Managing Earthquake Debris

Subjects: Public, Environmental & Occupational Health

Contributor: Spyridon Mavroulis , Maria Mavrouli , Efthymis Lekkas , Athanasios Tsakris

Earthquakes have the potential to cause severe and widespread structural damage to buildings and infrastructure in the affected area. Earthquake debris mainly results from building collapses during intense ground motion and the emergency demolition of damaged and unstable buildings following a devastating earthquake. Debris management constitutes a major challenge that must be met by all those participating in disaster management as it poses threats to both the natural environment and public health in an earthquake-affected area.

earthquake | debris | debris management | natural environment | public health | risk reduction

1. Introduction

Earthquake debris results mainly from collapsed structures during the shaking of the ground and the immediate removal of severely damaged and unstable buildings following an earthquake [1][2][3][4]. The composition and quantity of earthquake debris depend on the nature of the built environment that will be affected by the strong ground motion and the primary and secondary earthquake environmental effects [5]. Thus, an affected area mainly with wooden buildings will have a different debris composition than one with stone masonry buildings. The 2016 Kumamoto earthquake struck many wooden houses, which were completely or partially destroyed, resulting in a large volume of debris dominated by wood in addition to non-combustible materials, such as broken tiles and concrete rubble from collapsed walls [6].

As far as the debris quantity is concerned, the magnitude of the earthquake in combination with the seismic properties of the structures plays a primary role [5]. A moderate earthquake in a city characterized by poor construction criteria may produce a greater volume of debris than a strong earthquake that has struck a city where the buildings have been constructed with strict seismic regulations. The worst-case scenario in which a large volume of debris is generated and difficult to manage is a strong earthquake in areas where seismic regulations are not strictly followed. A typical example of the latter case is the region of East Anatolia, which was devastated by the 6 February 2023 earthquakes that caused severe structural damage to tens of thousands of building structures including their complete or partial collapse and the creation of millions of tons of debris from collapses due to the earthquake and subsequent demolition [7].

The management of the debris resulting from the earthquake disaster is an important step addressed early in the emergency response and recovery stages. The first stage of post-earthquake debris management comprises the emergency clearance of critical areas and infrastructure such as roads, hospitals, and healthcare facilities in order to facilitate access and ensure essential emergency response actions [8]. The removal of earthquake debris is imperative to create safe areas for search and rescue (SAR) teams to settle, operate, and reduce risks shortly after the earthquake. At this stage, it is important to activate crews with the appropriate equipment for debris removal. When the SAR operations are completed and the bodies of the trapped are recovered, the recovery phase begins and the collapse and demolition debris must be removed from the affected areas with the ultimate goal of returning the affected communities to their normalcy as soon as possible. In the second stage of debris management, actions related to sorting and separation of earthquake debris should also take place based on the type and the recyclability of materials to minimize waste and implement sustainable practices. To speed up the whole process, sorting and separation can be carried out at temporary sites or debris management facilities.

However, earthquake debris management poses a major challenge for disaster management staff and residents, as it presents considerable hazards to both the environment and the public health of the affected area [1][3][9][10][11][12].

2. Health and Environmental Hazards for Managing Earthquake Debris and Related Impact

2.1. Hazards from the Generation of Dust

2.1.1. Generation of Dust in Collapse, Demolition, and Debris Disposal Sites

The most hazardous material that can be contained in dust is asbestos, a group of fibrous serpentine and amphibole minerals that are non-biodegradable, have extraordinary tensile strength, poor heat conductivity, and are relatively resistant to chemical and thermal effects [13][14]. Because of its properties, asbestos has been widely used worldwide in thousands of applications, including the construction of buildings and infrastructures [13][15]. The most common products of asbestos comprise asbestos-cement building products, asbestos-cement pressure, sewage and drainage pipes, fire-resistant insulation boards, insulation products including spray, jointings and packings, friction materials, textile products, floor tiles and sheets, molded plastics and battery boxes, fillers and reinforcements, and products made thereof [13][14][15].

Regarding the impact of asbestos on public health, asbestos fibers that are 1200 times thinner than hair have the potential to pass through the human body’s natural filtration process, remain permanently in the trachea, lungs, and intestines, and have negative effects on the respiratory system. Asbestos can cause both acute and chronic lung damage by triggering an inflammatory response, with the participation of several cells involved in the production of cytokines, chemokines, oxidants, and growth factors [16]. Because the human body lacks chemical mechanisms for degrading this mineral and is unable to remove fibers that have already penetrated the tissues, there are some adverse effects that, over time, could contribute to the occurrence of several fatal diseases, such as asbestosis, lung cancer, and mesothelioma [14][17][18].

All types of exposure to asbestos fibers can exist for all those who live in earthquake-affected areas or have rushed to support the affected population during the emergency response and recovery, including (i) occupational exposure during job-related activities, (ii) incidental exposure during staying in buildings where the asbestos-containing materials and products have been disturbed, and (iii) the environmental exposure during staying in areas where the ambient air contains asbestos fibers [14]. High-risk groups for asbestos exposure comprise (i) rescued residents near the collapsed buildings in the first hours and days after the earthquake, (ii) members of SAR teams trying to save people from the rubble during the immediate response, (iii) workers and volunteers employed at collapse, demolition, and disposal sites during the immediate response and recovery, and (iv) volunteers called upon to assist in various emergency actions.

