Review

Earthquakes Reconnaissance Data Sources, a Literature Review

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Abstract: Earthquakes are one of the most catastrophic natural phenomena. After an earthquake, earthquake reconnaissance enables effective recovery by collecting building damage data and other impacts. This paper aims to identify state-of-the-art data sources for building damage assessment and guide more efficient data. This paper reviews 38 articles that indicate the sources used by different authors to collect data related to damages and post-disaster recovery progress after earthquakes between 2014 and 2021. The current data collection methods have been grouped into seven categories: fieldwork or ground surveys, omnidirectional imagery (OD), terrestrial laser scanning (TLS), remote sensing (RS), crowdsourcing platforms, social media (SM) and closed-circuit television videos (CCTV). The selection of a particular data source or collection technique for earthquake reconnaissance includes different criteria. Nowadays, reconnaissance mission can not rely on a single data source, and different data sources should complement each other, validate collected data, or quantify the damage comprehensively. The recent increase in the number of crowdsourcing and SM platforms as a source of data for earthquake reconnaissance is a clear indication of the tendency of data sources in the future.

Keywords: Earthquake reconnaissance; fieldwork surveys; closed-circuit television videos (CCTV); remote sensing (RS), crowdsourcing platforms and Social Media (SM).

1. Introduction

Each year, disasters cause significant human and economic losses. Out of these disasters, earthquakes are one of the most catastrophic natural phenomena. These events have caused more than 23 million deaths between 1902-2011 [1] and substantial physical, social, economic [2] and occasionally institutional, cultural and environmental losses. Following an earthquake, there is a substantial demand and need for spatial information [3, 4] about population location [5], evacuation routes, availability of resources [6], size of the affected area and distribution of damage. Later, during the emergency phase, it is necessary to collect more detailed data about damages in the structural components of buildings [7].

Earthquake reconnaissance enables collecting perishable data on building performance to prepare statistics, calibrate and validate engineering models, and identify the construction deficiencies that lead to inadequate structural performance. This paper aims to identify state-of-the-art data sources for building damage assessment and serve as a guide to make more efficient data collection based on the experiences in the last years. Damage is understood as a change in the mechanical, material and/or geometric properties of a building, affecting its performance and behaviour [8]. Damage data is highly 'perishable' or ephemeral since damaged structures may be altered or removed during rescue or early recovery [9] activities [10] or modified by aftershocks. A large earthquake produces extensive building damage and affects the operational conditions of other structures [11] in and around an urban area [12]. Additionally, economic and social consequences are usually related to loss of buildings usability [13, 14]. Buildings are essential places to live [15], to do business or to carry out activities [16]; this is the reason why most of the losses [1] and 75% of the casualties [17] in disasters are due to building damage [1]. Building damage assessment is a critical activity to secure the safety of the public [7] and provide information for disaster relief, early recovery planning [12] and later reconstruction [18-20], especially due to the threat of aftershocks. Moreover, damage assessment is essential for assessing disasters' social and economic impact [19, 21]. The effectiveness of post-disaster activities during the response and recovery phases depends on accurate and early damage estimation[22].

In the past, conventional recording and measurement tools, such as photography, note-taking and surveying, were used by reconnaissance investigators to collect data and document field observations. Nowadays, the availability of state-of-the-art instrumentation, mobile data collection technologies, training and field support services has increased the ability of field investigation teams to capture perishable data during post-disaster phases [10]. Currently, there are two data sources in the disaster management cycle: sensor-generated such as the data collected by remotes sensing (RS) tools, CCTV or satellites and user-generated content collected from social media (SM) platforms [23, 24]. Quantitative assessment of damage is the process of determining the physical damage of the exposed elements in the affected area. The result of the damage assessment will be the aggregate quantities of damages for an exposure unit. This quantitative assessment is used to assess the direct economic loss as the basis for calculating the value of economic losses: the replacement cost [19] or insurance payouts of value to international aid organisation, bi-lateral/multilateral donors and the insurance industry [25]. During the emergency or relief phase, the quantitative assessment of damage starts with the structural component of the buildings due to its essential role in the safety of the population affected by earthquakes and the estimation of temporary shelter needed [9]. Structural damage evaluation implies a visual inspection to establish whether the building structure components are damaged, which of them, and degree and if the degree of damage represents a risk for the building's occupants. These data are necessary for understanding the trend of natural disaster impacts and existing planning and building practices [26]. Earthquake reconnaissance enables collecting perishable data on building performance to prepare statistics, calibrate and validate engineering models, and identify the construction deficiencies that lead to inadequate structural performance [27]. Damage detection and characterization involve five closely related subjects [11], i.e., structural health monitoring (SHM), condition monitoring (CM), non-destructive evaluation (NDE), statistical process control (SPC) and damage prognosis (DP)[8].

This paper is divided into five sections. The introduction includes a brief background on the topic of earthquake reconnaissance and data sources over time. The second section, on methods, elaborates on the criteria for selecting the articles that comprise the literature review. The third section focuses on the results, including the data sources identified through the literature review. The fourth section focuses on discussing the interaction of data sources identified, and the fifth section contains the conclusions.

2. Materials and Methods

A literature review was conducted to identify state-of-the-art data sources for earthquake reconnaissance. Peer-reviewed research articles included in this literature review were identified from the Web of Science and in the framework of the project: Learning from Earthquakes (LfE) UK, a joint project undertaken by Newcastle University, the University College of London (UCL) and Cambridge University. Considering that we are

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interested in state-of-the-art, we focused on publications made in the last five years. The search was conducted between February 2019 and June 2021. In the literature review undertaken at the beginning of the project, we reviewed references published between 2014 and 2019. At the end of the project, we reviewed references published between 2016 to 2021. Eventually, this literature review included references published between 2014 and 2021, the last seven years. According to their relevance, older references were reviewed only when referred by the authors of identified references. Still, they are not counted among the total number of reference reviewed because we want to highlight only state-of-the-art data sources. Although the main focus was data sources for earthquake reconnaissance, data sources for damages assessment after other natural phenomena or anthropogenic events were reviewed but not counted in the review. The flow diagram of the methodology applied is depicted in Figure 1.

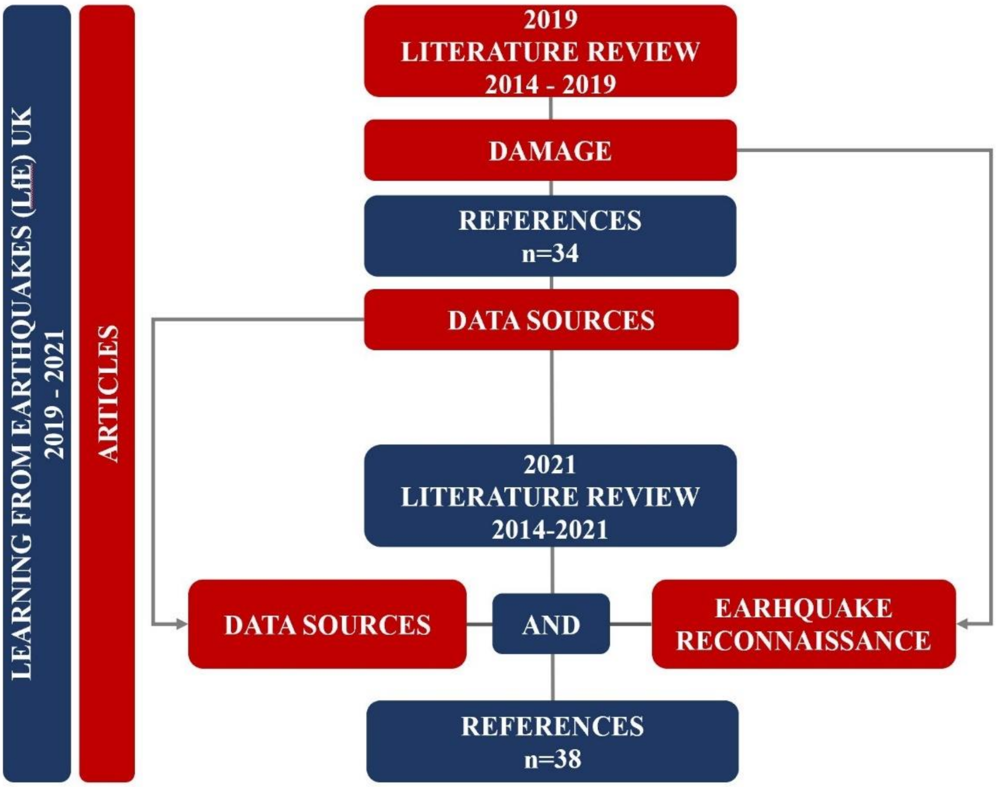

Figure 1. Methodology.

3. Results

This paper reviews more than 38 articles that indicate the sources used by different authors to collect data related to damages and post-disaster recovery progress after earthquakes between 2014 and 2021. The data collection sources and methods identified in our literature review have been grouped into seven categories: fieldwork or ground surveys, omnidirectional imagery (OD), terrestrial laser scanning (TLS), remote sensing (RS), crowdsourcing platforms, social media (SM) and closed-circuit television videos (CCTV). In the case of RS, we identified six sources: satellite images, unmanned aerial vehicles (UAVs) and small unmanned aerial vehicles (sUAV), light detection and ranging (LiDAR), high-resolution synthetic aperture radar (SAR), interferometric synthetic-aperture radar (InSAR), real aperture radar (RAR). We identified seven crowdsourcing platforms: did you feel it (DYFI), Earthquake network, LastQuake, MyShake, Raspberry Shake, Quick-Deform and TSER System. We identified three SM platforms as data sources for earthquake reconnaissance: Earthquake network, Facebook and Twitter. The summary of the references reviewed is listed in Table 2.

Table 2. Summary of references reviewed for this literature review.

Data sources		References
Fieldwork or ground surveys		[28], [29], [30], [10], [31], [22], [32], [33], [34]
Omnidirectional imagery (OD)		[35]
Terrestrial laser scanning (TLS)		[36]
Remote sensing (RS)	Satellite images	[37], [19]
	UAVs & sUAV	[22], [38], [39]
	LiDAR	[26]
	SAR	[12], [40]
	InSAR	[41], [42], [43], [44]
	RAR	[8]
Crowdsourcing platforms	DYFI	[45]
	Earthquake network	[46]
	LastQuake	[47]
	MyShake	[48]
	Raspberry Shake	[49]
	QuickDeform	[50]
	TSER System	[51]
Social media (SM) platforms	Earthquake network	[46]
	Facebook	[52]
	Twitter	[53], [54],[55]
Closed-circuit television videos (CCTV)		[56], [57]

Missions deployed, or missions that have had their results published during the period covered by this literature review are Albania [47, 58], Puerto Rico [45, 46], Mayotte [52], Mexico [28-30], Palu – North Sulawesi (Indonesia) [53, 56, 59], Hualien (China) [51], Central Italy [32, 33, 35, 60], Muisne (Ecuador) [35], Nepal [1, 40, 49], and Napa - California (USA) [54, 55], Haiti [12] and L'Aquila (Italy) [14, 37]. The location of major earthquakes epicentres from 2014 – 2019 included as case studies in this literature review is depicted in Figure 3.

