Chai and Wu
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REVIEW **Open Access**

Prevention/mitigation of natural disasters in urban areas

Jinchun Chai[1,2] and Hao-Ze Wu[1*]

Abstract

Preventing/mitigating natural disasters in urban areas can indirectly be part of the 17 sustainable economic and social development intentions according to the United Nations in 2015. Four types of natural disasters—flooding, heavy rain-induced slope failures/landslides; earthquakes causing structure failure/collapse, and land subsidence—are briefly considered in this article. With the increased frequency of climate change-induced extreme weathers, the numbers of flooding and heavy rain-induced slope failures/landslides in urban areas has increased in recent years. There are both engineering methods to prevent their occurrence, and more effectively early prediction and warning systems to mitigate the resulting damage. However, earthquakes still cannot be predicted to an extent that is sufficient to avoid damage, and developing and adopting structures that are resilient against earthquakes, that is, structures featuring earthquake resistance, vibration damping, and seismic isolation, are essential tasks for sustainable city development. Land subsidence results from human activity, and is mainly due to excessive pumping of groundwater, which is a "natural" disaster caused by human activity. Countermeasures include effective regional and/or national freshwater management and local water recycling to avoid excessive pumping the groundwater. Finally, perspectives for risk warning and hazard prevention through enhanced field monitoring, risk assessment with multi-criteria decision-making (MCDM), and artificial intelligence (AI) technology.

Keywords Preventing natural disasters, Sustainable urban development, Flooding, Slope failure, Earthquake, land subsidence

1 Introduction

Owing to convenient living environment in urban areas, an increasing number of people worldwide are choosing to live in these areas; that is, worldwide urbanization is occurring. Cohen [1] reported that almost half of humanity now resides in urban areas. Developing countries experience faster growth of this kind. In China, from 1980 to 2021, the ratio of people living in cities to the total population increased from 19.37% to 64.72% [2]. An increase in cities population results in the expansion of existing cities or the creation of new ones. For example, Shanghai, China has been developed/expanded to an urban megapolis with over 25 million inhabitants.

Although urban areas are convenient and comfortable for people, they are vulnerable for natural disasters, including floods, earthquakes, and landslides. In densely populated urban areas, natural disasters can cause serious property damage and death. For example, the Great Hanshin-Awaji Earthquake that occurred in the Osaka metropolitan area, Japan, on 17 January 1995, with a magnitude of 7.3 caused 6,434 casualties [3]. Furthermore, global warming is one of the major environmental problems worldwide. One of the consequences of global warming is the frequent occurrence of extreme weather [4], such as torrential rains or "a belt zone of heavy precipitation" [5], which can cause water-related disasters in urban areas. According to the United Nations

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*Correspondence:
Hao-Ze Wu
19hzwu@stu.edu.cn
[1] Department of Civil and Environmental Engineering, College of Engineering, Shantou University, Shantou 515063, Guangdong, China
[2] Graduate School of Science and Engineering, Saga University, 1 Honjo, Saga 840-8502, Japan

(September 2021), extreme weather-induced natural hazards have increased fivefold within the last 50 years. To maintain the sustainable development of cities, it is essential to consider the countermeasures for preventing/mitigating natural disasters in the city planning and construction stages.

In this article, the major natural disasters related to urban areas are discussed. The natural disasters considered are: flooding, heavy rain-induced slope failure (for cities adjacent to hills/mountains); earthquakes causing structure failure/collapse, and land subsidence (which is regarded as a natural disaster here despite being caused mainly by human involvement). For each type of disaster, first, its characteristics in recent years are described with some examples, and then the countermeasures are discussed.

To facilitate this review article, research publications related to the four natural disaster types from the Web of Science database from 2012 to 2021 were downloaded and analysed using VOSviewer [6]. The results of a brief bibliometric analysis are presented at the end of each topic.

2 Flooding

2.1 Occurrence tendency with some examples

Flooding is a major natural disaster occurring in urban areas. Sustainable flooding risk management is an important component of sustainable city development [7]. Urban flooding occurs when the stormwater increase rate exceeds the capacity of a city's drainage system (e.g. [8]). One of the consequences of global warming is the increased frequency and intensity of torrential rain or storms. If a city's drainage system does not consider this type of extreme rainfall, floods can easily occur. For example, in Beijing, the capital city of China, heavy flooding has occurred at least seven times over the past two decades. Among them, one case of flooding occurred on 21 July 2012, affected an area of 160,000 km^2 and 1.9 million residents, and caused 77 casualties. In the city centre area, the average daily rainfall was 215 mm [9].

In 2017, the Japan Meteorological Agency (JMA) introduced a new term for the phenomenon of intensive rainfall in a narrow belt area: "a belt zone of heavy precipitation" [5], which is caused by cumulonimbus clouds occurring linearly one after another, passing through and staying in almost the same place; and as a result, very heavy rain continues to fall in a specific belt area for a long time. Beginning in 2022, the JMA started to forecast the occurrence of belt zones of heavy precipitation. In Japan, in recent years, belt zones of heavy precipitation-induced floods have occurred almost every year. On 3–4 July 2020, a belt zone of heavy precipitation occurred in the Kuma River basin region, Kumamoto, Japan, with an accumulated rainfall of 400–500 mm, which caused the collapse of the bank of the Kuma River and serious flooding in the area. This flood caused 65 casualties; 2 people were missing, 557 houses were completely destroyed, 43 were partially destroyed, 5,895 were flooded above the beds on the first floor, and 1,990 were flooded below the beds on the first floor [10].

2.2 Countermeasures

(1) Natural flood management (NFM)

NFM emphasises by protecting, restoring, and emulating the natural processes such as catchments, floodplains, rivers and the coastlines to reduce the potential for flooding or mitigate the effects of floods [11].

One of the main reasons for the flood that occurred in Yamagata Prefecture, Japan, on 30 August 2022 was poor maintenance resulting in many agricultural ponds (Nippon Hoso Kyokai (NHK) news, 1 September 2022).

(2) Engineering methods

Engineering methods mainly consist of the following.

(a) Building new drainage channels or increasing the capacity of existing drainage channels in a city [9].
(b) Reinforcing river banks to prevent water overflow from rivers.
(c) Constructing retarding basins to reduce the surface runoff velocity and, therefore, the rate of water flow into rivers or urban centres.
(d) Increasing the pump capacity in lowland areas, such as the Saga Plain, Japan, where in some areas. the elevation of the land is lower than the riverbed, and the rainfall water must be pumped into the river or sea.