After earthquakes and under wind effects, the crushing and erosion of these asbestos-containing construction materials and products produce asbestos fibers and cement mixture being transported and distributed mainly via air and water and contaminating the entire environment to a large extent [13][14]. Airborne mineral fibers may travel significant distances from the source, while asbestiform fibers can be transported over a long range in water [19][20]. Despite the fact that asbestos fibers are relatively stable and are characterized by a high potential to persist under typical environmental conditions [13], they may suffer chemical and dimensional alterations, as well as absorb and carry several organic agents in the environment [21].

2.1.2. Generation of Dust during Earthquake-Triggered Landslides and Removal of Accumulated Materials

A typical example of dust cloud formation after landslides is the 17 January 1994, Mw = 6.7 Northridge earthquake in the San Fernando Valley region of the City of Los Angeles (USA). Dust clouds were formed as a result of the mainshock and its strongest aftershocks causing landslides in the Santa Susana Mountains north of Simi Valley [22]. Following landslides, the affected areas presented a sharp rise in coccidioidomycosis cases, which peaked 2 weeks after the earthquake and 203 cases of coccidioidomycosis or valley fever were identified. Fifty-six percentage of them were recorded in the town of Simi Valley. Inhalation of airborne spores of the dimorphic fungus *Coccidiodes immitis* was identified as the cause of this respiratory disease [23]. Three times as many people as those who did not recall being physically present in dust clouds during the Northridge seismic sequence were more likely to be diagnosed with acute coccidioidomycosis. The risk increased with increasing duration of stay and exposure to dust clouds [24].

2.1.3. Generation of Dust from Removal of Dried Earthquake-Triggered Liquefaction Deposits

Dust with the potential to harm human health can also be generated after earthquake-triggered liquefaction phenomena. When the liquefied material rises to the surface through ground cracks and is exposed to air, it dries out and forms ejecta dust, which can be easily transported by air. Due to the fact that liquefaction-related lateral spreading and ground cracks usually take place and cause damage to the sewage network, diffusion of the contents occurs and can result in contamination of the liquefied material with fecal pathogens and other hazardous materials. Therefore, ejecta dust may be transported by air into or near residential areas and directly lead to increased respiratory tract infections or increased susceptibility to infections, including pneumococcal pneumonia.

2.1.4. Generation of Dust from Removal of Dried Tsunami Sludge

Tsunami following earthquakes have the potential to cause significant damage in coastal areas and create a large amount of sludge from the bottom of the sea that contains chemical substances, heavy metals, oils, and pathogenic microorganisms. The 2011 Tōhoku tsunami left behind approximately 20 million tons of wrecks, or debris, and 10 million tons of soil sediments, composed of mud and sand, on the ground [25]. The treatment and removal of dried tsunami sludge from the affected areas adversely affected public health.

In Ishinomaki, the most severely affected area by the 2011 Tōhoku earthquake and tsunami, the number of hospitalizations for chronic obstructive pulmonary disease (COPD) exacerbations during the subacute phase (from the third to the fifth week) was significantly higher than before the earthquake ($p < 0.05$) [26]. The tsunami wrecked several structures in Ishinomaki, and the entire region was buried in a thick layer of mud. Inhalation of dust and fine particles, as well as exposure to chemicals, particulates, and biological elements from debris and tsunami sludge, may have exacerbated respiratory symptoms among COPD patients in the tsunami-affected area [26].

2.2. Hazards from Treated Wood and Wood Preservatives

In order to protect the wood from various degradation factors, such as fungi, pests, and wood-eating insects, it must be treated with various methods usually involving the application of water- or oil-based preservatives that contain mixtures of ingredients, some of which are hazardous. The water-borne wood preservative that is most frequently used is chromated copper arsenate (CCA), which has excellent fungicidal and insecticidal properties and a high potential to extend the useful life of treated wood by 45 years or more [27]. During the pressure treatment process, CCA is applied to the wood resulting in large copper (Cu), chromium (Cr), and arsenic (As) concentrations.

Another effective water-borne wood preservative is the ammoniacal copper zinc arsenate (ACZA) [28]. These preservatives are commonly used in buildings and infrastructures comprising walkways, piers, restraining walls, and bridges. Other wood preservatives include ammoniacal copper quaternary type B (ACQ-B), amine copper quaternary (ACQ-D), ammoniacal copper citrate (CC), and copper dimethyldithiocarbamate (CDDC) [28].

Due to the massive amount of treated wood in areas devastated by an earthquake, the dispersal of these preservatives could create health hazards for all involved in debris management, including workers, volunteers, as well as affected residents. During processing, risks to humans and the environment arise from (i) As, Cu, and Cr leaching at large concentrations [28][29][30]; (ii) mixing with untreated wood when recycling; and (iii) incineration when the resulting As emissions necessitate the utilization of suitable air pollution control apparatus and when the concentration of As, Cu, and Cr in the ash limits its management options [31][32][33][34].

2.3. Hazards from Heavy Metals and Other Chemicals

Earthquake debris may have a substantial influence on both surface and groundwater. They may introduce pollutants including heavy metals and other chemicals into nearby bodies of water, such as streams, lakes, rivers, and the sea, with long-term adverse effects on surface water ecosystems. Contaminated water bodies reduce the quality of water, making it harmful to aquatic life and dangerous for irrigation and supplies.