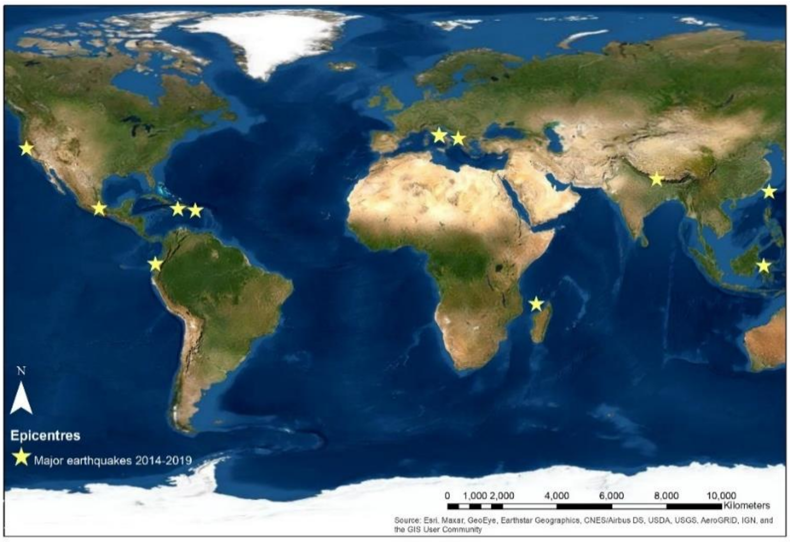

Figure 3. Spatial distribution of epicentres of major earthquakes occurred from 2014 – 2019.

3.1. Fieldwork or ground surveys

Post-disaster structural damage assessment is typically based on ground surveying methods [22]. The objective of these missions is to learn about the performance of infrastructure and structures under seismic loading, collecting accurate damage data [35] for further research [29], and scientific understanding of their physical, socio-economic, environmental [10], cultural and institutional consequences. In-situ structural observations sometimes include records not limited to the mechanism of structural failure and observations of undamaged structures and the extend and scale of damage to structures at a global and component level [35]. To develop a detailed building damage map, it is necessary to identify the damage for building-by-building [12, 53] after an earthquake or hurricanes; most building damage assessment relied on a foot-on-ground approach [61]. This detailed inspection is the most reliable [22] and generates invaluable information on the seismic performance of the affected building stock [31]. However, the limited period that the mission is deployed and the street level constraints on the extent of observations make it less reliable at collating damage statistics, which are particularly important for validating and developing fragility and vulnerability functions [35].

Fieldwork or ground surveys are a traditional approach to estimate the spatial distribution of earthquake impacts to building clusters, performed by volunteer groups consisting of structural engineers, architects, researchers with experience in building instrumentation, geotechnical and seismologist specialist [29] and undergraduate students of these fields. These missions collect structural, geotechnical, seismological and damage information[29]. Earthquake reconnaissance missions are undertaken by national or international organisations such as the Earthquake Engineering Field Investigation Team (EEFIT) [10, 27, 35, 58, 62, 63], the Geotechnical Extreme Events Reconnaissance Association (GEER)[10, 27, 32, 33, 62, 64], and Earthquake Engineering Research Institute (EERI) [10, 32, 35]. In Italy, the European Centre for Training and Research in Earthquake Engineering (EUCENTRE) and the Italian Network of University Laboratories for Earthquake Engineering (ReLUIS) have organized earthquake reconnaissance missions and conducted follow-on seismic policy analyses. For six decades, the New Zealand Society for Earthquake Engineering (NZSEE) has supported reconnaissance research of earthquakes and major tsunamis in the world [10]. The Asian Technical Committee (ATC3) 'Geotechnology for natural hazards', the Building Research Institute of Japan and the Nepalese Engineering Society has conducted reconnaissance missions in Asia after natural phenomena. Another organization that have supported reconnaissance missions in the United States (US) is the American Society of Civil Engineers (ASCE). Additionally, sometimes, self-organized teams with a focused-hypothesis driven research question or inquiry are formed to collect data [10]. In the 2017 Puebla-Morelos earthquake case, also known as the 2017 Puebla earthquake or the 2017 Mexico earthquake, the Applied Technology Council (ATC) deployed a team to Mexico city sponsored by the ATC Endowment Fund. This team was joined by practising architects, engineers, professors and local agencies [29]. The NZSEE, in collaboration with the Universidad Autonoma de Metropolitana (UAM) Azcapotzalco, the American Concrete Institute (ACI) Disaster Reconnaissance team, and the Colegio de Ingenieros Civiles de Mexico (CICM) also deployed a team for the same earthquake in Mexico [30] and the team of the Stanford's John A. Blume Earthquake Engineering Centre as well [28].

In a foot-on-ground survey, the assessment is conducted manually [34], one building after another [26], each reconnaissance mission takes one week. However, the ATC's reconnaissance mission after the 2017 Puebla-Morelos earthquake lasted three days[29]. To maximize the area to inspect, three teams from three to four structural engineers were deployed each day in this specific mission. Each team involved at least one Spanish speaker to interact with residents and one local structural engineer [29]. Usually, there is a preliminary data collection before going into fieldwork [32]. Traditionally paper forms were utilised, but nowadays, smartphones are used as tools to complete investigation forms and collect multi-media data (e.g. photos, audios and videos) [34]. One example was the damage assessment app used by the EEFIT mission team deployed to Albania to collect damage data after the earthquake in 2019 [58]. The EERI, through its program Learning from Earthquakes (LFE) was the first professional organization to organize reconnaissance missions to significant seismic events. This organization recently has formed a virtual earthquake reconnaissance teams (VERT) to conduct 'virtual' (i.e., not on-site) assessment within 48 hours after an earthquake[10]. The Applied Technology Council reconnaissance mission for the 2017 Puebla-Morelos earthquake focused not only on buildings with significant but also minimal damage. No inspections were undertaken on collapsed buildings, considering that those buildings do not have suggestive evidence of where or why the failures occurred[29]. This ATC's reconnaissance mission collected damage and geotechnical data, earthquake ground motions from several suites and ambient vibration recordings from buildings instrumented by the team during the reconnaissance trip [29]. This ATC mission instrumented seven of the inspected buildings with an array of accelerometers [29]. The NZSEE and UAM team focused on extensive and widespread damage where local site effect could have contributed to the significant damage in buildings. At the same time, that evaluated the performance of the repaired and retrofitted buildings after the 1985 Michoacan earthquake [30]. Stanford's John A. Blume Earthquake Engineering Centre surveyed the affected area in Mexico from the 29th to the 24th September. It complemented the database of collapsed buildings with data collected from newspapers and SM until the 1st November 2017 [28].

The GEER deployed two teams in Central Italy. The first team integrated entirely by Italians located potential landslides sites of interest. Later, a second team was deployed to collect data in the identified places by the first team [32]. Manual inspection and documentation of landslides were done by the GEER team in central Italy using standard geologist's tools: scale, measuring tape, clinometer, compass, rock hammers and total station. Key landslide dimensions were measured on each manually inspected point, i.e., length, wide, scarp heigh, and slope inclination [32]. Notes were taken about the slide mass or rockfall constituent materials, local geology, observed groundwater and seepage conditions, and anthropogenic activity in the area. The width and height of the rockfall source were measured using total stations, while slope inclination below the rock source was either estimated or measured [32]. The geologic hammer was utilized to infer the rock strength. Stratification, weathering, spacing, joint width and infill material were evaluated. Distances were estimated for most of the rock falls, given that lateral and vertical distances of the rollout were too large to measure manually. Boulder fragments were inspected with measurements of boulder size [32]. Parallel to the GEER mission and with its support during the planning phase and the support of the Italian Department of Civil Protection (DPC by its acronym in Italian), EERI, EUCENTRE, and ReLuis also deployed a mission in Central Italy to study the effects of the earthquake sequence not only on the built environment but also on the communities located in the affected areas. Another objective was to assess the retrofitting methodologies and evaluate their effectiveness in mitigating the damaging effects of ground shaking [33]. These three organizations also deployed two missions. The first mission was deployed following the 2016 Amatrice earthquake and the second mission after the earthquake sequence in 2017 when it was considered safe to enter the restricted zones [33]. The mission teams were formed by engineers with expertise in lifelines and structures focused on bridges and buildings. Besides engineering aspects, the mission collected data related to emergency management and the performance of critical infrastructures (CI) such as hospital and schools [33].

3.2. Omnidirectional imagery (OD)

The outcomes of the fieldwork or ground surveys can be improved by the unique viewpoints and perspectives delivered by the OD camera technology. Employing OD cameras is possible to collect chains of omnidirectional images. The development of online platforms to host the collected images makes it possible that those photo chains can be easily visualized to simulate an immersive 'walk through' of a landscape with 360 degrees, ideal for comprehensive damage inspections in reduced access zones [35].

Previous studies have reported an acceptable level of accuracy of virtual surveys compared to street ones [35, 65, 66]. Chains of OD images could be utilized to increase sample sizes by improving statistical structural damage data, allowing robust sampling techniques to be used across an area impacted by an earthquake [35]. EEFIT tested this data source in two different post-earthquake contexts: the 2016 Muisne earthquake in Ecuador and 2016 Central Italy. In both cases, the same camera equipment was used: a Ricoh Theta S. The imagery was visualized employing the Mapillary platform to assess construction typologies, number of stories and degree of damage [35]. The context of the two EEFIT missions is different in the scale of the damage, the buildings affected, the urban context, the local topography, and the earthquake's characteristics.

In the 2016 Muisne earthquake in Ecuador, damage data collected through a series of rapid visual surveys (RVS) conducted in the field was compared to the data collected virtually along the same routes using chains of OD images. This mission validated the utilization of OD imagery with RVS data to compare virtual surveys later using OD imagery to the damage data extracted from satellite imagery [35]. In 2016 Central Italy, the work was focused on testing OD imagery's ability, collected during the walk-through, to provide a better understanding of damage regarding the damage maps provided by the European Copernicus Emergency Management Service. These maps were delineated based on the timely geospatial information derived from RS and completed with available open data sources in situ for emergency response. [35].

This technology shows significant capabilities in identifying aggregated 'low' and 'high' damage grades, failure modes, number of stories and construction typologies. There are some potential issues with the proper identification of disaggregated lower damage (e.g.Damage grades 0-3 according to the European Macroseismic Scale-98)[35]. The comparison of RVS and OD based post-earthquake survey data identified challenges to overcome. Those challenges are poor image quality, insufficient photosphere captures related to the extent of its overlap, lack of photos close enough to each other, and obstructions such as trees, walls, or vehicles [35]. More advanced cameras could improve the quality of the image, and the gaps between pictures can be solved by reducing the distance between images (between 6 and 12 m), especially on obstructed streets (e.g. tree-lined). Moreover, uncertainties related to the validity of the information inferred using this method and the challenges associated with collecting detailed data still need to be addressed.

3.3. Terrestrial laser scanning (TLS)

Detailed structural surveys and landslide can be done to obtain high-resolution digital elevation models (DEM) using terrestrial laser scanning (TLS)[10]. This method managed to capture the entire geometry of the Baptistery of San Giovanni in Florence, Italy, with the level of detail required to identify and measure cracks, settlement, displacement, missing mosaic tiles and other types of damages [36]. This data collection method uses a scanner that reflects a laser off of a rotating mirror to acquire a sphere of measurements from one central point of view. TLS uses a time of flight measurement technique that calculates distance based on the time it takes for the laser to return from a surface or a phase shift method that compares the emitted and received phases of the laser [36, 67]. TLS provides accurate 3D geometry with millimetre [68] and range, reducing the effort involved in measuring and post-processing [69]. The laser scanner integrates GPS and correlates individual scans in post-processing, making it suitable for surveying based. Another technique for detailed survey is structure from Motion (SfM); this photogrammetric technique uses two-dimensional images taken from multiple viewpoints to compute a 3D representation of the scene being surveyed. Both TLS and SfM are line-of-sight (LOS) techniques, which means that the device only records measurements from the first surface it sees and nothing beyond that. In case of 3D environments, multiple imaging positions are therefore required to perform a complete digital 3D representation [36].

