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On civil engineering disasters and their mitigation

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Abstract: Civil engineering works such as buildings and infrastructure are the carriers of human civilization. They are, however, also the origins of various types of disasters, which are referred to in this paper as civil engineering disasters. This paper presents the concept of civil engineering disasters, their characteristics, classification, causes, and mitigation technologies. Civil engineering disasters are caused primarily by civil engineering defects, which are usually attributed to improper selection of construction site, hazard assessment, design and construction, occupancy, and maintenance. From this viewpoint, many so-called natural disasters such as earthquakes, strong winds, floods, landslides, and debris flows are substantially due to civil engineering defects rather than the actual natural hazards. Civil engineering disasters occur frequently and globally and are the most closely related to human beings among all disasters. This paper emphasizes that such disasters can be mitigated mainly through civil engineering measures, and outlines the related objectives and scientific and technological challenges.

Keywords: disaster; hazard; civil engineering disaster; earthquake

1 Introduction

Disasters have been a part of human experience from earliest times and have been significantly impacting human development and civilization. From a modern scientific viewpoint, a disaster is an abrupt event that leads to loss of human lives, properties, resources, or environmental wellbeing, exceeding the capacity of the hazard-bearing body, a term that is used herein to referred to any exposure of human society to a hazard. The following four characteristics are inherent to the above definition of disasters. Firstly, disasters are consequent to the presence of human beings and communities as hazard-bearing bodies. There would be no disasters if there were no humans; violent changes and movements have occurred since the beginning of the earth, but did not constitute disasters until the appearance of man. Secondly, disasters are uniquely expressed in terms of losses by human beings and communities. Such losses are not limited to life and property, but also include natural resources and the environment. Thirdly, there is a threshold of the extent of loss due to an event for it to be considered a disaster. In other words, not all loss-causing events are considered disasters. For example, the collapse of an ordinary warehouse, everyday car accidents, and robberies may cause losses, but such are not generally categorized as disasters. The loss threshold for categorizing an event as a disaster primarily depends on the capacity of the hazard-bearing body to resist the disastrous event and accommodate the loss. While a car accident may constitute a disaster for a family, it is far from a disaster to the city. Moreover, there are always fortunate individuals or families that remain intact during major earthquakes, which may otherwise constitute devastating disasters to local communities. Hence, the aim of disaster mitigation is not necessarily to eliminate loss entirely, but to decrease the loss below the disaster threshold, which is often a more practical strategy. Finally, the above definition of disaster emphasizes the abruptness of the event. Disastrous events are typically abrupt, such as earthquakes, landslides, aviation accidents, and terrorist attacks. However, some disastrous events may occur gradually, such as global warming due to excessive and extended carbon emission, metropolitan smog due to air pollution, and the desertification of a forest or prairie. In contrast to such gradual events, which are to some extent expected and observed during their development, abrupt disasters take place suddenly without effective forecast or prediction. Their durations are short, but they cause significant and often lasting consequences. In addition, such unexpected

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events frequently impose severe mental pressure on the public, and this may exacerbate the disastrous consequences. Abrupt and gradual disasters differ in other ways, including in their occurrence mechanisms, consequences, and mitigating measures. However, the present paper focuses on abrupt disasters.

From a philosophical viewpoint, a disaster is a consequent of the interaction between contradicting factors, e.g., a hazard and the hazard-bearing body. The hazard is the cause of the disaster and may be a natural phenomenon such as an earthquake, rainstorm, flood, drought, or plague. It may also be a human action such as a technical mistake, human fault, or hostile action such as a war or terrorist attack. Conversely, the hazard-bearing body is the potential victim that is liable to suffer potential loss due to the hazard. The occurrence of a disaster is frequently conceived as a one-way action of a hazard on the hazard-bearing body, and therefore, no disaster could occur without a hazard (Jovanovic, 1986). However, this may lead to the faulty understanding that the hazard itself is a disaster, based on which disasters are usually classified by the hazards. In this context, disasters are first classified into two categories, namely, natural disasters (caused by natural hazards) and man-made disasters (caused by man-made hazards). While this emphasizes the importance of hazards in the disaster system, it overlooks the roles of the resistance capacity of the hazard-bearing body, mitigating measures, and avoidance actions.

