Learning from Earthquakes

External and internal damage to a house in Orehovečki brijeg

The Zagreb Earthquake of 22 March 2020

A remote study by the LfE UK team for EEFIT

Newcastle University UCL UNIVERSITY OF CAMBRIDGE

with the support of

EEFIT

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THE ZAGREB EARTHQUAKE OF 22 MARCH 2020

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Contents

List of Figures

List of Tables

1. Introduction

(Authored by: ES, EV)

1.1 Preamble

The 2020 Zagreb earthquake - Mw5.3 (USGS, 2020) - occurred at 06:24 local time on Sunday 22 March. The epicentre was located 5.56 km north of Zagreb and 7 km northeast of its city centre. The maximum felt intensity was reported as VII-VIII (Strong) on the MCS Macroseismic Intensity Scale. The main shock was followed by a Mw5 aftershock, which occurred at 07:01. One fatality and 26 injuries were directly caused by the earthquake (Reliefweb, 2020). Two people died subsequently due to accidental falls during the clear-up operations (Herak, 2020). As of 28 April 2020, over 1,100 aftershocks have been recorded (Herak, 2020).

The ground shaking resulted in damage to buildings and critical infrastructure (CI) such as hospitals and schools. The most affected buildings were in the old city centre, including both upper and lower town of Zagreb, and clustered around streets where many buildings were built before modern seismic codes. Several heritage buildings in the upper town were also damaged to various degrees, including the Parliament of Croatia, the Museum of Arts and Crafts, and many theatres and churches. In the surrounding areas, ten villages across three municipalities were significantly affected. The damage was extensive in the village of Kašina.

Even though the event is minor in terms of its reported casualties and damage, its timing makes it noteworthy. At the time of the earthquake, Croatia - like most of Europe - was in partial lockdown in response to the Coronavirus (COVID-19) pandemic (Sigmund, Z. et al., 2020). The immediate response by the national civil protection in Croatia, as well as the ability of European countries to offer and dispatch help, were affected by the COVID-19 emergency.

After an earthquake, there is only a small window of opportunity to gather perishable data, and the peculiar circumstances of this event make an even more compelling case for the collection of unique information about how and to what extent the COVID-19 lockdown impacted the post-earthquake response. The still-ongoing pandemic and the unprecedented restrictions imposed on air-travel make it impossible to launch a traditional earthquake reconnaissance mission in a suitable timeframe, so new means of remote data collection have been sought, and their effectiveness tested. This initiative is particularly important, considering the uncertainty surrounding this novel virus. It is currently unclear what level of immunity is imparted on recovered people or how long any vaccine that may be developed will be effective. While we all hope that this pandemic will be a one-off and that normalcy will be regained, we cannot exclude that we may see more of these events in the future. Earthquake reconnaissance missions may need to be carried out remotely and in similar circumstances. Understanding how novel sources of information can be employed to conduct both damage and needs assessments remotely is a step towards better resilience in the face of such complex disasters.

As part of the Learning from Earthquakes (LfE) project funded by the EPSRC, this report summarises the findings and challenges of performing a remote earthquake reconnaissance mission effectively and using information gathered primarily from the internet and social media. The report also illustrates how the newly developed EEFIT data collection app and spatial tools have been deployed and used by local earthquake engineering students in Zagreb. Building structure and damage information data could be gathered on-site but analysed in the UK. We considered the Zagreb earthquake a good case study for testing methods and analyses under development in the LfE research project, and we intend to use the findings of the remote mission to improve the methodologies and provide recommendations on the use of these tools in standard EEFIT missions in the future.

1.2 Aims and objectives of the remote mission

Given the constraints of acquiring data remotely, this study only focused on two aspects of the earthquake: building damage and disaster response. Preliminary information about clean-up and recovery operations are also provided, however - at the time of writing - these are still ongoing.

The main objectives of the remote mission were to:

1. Assess the effectiveness of remote earthquake reconnaissance surveys in collecting damage and consequence information.
2. Train and deploy a small local team to carry out damage assessments based on the tools under development in the LfE project.
3. Assess earthquake damage to buildings and infrastructure in the near-fault region.
4. Report on earthquake response and reconstruction activities by emergency response teams, evacuees, volunteers and other organisations, mainly focusing on the impact of these activities during the COVID-19 outbreak and lockdown.
5. Establish contacts and exchange information with the Croatian academic community involved in the post-event activities.

It is important to note that the team devoted extensive time and resources to gain an understanding of the distribution of damage in the city centre of Zagreb. For this purpose, virtual building damage assessments were conducted using the available drone and CCTV footage and images, all acquired from webpages, various YouTube channels, tweets, Facebook posts, etc. However, for most of the buildings in the city of Zagreb, the damage were mainly observed on the roofs (e.g., broken and/or fallen chimneys and displaced tiles) and, as such, could not be detected in the photos and videos taken at street level and published online by members of the public. The partial lockdown imposed by the pandemic also influenced the amount of available information, and the most damaged streets were likely evacuated and cordoned off before pictures could be taken. Citizens were advised to remain in lockdown and keep observing social distancing (Walker, 2020).

With remote data proving limited information about the damage extent and distribution, attempts were made to obtain such information through our local academic partners. However, the City of Zagreb authority chose not to release any of the data pertaining the distribution and number of the buildings inspected after the earthquake. The lack of this information, which was deemed essential to validate the remote damage assessment, motivated the team to focus the attention on the villages around Zagreb, where groups of local assessors were conducting house inspections. This decision was, in hindsight, a significant one as villages received much less media coverage than the city centre of Zagreb, even though some buildings sustained more significant damage (see section 5). The on-site damage collection - carried out in collaboration with Professor Josip Atalić, his pupils, and the GARK team - has focused on assessing damage to properties in the near-fault region.

A diary of the on-site data collection has been published in a blog (https://lfemissiontozagreb.wordpress.com/). Figure 1.1 provides an overview of the location of the areas and villages affected by the earthquake surrounding Zagreb.

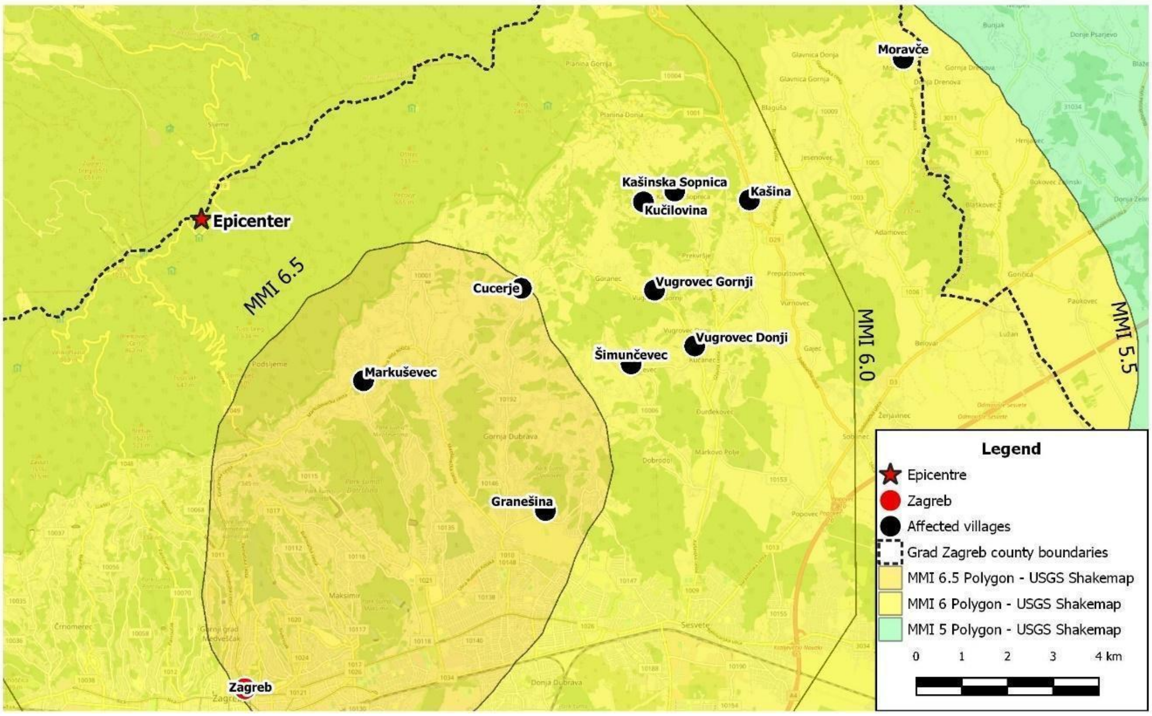


Figure 1-1– Main locations affected by the Zagreb Earthquake of 22 March 2020 (MMI – Mercalli Intensity Scale)

1.3 Report structure

The remainder of the report is organised in six sections.

Section 2 presents an overview of the information sources examined by the team in this study and assesses the reliability of the data available. It also highlights the limitations of acquiring data from the virtual platforms. Section 3 examines the seismicity of the region and reviews the historical records of past earthquakes. This section provides insight on the seismological setting of this event. Section 4 describes the Croatian building stock and seismic codes. Section 5 presents the damage assessment data collected remotely and from ground surveys. An attempt is made to quantify the damage sustained by buildings and infrastructures. Section 6 presents some observations on the relief, response and recovery efforts, based on the information posted by the national ministries and acquired through interviews with locals and social media. Finally, Section 7 provides a commentary on the lessons learnt from conducting this virtual mission. The main contributing authors to the sections are as follows:

Table 1.1 – List of authors for each section of the report

Section	Title	Authors
2	Overview and assessment of sources of information for the virtual mission	DC, EV, ES, CK, SW
3	Seismotectonic overview	ES
4	Croatian building code and inventory	TR
5	Building damage observations and surveys	VP, EV, AB, HM, ES
6	Relief, response, and recovery observations	DC, EV, SW
7	Lessons learnt from conducting a virtual mission	ES

1.4 References

Herak, M (2020) Personal interview on 28/4/2020

Reliefweb (2020). Croatia: Earthquake DREF Operation n° MDRHR003, Emergency Plan of Action (EPoA). Retrieved from https://reliefweb.int/report/croatia/croatia-earthquake-dref-operation-n-mdrhr003-emergency-plan-action-epoa (15/4/2020)

Walker, S. (2020, The 22nd March 2020). Zagreb hit by earthquake while in coronavirus lockdown. The Guardian. Retrieved from https://www.theguardian.com/world/2020/mar/22/croatia-earthquake-causes-widespread-damage-zagreb

Sigmund, Z., Uroš, M., & Atalić, J. (2020). The Earthquake in Zagreb amid the COVID-19 Pandemic: OPINION. Retrieved from https://www.undrr.org/news/earthquake-zagreb-amid-covid-19-pandemic-opinion

2. Overview and assessment of sources of information for the virtual mission

One of the main objectives of this study is to examine how much of what an EEFIT team does in the field on a reconnaissance mission can be replicated and carried out virtually. The exercise is timely as globally over 100 countries (at the time of writing the report – BBC, 2020) are in some form of lockdown, with restricted movements and physical access to local relief. Conducting a virtual mission for the Zagreb earthquake has been quite challenging but the exercise has given us a deeper understanding of the extent to which social media (SM) data and other internet-based resources can support virtual remote missions for future events.

2.1 The traditional EEFIT model

(Authored by: ES, EV)

The main objectives of the EEFIT reconnaissance missions are:

- To carry out a detailed technical evaluation of the performance of structures, foundations, civil engineering works and industrial facilities within the affected region.
- To collect geological and seismographic data, including strong motion records.
- To assess the effectiveness of earthquake protection methods, including repair and retrofit, and to make comparisons of the actual performance of structures with the expectations of designers.
- To study disaster management procedures and socio-economic effects of the earthquake, including human casualties.

In the field, the team would attempt to gather first-hand data on the following:

- Damage observations to the built environment including critical infrastructure and lifelines;
- Data on the evidence of secondary effects (e.g., liquefaction, landslides, lateral spreading);
- Data on emergency response and plans for repair, reconstruction and recovery in the long term
- Information on personal earthquake experiences
- Evidence of circumstances that have aggravated damage/ slowed response to the event (e.g., planning and land-use considerations, evidence of substandard building)

In reviewing what is possible to do remotely, Table 2.1 summarises remote methods currently in use by EEFIT for different types of assessments. This Table also contains an appraisal of what could potentially be obtained from SM data mining and citizen science efforts (e.g., 'Did you feel it?' reports, social media groups).

Table 2.1 – Potential data collection methods employed for an earthquake reconnaissance mission

	Data Collection Methods								
	Survey Inventory	**Optical remote sensing - Satellite and aerial images**	**Optical Remote sensing - Night Lights**	**Omni-directional cameras**	**Drone deployment**	**On-foot deployment**	**News outlet data mining**	**Social Media data mining (*)**	**Citizen science/ Remote Mapathon (*)**
Situational Assessments	**Presence of debris/ blocked roads**	Y	N	Y - Subject to access and permission to deploy	Y	Y - Subject to access and permission to deploy	Y - but limited to news coverage	Y- but limited to usage of SM. It also presents inherent bias in the users' demographic	Y - needs a bit of an infrastructure to be set up remotely
	Absence of traffic	Y	N	Y - Subject to access and permission to deploy	Y	Y - Subject to access and permission to deploy	Y - but limited to news coverage	Y - but limited to usage of SM	Y - needs a bit of an infrastructure to be set up remotely
	Outages-Electricity	N	Y	N	N	Y - Subject to access and permission to deploy	Y- but limited to news coverage	Y - but limited to usage of SM	Y - needs a bit of an infrastructure to be set up remotely

Table 2.1(continued) – Potential data collection methods employed for an earthquake reconnaissance mission

	Data Collection Methods								
	Survey Inventory	**Optical remote sensing - Satellite and aerial images**	**Optical Remote sensing - Night Lights**	**Omni-directional cameras**	**Drone deployment**	**On-foot deployment**	**News outlet data mining**	**SM data mining (*)**	**Citizen science/ Remote Mapathon (*)**
Damage assessment	**Damage to building roofs**	Y	N	N	Y	N	Y- but limited to news coverage	Y- but limited to usage of SM	Y - needs a bit of an infrastructure to be set up remotely
	Damage to building facades	N	N	Y	Y	Y - Subject to access and permission to deploy	Y- but limited to news coverage	Y- but limited to usage of SM	Y - needs a bit of an infrastructure to be set up remotely
	Damage to important buildings	Y - depending on degree of damage	N	Y	Y - depending on degree of damage	Y - Subject to access and permission to deploy	Y- but limited to news coverage	Y- but limited to usage of SM	N
	Damage to critical facilities	Y - depending on degree of damage	N	Y	Y - depending on degree of damage	Y - Subject to access and permission to deploy	Y- but limited to news coverage	Y- but limited to usage of SM	N
	Damage to lifelines over ground networks	N	N	N	N	Y - Subject to access and permission to deploy	Y- but limited to news coverage	Y- but limited to usage of SM	N

2.2 *Sources of Information and observed limitations*

(Authored by: ES, EV)

The team consulted different media to collect data on the event remotely, the types of data available from these various sources and, most importantly, their limitations which are summarised in Table 2.2. Notably, while EEFIT has traditionally used some of these resources in the pre-mission phase (i.e., Google Earth, Newspapers, Local institution websites, and personal contacts), the others are more novel means of information. Although accompanied by restricting and striking limitations today, novel means may open new avenues to data collection operations in the future once these limitations are overcome. This argument is particularly compelling for some branches of information technology (such as Remote Sensing and GIS), which are nowadays pervasive in Disaster Risk Reduction (DRR) but still presented significant limitations for application twenty years ago.

During the Zagreb remote mission, the team has tested for the first time in a UK earthquake reconnaissance mission the use of SM and, more specifically Twitter, Facebook, Instagram, and GoFundMe pages as potential alternative sources of data for damage assessment and post-disaster needs assessments.

Some critical limitations were identified:

1. Social media photos and videos released on the internet by non-technical users may not have the correct angle of capture, distance from the building and/or scale to allow for the full-façade assessment of the damage pattern.
2. Trying to build a picture of the type of damage and its distribution using solely SM data is a complex endeavour because such resources are not geolocated and may even present the wrong geolocation.
3. There is a persistent and inherent bias in terms of the demographic of users using these technologies, which impact the frequency SM interaction. Social media are used only by users with SM accounts, which are predominantly from a younger demographic.
4. In comparison, the limitations identified for other data sources were more manageable but still noteworthy. For instance, most of our searches were done in English, but some used words in Croatian like 'potres', which means 'earthquake'. Where the landing pages were in Croatian, the team had to use Google Translate to help with our review. There were no native speakers on the team, but again the help of local academics and contacts were invaluable as they kept us informed on important news from the local newspaper that would have not reached us otherwise.
5. The limitation of the using moderate resolution Sentinel data (10 m) could have been overcome by purchasing high-resolution data from a vendor.

Table 2.2 – List of sources and their limitations

Media	**Types of Data**	**Limitations**
Academic and local institution websites	Background on seismology, geology and building regulations and exposure. Some situation reports from Croatian Red Cross.	Language barriers. Use of google translate is not ideal but necessary. Naturally many more papers (and in more detail) are published in the local language.
Newspaper websites	Reports from the ground immediately after the event and some reflections of 'a month on'	Usual media bias. Copyrighted images.
Satellite Imagery	Google Earth Sentinel data	Google Earth archive data is a good source of information for pre-event data, but post-event images may be released too late (if at all). Sentinel data and other free of charge moderate resolution imagery can only help detect patches of debris in very damaging earthquakes. Not suitable for this event.
CCTV (websites and YouTube)	Footage of the moment the earthquake stuck from street cameras/ cameras at different institutions, e.g. Faculty of Medicine of the University of Zagreb	Interesting in terms of recording the responses of structural and non-structural elements to ground shaking. Not useful for completing surveys.
Drone footage (YouTube)	Flyover drone footages taken by the general public/ for this event the Military.	No control of the date and aerial coverage of the footage. Need georeferencing.
Twitter	Citizens and people with interest/ connect to the affected area tweeting about the event. Images	Big data, a lot of information (which may or may not be relevant to comb through). Images in tweets are not georeferenced to the actual place where these are taken. Retweets make it even more difficult to locate the origin of the photographs.

Table 2.2 (continued) – List of sources and their limitations

Media	Types of Data	Limitations
Facebook groups	Citizen science/ local discussion forums; images	Difficult to extract direct damage data. Need to contact groups and individuals. Need Facebook account.
GoFundMe pages	Some images from outside of the old town of Zagreb of substantial damage to residential buildings needing urgent repair (hence the plea for financial help)	Difficult to extract direct damage data. Need to contact individuals to follow up.

In addition to the list of sources above, the EEFIT team also sent a request to the wider EEFIT network for local contacts and information and were able to obtain some data and additional insights from these individuals through interviews and email correspondence.

2.3 Assessment of different information sources

The following section presents the different information sources that were used specifically to inform this virtual mission. The advantages and disadvantages of each of the media used in this study are highlighted.

2.3.1 Satellite, Aerial, Google Earth Imagery and third-party maps
(Authored by: EV)

Satellite and aerial imagery, as well as drone footage, are often used in post-disaster situations to obtain a bird's eye view that can help rapidly assess the intensity and geographical extent of the damage. The resolution of the imagery, however, can constrain significantly the detail to which damage can be detected. As this event was not a major earthquake, moderate resolution satellite data (less than 10m) - that can help assess the location of clustered collapsed structures in big events – was not suitable to detect the subtler damage caused by this earthquake.

Concerning the availability of high-resolution datasets (less than 1 m), Google Earth Imagery archives provided enough coverage of the city centre of Zagreb and surrounding villages to allow for the assessment of the pre-earthquake conditions. The most recent pre-event imagery dated back to 2016 and the Google Street View footage was captured in 2011. Due to the time lags between the date of capture and the event, the Google archive do not depict precisely how the Zagreb rooftops and streets would have looked like just before the earthquake. However, such a time gap between the "before" and the "after" images would have still be considered acceptable in comparison to the much larger timeframe in which cities - and especially historical and well-established ones - replace their building stock. The most recent Google Street View images were also used to carry out a preliminary appraisal of the typical architecture, construction typologies and material used, as well as the state of maintenance of buildings in Zagreb and the surrounding villages.

Post-earthquake high-resolution satellite or aerial imagery was not available free-of-charge, and the drone footage published online was subjected to copyright. Commercial imagery could have been purchased to compare against the pre-earthquake Google archive images. The bird's-eye view could have helped assess the number of partial and total collapses structures and any damage to the roof sustained by the less damaged buildings (including fallen chimneys, displaced tiles, broken roof battens and/or the presence of protective tarpaulins). However, this comparison would not have been exhaustive without additional data of the damage to the façades of the buildings. Since it was not possible to deploy enough local engineers to capture photos of buildings in the city centre of Zagreb, the purchase of post-earthquakes was not considered necessary.

An overview of the extent and degree of damage in the city centre on Zagreb can be gained by looking at damage maps released by the Copernicus Emergency Management Service (CEMS) agency, which operates under the auspice of the European Commission. The Copernicus EMS program responded to the activation sent by the Civil Protection Directorate of the Croatian Ministry of Interior on 31st March 2020 and was tasked to produce two sets of maps to illustrate respectively the damage to roofs and chimneys and the progress of reconstruction one month after the event. A full report and a complete and downloadable geodatabase have been released by CEMS on 15th May 2020 (EC - CEMS, 2020). The damage assessment has used both pre- and post-earthquake satellite imagery and VHR drone footage. Building footprints from OpenStreetMap (OSM) were also used.

Figure 2-1 and Figure 2-2 provide, respectively, excerpts of the damage and the reconstruction monitoring maps covering the city centre of Zagreb. In the damage map, building footprints marked in red have been destroyed. In the same map, vivid orange footprints symbolise severely damaged buildings, burnt orange ones are instead moderately damage, and lastly, the yellow footprints show buildings for which damage could be possible but could not be fully ascertained. The reconstruction maps depict progress as of 4th May 2020. Footprints are marked in green for the fully reconstructed/repaired buildings, in yellow if the reconstruction is on-going and in orange if the building remained unchanged.

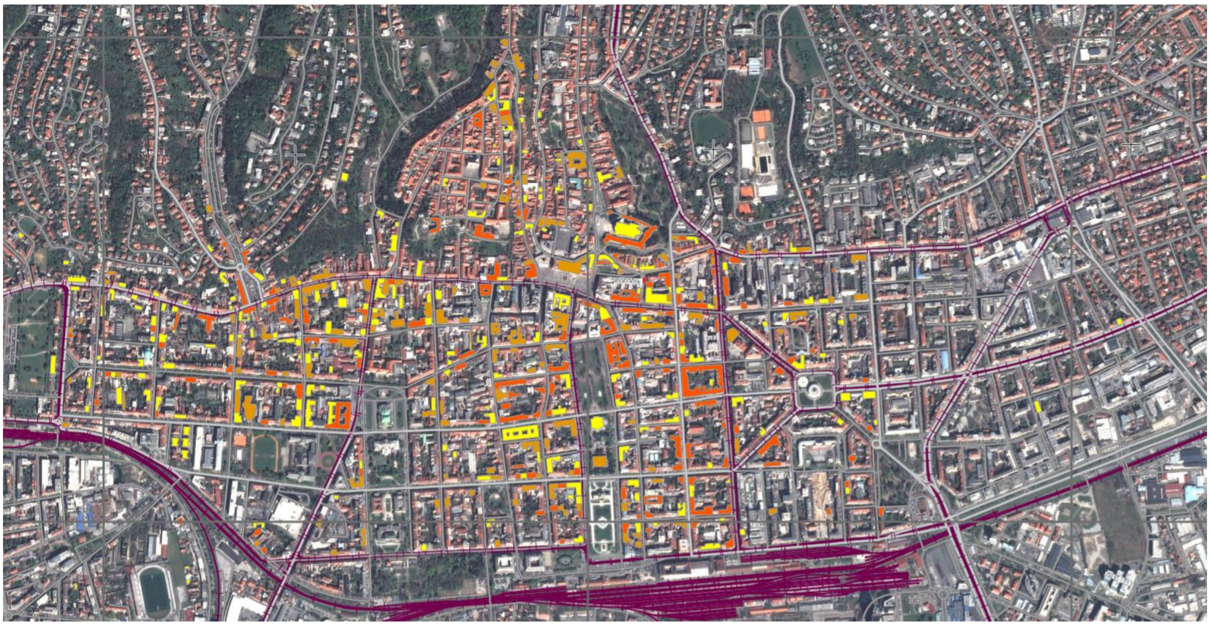


Figure 2-1 – An excerpt of the damage assessment map released by CEMS on 15th May 2020.