(3) Soft countermeasures

(a) Development of early and accurate flood prediction techniques and warning systems. With the rapid development of computational capacity and high-resolution satellite imagery, early and accurate weather forecasting has gradually become possible. Based on the results of earlier predictions, earlier warning system can be established (e.g. [12, 13]).

(b) Create detailed high-accuracy flood hazard maps, educate residents to understand them, and effectively use them for evacuation.

2.3 Brief bibliometric analysis results

(1) Identified Research cluster

The search strategy code was theme = (flooding) AND ((urban area). The four top research clusters were identified as follows:

Cluster 1: flood vulnerability (e.g. [14–18]).
Cluster 2: urban flood management and mitigation (e.g. [19–27]).
Cluster 3: simulation of flood evolution and inundation (e.g. [28–36]).
Cluster 4: leading cause of urban flooding (e.g. [37–45]).
Number of publications and top 10 journals publishing the papers.

Figure 1 shows the yearly number of research articles related to urban flooding published from 2012 to 2021. The number of articles has increased because of the increasing number of floods caused by extreme rainfall since the 2010s [46]. Table 1 shows the top ten journals in which research papers related to flooding were published.

Table 1 Top 10 journals in which flooding-related research papers were published from 2012 to 2021

Journal title	Publications
Water	342
Natural Hazards	263
Journal of Hydrology	205
Sustainability	198
International Journal of Disaster Risk Reduction	130
Science of the Total Environment	122
Natural Hazard and Earth System Sciences	116
Remote Sensing	96
Journal of Flood Risk Management	94
Environmental Earth Sciences	62

3 Rainfall-induced slope failures/landslides

3.1 Occurrence and social impacts

Schuster [47] reported that the annual economic losses attributable to slope fluctuations in Japan and Italy are around US$ 4.5 billion per year, US$ 2.6 billion per year, respectively. Landslide activity is increasing because of changing climate patterns result in increased regional precipitation [47]. In recent years, the number of rainfall-induced slope collapses and landslides has increased owing to the increased frequencies of extreme rainfalls. The Ministry of Land, Infrastructure, Transport and Tourism (MLIT), Japan [48] reported that the total number of sediment disasters that occurred in Japan in 2018 was 3,459, of which approximately 70% were rainfall-induced landslides and slope collapses. There were 161 casualties and 117 injuries.

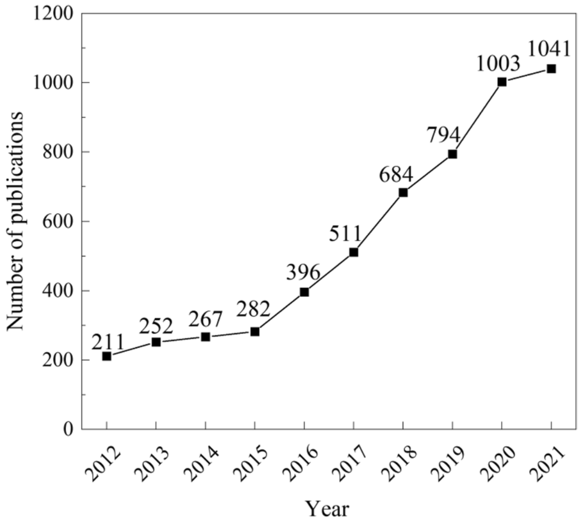


Fig. 1 Number of publications on flooding disasters

Many cities are located in landslide-prone areas, such as Hong Kong, where landslides and slope failures occur almost every year [49]. The most famous landslides in Hong Kong were a string of large landslides that occurred in June 1972 [50]. The landslides occurred because of the severe rain that pounded Hong Kong in the days leading up to them. It is estimated that at least 156 people were killed, and several apartment buildings and houses were destroyed. Particularly, a "mammoth" downpour of around 640 mm in 72 h precipitated the tragedies on 18 June 1972, which resulted in the collapse of a luxury block in the Mid-Levels and the loss of 67 lives.

At around 10:30 am (JST) on 3 July 2021, a large-scale slope failure and debris flow occurred in the Aibatsu River in the mountain district of Izu, Atami City, Shizuoka Prefecture, Japan [51]. 27 people died (including one disaster-related death, and one missing person). According to the Japan Meteorological Agency, 2–3 days before the disaster, warm and moist air flowed continuously toward a stagnant front from western to eastern of Japan, and the atmospheric conditions became extremely unstable at the site. At the observation point in Ajiro, Atami City, which was relatively close to the site, 321 mm of precipitation was recorded in 48 h, ending at 3:20 pm on 3 July. Upstream of the river, there was land developed on a sloped area by embankments. Forensic investigation showed that the fill of the embankments was not properly compacted, was in a loose state, was almost saturated by the rainstorm, and thus failed first. Successive heavy rain then brought the failed embankments into a debris flow.

3.2 Predicting rainfall-induced landslides

Depending primarily on the hydromechanical qualities of the associated soils, rainfall-induced landslides can occur during brief, strong precipitation or after lengthy periods of rain. There are two types of rainfall-induced landslides: shallow and deep-seated position. Rainfall-induced deep-seated landslides (e.g. [52]) are generally caused by rainfall-induced groundwater level rise, which causes positive pore water pressures along the surface with the risk for slipping. This situation is normally associated with not only surface precipitation, but also the formation of preferential water flow pathways to bring surface rainfall into deeper locations of a slope, such as the formation of vertical cracks. There are two trigging mechanisms for shallow landslides [53]. One is rainfall precipitation into the surface of unsaturated soil layers, which reduces the suction,therefore, the decrease in shear strength of the soil layers causes landslides. Additionally, pore water pressures inside slopes are raised resulting from the formation of water tables, which occurs when a permeable soil layer rests above a substantially lower permeable layer. Contel et al. [53] proposed a straightforward criterion to identify the potential initiating mechanism of shallow landslides triggered by rainfall in accordance with the slope geometry, weight of unit, and strength characteristics of the concerned soil, as follows:

$$SF_d = \frac{c'}{\gamma Z \sin\alpha \cos\alpha} + \frac{\tan\phi'}{\tan\alpha} \tag{1}$$

where α is slope angle; Z is the depth of potential failure; γ is the unit weight of soil; c' is the cohesion intercept under effective stress, and ϕ' denotes the effective stress angle of the soil's resistance to shearing. If $SF_d \leq 1$, a landslide may be induced at a depth Z due to a decrease in the initial suction caused by rainwater infiltration. If $SF_d > 1$, landslides can only occur when the potential failure surface is subjected to positive pore water pressures due to rainfall.

