resistance force was reduced in both samples – in the case of straight track the resistance was reduced by 37 % and amounted to 5.3 kN for 2 mm sleeper displacement, while in the case of track in curve the resistance was reduced by 24 % and it amounted to 6.2 kN. When the sleeper displacement exceeded 4 mm, there was no difference in the lateral resistance force between the two samples [11].

The influence of various values of peak ground acceleration on rails and sleepers is analysed in [2]. Seismic action has a considerable effect on axial forces of rails, which increase with an increase in the peak acceleration value. However, even the greatest force values are smaller than the allowable ones for the 60 E1 rail. Shear force values increase with an increase in peak acceleration values. Even in the case of greatest values, the force still does not exceed the maximum force of 200 kN for the 60 E1 rail [1]. In addition, the bending moment of rail also increases with an increase in acceleration value, but maximum moments are still lower than the allowable 120 kNm for the mentioned rail type [2]. In the case of rails, the greatest danger is the generation of huge axial forces during earthquake action.

Buckling is one of the most frequent problems that occur during earthquakes, as it impairs functionality of the railway track. If axial forces exceed critical rail forces, buckling will cause changes in track geometry and deviations from its initial position. The critical force can be calculated using the following expression [2]:

$$P_{cr} = \frac{\pi^2 \cdot E \cdot I}{l_e^2}$$

where:

P_{cr} – critical force of rail

E – elastic modulus of rail

I – moment of inertia of rail

L_e – rail buckling length which depends on geometrical properties and rail quality.

Figure 4 shows the relationship between critical rail forces as related to various buckling lengths, and for various rail types (50 E1, 54 E1, 60 E1). It can be seen that, if the buckling is less than 3 m in length, axial forces caused by seismic activity are less pronounced compared to critical forces, even at peak ground acceleration (PGA) of 10 m/s^2 (1000 gal), and so buckling will not occur. This buckling length value is applicable in track structures with properly tightened rail fastening, and with high lateral resistance. In addition, the buckling length can be limited via the distance between individual sleepers. In case the buckling length exceeds 9 m, rail buckling will occur even at the peak acceleration value of 2m/s^2. This is the case in tracks with weak rail fastening and with low lateral resistance. For rails where the buckling length varies between 3 and 9 m, buckling length will depend on the rail type and peak acceleration.

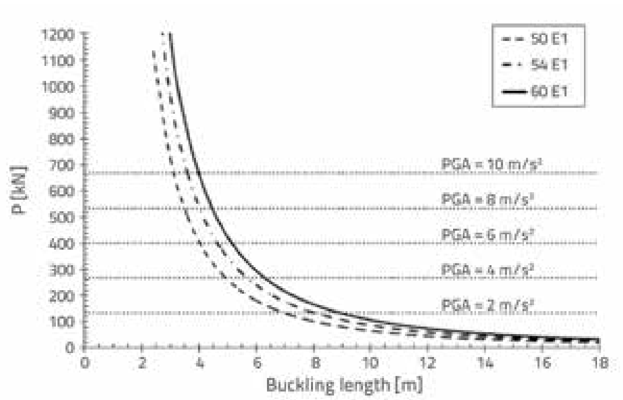

Figure 4. Critical forces in rail as related to buckling length for various PGA values and rail types [2]

Shear force in sleepers increases with an increase in acceleration, and so a maximum value is 60 kN for an acceleration of 10 m/s^2. However, the force value is lower than the maximum allowable one which amounting to 150 kN. In addition, bending moment increases with an increase in acceleration, but even the greatest moment exhibited at an acceleration of 10 m/s^2, amounting to 45 kNm, is lower than the maximum allowable moment of 200 kNm. These values show that sleepers will suffer no structural damage regardless of the strength of seismic activity [2].

In the case of small-magnitude earthquakes, safety-signalling devices will exhibit small damage that can easily be remedied. However, safety-signalling devices can break down as a result of greater-magnitude earthquake events [12]. Thus, safety-signalling devices suffered severe damage during the Gujarat Earthquake, which is why railway turnouts (points) had to be operated manually, while train speeds had to be reduced considerably [13]. Earthquakes can also cause tilting or breaking of overhead contact line poles, and even full power supply breakdown via the top line, as was the case during a large scale earthquake that hit Japan in 2011 [14].

Signalling equipment will suffer considerable damage during earthquake events. Thus, damage to signalling cables and relays was registered in several earthquakes in Japan. In addition, ground deformations cause tilting of telecommunication poles and detachment of cables, while damage to rectifier stations and related equipment can result in electric power breakdown [15].

1.2. Seismic effects on metro tunnel tube

It was established during analysis of ground acceleration effects on a tunnel, as conducted in [16], that great damage to tunnels occurs very rarely, i.e. only in extreme conditions, and that no damage will occur when ground acceleration is lower than 1.86 m/s^2 and/or if the speed is lower than 0.2 m/s. Negligible to moderate damage occurs in the case of accelerations of up to 4.9 m/s2 and at speeds of up to 0.9 m/s. Moderate to heavy damage has been registered in accelerations exceeding 4.9 m/s^2. Singh M. et al. analysed in [17] the effect an earthquake with the magnitude of 6.8 degrees on the Richter scale and 3.53 m/s^2 ground acceleration will have on the metro tunnel 6.26 m in diameter situated 16.87 m below the ground level. It was established that the acceleration values induced at ground surface are greater than accelerations registered at the tunnel (Figure 5), which means that tunnels are much safer that structures located at the ground level [17, 18].

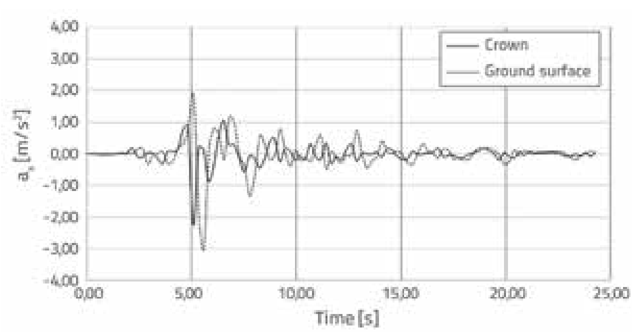

Figure 5. Horizontal accelerations at ground surface and at tunnel crest [17]

In effect, the ground surrounding an underground structure acts as a vibration damper of a sort. The change in acceleration with ground depth is shown in Figure 6. It can clearly be seen that horizontal acceleration increases with the reduction in ground depth. Figure 7 shows that shear force and bending moment change with the change in the tunnel depth to tunnel diameter ratio.

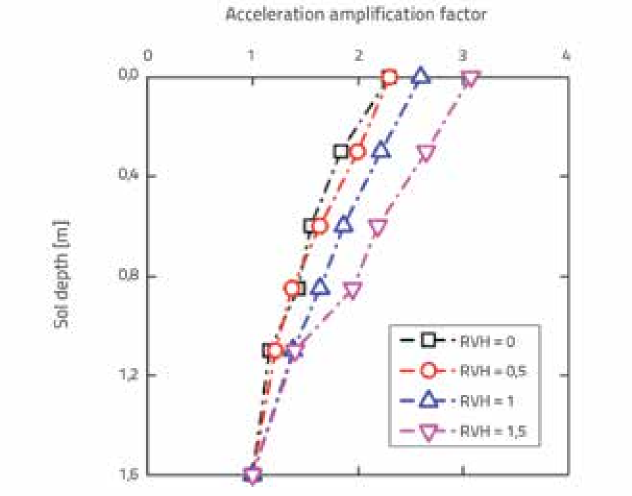

Figure 6. Acceleration amplification factor at various ratios of vertical to horizontal peak ground acceleration (RVH) [19]

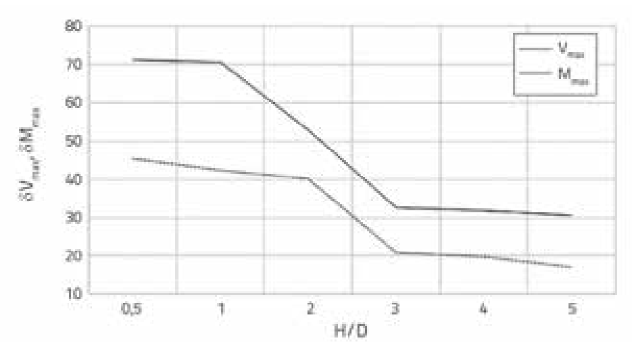

Figure 7. Effect of tunnel depth to tunnel diameter ratio on shear force and bending moment [17]

According to [18], damage to buried structures reduces with an increase in depth, while buried structures in soil material suffer greater damage compared to such structures in solid rock. Particular significance must also be given to duration of very strong earthquake vibrations, as this can result in fatigue-induced failure and considerable deformations.