The case of demolition debris from the town of Boumerdes in northern Algeria, five years after the 21 May 2003, Mw = 6.8 earthquake, is a typical example of the effects of earthquake debris on groundwater [35][36]. Benmeni and Benrachedi [37] found that the concentrations of heavy metals (cadmium, chlorine, zinc, and nickel) in samples of the leachate of the landfills and control wells were above acceptable limits, causing two types of pollution: (i) an organic one leading to high chemical oxygen demand (COD) and (ii) a mineral one leading to high concentrations of additional heavy metals in the drainage. Furthermore, the considerable prevalence of coliforms and fecal streptococci can only be explained as a result of contamination caused by drainage penetration through cracks in the porous soil [37].

2.4. Hazards from Putrescibles

When the earthquake causes extensive damage to elements of the electricity network, there are extensive interruptions in electricity supply to homes and businesses that can compromise the safety of food supplies. The risk is higher in commercial properties including supermarkets, food warehouses, cool stores, and hospitality businesses, where large quantities of perishable products are stored. If proper storage and refrigeration are disrupted, perishable food can spoil quickly, providing an ideal environment for the growth of bacteria, such as *Escherichia coli*, *Salmonella* spp., and *Campylobacter* spp. These bacteria have the potential to cause foodborne diseases, which manifest as nausea, diarrhea, vomiting, and abdominal pain when consumed.

Food may also be exposed to moisture and insufficient ventilation, both of which promote mold growth. Consuming food contaminated with mold or mold-derived compounds (mycotoxins) can cause respiratory issues and, occasionally, mycotoxicosis. In particular, mycotoxicosis can cause both acute and chronic negative health effects in humans via inhalation, ingestion, skin contact, and entry of mycotoxins into the bloodstream and lymphatic system [38].

2.5. Hazards from Fecal-Contaminated Materials in Debris

When the earthquake causes damage to the sewage network either due to the rupture of wastewater pipes or due to the destruction of treatment facilities, then the waste may contaminate surrounding geological deposits, the surface water bodies, and the groundwater systems. This contamination with fecal matter and pathogens has the potential to transmit waterborne diseases, such as cholera, typhoid fever, and hepatitis A, to workers, volunteers, and residents involved in debris removal and damage repair without using the appropriate personal protective equipment. This hazard prevails in areas affected by extensive liquefaction phenomena. The resulting cracks can affect parts of the sewer network, such as wastewater pipes and cesspits, and lead to extensive soil and water contamination with subsequent impact on public health [39].

2.6. Hazards from Injuries and Wounds from Earthquake Debris

Another threat to the health of those either living close to or working in the collapse, demolition, and earthquake debris disposal sites during the immediate response and recovery phase is tetanus, an infectious disease brought on by spores of *Clostridium tetani* coming into contact with open, exposed wounds. This disease is fatal but can be prevented through vaccination. During the evacuation, the debris removal, and subsequent demolitions, there is an increased risk of injuries, such as cuts, punctures, and abrasions to the skin, during the evacuation, the removal of debris, and the subsequent demolitions. Debris management workers, volunteers, and residents are in direct contact with hazardous materials of various origins, e.g., building and infrastructure construction materials, which may contain or be mixed with hydraulic materials, human or animal faces, and rusty objects. Any break in the skin allows *C. tetani* to penetrate the human body and cause tetanus.

2.7. Hazards from Debris Associated to Disrupted Sanitation and Waste Management Systems

Earthquake debris combined with disrupted sanitation and waste management systems can either create favorable breeding grounds for arthropods such as mosquitoes, flies, and mites or result in an increased presence of reservoir hosts such as rodents that contribute to the transmission of various infectious diseases. In particular, stagnant water accumulated in debris, damaged sewage systems, and unsanitary conditions can contribute to disease-carrying vector proliferation and raise the possibility of arthropod-borne diseases emergence. Flies can transfer enteropathogenic bacteria like *E. coli*, *Campylobacter* spp., *Shigella* spp., or *Salmonella* spp. from contaminated debris to fresh food, increasing the risk of foodborne infections [40][41]. Mosquitoes may transmit mosquito-borne diseases including West Nile fever, dengue fever, Zika virus disease, and malaria, while rodents can carry and spread spirochetes of the genus Leptospira that cause leptospirosis.

2.8. Hazards from Dumping Debris Either Close to or within Natural Habitats

The disposal of earthquake debris may have a substantial impact on natural habitats. Improper disposal methods, including throwing debris into or near water bodies, can change the way water flows naturally, lead to sediment built-up, and harm aquatic life by limiting sunlight and oxygen availability. Furthermore, the disposal of debris into natural habitats may impair their natural ecological processes. Habitat destruction can restrict wildlife migration patterns, disturb breeding regions, inhibit the recycling of nutrients, and disrupt food and shelter availability. These changes can cause a domino impact on biodiversity, population dynamics, and resilience of natural habitats throughout the ecosystem.

Another hazard that can emerge and affect natural habitats by debris disposal is the introduction of invasive or non-native species into habitats. The debris may contain seeds from soil or other materials that carry non-native species that may spread and dominate at the expense of existing species, limiting biodiversity, leading to a disruption of the ecological balance and to negative impacts on native flora and fauna.