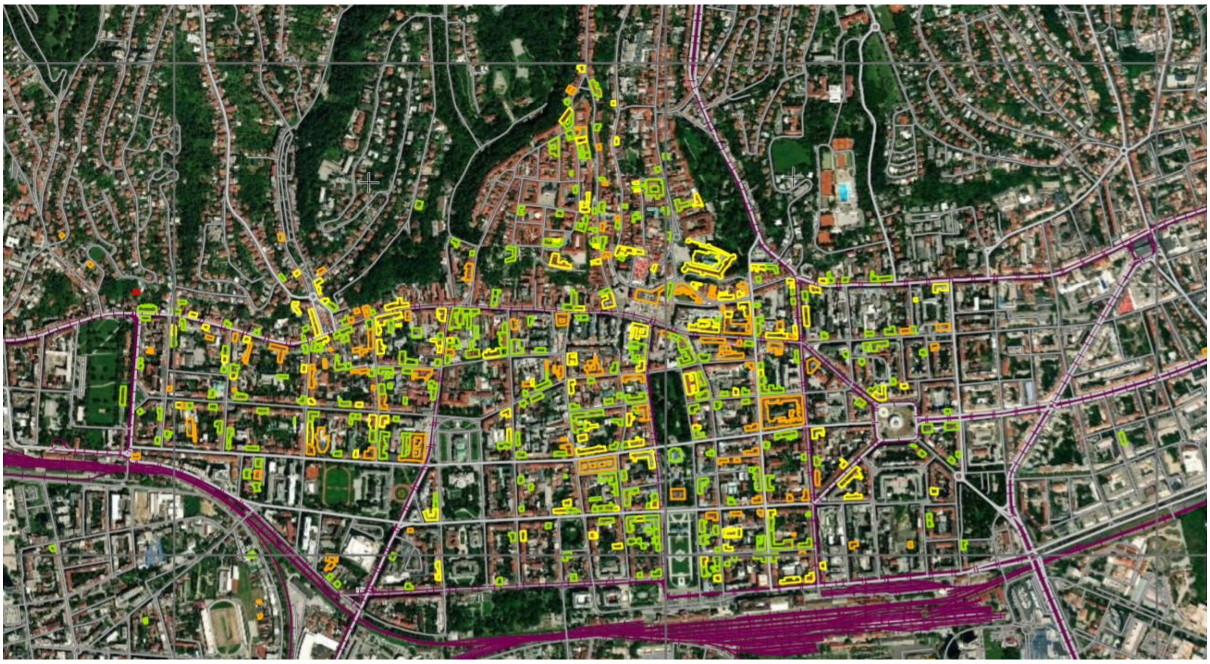


Figure 2-2 – An excerpt of the reconstruction monitoring map released by CEMS on 15th May 2020.

Limitations

The resolution and number of images available for review and analysis are entirely restricted by what is published by the vendors and what constitutes a valid purchase in consideration of the other available source of data that can be used for the pre- and post-event comparison. Although less detailed than an on-site survey – when suitable data are lacking – third party maps can provide some understanding of the damage caused by the event.

2.3.2 *Internet searches*
(Authored by: ES)

Like any other pre-mission desktop study, preliminary background information on the damage and casualties caused by the event, as well as seismological settings, fault rupture, ground motions and data on the local building stock and codes, were sought on the Internet. The search was built primarily on data released by reliable sources such as local and international media reports, governmental websites, and the Croatian Red Cross. In addition to these, further information were obtained from the webpage created by volunteers forming the Croatian Centre for Earthquake Engineering (https://www.hcpi.hr) for the assessment of building damage. Their assessment provided preliminary and near-real time information on the number of buildings surveyed and on the assigned damage grade. The damage data were not correlated to intensity maps. The European-Mediterranean Seismological Centre (EMSC) also had a page dedicated to the Zagreb earthquake. This contained useful links and seismological information and maps, alongside a gallery of pictures uploaded by local users. While the online portal was still being built at the time of writing, the EMSC page is great resource which can provide important information for future events in the area. EMSC have a great presence in the region, with over 100K app users in Zagreb area alone (Bossu, 2020).Their Twitter account is @LastQuake.

Limitations

Internet searches can portray biased information. Politicised stories are common in news articles. The photos showing the most catastrophic damage are posted multiple times and by different outlets, but non-damaged buildings receive scarce attention in the media. Other limitations concern the spatial coverage of the news, which focus on the more important and populated urban areas. Fewer news, if any, are available for the smaller villages.

With regard to the EMSC data, the geolocation of images uploaded by the users may not be correct or detailed enough to geolocate the exact building. EMSC do not harvest pictures from social media and only collect pictures uploaded with their 'did you feel it' app or sent via email (Bossu, 2020). The geolocation is extracted automatically from the metadata of the picture, when these exists. In alternative, users can be contacted via email to acquire the details of images with no metadata. Errors in the geolocation of the images can be present because the 'distance from the epicentre' associated to each image is calculated from the position of the person uploading the image and not from the location of the captured building. Hence, the images uploaded by the users at a different location, those taken from a distance, and the ones that users take from the web and upload to the portal do not have correct geolocations. Case in point, during the review of the data, the team found a set of photos geotagged in the Atlantic Ocean.

Upon contacting EMSC, the team learned that the great interest on the event led to many images being processed very quickly without thorough checks. In general, the coordinates of the images are correlated to the expected PGA at the location before being posted on the gallery.

2.3.3 Interviews with local contacts
(Authored by: ES)

The interviews with local contacts proved to be the most fruitful means of gaining direct information for furthering our enquiries for the earthquake, supplementing and verifying the information found online in newspaper reports, Facebook pages and Twitter. Various academics of the University of Zagreb and the University Hospital Centre were approached through personal contacts and introductions of the team and other EEFIT members and of the interviewees themselves. In all, the team carried out four interviews/ discussions of an hour each (Table 2.3). The final interview with Prof. Atalić was a pre-deployment discussion of the damage assessment carried out by our local team members.

Table 2.3 – Summary of the information acquired with the interviews

Interviewee	Discipline	Information acquired	Date of Interview
Professor Marijan Herak	Seismology	A seismotectonic overview of the earthquake. Work of local seismologists since the event and aftershocks.	28/4/2020
Dr Jaksa Babel	Medicine	the impact on the medical facilities and personnel. Issues with managing a pandemic at the same time.	29/4/2020
Mr Željko Koren	Civil Engineer	The preliminary damage assessment and the organisation and process.	8/5/2020
Professor Josip Atalić	Structural Engineering and post-earthquake reconstruction	The overall damage sustained by different types of buildings. The work currently underway in terms of post-earthquake reconstruction.	15/5/2020

Limitations of interviews

The team were fortunate to speak to professionals who have been directly involved with the response to the earthquake, including a medic, a seismologist and other professionals and academics coordinating the structural damage assessment. Our interviewees were all very generous with their time, but though we were able to follow up with questions by emails after the interviews, the contact is minimal compared to being in the field. Unfortunately, the team were unable to speak to representatives from the Croatian Red Cross and the City of Zagreb's mayor's office due to their heavy workload in dealing with the earthquake and COVID-19. If the team had deployed, face-to-face interviews may have been arranged.

2.3.4 Social Media (SM)

Twitter
(Authored by: DC, EV, CK, SW)

Aware of the potential bias and limitations stated in Table 2.1, information derived from the analysis of Twitter posts (i.e., tweets) and images were used primarily to gather information on the type of damage sustained by buildings and on the location of the debris (Mangalathu and Burton, 2019), and, also, on emergency management response, post-disaster needs and the effects on population (Ragini et al., 2018).

By monitoring Twitter, it is possible to identify and select the most popular hashtags used in the tweets related to the event. Through this process, a set of hashtags in English as well as in Croatian were identified. These are simple keywords such as 'earthquake', which in Croatian translates into 'potres'.The selected hashtags can be used to filter out the tweets that are unrelated to this event. The hashtags are not case-sensitive (i.e., hashtags such as #Croatia and #croatia return the same tweets). Hence, only the lowercase hashtags were used for the selection of the tweets. Generic hashtags such as #disaster, #quake, #Terremoto and others such as #igerscroatia, #volimhrvatsku, #Zagabria, were discarded because they contained data that was unrelated to this earthquake. The final hashtags chosen were: *#Croatia. #croatiaearthquake, #CroatiaFullofLife, #CroatiaQuake, #eartquakecroatia, #earthquakeinzagreb, #hrvatskapotres, #LoveZagreb, #potres, #potreszagreb, #potresZg, #PrayforZagreb, #Zagreb, #ZagrebEarthquake, #zagrebearthquake, #zagrebpotres, #ZagrebQuak, #zagrebquake, #ZagrebStrong, #zagrebstrong and #zagrebstaystrong.* The data mining process sued to select the tweets related to the Zagreb earthquake is shown in Figure 2-3.

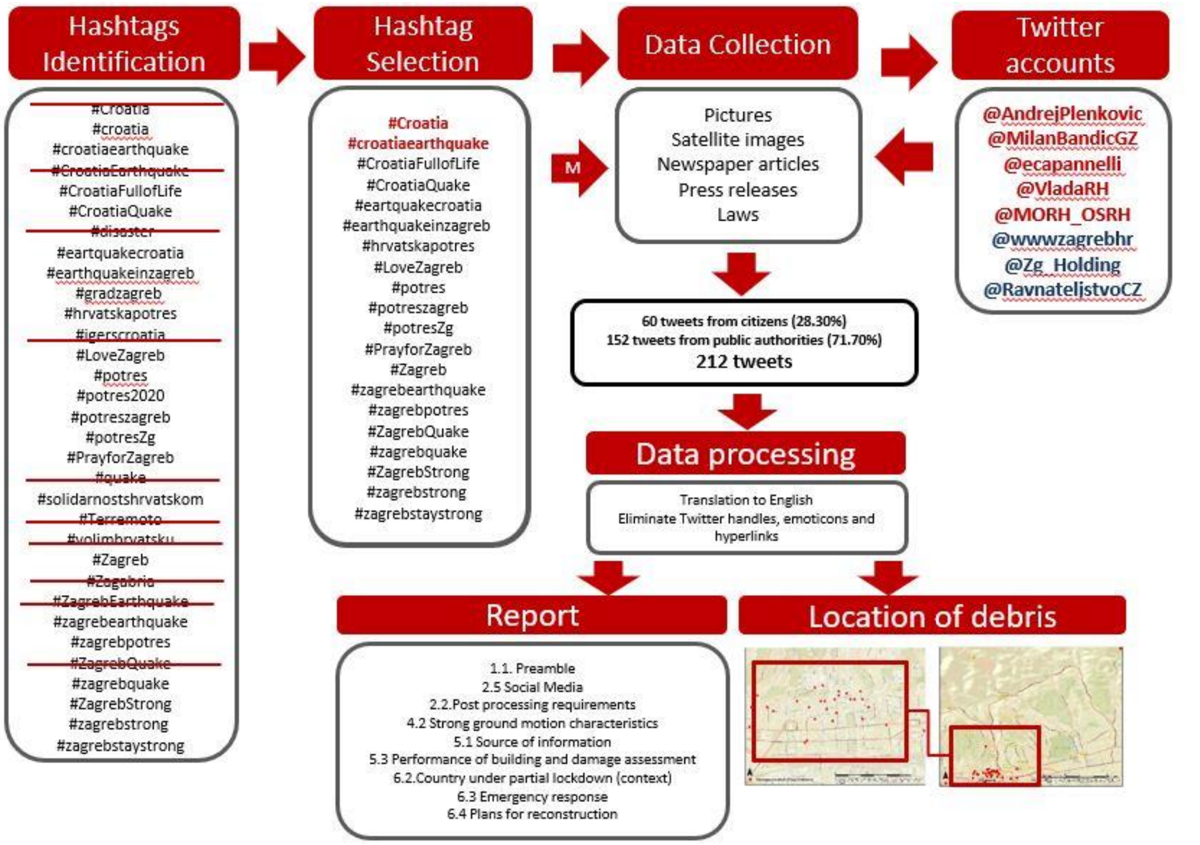


Figure 2-3 – Data mining process for the selection of the tweets related to the Zagreb earthquake

To explore this data further, the team purchased tweet data from a third-party vendor called 'tweet binder' and, using the selected hashtags, obtained 59,246 tweets posted between 20th March and 30th April 2020. The tweet activity, plotted in Figure 2-4, shows that immediately after this earthquake, the twitter traffic of the tweets with the selected hashtags increased by 2000%. However, this increase was relatively short-lived, as the Twitter activity dropped to near background levels about a week after the event. After this time, that twitter traffic was most associated with COVID-19, rather than with the impacts and consequences of the earthquake, even though these were still visible. This change in the Twitter activity may be linked to the relatively small impact of the earthquake compared to the global significance of the pandemic. This does not mean that the Twitter users were unconcerned about the earthquake. Tweets are aggregated over a large area and, since it is not possible to filter the data by location, it likely that in Zagreb and the surrounding areas the earthquake would have been a much greater concern than the virus. However, due to the aggregation of the tweets, it is likely that the number of the tweets related to the event disperse in the much greater number of tweets pertaining to COVID-19 which may come from areas totally unaffected by the earthquake, where COVID-19 is the greatest concern for the users.

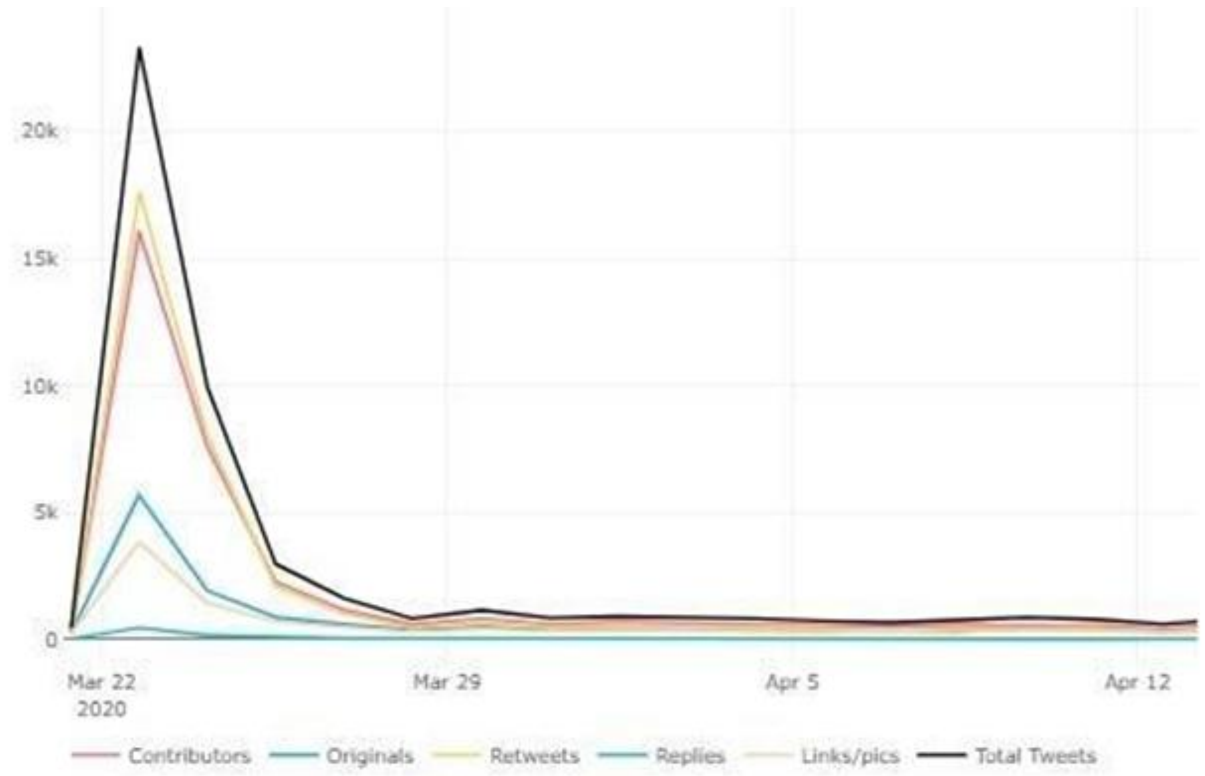


Figure 2-4 – Twitter activity related to the earthquake in Croatia from 20 March to 30 April 2020. Source: adapted from 'tweet binder'

The Twitter binder produces the two word-clouds which provide a narrative of the earthquake, based purely on tweets. The first word cloud is produced by analysing the word frequency (Figure 2-5). In this cloud, the most frequently used word is COVID-19 and this confirms the hypothesis that the earthquake tweets are less frequent and/or come from a smaller area compared to the ones related to the pandemic. The second cloud, which is based on the relevance of the words, show how words like damage, citizens, hospitals, city become more predominant (Figure 2-6).

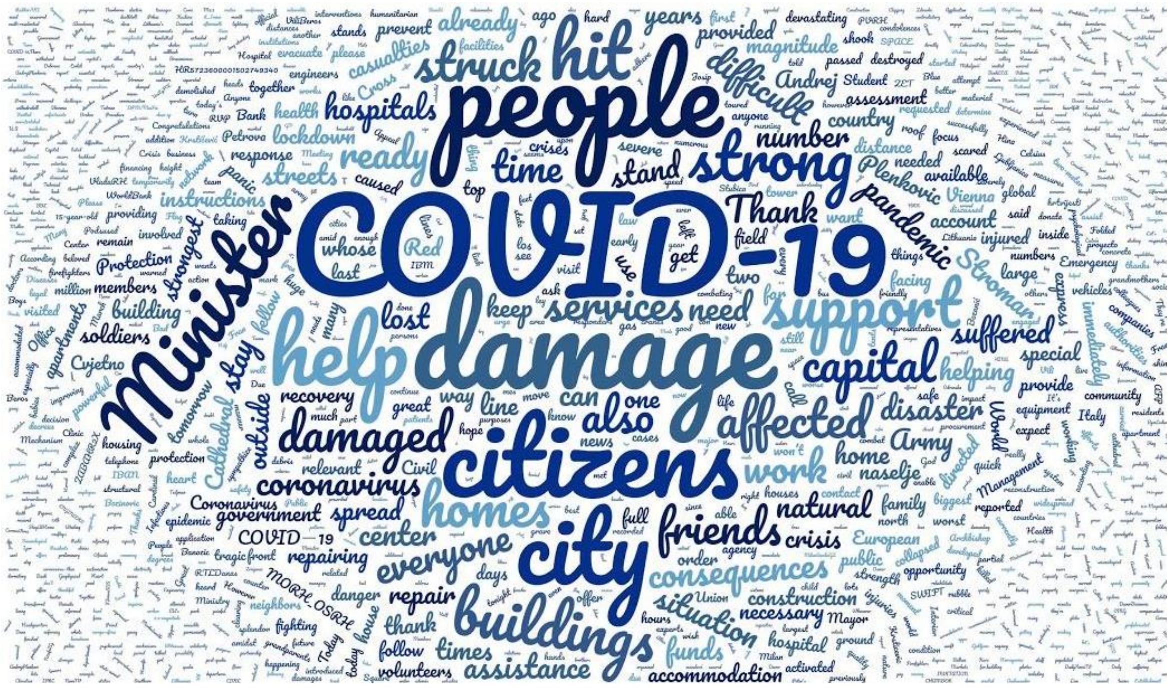


Figure 2-5 – Word cloud based on the frequency of words

Figure 2-6 – Word cloud based on words relevance

After the tweets were extracted, they were analysed manually to see what useful information they contained. For example, some tweets contained images useful to identify damage in buildings, and some of these images were also published on Instagram. The team obtained 116 images from Twitter and Instagram, which were posted online immediately after the event. These images were accompanied by text describing the image/ situation post-earthquake. However, most of the images showed building debris on the streets, rather than damage. The presence of debris does indicate that some damage has occurred, however it does not indicate precisely which building is damaged and to what extent. Therefore, this information cannot be used to estimate how many buildings have been damaged. Also, since debris can also be moved to a different location during early clean-up operations, if they hinder the search and rescue and relief operations, their locations do not indicate with certainty that damage has occurred nearby.

Only a small percentage (10%) of the images collected with the tweets were suitable for damage assessment. Damage grading is, however, only one of the steps of a damage assessment. To really understand the earthquake impact, the damage to the buildings must be correlated to the earthquake intensity at the location, which implies that the position of the building should be directly extracted or inferred from the image. Because of the privacy restrictions on the Twitter accounts, the position of the tweets is not released in the metadata available with Twitter Binder. Hence, the only way to acquire the position of a building is by inferring it using points of reference that appear in the picture, such as landmarks, street names and crossing, and then use Google maps and Google street view to attempt to identify where the image was taken. The damage to the landmarks, such as the Zagreb Cathedral, the fish market, the Petrova hospital, the children's hospital, the Croatian Society of Fine Arts and the Archaeological Museum, was easy to geolocate. However, these buildings were also covered in the media and therefore some of the information was extracted with the tweets was already available from the media coverage. For the other damaged buildings, the manual geolocation was productive in central Zagreb where street and shop names helped identify locations through searches on Google Maps. The process was however very time-consuming because the most recent images available on Google Street View dated back to 2011 and so many shop and streets had changed in the time interval between the capture of the Google Street View footage and the event. The geolocation was even more difficult in the rural villages surrounding Zagreb, such as in Kašina, which were closer to the epicentre and sustained substantial but much less documented damage. In the villages, there were fewer landmarks and points of reference. The identification of churches and governmental buildings (i.e., local municipalities) helped with the geolocation. Also, the available Google Street View footage, which were only a few, was used to "virtually" walk-through the main roads, to see if some of the footage would match the images in the tweets. In general, this technique had limited success for geolocating residential structures. When the analysts were able to unequivocally locate damage, the associated tweet image was mapped. Some of the damages georeferenced are shown in Figure 2-7.

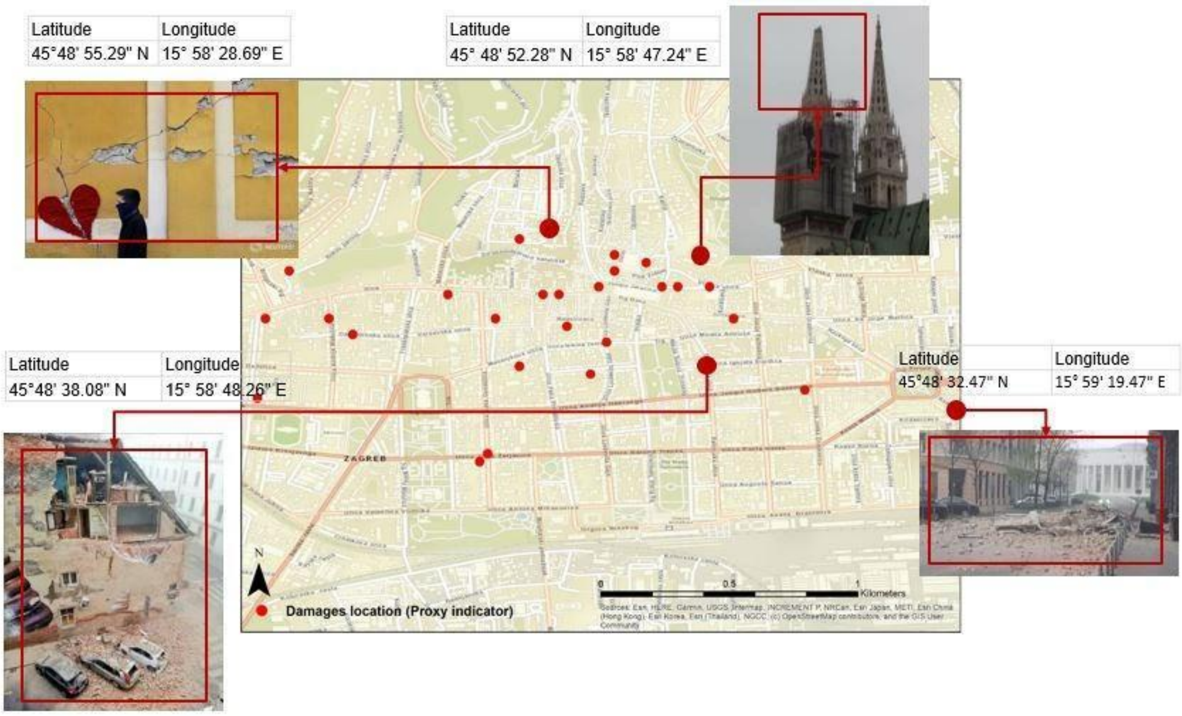


Figure 2-7 – Some of the tweet images georeferenced using the manual geolocation process.

Limitations of using Twitter

The use of Twitter has shown significant limitations which restrict the application of this data source to EEFIT missions.

The lack of accurate tweets coordinates hinders the geolocation of the damaged buildings and, in turn, the quantification of the types of structures that have been damaged and how these are spatially distributed. The location feature is deactivated in most of the Twitter accounts and, even when active, it shows the place where the tweeter is located rather than the location of the tweets and the associated pictures. Without coordinates, the geolocation is done manually, and this is a very time-consuming process. The only alternative to the manual process is to contact the Twitter user and ask the location of the images in the tweet. The team did attempt this and were able to contact one of the photographers from Reuters who indicated the name of the streets where he took the pictures. However, this is also a very long process which implies that substantial time is invested in pursuing these contacts with no guarantee of success.

Also, the Twitter users - who are mainly citizens and journalists - often take pictures that are not always suitable for assessing the damage grade of the photographed buildings. Images of the debris, citizens in the streets, and evacuations may quickly capture the attention of Twitter followers do not help quantify the impact of an earthquake.

Furthermore, the number of tweets per se cannot be used to make a comparative assessment on the overall intensity of damage across locations as the use of Twitter has a biased demographic (i.e., urban areas with younger people would have more tweets, but not necessarily more damage that villages were fewer tweets are recorded).

Facebook and GoFundMe pages
(Authored by: EV)

Facebook and GoFundMe pages have been used to gather information about the damage sustained by buildings in Zagreb and surrounding villages. Several new social groups emerged on Facebook after the earthquake. Posts to these groups were actively followed. The great majority of the posts referred to the damage in the city centre of Zagreb.

A 'social experiment' was also conducted. The users of the Facebook groups were asked to share geolocated pictures of the damage that they could see from their windows while in lockdown. Even though the credentials of the LfE team member who instigated the exercise were provided, the request was often met with scepticism due to the sensitive nature of the information required. Some users were concerned about the necessity of providing geotagged photos since these could give away the location of the evacuated buildings, which were left without surveillance.