Various studies have shown that seismic response of tunnel tubes is dependent not only on tunnel properties but also on the response of surrounding soil. According to [18] and [20], the following three types of deformation characterize the response of buried structure to seismic activity (Figure 8): axial compression and extension, longitudinal bending, and shear. Axial deformations occur in tunnels due to the seismic wave component that generates motion parallel to tunnel axis and causes alternating compression and extension. Bending deformations are caused by the seismic wave component that causes motion of particles perpendicular to the longitudinal axis of the tunnel. Shear deformations occur when shear waves propagate toward the tunnel axis and cause distortion of the tunnel tube cross section.

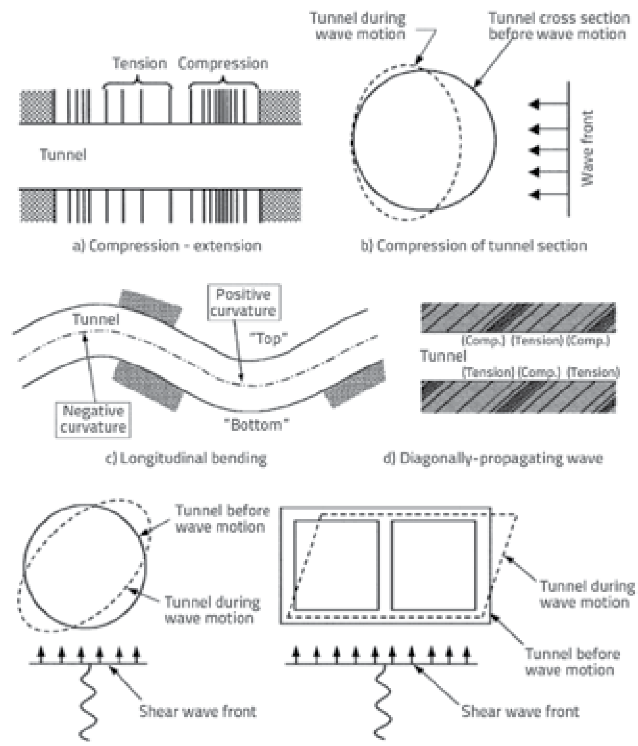

Figure 8. Examples of tunnel deformation due to seismic action [18]

The Taiwan Metro has issued instructions about the way users should react depending on earthquake magnitude [21]. If an earthquake is less than 2 in magnitude on Richter scale and if no damage is observed, the traffic can be operated as usual. If an earthquake varies between 2 and 3 in magnitude, the traffic will be operated at a speed of 40 km/h, until final inspection of track is completed. In case of earthquakes varying between 4 and 5 in magnitude, with ground accelerations of less than 1 m/s^2, the vehicle will operate at reduced speed until the first station where passengers will be evacuated. In case of earthquakes of more than 5 m/s^2 in magnitude, with ground accelerations greater than 1 m/s^2, the train crew will get off the train and inspect track condition, after which the train will be operated at a very low speed until reaching the next station where passengers will be evacuated. After that, the train service will be suspended and will resume only after the entire network has been checked.

2. Effect of rail vehicle vibration on earthquake-damaged buildings

2.1. Propagation of vibrations from track to surrounding buildings

Although vibration amplitudes generated by traffic are very low, they can still be harmful to historic masonry buildings due to great number of cyclic loads. As masonry buildings are not resistant to tensile stress, these vibrations result in damage to plaster and in the detachment of masonry elements, which can gradually lead to decreased resistance of the entire structure. Structures exhibiting

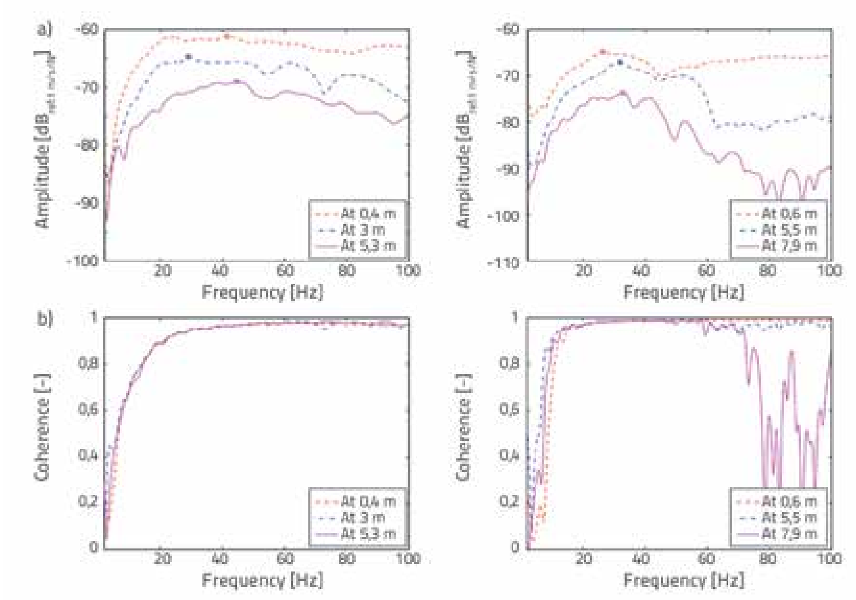

Figure 10. Functions of mobility of transfer, frequency and coherence: a) track with ballast bed, b) track on solid base [26]

the problem of settlement, either at the level of their foundations or the entire structure, which were exposed to earthquake vibrations, are extremely vulnerable if they are subsequently also exposed to traffic-related vibrations [22]. It is stated in [23] that vibrations caused by traffic do not result in visible damage at the wall level, but they do cause widening of cracks on the already damaged walls. These vibrations cause invisible changes in the walls of the buildings, such as the microscopic crumbling of plaster and subsequent softening and disintegration of walls, resulting in changes of dynamic properties of such walls, and in compressive and lateral deformations. It has also been established that visible changes of wall characteristics occur after structures have been exposed to several tens of thousands of vibration cycles, which shows that the amplitude and duration of vibrations is a very significant parameter [23]. As a result of microcracks in plaster and disintegration of walls, the vibrations generated by traffic cause reduced ductility, which in turn reduces energy dissipation capacity and may lead to reduced seismic resistance of buildings [23].

Some loss of vibration energy occurs during transport of vibrations from the source through the surrounding soil, and to the final recipient (building foundations). At that, as vibrations pass through sleepers their value is reduced to 90 % of their initial value. However, as waves propagate through the soil, their reduction is much slower, and it increases with the distance, so that vibrations at the recipient can be reduced by 2 to 15 dB [24, 25]. Reduction of vibrations with an increase in distance is shown in Figure 9.

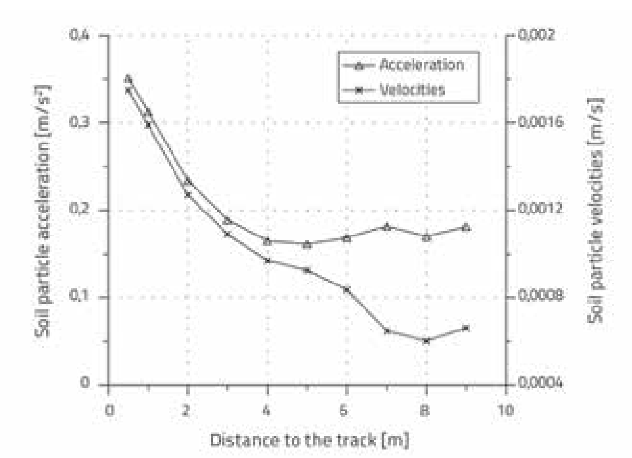

Figure 9. Reduction of vibrations with an increase of distance from track [25]

Vibrations caused by the passage of a rail vehicle are measured in [26] at various distances from the track. At that, one sensor was placed on the track, and the other at the foundations of a building. The testing campaign was conducted at several locations on tracks with ballast bed, and on tracks resting on solid base. The analysis of results has revealed that the level of vibrations from the source to the recipient reduced by almost 10 dB. At that, tracks on solid base exhibited better results compared to the traditional track structure with ballast bed. The particle velocity analysis has shown that the speed reduces with the distance at almost all measuring points, Figure 10.