The dumping of debris in natural habitats can lead to their segmentation and create isolated patches resulting in a reduction in the ability of species to adapt to changing conditions and increase their vulnerability.

A typical and very recent example of an uncontrolled disposal of earthquake debris in a natural habitat comes from East Anatolia and in particular the Samandağ coastal area of Hatay province, which was profoundly impacted by the devastating earthquakes that occurred in early February 2023. This site was created in a coastal zone with geological, geomorphological, and historical features that make it particularly vulnerable to human intervention and activity [42].

2.9. Hazards from Noise Related to Debris Management Activities

Increased traffic during debris transport as well as utilization of heavy machinery and equipment in demolition and transportation can all contribute to noise pollution from debris management following earthquakes.

The transportation, processing, and disposal of earthquake debris, as well as the construction and preparation of debris disposal sites, often require the use of heavy machinery and associated equipment that generate significant noise from the continuous operation of engines, audible alarms, warning systems, and the constant movement of machinery, as well as from the demolition of structures, the breaking of concrete, and the compaction of debris. This increased noise can cause disturbance to the tranquility of a residential region or the equilibrium in sensitive natural habitats.

2.10. Hazards from Disturbance of Aesthetics

Visual pollution is related to the selection of unsuitable locations for debris disposal close to residential areas, areas of scenic ecological value, and sensitive natural landscapes, as well as the application of inappropriate treatment and disposal methods, which can significantly affect the aesthetics and tranquility of the environment. When residents are confronted with images of scattered random debris or inadequate mitigation measures to limit the adverse impacts of debris disposal, it can create a sense of neglect by the relevant disaster management agencies and a sense of environmental degradation in the area in which they live and work with possible subsequent negative impacts on various aspects of human life.

3. Measures to Address Debris Management Risks on Public Health and the Natural Environment

3.1. Protective Measures for All Involved in Debris Management

3.1.1. Protection Measures against Exposure to Dust Containing Asbestos

As for the workers involved in debris management from the first phase of loading at the collapse and demolition sites to the final disposal phase, they should be fully informed about the hazards they will face when handling debris and the best practices they are required to apply when involved in the clean-up process. If they are not adequately informed, training and awareness-raising activities should be carried out either by the relevant government authorities involved in disaster management and recovery or by the appropriately trained staff of the contractors involved in debris management.

Workers, volunteers, and residents should use appropriate personal protective equipment (PPE) at all times during their involvement in debris management [3], at the sites of collapses and demolitions, during transport, and at the final disposal site. The PPE should primarily and above all comprise protection masks not only against dust and large grain contaminants but also against hazardous materials, including asbestos fibers as well as hazardous vapors and liquids. The PPE should also include disposable mechanical, chemical, and microorganisms-resistant work gloves in order to prevent toxic or irritating substances from coming into contact with the skin; fully enclosed goggles (better for ash) or safety glasses whenever there is a risk of physical, biological, or chemical eye injury; and disposable or replacement clothes so that those involved do not take contaminated clothing back home and place other people at risk. The PPE users must be trained and authorized to use it and must inspect it prior to each use. Contaminated PPE and clothing should be disposed of in the same manner as other construction materials from demolition and collapses containing asbestos.

Similar PPE should be used by people living and working close to the above sites, for example, in camps for the accommodation of earthquake-affected people. If this equipment is not available and dust generation continues to make a big difference in the surrounding area despite the implementation of risk reduction measures, then residents should be evacuated until the debris management process is completed.

In order to prevent residents from being exposed to hazardous materials during the processing and transport of debris, additional measures should be taken to limit the generation of dust. During the loading of debris in the demolition and collapse sites, the loading area should be sprayed with water in order to ensure the precipitation of dust and free asbestos fibers.

For the proper management of debris and asbestos-containing materials, specific procedures must be implemented to avoid the dispersion of asbestos fibers in the environment. These are the following according to WHO [43]:

- Materials containing asbestos should be transported without breaking and should not be mixed with other debris before final disposal. If it becomes necessary to move or disperse these materials, they should be kept well dampened to limit the amount of fibers that can become airborne.

- Materials containing asbestos should be disposed of in areas appropriately selected and designed to prevent the release of asbestos fibers into the environment. Such sites must be equipped with a drainage collection system and a system for the immediate covering of newly deposited waste with a layer of suitable inert material. In addition, future construction work such as gas extraction wells or drainage wells should not be carried out on the sites where asbestos-containing materials are disposed of in order to avoid re-exposure to asbestos. All these sites should be recorded in databases in great detail and analysis. This information should be available at all times to prevent any future construction and intervention from disturbing them.

- On arrival of trucks at the disposal sites and before unloading, any surface exposed to asbestos should be sprayed with water. The storage or disposal of asbestos-containing materials shall be in sealable containers.

These containers shall be made of metal, plastic, or polyethylene. If the containers are crates, barrels, or sacks, they should be securely sealed and specially marked with information messages about the harmful contents and the risks involved.