Some users asked for the post advertising the social experiment to be removed, others were more cooperative and pointed out that trust could be built within the online community with the direct involvement of a local university. Offers to reach out to the local academics participating in the damage assessment were shared.

Undoubtedly, Facebook is a good resource to gauge how the post-earthquake situation is evolving. The posts shared on Facebook allowed, for instance, to identify the greatest concern for the inhabitants of the city centre of Zagreb. The lack of shoring, the delayed clean-up, the perceived abandonment in the streets of detached building pieces - including elements of cultural importance (e.g., external decorations and statues fallen from churches), were recurrent themes. The Facebook groups were also used by the members to offer help (e.g., exchanging goods – especially furniture) and moral support. At the time of the review of this report (22nd September 2020) all the monitored Facebook groups are still active, and users are still debating on the rapidity of the clean-up operations. Some users reported concerns about the reopening of the tram line in the city centre and expressed concerns that the necessary works would take priority over the clean-up.

GoFundMe pages were also used to obtain photos from the campaign moderators. Some photos were obtained, although their usability for damage assessment was limited because the pictures were often too detailed (e.g., showing small cracks rather than the entire façade of a building). These campaigns often provide images for single or a small number of buildings, which again does not support the comprehensive assessment of the earthquake impact. As for the Twitter data, contacting the users directly is time-consuming and the availability of data depends on the reply of the user.

Limitations of using Facebook and GoFundMe pages

Overall, the monitoring of the Facebook groups and GoFundMe pages provided a wealth of first-hand information about the impact of the damage and the recovery that could have not been acquired using any other sources. However, this is not an ideal means for gathering crowd-sourced data, since the posts of both portals will need to be monitored and, at times, translated. The process is very time-consuming. At the same time, the ability to gather direct information on the location of the damage is very limited, since posts are not georeferenced, and pictures are often to detailed to be able to see the entire façade and thus assess damage remotely.

That said, the existence of these groups is testimony of how much citizens have become involved and interested in the post-disaster process. It is therefore reasonable to conclude that by engaging with the users before-hand, and by partnering up with local institutions, more suitable data could be sourced with the help of groups of citizens on Facebook.

2.4 References

BBC, 2020 - Coronavirus: The world in lockdown in maps and charts

https://www.bbc.co.uk/news/world-52103747

European Commission – CEMS, 2020 https://emergency.copernicus.eu/mapping/list-of-components/EMSN074

3. Seismotectonic Overview

(Authored by: ES; Reviewed by: Prof Marijan Herak)

This section presents the seismotectonic setting of the Northwest of Croatia, significant historical earthquakes in the area and a commentary on the Zagreb earthquake.

3.1 Sources of information

- Seizmoloska Sluzba (Seismological Service) - Figure 3-1

  https://www.pmf.unizg.hr/geof/seizmoloska_sluzba

  https://www.youtube.com/watch?v=FI4Vqm_FvGI&t=2s

  https://twitter.com/seizmo_hr

- Literature review - journal papers
- Interview with Prof. Marijan Herak from the Faculty of Geophysics, University of Zagreb

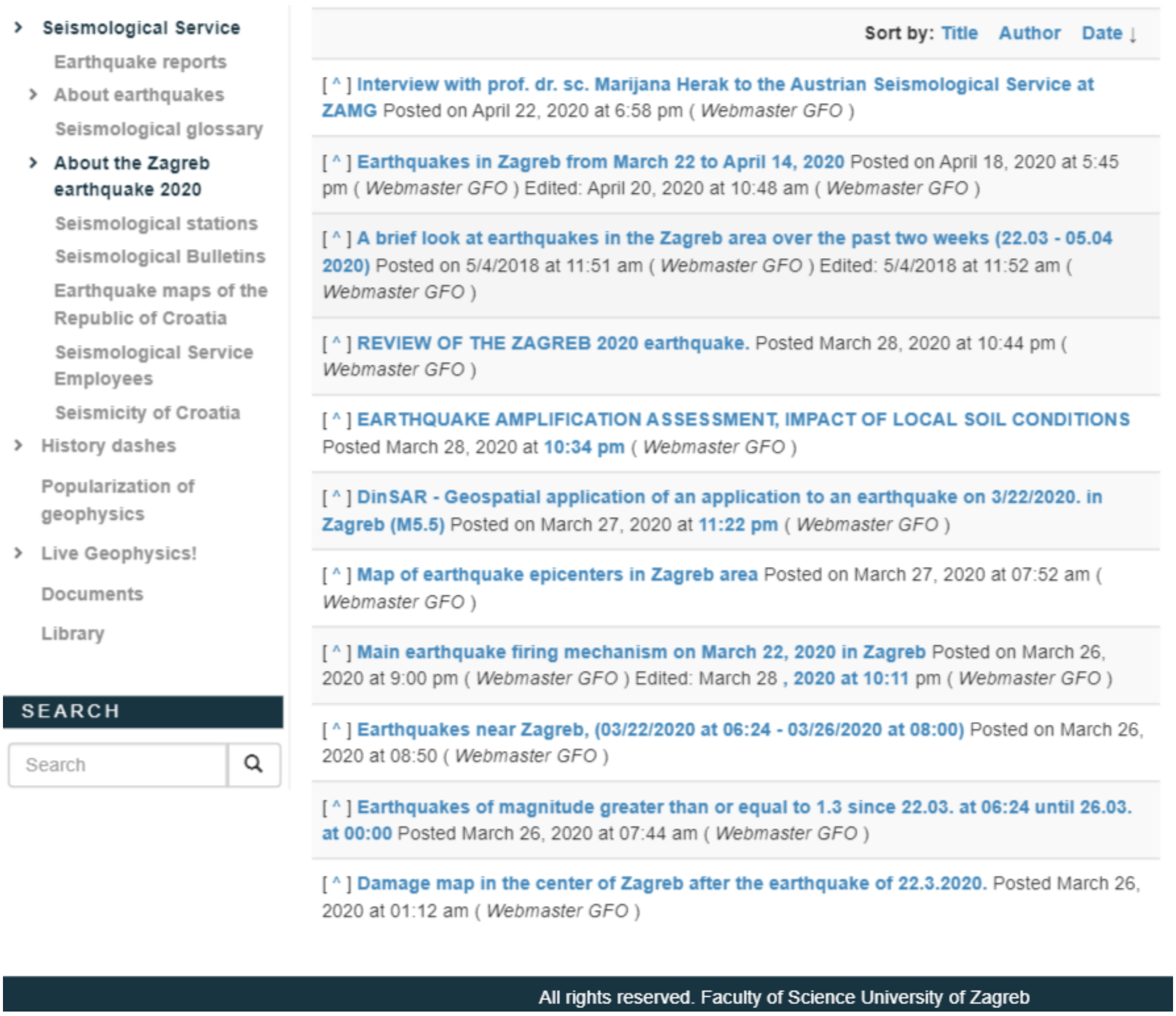


Figure 3-1 – A dedicated page for the Zagreb earthquake online at the Faculty of Science website

3.2 Historical records of significant events in the region

Although the northwest region is not the most earthquake-prone in Croatia, it is seismically the most vulnerable due to its economic and population exposures as it includes the capital, Zagreb. It covers 30% of the area of the country, with 45% of Croatia's population and over 55% of its national gross product. Tectonically, it lies on the border zone between the Alps, the Dinaric Alps and the Pannonian basin, at the "triple junction" between the Peri Adriatic, Balaton and Drava transcurrent faults, all playing an essential role in the Neogene-Quaternary tectonics in this and the surrounding regions (Herak et al., 2009).

Records on historical seismicity rely heavily on reports by Kišpatić (1888, 1891, 1892, 1905, 1907) and Ribarič (1982). These reports identified several strong earthquakes with epicentral intensities up to IX on the MCS in the region. The Medvednica–Zagreb area experienced strong seismic activity in the 18th, 19th and at the beginning of the 20th century. The strongest earthquakes occurred on 13 October 1775 with the epicentral intensity of VII–VIII on the MCS, destroying a church in Bedekovčina.

The great 1880 Zagreb earthquake (Mw 6.3) killed two people but damaged almost every building in Zagreb (Atalić et al. 2019). This Mw 6.3 earthquake on 9 November 1880 had an intensity VIII on the MCS. The epicentre of this event was in the village of Planina, about 17 km northeast of Zagreb, where almost all masonry buildings were destroyed. Liquefaction and mud volcanoes were observed in the villages in the valley of the Sava River. The earthquake was felt over an extensive area, even in Dubrovnik, some 400km away. This earthquake is one of the most important Croatian earthquakes which practically defines the lower hazard bounds in the Zagreb metropolitan area.

Damage to 1758 houses was officially reported, with a 13% collapse rate (Simović, 2000). Zagreb was a town with a population of around 30,000 at the time (Herak et al., 2009) and many citizens deserted the city after the earthquake and never returned. It also caused economic damages estimated at between 2M Forints (only housing) to 50M Forints for the total damages (equivalent to approximately 50% of GDP at the time).

Two other damaging earthquakes in the Zagreb region include a Mw5.6 (17 December 1905, MMI VII-VIII) and Mw6.1 (2 January 1906, MMI VII–VIII). Almost all houses were destroyed in Planina village (Kišpatić, 1905, 1907). Heavy damage occurred also in Čučerje, Vugrovec and Kašina (some 15 km NE from Zagreb city centre), where churches and many houses were ruined (Mohorovičić, 1908).

All three earthquakes are shown in the isoseismal maps below (Figure 3-1 - Figure *3-3*)

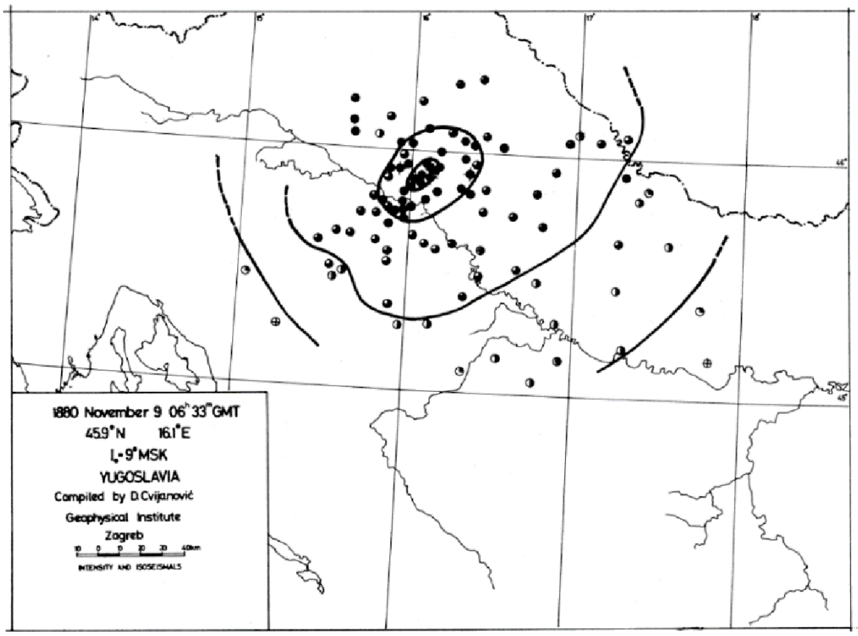


Figure 3-2 – Isoseismic contour for the great 1880 Zagreb earthquake (Mw 6.3).

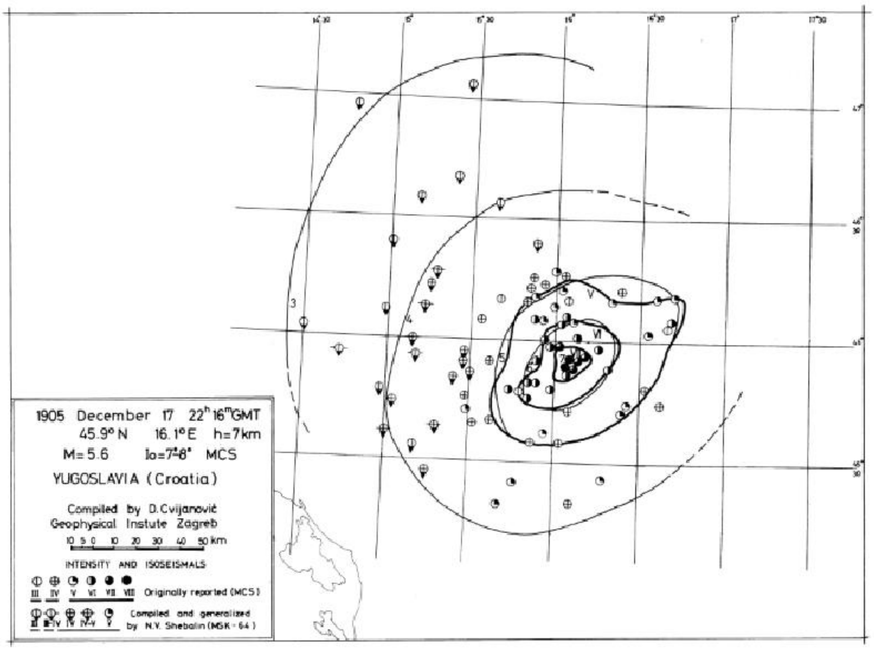


Figure 3-3 – Isoseismic contour map for the 1905 Zagreb earthquake (Mw 5.6)

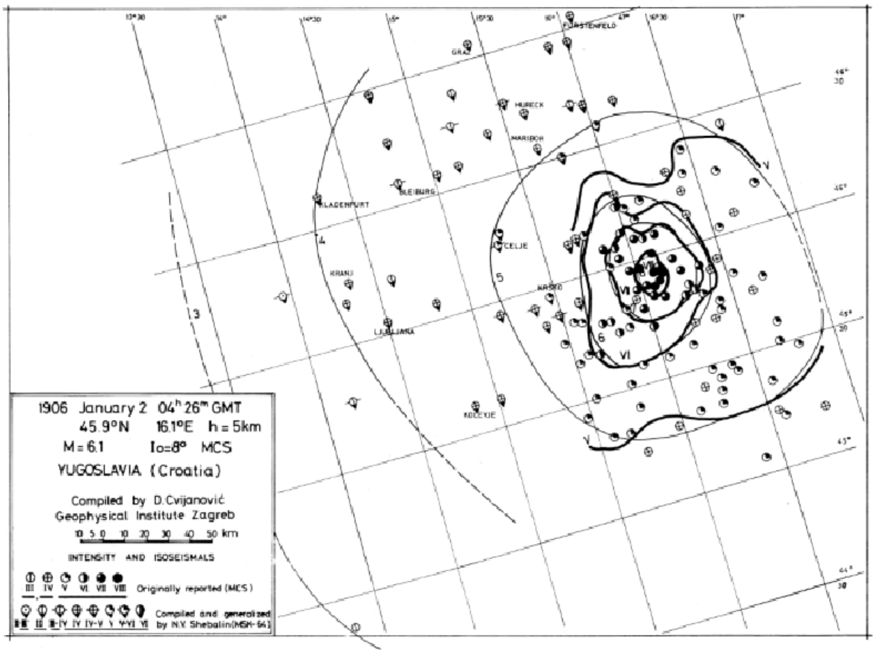
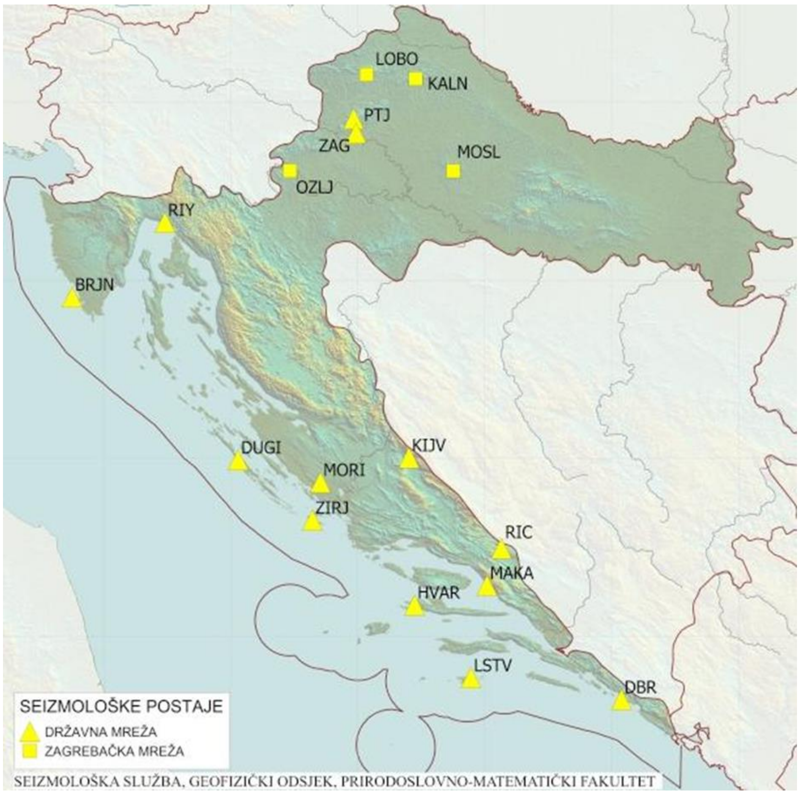


Figure 3-4 – Isoseismic contour map for the 1906 Zagreb earthquake (Mw 6.1).

The great Zagreb earthquake of 1880 is very well documented (Sigmund et al. 2020), due to efforts of the Earthquake Committee founded by the Academy immediately after the earthquake. This earthquake is the first Croatian earthquake for which focal depth (16 km) was ever estimated based on macroseismic and other observations. All three earthquakes prompted local authorities to finance the installation of the Vicentini-Konkoly seismograph in Zagreb (Herak and Herak, 2007).

All felt events in the area have occurred below 6 km, and recent seismicity suggests the seismogenic layers extend to depths of about 16 km (Herak et al., 2009). The permanent seismograph network in Croatia now consists of the stations mapped in . Additionally, 15–20 stations are deployed in the framework of research projects or contracts with industry.



Station Name	Location
BRJN	Brijuni
DBR	Dubrovnik
DUGI	Dugi otok
HVAR	Hvar
KALN	Kalnik
KIJV	Kijevo
LOBO	Lobor
LSTV	Lastovo
MAKA	Makarska
MORI	Morići
MOSL	Moslavačka gora
OZLJ	Ozalj
PTJ	Puntijarka
RIC	Ričice
RIY	Rijeka
ZAG	Zagreb
ZIRJ	Žirje

Figure 3-5 – Map and list of the stations of the permanent seismograph network in Croatia.

There have been at least 120 damaging earthquake events in Croatia since 1900 in CATDAT (Daniell, 2020) indicating at least one damaging earthquake on average per year. Epicentres of historically and instrumentally recorded earthquakes with estimated magnitudes equal to and greater than M 5.4 in the Zagreb regional area are shown in Figure 3-6.

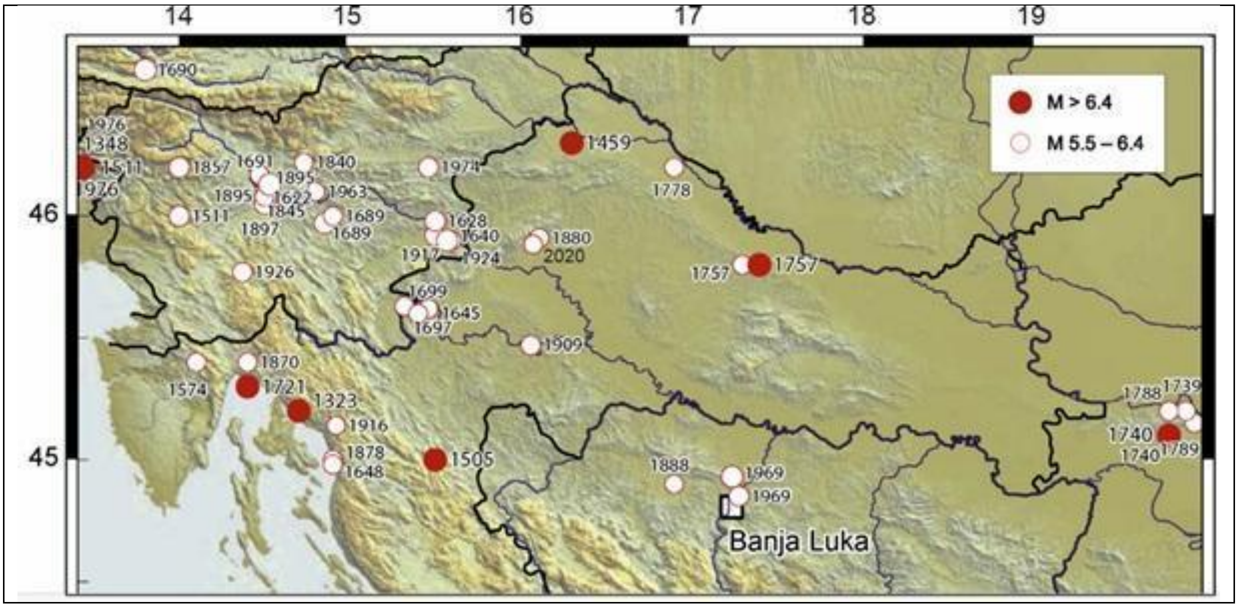


Figure 3-6 – European-Mediterranean Earthquake Catalogue (EMEC), taken from Ustaszewski et al. (2014) amended to include the Zagreb Earthquake 22/03/2020 (Tomljenović, B., 2020).

Some other notable earthquakes in the wider region include the Dubrovnik earthquake in 1667 estimated to have destroyed 5,000 homes and caused 3,000 deaths. If the same event were to occur today, the damages in today's exposures are estimated to be around $7 billion (Daniell and Schaefer, 2014). The Ston–Slano earthquake sequence, with a Mw 6 mainshock occurring on the 5 September 1996 is the largest and most important earthquake in the southern Dalmatia zone, i.e., Dubrovnik epicentral area, since the catastrophic Dubrovnik earthquake of 1667 (Govorčin et al., 2020). The mainshock was felt at distances of up to 400 km away and caused devastation at several localities in the epicentral area. The municipality of Ston was most affected, and in total, approximately 1,400 buildings were damaged, of which 474 were uninhabitable. The peak horizontal ground acceleration of 0.64g was recorded in Ston, the largest ever observed in Croatia (to date, as the Zagreb earthquake recordings have not been released).

In 2004, an Mw5.2 event (MMI VI to VII) occurred in a rural area of neighbouring Slovenia, damaging 1700 buildings, with total funding for the implementation of reconstruction estimated at $88M (2004). The Skopje earthquake 1963 triggered the inclusion of seismic actions in the Croatian building code in 1964 and lastly, the 1979 Montenegro earthquake, which also triggered a change in the Croatian building code. Most of the damage due to this earthquake occurred in Montenegro and Albania; however, 1,071 buildings were damaged in Dubrovnik, Croatia, including the Walls of Dubrovnik. In villages in Konavle and Župa Dubrovačka, south of Dubrovnik which were built on unsecured mountain slopes, 80% of houses were uninhabitable.

3.3 Background seismicity of the region

Error! Reference source not found. is taken from Herak et al. (2009), showing the fault plane s olutions of past earthquakes in the region since 1938. Calculated and available fault-plane solutions (FPS No. 5, 10, 12, 14 and 22 above) indicate seismogenic activity on (1) reverse ENE–WSW striking faults and (2) along dextral or sinistral NW–SE and ENE–WSW striking faults, respectively. The hypocentres in the western part of this area lie in a steeply SSE-dipping zone in agreement with the Quaternary active SE dipping reverse fault mapped along the northern margin of Mount Medvednica. This fault corresponds well in orientation and kinematics with the NE–SW striking and SE-dipping nodal plane of FPS No. 5 indicating reverse, top-to the-NW hanging wall motion direction. The seismogenic zone of the North Medvednica fault was most likely the cause of numerous weaker and stronger earthquakes between the last catastrophic Zagreb earthquake of 1880 and the earthquake of March 22, 2020. Considering the length of this seismogenic zone by extension (about 20 km) and the depth to which it reaches below the surface (about 12 km), the seismogenic potential of this zone, or the maximum expected magnitude of the earthquake it can cause is estimated to be Mw6.5 (Tomljenović, B., 2020).