2.2. Propagation of vibrations across several floors of a building

The spread of vibrations from foundations to the structure causes the trembling of walls, ceilings and floors. The quantity of vibrations to be passed on to the building will depend on the connection between the soil and the foundations of the building. The vibration level reduces precisely when the waves leave the soil and enter the building foundations. Vibrations of a foundation slab that is fully in contact with soil will be similar to soil vibrations. In this case, the loss at the connection between the soil and foundations will be 0 dB for the frequencies that are lower than the resonant frequencies of the slab. The loss at the connection between the soil and foundations will also amount to 0 dB for lightweight structures, as well as for structures resting on a stone support. Depending on the frequency and type of foundations, the loss at the connection will vary from 2 to 15 dB [27].

A numerical simulation of vibrations at foundation slabs and at individual floors of buildings was conducted in [25]. At the foundation slab, vibrations were analysed at four measuring points. The values obtained during this measurement are presented in Figure 11. It can be seen that horizontal vibrations are almost equal at all measurements positions, while vertical vibrations at edges assume much greater values. Only small vibration frequencies are passed on to building foundations [28].

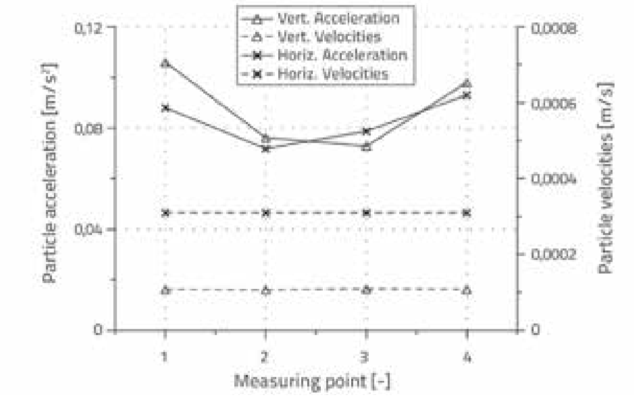

Figure 11. Vertical and horizontal maximum accelerations and velocities at four measuring points on the foundation slab [25]

Horizontal velocity of particles increases significantly by propagation of vibrations toward the top of the structure, while vertical velocity and horizontal and vertical accelerations remain almost constant (Figure 12) [25].

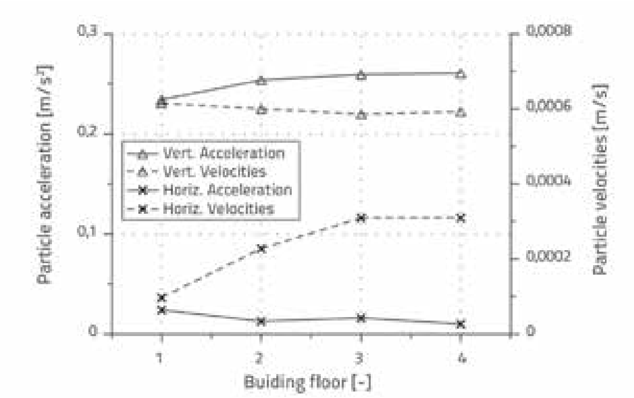

Figure 12. Vertical and horizontal maximum velocities and accelerations of vibrations at individual floors of buildings [25]

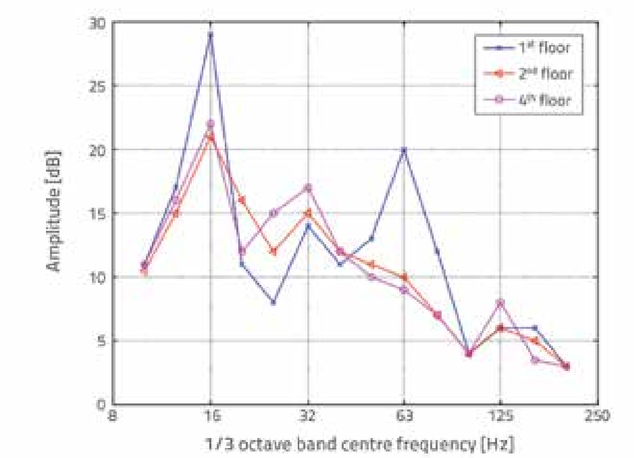

Figure 13. Function of vibration transfer during passage of a rail vehicle [26]

Tram traffic vibrations on building floors are analysed in [26]. The corresponding results are presented in Figure 13. It can be noticed that the typical building resonance amounted to 16 Hz for all floors, while it amounted to 63 Hz for the first floor. In addition, the vibration level reduces considerably at frequencies greater than 63 Hz.

Greatest building damage caused by human factor ranges from 1 Hz to 150 Hz in frequency, while for natural disasters, such as earthquakes, this damage varies from 0.1 Hz to 30 Hz. According to the prevailing European standard relating to the measurement and estimation of the effect of vibrations on structures, the following values are suggested for vibrations caused by traffic: frequencies range from 1 to 100 Hz, amplitude ranges from 1 to 200 µm, vibration velocity varies from 0.2 to 50 mm/s, while acceleration varies from 0.02 to 1 m/s² [29]. More specifically, vibration velocity levels presented in Table 2 can be expected from rail traffic.

Table 2. Vibration amplitudes caused by rail traffic at the level of building foundations [29]

Frequency range [Hz]	**Amplitude** [mm/s]	**Distance between track and facade**
35	1.5 - 2.0	10 - 20 m
8 - 50	2.0 - 3.0	
60	2.0	
10	0.5	
51	1.9	
20	2.2	
90 -110	2.5	

It was established in [27] that the range of frequencies registered on structures during passage of vehicles varies from 10 to 250 Hz: Peak vibrations were noted at frequencies varying from 20 to 40 Hz. According to [30], the worst damage will affect the buildings that are situated less than 7 m away from the track axis, while the effect on buildings will be negligible at distances greater than 25 meters [24]. According to current research in this area, the probability is very small that vibrations lower than 50 mm/s will create structural damage to the structure, while almost no damage is expected to occur at vibrations lower than 25 mm/s. However, a stricter criterion is used when dealing with historic and old buildings [28].

The effect vibrations have on a building situated near railway tracks is analysed in [31]. The building was built in 1936, it has three floors, and the walls are made of brick. Vibrations were measured in three vertical dimensions at the source and at the building, and here separately on load bearing walls (Figure 14a) and separately at floor structures (Figure 14b). It was established that the velocity of particles reduces from 1 - 1.5 mm/s at the railway tracks, to below 0.5 mm/s at the basement of the building. In addition, vertical components of vibrations are greater at floor structures compared to load bearing walls. Maximum vibrations were observed at the floor structure of the first floor where they amounted to 2.41 mm/s, and were 1.6 times greater compared to those on load bearing walls.