To predict rainfall-induced landslides, rainfall precipitation (seepage) analysis and/or coupled seepage and stress–strain analysis of unsaturated soil slopes must be performed [54], in which numerical simulations, such as finite difference or finite element methods, are normally required. These techniques are described elsewhere and will not be explained here. To perform this type of analysis, hydromechanical properties, especially soil hydraulic characteristics under unsaturated conditions, that is, soil water characteristic curve (SWCC) and permeability functions, are required. Figures 2 and 3 show the typical SWCC and permeability functions of unsaturated soils [54].

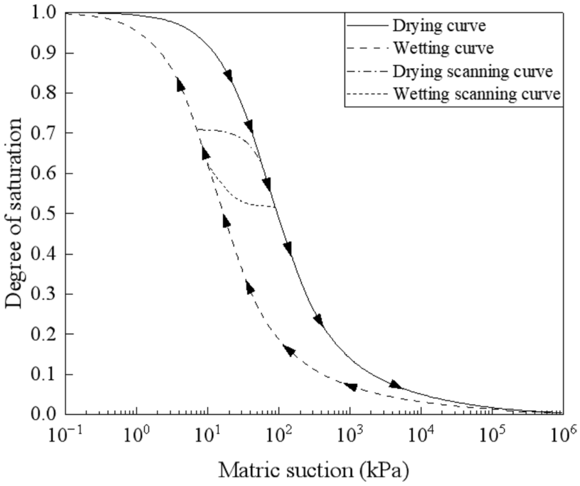


Fig. 2 Typical SWCCs of an unsaturated soil

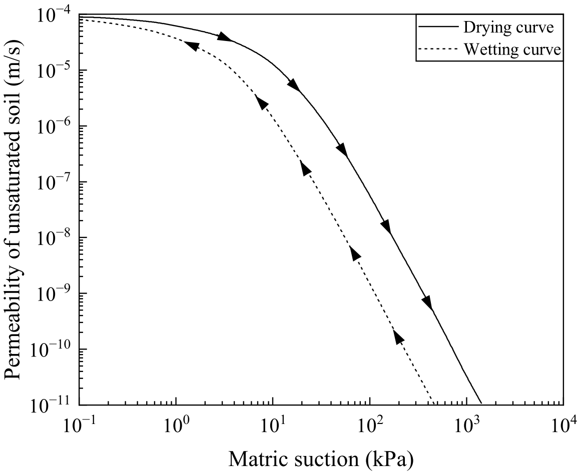


Fig. 3 Typical permeability functions of an unsaturated soil

The most commonly used SWCC functions are those proposed by Van Genuchten [55] and by Fredlund and Xing [56]. Although several permeability functions exist in the literature, a generally adopted method is to deduce them from SWCC functions,for example, the permeability function [57] can be combined with and SWCC function [55], which has an explicit expression,and Fredlund et al.'s [58] method, which does not have an explicit expression (an integration form). In these mathematical functions, fitting parameters must be determined using measured data. However, to measure the SWCCs of soils, special equipment is required, and this process is time-consuming (sometimes it may take several months). Therefore, in routing geotechnical site investigations, measuring the SWCCs of soils is not included. This type of situation limits or restricts the application of unsaturated soil mechanics in geotechnical designs. To provide a pragmatic solution, Chai and Gao [59] and Gao and Chai [60] proposed empirical methods to estimate the fitting parameters in the SWCCs of Fredlund and Xing [56] and Van Genuchten [55] using easily measured basic soil properties, such as saturated permeability, grain size distribution curve, and plastic index. It is believed that this type of estimation can effectively promote the application of unsaturated soil mechanics in predicting rainfall-induced slope failure or landslides.

Several factors influence rainfall-induced shallow slope failures. Except for the geometry and hydromechanical properties of the slope, the most important factors are the rainfall rate, rainfall duration, and initial moisture content of the slope soil preceding a rainstorm. Figure 4 illustrates a chart for predicting whether rainfall will induce a shallow slope failure. In the figure, the "lower" and "higher" initial moisture contents are qualitative or relative conditions. Defining precise values is considered impractical. For a given slope, the type of chart can be proposed by using the hydromechanical characteristics of the slope soil and the findings of precipitation analysis. In a region, the natural slopes may have different slope angles, different thicknesses of weathered soil layers, and different vegetation conditions. In practice, the slopes can be classified into several groups, and a prediction chart for each group can be proposed. Then, using weather forecast information on the rainfall rate and duration, possible rainfall-induced slope failures can be predicted.

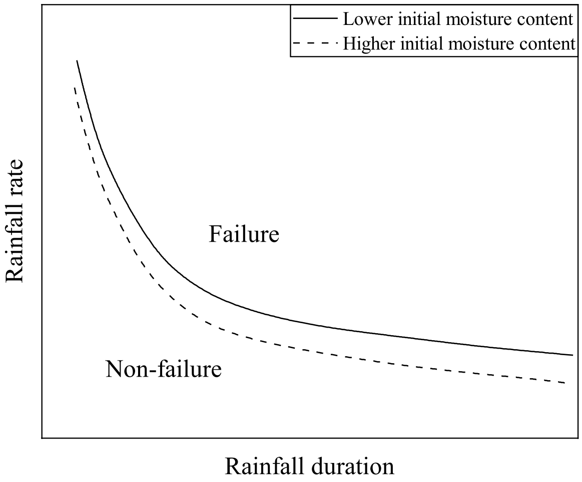


Fig. 4 An illustration of a chart for predicting shallow slope failures caused by rainfall

Deep-seated rainfall-induced slope failures are more difficult to predict. They are mainly influenced by the hydrogeology of a slope, and sometimes a site investigation cannot reveal all the relevant details.