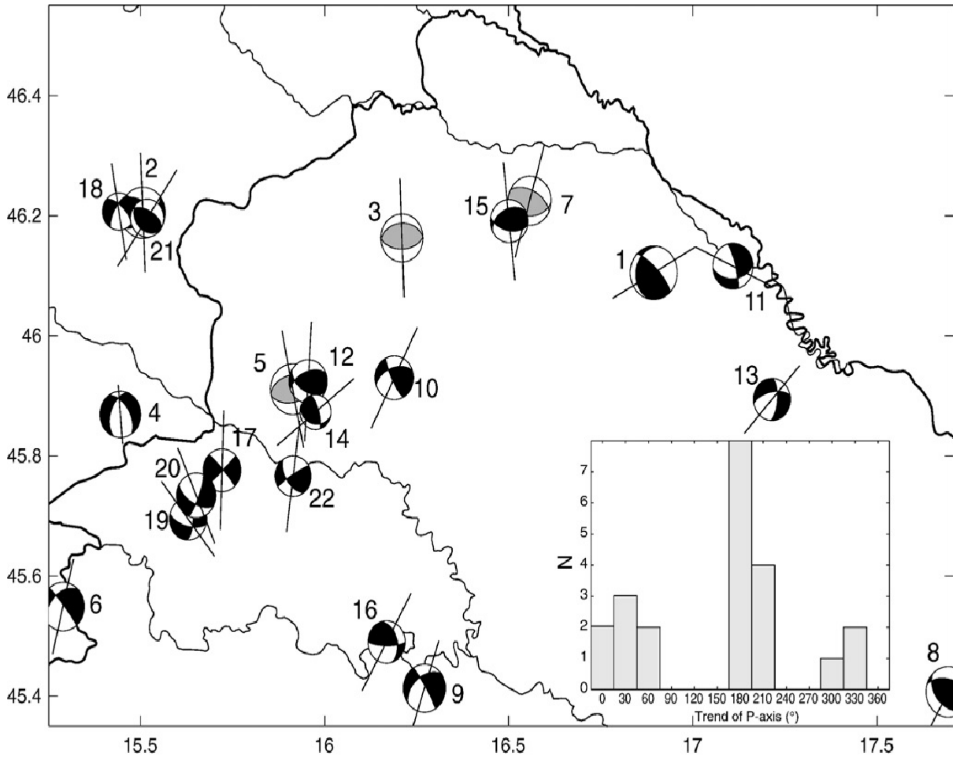


Figure 3-7 – Map showing fault plane solutions past earthquakes in the region since 1938. The beach-balls' radius is scaled with magnitude. The bars are in the direction of the P-axis, their length being proportional to its horizontal projection. The number adjacent to each earthquake corresponds to numbers in Table 1 of Herak et al., 2009. The histogram (inset) shows the distribution of P-axis trends (clockwise from N).

3.4 The Earthquake of March 22, 2020

3.4.1 Shakemap

At 06:24 (CET) on 22nd March a Mw5.4 earthquake struck the northwest of Croatia, with epicentre in the *Medvednica–Zagreb area*, near the village of Markuševec and with a fault rupture depth of 10 km. Figure 3-8 shows the peak ground acceleration contour map derived from intensity-PGA conversion equations by the USGS.

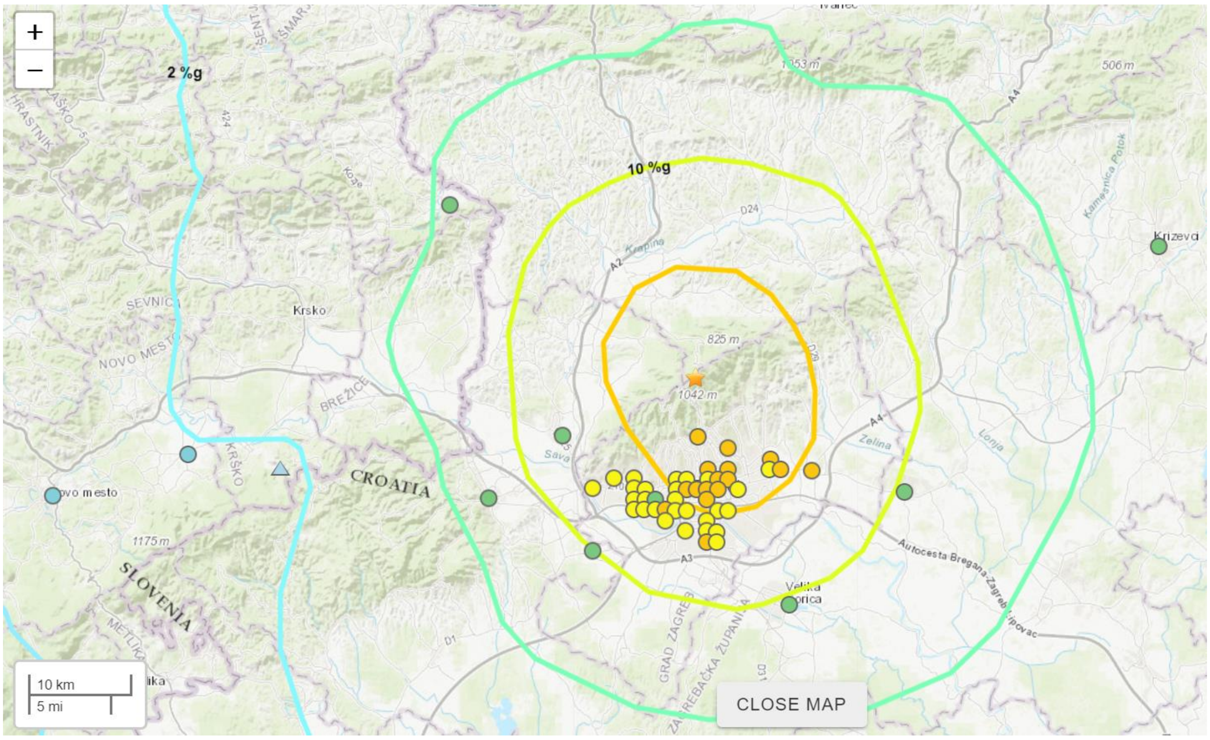


Figure 3-8 – Map of predicted surface ground motions expressed as peak ground accelerations g = 9.81ms2. The dots show locations of 'did you feel it? reports which help constrain the Shakemaps. Source: USGS

3.4.2 Aftershocks distribution

The locations and magnitudes of earthquakes of Mw1.3 and greater in the epicentral area of the Zagreb earthquake were recorded and published on the Faculty Geophysics website (Figure 3-9).

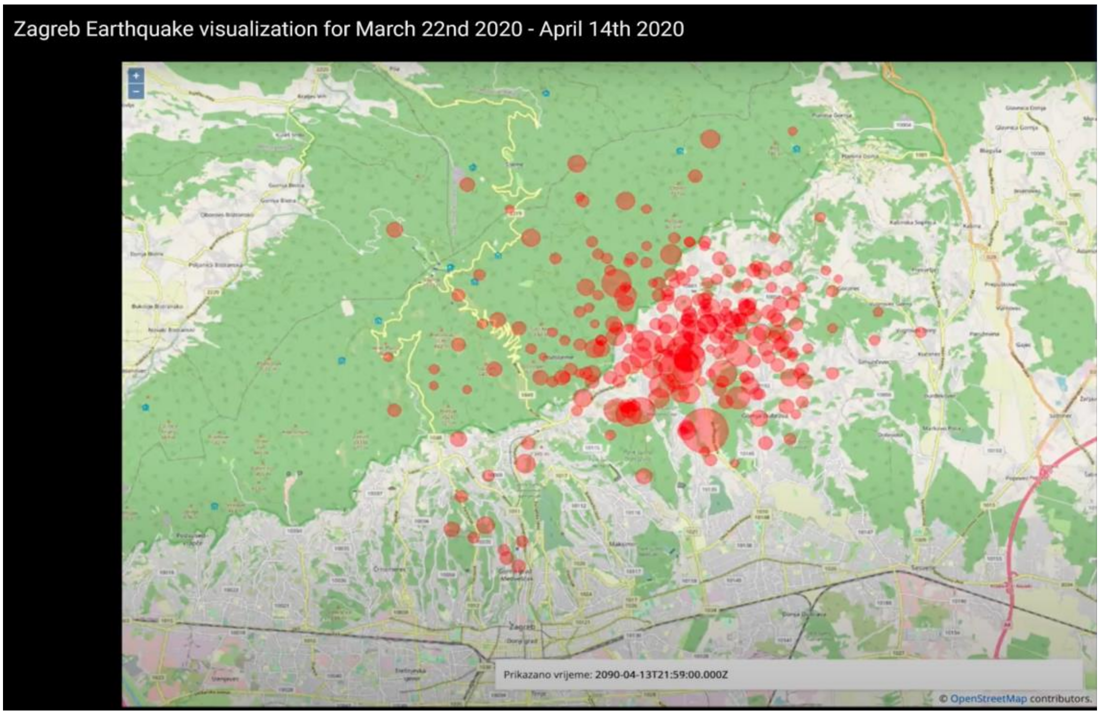


Figure 3-9 – Visualisation of the epicentres of the main and aftershocks of the Zagreb Earthquake (PMZ,2020)

3.4.3 Analysis of the Zagreb Earthquake

Based on the analysis of the direction and amplitude of the first P-wave displacement taken from the 144 seismograms recorded in Croatia and across Europe, the team of seismologists, working from home at the time of the lockdown, calculated the focal mechanism of the strongest earthquake that occurred on March 22, 2020 (Figure 3-10).

Professor Marijan Herak from the Faculty of Geophysics, Faculty of Science, University of Zagreb noted that it was more difficult for the seismological survey to work in emergency mode, to organise field measurements, to install provisional stations and to speak to the media in the middle of the lockdown.

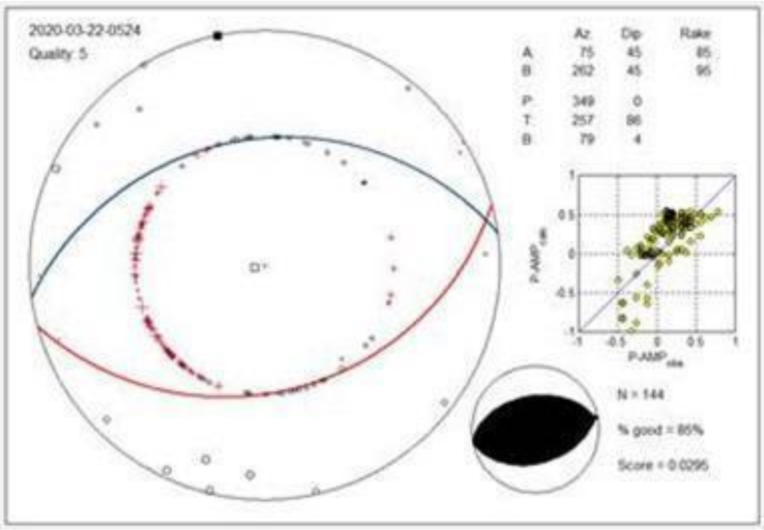


Figure 3-10 – Focal mechanism of the main shock calculated with the direction and amplitude of the first P-wave displacement taken from the 144 seismograms recorded in Croatia and across Europe.

The earthquake focal mechanism plot shows the orientations of two planes of blue and red traces, one of which is a seismic source of this earthquake. The first P-wave compression hits are marked with red crosses, and the first tension hits with black circles. The axis of the highest tectonic pressure (P-axis, black box) is horizontal with the provision of SSZ-JJI, while the axis of lowest pressure (T-axis, white square) is vertical.
This information was posted on website of the Faculty of Geophysics (http://www.pmf.unizg.hr/geof/seizmoloska_sluzba/o_zagrebackom_potresu_2020? @ = 1lq0o # news_97581)

The local seismologists identified two faults where an earthquake could have occurred, as well as how the fault planes moved relative to each other. The data indicates that the earthquake occurred on a reverse fault whose fault plane falls at an angle of 45 ° to the north-northwest (blue arc in Figure 3-10) or south-southeast (red arc in Figure 3-10). The CMT solutions (Centroid Moment Tensor) shown in Figure 3-11, derived by international agencies using analysis of the waveforms attained from seismograms reached the same conclusions about the responsible focal mechanism.

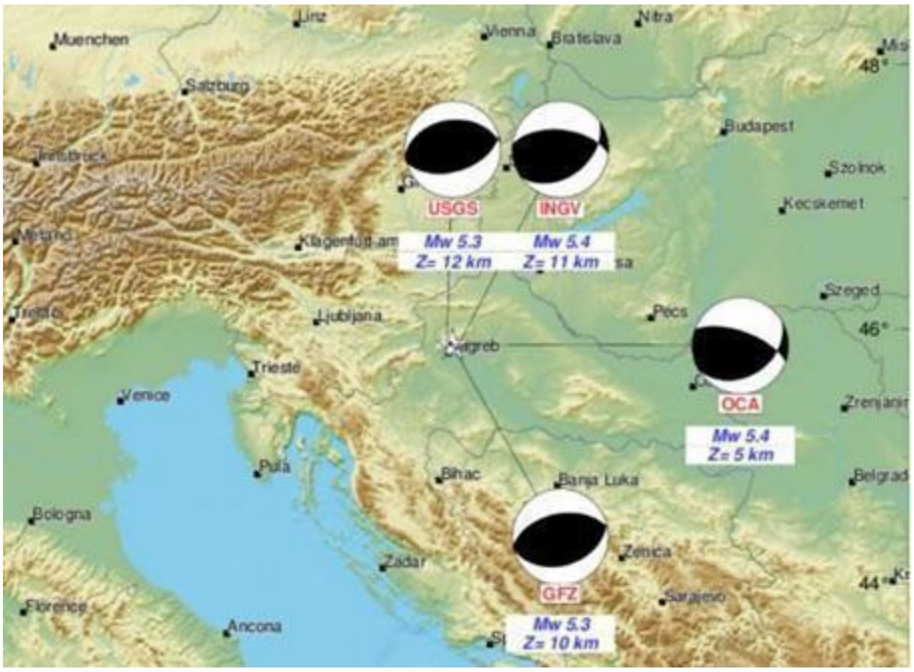


Figure 3-11 – Map published by the European Mediterranean Seismological Center (EMSC) which also shows CMT solutions according to USGS (USA), INGV (Italy). OCA (France) and GFZ (Germany).

By comparing seismological data on the main earthquake (i.e., the location of the focal point and the orientation of two nodal planes on the focal mechanism, one of which represents an earthquake source) and the data on the geological structure of the Medvednica, it can be assumed, that the reverse fault, or reverse faults belonging to the seismic zone of the North Marginal Medvednica fault, is the seismogenic earthquake source responsible for the main shock and the aftershocks. The surface fault of this seismogenic zone, which extends along the northern edge of Medvednica (Figure 3-12) , was recorded by geological mapping and interpretation of seismic reflection profiles, dipping to the SE under the central part of Medvednica (Tomljenović, B, 2020).

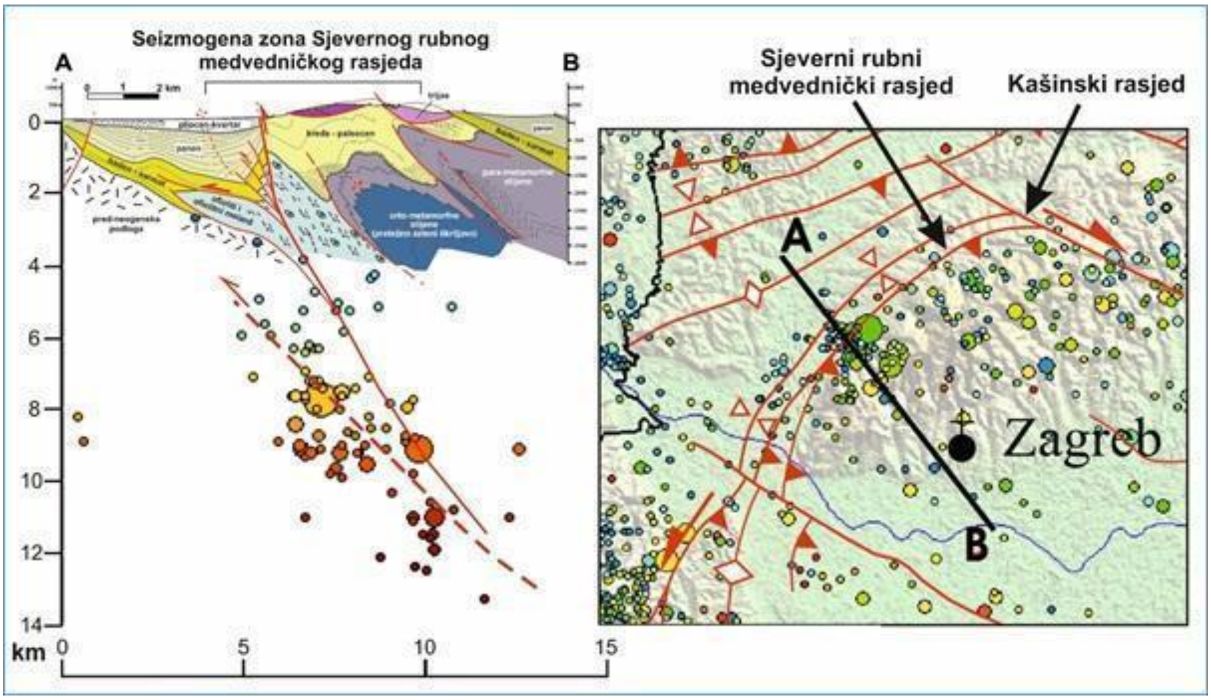


Figure 3-12 – Left: Seismotectonic profile through Medvednica and the seismogenic zone of the North Marginal Medvednica fault, where projected foci of earthquakes recorded in the period 1970 - 2016, in the area around the plane of the profile 10 km wide. Right: Traces of two major seismogenic faults in the Medvednica area, based on geological and geophysical studies (source: Tomljenović, B., 2020).

3.4.4 Surface Fault Rupture

In this event, the fault ruptured about 10 km below the surface. One interpretation of the surface displacement caused by the earthquake was carried out by Dr. Sotiris Valkaniotis , who posted it on Twitter. In Figure 3-13, the author shows that the Sentinel 1 interferogram reveals a surface displacement of ~2-3 cm over Mount Medvednica and that the crustal deformation hints at a deep rupture along the Bistra fault.

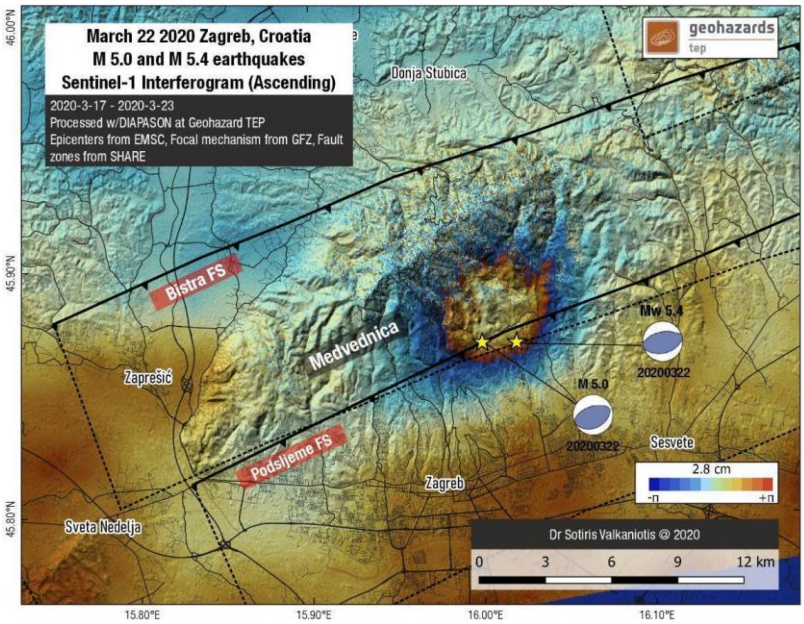


Figure 3-13 – Surface Displacement caused by the earthquake. Author: Dr. Sotiris Valkaniotis from the National Observatory of Athens - Geohazards TEP.

In addition to Dr. Valkaniotis' post, the photograph in Figure 3-14 was posted on EMSC (and reposted on other outlets) on numerous platforms associating the shown movement to the Markusevec fault. Still, the location of this slope failure has not been found. The photo almost certainly shows a slope that has undergone failure, but it is unclear if it is due to the ground shaking from this earthquake.

Figure 3-14 – Slope failure tagged as 6km from the epicentre on the EMSC website but not supported in any other official sources. https://www.emsc-csem.org/Earthquake/Gallery/?id=840695

These two posts were the only information the team were able to find online relating to surface deformation caused by the earthquake. In our interview with Professor Herak, he stated that to his knowledge, there was no evidence of surface rupture as the fault rupture was about 10 km below the ground surface. This difference in the data collected highlights a potential issue with relying on posts from online sources which makes the verification process time consuming but necessary.

3.4.5 Strong ground motion characteristics

Not published at the time of completion of this report.

3.4.6 Site response and geotechnical observations

No official data on-site response and geotechnical observations were posted at the time of publication. Still, a self-directed analysis by Dr. Davor Stanko from the University of Zagreb was found online.

One study (in Croatian) was found online by Dr. Davor Stanko from the Faculty of Geotechnical engineering at the University of Zagreb. He had carried out his study on the likely soil amplification effects on three damaged buildings and locations based on estimated ground motions (no data have been published) and his understanding of the local site conditions. Based on his calculations, the earthquake amplification estimation in the Zagreb earthquake-affected area, assuming a peak acceleration of 0.159-0.185g is as follows: "The amplification of seismic motion on the surface in the Podsljeme[1] area and central Zagreb area is approximately 1.5–1.8. The amplification of seismic motion on the surface of the alluvial Sava River is approximately 1.3 due to nonlinear behaviour of sand and gravel on a strong incident seismic motion. Finally, the amplification of seismic motion with a resonant period was estimated to be about 2.1-2.2 in the affected area. He goes on to say that "many distressed single-family homes have not been built to a building code considering the seismic calculations and the impact of local soil conditions, i.e. local amplification"(Stanko, 2020).

3.5 Conclusions

Every effort was made to find information on the fault rupture, recorded ground motions and any geotechnical findings related to this event. Still, these have not been available at the time of publication of this report.

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[1] city district situated in the foothills of Zagreb's mountain Medvednica about 5km north of the centre of Zagreb, include neighbourhoods Šestine, Gračani, Prekrižje, Mlinovi, Bliznec, Dolje, Remete, Markuševec.

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4. Overview of the Building Code and Inventory in Croatia

(Authored by: TR)

4.1 Sources of information

- Journal papers
- Seizmoloska Sluzba (Seismological Service)

In this section, the development of building codes in Croatia, a description of the different building types and distribution in the city and the surrounding region are presented. This section does not address the issue of code compliance, as no information was found in this regard, particularly for buildings built after the post-Soviet period, in the city of Zagreb and surrounding rural areas.

4.2 Development of building codes in Croatia

The first technical code for the calculation of building loads was introduced in Croatia in 1946. The Croatian building design codes for reinforced concrete buildings first explicitly considered seismic actions in 1964, when it was updated following the damage observed in the 1963 Skopje earthquake. A seismic hazard map was introduced with the 1964 code. The seismic component of the code was further modified in 1981, after the occurrence of the 1979 Montenegro coast earthquake. During the application of the 1981 seismic code, the hazard map was updated in 1981 and 1988 (Šavor Novak et al. 2019).

Between 1992 and 1998, Eurocodes for structural design were introduced into the Croatian building regulation, but due to difficulties of harmonization with national legislation, they maintained a pre-standard status (ENV label, Kalman Šipoš and Hadzima-Nyarko, 2018). The implemented Eurocodes only applied to the design of masonry and reinforced concrete buildings, with older Croatian standards still applicable to timber and steel building design. Between 1998 and 2013 the Eurocodes were systematically integrated into the Croatian building codes, but for a time, use of both the old Croatian Building codes and Eurocodes was permitted. Use of the Eurocodes in Croatia became mandatory in 2008, with the new technical codes for Concrete Structures (OG No. 101/05, 85/06, 64/07, NN 139/2009) and Masonry structures (OG No. 01/07) being issued to support this. However, these still adopted the European pre-standards (ENV) with national specifications (Radić, et al. 2008). For timber and steel building design, instead, use of the older Croatian building standards continued, effectively until 2013, when the full Eurocode EN standards, with Nationally, determined parameters and annexes, were adopted and became mandatory in Croatia.

In terms of seismic code, the implementation of Eurocode 8 in Croatia started in 1998 (ENV 1998 version) following the Construction Product Directive (89/106/EEC) (Zamolo, 2008). The accompanying National Application Document (NAD, HRN ENV 1998-1-1) adopted most of the parameters (boxed values) recommended in ENV 1998, without modification (Zamolo, 2008). However, one issue was the seismic hazard map for Croatia, which was not probabilistic, dated from 1988 and expressed hazard in terms of Macroseismic Intensities (MSK-94). Hence, for EC8 (ENV) to be adopted, the intensity values were converted to peak ground acceleration values using several empirical formulae. The final adopted conversion, as presented in Zamolo, (2008) is reproduced in Table 4.1.

Table 4.1 – Conversion between MSK-64 and average maximum pga adopted in the NAD, HRN ENV 1998-1-1.

MSK-64	VI	VII	VIII	IX
pga (g)	0.05	0.1	0.2	0.3

According to Zamolo (2008), the seismic hazard map was supposed to represent a 500-year return period, and a building design life of 100 years is adopted instead of the 50 years typical in EC8 (ENV1998). Accordingly, the seismic hazard map is supposedly representing a significantly lower design seismic load, i.e. with 18% exceedance probability during the 100-year design life or a return period of 252 years for an assumed 50-year design life. However, the same importance factors were used as in ENV1998. Only three soil types were adopted in this code and a single spectral shape for each soil class. According to Zamolo (2008) the difficulty in adhering to all the design requirements and material specifications of the high ductility class (DCH) in the ENV code resulted in most reinforced concrete buildings being designed for low or medium ductility (DCL and DCM).

In the first two years of the Eurocode 8 ENV implementation, the technical regulation for concrete structures allowed building designs to either follow the old regulations or Eurocodes. This was done to allow for the training of engineers in the Eurocodes and facilitate the transition to the new code (Zamolo, 2008). In 2013, Eurocode 8 (EN standard), with appropriate nationally determined parameters and new seismic hazard map, expressed in terms of PGA, and consistent with EC8, was implemented and became mandatory in Croatia. The current seismic hazard map for Croatia was compiled in 2011 and shows PGA values on bedrock according to EC8 with 10% probability of exceedance in 50 years and 10% probability of exceedance in 10 years. This map shows the entire coastal region and north-west part of Croatia as having high seismic hazard, with Dubrovnik-Neretva County having mean pga = 0.3g (for 475 year return period). The probability of earthquakes with peak ground acceleration of 0.3g or above includes 5.53% of the territory where approximately 21.02% residents live in the country. According to the 475-year hazard map shown in *Table 4.1*, Zagreb has a PGA of 0.259g for the return period of 475 years.