3.4. Remote sensing (RS)

The building-by-building inspection may not be possible in areas with significantly damaged structures. Therefore is necessary to consider alternative contactless, non-invasive RS techniques and means to safely inspect and report about the operative conditions and structural health and of affected buildings[11]. The use of imaging technology has been increasing rapidly as data gathering, and enriching tool boosting mission capabilities and ensure their safe deployment in areas affected by earthquakes [35]. For about the last decade, high-resolution optical satellite and aerial images have been increasingly used for a rapid building-damage survey after an earthquake [25]; they have become an important tool for rapid and reliable structural damage assessment (SDA) [22]. We identified in our literature review six RS data sources used for earthquake reconnaissance. Those sources are satellite images, unmanned aerial vehicles (UAVs), small unmanned aerial vehicles (sUAV), light detection and ranging (LiDAR), high-resolution synthetic aperture radar (SAR), interferometric synthetic-aperture radar (InSAR). The RS data sources are organized below according to the complexity to extract and process the data collected.

3.4.1. Satellite images

Aerial photography was the source of damage data to estimate the size of the impact area quickly, before the availability of very high resolution (VHR) satellite images. The spatial extent of building damage after earthquakes can be detected by combining pre and post-disaster very high-spatial-resolution (VHR) satellite images such as Quickbird[37]. Images are compared for change detection (CD)[38] using approaches such as Pixel or object-based image analysis (OBIA), visual or manual interpretation with the support of GIS software [19, 37]. Damages in buildings are detected according to changes detected in relational (borders), spectral (ratio, mean, GLCM texture, brightness) and spatial (compactness, volume, shape) features [37]. Very high-resolution satellite images can also be used to reference historical data compared with VHR images acquired by UAVs for CD[38]. Satellite imagery accurately captures the higher damage levels, but it is coarser in capturing lower damage degrees due to technical limitations of the distance and the atmospheric conditions when an image is captured and the satellite optical radius, affecting levels of the output accuracy. Then in the case of building damage assessment, further data is required given that the level of detail provided by satellite images is not satisfactory [35]. Satellite images are also valuable for generating accurate digital elevation models (DEM)[70], which are later used to detect and monitor ground and structural deformations [37].

3.4.2. Unmanned aerial vehicles (UAVs) and small Unmanned aerial vehicles (sUAV)

After earthquakes, overflights with aeroplanes and helicopter are initially done to identify the extent of the affected area. However, in recent years a new source of post-disaster aerial data has matured with unmanned aerial vehicles (UAVs) [10, 22]. This method can be effectively used to acquire images of a target region quickly. It is even more effective when the UAV images are sent immediately for processing to an operational ground control station. The spectral information is a crucial aspect of the change detection problem, depending on the sensor loaded on the UAV platform and less on the reference image. UAVs captures multi-perspective high-resolution imagery, are easy to transport, deploy and fly, accesses easily destroyed areas and are cost-effective than traditional airborne approaches [38, 39]. The GEER mission for the Central Italy case study selected based on their portability, rapidity in data collection and superior field of view, UAVs to take images for assessing potential landslides, being one of the principal data collection tools [32].

The GEER team utilised three UAV platforms. Two commercial off-the-shelf (COTS) UAV platforms and one customized/modified for aerial photography: DJI Phantom 4, Sensefly eBee, and Align TRex 800e, respectively [32]. The first UAV platform was employed to collect high-resolution imagery from a sloped or vertical surface, where vertical control was required. The second UAV platform was utilized to capture nadir images of places over large areas, given their superior speed and flight endurance. The third platform was employed in only one location, considering constant heavy winds in that specific place. Although LiDAR is significantly slower than UAV-based inspections, it was still faster than manual inspection of large areas and its accuracy higher than UAV-based remote sensing [32]. The onboard camera of the UAV is the governing factor that determines the quality of the data collected. Speed and altitude can be adjusted mid-flight, while minimal adjustment can be made for improving camera performance. Digital single-lens reflex (DSLR) or DSLR-equivalent cameras are chosen over point-and-shoot cameras, but they require larger UAV platforms to carry them[32].

Automated small unmanned aerial vehicles (sUAV) acquired images of damages in the mountain village of Pescara del Tronto after the earthquake in 2016 and later images of the progress of the reconstruction efforts in 2018 [64]. The imagery data was used for 3D reconstruction using SfM. The sequential 3D reconstructed models enable building identification, movement detection, and volumetric measurements and document the building identification, movement detection, volumetric measurements, and document recovery progress [64]. The 3D models were developed using Bentley™ ContextCapture. This software establishes the 3D point locations in a scene using camera metadata and GPS. The photos contain the data utilized to calculate inter-spatial intersections[64]. A view-planning algorithm delineated optimized angles and photo locations through 'greedy heuristics' to capture better orthogonal views of Pescara del Tronto and solve the drawbacks of the nadir grid approach. This view-planning algorithm identifies the best sensor location for observing a site or an object by planning oblique images for optimized SfM [64]. These computational tools together produce photogrammetric outcomes that look down vertically and at several oblique angles. In 2018, two new algorithms were applied to capture the images during the return mission: optimized view and flight path, which increased the completeness of the 3D models by providing oblique angles. The images captured in this return mission generate textured mesh models and dense point clouds to collect data about the progress of the city's reconstruction, its geotechnical background and the surrounding countryside [64]. The advantages of utilising sUAV in earthquake reconnaissance are that it makes it unnecessary for the missions to enter damaged areas, reduces the inspection time for data collection [47], and collects data in both the physical and the social and economic dimension.

One of the constraints to obtain data through this source is the increasing regulation for the operation of UAVs and the rapidity that these regulations are evolving. Nevertheless, UAV's useful role for impact estimation after natural phenomena is now acknowledged by most regulatory agencies, favouring the acquisition of the flight permit [32].

3.4.3. Light Detection and Ranging (LiDAR)

The LiDAR approach has been used to estimate the damage after hurricanes [10] and earthquakes[71]. One approach consists of laser-generated point cloud data that contains 3-dimensional (3D) coordinate information and reflection intensity of a building, which integrated into an algorithm are used for the structural assessment using photogrammetric techniques [71]. Another approach consists of a density-based algorithm extract building clusters. Then, a cluster matching algorithm is developed to match post-event and pre-event building clusters using multi-temporal datasets. Roof features involving changes in the area, volume, orientation and shape are identified as indicators of building damage [72]. High-rise or median-rise buildings are relatively easy to detect in airborne point cloud data as they have large footprints as compared to residential homes [72].

Detailed structural surveys can be done using terrestrial light detection, and Ranging (LiDAR) and the GEER team used it at landslide locations during the reconnaissance mission in central Italy [32]. Light Detection and Ranging can cover large areas and be highly accurate, but shadows cast by changes in hillsides and slopes can block critical areas of view. In this case, additional surveys from alternative directions are necessary or fusing with a UAV-bases SfM point cloud model [32].

3.4.4. High-resolution synthetic aperture radar (SAR)

Synthetic aperture radar (SAR) is an essential mean for obtaining disaster information given its strong penetrability, speediness, comprehensive coverage and all-time/all-weather imaging capabilities. It is often used to detect not only building damage but also to monitor ground and structural deformations [50]. In 2010, after the earthquake in Haiti, heavily damaged urban areas were assessed using SAR intensity images (TerraSAR-X and COSMO-SkyMed) and building footprints [12]. The backscattering coefficient between pre- and post-earthquake images changes more in collapsed buildings than in less damaged ones because there is a stronger reflection from the rubble. A linear discriminant function based on the difference and correlation coefficient between the images was developed to detect collapsed buildings. This discriminal analysis has managed to detect almost 75% of the buildings correctly [12].

Post-event dual polarimetric SAR images for earthquake damage assessment are used for the 2015 Nepal earthquake. The radar scattering characteristics of undamaged and damaged urban areas are compared using polarimetric features derived from PALSAR-2 and Sentinel 1 images [40]. Supervised classification, feature selection and split-based image analysis were utilized on a PALSAR-2 image [40]. Higher correlations were found between the damaged and texture features derived from the intensity cross-polarization [40]. Employing 30% data for testing and 70% of the data for training, the support vector machine (SVM) classifier reached an accuracy of 80.5% compared with the reference data generated from the damage map produced by the United Nations Operational SatelliteApplications Programme (UNOSAT)[40]. This method has the advantage that only a post-event SAR dataset is needed [40]. Earthquake damage Visualization (EDV) use SAR data for rapid detection of earthquake damage. The normalized difference between pre-seismic and co-seismic coherences, and vice versa, are employed to calculate the forward (from pre-seismic to co-seismic) and backward (from co-seismic to pre-seismic) change parameters, correspondingly [1]. The average values of the pre-seismic and co-seismic coherence maps are the third change-free parameter. These three parameters were eventually merged into the EDV as a red, green and blue (RGB) composite imagery [1]. The earthquake damage is visualized efficiently through the EDV employing Horizontal transmit and Horizontal receive (HH), and Horizontal transmit and Vertical receive (HV) polarizations data from the Advanced Land Observing Satellite-2 (ALOS-2) [1]. The performance of the EDV was tested in the Kathmandu Valley, struck by the 2015 Nepal earthquake [73]. The cross-validation results indicated that the EDV is more sensitive to building damage than other methods and its utilization in other earthquakes is feasible [1]. In the last years, SAR based techniques have been also applied to recognize deformation phenomena such as earthquake-related surface deformation and ruptures, massive landslides and subsidence [70]. High-resolution synthetic aperture radar data from Sentinel-1 and near-field

GPS data from four stations, i.e. CHLM, KKN4, NAST, and NDL Nepal Geodetic Network, was utilised to investigate the coseismic and postseismic surface displacement associated with the Gorkha earthquake[42]. The first Sentinel-1 data acquisition after the Gorkha earthquake was made on the 29th April 2015, and it was taken as a reference date. Three deformation maps were generated for the reference date on the 11th May, 4th June and 22nd July 2015 [42]. An upliftment of about 1 m near Khatmandu and subsidence of about 0.8 m toward the north along the LOS of the correspondent satellite was revealed by the deformation map generated from the coseismic interferogram [42].