Disasters are indeed the consequences of the interactions between hazards and hazard-bearing bodies. A disaster occurs when the hazardous action overcomes the resistance capacity of the hazard-bearing body. There is no disastrous event when the hazardous action is within the resistance capacity of the hazard-bearing body. The role of the hazard, which only forms one side of the disaster, tends to be overemphasized. This was particularly the case in ancient times, when hazards were conceived as acts of God. From a modern scientific viewpoint, however, while hazards remain an important aspect of disasters, they are by no means the decisive factor in the scope of the disaster. The decisive factor is the resistance capacity of the hazard-bearing body. In this context, not all hazards lead to disasters. For example, volcanic eruptions on remote islands and earthquakes in uninhabited deserts are hazards that do not cause disasters because there are no hazard-bearing bodies at the locations. Furthermore, through modern scientific and technological innovations, disasters can be mitigated or avoided. For example, earthquake disasters can be greatly mitigated by enhancing the seismic performance of buildings and infrastructure. Nowadays, thanks to advanced earthquake engineering technologies, moderate or even major earthquakes in countries such as Japan, the US, and Chile do not necessarily result in disasters, even if the affected areas are densely populated. Disasters are thus only a subset of hazards, being the intersection between hazards and hazard-bearing bodies (Fig. 1). Although it is extremely difficult to control hazards, especially natural hazards, the causes and mechanisms of hazards can be investigated, the occurrence probabilities of the hazards can be assessed (e.g., by the analysis of the seismicity of a specific site or of the moving paths of a hurricane), and the findings can be used to improve the resistance capacity of the hazard-bearing bodies.

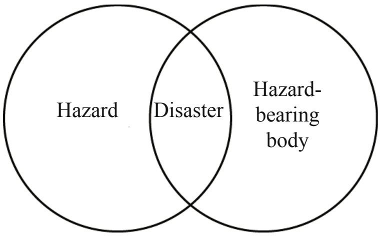


Fig. 1 Disaster system

2 Civil engineering disaster

2.1 Definition

Disasters have been classified into two major categories based on the natures of the related hazards, namely, natural disasters and man-made disasters. Natural disasters are further classified as (1) geological disasters, which are caused by hazards in the lithosphere, such as earthquakes, landslides, debris flows, and volcanic eruptions; (2) meteorological disasters, which are caused by hazards in the atmosphere and hydrosphere, such as hurricanes, tornados, droughts, forest fires, heavy rains, and floods; and (3) biological disasters, which are caused by hazards in the biosphere, such as plagues and pests. Man-made disasters can also be classified by hazards into the following three categories: (1) disasters caused by technical mistakes, such as nuclear accidents, explosion of dangerous substances; (2) disasters caused by human faults, such as fires in buildings, traffic accidents, and gas explosions; and (3) disasters caused by hostile actions, such as wars, riots, and terrorist attacks.

Human beings play a special role in a disaster system. They are usually the hazard-bearing bodies, being the direct or indirect victims of disasters. However, people may also be the hazards that cause disasters. In some cases, people are simultaneously both the hazards and hazard-bearing bodies. Civil engineering works are major examples in which humans play this dual role. In the evolution of many disasters, civil engineering works are attacked by external hazardous actions such as earthquakes and winds, and they may then go on to constitute deadly hazards to human life and property in the event of their failure or collapse due to insufficient resistance capacity. The terrorist attack on the World Trade Center in 2001 fully demonstrated this dual character of civil engineering works. In this particular case, the attack was the initial hazard, with the people and buildings being the direct hazard-bearing bodies. However, the buildings became hazards when they collapsed owing to structural inadequacy, causing significant losses of human life and property (Fig. 2).

During destructive earthquakes, civil engineering works are initially the hazard-bearing bodies. Their failure or collapse due to insufficient seismic resistance may, however, cause them to become hazards that may cause further casualties and financial loss (Fig. 3). The loss of life and property through past earthquakes has actually been primarily attributed to the failure and collapse of buildings. Approximately 80% of the deaths that resulted from the 1995 Kobe earthquake in Japan were caused by collapsed buildings. Among the 2456 deaths in the city of Kobe, 2221 were dead within 15 minutes of the earthquake (Wikipedia, 2015). On July 28, 1976, an M7.8 earthquake hit the city of Tangshan, China, resulting in the collapse of 90% of single-story buildings and 85% of multi-story buildings in the city (Ren *et al.*, 2014). The extensive building collapse caused numerous immediate deaths and injuries.