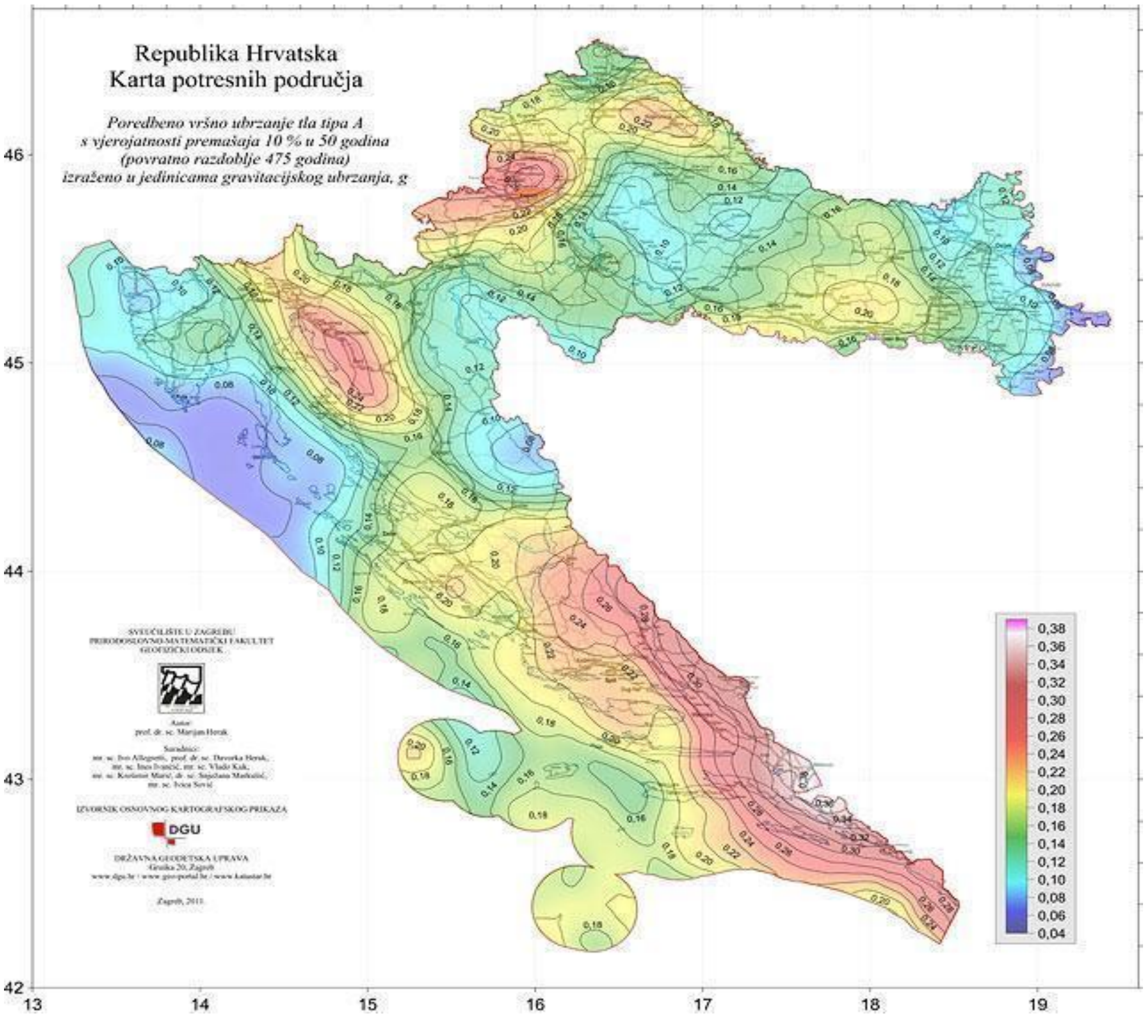

Figure 4-1 – 475yr Return Period Seismic Hazard Map for Croatia

Table 4.2 in Section 4.4 presents a summary of the key dates in seismic design and indicative values of the design base shear over time, with respect to current values.

4.3 Building Exposure

Several efforts have been conducted to classify buildings for seismic risk assessment and to create exposure databases for Croatia and several of its cities. Amongst others, notable examples include the exposure databases presented for Croatia by Crowley et al. (2014), Atalić & Hak (2014), Atalić, et al. (2018b); by Atalić et al. (2018a) for Zagreb; and by Pavić et al. (2019, 2020) for Osijek.

As in most countries, inventory data available from national statistics institutes is presented at the dwelling level, rather than the building level. For example, as reported in Pavić et al. (2020), the Housing and Population Census of 2011 showed the presence of 2,246,910 apartments in Croatia with an average number of members per household being 2.87. Furthermore, the national statistics are not designed to incorporate all the features of a building that are of interest for its seismic assessment. Hence, though information on construction material and age is available, data on the lateral load resisting system is not. The lack of more detailed information about the building typology has created some difficulty in assembling an exposure database suitable for use in seismic assessments (Atalić et al. 2019, Pavić et al. 2020).

In addition to the above, the data available through the census focuses on residential properties. Atalić et al. (2019) note that critical infrastructure facilities have been systematically ignored in past exposure evaluation projects. To overcome these limitations, recent exposure studies for Croatia adopt a range of approaches to develop building exposure databases suitable for use in seismic risk assessment. These approaches include the use of remotely sensed data, detailed structural surveys and expert judgement.

The main exposure models are not reviewed in detail here but have been looked at by the EEFIT Team in order to:

1. Determine how best to classify the buildings for which there are images of damage available (see Section 4.4).
2. Obtain an inventory of the buildings in Zagreb and other damaged towns, from which to potentially develop damage statistics.

Hence, the following sections focus on the determination of factors determining building classes that are representative of earthquake fragility and for use in the damage assessment, with an interest on Zagreb.

4.4 Building Classification

The majority of Croatian residential housing is constructed of reinforced concrete (RC) or masonry with only a few timber and steel buildings in existence. According to Crowley et al. (2014), the main types of residential buildings in urban areas in Croatia fall into the following categories:

- Masonry buildings with RC floors (23%), or with timber floors (2%).
- RC wall buildings built before 1981 (23%) or after 1981 (19%),
- Reinforced or confined masonry buildings (18%),
- RC moment resisting frames built before 1981 (9%) or after 1981 (6%)

A key determinant of the performance of these structures in earthquakes is their level of seismic design. In the review of building codes, key dates determining significant changes in the seismic code can be identified, summarised as per Table 4.2.

Table 4.2 – Key dates in the seismic design of buildings in Croatia, and indicative values of the design base shear with respect to current values.

Date	**Seismic Code level**	**Indicative design seismic base shear as a % of EC8 (2013) Code in Croatia (Šavor Novak et al. 2019)**
≤1963	No seismic code (NC) – some wind loading considered	<10%
1964-1980	Low seismic code (LC) – low values of lateral seismic forces included in the design	30-50%

Date	Seismic Code level	Indicative design seismic base shear as a % of EC8 (2013) Code in Croatia (Šavor Novak et al. 2019)
1981-1997	Medium seismic code (MC) – lateral seismic forces included in the design and some seismic detailing (capacity design not present)	30-50%
1998-2012	Medium to High seismic code (Eurocode 8 ENV) (MHC) – modern seismic code applied, with capacity design principles, but seismic hazard levels less than in 2013 EC8 EN.	75-100%
≥ 2013	High seismic code (Eurocode 8 EN) (HC) – modern seismic code applied, with capacity design principles	100%

Hence, according to Crowley et al. (2014) exposure model, it is expected that at least 75% of all buildings in Croatia have either no or inadequate seismic design. This trend is reflected in the city of Zagreb, where Atalić et al. (2019) report that one-third of its building stock was built prior to 1964, having no seismic design, and more than half of the building stock was built between 1964 to 2013 and designed with seismic forces a few times lower than those specified in the current building codes.

Table 4.3 presents a summary of the dominant construction techniques in Croatia over time, as collected from several literature sources and Croatian exposure studies. It is interesting to note that between 2006-2009 there appears to be dominance in RC construction. This is assumed to be due to the availability of good technical standards for the design of these structures in the Croatian codes.

Recent risk studies for Zagreb have conducted specific exposure evaluations. A study (Atalić et al. 2018a) has categorised buildings into 14 classes. These are defined as unreinforced masonry buildings (URM), buildings with reinforced concrete walls (RC2), concrete frame buildings with infills and confined masonry (RC4), large panel reinforced concrete buildings, so called “cans” (RC5), reinforced concrete mid-rise and high-rise buildings (NEB) combined with letters L (low-rise, 1-3 storeys), M (mid-rise, 4-7 storeys) and H (high-rise, 8+ storeys) added to describe the building height. In the second phase of the study, a building categorisation scheme with 42 typologies was introduced. These extended the 14 building categories to include additional information on the structural system, construction period and specific local construction practices. In this respect, four construction periods accounting for different design categories (codes). The seismic code date ranges adopted in that study were: PC before 1964 (precode); LC 1964-1981 (low code - low seismic resistance), MC 1981-2005 (medium code -medium seismic resistance and rigorous design conditions, e.g., ductility), and HC after 2005 (high code with graduate introduction and application of Eurocode 8). These age ranges differ slightly in the later thresholds with those presented for Croatia in Table 4.3, and are more specific to Zagreb. In this study, detailed building class profiles were produced, that gave a pictorial and descriptive summary of the typical building classes and their characteristics.

Table 4.3 – Predominant construction materials and techniques for building in Croatia across time, according to several literature sources.

Date	Seismic design code level	Construction characteristics
≤1940	NC	Unreinforced masonry buildings (URM) were built with brick or stone, and their walls were usually 25–38–51 cm (brick) and 30–50 cm (stone) thick. Floor structures were of wood beams, or, at the end of the period, of concrete elements (ribbed concrete floors). (Pavić et al. 2020)
1941-1963	NC	1920 monolithic reinforced concrete floors were introduced in masonry buildings (Šavor Novak et al. 2019). 1945-1963, monolithic reinforced concrete floors were predominantly used in masonry buildings (Kalman Šipoš and Hadzima-Nyarko 2018). No confining elements in masonry buildings (Šavor Novak et al. 2019). In addition to the use of traditional techniques and materials, new materials started to be used, such as reinforced concrete (RC) (Pavić et al. 2020)
1964-1980	LC	Masonry buildings were systematically built with horizontal tie-beams and vertical tie-columns to provide confined masonry buildings (Kalman Šipoš and Hadzima-Nyarko 2018) RC structures were built lighter and thinner, and walls were made with minimum structural thicknesses of 16 and 18 cm (Pavić et al. 2020)
1981-1997	MC	Masonry, RC structures, steel, and laminated wooden Structures (Pavić et al. 2020). A rise in illegally constructed buildings and extensions added to existing buildings without proper checking (Šavor Novak et al. 2019).

Date	Seismic design code level	Construction characteristics
1998-2005	MHC	Masonry, RC structures, steel, and laminated wooden Structures (Pavić et al. 2020)
2006-2012	MHC	The load-bearing structure of the buildings was mostly reinforced concrete (Pavić et al. 2020)
2013-	HC	All modern construction materials used (Pavić et al. 2020)

4.5 References

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5. Building Damage Assessments

(Authored by: VP, AB, HM, EV, ES)

5.1 Sources of information

- Images from Twitter
- Online newspaper articles
- Facebook (all museums had a dedicated FB page)
- Drone footage found on YouTube from MOHR and the general public
- GoFundMe pages
- Press releases from the Ministry of Construction and Physical Planning

In this section, an overview of the performance of buildings during this earthquake is presented, including those inside the city of Zagreb and the surrounding villages. The report does not include any assessments of infrastructure damage as none have been reported (or found). The Krško nuclear power plant (40km away from the city) was reported safe and was not affected by the earthquake. There have been reports of structural damage to twelve hospitals, but the data obtained on critical infrastructure has been sparse. A separate section on the performance of heritage and important (educational, cultural) buildings is included, based on what was reported on their own Facebook pages.

5.2 Performance of Buildings and Damage Assessments

Buildings constructed after 1964 were not highly impacted by the 2020 earthquake. Damage was reported in the historical city centre of Zagreb, where a significant number of buildings were constructed before 1950's. Among the severely affected public buildings is the Zagreb Cathedral from which part of the southern spire fell, the Croatian Parliament, the Museum of Arts and Crafts, and the Komedija theatre, amongst others. These buildings are mainly brick masonry.

The City of Zagreb has received over 26,000 applications for damages, among which some 9,647 are for residential houses according to the City of Zagreb Headquarters for Crisis Coordination. The rapid inspection teams have been sent to these addressed to carry out the preliminary tagging. The Markuševec quarter, located 8.8 km to the North-East of the centre of Zagreb, was also highly impacted. It was reported that most of the highly damaged buildings in this area were either illegal and poorly constructed, or very old (Sigmund et al., 2020)

The damage to roofs, chimneys and interior have been the most severe and common, but these are difficult to observe at ground level. Military drones had therefore, been deployed to help with the on-the-ground rapid assessment efforts (Koren, 2020). Since the event, the detrimental advice of conservationists in Croatia who have insisted that historical buildings retain old-fashioned and decorative chimneys instead of newer aluminium ones have come to light. Requests by residents to upgrade their chimneys have been rejected for this reason in the past (Koren, 2020). These chimneys caused the most damage to the roofs in Lower Town, as shown below.

Figure 5-1 Damage of chimney falling indoor Source: City of Zagreb

5.2.1 Performance of Religious buildings

Information on the performance of heritage structures and critical structures such as hospitals were found from ministry websites, news webpages, twitter and Facebook.

Zagreb Cathedral

The Zagreb Cathedral was possibly the most photographed damage from our virtual search of images. The base of the Roman Catholic cathedral dated to the 11th century when the Diocese of Zagreb was established. Construction began around 1,100 and was completed by the year 1217. In 1242, Mongols invaded the city and heavily damaged the cathedral, which later underwent a major reconstruction. During the 16th century, the city fortified the cathedral with walls and towers; by the 17th century, its square renaissance bell tower was complete. The Cathedral was severely damaged during the 1880 earthquake and had been restored in the Neo-Gothic style. The Zagreb Cathedral has two 100m spires which makes it the tallest building in Croatia. The tip of the south spire of the Cathedral fell during the earthquake and damaged the roof of the adjacent Archbishop's Palace. The north spire was taken down on the 17th April 2020 as it was deemed unsafe after inspection.

Other Churches

Over a dozen churches were damaged during the earthquake, most notably the famous landmarks such as Churches of St Katherines' and St Mark's, and the Basilica of the Heart of Jesus in Zagreb.

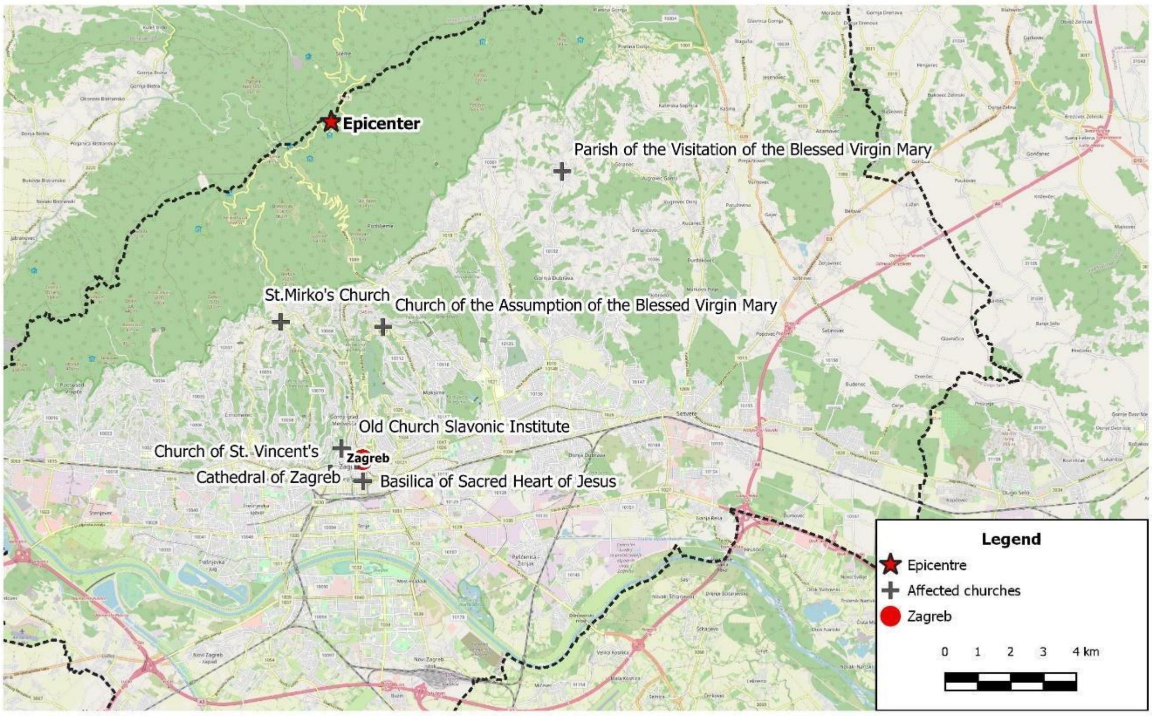


Figure 5-2 – Map indicating the epicentre of the seismic event and the affected churches

https://glashrvatske.hrt.hr/en/news/culture/fixing-earthquake-damage-to-zagrebs-churches-could-take-years/

e.g. Basilica of the Heart of Jesus

Figure 5-3 –The outside of the Basilica

Figure 5-4 – Indoor damage of the Basilica of the Heart of Jesus – Zagreb

5.2.2 *Performance of Cultural Buildings*

Most museums of national importance are in Zagreb. According to data from the MDC's Register of Museums, Galleries and Collections in the Republic of Croatia, in the City of Zagreb alone, there are 41 museums (which include displaced collections too) containing 3.5 million or 57 per cent of all museum objects in Croatia in 615 museum collections. Several museums in the capital were badly damaged including the Croatian History Museum, the Croatian School Museum and the Croatian Sports Museum - whose buildings have been given the red tag. Others such as The Archaeological Museum, The Museum of Arts and Crafts (MUO), and the Croatian Museum of Natural History were given yellow tags. All suffered non-structural and contents damage.

A selection of buildings is highlighted below, but since no direct observations or images were available for a remote assessment of our own, these are for information only. A summary of reported damage (not verified) of all museums can be found here: https://www.tportal.hr/kultura/clanak/pregled-stete-zagrebacki-muzeji-dugo-ce-se-oporavljati-od-posljedica-potresa-foto-20200325

The Croatian History Museum

The Croatian History Museum has been housed in the Vojković-Oršić-Kulmer-Rauch Palace which was built in 1764 and is one of the oldest and largest Baroque palaces in Zagreb, since 1959. A video of the showing both internal and external sustained from the earthquake can be found here:

https://www.facebook.com/HISMUS.zagreb/videos/2666940120205037/

The Museum of Arts and Crafts (MUO)

The images below of the MUO have been taken from their Facebook page, showing damage falling ornaments off the façade onto the street below and a roof collapsing inward at one part of the museum complex.

Figure 5-5 – Damage on the façade of the Museum of Arts and Crafts (MUO)

Figure 5-6 – Images from MUO FB page https://www.facebook.com/muozagreb/

<u>*Zagreb Archaeological Museum (Arheološki muzej u Zagrebu – AMZ)*</u>

On Friday, March 25, 2020, the Vranyczany-Hafner Palace, built-in 1879 housing the Zagreb Archaeological Museum since 1945 was inspected by the building statics assessment team and given a yellow tag (TEMPORARILY UNUSABLE PN1 - DETAIL REVIEW REQUIRED). AMZ also reported that building inspections, inspections and securing of items and documentation of damage were done by the minimal, necessary number of Museum staff following coronavirus protection measures that were in place. The Facebook post (in Croatian and translated by Google translate to English) goes on to say that though the building is not directly compromised, it is safest to declare it temporarily unusable with an additional indication of the need for a more detailed inspection. The museum had expected a more detailed examination o the buildings to be two weeks after the initial inspection, but nothing had been posted on the buildings since 25th March 2020.

The post also refers to significant damage to offices where the Museum staff are located, stating that "there is a large hole in the north gable and entry into two offices along the north gable is not recommended until further notice". However, no photographs were included for our team to view and assess the damage.

The Zagreb Archaeological Museum holds the largest and most significant collection of Greek vases in Croatia, with nearly 1500 vessels, of various shapes and styles dating from the 8th to the 3rd centuries BC. Cr. 25 vessels from the largest and most significant collection of Greek vases in Croatia were damaged in the earthquake, some of which have been broken into many parts and will require very complex conservation and restoration work.

Figure 5-7 – Damage to the artifacts of the Museum of Arts and Crafts (MUO)

According to preliminary estimates by AMZ, the conservation and restoration operations will last for two months and will be carried out in five phases: cleaning old adhesive, reassembling and gluing the fragments, fixing with the plaster glued fragments to avoid potential cracks destructive to the statics of the vessel, plaster treatment and toning of plaster.

5.2.3 Performance of Educational Facilities

Damage to 63 educational facilities was reported to the Croatian Ministry of Science and Education (MZO) (Croatia Week, 2020). On the MZO website, one can find "*Instructions for reporting damages in educational institutions resulting from the March 22, 2020 earthquake"* and text that encourages heads of educational institutions to complete a notification for the "Application for inspection of buildings after an earthquake", prepared by the City Office for Crisis

Management. It goes on to say that "If you notice damage to your institution-building, we encourage you to complete the questionnaire below to accelerate the damage assessment process - https://survey123.arcgis.com/share/368d3122808f4323a8b27369a6cda832 ."

Twenty-three primary schools, two secondary schools, 20 faculties and 18 institutes sustained damage ranging from cracks on classroom walls and staircases, plaster falling from ceilings, glass breaking to roof tiles falling, larger cracks in walls and entire ceilings collapsing (MZO).

There is no further information on damage to primary and secondary schools in the area posted online but the MZO has received information that the buildings housing the Old Church Slavonic Institute and the Institute for Medical Research and Occupational Health are unusable, as well as those housing the University of Zagreb's Rectorate and the School of Medicine, which also reported damage.

5.3 Local Damage Assessments

The official post-earthquake damage assessment was led by the Faculty of Civil Engineering at the University of Zagreb. They had established 12 teams (of over 300 volunteers) to inspect and carry out damage assessments of buildings in the city, as part of the Zagreb Emergency Management Office. Two calls from the Croatian Chamber of Civil Engineering were made to the Zagreb chapter members to volunteer to help with the damage assessments (Koren, 2020). A three-level tagging system is used: red-tag for buildings that are unsafe and may have to be demolished; yellow-tag for buildings that have limited use (entry for owners/occupiers for the collection of possessions) and requiring a more detailed assessment and/or urgent intervention; and green-tag for buildings that have unrestricted use. The assessments were recorded using an app developed and donated by GDI https://gdi.net/2020/04/15/collecting-earthquake-damage-information-using-mobile-digital-tools/. According to the Ministry of Construction, the preliminary assessment of damaged buildings declared 2,516 out of 6,305 buildings surveyed as uninhabitable (as of 1 April).

The team's contact, Professor Marta Savor Novak is part of the team organising the damage efforts. She has also been tasked with helping the Government draft the Law on reconstruction and all related documents. Hence, although the rapid assessments were scheduled to be completed by the end of April, the evaluation of buildings through field surveys is still ongoing (as of 29th June 2020). A summary of the process of tagging and the statistics on damage can be found on https://www.hcpi.hr/ (accessed 9/5/2020). https://www.hcpi.hr/

The latest unofficial estimates show approximately 26,000 buildings have been damaged, of which over 25,000 have been inspected (https://www.hcpi.hr/) Of these, around 75% were classified as "green" (safe or slight damage), around 20% in "yellow" (possible structural damage) and around 5% in "red" (unusable).

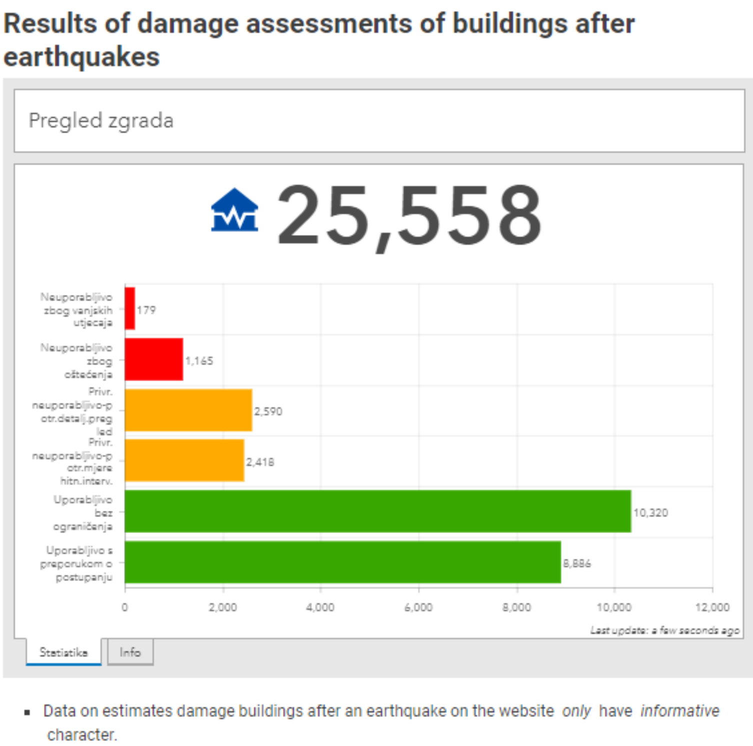


Figure 5-8 – The breakdown of the damage assessments of over 25,000 buildings submitted as part of the rapid damage assessment exercise by volunteers on https://www.hcpi.hr/ (accessed on 08/07/2020)

5.4 Remote assessment of damage (published 26/3/2020)

The ARIA (Advanced Rapid Imaging and Analysis) team at NASA's Jet Propulsion Laboratory and the California Institute of Technology, Pasadena, California created a Damage Proxy Map (DPM). The map covers the wider Zagreb area and indicates locations that are highly likely to be damaged by the earthquake. The map was generated based on the European Space Agency (ESA) Copernicus Sentinel-1 satellite imagery. The team compared the post-earthquake images (3/23/2020) with the before images taken during January 2020.