3.1.2. Protection Measures against Exposure to Treated Wood

To avoid impacts from treated wood on humans and the environment, the first priority is to keep treated wood out of the debris, which can be achieved by collecting and reusing it if it still meets the requirements of its original design [44][45]. If it does not meet the requirements for reuse and must be discarded, appropriate treatment as per international practices should be followed. Further treatment should include storage in a permitted bulky waste landfill or burning in a burner facility properly equipped with the appropriate specifications for burning treated wood. These residues should never be burned in open outdoor areas as burning releases chemicals in ash and smoke [12]. If this wood is in the form of sawdust, chips, and other small residues, composting should not be the preferred approach [44][45][46], but rather the above treatment should be used. In all cases, the regulations and restrictions provided in any local or regional plan for earthquake debris management and for the management of hazardous materials including treated wood should be applied [44][45].

3.1.3. Prevention and Control Measures for Tetanus

Although tetanus can be prevented with a highly efficient vaccine, it remains a leading cause of morbidity and mortality globally, especially in earthquake-affected areas during the recovery period. The mortality rate remains high in countries where the coverage of tetanus vaccination is low to non-existent. In cases of trauma exposure to microbial spores, the factors that shape successful tetanus treatment are early diagnosis, early administration of muscle relaxants and sedative therapy, keeping the airways open and the potential use of a mechanical ventilator to assist in respiratory failure management [39].

3.2. Preparation and Implementation of Earthquake Debris Management Plans

For the proper and effective management of debris from an earthquake, the agencies involved in disaster management, in cooperation with communities and scientific institutions, should develop an earthquake debris management plan. This plan should include and cover the following issues: composition and quantity of the generated debris; their collection, handling, treatment, and disposal; and the management of the associated hazards, as well as the strategic and operational management, the funding for management of earthquake debris, and the associated regulations [3][47][48]. These management plans should be guided by the principles of sustainable disaster debris management and adopt the results of research related to the circular economy, the reduction of debris to a minimum, the extension of the life cycle of materials, and the creation of further value [49][50][51].

With regard to the debris composition and quantity, the main categories of buildings in each residential area should be assessed and the units, the volume, and the area of debris should be estimated. The results should be taken into account in the subsequent debris management phases.

With regard to debris collection, the transport routes for prioritizing debris removal, the facilities and equipment for debris removal, and the debris collection strategy for the recovery stage should be identified [47].

The procedure is not the same for all cases, even for earthquake events that have occurred in the same country with the same general institutional framework for the management of debris from disasters induced by natural hazards. For example, in Italy after the 2009 L'Aquila earthquake, the debris was first pretreated on-site before being transported to an old quarry for storage, final treatment, and disposal [52]. Following the Emilia-Romagna earthquake in 2012, all the debris were taken straight to facilities for recovery and disposal [52].

Information on vehicles, facilities, and equipment for demolition and removal of debris from the collapse and demolition sites should be included. Issues related to the provision of fuel for vehicle facilities and food and water for those involved in debris collection should be resolved. Approaches to debris transportation and temporary storage and disposal strategies should be adopted. The roles of the public agencies involved should be clearly defined.

For assessing the suitability of the sites, an initial environmental analysis and assessment of the environmental and seismic risks should be performed on these sites. Appropriate types of debris and suitable activities for these sites should be identified, such as the sorting and recycling of demolition and collapse debris and the treatment of hazardous materials and their disposal. Contractors, staff needs, and related facilities should also be specified.

With regard to the management of associated risks, the numerous environmental and public health hazards and risks must be assessed and the impact of their potential occurrence must be mitigated during management.

As far as the related funding is concerned, the private and public funding sources for the different stages of management shall be determined before the occurrence of the destructive events.

All of the above must be governed by regulations that ensure proper environmental management and public health safety, post-disaster management of buildings, and waste management in general.

In terms of debris recycling and disposal, debris management facilities including construction and demolition landfills, cleanfills, recycling facilities, processing plants, and composting facilities, as well as hazardous materials treatment facilities should be initially defined along with the service providers comprising collection contractors for demolition and transport companies [47]. The assessment of existing capacity and cost–benefit analysis of recycling and disposal options should follow with the assessment of the availability of temporary and permanent sites, personnel, and facilities for debris management.

In order to identify and select suitable disposal sites, the primary and secondary criteria for their selection must be strictly defined and the potential problems and environmental impacts of the sites must be identified [47]. The primary criteria are related to (i) the ownership of the site, (ii) its proximity or location within areas that are susceptible to the occurrence of geophysical or hydro-meteorological hazards.

3.3. Dissemination of Related Information to the Affected Population

One of the most important actions for effective debris management is the coordination and dissemination of information to the public in terms of effective debris disposal from residential and commercial properties [47]. It is very important for residents to promptly understand the right actions to take in disposing of earthquake debris and waste from their daily activities. For this reason, a communication and information strategy should be developed to inform communities so that they know in advance the actions they need to take before the earthquake. The compilation of communication and information dissemination plans should involve the emergency services, government agencies at all levels (local, regional, and national), debris management teams, debris collection and disposal contractors, local authorities, and communities, with the final beneficiaries being the citizens of the earthquake-affected areas.

3.4. Systematic Instrumental Monitoring of Environmental Parameters

A very important measure to address the risk from hazardous materials and substances at the sites of removal and disposal of debris is the systematic instrumental monitoring of environmental parameters within the sites and in the surrounding areas [12][53]. In the case of the 2016 Kumamoto earthquake, monitoring included visual inspection for contamination control and soil analyses, according to the results of which countermeasures against soil contamination were taken as needed [53].