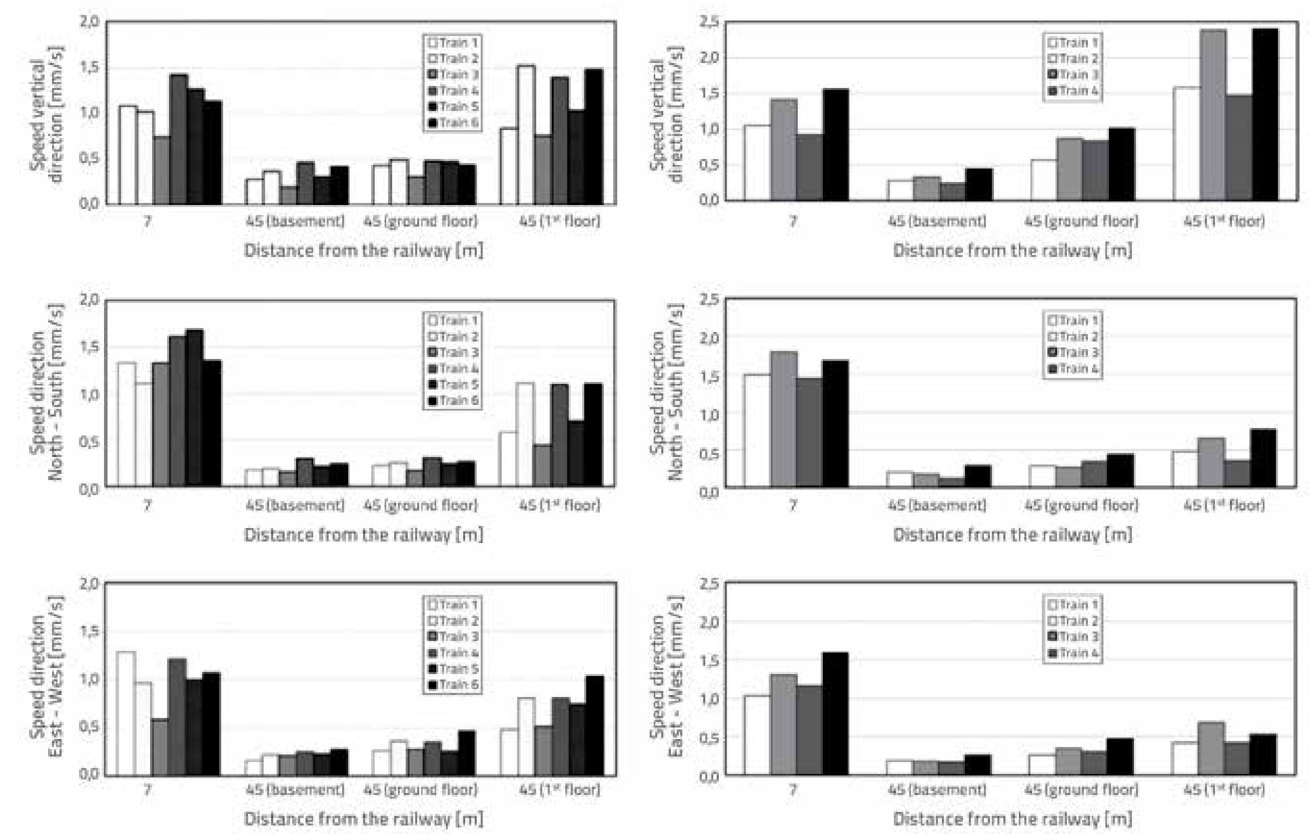

Figure 14. Transfer of vibrations from track to building a) measured at source and at load bearing walls of the building, b) measured at source and at floor structures [31]

According to DIN 1999, maximum vibrations at which historic or sensitive buildings will suffer no damage amount to 2.5 mm/s.
It has been established that the frequencies that cause vibration of rail vehicles range from 5 to 40 Hz, and that frequent passing of trains imposes cyclic load on buildings, which can result in fatigue of a structural element of the building, particularly when we take into account very low tensile or compressive strength of masonry buildings. It has been demonstrated that vibrations generated by a rail vehicle can cause damage to historic and sensitive buildings [31]. Maximum allowable velocities of impulsive vibrations at the level of building foundations are shown in Table 3 [32].

Table 3. Maximum allowable velocities of impulse vibrations (in mm/s) at ground floors of buildings (NP2074:1983) [32]

Construction	Foundation soil		
	Loose incoherent or soft coherent soils (c < 1000 m/s)	Compact incoherent or hard coherent soils (1000 m/s < c < 2000 m/s)	Very hard coherent soils (c > 2000 m/s)
Sensitive buildings	1.75 – 2.5	3,5 – 5	7 – 10
Current buildings	3.5 – 5	7 – 10	14 – 20
Reinforced – concrete buildings	10.5 – 12.5	21 – 30	42 – 60

Table 4. Proposed limit values for effective velocities of continuous vibrations [32]

Type of construction	Duration of vibrations	
	< 1 hour/day	> 1 hour/day
Sensitive (monuments and other historical buildings, hospitals, old houses, water reservoirs, masonry chimneys, etc.)	1	0.7
Current (buildings with sound masonry structure, older industrial buildings, etc.)	2	1.8
Reinforced (concrete reinforced buildings recent industrial buildings, etc.)	5	5

Table 5. Limit values for vibration velocity in mm/s according to DIN 4150 and UNI 9916 for sensitive buildings [32]

	From 1 to 10 Hz	From 10 to 50 Hz	> 50 Hz	Global
Structural damage induced by short duration vibration	3[a]	3 (10 Hz) to 8 (50 Hz)[a]	8 (50 Hz) to 10 (100 Hz and moree)[a]	8[b]
Structural damage induced by permanent vibration	-	-	-	2,5[c]

[a] foundations, [b] high points, [c] all structure

In the case of continuous vibrations, the proposed maximum vibration values depend on the type of structure (as shown in Table 4). Maximum vibration values proposed by DIN 4150 te UNI 9916 for sensitive buildings are shown in Table 5.

3. Analysis of post-earthquake tram system in the City of Zagreb

Numerous multistorey masonry buildings situated in the wider urban area of the city of Zagreb, and especially those located in the old town core, suffered significant damage in the destructive Richter 5.5 earthquake that hit this city on 22 March 2020. Earthquake engineering experts have been predicting such seismic event and warning general public on state and vulnerability of masonry buildings in that exact area [33]. Highly significant feature of the old town core is that it is integrated into the public urban transport system via a tram network that uses two routes in the east-west direction: from Črnomerec to Dubrava (along Ilica, Jurišićeva, Vlaška and Maksimirska streets), and from West Railway Station (Zapadni kolodvor) to Borongaj (along Jukićeva, Vodnikova, Branimirova, Mislavova and Zvonimirova streets), including appropriate north-south links: Savska and Frankopanska streets, Praška street, Draškovićeva street (link from Mihaljevac and Dolje) and Šubićeva street, Figure 15. This view of the tram network clearly shows that tram passes through the very town core, using narrow streets, and that it is very close to the surrounding buildings.

The above figure shows that the tram network passing through the central part of the city traverses the area with a considerable number of permanently unusable (red) and temporarily unusable (yellow) buildings. Immediately after the earthquake, activities aimed at estimating seismic damage to tram infrastructure were initiated, including the analysis of influence the tram traffic resumption will have on earthquake-damaged buildings. Primary activities for earthquake-damaged critical infrastructure requiring a more detailed verification included identification of overhead line anchoring points situated at building facades in the central part of Zagreb, and identification of tram tracks whose condition will directly affect propagation of vibration onto the neighbouring earthquake-damaged buildings. In addition, preliminary inspections were made immediately after the earthquake to identify damage to buildings caused by earthquake action either directly (damage to buildings and plants) and indirectly, due to fall of material form damaged buildings onto the rail infrastructure (contact lines and tram track).

3.1. Analysis of overhead line anchor points at facades of earthquake-damaged buildings

Power supply to tram vehicles used in the city of Zagreb is ensured via a direct current contact-lines system operating at 700 V. The contact conductor is positioned at the height of 4.5 to 5.5 m from

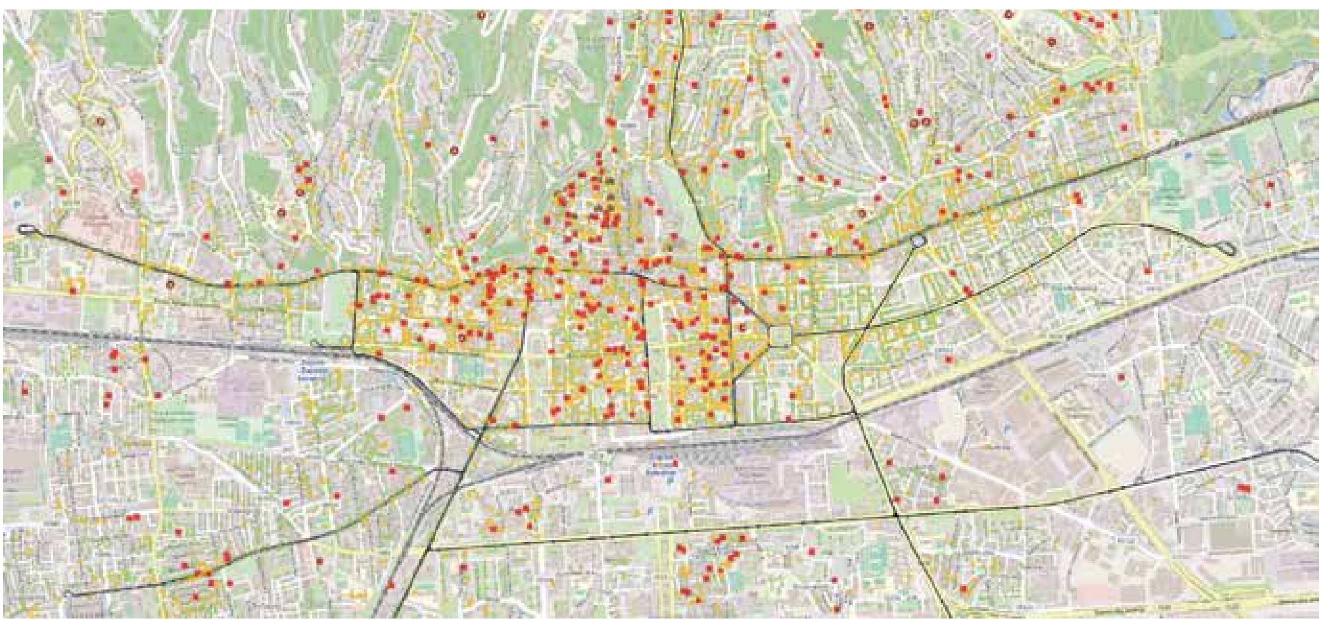

Figure 15. Tram network and earthquake damage to buildings based on initial inspection

Slika 16. Overhead line anchor points: a) Decorative rosette, b) Plate with four anchoring screws, c) Hook on anchoring screw, d) Connection of several ties on a single fastening point

the top edge of the rail, and +/- 30 cm transversely to the track axis. The contact conductor's position is secured with the overhead line suspension system, which is constructed in Zagreb in two ways: by suspension to overhead line poles (in approximately 75 % of all cases) and by suspension to building facades (in approximately 25 % of cases) [34]. In the current post-earthquake situation, the anchor points at building facades are the most delicate group of overhead line suspension system, and this for several reasons:

- these anchor points are old (some were installed more than fifty years ago),
- they are installed at building facades of questionable strength and wall condition,
- damage to walls during the earthquake
- damage to overhead line system during the earthquake (due to fall of rubble from roofs).