The complete satellite image (within the area indicated by the red line) covers an area of 166x56km, with a resolution of about 30m. The illustration shows an analysis (inside a white rectangle) covering the central part of the city. The variation of colour, from yellow to red, indicates a more significant change on the surface and therefore a higher intensity of damage. The preliminary check was made based on photographs from various sources, including media reports. This damage map should be used to identify the damaged areas (and the extent of the damage itself) and what is most vulnerable to construction damage.

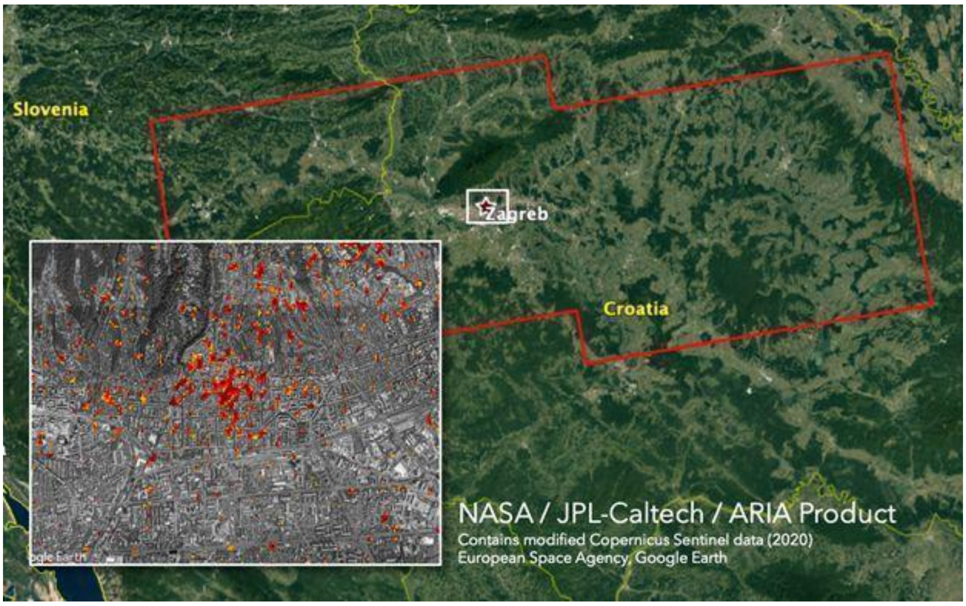


Figure 5-9 – The detail of the damage proxy map (DPM) interpreted by a team at Caltech and funded by NASA and the full extent of the analysed area (in the red polygon). The full map is available at: https://maps.disasters.nasa.gov/arcgis/home/webmap/viewer.html?layers=db20d487cee24810bd7b8cc96ccbcf3b

5.5 Damage to buildings observed by our team remotely

Conducting remote damage assessment requires a preliminary screening of all sources of information available on the web, which could correspond to the preliminary desk study required before physical field deployment.

Social media (SM) has proved to be a need-oriented source of information, as users are predominantly focusing their tweets/posts on expressing needs related to water, food, shelter, medical support, electricity failures (Ragini et al 2018) and evacuation conditions. Very often, these posts show debris on the streets, and only very few cases include damage to buildings which can be used as base information to conduct a damage assessment. Moreover, there are existing issues with geolocating the sources of information which can, at times, become a resource-consuming activity.

In addition to georeferencing issues, the critical aspect to consider when conducting remote damage assessments is the completeness of the information provided by the picture (e.g. can the building typology be established, is all the damage evident in the picture). Remote damage assessment can be achievable if photos of damaged buildings are taken following a protocol or – in any case – having in mind that the building observed must be included in its entirety. To date - very few information could be used from tweets and SM directly for the purpose of conducting assessments. The scarcity of useful information is also undoubtedly due to the limited extent of damage observed in Zagreb city after the March 2020 event.

In terms of understanding the total extent of damage (i.e. how much damage the city received and the location of this damage) as well as obtaining a more complete picture of the extent of damage to a single building, more useful insights were offered by drone footages available on-line. However, this may not have always captured damage to the lower storeys of buildings. For data protection reasons, it was decided to use Google Earth snapshots of the damage observed on the copyrighted drone footage, taken from the Google Earth Imagery archive and modified to indicate where and which type of damage was observed.

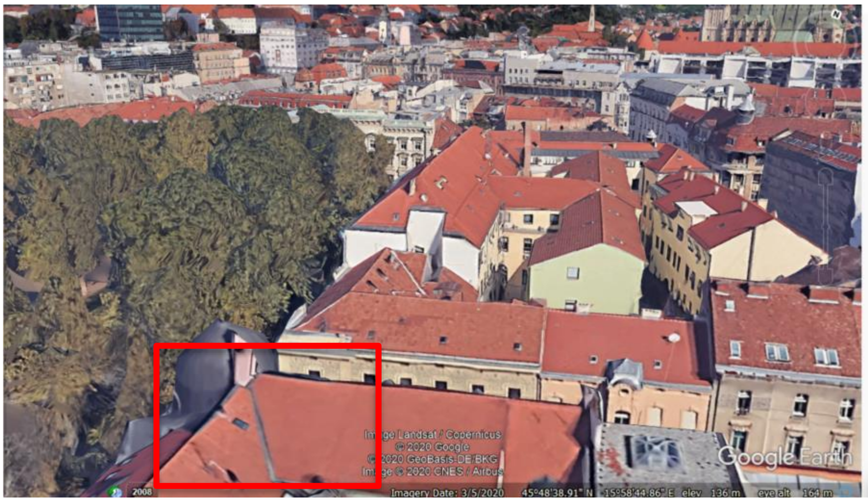


Figure 5-10 – Google Earth image indicating tiles spalling

Damage at roof level: displacement of tiles in the area bounded by the red box

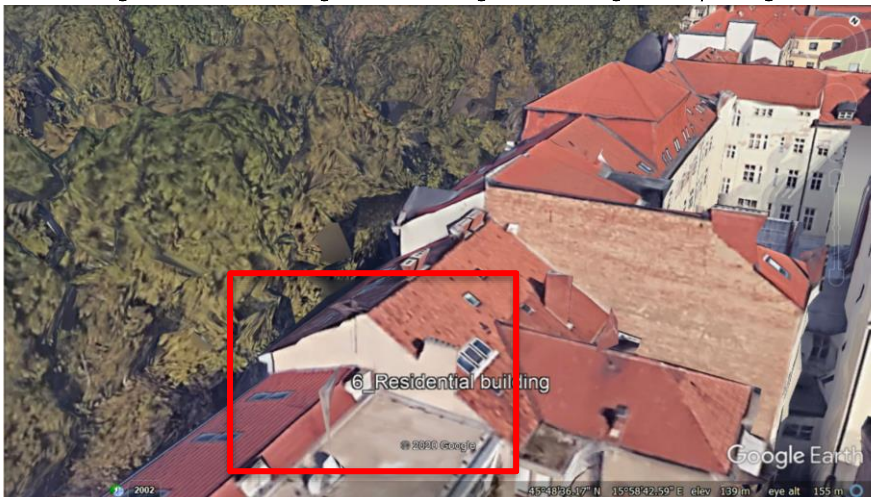


Figure 5-11 – Google Earth image indicating gable failure

Gable failure of a residential building. The damage is contained within the upper part of the façade bounded by the red box

Figure 5-12 – Google Earth image indicating gable failure

Gable Failure of a residential building. The damage is limited to the upper portion of the façade facing the courtyard.

Most of the damage was observed at roof level (5.10). Tile displacement is one of the most common types of damage, followed by the collapse of gables, as shown in Fig 5.11 and 5.12. Secondary damage to the inner part of the building because of the fall of tiles can be assumed, although not visible from the outside. Spalling of ornamental beams was observed because of the shaking, which might indicate that these were added at later stages in the construction and therefore not structurally attached to the main building itself.

5.6 LFE Damage assessment app: where was it used and why

During our search for damage reports, images and data on the event, the team came across images of the historical part of Zagreb, countless images of debris and naturally the Cathedral. However, there were reports of rehousing of residents in inhabitable dwellings in the county, very little physical evidence was found of the extent of the damage to these residential houses and where they were located. The team were able to find (again in English) an article in Total Croatia News (Sestak, 2020) published two days after the main shock, criticising the authorities for solely focusing their attention on the city centre of Zagreb. These images taken from the article show more serious damage to family dwellings near the epicentre.

Figure 5-13 – Collapse of the whole façade – credits to Dolores Rogic

Figure 5-14 – Roof damage, credits to Dolores Rogic

Figure 5-15 – Gable failure, credits to Dolores Rogic

The photos in the articles show moderate to massive damage in residential dwellings and Sestak writes, "People from Čučerje, Markuševac, and surroundings were sleeping with their clothes and shoes on, in the houses which are no longer habitable. Some people were sleeping in cars on meadows, because of the fear. Nobody answered on those telephone numbers."

Despite attempts to locate these based on suggestions of the names of villages visited by the reporter, this search drew a blank. The team also contacted the newspaper but never heard back. These and other constraints encountered when collecting information and relevant data for this remote study are further discussed in Section 7.

In discussion with the Faculty of Civil Engineering, the team were fortunate to have Ms Anamarija Babić and Ms Helena Majetić join the mission. They helped to supplement our remote findings with local input, including conducting a field survey of the suburban villages of Zagreb, using the LfE damage assessment app. The work carried out by our local partners include:

5.7 Field Surveys

A detailed damage survey of villages around the city of Zagreb was conducted from the 18th May to the 22nd May 2020, and five villages were surveyed. Anamarija and Helena were supervised and led by the GARK team, who had been surveying in the affected area and were familiar with the surroundings. The EEFIT team took the opportunity to train and test our local team with the damage assessment LfE app and uploading features of the developing SDI during this mission. The training was carried out online and additional training material was sent by email to the team for review. The EEFIT team were able to track the local team's progress and address any issues online via the online chat platform WhatsApp. The local team also provided daily blogs which have been posted online: https://lfemissiontozagreb.wordpress.com/

The 5 villages visited during the deployment were:

- Village Kašina (15.46 km NE of Zagreb)
- Village Markuševec (8.8km NE of Zagreb)
- Straznjicki put (7.33 km NE of Zagreb)
- Orehovecki brijeg (6.28 km NE of Zagreb) and Barutanski jarak (2.72 km E of Zagreb)
- Kozjak, Rim, Gorice (3.79 km NE of Zagreb)

A total number of 106 submissions were made as shown in Fig AA

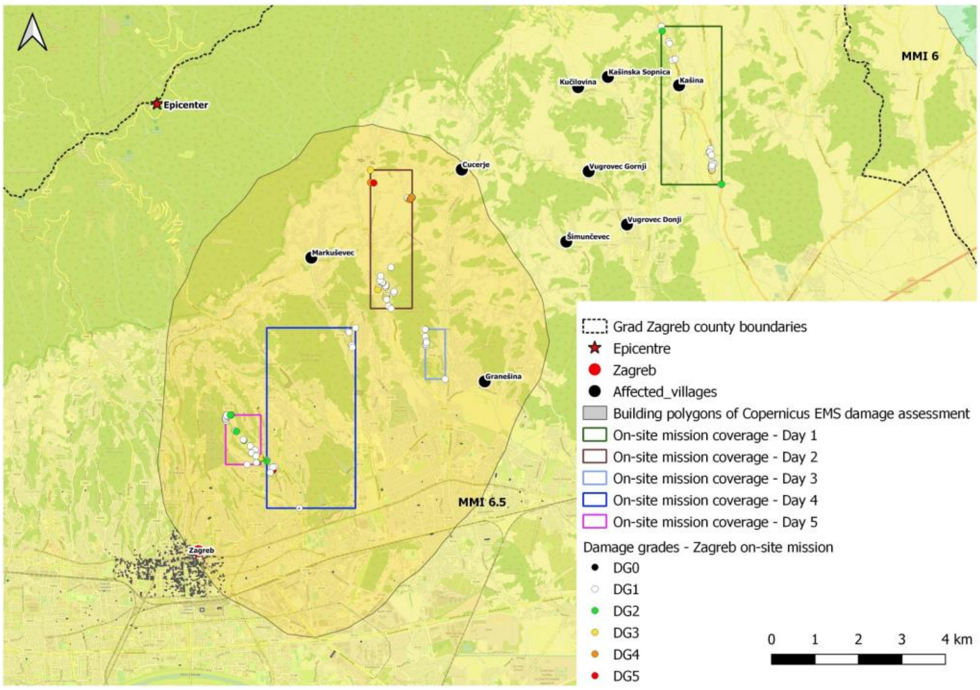


Figure 5-16 – This map shows the location of the building polygons assessed remotely by EMS Copernicus (in the Zagreb city centre) and the coverage and location of the app submissions for each *day of the Local EEFIT team mission. The position of the epicentre and the MMI boundaries extracted from the USGS Shakemap are shown for reference.*

The LfE Damage Assessment App constitutes several tiers of assessment, aimed at gathering increasingly in-depth information on the structural characteristics of the building being investigated to enable a thorough damage evaluation. Each tier guarantees that all buildings surveyed can be classified according to a set number of information specific to the given level of investigation. The controlling factor of the number of entries at each tier is the amount of time the assessor can spend on assessing a specific building and what can be observed. What is captured in the app is also governed by the overall level of safety and damage of the surrounding areas. If the assessor wishes to survey inside a building, she must review how easy/safe it is to enter the building being examined.

The overall structure of the LfE Damage Assessment App is summarised as follows:

- Tier 1 - Driving: Very expeditious assessment done by driving: the user is only asked to take a picture of the building, attribute a tag to assess the accessibility and assign a damage grade in accordance to EMS-98 scale. The estimated time per building is about 1.5 mins.
- Tier 1 - Walking: Very expeditious assessment done while walking: the user is asked to specify the primary structural system, the number of floors, their average height and provide with the tag and damage grade in accordance to EMS-98 damage scale. The estimated time per building is about 3.5 mins.
- Tier 2 - Walking: the user is asked to detail the use of the different floors and in particular if any basement is present; the type and regularity of opening layout and roof material are also included as well as the type of occupancy of the building surveyed. The estimated time per building up to Tier 2 is 5/7 mins.
- Tier 3 - Walking with access to the building: the user is asked to add information per floor such as the type of horizontal structures, the height of each floor, the internal wall material and specify the features of the main structural components (i.e. wall thickness, width and height of columns and beams in the case of RC buildings, wall thickness at the top and bottom in the case of masonry walls/earthen structures; wall thickness, type of connections and average width of columns in the case of timber structures; main dimensions of columns, beams and braces in the case of steel structures). The user is also asked to specify the number of openings per floor and finally to assess the type of structural damage. The estimated time per building up to Tier 3 is 10 mins;
- Tier 3 - Walking with no access to the building: the user is asked to gather information per facade, therefore, specifying the total number of building's facades in accordance to the building's shape, and whether the facades are similar (i.e. similar height) or they are different (i.e. in the case of slopes). The user is also asked to give information on the dimensions and position of openings along the facade and to provide an assessment on the type of structural damage. The estimated time per building up to Tier 3 is 10 mins;
- Tier 4: Crack pattern assessment: in accordance to the user choice for Tier 3, the crack pattern assessment is carried out either at floor level or facade level. It requires the user to provide pictures and sketches to support the final assessment of the type of failure mechanism ultimately experienced by the floor/facade assessed. The estimated time per building up to Tier 4 is 20 mins, and this duration would vary depending on the number of floors and facades of the building compound.

Note that the first bifurcation (i.e. "Driving" or "Walking") sets the base for all other assessment tiers to "unlock", as they all continue to add layers of information to the "Walking" choice. For the Zagreb exercise, considering that the overall damage extent experienced at building stock level was very limited and that it was prohibited to enter any building due to COVID-19 restrictions, the overall damage assessment could only progress to Tier 2.

The sample of damaged buildings surveyed on-site by our local team was then re-surveyed remotely by three experienced academics on the LfE team, with a well-established track record as EEFIT Team Leaders and experts in the field of damage assessment. The following figures show the data collected from the field by day and compare the "First Assessment" done by the local team and "Secondary Assessment" conducted remotely. The locations and the damage level that were recorded are shown in these figures.

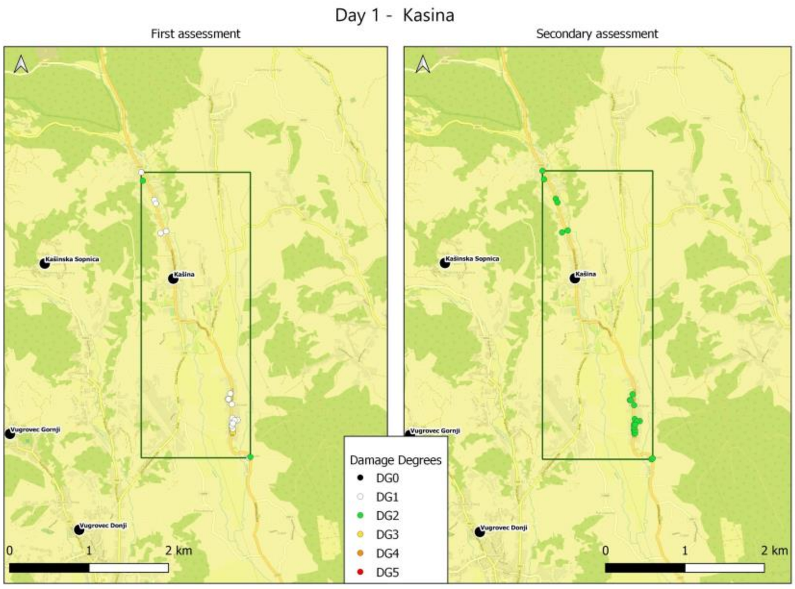


Figure 5-17 – Day 1 Kašina village – First and Secondary Assessment's maps

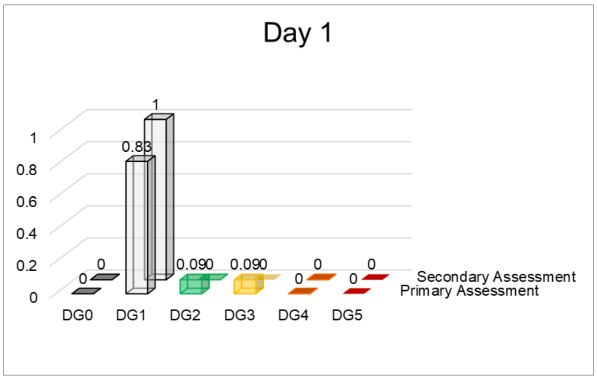


Figure 5-18 – Day 1 Kašina village – First and Secondary Assessment's Results

Figure 5-19 Day 1 Figure 5-20 Day 1

Figure 5-21 shows the damage assessment undertaken in the village of Kašina, on Day 1. 23 units were surveyed and 82% of them fell into the DG1 category. The secondary assessment categorised the whole sample to DG1. There is therefore a 18% discrepancy between the two assessments. *Figure 5-22 Figure 5-23* are representative of the building conditions with very limited damage.

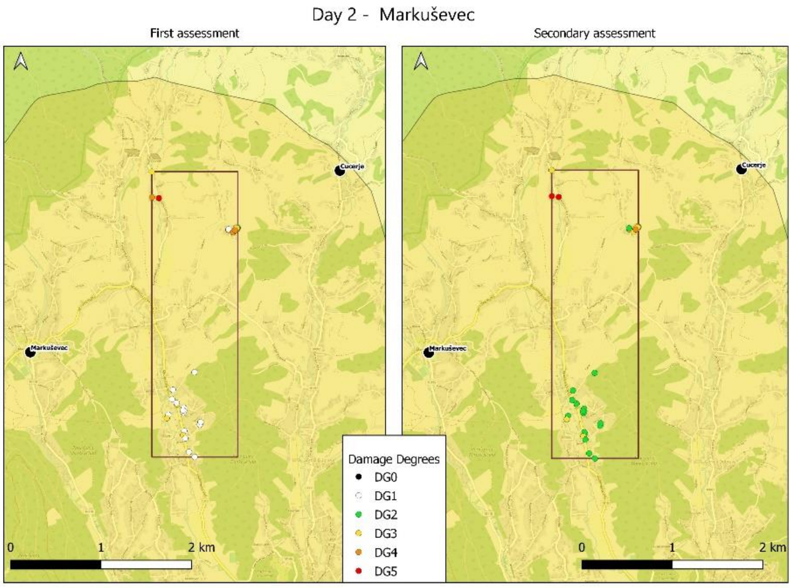


Figure 5-24 – Day 2 Markusevec village – First and Secondary Assessment's maps

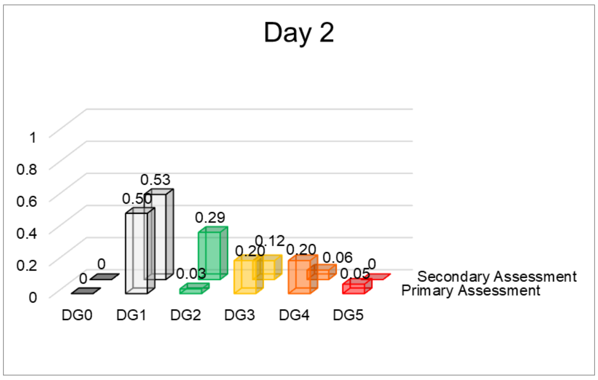


Figure 5-25 – Day 2 Markusevec village – First and Secondary Assessment's Results

Figure 5-26 – Day 2 Figure 5-27 – Day 2

The survey carried out in the village of Markuševec showed a more varied set of damage grades which were also confirmed in the secondary assessment. While the two assessments resulted in very similar proportions of buildings being in DG1, a slight damage overestimation was noted, where the first assessment had assigned DG4 instead of DG2, in the secondary assessment exercise. Such a discrepancy might be ascribable to the partial information provided to the assessors conducting the remote survey as well as the scarce occurrences of severe damage in the village, beside the two cases as shown in Figure 5.26 and Figure 5.27.

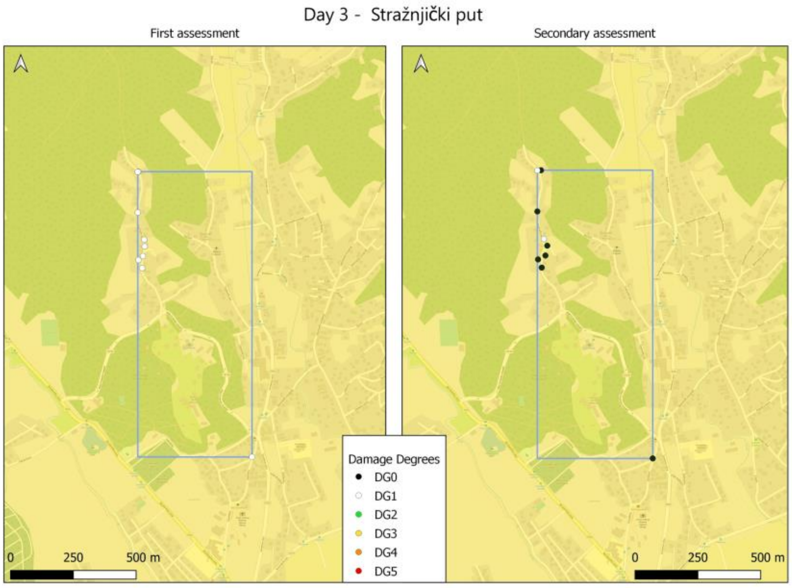


Figure 5-28: Day 3 Straznijicki put village – First and Secondary Assessment's maps

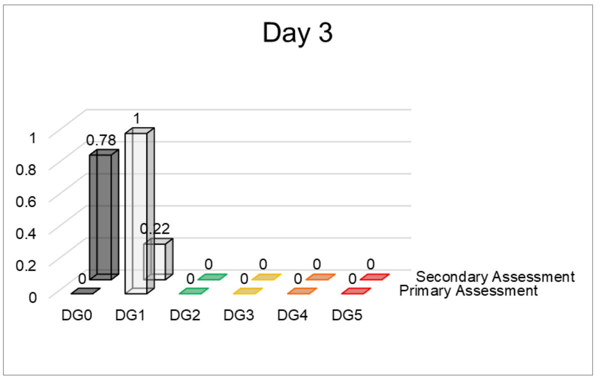


Figure 5-29: Day 3 Straznijicki put village – First and Secondary Assessment's results

Figure 5-30: Day 3

All the surveyed buildings from the first assessment were given a DG1 grade, which signifies damage such as air crack lines or detachment of plaster or limited fall of rubbles from chimneys or balconies. In the secondary assessment, the majority were graded at DG0.