The results of these measurements must be taken into account by the authorities concerned, which will take the necessary measures to protect both the natural environment and public health. It is very important that these results are freely available to the general public.

4. Conclusions

Buildings and infrastructures in earthquake-affected areas are susceptible to significant and widespread structural and nonstructural damage. Earthquake debris mainly results from the collapse during the ground motion of the earthquake and the emergency demolition of unstable and damaged buildings in the course of emergency response and rehabilitation.

Several critical elements must be carefully considered during earthquake debris management. First and foremost, protecting public safety is critical. Debris removal from streets, public places, and residential areas should be prioritized in order for emergency services to reach affected people as quickly as possible. Assessing and mitigating possible debris-related hazards is critical in order to protect both rescuers and survivors from additional hazards and risks since hazardous debris elements pose threats to both the natural environment and public health in an earthquake-affected area.

Measures to reduce or eliminate the risks arising from earthquake debris management include the preparation and implementation of a flexible debris management plan that must take into account and adapt to the earthquake parameters and the demographic characteristics of the affected area, the adoption of safety precautions for all those participating in the debris management processes, the dissemination of information to the affected population, and the systematic monitoring of environmental parameters.

To reduce the harmful impact on the environment, proper debris removal and recycling should be addressed. When possible, salvaging and reusing items can help decrease waste and lessen the burden on resources. To ensure ecologically acceptable procedures are followed, it is critical to design and implement legislation and standards for earthquake debris disposal.

Earthquake debris management is a complex process that requires planning, implementation, and evaluation of relevant actions and measures, as well as the communication and cooperation among several stakeholders and agencies at different levels of governance. Transparency and collaboration may be improved by establishing open lines of communication, exchanging data on debris removal efforts and progress, and incorporating regional communities in decision-making procedures. Regular updates on debris management plans and progress can also provide reassurance and instill confidence in the recovery efforts.

References

1. Brown, C.; Milke, M.; Seville, E. Disaster waste management: A review article. Waste Manag. 2011, 31, 1085–1098.
2. Xiao, J.; Xie, H.; Zhang, C. Investigation on building waste and reclaim in Wenchuan earthquake disaster area. Resour. Conserv. Recycl. 2012, 61, 109–117.
3. Brown, C. Waste Management Following Earthquake Disaster. In Encyclopedia of Earthquake Engineering; Beer, M., Kougioumtzoglou, I., Patelli, E., Au, I.K., Eds.; Springer: Berlin/Heidelberg, Germany, 2014; pp. 1–16.
4. Dugar, N.; Karanjit, S.; Khatiwada, N.R.; Shakya, S.M.; Ghimire, A. Post-disaster Waste Management: Lessons Learnt from 2015 Nepal Earthquake. In Sustainable Waste Management: Policies and Case Studies; Ghosh, S.K., Ed.; Springer Nature Singapore Private Limited: Singapore, 2017; pp. 465–483.
5. Brown, C. Disaster Waste Management: A Systems Approach. Ph.D. Thesis, University of Canterbury, Christchurch, New Zealand, 2012.
6. Sakai, S.; Poudel, R.; Asari, M.; Kirikawa, T. Disaster waste management after the 2016 Kumamoto Earthquake: A mini-review of earthquake waste management and the Kumamoto experience. Waste Manag. Res. 2018, 37, 247–260.
7. Mavroulis, S.; Argyropoulos, I.; Vassilakis, E.; Carydis, P.; Lekkas, E. Earthquake Environmental Effects and Building Properties Controlling Damage Caused by the 6 February 2023 Earthquakes

in East Anatolia. Geosciences 2023, 13, 303.

8. Ranjitkar, M.G.; Upadhyay, S. Post-Earthquake Debris Management: Challenges and Opportunities in Nepal. Rural Infr. 2015, 6, 71–80.
9. Jang, Y.-C.; Townsend, T. Sulfate leaching from recovered construction and demolition debris fines. Adv. Environ. Res. 2001, 5, 203–217.
10. Jang, Y.-C.; Townsend, T.G. Occurrence of organic pollutants in recovered soil fines from construction and demolition waste. Waste Manag. 2001, 21, 703–715.
11. Dubey, B.; Solo-Gabriele, H.M.; Townsend, T.G. Quantities of Arsenic-Treated Wood in Demolition Debris Generated by Hurricane Katrina. Environ. Sci. Technol. 2007, 41, 1533–1536.
12. United States Environmental Protection Agency (EPA). Planning for Natural Disaster Debris; Office of Solid Waste and Emergency Response & Office of Solid Waste: Washington, DC, USA, 2019; pp. 1–150.
13. World Health Organization (WHO). Asbestos and Other Natural Mineral Fibres. International Programme on Chemical Safety & World Health Organization. 1986. Available online: https://apps.who.int/iris/bitstream/handle/10665/37190/9241541938-eng.pdf?sequence=1&isAllowed=y (accessed on 15 April 2023).
14. Dimiskovska, B. Environmental risks due to debris containing asbestos in post-earthquake conditions. Acta Geod. Geophys. Hung. 2010, 45, 299–306.
15. Commission of the European Communities (CEC). Public Health Risks of Exposure to Asbestos Report of a Working Group of Experts Prepared for the Commission of the European Communities, Directorate-General for Social Affairs, Health and Safety Directorate, Pergamon Press Ltd. for the Commission of the European Communities (EUR 5653e); Commission of the European Communities: Oxford, UK, 1977; pp. 1–160.
16. Robledo, R.; Mossman, B. Cellular and molecular mechanisms of asbestos-induced fibrosis. J. Cell. Physiol. 1999, 180, 158–166.
17. Uchiyama, I. Chronic Health Effects of Inhalation of Dust or Sludge. JMAJ 2013, 56, 91–95.
18. Świątkowska, B.; Szubert, Z.; Sobala, W.; Szeszenia-Dąbrowska, N. Predictors of lung cancer among former asbestos-exposed workers. Lung Cancer 2015, 89, 243–248.
19. Cooper, F.C.; Murchio, J.C. Preliminary Studies of Asbestiform Fibres in Domestic Water Supplies; Aerospace Medical Research Laboratory: Wright-Patterson Air Force Base, OH, USA, 1974.
20. Nicholson, W.J. Analysis of amphibole asbestiform fibres in municipal water supplies. Environ. Health Perspect. 1974, 9, 165–173.