3.4.5. Interferometric Synthetic-Aperture Radar (InSAR)

The European Space Agency (ESA) launched Sentinel-1A in 2014, the first half of a two-satellite constellation providing the most extensive and systematic coverage of SAR data to that date [74] and the first mission to deliver data on a near-real-time, open-access basis[41]. From that moment on, Sentinel-1A data have been utilised to make observations that are centimetres-to-centimetres in magnitude, associated with earthquakes such as the Mw 7.8 Gorkha, Nepal [41, 43, 44] and other geohazards. Comparing InSAR coherence maps from and after an extreme event can produce damage proxy maps (DPM) [32, 75]. Radar and optical images were combined to measure ground displacements and determine the kinematics and geometry of thrust faulting for the Himalayas. Interferometric Synthetic-Aperture Radar data from ESA was processed to derive surface offsets and surface line-of-sight ground motion from the correlation of amplitude images from Landsat-8 and SAR [76]. These observations were complemented with other published surface displacements from ALOS-2 SAR satellite and global positioning system (GPS) coseismic offsets. Up to 2 metres of south-southwest motion and almost 1 metre of uplift in Kathmandu basin and the surrounding Lesser Himalaya were observed, whereas north of this, a large region of the higher Himalaya subsided by about 0.6 metres [76]. Surface slip associated with the Main Frontal Thrust (MFT) was not shown by geodetic satellite measurements (InSAR, SAR azimuth correlation and optical image correlation), which had significant implications for interpreting seismological records. Nevertheless, a triggered near-surface slip was found with the Sentinel-1 coseismic interferograms along 26-Km-long discontinuity, 10 km north of the MFT. Broadly consistent surface offsets, peaking 60 millimetres of surface motion towards the radar, were showed by independent interferograms on two overlapping descending tracks with acquisition made 4 and 11 days after the main shock[76].

Interferometric Synthetic-Aperture Radar and GPS were utilised to study coseismic and early postseismic deformation associated with the Gorkha earthquake by mapping done by different groups [42]. The analysis of data collected found coseismic and early postseismic (4-88 days) surface displacement. The same data was jointly geodetic inverted for coseismic and postseismic slip on the Main Himalaya Thrust (MHT), providing a detailed slip distribution pattern on the causative fault. First, the coseismic and early postseismic InSAR and GPS data were inverted using a more realistic fault model with four-segment fault planes having variable dip angles representing the MHT geometry. Second, the spatiotemporal evolution of the early postseismic deformation of the Gorkah earthquake was mapped using InSAR and GPS data[42]. After correcting for orbital ramps and atmospheric phase delay, LOS were generated using 11 interferograms. The postseismic GPS displacement supports the InSAR observations and the inverted coseismic deformation closely matches the observed InSAR and GPS deformations. The InSAR data pair (29/04/2015-11/05/2015), along with the GPS-derived velocity for a window time of 13 days, was chosen for afterslip inversion as it represents early postseismic movements (4-16 days after the Gorkha earthquake), without being influenced by the Mw 7.3 main aftershock occurred on the same fault on the 12th May 2015 . The afterlift inversion was undertaken using the same fault parameterization as the coseismic slip inversion [42].

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3.4.6. Real Aperture Radar (RAR)

The RAR technology can be used for rapid building condition screening to provide in almost real-time, trustworthy information about its condition and performance. The basic principle is to record the dynamic properties of a structure under ambient vibration [77]. Monitoring kinematic variables makes it possible to extract complete modal information of the vibrational behaviour and then infer its operational conditions. [8].

The radar device can detect and range objects by acquiring echoes from different targets contained in its antenna field of view (FOV). The amplitude peaks correspond to responses from sections of the observed structure located at different distances. The operating distance and the characteristics of the backscattering surface strongly affect the radar response. A radar observation utilises the time elapsed between the transmission and reception of an electromagnetic waveform to provide a signal named range profile. This signal comprises peaks of different amplitudes and identifies the observed structure's main reflecting parts [8]. The measurement involves three steps. First, the amplitude profile as a function of the range is collected. Second, when the radar echo intensity assures an adequate signal-to-noise ratio (SNR), the corresponding part of the structure can be associated with the echo's interferometric phase; third, the displacement time record is extracted from the time variations of the phase[8].

Real aperture radar and numerical modelling were used to record the displacement response of a selected building severely damaged due to the M_W5.1 2011 Lorca earthquake (Spain). The IBIS-S, a radar device with interferometric capability, a sensor module, a control PC, a power supply and data procession software were employed to monitor the displacement time history of the vibration of the surveyed building [8]. The objective of this test was to determine the feasibility of the RAR-based method to identify the safe state of a damaged building after an earthquake, avoiding accessing unsafe structures [8]. The result shows a good consistency between the experimental and numerical approaches and the observed damage, demonstrating that RAR is a supplementary RS method to safely report operative conditions and structural health of a building after an earthquake [8].

3.5. Crowdsourcing platforms

Eyewitness reports have always been part of seismology, and large volumes of eyewitnesses observations can boost rapid situational awareness [47]. Online tools offer the possibility that ‘citizen engineers’ and volunteers to analyse large amounts of data to quickly provide a qualitative assessment of damage degree and different types of buildings post-earthquake [35]. We identified in our literature review seven crowdsourcing platforms used for earthquake reconnaissance: Did You Feel It (DYFI), Earthquake network, LastQuake, MyShake, Raspberry Shake, QuickDeform and The Taiwan Scientific Earthquake Reporting (TSER) System. The crowdsourcing platforms identified are listed below in alphabetical order.

3.5.1. ‘Did You Feel It’ (DYFI)

The United States Geological Survey (USGS) developed the ‘Did You Feel It’ (DYFI) in 1999. ‘Did You Feel It’ is an online system to collect macroseismic intensity (MI) data, shaking and damage reports from earthquakes eyewitnesses to process them automatically [47] for generating intensity maps right after an earthquake [45]. This system spread questionnaires distributed after earthquakes to collect information about their impacts [51]. In case of earthquakes outside the United States, DYFI data rapidly confirm its occurrence for seismic analysis and scientist at the USGS National Earthquake Information

Centre (NEIC), giving a quick indication of the impact of shaking effects. Intensity data collected through DYFI are utilized to provide shaking constraints for the USGS Global ShakeMap system. This shaking constraints input for the USGS Prompt Assessment of Global Earthquakes for Response system allows the USGS to alert agencies and users worldwide of significant earthquakes and their likely impact [45].

The DYFI software package is totally open source. Incoming entries from multiple web servers are processed and aggregated over postal ZIP codes (in the US), and 1-km and 10 km aggregated boxes for each earthquake to make interactive maps and plots served via the USGS Earthquake Program web pages [45]. 'Did You Feel It' is a program for community internet intensity maps (CIIM) developed based on the questionnaires filled in that assigns average intensity level to each ZIP code [55]. Aggregation allows to combine the observations from different users and complete the gaps in relevant intensity markers. Two relevant questionnaire indices are combined with other users within their community to produce an intensity calculation [45]. Did You Feel It contributors usually select the most recent earthquake when contributing or searching for information [45, 47]. Some of them still contribute for months after an earthquake; therefore, DYFI maps result from aggregated MI models that change over time. The DYFI questionnaire includes questions about user's situation, experiences, and behaviours, going beyond the calculation of MI. This data makes the DYFI database, the repository of millions of comments relevant for social sciences [45]. Essentially, DYFI depends on entries from the general public, being citizen-based science. Shakemap and DYFI have significantly facilitated the use of MI in the US, training citizens to think in terms of varying intensities produced by an earthquake [45].

3.5.2. 'Earthquake network'

Earthquake Network is a citizen science research project implementing an earthquake early warning system (EEW) based on smartphone crowdsourcing [52]. People install a smartphone application, and they receive real-time alerts when the smartphone network detects earthquakes [46]. Frequently, users install the app after strong earthquakes in their location; therefore, the network of smartphones soars to the point that it manages to detect aftershocks and future earthquakes. In the same way, users uninstall the app in periods of 'seismic calm' diminishing detections in the area [46]. The Earthquake Network app is, at the same time, the instrument to receive the EEW and to detect an earthquake. When the smartphone is unused and charging, the app monitors the accelerometer for detecting vibrations likely due to an earthquake. If a seismic movement is detected, a signal is sent to a server that collects signals from all the smartphones [46, 52]. Following the algorithm, the server decides in real-time if an earthquake is happening. If confirmed, the server infrastructure sends an EEW to the users located in the affected area. Those close to the epicentre receive the EEW first, possibly even before feeling the earthquake. Hence, the Earthquake network makes an early warning service available to users interested in making their smartphones available for detection when their smartphone is not in use[46].

For real-time detection of earthquakes, the Earthquake network sends signals to a server located in Europe. The infrastructure is currently based on nine servers that receive a large number of signals from the network and the numerous users opening the app when they experience the earthquake. Whatever signal received by the server infrastructure activates a statistical algorithm that determines if an earthquake is happening. Then the analysis is done at a global scale and in real-time [46]. Users can report the impact of an earthquake pushing a button in the app interface, reporting the earthquake's impact considering only three levels: mild, strong, and very strong, to make it fast. Spatial coordinates of the smartphones are automatically sent with the felt report. If several reports are received from a specific area simultaneously, a notification is sent to the smartphone users through the Firebase Cloud Messaging (FCM) platform. Usually, users receive first the EEW activated by smartphones, and within one minute, they receive the notification activated by users. The user is redirected to a map showing all felt reports by clicking on the notifications. As an example, reports were collected in Puerto Rico within 60 seconds after the 3.6 Magnitude earthquake; thus, users were aware of the low impact of the earthquake before any official information was released[46]. Earthquake Network app has a second strategy to send smartphone coordinates by SMS or email to a list of trusted contacts when an EEW is received. The aim is that SMS/e-mail will be sent before lifelines (phone network/Internet) are affected and the EEW received before the shaking starts. However, the smartphone must be on at the time of the earthquake. After receiving the SMS/e-mail, users can report their status by pressing a button in the app's user interface indicating: 'I am fine' or 'I need help'[46].

3.5.3. 'LastQuake'

The European Mediterranean Seismological Centre (EMSC) developed a multichannel rapid information system consisting of websites, a Twitter quakebot called LastQuake, and an eponym smartphone app [45-47, 52] at the interface between global users looking for information the EMSC. This multichannel has two objectives: To offer practical information in regions where an earthquake is felt and collect reports from users containing direct and indirect observation related to the intensity and damages caused by the earthquake [17]. LastQuake app also monitors people activity soon after the earthquake [46]. The rapid provision of tremor detection triggers the LastQuakep app and EMSC website user's engagement, who act as real-time seismic sensors. An earthquake can generate several automatic tweets published by the quakebot and updates on the website. These tweets and updates describe earthquake parameters, epicentral plot, maps, felt reports, historical seismicity, tsunami information and links to the user's comments [17].

There are two kinds of data collected from users: crowdsourced data (felt reports, geotagged pictures, videos and open comments) and crowdsourced detections (users reactions and experience on the ground)[17, 47]. Then it is only necessary to identify the geographic origin of the website visitors through their IP (Internet Protocol) to determine where the earthquake was felt without the need for any seismological data [17]. There are two other complementary crowdsourced earthquake detection methods in operation: Twitter Earquake Detection (TED). This approach identifies a surge in the number of tweets, including the keyword 'earthquake' in various languages and the traffic analysis generated by LasQuake app launches, which works like the website traffic analysis. If many people located in the same area open the app simultaneously, there is a high probability that an earthquake has happened, and hence an alert is sent [46]. A push notification is submitted to LastQuake app users once the crowdsourced detection has been confirmed. Felt reports are collected through a multilingual online macroseismic questionnaire available on the EMS website or using the 12 cartoons depicting different shaking and damage levels [51]. Each cartoon was representing an intensity level of the European Macroseismic Scale 1988 [47]. These cartoons have made more efficient the collection of reports at a global scale [17]. Plotting the location of the LastQuake app launches is possible to map the felt area automatically.