3.3 Methods for preventing/mitigating rainfall-induced slope failure

(1) Engineering/vegetation methods

(a) Failure of shallow slopes caused by rainfall

For rainfall-induced shallow slope failures, the most effective countermeasures are: (i) increasing the vegetation of a slope, and (ii) making the slope angle gentler. Other engineering methods include spraying a thin layer of concrete on the slope and rebar insertion methods [61].

(b) Failure of deep-seated slope

Countermeasures could be classified into two categories: methods of increasing the shear strength on a potential slip surface and/or reducing the driving force (moment) of a slope; and methods increasing the resistance force (moment) using other structures. The former methods include improving drainage systems for surface water and groundwater, removing certain soils from the upward part of a slope, and adding certain soils at the toe of a slope. The latter methods include the anchor, resistance pile, and retaining wall methods [62]. Normally, these methods are applied when there is a sign of slope instability.

(2) Soft methods

Soft methods aim to prevent or mitigate slope failure-induced damage to human lives and property. One method is to evacuate people from higher-risks areas, and if that is not feasible, another method is to establish a high-accuracy warning system.

3.4 Brief bibliometric analysis results

(1) Top four identified research clusters

The search strategy code used was: theme = (rainfall OR rain OR precipitation) AND (slope) AND (failure OR landslide OR lapse). The four top research clusters are as follows:

Cluster 1: failure mechanisms of landslides (e.g. [63–68]).

Cluster 2: landslide susceptibility evaluation (LSA) (e.g. [69–71]).
Cluster 3: prediction of rainfall-induced shallow landslides (e.g. [72–79]).
Cluster 4: soil erosion and landslide-type debris flow (e.g. [12, 80–83]).
Number of publications and top 10 journals publishing the papers

Figure 5 presents the number of publications on rainfall-induced landslides from 2012 to 2021. From 2014 to 2021, the number of related papers rapidly increased, indicating increased research activity in this area. Table 2 lists the top 10 journals in which landslide-related papers were published from 2012 to 2021.

Table 2 Top 10 journals in which landslide-related research papers were published from 2012 to 2021

Journal title	Publications
Landslides	349
Engineering Geology	197
Natural Hazards	163
Environmental Earth Sciences	147
Geomorphology	141
Bulletin of Engineering Geology and the Environment	118
Water	89
Journal of Mountain Science	85
Natural Hazards and Earth System Sciences	78
Catena	73

4 Earthquake

4.1 Occurrence and social impacts

It is commonly accepted that an earthquake is normally caused by “elastic rebound” of Earth’s crust, a theory proposed by Reid [84]. This theory states that a major cause of earthquakes is deformation due to external forces, primarily regional tectonic pressures. When the total amount of strain (energy) at a critical spot surpasses the capacity of the rock to withstand further strain, an earthquake will occur due to brittle fractures in competent rock or slip on preexisting weak zones. An earthquake fault is a region where the slip or displacement occurs [85].

Considerable attempts have already been made to predict the occurrence of an earthquake using observations of abnormal animal activities as well as monitored strain in bedrock (e.g. [86]. Although there have been some “successful” predictions, such as the Haicheng earthquake in 1975 (M 7.3) in China [87], generally, earthquakes still cannot be predicted precisely enough to avoid damage. The World health Organization [88] reported that nearly 750, 000 people worldwide died as a result of earthquakes between 1998–2017. In the emergency phase of the disaster, more than 125 million people were injured, made homeless or displaced affected by earthquakes during this period. If an earthquake occurs in a highly populated urban area, the damage to human lives and property is much larger than that in a rural area. To reduce or mitigate possible earthquake-induced damage, developing resilient structures for houses and public buildings has become a very important topic of research and city planning strategy for sustainable city development.

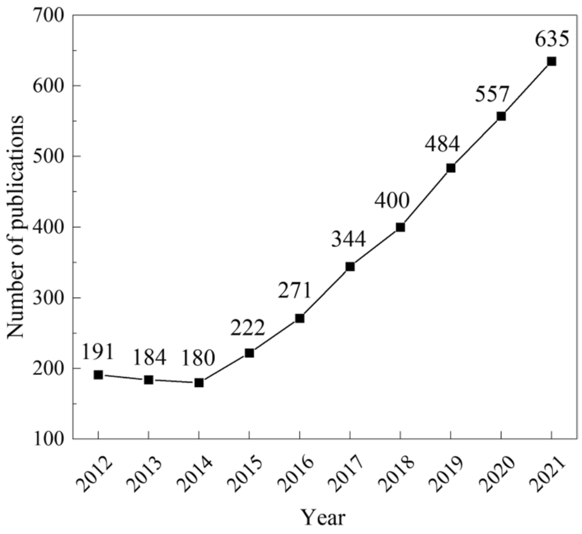


Fig. 5 Number of publications on rainfall-induced landslides

4.2 Resilient structures

MLIT [89], Japan, published the “Basis of Structural Design for Buildings and Public Works”, which stated that there are three basic performance requirements:

(a) Human life is protected from foreseeable events in and around structures.
(b) Structure functions are adequately protected from foreseeable threats.
(c) Restoring the structure within reasonable ranges of cost and time will enable it to continue to be used against foreseeable actions.

There are different detailed design considerations for the most important structures or buildings, such as nuclear power stations, and common office and/or department buildings. However, developing and innovating new techniques for structures resilient to earthquakes is a common and important task for sustainable city development.

Japan is an earthquake-prone country because it lies in the boundary region between the Eurasian and Pacific plates, and tectonic movement of the Plates causes earthquakes as well as active volcanoes. It is well known that many houses in Japan have wooden structures, which are more flexible and has better earthquake resistance compared to other common building types. However, they are more vulnerable to fire. It may be less well known that in Japan, most public buildings and apartment buildings have steel structures instead of reinforced concrete structures [90]. Steel structures for building have higher earthquake resistance but are more expansive.

Although there are ongoing studies about novel structures that are resilient against earthquakes, practically adopted resilient structures include earthquake-resistant structures, vibration-damping structures, and seismic isolation structures, as illustrated in Fig. 6. In earthquake-resistant structures, the pillars and beams that form the main frame of a building are strengthened to prevent the building from collapsing during an earthquake. On the other hand, for a seismic isolation structure, vibration isolation devices are installed under the structure, and for a vibration damping structure, dampers are installed between the beams and columns to absorb seismic energy and prevent damages to the main structures of a building [91].