21. Kramer, J.; Mudroch, O.; Tihor, S. Asbestos in the Environment. In Burlington, Ontario, Research Advisory Board; International Joint Commission and Environment: Windsor, ON, Canada, 1974; 50p.

22. Jibson, R.W. A Public Health Issue Related to Collateral Seismic Hazards: The Valley Fever Outbreak Triggered by the 1994 Northridge, California Earthquake. Surv. Geophys. 2002, 23, 511–528.

23. Stevens, D.A. Coccidioidomycosis. N. Engl. J. Med. 1995, 332, 1077–1082.

24. Schneider, E.; Hajjeh, R.A.; Spiegel, R.A.; Jibson, R.W.; Harp, E.L.; Marshall, G.A.; Gunn, R.A.; McNeil, M.M.; Pinner, R.W.; Baron, R.C.; et al. A coccidioidomycosis outbreak following the Northridge, Calif, earthquake. J. Am. Med. Assoc. JAMA 1997, 277, 904–908.

25. Hirashima, Y.; Hiraishi, K. Development of the Recycling Process for Tsunami Sediment Soil Containing Debris; Nippon Steel and Sumitomo Metal Technical Report No:109; Nippon Steel: Houston, TX, USA, 2015.

26. Kobayashi, S.; Hanagama, M.; Yamanda, S.; Satoh, H.; Tokuda, S.; Kobayashi, M.; Ueda, S.; Suzuki, S.; Yanai, M. Impact of a large-scale natural disaster on patients with chronic obstructive pulmonary disease: The aftermath of the 2011 Great East Japan Earthquake. Respir. Investig. 2013, 51, 17–23.

27. Gutzner, D.I.; Crowford, D.M. Comparison of Wood Preservatives in Stake Tests: 1995 Progress Report; Research Note FPL-RN-02; USDA FS FPL: Madison, WI, USA, 2011; 124p.

28. Lebow, S.T.; Lebow, P.K.; Foster, D.O.; Brooks, K.M. Environmental Impact of Preservative-Treated Wood in a Wetland Boardwalk; Research paper FPL, RP-582; USDA FS FPL: Madison, WI, USA, 2000; 126p.

29. Cooper, P.A. Leaching of CCA: Is It a Problem? In Environmental Considerations in the Manufacture, Use and Disposal of Preservative-Treated Wood; Forest Products Society: LaGrange, GA, USA, 1994; pp. 45–57.

30. Hingston, J.A.; Collins, C.D.; Murphy, R.J.; Lester, J.N. Leaching of chromated copper arsenate wood preservatives: A review. Environ. Pollut. 2001, 111, 53–66.

31. Townsend, T.; Solo-Gabriele, H.; Tolaymat, T.; Stook, K. Impact of chromated copper arsenate (CCA) in wood mulch. Sci. Total Environ. 2003, 309, 173–185.

32. Townsend, T.; Tolaymat, T.; Solo-Gabriele, H.; Dubey, B.; Stook, K.; Wadanambi, L. Leaching of CCA treated wood: Implications for waste disposal. J. Hazard. Mater. 2004, 114, 75–91.

33. Solo-Gabriele, H.; Townsend, T.; Hahn, D.; Moskal, T.; Hosein, N.; Jambeck, J.; Jacobi, G. Evaluation of XRF and LIBS technologies for on-line sorting of CCA-treated wood waste. Waste Manag. 2004, 24, 413–424.

34. Solo-Gabriele, H.; Townsend, T.; Messick, B.; Calitu, V. Characteristics of chromated copper arsenate-treated wood ash. J. Hazard. Mater. 2002, 89, 213–232.

35. Bounif, A.; Dorbath, C.; Ayadi, A.; Meghraoui, M.; Beldjoudi, H.; Laouami, N.; Frogneux, M.; Slimani, A.; Alasset, P.J.; Kharroubi, A.; et al. The 21 May 2003 Zemmouri (Algeria) earthquake Mw 6.8: Relocation and aftershock sequence analysis. Geophys. Res. Lett. 2004, 31, 19.