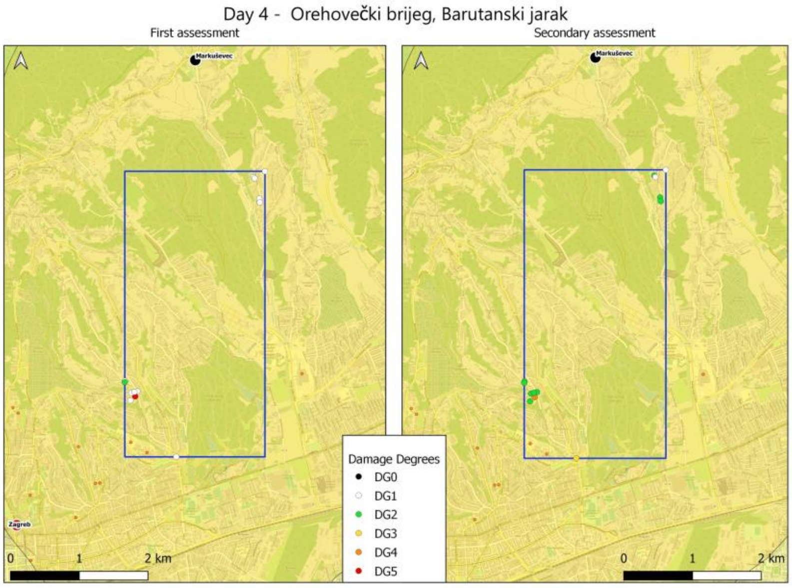


Figure 5-31: *Day 4 Orehiovecki brijieg and Barutanski jarak village – First and Secondary Assessment's maps*

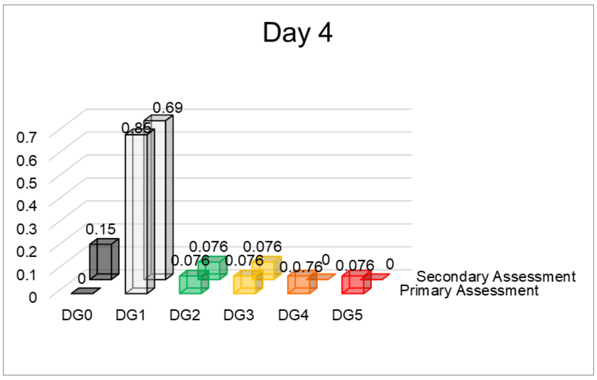


Figure 5-32: D *Day 4 Orehiovecki brijieg and Barutanski jarak village – First and Secondary Assessment's results*

Figure 5-33 and Figure 5-34: Day 4

A clear example of the discrepancy between damage assessment results is provided in Fig 5.31 and Fig 5.32 of Day 4 and shown in graph Fig 5.34 - Day 4. The building had been marked by the local team as DG3 and DG4 respectively, while, the secondary assessment had downgraded these to DG2 and DG3.

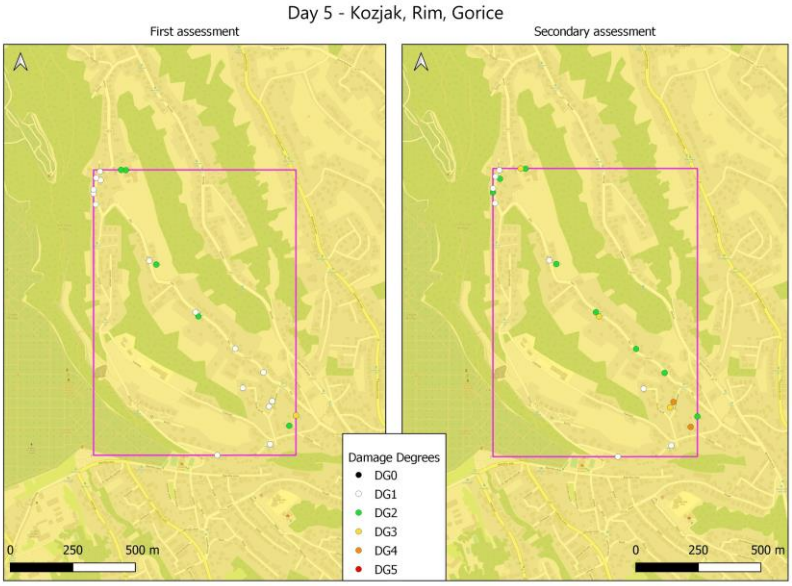


Figure 5-35: *Day 5 Kozjakm, Rim, Gorice village – First and Secondary Assessment's maps*

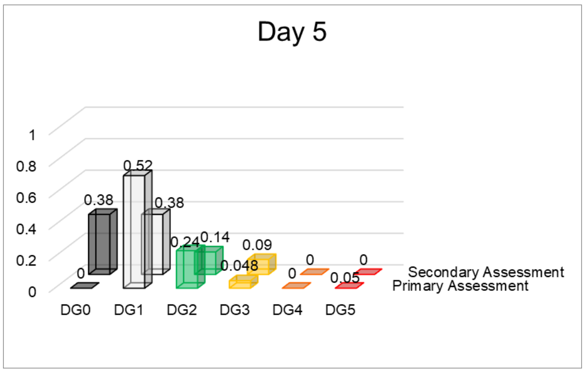
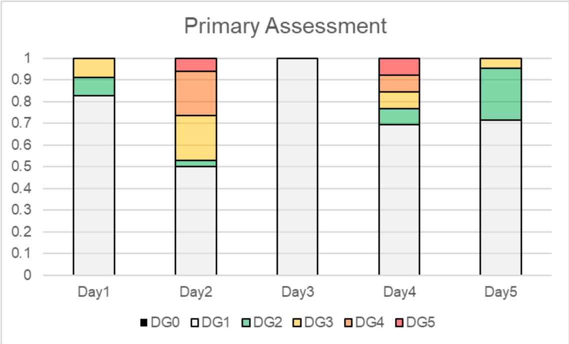


Figure 5-36: *Day 5 Kozjakm, Rim, Gorice village – First and Secondary Assessment's results*

Figure 5-37 and Figure 5-38: Day 5



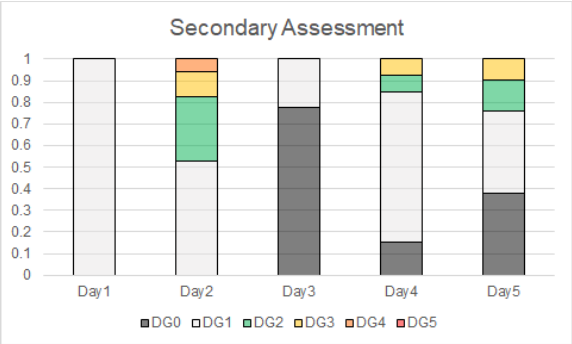


Figure 5-39: Primary Assessment Summary

Figure 5-40: Secondary Assessment Summary

A concise summary of the two assessments is provided in Fig 5.39 and Fig 5.40 where it is evident that the higher damage states reported in the *First Assessment* were all downgraded to lower damage grades in the *Secondary Assessment* exercise, which also reported a considerable number of building as DG0. Possible explanations to this consistent discrepancy are discussed in the final section of this chapter.

Finally, Figure 5.41 shows the types of buildings that were surveyed during this exercise. Most structures examined were masonry, though there were some discrepancies in the identification of reinforced concrete buildings between our primary and secondary assessments. This was one of the main reasons the team carried out this verification exercise. It is important to note what the limitations are when carrying out a damage evaluation exercise remotely, whether these are due to inexperience, entry error or misinterpretation of photographic evidence.

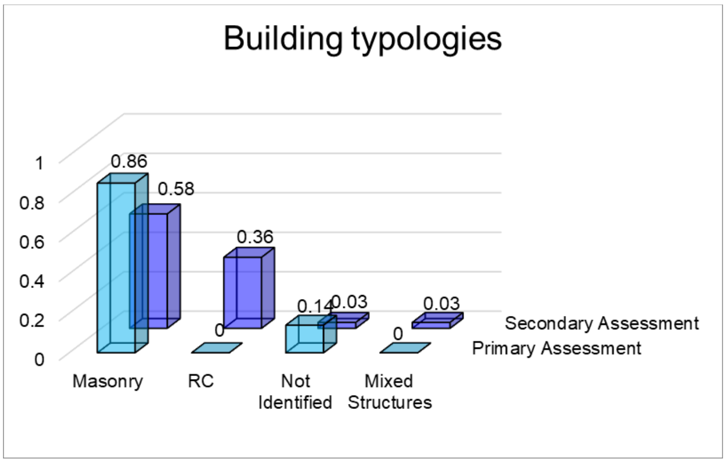


Figure 5-41: Building typology breakdown – results from primary and secondary assessment

Fig 5.42 reports two buildings (among the many surveyed from the students) which were mistakenly reported as RC buildings. The implications on this on the overall results of the damage assessment can be substantial, therefore highlighting the importance of training before deployment.

Figure 5-42: RC buildings mistakenly reported as masonry

In summary, the deployment of the LfE app proved there are clear advantages in terms of speed of data gathering and in transferring these data to more centralised systems, such as the Spatial Data Infrasfructure (SDI) under development in the LfE project. However, the input provided by the user is of utmost importance, as the LfE app – like any other tool – cannot scrutinise the quality of the data gathered, especially when it is qualitative (i.e. attribution of damage grades). This once again highlights the importance of the pre-deployment desk study and training.

5.8 Conclusions on the Performance of Buildings

The main building damage observed from remotely sensed images and photographs were at roof level. Collapses of chimneys, falling ornaments and loose tiles were common. Apart from the falling debris from the roof, the damage to these structures were not immediately evident at ground level, and internal inspections of residential properties were limited due to COVID-19. Some of the local engineers did gain access and were able to report significant damage due to chimney collapses as shown in Figure 5-1.

The main building type affected was old unreinforced masonry structures and failures of gables, and out of plane failures were evident in the City of Zagreb and the surrounding villages. Our local field surveys revealed more extensive damage to buildings that may have been self-built on the outskirts of the city of Zagreb.

One of the main objectives of this remote mission was to test the tools under development within the Learning from Earthquake project (LfE). The LfE App was tested in five different locations over five days, by first-hand users with very limited experience on field damage investigation. Notwithstanding this, the LfE app has satisfactorily proven to be an advanced tool for damage assessment by standardising the overall experience and speeding up the process. The following considerations have been extrapolated from the exercise:

- Training is a crucial step before deployment, both for experienced and less experienced users. A more straightforward definition of how to categorise the different levels of damage within a damage scale, such as the EMS-98 is of utmost importance to avoid discrepancies encountered when assessing buildings. Moreover, a provisional training session before deployment would help the users familiarise themselves with the tools at their disposal (both LfE and SDI repository). This training would play a key role in the quantity of damage data collected on-site and ensure that the data are safely stored by the end of each day in the field.
- Protocols are required and are currently under development in LfE, which would also include clear guidance on how to operate the LfE app with a limited number of available pictures per assessment. The user must be aware of the method to follow when having

to take an informative piece of evidence from the ground (such as a picture) to allow for a secondary assessor to obtain a comprehensive understanding of the building under examination.

Both the LfE App and SDI are currently being refined. The Zagreb exercise has shown that even at this stage of development, the ability to capture damage to buildings and seamlessly transfer the data to a single repository are significant steps towards a standardised method for future field deployments.

5.9 References

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Websites:

Croatia Reopens Museums, Zagreb Earthquake Creates Limitations in Capital By Lauren Simmonds 2 May 2020 https://www.total-croatia-news.com/lifestyle/43323-zagreb-earthquake (accessed 2/5/2020)

Damage to 63 educational facilities after Zagreb earthquake by croatiaweek March 24, 2020 in News https://www.croatiaweek.com/damage-to-63-educational-facilities-after-zagreb-earthquake/ (accessed 2/5/2020)

Zagreb Earthquake Epicenter in Kašina *in Pictures* By Janja Šestak Total Croatia News 23 March 2020 (accessed 24/4/2020)

On all museums: https://www.tportal.hr/kultura/clanak/pregled-stete-zagrebacki-muzeji-dugo-ce-se-oporavljati-od-posljedica-potresa-foto-20200325

https://www.tportal.hr/vijesti/clanak/sjever-zagreba-najblizi-epicentru-tesko-stradao-veliki-broj-gradana-spavao-je-nocas-u-autima-foto-20200323/slika-0a041d0f88c8bc7ddcff545d77347d3e

Drone of areas: https://www.youtube.com/watch?v=038iA_aD9PQ

Individual building e.g. Faculty of Medicine: https://www.vecernji.hr/vijesti/foto-video-u-potresu-tesko-stradao-medicinski-fakultet-prostor-je-neupotrebljiv-za-rad-1388544/galerija-411680?page=9

https://twitter.com/VladaRH/status/1242536159198117888

https://twitter.com/wwwzagrebhr/status/1242508551840567297

6. Relief, Response, and Recovery Observations

(Authored by: DC, SW, Reviewed by: EV)

6.1 Sources of Information

- Twitter
- Press releases
- Interviews
- City of Zagreb emergency response
- Ministry of Health (Vlada Republike Hrvatske @wwwvladahr)
- IFRC website
- ReliefWeb

Amongst the sources of information listed above, Twitter posts (i.e., tweets) from governmental institutions are used to derive most of the information discussed in this section. The use of Social Media (SM) is transforming the way disaster relief information is communicated. Compared to the other data sources, tweets have the advantage of being more immediate. They are also accessible at any time after they are tweeted, rather than only being accessible at the time of broadcast(as for press releases). Because they are not vetted by traditional media, they can provide more specific information to stakeholders. Users interested in specific information can connect and receive updates. Others can ignore the tweets that are not relevant to them, thus selecting the type of information they want to receive. However, this new means of communication does have its problems. Generally, the immediacy of communication and the brevity of the tweets may lead to miscommunication. Also, the ease of tweeting and the lack of traditional media vetting may lead to information overload, that could be overwhelming for the affected people.

The tweets reviewed for this section fall into four categories: 1) public safety information, 2) requests for information or resources, 3) information regarding government responses to the disaster and 4) messages of support and solidarity for victims. Currently, it is difficult to assess to what extent this new means of communication can improve the efficacy of relief efforts or the speed of relief. However, the use of social media is playing an increasingly important role in disaster risk management and relief, and this section provides several examples.

6.2 Country under partial lockdown (context)

The Croatian government imposed a partial lockdown across the entire country from mid-March, closing all shops, bars, restaurants, schools, universities and public transport and leaving open only food stores, pharmacies and petrol stations (Sigmund et al., 2020). Croats could leave their homes to buy essentials or seek medical treatment, go for a walk or exercise, but not in a group and avoiding social contact. Many people had been working from home.

The earthquake occurred at 06:24 on the 22nd March, followed closely by a 5Mw aftershock at 07:01. All our interviewees believed that the lockdown attributed to the low number of casualties. There was very little activity on the streets of Zagreb where significant tumbling of debris from the top floors of the buildings occurred. Religious events and masses were not taking place and schools were also closed.

One child, a 15-year-old who suffered severe head trauma when a part of the building collapsed on Djordjiceva Street, passed away at Klajic's hospital the following day. 26 people were injured, of which 18 severely. According to the Ministry of Health, 12 people were hospitalised , most with fractures to the extremities. Two construction workers, who fell from buildings while trying to repair them, died days after the earthquake.

After the number of COVID-19 infected patients declined in mid-April (1,832 cases of COVID-19 and 39 deaths), the government announced the lifting of some restrictions, which was implemented in three steps. Shops reopened on the 27th April as did libraries, museums, galleries and bookstores. From the 4th of May, the health system returned to full-scale operation. Services requiring close contact with customers, for example beauticians, pedicurists, barbers and hairdressers, were also reopened. Lastly, on the 11th May, schools reopened and gatherings of up to 10 people were also permitted (themayor.eu).

Healthcare system

The hospitals were not overwhelmed with people needing treatment for earthquake-related injuries, due to the low numbers of casualties. Croatia also had a low number of COVID-19 cases, so none of the hospitals was nearing capacity at the time of the earthquake. According to the Health Minister of Croatia, notwithstanding content losses and some damage, the seven affected hospitals were operational by the evening of the 22nd March. Structural damage was reported in several hospitals, such as the Children's hospital and the Petrova Hospital. News coverage documented the evacuation of the patients of the Petrova Hospital to the surrounding hospitals. Due to the low temperature (-4°C), the patients were evacuated with blankets. Newborns were evacuated in incubators, and the army was sent to support their transfer to KB Dubravu.

The EEFIT team were able to gain some insights on the evacuations. Given the sensitivity of the facilities, extensive details of the affected hospitals and wards have not been included in this report. A map of the hospitals reported as affected (at the time of writing) is shown in Figure 6-1
All patients were evacuated from the affected hospitals. The decision to evacuate was taken by the doctors on call at the time, with no official order given by the hospital administration or by the Ministry of Health. It is reported that doctors and hospital staff had not received training on what to do in the case of an earthquake. Patient evacuation drills had never been considered in the past.

At the time of the earthquake, there were no COVID-19 patients in the evacuated hospitals, as these were not selected to dispense such treatments. Of the two hospitals equipped for the COVID-19 treatments, one was empty at the time of the earthquake. The preparation of the wards was still in progress, but the hospital was not damaged and was used to house critical care patients evacuated from the other hospitals.

The earthquake damaged a hospital where 22 ICU patients were being treated. The staff was able to evacuate these patients within 20 minutes of the ground shaking, with the aid of mobile ventilators (used for the transportation of critical patients in ambulances) and oxygen tanks, which provided patients with up to two hours of support. Some patients were transported to other hospitals. The non-critical patients waited in the hospital parking lots where it was reportedly difficult to maintain the recommended social distancing. After three hours, hospital staff and patients were told that they could re-enter the hospital buildings. It is unclear how this decision was made, but an initial quick building damage assessment had been conducted by that time. The most severe damage was identified at the Children's hospital. According to the Ministry of Health, the Zagreb healthcare system was fully functional by the evening of the earthquake.

A more thorough damage assessment of the affected hospital buildings was conducted within 48 hours of the earthquake. Each building was classed either as "immediately useable", "useable following some repair" or "unsafe". Two buildings hosting crucial medical and surgical wards were closed due to the damage sustained in the same hospital. Overall, 400 patient beds were lost and around 30% of the patients who could be treated from their homes were discharged to provide beds for the patients of the closed wards. To compensate for closed wards, the unaffected wards and departments reduced the intake of new patients, if these can be treated elsewhere, until repair and reconstruction works were concluded.

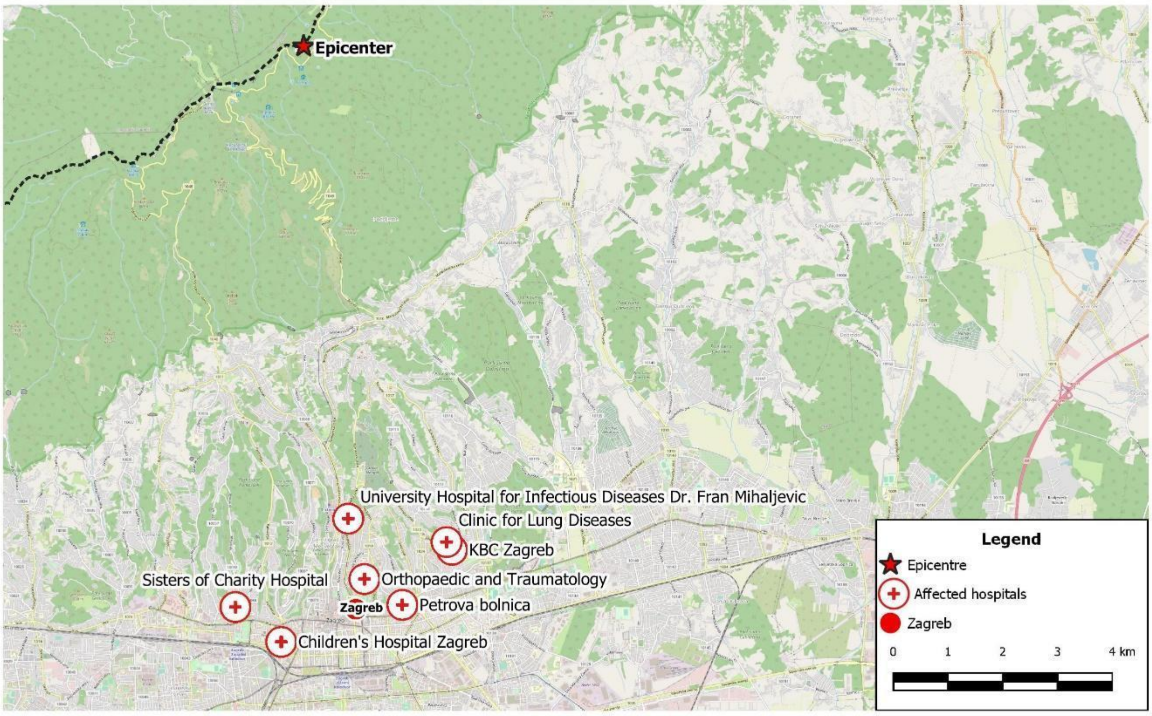

Figure 6-1 – Location of the affected hospitals and the epicentre

Immediately after the earthquake, the Prime Minister urged citizens to be extra careful. He recommended initially staying outside but maintaining the recommended social distancing (Walker, 2020). The day after the earthquake, Croatia's COVID-19 crisis management team banned all travel inside the country after many residents of Zagreb fled the city. The health minister exhorted citizens to still comply with social distancing measures and claimed that "earthquakes are dangerous, but coronavirus is even more so". As part of this message, Croatians were urged to avoid public squares and parks (Walker, 2020). Croatia had 254 confirmed cases of COVID-19 at the time of the earthquake (Sigmund et al., 2020).

6.3 Emergency response

The Prime Minister of Croatia toured Zagreb on the morning of the earthquake to appraise the impact of the event. The Croatian government urged citizens who evacuated after the earthquake to keep their distance (Poslovni.hr, April 02, 2020)). On the next day, he visited the surrounding villages, including Markuševca, Čučerja, Vugrovca and Kašina, and made a call for solidarity to the citizens affected by the earthquake. From 22nd March, the Government tasked the Ministry of Defence with the clear-up of the debris around the city, and with the support of the hospitals and citizens in need. He also issued a call to all structural engineers to help inspect damaged buildings. Between 230 and 285 soldiers of the Croatian Army helped with the clean-up operations in the wider area of Zagreb. With the help of the Bad Blue Boys, the supporters of the Dinamo Football club of Zagreb, the army moved newborn babies, their mothers, all pregnant women and equipment from the Petrova hospital to another hospital. The Bad Blue Boys also helped other patients in the Infectious Diseases Hospital Dr Fran Mihaljević. The military set up three temporary shelters and tents around this hospital. Within four hours of the event, temporary shelters, with a capacity of 500 people, were set up on Dr Franjo Tuđman Square. The emergency response plan drafted by the Prime Minister prioritised the hospitals and the provision of services to citizens in need of accommodation.

The Mayor of Zagreb declared a state of emergency on the 23rd March 2020. The municipality urged citizens not to walk through the city centre or near the damaged buildings and offered accommodation to those who could not return to their homes due to the damage or other safety concerns.

On the 24th March, the Gradska Plinara Zagreb, the company in charge of gas distribution, announced a procedure to safely release gas back to the disconnected households. The precautionary disconnections had been implemented to avoid the risk of carbon monoxide (CO) poisoning from the collapsed chimneys. The company warned customers not to use the boilers connected to collapsed or damaged buildings and recommended not to use gas water heaters before a full inspection of the chimneys had been conducted by regional chimney sweeps. Due to the damage caused in Zagreb by the earthquake, the Čistoća branch set up skips so that citizens could dispose of the rubble. All these communications were sent from these companies to their customers via social media. These examples underscore the emerging role of social media in disasters and their potential in supporting and supplementing traditional media in providing urgent public information.

The emergency response has been coordinated primarily by the City Office of Emergency Management (OEM) (Sigmund et al. 2020). Other institutions involved in the response include: the Government of the Republic of Croatia's Headquarters for Crisis Coordination, Ministry of Interior; the Civil Protection Directorate; Ministry of Health; the Croatian Institute of Public Health the State Commodity Reserves; Ministry of Education; Ministry of Defence; Ministry of External Affairs; Ministry of Economy, Crafts and Entrepreneurship; Ministry of Demographics, Family, Youth and Social policies; UNICEF; the Croatian Red Cross (CRC) and other local NGOs.

The emergency departments were also mobilised (e.g. firefighters conducted 2000 emergency operations related to earthquake rehabilitation). The City Office of Emergency Management organised meals for all citizens who could not return to their homes, and the City of Zagreb introduced two free telephone lines for citizens directly affected by the earthquake, and for those who needed assistance from the city due to severe damage to their homes. On the 24th March 2020, the municipality of Zagreb opened a bank account to financially support the repair of the damage caused by the earthquake.

Based on an estimate of the CRC completed in early April, around 50,000 people have been affected by the earthquake. It is difficult to estimate how many people were displaced because many left Zagreb after the earthquake and are staying with relatives in other parts of the country (Sigmund et al, 2020).

According to CRC, 475 people have been housed at the Cvjetni naselje student dormitory. The Croatian government also promised to provide equipment to school children hosted at the Cvjetno naselje so that they could attend online classes. A fully-equipped office was also provided for citizens that needed to report damage or perform other administrative tasks. On the 26th March, the Minister of State Property of Croatia announced that the government had readied 30 state-owned furnished apartments for those who lost their home in the earthquake. The award criteria would be determined by the Civil Protection Headquarters.