Based on the request to check condition of the overhead lines to ensure safe resumption of tram traffic, the Faculty of Civil Engineering of the University of Zagreb is checking condition of overhead line anchoring points to building facades. Following inspection of the database developed in the scope of the *Study of Tram Traffic in the City of Zagreb, Report II* [34], it was determined that there are currently 912 overhead line anchoring points on building facades. There are three basic types of anchoring these connections to building facades:

- Decorative rosettes (of vertical and horizontal orientation) are fixed to the facade using four tapered self-tightening screws (Figure 16.a).
- Plate connectors – anchored with four tapered self-tightening screws onto plate that has a link for ties (Figure 16.b).
- Hooks (of longer and shorter design) – fixed to the facade with one conical self-tightening pin (Figure 16.c).
- Sometimes several ties are installed at individual anchoring points, especially at tram intersections (Figure 16.d).

Reasons for deterioration of overhead line anchor points can be classified as follows:

- Fall of material from the roof, or damage by tower crane during building repair operations. At such sites, the damage included pulling out or breaking of overhead lines, ties, rosettes, etc. In such cases, it is important to check all neighbouring anchoring points that did not suffer direct damage from detachment and fall of material from the roof, but were very likely subjected to loads exceeding by far nominal loads that could be expected in normal operation.
- Loss of mechanical resistance and stability of walls due to seismic action. Cracked places on facades, places with significant wall damage where detachment or pull-out of pins and rosettes is probable.

Two levels of inspection are planned for the inspection of overhead contact line connections: Level 1 – Visual inspection of the contact line connection point. Level 2 – inspection of potentially unsafe contact line anchoring points. Potentially unsafe contact line connection points (Figure 17) were determined by visual inspection and this information was entered in the GIS database.

Figure 17. Example of a potentially unsafe anchor point

In the scope of the Level 2 Inspection, potentially unsafe connection points were subjected to a simple tensile test which involves controlled application of load via a pulley system by applying a force of approximately 500 N to the anchoring point in the direction of the longitudinal tie, Figure 18. Elements of the load application and measurement equipment are attached to the longitudinal tie insulator where a load cell is used for continuous load measurement.

Figure 18. Force measurement and readout system

After inspection of all contact line connections anchored to building facades, appropriate recommendations were issued for the repair of inadequate anchor points in order to restore their stability and ensure an undisturbed and safe operation of tram traffic.

3.2. nfluence of tram traffic on earthquake-damaged buildings

Considering the character of tram traffic, and irregularities along the tram track, tram vehicles may cause high levels of vibrations that spread to the surrounding area and, in central parts of cities, to the buildings situated in the immediate vicinity of the tram track. According to [30], worst damage will affect buildings situate less than seven m away from the track axis, while the influence on buildings is negligible for distances greater than 25 meters [24]. The analysis of tram traffic in the wider centre of the city shows that 35 % of tracks are situated less than 7 meters away from building facades, 38 % of tracks are at 7-15 m from the facades, and 12 % of tracks are more than 15-25 m away from the facades, with 15 % of tracks situated at more than 25 m away from building facades. Considering the vicinity of the source of vibrations, it is possible to define risk zones where possible tram traffic vibrations might affect earthquake-damaged buildings. An example of such analysis can be seen in Figure 22, where tram corridors with greater or smaller risk of the impact of vibrations on damaged buildings are presented based on the level of building damage according to the rapid estimate of the Emergency

Table 6. Assessment of tram track vibration risk and its impact on earthquake-damaged buildings

Risk assessment	Level of building damage	Distance from track axis
Rating 1	N (unusable)	< 7 m, 7 – 15 m, 15-25 m
Rating 2	N (unusable)	> 25 m
Rating 3	PN (temporarily unusable)	< 7 m, 7-15 m
Rating 4	PN (temporarily unusable)	15-25 m, > 25 m
Rating 5	U (usable)	< 7 m, 7-15 m, 15-25 m, >25 m

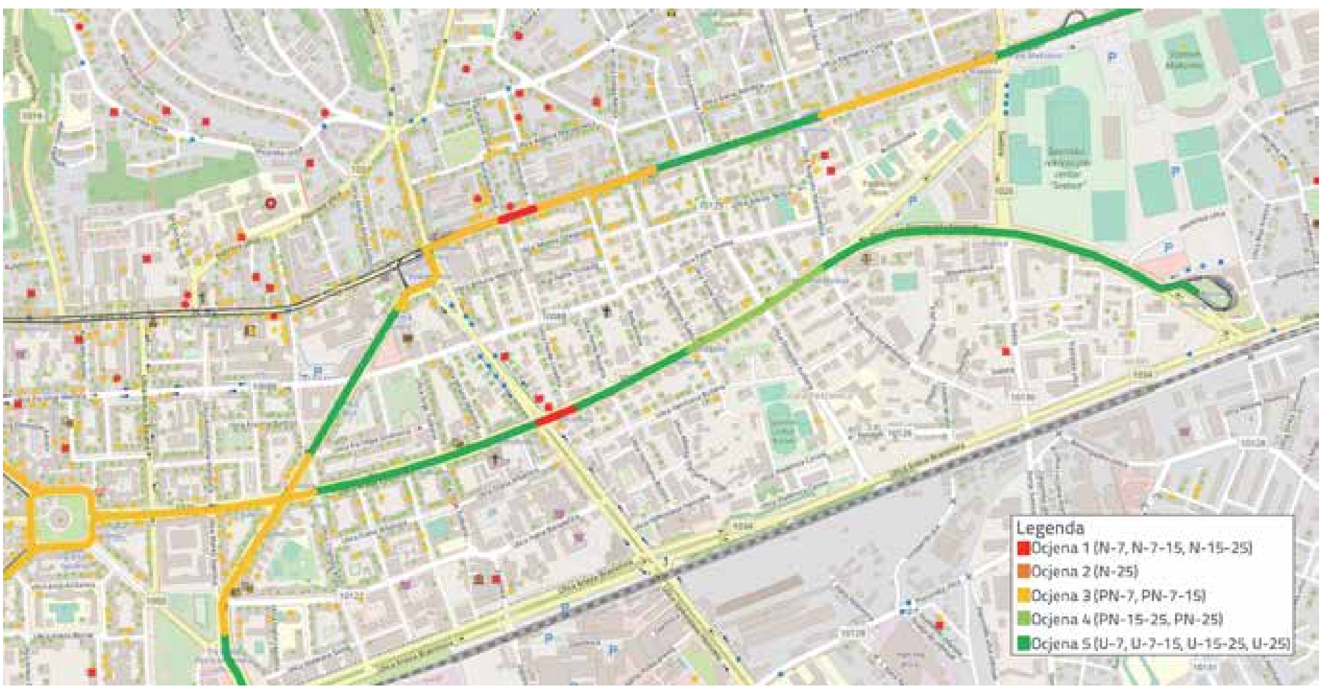

Figure 19. Analysis of tram network with regard to track distance and building damage by earthquake