3.5.4. MyShake project

The 'Myshake' project aims to build a global smartphone seismic network to develop a large-scale earthquake early warning (EEW) and other application to boost the power of crowdsourcing [46, 48]. This project implemented by UC Berkeley Seismological Laboratory [46] is based on MyShake mobile application, which first detects earthquake shaking on a single phone. Then this detection is confirmed on the MyShake servers using a 'network detection' algorithm activated by multiple single-phone detections[48]. This app is utilised to continuously monitor the smartphone accelerometer to measure earthquakes and send alerts [46]. It is assumed that 0.1% of the population in each region has the MyShake mobile application installed on their smartphone. The system works better (alerts generated between 4 and 6 seconds, errors are similar to 0:5 magnitude units, and epicentres are typically within 10 km of true locations) in high-density populations and onshore regions with an upper crustal earthquake with a magnitude higher than M7:0. In the opposite case, low density and offshore areas, alerts are slower, and the uncertainty in magnitude and location soar, but the system still works for earthquakes with a magnitude higher than M 5.5 [48].

3.5.5. Raspberry Shake

Raspberry Shake is a crowdsourcing operation based on relatively affordable seismic sensors that can be easily installed in houses or schools, used in several citizen seismology projects [52]. After the 2015 magnitude 7.8 Ghorka earthquake in Nepal, it was found that the population was not aware of their country's high seismic hazard. Therefore, they had an insufficient level of preparedness. One of the reasons for this problem is that earthquake-related topics are not part of the school curriculum. Hence, an initiative to introduce seismology in schools, focusing on education and citizen seismology, was implemented in Nepal [49]. Considering its performance in a laboratory test, suitability for the field conditions, the seismic sensor installed in schools was a Raspberry Shake 1D (RS1D). Additional criteria to select this sensor were low cost (below 500 USD), easily applicable for educational purposes, high sensitivity to detect local earthquakes, ease to handle and the possibility of recording data without an additional computer. These seismometers installed in 22 schools develop the Nepal School Seismology Network delivering online data openly [49]. This program started in Western Nepal, because people there have limited opportunity to learn about earthquakes. There has been no significant earthquake for 500 years in this region [49], and it has an acceptable travel time between different sites where the seismometer was installed. Facebook and Twitter were used in Nepal to spread information about the Nepal School Seismology Network and ask interested schools to fill in the request form[49]. The criteria to select the 22 schools among 100 that submitted the request form were: number of students, motivation, feasibility to instal the seismometer on the ground floor, 200 m as minimum distance to road or highway to avoid anthropogenic noise, own internet connection, alternate power supply and reachability of the school by vehicle or a short walk [49]. Each seismometer installed in a school inform students about earthquakes, waveforms, distance and magnitude of the event. Thus the network is used for both sharing locally recorded data openly and teaching[49].

3.5.7. QuickDeform

Near real-time ground deformation maps generated after earthquakes are essential for hazard assessment and usually take a couple of hours or longer to be generated by conventional means [50]. A near-real-time coseismic ground deformation map generation system to assist emergency response is developed. This system adopts source parameters published by the United States Geological Survey National Earthquake Information Centre (USGS-NEIC) and empirical equations to generate the real-time (within seconds) coseismic ground deformation maps [50]. The ground deformation is integrated as self-adapting spatial data fusion and visualised on an interactive WebGIS platform, named: QuickDeform. This GIS user-oriented platform provides real-time evaluation and emergency response information by viewing, searching, and customizing the seismic deformation.

3.5.6. The Taiwan Scientific Earthquake Reporting (TSER) System

In the past decades, dense instrumental seismic and geodetic networks have been installed in Taiwan. However, earthquake-induced ground damage is not easily identified by seismic instruments immediately after an earthquake [51]. The TSER is a crowdsourcing system designed for acquiring quantitative data collected by trained volunteers for earthquake-triggered surface damages [51]. This TSER is an experimental program launched by the Institute of Earth Sciences, Academia Sinica, and Taiwan's Seismological centre in 2016. These institutions incorporated in the program: (1) computer-aided volunteer management system (VMS), (2) educational training course and (3) online report and mapping platform [51]. Additionally, volunteers were trained to ensure the quantity, completeness, quality and reliability of the data collected when they report the damages produced by earthquakes. The TSER was developed in the framework of a citizen seismology program that includes training courses and VMS with the web GIS-based platform to crowdsource scientific users reports for earthquake-triggered surface natural damages[51]. The on-site field reports complement the field ground observations with real-time instrumental data and results to better understand the surface damages and geohazards produced by earthquakes and support SAR activities and later social impacts [51]. The TSER system was constructed adopting the pre-existing Ushahidi mapping platform, widely used in the past with success for several purposes [51]. The VMS notifies a trained volunteer of a potentially damaging earthquake through email. These notifications indicated the epicentral area to carry out field surveys. Volunteers must log into the TSER platform. To report earthquake-induced surface damages, they must identify the ground damage category from a menu, describe it, locate it, and upload the corresponding picture [51]. The collected information is made available to the public after being checked by the on-duty scientist. The TSER platform was tested after the 2018 Mw 6.4 Hualien earthquake providing the distribution of the surface ruptures, rupture orientation, type of faulting and offset dimension [51].

3.6. Social media (SM)

Social platforms and smartphone apps are playing an increasing role during disasters[78]. They offer not only public participation but also constitute backchannel communication. Considering that the internet and SM become the digital nervous system of our planet [17], the last ones are a valuable tool for quickly collecting large amounts of data relating to disasters. It offers first-hand data, observations, sentiments, and perspectives [79]. This data can range from photos, videos, and comments uploaded to various internet platforms and Facebook, Twitter, Instagram and Youtube.

The first fieldwork or ground survey that reported have extracted data from SM was the mission deployed by Stanford's John A. Blume Earthquake Engineering Centre for the 2017 Puebla-Morelos earthquake. This mission complemented the collapsed buildings' database during the mission with data from newspapers and SM [28]. Nowadays, SM platforms have become another media to share early scientific analysis, forming collaboration bases among multidisciplinary teams. We identified in our literature review six SM platforms used for earthquake reconnaissance: Earthquake Network, Facebook and Twitter. The SM platforms identified are organized below in alphabetical order.

3.6.1. Earthquake Network

Probably the first social network about earthquakes was Earthquake Network. This platform has chatrooms in 10 languages, where users can share information right after an earthquake, either in private messages or in the public space. Chat moderators in the public space keep the discussion focused on relevant issues and block users that misbehave [46]. Earthquake Network supports people after they experienced an earthquake because having someone to discuss is suitable to reduce the anxiety and fear caused by it. Those users active in the chatrooms tends to keep the app installed for months to years [46].

3.6.2. Facebook

Facebook is the most popular SM platform [52, 53] for user-generated content. Lastquake app users have the option to share their comments on their Facebook account [17]. Earthquake Network is on Facebook with 91,419 followers [46]. Facebook was used in Nepal to spread information about the Nepal School Seismology Network based on Raspberry Shake sensors and ask interested schools to fill in the request form[49]. In May 2018, the French Islan of Mayotte in the Indian Ocean was struck by a series of earthquakes. At the beginning of the seismic swarm, there was a gap in seismic data and explanations of the phenomenon and a mistrust of the scientific community. The author's of this study suggest that Facebook is an important part of technology culture and information in Mayotte. People interviewed in these islands describe how bookings and checking of traffic and doctor's schedules can be made through this platform [52]. Additionally, residents using the LastQuake app[17], created their citizen seismology network based on a Facebook group named: Mayotte Earthquake Support (STTM by its acronym in French)[52]. The members of this group on Facebook expressed their scepticism about the lack of information from the seismologist community. After the first earthquake, they started to discuss its effects on the road traffic group. Following this, one group administrator decided to create a group dedicated to earthquakes [52]. Citizens created this group for citizens to exchange knowledge and feelings about earthquakes. Mayotte Earthquake Support is a public Facebook group, and anyone with a Facebook account can join it. Volunteers moderate and decide the group rules, excluding members who do not comply with them[52]. Generally, after an earthquake, citizens post messages indicating when and where they felt it and, in some cases, ask for additional information such as magnitude. They also show and ask for emotional support, commenting on each others' posts and questions, uploading pictures of cracks or trees on the roads and discuss the potential causes of the earthquakes[52]. Over time, this group took a more scientific direction, and some of the members shared reliable seismic information in an understandable way for their fellow citizens. The information shared was about seismology in general, seismological concepts (magnitude and intensity) felt earthquakes, earthquake causes, comparisons with other earthquakes swarms, historical seismic data and safety measures to take[52]. These citizens collected data, reviewed scientific literature and produce collated forms of knowledge, listing all felt earthquakes mentioned in the group, comparing them to the French Geological Survey (BRGM's by its acronym in French) seismic reports. Furthermore, a few months after the earthquakes one of the users suggested equipping the island with a Raspberry shake seismometer [49, 52].

3.6.3. Twitter

Earthquake Network has a Twitter account with 112,000 followers [46]. Lastquake app users have the option to share their comments on their Twitter account [17]. Twitter was used in Nepal to spread information about the Nepal School Seismology Network based on Raspberry Shake sensors and ask interested schools to fill in the request form [49]. The Palu M_W 7.5 earthquake and tsunami in Indonesia and other events have demonstrated how Twitter quickly generates knowledge in the minutes to hours and days following an event developing an efficient exchange of information and active discussion between the public and scientist themselves [53]. In the aftermath of an earthquake, it is essential to promptly establish its geological and geophysical characteristics to be able to explain it to the media and stakeholders and evaluate the risk of secondary effects [53]. In Hurricane Sandy, the Twitter activity was correlated with damage and therefore was useful for impact assessment and response [17, 80]. Correlation between the number of tweets and the intensity of an earthquake was observed for the first time in 2010. During the Tohoku earthquake, researchers observed a high correlation between the number of tweets and the earthquake's intensity in some locations [81, 82]. Informative tweets about geophysical data were made for the 2018 Palu - Sulawesi island, Indonesia. Based on these tweets, a timeline was built of the rapid progress of understanding the earthquake rupture and its effects. Published papers, maps about the seismotectonic context in Indonesia, teleseismic data, local seismic waveforms, high-resolution optical satellite images, SAR, tide gauge records, and field observations from both science groups and local residents were shared on Twiter, getting rapid and varied feedback from fellow researchers [53]. The correlation between the number of tweets and Mercalli intensity was demonstrated in the earthquakes of Napa, California [55], Japan, and Chile [54].

3.7. Closed Circuit Television Videos (CCTV)

The Collection of 38 amateur videos and CCTV's at 14 sites around Palu bay were used [53, 56] to estimate tsunami arrival times, amplitude and wave periods around different locations, where more damage was reported after the MW 7.5. 2018 Palu earthquake. The Pantoloan tide gauge data was complemented with an innovative approach that combines the analysis of video footage and post-tsunami surveys. The video images captured the formation, propagation and inundation of the tsunami. Timed waveforms were constructed from the quantitative interpretation of video footage [83, 84] by tracking sea levels changes from image pixels in subsequent frames. The quality and the quantity of the videos determined the richness of the tsunami data. While several CCTV cameras precisely capture tsunami scenes, others were captured by amateur videos. This analysis provides temporal data that is not possible to recover in field surveys. The video footage combined with post-tsunami surveys indicated evidence of potential locations of submarine landslides as tsunami sources that would correspond with the arrival times of the waves.

An image-based damage assessment system named IDEAS has been developed to evaluate damage assessment inside buildings. This system first compares images taken inside a building before and after an earthquake. Later these images are used to map the damage according to a Mercalli intensity scale [57]. To perform the earthquake intensity scale assessment, IDEAS adopts scale-invariant feature transformation (SIFT) to extract the information of non-structural objects moved. Afterwards, IDEA uses the information and the size variants of non-structural objects moved for damage assessment of the buildings [57]. To determine the accuracy of IDEAS, 40 pairs of CCTV images from Youtube website were collected. The test reports an accuracy of 97.6% in mapping the Mercalli intensity scale [57].