4.3 Brief bibliometric analysis results

(1) Top four identified research cluster

The search strategy code was theme = (earthquake or temblor or seism or quake) AND ((urban area). The four top research clusters are as follows:

Cluster 1: ground-motion parameters and prediction (e.g. [93–95]).
Cluster 2: earthquake disaster response and evaluation (e.g. [96–101]).
Cluster 3: earthquake-related geotectonic research (e.g. [98, 102, 103]).
Cluster 4: the site amplification effect of seismic ground motion (e.g. [104–107]).
Number of publications and top 10 journals publishing the papers

The yearly number of publications on earthquakes in urban areas from 2012 to 2021 is plotted in Fig. 7. From 2014 to 2021, papers related to earthquakes increased steadily, indicating with urbanisation, this subject has received increasing attention. Table 3 shows the top 10 journals in which the earthquake-related research papers were published from 2012 to 2021.

5 Land subsidence

5.1 Causes and social impact

The major reason of land subsidence or land-level lowering is excessive groundwater pumping [108]. It appears to occur naturally, but is a result of human activities. Land subsidence can damage infrastructure, increase flooding potential and damage drainage systems of cities, and it endangers human lives and property. With an increasing urban population

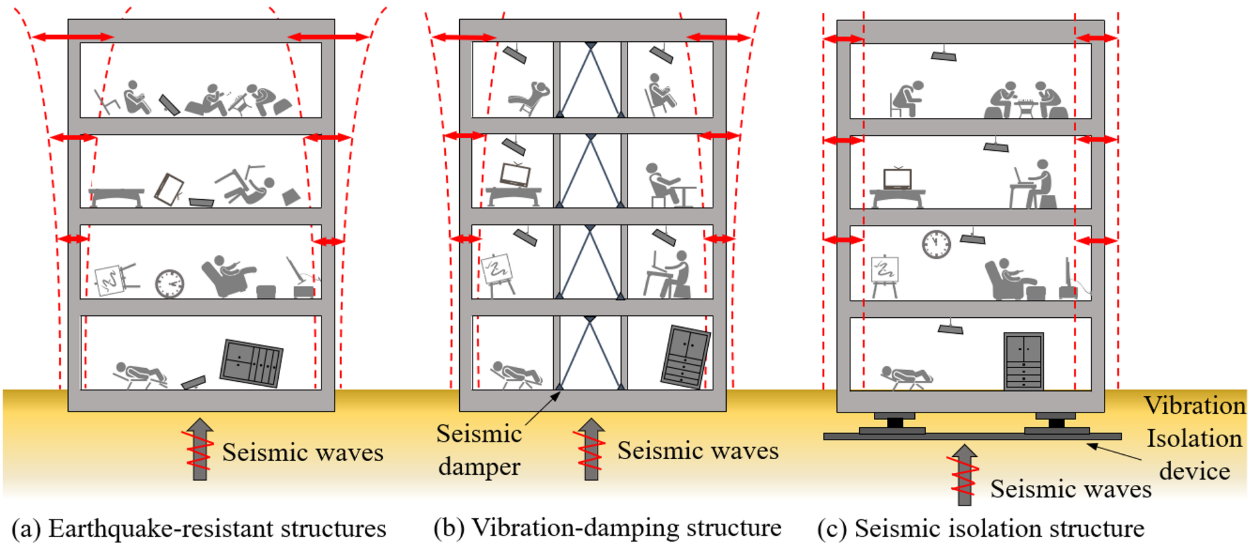


Fig. 6 Structures resilient against earthquakes (adapted from www.eng.nipponsteel.com) [92]

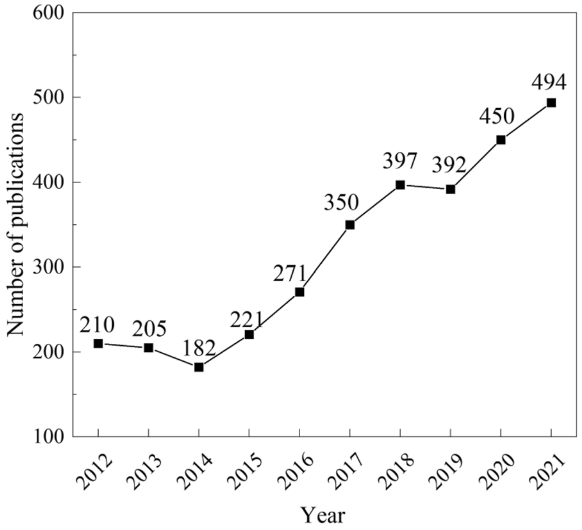
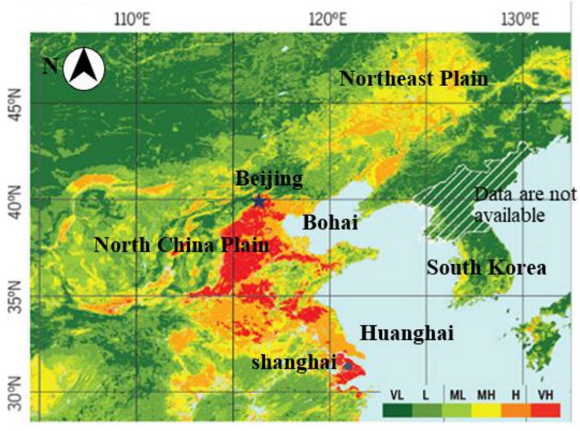


Fig. 7 Number of publications on earthquakes in urban areas



Note: VL: very low; L: low; ML: middle low;
MH: middle high; H: high; VH: very high

Fig. 8 Potential land subsidence areas in East Asia (adapted with permission from [110], Copyright 2021 AAAS)

Table 3 Top 10 journals in which the earthquake-related research papers were published from 2012 to 2021

Journal title	Publications
Natural Hazards	226
Bulletin of Earthquake Engineering	117
International Journal Disaster Risk Reduction	117
Bulletin of the Seismological Society of America	87
Soil Dynamics and Earthquake Engineering	78
Pure and Applied Geophysics	70
Natural Hazards and Earth System Sciences	66
Earthquake Spectra	58
Seismological Research Letters	57
Journal of Seismology	51

(urbanisation), the global demand for freshwater increases every year. If there is insufficient fresh surface water, people will inevitably use groundwater, and if this usage is not well managed, it will induce land subsidence. Potential subsidence areas threaten 1.2 billion people and 21% of the major cities worldwide, especially in coastal areas. Among them, 86% of the exposed population lives in Asia. Figure 8 shows a map of potential areas of land subsidence in East Asia. United Nations Office for Disaster Risk Reduction (UNDRR) asserts this study enhances subsidence comprehension, uncovers new subsidence areas, and informs mitigation strategies [109]. This clearly shows that Eastern China has the highest potential in this region. Therefore, for sustainable city development, an economical and effective plan to ensure safe access to water resources is essential.