36. Bouhadad, Y.; Nour, A.; Slimani, A.; Laouami, N.; Belhai, D. The Boumerdes (Algeria) earthquake of 21 May 2003 (Mw = 6.8): Ground deformation and intensity. J. Seismol. 2004, 8, 497–506.

37. Benmenni, M.S.; Benrachedi, K. Impact of Earthquake Demolition Debris on the Quality of Groundwater. Am. J. Appl. Sci. 2010, 7, 545–550.

38. Awuchi, C.G.; Ondari, E.N.; Nwozo, S.; Odongo, G.A.; Eseoghene, I.J.; Twinomuhwezi, H.; Ogbonna, C.U.; Upadhyay, A.K.; Adeleye, A.O.; Okpala, C.O.R. Mycotoxins' Toxicological Mechanisms Involving Humans, Livestock and Their Associated Health Concerns: A Review. Toxins 2022, 14, 167.

39. Mavrouli, M.; Mavroulis, S.; Lekkas, E.; Tsakris, A. The Impact of Earthquakes on Public Health: A Narrative Review of Infectious Diseases in the Post-Disaster Period Aiming to Disaster Risk Reduction. Microorganisms 2023, 11, 419.

40. Graczyk, T.K.; Knight, R.; Gilman, R.H.; Cranfield, M.R. The role of non-biting flies in the epidemiology of human infectious diseases. Microbes Infect. 2001, 3, 231–235.

41. Collinet-Adler, S.; Babji, S.; Francis, M.; Kattula, D.; Premkumar, P.S.; Sarkar, R.; Mohan, V.R.; Ward, H.; Kang, G.; Balraj, V.; et al. Environmental Factors Associated with High Fly Densities and Diarrhea in Vellore, India. Appl. Environ. Microbiol. 2015, 81, 6053–6058.

42. Mavroulis, S.; Mavrouli, M.; Vassilakis, E.; Argyropoulos, I.; Carydis, P.; Lekkas, E. Debris Management in Turkey Provinces Affected by the 6 February 2023 Earthquakes: Challenges during Recovery and Potential Health and Environmental Risks. Appl. Sci. 2023, 13, 8823.

43. World Health Organization. Asbestos—Hazards and Safe Practices for Clean-Up after Earthquake. 2008. Available online: https://cdn.who.int/media/docs/default-source/chemical-safety/asbestos/asbestos-after-earthquake.pdf?sfvrsn=1e7e60d_2&download=true (accessed on 1 April 2023).

44. Government of Canada. Staying Safe around Treated Wood. Available online: https://www.canada.ca/en/health-canada/services/consumer-product-safety/reports-publications/pesticides-pest-management/fact-sheets-other-resources/staying-safe-around-treated-wood.html (accessed on 10 April 2023).

45. Connecticut Department of Energy and Environmental Protection. Green Building: Proper Use and Disposal of Treated Lumber. Available online: https://portal.ct.gov/DEEP/Reduce-Reuse-Recycle/Proper-Use-and-Disposal-of-Treated-Lumber (accessed on 10 April 2023).

46. Centers for Disease Control and Prevention. CCA-Treated Wood. Available online: https://www.atsdr.cdc.gov/CCA-Treated_Wood_Factsheet.pdf (accessed on 10 April 2023).
47. Johnston, D.; Dolan, L.; Saunders, W.; van Schalkwyk, R.; Killeen, C.; Cousins, J.; Glavovic, B.; Brown, C.; McIntyre, I. Disposal of Debris Following Urban Earthquakes: Guiding the Development of Comprehensive Pre-Event Plans; GNS Science Report 33; GNS Science: Lower Hutt, New Zealand, 2009; 30p.
48. Askarizadeh, L.; Karbassi, A.R.; Ghalibaf, M.B.; Nouri, J. Management of post-earthquake construction debris in Tehran Metropolitan. Int. J. Environ. Sci. Technol. 2016, 13, 639–648.
49. Kabirifar, K.; Ashour, M.; Yazdani, M.; Mahdiyar, A.; Malekjafarian, M. Cybernetic-parsimonious MCDM modeling with application to the adoption of Circular Economy in waste management. Appl. Soft Comput. 2023, 139, 110186.
50. Yazdani, M.; Kabirifar, K.; Frimpong, B.E.; Shariati, M.; Mirmozaffari, M.; Boskabadi, A. Improving construction and demolition waste collection service in an urban area using a simheuristic approach: A case study in Sydney, Australia. J. Clean. Prod. 2021, 280, 124138.
51. Ghafourian, K.; Kabirifar, K.; Mahdiyar, A.; Yazdani, M.; Ismail, S.; Tam, V.W.Y. A Synthesis of Express Analytic Hierarchy Process (EAHP) and Partial Least Squares-Structural Equations Modeling (PLS-SEM) for Sustainable Construction and Demolition Waste Management Assessment: The Case of Malaysia. Recycling 2021, 6, 73.
52. Gabrielli, F.; Amato, A.; Balducci, S.; Magi Galluzzi, L.; Beolchini, F. Disaster waste management in Italy: Analysis of recent case studies. Waste Manag. 2018, 71, 542–555.
53. Karunasena, G.; Rameezdeen, R.; Amaratunga, D. Post-disaster C&D waste management: The case of COWAM project in Sri Lanka. In AJCEB Conference Series; AJCEB: Burwood, Australia, 2012; Volume 1, pp. 60–71.