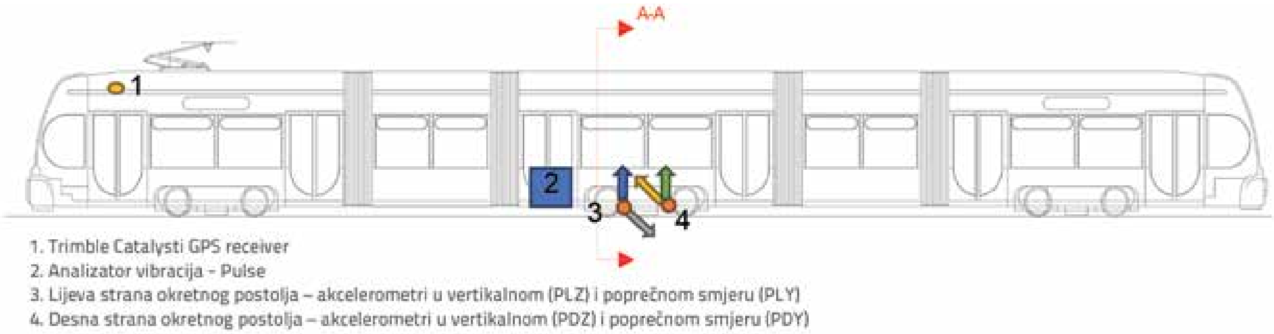

Figure 20. Accelerometer positions on TMK 2200 tram

Management Office of the City of Zagreb, and also based on the distance between the track axis and building facades (cf. Table 6). The analysis of the impact of tram traffic vibrations on earthquake-damaged buildings is a very complex engineering task as it necessitates an interdisciplinary approach involving a number of experts (structural engineers, designers, geotechnical engineers, experts for track structures, and vibration analysis experts) tasked with determining the influence of a relatively small excitation (vibrations generated by passage of a tram vehicle) of repetitive character (in some instances, the frequency of tram vehicle passage amounts to more than sixty vehicles per hour) on earthquake-damaged buildings. It can generally be assumed that vibration levels generated by rail vehicles will not cause damage to load bearing elements of buildings. However, without appropriate repair, some building elements (such as chimneys, gable walls, ornaments, cornices, etc.) that have suffered considerable earthquake damage could be additionally damaged through a relatively small excitation generated by rail vehicles, and thus these elements could put in jeopardy safety of local residents and other citizens. Furthermore, as indicated in [23], long-term exposure to traffic vibrations may lead to the crumbling of plaster, disintegration of walls, and to widening of cracks initially generated by earthquake action.

For that reason, decision was made to initiate a more detailed analysis of vibrations caused by operation of tram vehicles, and of their influence on earthquake-damaged buildings. These activities are divided in two groups: determination of vibrations at the source – tram track, and determination of the influence of vibrations on typical buildings.

3.2.1. Analysis of tram track vibrations during passage of tram vehicles

Tram vehicle vibrations are measured during movement of tram along the analysed tram track sections. This kind of test provides a detailed insight into the dynamics of tram vehicle movement along the existing track infrastructure, points to irregularities along the tram track, while also providing information on the tram operation safety and riding comfort [35]. At all sections, the measurements were conducted immediately before resumption of traffic (which was suspended due to COVID-19 epidemic and later on because of earthquake effects). The tram vehicle type TMK 2200 was used in the measurement. To make comparison with vibration levels registered on tram tracks prior to earthquake (in the scope of the *Study of Tram Traffic Development in the City of Zagreb, Report I* [36]) it was necessary to repeat a similar test and to position the vibration measuring equipment in a similar way, Figure 20. Therefore, the measurement setup similar to that described in the Study was used in this test. Laptop computer and multichannel vibration analyser were placed in the passenger area near the second (central) pivoting bogie, and four accelerometers were installed at the central pivoting bogie of the vehicle. At the pivoting bogie of the vehicle, two uniaxial accelerometers were placed near the left front wheel, and two accelerometers were placed near the right back wheel, Figure 21. The positions were choses in such a way to enable analysis of the effect of irregularity at the left-side and right-side rails, and rail weld. In addition to the vibration collection system, an accurate GPS receiver, placed at the top of the vehicle, was used for data georeferencing, while a high-resolution video camera, placed at the operator's cab, was used for visual inspection and coordination of signals. According to [35], vibration-related data obtained by means of tram vehicles equipped with measuring devices can be used for detecting deficiencies on the track structure (weld, rail corrugation, rail cracks, track geometry), which may have an unfavourable influence on the surrounding buildings.

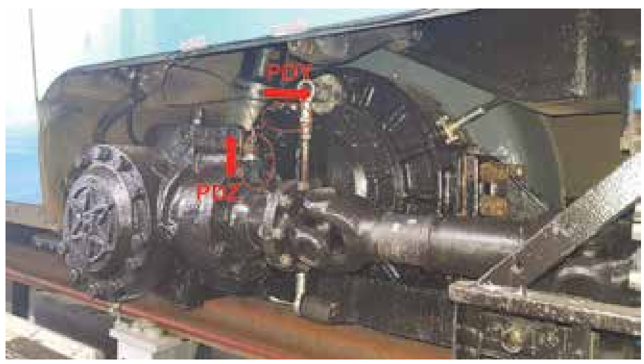

Figure 21. Accelerometer position on bogie during measurements

Measured vibrations were analysed in the frequency range from 0.5 Hz to 3000 Hz. The analysis was made for all tram tracks on which tram traffic is operated in the wider centre of the city of Zagreb. The analysis of influence of tram vehicle vibrations on the surrounding buildings was performed in the frequency range from 0.5 to 31.5 Hz to detect harmful influence on buildings at lower-frequency excitations. The results are presented as average values of acceleration La [dB] in one-second time intervals. Thus

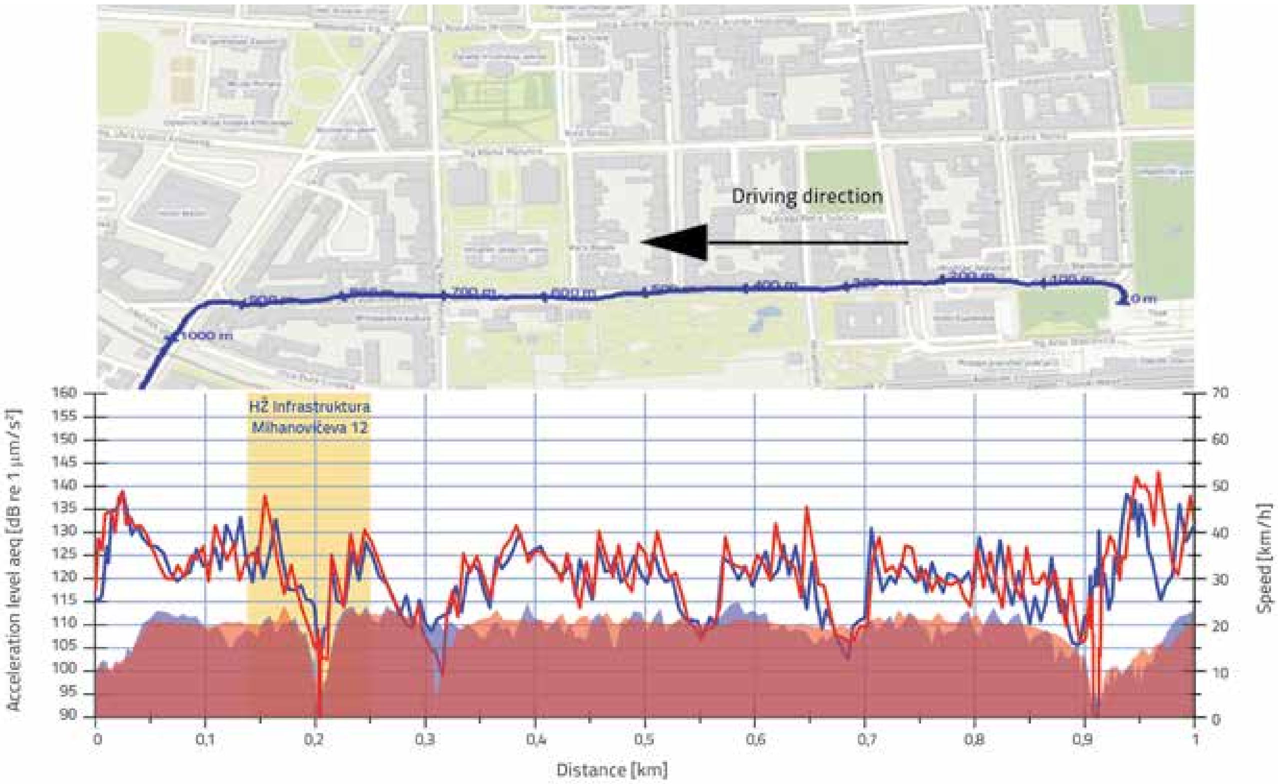

Figure 22. Vibration during tram passage along the section: Glavni kolodvor – Mihanovićeva – Vodnikova – Savska cesta (2018 = marked in blue, 2020 = marked in red), with marked passage in front of the HŽ Infrastructure building

the 120 dB level represents an acceleration of 1 m/s². In addition, maximum vibration values registered on the four mentioned accelerometers are shown on indicative diagrams (Figure 22).
Based on the analysis of vibrations generated by tram vehicles operating at 20 km/h, it is possible to detect points of higher vibration, as compared to vibrations registered in 2018, which points to possible new damage, i.e. damage possibly caused by earthquake.