4. Discussion

In 2019, this review was planned as a systematic review. However, only using the keywords: 'damage' AND 'earthquakes' excluded important references about innovative data sources, methods and tools for collecting building damage data due to other natural phenomena such as hurricanes or the trace of time. The outcome of the search using these two keywords was 34 references, which were reviewed. In 2021, we revisited the data sources, methods, and tools identified in the first literature review to narrow the focus only on those references relevant to earthquake reconnaissance and/or addressed during the LfE UK project. Then we used the keywords 'earthquake reconnaissance' and each of the data sources identified in the first literature review. In both literature reviews, the references were identified from Web of Science because we consider it the most comprehensive curated database available. Although SM platforms tend to be the new data sources and given the travel restrictions imposed by the COVID-19 pandemic, we also used them as data sources for this paper. We did not focus the review on them because there was already a literature review on this topic [83]. Furthermore, through the literature review, we found other data sources that include other cutting-edge methods and tools that collect data at more detailed scales and complement the data collected through SM. While we considered and included the references published in 2014 and 2015 identified in the first literature review, we did not count them because we aim to highlight state-of the-art (last five years).

Building-by-building foot-on-ground surveys collect highly detailed data that be used forensically to validate RS data o models such as structural models or fragility curves [85]. However, they are expensive and time-consuming [61], and the duration of these inspections can last for months[53] depending on the availability of volunteers [86] to reach a good understanding of the event's characteristics [53]. According to Mangalathu and Burton [86], this aspect makes them slow, labour-intensive [26] and inefficient [34], thus unfeasible for supporting emergency response and early recovery planning. Nevertheless, it is necessary to differentiate between a rapid building damage survey [87], which is focused on buildings safety during the emergency phase and a detailed damage survey oriented to assessing the performance of building structures or the restoration of historic buildings [36]. This second kind of damage survey can support early recovery planning and help to accomplish build back better and built to last goals. Now, smartphones allow quicker and more rigorous structural evaluations by filling in forms in apps and collecting multimedia data to reduce time-consuming matching work. The collected photos can be indexed by their locations using the global positioning system (GPS) coordinates [88] or what3words. Eventually, post-earthquake investigation data can be quickly uploaded to servers through the network of smartphones so that seismic damage data can be quickly shared to support decision making for post-disaster recovery [34]. The OD imagery proved very useful in integrating data in Copernicus EMS maps and is the fastest and only option to capture image data when on-site safety conditions are dangerous [35]. The use of TLS to capture the entire geometry of the Baptistery of San Giovanni in Florence, Italy, was not used in the context of an earthquake reconnaissance mission. However, we decided to include this reference for the suitability of this method in reconnaissance missions when they need to focus on the forensic analysis of world heritage (WH) buildings.

The main advantage of using RS for building damage assessment is that large damaged areas could be surveyed rapidly without being hampered by the emergency operation on the ground [25]. Remote sensing sources provide timely information for planning emergency response, including search and rescue [35]. This data source is an efficient approach to assess building damage after earthquakes in large areas; however, it is limited to heavy and visible damage from the roof. Smaller and particularly complex urban disaster scenes, multi-perspective aerial imagery obtained with UAVs and sUAV and derived dense colour 3-D models are progressively more employed, avoiding only severely damaged buildings [64, 88] with visible damage roof were detected using RS. Hence, it would be interesting to investigate if the regulation for the operation of sUAV is less strict because its use supports the rate and delineation of areas struck by earthquakes and the resulting models provided a detailed reference source for the tracking of recovery efforts during return missions. These data sources are an alternative to identify damage not based on CD in satellite images and remove challenges such as the images do not match each other [38]. Currently, satellites are equipped with several RS payloads to complement airborne remote sensing and other UAVs. The result is a collaborative operated network involving multiple satellite observations, airborne RS, and ground operations [19].

The ubiquity of smartphones and SM have opened new opportunities for fast crowdsourcing and two-way communication between affected people and institutions/authorities [47]. In some cases, one geotagged picture, an individual observation or comment, on SM platforms can substantially reduce uncertainties regarding impacts [47]. However, the scientific community still cast doubts on the utility and reliability of data collected in the framework of citizen science projects. To ensure the quality of data collected through the crowdsourcing TERS system, the Institute of Earth Sciences, Academia

Sinica in Taiwan, selected volunteer users among high school or junior high school teachers in natural sciences. This institution trained volunteers in regional and local geology, historical earthquakes and associated surface damages, geohazards, TERS and volunteer reporting system, citizen seismology and field geology excursion with on-site practices [51].

Crowdsourcing information can be a cost-effective option to form a dense real-time accelerometric network, reducing uncertainties of rapid earthquake scenarios[47]. Although the intrinsic variability felt reports, based on 20 years of DYFI experience [45], it is possible to observe how felt reports have contributed to earthquake response and science and behaviour studies [45, 47]. The integration of DYFI data in ShakeMaps improves shaking estimates and the rapid assessment of earthquake's impact [45, 47]. Earthquake Network app and MyShake app are similar. The main difference between these apps is that the data recorded by the accelerometer in MyShake app is not used to make any seismological analysis and EEWs are sent only when several smartphones in the same area detect accelerations above a specific threshold [46]. Currently, the main limitations of the EEW system implemented by the Earthquake Network are the lack of accuracy in the information of the earthquake intensity and that the geometry of the location of the smartphone network is not optimized regarding known faults [46]. Among these apps, the EMSC was the first to consider the behaviour of users and their associated digital footprints to detect a widely-felt earthquake in an intersection between seismology, citizen science and digital communication [17]. EMSC's use of cartoons representing different shaking and damage levels was validated by comparing it with the USGS's DYFI macroseismic questionnaire system[45]. This approach was also compared with the manually and independently derived macroseismic datasets from DYFI[47]. However, when looking at intensity levels reported by users, it is necessary to keep in mind that those living in low seismic zones tend to report a strong earthquake, regardless of the small magnitude and/or impact displayed in the app user interface [46]. Another common problem among citizen science projects is user retention, which could be solved by encouraging interaction with the app and other users to boost user lifetime value [46]. In the STTM Facebook group, citizens launched a form of citizen seismology to share knowledge and information about earthquakes without the support of the seismologist community[52]. In the case of Mayotte, it was observed that while scientists were gathering on Twitter [53], citizens were debating on Facebook about the same seismic phenomenon. The answers to the questions formulated on the STTM group were available on Twitter. This situation can be explained by the socio-technical design of the platforms and the technological culture. People use Facebook for daily and personal uses. Instead, Twitter has become a handy platform for researchers to exchange ideas, collaborate and share preliminary outcomes [52]

Earthquake reconnaissance missions can also take advantage of images uploaded on SM platforms such as Flickr. This platform is an American image and video hosting, which has been used in defence [89], to monitor and evaluate post-disaster tourism recovery after typhoon Haiyan [90] and to prioritize the collection of RS imagery as a filtering tool after the Colorado floods[91]. However, Flickr has not been used yet in earthquake reconnaissance and could also another suitable data source.

5. Conclusions

This literature review was beneficial not only to go through each of the most used data sources in the last five years but also to recall the most significant seismic events in the same period. Considering an initial literature review undertaken in 2019 plus the experience gained in the project: Learning from Earthquakes, UK: We conclude that the current data collection sources can be grouped into seven categories: fieldwork or ground surveys, OD, TLS, RS, crowdsourcing platforms, SM and CCTV.

The most detailed and reliable data is collected through fieldwork or ground surveys that last between three days to one week on-site [29]. There must be a previous week to collect information of the affected area, searching for local contacts and logistic preparation (Team members selection, flight tickets purchasing, hotel booking, equipment preparation, visas and so forth). After the mission, it is necessary to allocate time to process the data to produce a final report. The partnerships between visiting earthquake reconnaissance teams (who have reconnaissance experience) and local institutions (who have local knowledge) are essential for efficient and effective data collection and interpretation. The fieldwork or ground surveys usually rely on traditional methods for data collection. However, the earthquake reconnaissance missions in the period covered by this literature review started to incorporate new technologies and sources, e.g. the app customized in the framework of the Learning from Earthquakes (LfE) project in the UK tested by EEFIT mission for the 2019 Albania earthquake; the omnidirectional imagery for the 2016 Muisne earthquake and Central Italy, the data extracted from SM by the Stanford's John A. Blume Earthquake Engineering Centre for the 2017 Puebla-Morelos earthquake and the ambient vibration recordings done by the ATC mission for the same event. Smartphones have already replaced paper forms, overcoming issues such as the duration of the charge in the battery and technical compatibilities are still issues to solve. OD imagery represents a significant improvement in damage assessment accuracy over satellite imagery, especially for lower damage grades [35]. TLS is the data collection method suitable for historic structures affected by earthquakes that need a precise restoration to keep their world heritage (WH) condition and precisely estimate the cost and time needs for their reparation or reconstruction [92].

The RS data sources are satellite images, UAVs, sUAV, LiDAR, SAR, InSAR, and interact between them. Satellite images are suitable for CD to identify damages in buildings and infrastructure, while SAR and InSAR techniques are more suitable for CD in land-surface altitude. The Building Safety Evaluation (BSE) teams conducted the field survey on behalf of Christchurch City Council in the weeks following the Feb 22, 2011, earthquake to validate findings from RS images [25]. The GEER fieldwork mission on Central Italy integrated data from several sources satellite-based interferometric DPM, published reports about landslides in the case study area, digital imagery from UAV, manual observations and TLS. Good agreement was found between the UAV images, and the zones of the significant ground surface changed detected by DPMs[32]. Observations on steep terrain relied on UAV and LiDAR to collect data. The combined use of UAV and targeted terrestrial imagery allowed to build a large dataset of images with the outcome of various two- dimensional (2-D) and 3-D scaled representations of the observed landslides [32]. Terrestrial LiDAR point cloud models demonstrated to be handy intermediaries between manual inspections and UAV[32]. There is no unique RS method to reach the accuracy and coverage expected in a post-earthquake reconnaissance mission. It is ideal to start with coarse RS methods such as optical image correlation and satellite-based interferometry to detect surface deformations and deploy more accurate RS data sources such as UAV-based SfM and/or terrestrial LiDAR to specific points of interest [32]. The inclusion of ground control points (GCP) and checkpoints (CPs) in the UAV-based reconnaissance landslide sites increases the accuracy of the resulting products [26] significantly. The Geotechnical Extreme Events Reconnaissance Association believes that data collection should rely in the future more upon UAV-based SfM and terrestrial LiDAR RS methods than in traditional manual observations. At the same time, they conclude that to increase the efficiency of a data collection task, earthquake reconnaissance missions must incorporate a phased reconnaissance approach where traditional measurements are only performed on valuable and essential places [27].

The crowdsourcing platforms used for earthquake reconnaissance are DYFI, Earthquake network, LastQuake, MyShake, Raspberry Shake, QuickDeform and TSER System.