Shanghai is the largest economic city in China and has suffered serious land subsidence problems. As seen in Fig. 9, The deltaic deposit of the Yangtze River forms the foundation of Shanghai, as illustrated in Fig. 9. The primary geological layers are shown in Fig. 10, and Quaternary deposits are approximately 300 m thick. In Shanghai, land subsidence was brought on by an excessive amount of ground water pumping, which also caused the Quaternary deposit to become compressed. In 1921, Shanghai established a programme to monitor the subsidence of the soil. Up until the year 2000, the centre part of Shanghai had a cumulative subsidence of between 2 and 3 m (Fig. 11). In Fig. 11, the subsidence of land in the urban area of Shanghai can be divided into two distinct time periods, the rapid subsidence era, which occurred between the years 1921 and 1965, and the regulated phase, which occurred after 1965. From 1965, pumping of groundwater in the Shanghai area was strictly controlled by the local government, and the land subsidence was clearly mitigated. Land subsidence in Shanghai has caused many social issues. An increase in the likelihood of flooding is the issue that needs to be addressed right away. Flooding due to precipitation occurred 22 times between 1981 and 1994, which is an average of nearly twice per year [111]. Recently, there has been a concurrent rise in the likelihood of floods caused by tides. Dike heights along the coastline increased four times from 1956 to 1960, with crest elevations rising from 5 to 6.8 m. Damage to sewerage systems, roads, buildings, and underground tunnels are among the other issues created by land subsidence.

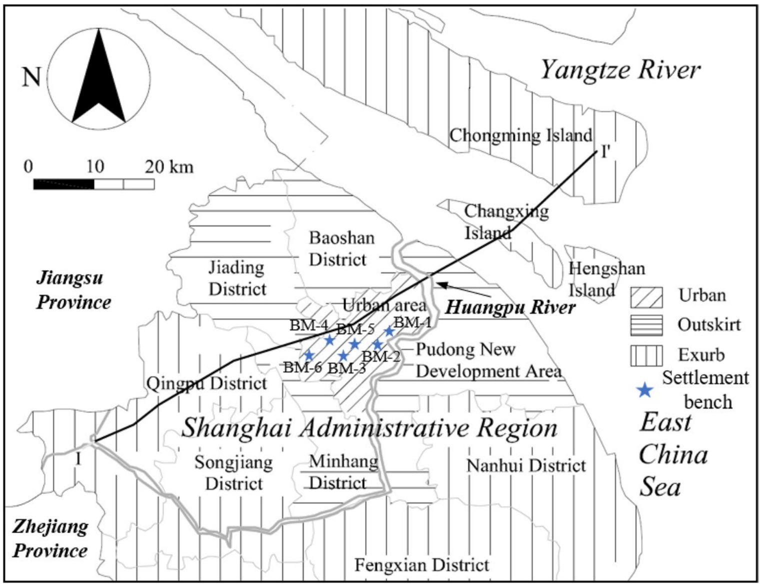


Fig. 9 Locations of some monitoring points and cross section I-I'(data from [108] and [112])

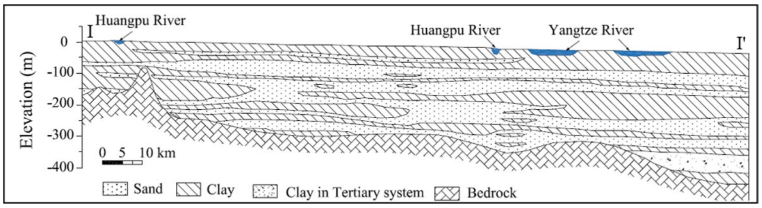


Fig. 10 Geological strata in Shanghai (cross section I-I'in Fig. 9) data from [108] and [112]

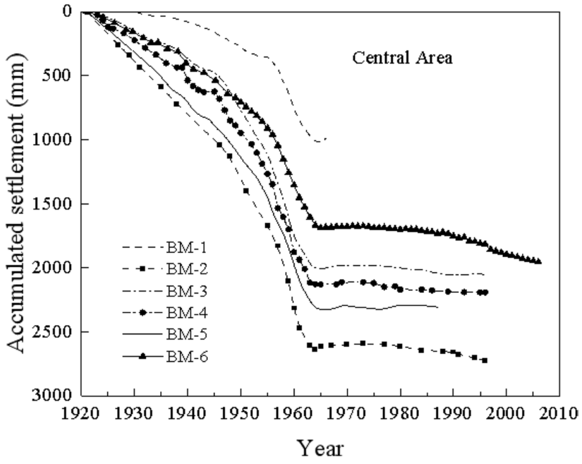


Fig. 11 Subsidence curves of several benchmarks (Fig. 9) located in the Shanghai centre (data from [108] and [113]

5.2 Countermeasures to maintain sustainability of cities

(1) Regional and/or national water management

In most regions or countries, the distribution of freshwater resources is unbalanced;freshwater may be rich in certain parts and lacking in other parts. It is essential for local governments to efficiently and economically manage water resources.

In China, freshwater is rich (more than enough) in the South, but in the North, there is not enough freshwater. To solve this type of national freshwater shortage problem, the national project of the South-to-North Water Division (Fig. 12) was commenced in 2002; parts of it have been completed and parts are still under construction. It is one of the greatest projects in Chinese history, and it can mitigate freshwater shortages and therefore land subsidence problems in North-Eastern parts of China.