3.2.2. Analysis of the impact of tram traffic vibrations on earthquake-damaged buildings

The influence of tram traffic vibrations on earthquake-damaged buildings is a long-term process because of low-level vibrations that do no cause any immediate damage. It is only the accumulated action of a considerable number of repeated vibrations that can have an influence on masonry buildings of the type that mostly suffered damage in the earthquake that hit the city of Zagreb, as documented in [24]. Thus an initial testing of the influence of tram traffic vibrations on buildings was conducted for the purpose of conducting a long term monitoring of buildings that suffered damage in this earthquake. The testing was conducted on the HŽ Infrastructure head-office building built in 1903, which is situated at Mihanovićeva 12, Figure 23. As a result of the earthquake, the building suffered considerable damage to central staircase, partition walls, and load bearing walls on higher floors of the building. The building is also situated in the immediate vicinity of the tram track passing through Mihanovićeva street. The axis of the closer track is situated only 5 m away from the facade of this building.

Figure 23. Tram passing in front of HŽ Infrastructure head-office building

The measurement setup consisted of ten vibration measuring points (triaxial accelerometers) and five crack-width measuring points (extensometers), as shown in Figure 24. The passage of all tram types, and subsequent aftershocks of varying intensity, were registered at these points.

Figure 24. Installation of triaxial accelerometer for acceleration measurements, and extensometer for crack width measurements

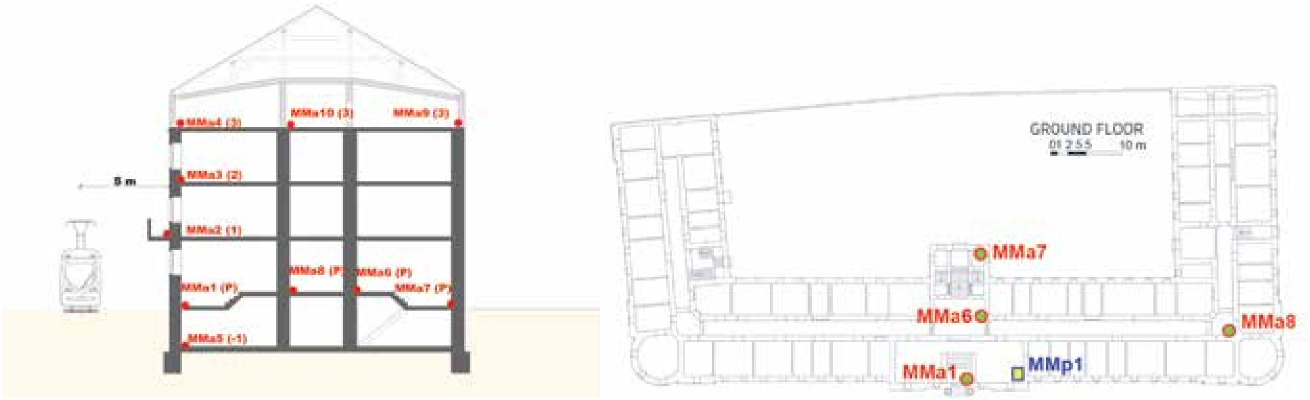

Figure 25. Arrangement of measuring points at facade of the building (left) and at ground floor (right)

The analysis of the vibration and displacement data registered during the passage of tram vehicles is based on standards relating to the influence of vibrations on buildings, on current international experience, and on comparison with the excitation spectrum of aftershocks that followed the main earthquake. The arrangement of measuring points along the facade of the building at Mihanovićeva 12, with plan view of the ground floor, is shown in Figure 25.

Some differences in vibrations generated by passage of tram vehicles were observed during preliminary investigations at some points within the building. In this respect, it is interesting to note that the highest levels of vibrations in this building were registered at points MMa8 and MMa10, which are situated at the eastern corner of the building (Figure 26). Higher vibration levels were also registered at this locality (intersection with Ljudevita Gaja street) during vibration measurements in tram vehicle (Figure 26).

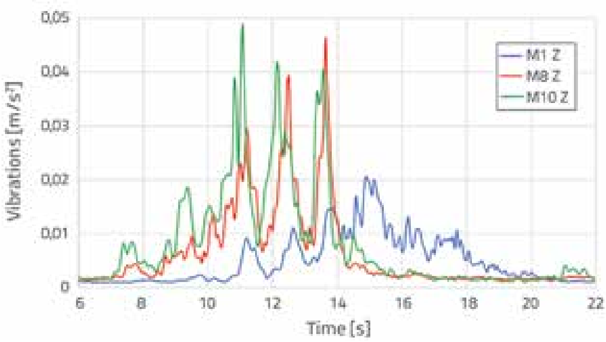

Figure 26. Vibration levels measured in vertical direction during passage of tram type TMK2200 at measuring points MMa1, MMa8, and MMa10

In addition to vibrations generated by tram passage, the vibrations generated by earthquake aftershocks were also measured during this testing. Thus earthquakes of magnitude 3.0, 2.2, 1.9, 1.5, 1.4, and 1.0 on the Richter scale, and their influence on the studied building, were registered during the testing period. The understanding of the influence of several subsequent aftershocks will also enable direct comparison with the impact of tram vibrations. Preliminary analyses of the Richter 3.0 earthquake reveal that the building is much more affected by earthquake aftershocks than by tram vibrations, which is especially due to the frequency content of seismic excitations. In effect, during the subsequent aftershocks, the excitation of this building is the highest in the low-frequency range (0.5 to 20 Hz). These accelerations succeeded in provoking response of this building which, after initial excitation, exhibits a characteristic response at natural frequencies of 2-4 Hz. During earthquake action, vibration velocities attained the values of up to 3 mm/s. On the other hand, the tram passage excitation causes accelerations at much higher frequencies, ranging from 20 to 50 Hz, while vibration velocities are much lower (up to 0.2 mm/s), as shown in Figure 27. Thus it can be stated, based on preliminary analysis, that the analysed building is much less affected by tram passage than by earthquake generated aftershocks. More detailed conclusions requires a detailed analysis of all tram vehicle types, and of various seismic activities registered in this period, including also monitoring of long term effects of repeated excitations generated by tram vehicles.

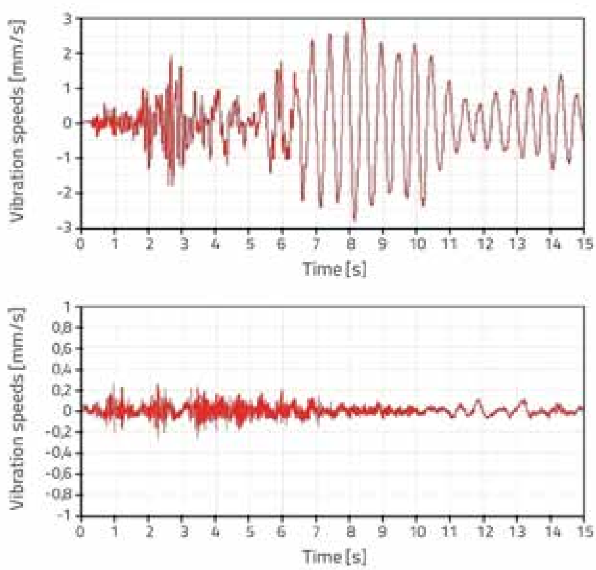

Figure 27. Comparison of vibration velocities generated during the Richter 3.0 earthquake (top) and during passage of a tram vehicle type TMK2200 (bottom) at locality MM3, in the direction Y (perpendicular to track axis)

Development of cracks caused by the earthquake is analysed in parallel with vibration measurements in order to determine the impact of tram vehicles and aftershocks on possible widening of existing cracks. Accurate estimation of crack development will only be possible on the basis on long-term monitoring results.