Crowdsourced detections are an efficient filter to identify earthquakes that attract public attention [17]. Social media platforms used for earthquake reconnaissance are Earthquake Network, Facebook and Twitter. Crowdsourcing and SM interact between them, complementing each other. Social media is a complementary data source of damage in buildings and lifelines, post-disaster needs, emergency response, and post-disaster recovery and situation awareness in general. However, it is still necessary to train citizens to provide more helpful information. The main aim of using SM is to extract useful information from image and text data to support data-driven decisions in earthquake reconnaissance. Crowdsourcing and SM are efficient sources of interdisciplinary data collection considering that they are within reach of everyone and interact between them, allowing users to share information, attract new users, boost new users, and boost information and dissemination. Crowdsources such as the LastQuake system has evolved, elaborating on the earliest crowdsource experience, such as DYFI.Additionally, crowdsourcing and SM collects relevant data regarding damages description done by users, their emergency response actions, and their fears given their vulnerable condition. Currently, the information contained in this data has not been sufficiently explored. It is necessary to encourage citizens to keep on their smartphones apps such as Earthquake network, LastQuake app and My Shake. In this way, it is possible to ensure earthquake detection, receive EEW and collect first-hand data about injuries and casualties, building damages, tsunami and geotechnical effects, emergency response actions are taken, and level of preparedness among users. To the best of our knowledge, the less explored data source is CCTV. This data source has been demonstrated to be useful in tsunami-prone areas such as Chile, Japan and the south Asian coast. Closed Circuit Television Videos (CCTV) can record the collapse pattern in buildings. In the future, the data collected can be used to monitor socio-economic recovery, counting pedestrian traffic during the early recovery, recovery and development phase [9].

We conclude that the criteria to select a data source for earthquake reconnaissance include the time after the event (usually the post-disaster phase to carry out inspection); the size and topography of the area to survey;the window time to collect data, the estimated degree of damage; the type of assets damaged (e.g. structural vs. non-estructural elements) and the specific character of the inspection area. It is necessary to collect data in different scales for different levels of detail according to the assets damaged, each post-disaster phase's needs, and to consider several data sources, to have comprehensive information of one event. Currently, no reconnaissance mission can rely on a single source of data. It is necessary to combine different sources to complement and validate the data collected [37], especially in large survey areas, to quantify the damage comprehensively.

Data regarding physical damage and reconstruction can be collected through field surveys, OD, and TLS, which inspection area or points can be previously delimited according to data collected through RS, crowdsourcing, SM platforms and CCTV. The socio-economic, institutional and cultural impact can be derived from SM platforms and CCTV right after the event during the relief or emergency phase and the early recovery, recovery and development phase. The increase in the number of Crowdsourcing and SM platforms as a source of data is a clear indication of the tendency of data sources in the future. Currently, data do not exclusively come from scientists and/or authorities but also citizens. These citizens as sensors[93] are the group to be trained to obtain from them meaningful data to understand the characteristics of the earthquake and their impact on the social, economic, institutional, cultural and environmental dimension avoiding gaps in knowledge and information that give space to rumours and fake news.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used 'Conceptualization, S.W. and P.J.; methodology, D.C.; investigation, D.C.; data curation, D.C.; writing—original

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References

1. Sharma, R.C., et al., *Earthquake Damage Visualization (EDV) Technique for the Rapid Detection of Earthquake-Induced Damages Using SAR Data.* Sensors, 2017. **17**(2): p. 235.
2. Zucconi, M., R. Ferlito, and L. Sorrentino, *Simplified survey form of unreinforced masonry buildings calibrated on data from the 2009 L'Aquila earthquake.* Bulletin of Earthquake Engineering, 2018. **16**(7): p. 2877-2911.
3. Zook, M., et al., *Volunteered Geographic information and Crowdsourcing Disaster Relief: A Case Study of the Haitian Earthquake.* World Medical & Health Policy 2010. **2**(2).
4. Abbasi, A., et al., *Social Networks Perspective of Firefighters' Adaptive Behaviour and Coordination among Them*, in *Proceedings of the 2010 IEEE/ACM Int'l Conference on Green Computing and Communications & Int'l Conference on Cyber, Physical and Social Computing*. 2010, IEEE Computer Society. p. 819-824.
5. Durham, T.S., P. Johari, and D. Bausch, *Strategic directions in seismic modeling: HAZUS® development and current applications for catastrophe planning* in *Risk Assessment, modeling and decision support: strategic directions* A. Bostrom, S. French, and S. Gottlieb, Editors. 2008, Heidelberg: Springer - Verlag Berlin p. 101-116.
6. Vieweg, S., et al., *Microblogging during two natural hazards events: what twitter may contribute to situational awareness*, in *The 28th international conference on Human factors in computing systems Atlanta: Association of Computing Machienry*. 2010. p. 1079 - 1088.
7. Nazarian, E., et al., *Machine-learning-based approach for post event assessment of damage in a turn-of-the-century building structure.* Journal of Civil Structural Health Monitoring, 2018. **8**(2): p. 237-251.
8. Gonzalez-Drigo, R., et al., *Assessment of Post-Earthquake Damaged Building with Interferometric Real Aperture Radar.* Remote Sensing, 2019. **11**(23): p. 2830.
9. Contreras, D., *Fuzzy Boundaries Between Post-Disaster Phases: The Case of L'Aquila, Italy.* International Journal of Disaster Risk Science, 2016. **7**(3): p. 277-292.
10. Wartman, J., et al., *Research Needs, Challenges, and Strategic Approaches for Natural Hazards and Disaster Reconnaissance.* Frontiers in Built Environment, 2020. **6**: p. 17.
11. Farrar, C.R. and K. Worden, *An introduction to structural health monitoring.* Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 2007. **365**(1851): p. 303-315.
12. Miura, H., S. Midorikawa, and M. Matsuoka, *Building Damage Assessment Using High-Resolution Satellite SAR Images of the 2010 Haiti Earthquake.* Earthquake Spectra, 2016. **32**(1): p. 591-610.
13. Stannard, M., et al., *Field guide: Rapid Post Disaster building usability assessment - earthquakes*. 2014, Wellington: Ministry of Business, Innovation and Employment.
14. Contreras, D., G. Forino, and T. Blaschke, *Measuring the progress of a recovery process after an earthquake: The case of L'Aquila, Italy.* International Journal of Disaster Risk Reduction, 2018. **28**: p. 450-464.
15. Matsuoka, M. and F. Yamazaki, *Use of Satellite SAR Intensity Imagery for Detecting Building Areas Damaged Due to Earthquakes.* Earthquake Spectra - EARTHQ SPECTRA, 2004. **20**.

16. Contreras, D., T. Blaschke, and M.E. Hodgson, *Lack of spatial resilience in a recovery process: Case L'Aquila, Italy.* Technological Forecasting and Social Change, 2017. **121**: p. 76-88.
17. Bossu, R., et al., *LastQuake: From rapid information to global seismic risk reduction.* International Journal of Disaster Risk Reduction, 2018. **28**: p. 32-42.
18. Dong, L. and J. Shan, *A comprehensive review of earthquake-induced building damage detection with remote sensing techniques*. Vol. 84. 2013. 85–99.
19. Fan, Y.D., et al., *Quantifying Disaster Physical Damage Using Remote Sensing Data-A Technical Work Flow and Case Study of the 2014 Ludian Earthquake in China.* International Journal of Disaster Risk Science, 2017. **8**(4): p. 471-488.
20. Li, L., et al., *Building damage assessment from PolSAR data using texture parameters of statistical model.* Computers & Geosciences, 2018. **113**: p. 115-126.
21. Contreras, D., et al., *Myths and realities about the recovery of L'Aquila after the earthquake.* International Journal of Disaster Risk Reduction, 2014. **8**(0): p. 125-142.
22. Cusicanqui, J., N. Kerle, and F. Nex, *Usability of aerial video footage for 3-D scene reconstruction and structural damage assessment.* Natural Hazards and Earth System Sciences, 2018. **18**(6): p. 1583-1598.
23. Qadir, J., et al., *Crisis analytics: big data-driven crisis response.* Journal of International Humanitarian Action, 2016. **1**(1): p. 12.
24. Ragini, J.R., P.M.R. Anand, and V. Bhaskar, *Big data analytics for disaster response and recovery through sentiment analysis.* International Journal of Information Management, 2018. **42**: p. 13-24.
25. Foulser-Piggott, R., et al., *Using Remote Sensing for Building Damage Assessment: GEOCAN Study and Validation for 2011 Christchurch Earthquake.* Earthquake Spectra, 2016. **32**(1): p. 611-631.
26. Zhou, Z. and J. Gong, *Automated Analysis of Mobile LiDAR Data for Component-Level Damage Assessment of Building Structures during Large Coastal Storm Events.* Computer-Aided Civil and Infrastructure Engineering, 2018. **33**(5): p. 373-392.
27. Rossetto, T., et al., *The value of multiple earthquake missions: the EEFIT L'Aquila Earthquake experience.* Bulletin of Earthquake Engineering, 2014. **12**(1): p. 277-305.
28. Galvis, F.A., et al., *Overview of collapsed buildings in Mexico City after the 19 September 2017 (M(w)7.1) earthquake.* Earthquake Spectra, 2020. **36**(2_SUPPL): p. 83-109.
29. Lan, Y.J., et al., *ATC Mw7.1 Puebla-Morelos earthquake reconnaissance observations: Structural observations and instrumentation.* Earthquake Spectra, 2020. **36**(2_suppl): p. 31-48.
30. Roeslin, S., et al., *The September 19th, 2017 Puebla, Mexico earthquake: final report of the New Zealand Reconnaissance Team.* Bulletin of the New Zealand Society for Earthquake Engineering, 2020. **53**(3): p. 150-172.
31. Mangalathu, S. and H. Burton, *Deep learning-based classification of earthquake-impacted buildings using textual damage descriptions.* International Journal of Disaster Risk Reduction, 2019. **36**: p. 101111.
32. Franke, K.W., et al., *Phased Reconnaissance Approach to Documenting Landslides Following the 2016 Central Italy Earthquakes.* Earthquake Spectra, 2018. **34**(4): p. 1693-1719.
33. Mazzoni, S., et al., *2016-2017 Central Italy Earthquake Sequence: Seismic Retrofit Policy and Effectiveness.* Earthquake Spectra, 2018. **34**(4): p. 1671-1691.
34. Xu, Z., et al., *A smart phone-based system for post-earthquake investigations of building damage.* International Journal of Disaster Risk Reduction, 2018. **27**: p. 214-222.
35. Stone, H., V. Putrino, and D. D'Ayala, *Earthquake Damage Data Collection Using Omnidirectional Imagery.* Frontiers in Built Environment, 2018. **4**: p. 14.
36. Hess, M., et al., *Terrestrial laser scanning for the comprehensive structural health assessment of the Baptistery di San Giovanni in Florence, Italy: an integrative methodology for repeatable data acquisition, visualization and analysis.* Structure and Infrastructure Engineering, 2018. **14**(2): p. 247-263.