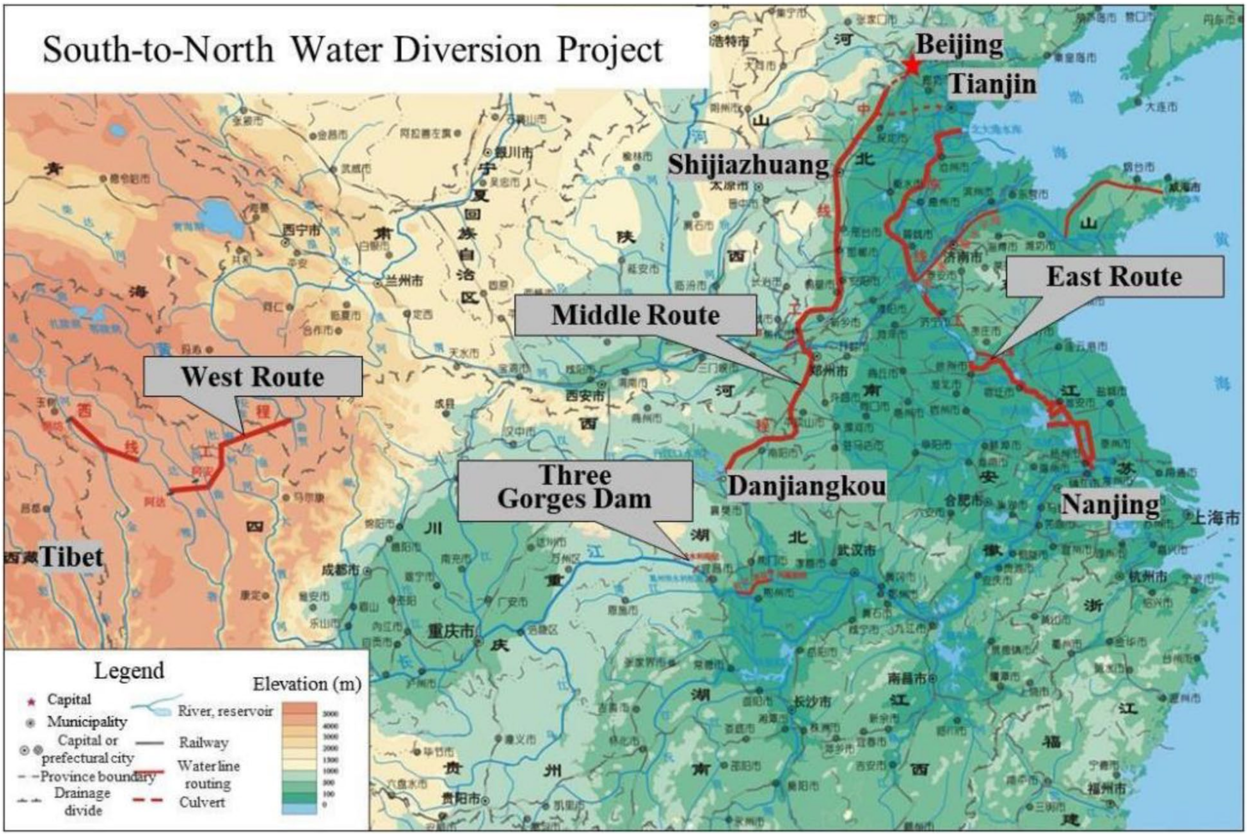


Fig. 12 China national project: South-to-North Water Division route map (adapted from http://nsbd.mwr.gov.cn/) [114]

Quaternary clayey soils of 10 to 30 m thickness were deposited in the Saga Plain, Japan [115]. In Shiroishi District, Saga, the Quaternary soil layers were compressed due to excessive groundwater pumping for agricultural purposes and approximately 1.0 m of subsidence from 1970 to 2000. After that, there were restrictions on the amount of groundwater to be pumped, and land subsidence was mitigated. Furthermore, from 2012, surface water from Kasegawa Dam was diverted to Shiroishi District and pumping of groundwater was largely stopped, which prevented further land subsidence.

(2) Efficient use of water

With the increasing of world populations and limited freshwater resource, aside from diverting water from rivers into cities, recycling locally available water resources is an effective way to ensure water safety in urban areas and maintain sustainable development. A community can recycle its wastewater, such as from bathtubs and washing machines, to flush toilets, wash cars, and water plants. This could help reduce the amount of groundwater used in certain areas and mitigate possible land subsidence.

5.3 Brief bibliometric analysis results

(1) Top three identified research clusters

The search strategy code was theme = (land OR ground OR soil OR earth surface) AND (subsidence OR settlement) AND (urban area). The top three identified top three research clusters are as follows:

Cluster 1: the possible causes of urban ground subsidence (e.g. [116–118]).
Cluster 2: land subsidence monitoring techniques (e.g. [119–121]).
Cluster 3: the land subsidence prediction model (e.g. [113, 117, 122, 123]).
Number of publications and top 10 journals publishing the papers

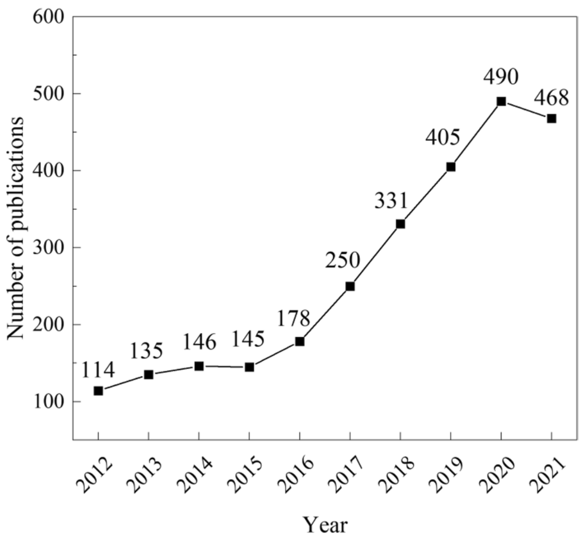


Fig. 13 Number of publications of land subsidence

Table 4 Top 10 journals in which the land subsidence-related research papers were published from 2012 to 2021

Journal title	Publications
Remote Sensing	197
Sustainability	137
Environmental Earth Sciences	72
Natural Hazards	58
Remote Sensing of Environment	49
Tunnelling and Underground Space Technology	45
Engineering Geology	39
Science of the Total Environment	38
Arabian Journal of Geosciences	29
Landscape and Urban Planning	29

Figure 13 presents the number of publications on land subsidence in urban areas from 2012 to 2021. Table 4 shows the top 10 journals in which the land subsidence-related papers were published from 2012 to 2021.