The Croatian Red Cross sent a message to the population through Twitter encouraging people, who were not affected by the earthquake, to check on others but keeping the necessary protective measures against the coronavirus. The CRC report goes on to state that the COVID-19 situation exacerbated the effects of the earthquake. *"Even in the first minutes after the earthquake, people left their homes, and they needed to keep physical distance, in a situation which normally would keep people closer. Hence, psychosocial consequences will be much more difficult than in other disasters: fear is extremely high as people are just switching from fear of earthquakes to fear from potential infection. Providing any kind of assistance is also difficult as affected people must keep distance and cannot make face-to-face social contacts. Usual psychosocial support cannot take place due to restrictive health measures. Resources of all organizations, including Croatian Red*

Cross are reaching its limits in a very demanding socio-economic situation. The focus of the public is mostly on COVID-19 outbreak, leaving people affected by the earthquake forgotten.”

The emergency response activities carried out, and the amount of aid that has been distributed by the CRC so far is summarised in Figure 6-2.

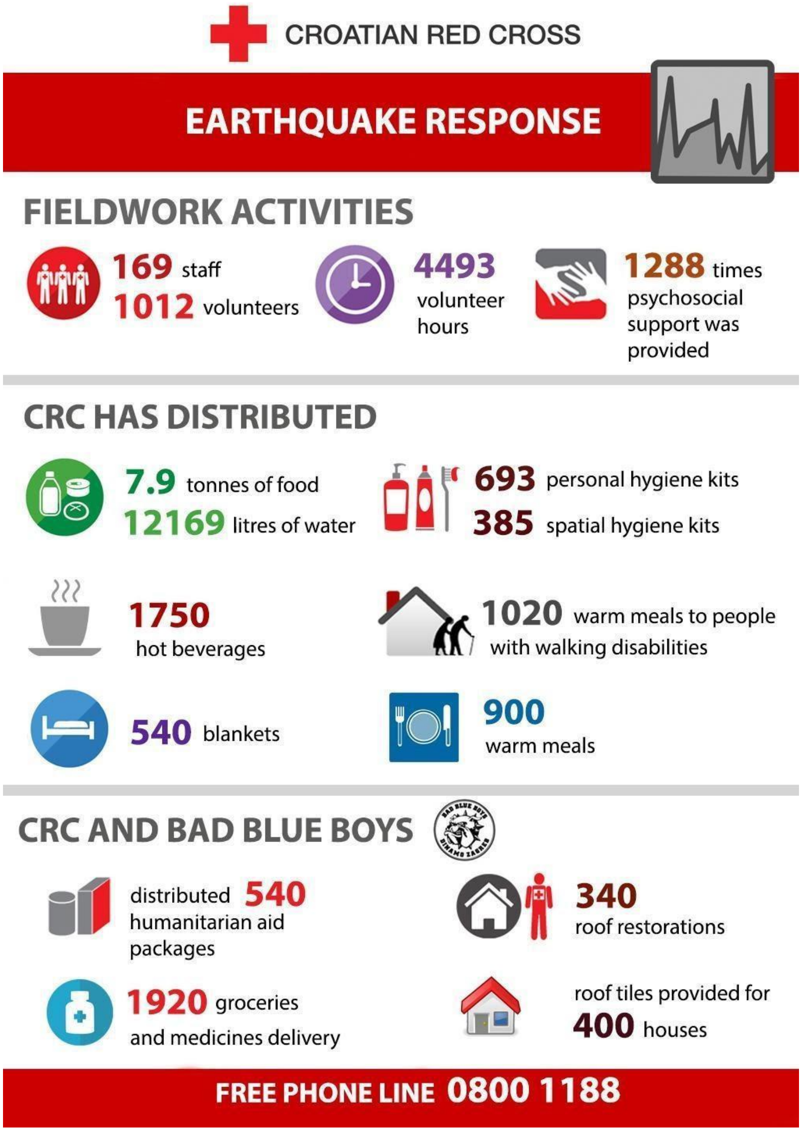

Figure 6-2 – Emergency response activities and humanitarian aid distributed by the CRC. Source: CRC

In response to the earthquake, Croatia activated the European Union (EU) Civil Protection Mechanism and obtained support from Slovenia, Hungary, Austria, Italy, and Bosnia Herzegovina. The World Bank (WB) Country Manager for Croatia and Slovenia expressed her solidarity to Zagreb and its residents and promised to liaise with the country authorities to support the recovery. Croatia also obtained support from Lithuania, that provided 21 shelters, 200 sleeping bags, and 21 electric air heaters. The United States (US) companies 3M, Ecolab, and IBM respectively provided protective gear, cleaning and disinfection supplies, and deployed artificial intelligence (AI) to keep citizens informed.

UNICEF prepared 5,500 hygiene supplies that were distributed to people temporarily housed at the student dorm Cvjetno naselje in cooperation with the Red Cross. UNICEF also pledged donations to socially deprived families living in Markuševac and Čučerje areas whose homes have also been significantly damaged in the earthquake. These initiatives were advertised on the UNICEF webpage on the 20th of April. The multi-national company Unilever also donated a package for each family which included personal hygiene products (towels, shampoos, liquid soaps, shower gels, toothpaste, toothbrushes, body creams) and cleaning products for a total worth 90,000 HRK (approximately 10000 GBP).

On the 26th March, the municipality established a telephone network (5 telephone lines) to offer psychological help and alleviate stress reactions, panic and fear, and other the psychological issues caused by the COVID-19 pandemic and the earthquake. The Teaching Institute for Public Health "Dr Andrija Štampar" opened its telephone lines daily from 8 am to 10 pm. The Croatian Psychological Association, in cooperation with the Croatian Psychological Association and the County Psychological Association also established a network of telephone lines, with psychologists providing 24 hours support, counselling and therapeutic interventions for the City of Zagreb and Zagreb County (Zagreb,2020).

On the 6th April 2020, the Croatian Minister of Foreign and European Affairs, Mr Gordan Grlić-Radman announced that many countries immediately assisted Croatia after the earthquake, with the European Union (EU) allocating € 38 million to Western Balkan countries for the procurement of medical equipment. A timeline of the emergency response actions implemented after the earthquake is shown in Figure 6-3.

03/2020
- Lockdown due to COVID-19

22/03/2020
- Earthquake
- Prime Minister (PM) recommend staying outside but maintaining distance and toured the city to observe the degree of damage
- Patients are evacuated from several hospitals around the city with the support of the army and the cheering group from the local football club: The bad blue boys
- Army clean debris from the streets
- Municipality urged citizens not to walk through the city centre or near buildings
- A tent settlement was set up on Dr. Franjo Tuđman Square with a capacity of 500 people.
- Government issued a call to structural engineers to inspect damaged buildings
- Heath minister announced that all evacuated patients have been redistributed

23/03/2020
- Covid-19 crisis management team banned all travelling inside the country
- Health minister exhorted citizens to still comply with social distancing measures
- PM visited Markuševca, Čučerja, Vugrovca and Kašina
- Croatia activated the EU Civil Protection Mechanism and obtained support from Slovenia, Hungary, Austria, Italy, Bosnia, Herzegovina and Lituania
- Mayor of Zagreb declared a natural disaster
- National Committee of Crisis decided that markets would not open
- ZET bus lines changed routes due to the damage caused in the city center

24/03/2020
- Company in charge of gas distribution announced a procedure to safely release gas back to avoid the risk of CO poisoning due to collapsed chimneys
- The OEM organised meals for all citizens who could not return to their homes
- The municipality introduced two telephone lines for those who need assistance and opened a bank account to financially support the repair of the damage
- 475 people have been housed at the Cvjetni naselje student dormitory
- Government promised to provide equipment to school children hosted at the Cvjetno naselje to attend online classes and an office with all necessary equipment so that citizens could report damage and perform other administrative tasks

25/03/2020
- OEM, announced that 20,000 reports of damage to buildings have been received and more than 1,400 buildings. had been visited

26/03/2020
- Minister of State Property announced that 30 state-owned furnished apartments that can be inhabited
- Municipality allocated phone numbers for providing psychological support

Figure 6-3 – Timeline of the emergency response actions

6.4 Plans for reconstruction

On the day of the earthquake, teams of construction experts from Zagreb conducted rapid post-earthquake damage assessments. On the 23rd March, the Chamber of Civil Engineers invited all structural experts in the field of masonry and concrete as well as auditors to join the OEM in Zagreb. The pandemic posed new challenges for the civil engineers who were inspecting the buildings, but also for the workers who were tasked with removing the many overturned chimneys and repairing broken roof tiles. As previously reported, two people died during this clean-up operations. The team contacted one of the volunteer engineers, Mr Koren, who said that all volunteers knew the risks, took precautions when carrying out the inspections but, in the beginning, they had to provide their protective equipment. After a week, the mobile app which the team used to record their assessments included maps of the location of the reported COVID-19 cases and people in quarantine (Koren, 2020). Each building inspection was georeferenced using GPS coordinates and maps. The damage grade of the building was recorded into the system and analysed further (Štromar,2020).

On the 25th March 2020, the head of the OEM, Mr Pavle Kalinic announced that 20,000 reports of damage to buildings have been already received by the municipality, and the teams had visited more than 1,400 buildings. In all, OEM had formed 80 specialist teams with 170 engineers on-site who visited facilities every day (Bandić,2020).

On the 26th March 2020, the Municipality of Zagreb invited all business entities that had specialized vehicles that could reach the height of 30m, smaller vehicles for work at the height of 18m or mobile cranes (truck cranes) suitable for removing debris from the roofs of buildings to join the repair tasks. The Deputy Mayor and Chief of Staff of the Civil Protection of the City of Zagreb also invited all construction companies in Zagreb and Croatia to apply for the tender to help all public services repair all damage as soon as possible, starting from the directly actionable minor damage.

The next day, the Ministry of Construction and Physical Planning invited construction material stores to join the donations to repair the roofs of the damaged buildings as soon as possible. Reinforced foil, construction nylon, planks battens and nails were requested (Štromar, 2020). Through social media, the Ministry of Construction and Physical Planning also joined the call of the Municipality inviting all companies or crafts with available workers and mobile cranes to join the repairs. The companies were asked to contact the City Housing and Communal Services and invite other building managers to contact the Ministry to organise the preventive rehabilitation (Štromar, 2020). These calls highlight once again the use of SM by public services in coordinating disaster response.

Financing the recovery and reconstruction

The Prime Minister Andrej Plenković announced on 24th March 2020 that members of the government would donate their March pay to create a fund for the damage caused by the earthquake in Zagreb. On 9th April 2020, the Minister of Construction and Physical Planning declared that 15 million HRK (2,225,860 USD) was needed to subsidise housing loans and that the budget had been secured, with 260 applications already processed up to that day. On the 16th April 2020, the Minister of State Property announced by Twitter the relief measures available to entrepreneurs. Lessees would receive a form to complete, and if they met the eligibility criteria, their monthly leases would be written off on a month-by-month basis. Other relief measures were made available for closed or damaged businesses which could demonstrate a fall in revenue over 50% and that had not laid offs employees above the fixed thresholds (i.e., 40% in companies with up to 10 employees, or 20 % in small, 15% in medium and 10% in large enterprises).

On 7th May 2020, the Minister of Construction and Physical Planning announced that every household whose apartment or family house had been destroyed in the earthquake, would receive 20,000 HRK (2,967.82 USD) for the necessary repairs (Plenković, 2020). The financial resources for the implementation of this financial support would come from the State Budget of the Republic of Croatia for 2020 (100.000.000.00 HRK - 14,839,100 USD), the Financial Plan of the Environmental Protection and Energy Efficiency Fund for 2020 (41,000,000.00 HRK - 6,084,030 USD), while the rest would be covered with a contribution from the European Union Solidarity Fund. In all, the EU Solidarity Fund has 500,000,000.00 EURO (562,361,000 USD) per year available to provide financial support to the Member States, as well as non-member states with standing bilateral agreements. The fund covers major natural disasters with severe consequences for the living conditions of the citizens, the natural environment, or the economy of one or more regions in a Member State or a country applying for membership (Plenković, 2020).

The monetary assistance granted is intended for the temporary and necessary protection and repair of damage caused by earthquakes in the area of the City of Zagreb, Zagreb County and Krapina-Zagorje County (Štromar, 2020). A maximum of HRK 12,000 (USD 1,780.69) will be made available for the cost of repair of eligible buildings in the following categories:

- Family houses (a residential building with no more than three separate parts of which at least one is an apartment);
- Residential office buildings (a building consisting of at least one apartment and at least one office space, not a family house);
- Multi-residential buildings (a building intended for housing and consisting of at least four apartments).

A maximum of HRK 8,000 (USD 1,187.13) will be made available to the owners of eligible damaged buildings to cover the costs for:

- Necessary temporary protection of the building from the influence of atmospherics and the removal/storage of hazardous parts of the building that could or may endanger human life or health;
- Repair or replacement of chimneys;
- Repair or replacement of the gable wall;
- Repair of lifts.

The owners of damaged buildings, apartments and family homes may also ask for compensation for the 80% of the eligible costs of purchasing condensation boilers to replace existing non-condensing boilers (Plenković, 2020).

In addition to the financial support of the EU, the World Bank (WB) announced on the 21st May 2020 that the institution is supporting the Croatian government in assessing the damage and recovery needs in the five most affected sectors: housing, education, health, culture and business. This announcement was followed on the 27th June 2020 by the launch of two new projects worth USD 500 million (0.9 per cent of Croatia's GDP) under the joint patronage of the Croatian Government and the WB to mitigate the effects of the economic shock, advance recovery, facilitate earthquake reconstruction and strengthen national systems for public health preparedness for future pandemic outbreaks (Frajtic and Smithies, 2020). From this budget, 200 million USD will be used for the Earthquake Recovery and Public Health Preparedness/ Emergency Recovery Project, which is the first big reconstruction loan for Zagreb. This project aims to support the design of a financial support program for private housing reconstruction, financed through private, public and other financiers, to strengthen the institutional capacity of the national authorities to respond to future disasters and manage future risks (Frajtic and Smithies, 2020).

Reconstruction plans

The PM announced at the end of March that he had agreed with the representatives of Zagreb on three essential action points to repair earthquake damage: 1) Continued work on securing high-risk buildings and clearing materials for the safety of citizens; 2) Drafting a special reconstruction law to regulate the situation; 3) Establishment of local, national or international sources of financing/funding for damage repair.

On 30th March 2020, the Minister of Construction and Physical Planning announced that the working version of the reconstruction law that will regulate the situation after the earthquake was completed, and the law was expected to be approved by the summer. He explained that the process of drafting a new reconstruction law has been made more complex by the presence of buildings that are more than 100 years old in the centre of the capital. The definition of the reconstruction plans for these structures required the involvement of several specialists from the Croatian Chamber of Civil Engineers, the Croatian Chamber of Architects, the University of Zagreb Faculty of Civil Engineering, as well as machine and electrical engineers. The Vice President of the International Institute for Conservation of Historic and Artistic Works (IIC), however, criticised the bill because the heritage specialists were not consulted.

The Minister of Construction and Physical Planning reiterated that the priority of the reconstruction law was to help and rehouse the citizens and that an expert council will be established to coordinate the renovation of multi-residential and public buildings and houses. All the available funds will be used to reach the highest possible quality. He also announced that that the Croatian Government and the government from Zagreb were working together to make the city and state housing available to citizens living in dormitories so that no one will be left homeless. The reconstruction program would determine how to help citizens whose family home must be demolished. The government stated that a replacement house (for example, a prefabricated house) or a monetary compensation would be provided to these families.

Despite the rapidity of the drafting of a working version of reconstruction law, no further plans were announced on the reconstruction following the earthquake. The daily governmental updates on the pandemic were also stopped at the end of April. The lack of follow-on information left residents impatient (Babel, 2020). However, by the end of May, the Faculty of Civil Engineering of the University of Zagreb and the Croatian Chamber of Civil Engineers prepared and uploaded a comprehensive 130-page manual on the repair and reconstruction of damaged buildings called "Emergency seismic reconstruction program - UPPO". The manual is available for download at http://www.grad.unizg.hr/_download/repository/UPPO_Prirucnik_GF_HKIG.pdf. In the manual, several special provisions and technical solutions are proposed for the renovation of chimneys, gable walls and other attic structures, which had suffered substantial damage in the earthquake.

On 3rd July 2020, the Ministry issued an *Instruction on the existing legal possibilities for restoring buildings damaged in the earthquake* after the Technical Regulation on Amendments to the Technical Regulation on Building Structures are put in place.

At the time of writing, the actual implementation of these plans and the tendering process for reconstruction remain unclear.

6.5 Conclusions on the relief and recovery

Since mid-March, a series of partial COVID-19 lockdowns were imposed by the Government of Croatia to contain the virus. The occurrence of the earthquake during the pandemic is an example of a multi-hazard disaster. The unprecedented circumstances placed additional pressure on the reconstruction and recovery efforts and affected the speed of the repairs. It is reasonable to presume that the lockdown significantly contributed to the low numbers of casualties. In the city of Zagreb, the main structures affected were the cathedral, the Archaeological Museum and seven hospitals. Due to the lockdown, nobody was attending the early mass in the cathedral and the streets were emptier than usual. The hospitals did not suffer significant structural damage and could return to operation, through internal reorganization of the hospital beds and some evacuations, in a short time.

There was a strong and quick presence by the National Government in the efforts to return to normality. The Ministry of Interior allocated resources. The Ministry of Health addressed the evacuation from the hospitals (with the support of the Ministry of Defence and the army for the evacuations and the cleaning of debris in the streets). The Ministry of State Property provided houses to the displaced. The Ministry of Construction and Physical Planning lead reconstruction efforts from the day after the earthquake and the Ministry of Finance organized resources to fund the reconstruction. The City of Zagreb through the City Office of Emergency Management (OEM) also deployed firefighters, made available telephone lines for citizens directly affected by the earthquake and provided accommodation. The recovery efforts are financially supported by the European Union (EU) and the WB. In-kind donations for the emergency response from other European countries, international NGOs - such as the International Federation of Red Cross (IFRC), and private companies were also received.

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7. Lessons learnt from conducting a virtual mission

(Authored by: ES)

7.1 Data availability, processing and limitations for this event

As stated in the preamble of this report, the Zagreb earthquake is an event which has generated a “modest” and “localised” response. This has possibly made it more difficult to find materials online. The difficulty of sourcing relevant data and information remotely has been magnified by the unprecedented circumstances of the COVID-19 pandemic which have affected the work of the earthquake emergency responses and management teams, the local scientists, and the field mission team as well. In his interview with the team, Prof. Herak said “it was more difficult for the seismological survey to work in emergency mode, to organize field measurements, to install provisional stations and to speak to the media. They handled the emergency mode very well, mostly from their home office. The aftershock analyses were timely; several additional instruments were used a day after the main quake, the cooperation with the official bodies was professional, as were the media reports and the moderation of the social media.”

The resource and access constraints of our peers on the ground was also evident in the speed at which information were made available. There are obvious gaps in this report. At the time of publication, the preliminary damage assessment database and ground motion data of the event have still not been published. The City of Zagreb holds the data but they have had a pandemic to manage and the preparation of documents to support the reconstruction has taken priority above all else, so that these could be passed through the parliament before the elections of July, 5th.. The situation would not be different on-site, but a walkthrough the city and other affected areas by the Team may have helped with mapping the areas and types of damage more rationally.

In terms of information gathered from SM, there are obvious limitations with searching in English, and there may be other valuable tweets, articles and information in other languages, e.g. Italian sources. To overcome these limitations, keyword searches were done in both English and the local language, e.g. earthquakes ‘potres’ or street, ‘ulica’ in Croatian. The automatic translation from Google and Twitter helps but as with many of these platforms, the translations are not perfect, and a supplementary effort by native speakers to support the translation is sometimes needed.

The number and duration of interviews were also limited. The team were not able to access, as normally done in a standard EEFIT mission, the emergency management offices and the temporary housing units to talk to the displaced and those providing post-earthquake care. We had acquired most of the relief and reconstruction information from the SM outlets of the official channels but there are inherent biases. Although this negates false information, it also does not necessarily present the reality on the ground or the needs and concerns of the affected population. For example, on the page of a Facebook group created by Zagreb citizens in the aftermath of the event, there were repeated concerns about the lack of temporary shoring measures in the city of Zagreb. Although plenty of remedial works was carried out on roofs to make safe the damaged elements, there were reports of falling debris both internally and externally due to aftershocks and vibrations from the trams.

7.2 Validation of virtual assessments

There is a large amount of data flooding all SM platforms after an earthquake. Given the amount of information and potential for misinformation, it is essential to identify valid official sources of data on the outset. One strategy was to check the official twitter accounts of government officials such as the PM of Croatia (@AndrejPlenkovic), from the Croatian government (@VladaRH), Ministry of Defence (@MORH_OSRH) Ministry of the Interior (@mup_rh), Croatian civil protection

Directorate (@RavnateljstvoCZ), the municipality of Zagreb (@wwwzagrebhr), the mayor of Zagreb (@MilanBandicGZ), The Zagrebački holding, the public utility company of Zagreb (@Zg_Holding), The World Bank Country Manager for Croatia and Slovenia (@ecapannelli), internationally renowned NGOs such as the International Federation of the Red Cross (@ifrc), the Croatian Red Cross (@crvenikriz_hr) and local news agencies such as HRT News (@hrtvijesti), RTL DAnas (@RTLDanas) and well known international press agencies such as Reuters and EFE.

However, although this strategy negates the use of 'fake news', the information presented is biased. This bias comes from the experience of the users or the policies of the Government, and we cannot ground truth what is being posted through these channels. We found on several occasions when searching for information on post-earthquake evacuations and on the current state of the city, that the citizens' platforms (Facebook groups and GoFundMe pages) reveal a slightly less rosy picture of the situations. This is one of the main challenges of conducting a virtual mission. The inability to verify the findings online with personal objective observations and interviews.

7.3 Recommendations for future EEFIT missions

Our virtual mission was designed to mimic an on-the-ground mission and the team dedicated a week (27/4- 1/5/2020) to complete different tasks which would traditionally be carried out in the field, e.g. damage area overview, building damage surveys, interviews with emergency managers and local academics. This mission was an opportunity for us to test what we can gather entirely remotely, and under COVID-19 conditions, therefore considering the implications of a multi-hazard event as well.

During this COVID-19 pandemic and the uncertainty of when life will indeed 'return to normal', it is likely that many aspects of our working lives will have to be conducted virtually. The team have learnt some valuable lessons in terms of conducting a remote reconnaissance exercise under the restrictions imposed by the pandemic and would like to make the following recommendations for future virtual missions.

1. As with all EEFIT missions, establishing a list of key institutions involved in the post-earthquake management and assessments is important, especially if official requests must be made for interviews and sharing of data. During this Zagreb exercise, the team did not have a native Croatian speaker in their midst but were fortunate in locating several key players in DRR from academia.
2. Local knowledge and contacts are crucial. A good understanding of the local seismology, topography, building stock, and the general 'lay of the land' of the affected area is even more important than usual. Otherwise, the teams will have to rely entirely on remotely sensed imagery (satellite, drones, CCTVs, drive-throughs and photographs) and without having visited the area, orientation and navigation can be problematic. Besides, the bird's eye can supplement but not entirely replace the value of the "boots on the ground".
3. All team members need to be familiar with the background material before 'deploying'. It is not a simple data collection exercise as a critical interpretation and analyses of data needs to happen currently. There needs to be a clear delegation of tasks amongst the team members. Familiarity with the data is crucial in all circumstances. EEFIT missions are becoming more and more "data-rich" – and remote missions are even more data-dependent. But, there is a fine line between data richness and information overload.
4. Sharing files online is standard practice but having a debrief at the end of each day and going through the data acquired together is essential. This helps to ensure that knowledge is shared, and all members of the team have the same understanding/situation

awareness. This is a given with field missions, but it is harder to immerse yourself in the comfort of your own home.

5. Once a team is established, setting a period of intense internet searches, online interviews and post-processing is a good idea. Setting standards for categorising the data is also important. This would mimic an actual reconnaissance mission but also limit the time spent on gathering data and will avoid potential duplication of effort. The team found it challenging to put a definitive end to the mission as information was continually being updated, and there is always more to be found online.
6. Social media data is big data! For this one moderate earthquake with only one death and 26 injured, the number of tweets was in the 50k range. For larger and higher-profile events, this is likely to increase dramatically. Though the tweets are of interest and are content-rich, the inherent demographic bias (i.e., who tweets) and inability to extract geotagged data cannot be ignored. The LfE project team are currently exploring the scope for the use of SM data for field missions in their research, hopefully, our findings can be shared soon.
7. Mapping has been and continues to be a central part of reconnaissance missions. Having an GIS proficient team member is vital.
8. Although the team were able to review images of damaged buildings online, a systematic assessment of the spatial extent of damage and the affected building types was not possible. Besides, though the City of Zagreb had carried out a preliminary building damage assessment, this data is not publicly available for review. One would assume this would be the case in many post-earthquake regions where the collected data will be proprietary. The team were fortunate in gaining the collaboration of local partners to help conduct a ground survey of buildings in the epicentral area. In all, over 100 buildings were surveyed and the exercise, both in terms of the process of data collection and the information collected, were of tremendous value. This would be a key recommendation for future remote missions. The LfE project team are developing a damage assessment app and a Spatial Data Infrastructure (SDI) for uploading survey and other metadata from field missions as part of their research. We hope that online training and use of these tools will enable both field and remote missions in the future.

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