37. Contreras, D., et al., *Monitoring recovery after earthquakes through the integration of remote sensing, GIS, and ground observations: the case of L'Aquila (Italy).* Cartography and Geographic Information Science, 2016. **43**(2): p. 115-133.
38. Fytsilis, A.L., et al., *A methodology for near real-time change detection between Unmanned Aerial Vehicle and wide area satellite images.* ISPRS Journal of Photogrammetry and Remote Sensing, 2016. **119**: p. 165-186.
39. Nex, F. and F. Remondino, *UAV for 3D mapping applications: a review.* Applied Geomatics, 2014. **6**(1): p. 1-15.
40. Bai, Y., et al., *Building Damage Assessment in the 2015 Gorkha, Nepal, Earthquake Using Only Post-Event Dual Polarization Synthetic Aperture Radar Imagery*. Vol. 33. 2017.
41. Parker, A.L., M.S. Filmer, and W.E. Featherstone, *First Results from Sentinel-1A InSAR over Australia: Application to the Perth Basin.* Remote Sensing, 2017. **9**(3): p. 19.
42. Sreejith, K.M., et al., *Coseismic and early postseismic deformation due to the 25 April 2015, Mw 7.8 Gorkha, Nepal, earthquake from InSAR and GPS measurements.* Geophysical Research Letters, 2016. **43**(7): p. 3160-3168.
43. Diao, F., et al., *The 2015 Gorkha earthquake investigated from radar satellites: slip and stress modeling along the MHT.* Frontiers in Earth Science, 2015. **3**(65).
44. Grandin, R., et al., *Rupture process of the Mw = 7.9 2015 Gorkha earthquake (Nepal): Insights into Himalayan megathrust segmentation.* Geophysical Research Letters, 2015. **42**(20): p. 8373-8382.
45. Quitoriano, V. and D.J. Wald, *USGS "Did You Feel It?"—Science and Lessons From 20 Years of Citizen Science-Based Macroseismology.* Frontiers in Earth Science, 2020. **8**(120).
46. Finazzi, F., *The Earthquake Network Project: A Platform for Earthquake Early Warning, Rapid Impact Assessment, and Search and Rescue.* Frontiers in Earth Science, 2020. **8**(243).
47. Bossu, R., et al., *Rapid Public Information and Situational Awareness After the November 26, 2019, Albania Earthquake: Lessons Learned From the LastQuake System.* Frontiers in Earth Science, 2020. **8**(235): p. 1-15.
48. Kong, Q.K., R. Martin-Short, and R.M. Allen, *Toward Global Earthquake Early Warning with the MyShake Smartphone Seismic Network, Part 2: Understanding MyShake Performance around the World.* Seismological Research Letters, 2020. **91**(4): p. 2218-2233.
49. Subedi, S., et al., *Seismology at School in Nepal: A Program for Educational and Citizen Seismology Through a Low-Cost Seismic Network.* Frontiers in Earth Science, 2020. **8**: p. 19.
50. Zhao, R., X.T. Liu, and W.B. Xu, *Integration of coseismic deformation into WebGIS for near real-time disaster evaluation and emergency response.* Environmental Earth Sciences, 2020. **79**(18): p. 11.
51. Liang, W.T., J.C. Lee, and N.C. Hsiao, *Crowdsourcing Platform Toward Seismic Disaster Reduction: The Taiwan Scientific Earthquake Reporting (TSER) System.* Frontiers in Earth Science, 2019. **7**: p. 12.
52. Fallou, L., et al., *Citizen Seismology Without Seismologists? Lessons Learned From Mayotte Leading to Improved Collaboration.* Frontiers in Communication, 2020. **5**(49): p. 1-17.
53. Lacassin, R., et al., *Rapid collaborative knowledge building via Twitter after significant geohazard events.* Geosci. Commun., 2020. **3**(1): p. 129-146.
54. Kropivnitskaya, Y., et al., *The Predictive Relationship between Earthquake Intensity and Tweets Rate for Real‐Time Ground‐Motion Estimation.* Seismological Research Letters, 2017. **88**: p. 840-850.
55. Kropivnitskaya, Y., et al., *Real-Time Earthquake Intensity Estimation Using Streaming Data Analysis of Social and Physical Sensors.* Pure and Applied Geophysics, 2017. **174**(6): p. 2331-2349.
56. Carvajal, M., et al., *Nearly Instantaneous Tsunamis Following the Mw 7.5 2018 Palu Earthquake.* Geophysical Research Letters, 2019. **46**(10): p. 5117-5126.
57. Chu, E.T.H. and C.C. Wu, *An image-based seismic damage assessment system.* Multimedia Tools and Applications, 2016. **75**(3): p. 1721-1743.

58. Freddi, F., et al., *Observations from the 26th November 2019 Albania earthquake: the earthquake engineering field investigation team (EEFIT) mission.* Bulletin of Earthquake Engineering, 2021.
59. Chian, S.C., et al., *Lessons Learnt From the 2009 Padang Indonesia, 2011 Tōhoku Japan and 2016 Muisne Ecuador Earthquakes.* Frontiers in Built Environment, 2019. **5**(73).
60. De Luca, F., et al., *RC infilled building performance against the evidence of the 2016 EEFIT Central Italy post-earthquake reconnaissance mission: empirical fragilities and comparison with the FAST method.* Bulletin of Earthquake Engineering, 2018. **16**(7): p. 2943-2969.
61. Friedland, C.J., *Residential building damage from hurricane storm surge: proposed methodologies to describe, assess and model building damage*, in *Civil and Environmental Engineering Commons*. 2009, Louisiana State University. p. 2015.
62. Wilkinson, S., C.K. Huyck, and T. Rossetto, *Editorial: Earthquake Reconnaissance – Building the Risk and Resilience Evidence Base.* Frontiers in Built Environment, 2020. **6**(55).
63. Goda, K., et al., *The 2016 Kumamoto Earthquakes: Cascading Geological Hazards and Compounding Risks.* Frontiers in Built Environment, 2016. **2**(19).
64. Freeman, M., et al., *Sequential Earthquake Damage Assessment Incorporating Optimized sUAV Remote Sensing at Pescara del Tronto.* Geosciences, 2019. **9**(8): p. 24.
65. Nguyen, Q.C., et al., *Using Google Street View to examine associations between built environment characteristics and U.S. health outcomes.* Preventive Medicine Reports, 2019. **14**: p. 100859.
66. Berland, A. and D.A. Lange, *Google Street View shows promise for virtual street tree surveys.* Urban Forestry & Urban Greening, 2017. **21**: p. 11-15.
67. Lemmens, M., *Terrestrial laser scanning. Geoinformation*. 2011: Springer.
68. FARO. *Laser Scanner FARO Focus3D – Overview – 3D Surveying*. 2017 [cited 2017 The 19th January 2017]; Available from: http://www.faro.com/en-us/products/3d-surveying/faro-focus3d/overview.
69. FARO. *FARO FOCUS X330*. 2019 [cited 2019 The 29th October 2019]; Available from: https://manchester-metrology.co.uk/equipment-hire/1082-2/?gclid=CjwKCAjwxt_tBRAXEiwAENY8hfSb-KsKfdOIRGIdkd28yLugEKWYAhFjLJQxenZVVwKV335lSZApFRoCVMQQAvD_BwE.
70. Rathje, E.M. and B.J. Adams, *The Role of Remote Sensing in Earthquake Science and Engineering: Opportunities and Challenges.* Earthquake Spectra, 2008. **24**(2): p. 471-492.
71. Dai, K., et al., *Surface damage quantification of postearthquake building based on terrestrial laser scan data.* Structural Control and Health Monitoring, 2018. **25**(8): p. e2210.
72. Zhou, Z., J. Gong, and X. Hu, *Community-scale multi-level post-hurricane damage assessment of residential buildings using multi-temporal airborne LiDAR data.* Automation in Construction, 2019. **98**: p. 30-45.
73. S. Tallett-Williams, B.G., S. Wilkinson, C. Fenton, P. Burton, M. Whitworth, S. Datla, G. Franco, A. Trieu, M. Dejong, V. Novellis, T. White, and T. Lloyd., *Site amplification in the Kathmandu Valley during the 2015 M7.6 Gorkha, Nepal earthquake.* Bulletin of Earthquake Engineering 2016. **14**(12).
74. Torres, R., et al., *GMES Sentinel-1 mission.* Remote Sensing of Environment, 2012. **120**: p. 9-24.
75. Fielding, E.J., et al., *Surface ruptures and building damage of the 2003 Bam, Iran, earthquake mapped by satellite synthetic aperture radar interferometric correlation.* Journal of Geophysical Research: Solid Earth, 2005. **110**(B3).
76. Elliott, J.R., et al., *Himalayan megathrust geometry and relation to topography revealed by the Gorkha earthquake.* Nature Geoscience, 2016. **9**(2): p. 174-180.
77. Lieven, N.A.J., et al., *Vibration–based structural damage identification.* Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences, 2001. **359**(1778): p. 131-149.
78. Veil, S.R., T. Buehner, and M.J. Palenchar, *A Work-In-Process Literature Review: Incorporating Social Media in Risk and Crisis Communication.* Journal of Contingencies and Crisis Management, 2011. **19**(2): p. 110-122.

 doi:10.20944/preprints202106.0714.v1

79. Yan, Y., J. Chen, and Z. Wang, *Mining public sentiments and perspectives from geotagged social media data for appraising the post-earthquake recovery of tourism destinations.* Applied Geography, 2020. **123**: p. 102306.
80. Kryvasheyeu, Y., et al., *Performance of Social Network Sensors during Hurricane Sandy.* PLOS ONE, 2015. **10**(2): p. e0117288.
81. Murakami, A. and T. Nasukawa, *Tweeting about the tsunami?: mining twitter for information on the tohoku earthquake and tsunami*, in *Proceedings of the 21st International Conference on World Wide Web*. 2012, ACM: Lyon, France. p. 709-710.
82. Doan, S., B.-K.H. Vo, and N. Collier. *An Analysis of Twitter Messages in the 2011 Tohoku Earthquake*. 2012. Berlin, Heidelberg: Springer Berlin Heidelberg.
83. Fritz, H., et al., *2004 Indian Ocean tsunami flow velocity measurements from survivor videos.* Geophysical Research Letters - GEOPHYS RES LETT, 2006. **332**.
84. Koshimura, S. and S. Hayashi, *Tsunami flow measurement using the video recorded during the 2011 Tohoku tsunami attack*, in *IEEE International Geoscience and Remote Sensing Symposium* 2012: Munich, Germany. p. 6693–6696.
85. Booth, E., et al. *EEFIT: The UK earthquake engineering field investigation team*. 2011.
86. Mangalathu, S. and H. Burton, *Deep learning-based classification of earthquake-impacted buildings using textual damage descriptions*. Vol. 36. 2019. 101111.
87. Contreras, D. *Designing a spatial planning support system for rapid building damage survey after an earthquake: the case of Bogotá D.C., Colombia.* in *URISA 2009 Annual Conference*. 2009. Anaheim, California (USA).
88. *What3 words*. 2021 [cited 2021 The 18 May 2021]; Available from: https://what3words.com/suene.madera.granja.
89. Papapesios, N., et al., *Exploring the use of crowdsourced geographic information in defence: challenges and opportunities.* Journal of Geographical Systems, 2019. **21**(1): p. 133-160.
90. Yan, Y., et al., *Monitoring and Assessing Post-Disaster Tourism Recovery Using Geotagged Social Media Data.* ISPRS International Journal of Geo-Information, 2017. **6**(5): p. 144.
91. Cervone, G., et al., *Using Twitter for tasking remote-sensing data collection and damage assessment: 2013 Boulder flood case study.* International Journal of Remote Sensing, 2016. **37**(1): p. 100-124.
92. Al-Nammari, F.M. and M.K. Lindell, *Earthquake recovery of historic buildings: exploring cost and time needs.* Disasters, 2009. **33**(3): p. 457-481.
93. Cervone, G. and C. Hultquist. *Citizen as indispensable sensors during disasters*. in *Population-environment research network cybeseminar, people and pixels revisited*. 2018.