6 Perspectives for risk warning and hazards prevention

6.1 Strengthening field monitoring

Natural disaster monitoring is a prominent component of response strategies for natural hazards. Field monitoring not only enables the evaluation of the risks associated with these hazards, but also allows the optimization of their prevention. For instance, remote sensing technologies are highly effective for enhancing the understanding of spatial and temporal trends of phenomena such as flooding [44, 100], landslides [124, 125], earthquakes (..), and land subsidence [43, 126]. However, these technologies should be operated in parallel with traditional methods to provide explicit insights into the investigated systems. Tools such as multiple-sensor, high-precision GPS, radars and geodetic methods (e.g., levelling) generally help in natural object monitoring, while automatic monitoring systems allow the approximation of future seismological, climatic, and groundwater level changes associated with hazard occurrences. Furthermore, with technological breakthroughs, satellite technologies are increasing utilised for monitoring natural disasters. The primary advantage of this approach is its relatively large and movable coverage range. Adopted by agencies such as the Asia–Pacific Regional Space Agency Forum (APRSAF), the hybridisation of space-based technology and WEB-GIS technology has proven to be an efficient tool for disasters management [127]. Although strengthening field monitoring can improve the understanding of natural disasters, the assessment of the risk associated with these hazards as well as early warnings of their occurrence is imperative to achieve disaster resilience.

6.2 MCDM risk assessment

Disaster risk assessment in urban areas is crucial for long-term planning and policymaking processes for local communities. The aim of quantifying disaster risks is typically to determine their nature and magnitudes such as the probability of high-intensity flood [42], areas affected by landslides [128], seismic intensity [129], and degree of land subsidence [101]. This is carried out by analysing hazards and assessing the punctual states of vulnerability that could endanger exposed people and their immediate environment. In this regard, tremendous developments have been achieved in recent years to quantify the effects of disasters occurring in urban areas. Current state-of-the-art risk assessment approaches include probabilistic and statistical [130], fuzzy set ([131], [132], GIS-enabled zoning [133], and risk characterisation [134] methods. Nevertheless, a resurgence of some traditional frameworks (that are continuously improving) such as scenario analysis, comentropy, or grey system techniques has also been observed in recent years [135]. Because the precision of disaster risk assessment is primarily contingent on the data quality and spatial–temporal coverage of the assessment model, existing methods inherently embody or generate constraints that limit their efficiency in assessing the true exposure of people and their environment to natural disaster risks. Focusing on climate risk assessment, Arribas et al. [136] argued that improvements should be made to consider compounding risks, comprehensive databases, and comparison/combinations of different assessments results.

6.3 AI-enabled early warning systems

The stochastic nature of disaster phenomena has driven global efforts to target the integration of AI in disaster-management systems. AI possesses huge potential for strengthening disaster mitigation owing to the seamless availability of data and the increasing performance of forecasting algorithms. These two features are critical for enabling early warning systems, that is, technologies and processes that aim to predict and mitigate the harm of natural disasters. The data must be sufficient, representative, precise (e.g. in terms of resolution), and consistent (e.g. sequential data, real-time data) with the operating algorithm. However, the rarity of some events, such as earthquakes, can hamper the creation of sufficiently large database for training algorithms. Kuglitsch et al. [137] postulated that producing synthetic data could be a viable solution to this problem. Furthermore, predicting algorithms have mainly adopted the deep learning paradigm because of its ability to explore massive design spaces, deal with nonlinearity, and identify multidimensional correlations. These algorithm can predict the future occurrence of hazards, which is critical for organising appropriate responses. Recent successes include deep learning-based ground characterisation [138–142], real-time and dynamic modelling [143–146]), ensemble models, and hybrid model-based forecasting of the occurrence of future phenomena [147, 148]. To take full advantage of these technologies, they must be integrated into an interdisciplinary platform to allow the seamless understanding of both the operating process and predictive analysis by relevant actors, including researchers, engineers, multi-stakeholders, and decision-makers.

7 Concluding remarks

In 2015, the UN set 17 goals for sustainable economic and social development. Goal 11 seeks to make cities accessible and safe for all people; Goal 13 seeks to immediately mitigate the effects of climate change. Preventing and mitigating natural disasters in urban areas can be an indirect part of these two goals. Four types of natural disasters—flooding, heavy rain-induced slope failures/landslides, earthquakes causing structure failure/collapse; and land subsidence—are considered in this study. The characteristics of each disaster in recent years and the possible countermeasures are also discussed.

With the increasing frequency of climate change-induced extreme weathers, the number of floods has increased in recent years in metropolitan regions. The countermeasures include natural flooding management, such as increasing vegetation coverage of lands, engineering methods for enhancing drainage capacities in urban areas, increasing elevation of dikes, and soft methods such as early warning systems and evacuation plans.

Heavy rain-induced slope failures/landslides affect cities adjacent to hills/mountains (such as Hong Kong). Again, extreme weather-induced torrential rains cause more slope failures and landslides. Engineering measures for preventing slope failures or landslides are often implemented after observing the signs of slope instability. Therefore, it is important to predict rainfall-induced slope failures/landslides. With an accurate early prediction/warning system, damage resulting from slope failures/landslides can be substantially mitigated.

Although considerable efforts have been made to predict earthquake, they still cannot be predicted effectively enough to avoid damage. Therefore, developing structures resilient to earthquakes is an essential engineering task for sustainable city development. Three types of structures can be adopted: earthquake-resistant structures, vibration damping structures, and seismic isolation structures.

Land subsidence is a human activity, that is, the main cause is excessive groundwater pumping. With rapid urbanisation, the demand for more freshwater is increasing worldwide, and some of the freshwater is obtained by pumping groundwater, which can cause land subsidence. Approximately, 1.2 billion people are affected by land subsidence worldwide. The corresponding countermeasures include effective regional and national freshwater management as well as locally water recycling.

To mitigate potential disasters in urban areas, the following perspectives are recommended: 1) establishment and strengthening of field monitoring systems, 2) conducting risk assessments and providing warnings based on multi-criteria decision making models, and 3) establishment of early warning systems based on artificial intelligence technologies.

Authors' contributions

The conception of the review article was primarily contributed by Jinchun Chai, who also drafted the manuscript and performed critical revisions. Hao-Ze Wu was responsible for the extensive literature search and data analysis. Hao-Ze Wu also contributed to reviewing and editing the manuscript. Both authors have read and approved the final version of the manuscript.

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