4. Discussion

In the case of strong earthquakes, great damage will occur at the level of track substructure components – embankments, cuttings, bridges, and culverts, which results in extremely strong degradation of the permanent way, while the track traffic can in such cases be resumed only after very extensive remedial activities. On the other hand, in the case of earthquakes that will not cause degradation at the substructure level, it is necessary to check the permanent way (ballast bed, rails, sleepers, fastening system) in order to detect potential damage that could occur due to earthquake action. Good knowledge of track geometry is essential for proper definition of the impact of earthquakes on permanent way elements. If the track geometry is at its limit values, seismic load can increase lateral forces on straight segments and in curves, often resulting in derailment, which will additionally cause damage to permanent way elements. When a train passes through a curve, and when a greater load is exerted on the external or internal rails (depending on the speed of train and superelevation), seismic load can result in train overturning at the internal or external side of the curve. The most plausible analysis of the effect the earthquake load has on track quality would be possible if a relationship between the earthquake and track quality can be detected, i.e. if the risk of track buckling and derailment can be identified.
In areas with frequent seismic activities, it is of utmost importance to improve seismic behaviour of buildings to make them more resistant to earthquake events. One of the ways for preventing deformations and displacements caused by earthquakes is to use alternative aggregates in combination with ballast bed or subgrade material [37]. Seismic activity is analysed on various railway embankment samples in [37]. The testing was conducting on the shaking table, and three samples were analysed. One sample is a traditional railway structure with ballast bed, where ballast bed was placed on firm soil (subgrade). In the second sample, 20 % of subgrade material was replaced with tire-derived aggregate, while in the third sample the subgrade was formed of expanded clay aggregate (70 %), tire-derived aggregate (20 %), and firm soil (10 %). The results show that the earthquake impact on track structure can be reduced by replacing subgrade material with tire-derived aggregate and expanded clay aggregate.
Due to earthquake action, the wheel flange can move upward, loose contact with rail, and cause derailment to occur [38]. This type of derailment occurs when strong lateral forces act on the wheel, while vertical contact forces are reduced [38]. The vehicle operating safety is in this case defined with the lateral force to vertical contact force ratio. According to the European technical specification for interoperability (TSI), the limit value of this ratio is 0.8. Train operation safety during an earthquake event is analysed in [38] by means of the finite element method. The factor of derailment increases with an increase in speed. When train operates at a speed of 90 km/h, the derailment factor at maximum acceleration of 19.62 m/s^2 (2 g) exceeds the allowable value of 0.8. It is stated in the paper that a train operating at 70 km/h will operate quite safely even in the case of maximum ground acceleration values. Critical train speed as related to ground acceleration is presented in Figure 28.

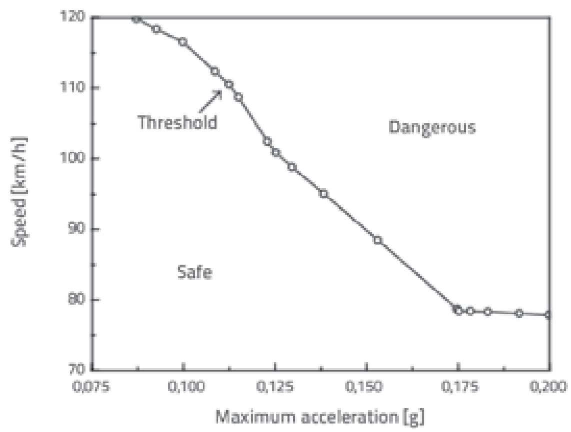

Figure 28. Critical train speed as related to maximum ground acceleration [38]

Based on the analysis of soil motion, scientists have established that, during an earthquake event, P waves (primary waves that cause preliminary trembling) move much faster than S waves (secondary waves) whose propagation results in seismic damage [39]. These findings served as basis for the development of warning systems for stopping the

Table 7. Area vulnerable to various amplitudes of seismic events

Earthquake magnitude	Level of response	California and California Bay	The rest of North America
0.0 to 4.99	1		
5.0 to 5.99	2	80 km	160 km
6.0 to 6.99	3	160 km	320 km
	2	240 km	480 km
≥ 7.0	3	According to instructions, but no less than 6.00-6.99	
	2	According to instructions, but no less than 6.00-6.99	

rail traffic in the case of an earthquake event. Such systems are capable of detecting earthquake parameters such as the amplitude and distance from epicentre and hypocentre of the earthquake [40]. Once waves are detected, the power supply from rectifier stations to rail vehicles is automatically interrupted, and the emergency braking system is activated in all vehicles along the railway. Vehicles are stopped before the arrival of S waves, which has reduced the possibility of train derailment. Such a system – installed at the north-eastern coast of Japan – identified P waves during the earthquake that hit Japan in 2011. As soon as P waves were detected, a train stopping signal was sent out and twenty-seven high-speed trains operating at that time along this route were stopped. Moments later, Japan was hit by a devastating 8.9 magnitude earthquake, but it did not cause derailment of any of these trains [39].

The use of systems for detecting earthquake, magnitude and epicentre data is also recommended by the American Railway Engineering and Maintenance-of-Way-association in the Manual for Railway Engineering [41] as a means for sending timely train speed reduction instructions. After earthquake, it is necessary to check the track, structure, signalling and communication devices within the radius dependent on the strength of the earthquake (Table 7).

In Table 7, responses to seismic activity are divided into three levels [41]:

- Maximum train speed must be reduced, and the need for further track condition checking will be considered.
- All trains operating within the defined distance from the epicentre will operate at reduced speed until the track structure has been checked and a new appropriate speed defined.
- All trains operating within the defined distance from the earthquake epicentre must be stopped. Traffic must not be resumed until the track structure has been checked and a new speed defined.

If the earthquake activity does not cause damage to rail infrastructure, and if normal traffic is therefore considered possible, it is important to conduct, before resumption of traffic, an analysis of the influence of vehicle vibrations on earthquake-damaged buildings situated near the track. In effect, vibrations generated by rail vehicles propagate as seismic waves and, at that, the greatest part (67 %) of such waves is transferred in the form of surface R-waves [24, 27] and can cause additional damage to buildings.

During the Richter 5.5 earthquake that hit the city of Zagreb, rail infrastructure did not suffer greater damage due to this seismic event. Considerable damage was inflicted on historic building in the wider centre of the city and, indirectly, on tram infrastructure situated in the vicinity of damaged buildings (due to fall of parts of buildings, or due to use of heavy construction machinery during urgent repairs on buildings). Previous investigations have shown that vibrations caused by traffic can affect traditional masonry buildings [23]. Further research will therefore focus on the effect of traffic load on the level of damage on buildings affected by earthquake. Future studies will also consider the effect the resumption of tram traffic will have on earthquake-damaged buildings.

5. Conclusion

Rail infrastructure must be inspected after earthquake events to determine if it has incurred any damage. Measures that must be taken on rail infrastructure, depending on the distance from epicentre and earthquake magnitude, are defined in numerous guidelines. In case of strong earthquakes, damage occurs at the substructure level, which is why the entire track structure has to be repaired. On the other hand, in case of weaker earthquakes, permanent way must be checked for possible damage. In their studies, many researchers have analysed behaviour of permanent way elements in response to seismic load. It was established that damage to ballast bed occurs at the ground acceleration of 6 m/s^2 and more, while lateral resistance starts to reduce at an acceleration of 7.5 m/s^2. In the case of rails, the greatest danger is the generation of large axial forces during an earthquake action. In case these axial forces are greater than critical forces of the rail, buckling will cause changes in track geometry and deviation from its initial position. On the other hand, regardless of the magnitude of seismic activity, no structural damage will occur on sleepers. If it is established during inspection that track infrastructure did not suffer any damage during the earthquake, then an analysis of the influence of rail vehicle vibrations on nearby buildings will have to be conducted before resumption of rail traffic. In effect, the influence of rail traffic vibrations on earthquake damaged buildings has to be analysed with special care. The Faculty of Civil Engineering of the University of Zagreb conducts, in cooperation with Končar Institut za elektrotehniku d.o.o. and Veski d.o.o., detailed analyses of such influence through long-term monitoring of typical buildings in the city of Zagreb in the vicinity of tram tracks. The analysis of results of such long-term monitoring will enable estimation of accumulated effects the frequent tram traffic has on nearby buildings.

Acknowledgment

Initial testing of tram traffic vibration influence on buildings damaged in earthquake that struck Zagreb on 22 March 2020 is conducted by University of Zagreb Faculty of Civil Engineering on HŽ Infrastructure head-office building that the owner generously conceded for this purpose. Data collection and analysis have been performed in cooperation with Končar - Electrical Engineering Institute d.o.o. and Veski d.o.o. Authors would like to thank mentioned parties on cooperation.

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