The failure of civil engineering works also usually disrupts the delivery of emergency services. For example, the damage of transport and water supply infrastructure may impede rescue operations, hamper the delivery of health services, and cause disease. Nine months after the deadly M7.0 earthquake in Haiti in 2010, an outbreak of cholera due to the consequent water pollution claimed 8000 lives, in addition to the earlier fatalities of the earthquake. The failure of civil engineering works may also result in the damage of other utility systems such as gas supply pipes, a particularly case that may cause serious fire. Immediately after the 1995 Kobe earthquake, a widespread fire burned in the Nagata district of the city, claiming approximately 7000 houses and 400 lives.

It is thus clear that, in many natural and man-made disasters, civil engineering works are not only the hazard-bearing bodies, but their failure also constitutes further hazards. Especially in earthquake disasters, building collapse is the most significant cause of casualties and financial loss. This mechanism is yet to receive adequate emphasis in the investigation of disasters. Indeed, losses that have been attributed to many so-called natural disasters, such as earthquakes or winds, were actually caused by civil engineering factors rather than the actual natural phenomena. This is the key to developing proper methods for disaster prevention and mitigation.

To clarify the aforementioned mechanism, the concept of *civil engineering disaster* is here proposed. As already noted, civil engineering works including buildings and infrastructure are the carriers of human civilization. However, such developments may also harm civilization by inducing disasters. We define ***a civil engineering disaster*** **as a disaster caused by the failure of a civil engineering work due to technical issues.** The concept of civil engineering disaster does not conflict with the recognition of natural phenomena and man-made events as hazards. Nevertheless, the latter are merely necessary but not sufficient conditions for the occurrence of disasters. Civil engineering works may fail because of their own defects and therefore evolve into hazards that cause disasters. This is the most important mechanism of a civil engineering disaster event.

The concept of a civil engineering disaster has the following two implications. First, all the losses are essentially due to the failure of civil engineering works. Second, civil engineering methods are the primary means of preventing and mitigating such disasters. The

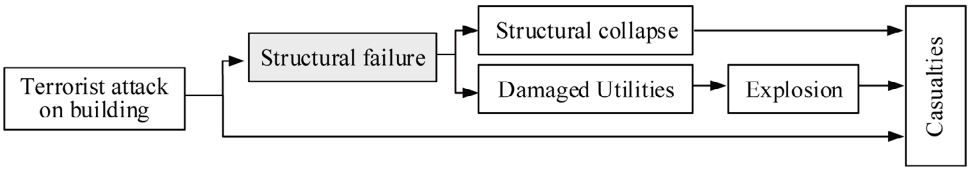


Fig. 2 Evolution of terrorist attack-induced disaster

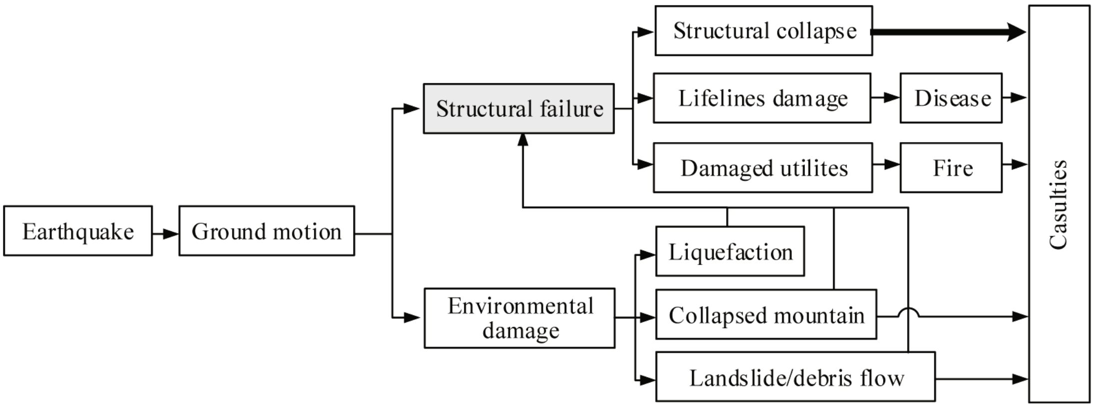


Fig. 3 Evolution of earthquake disaster

first implication has been discussed above. With regard to the second, it is noteworthy that the mitigation of civil engineering disasters connotes the enhancement of the capacity of civil engineering works with the purpose of reducing the likelihood of their transformation into hazards. Considering the case of earthquake disasters as an example, on May 12, 2008, the M_s8.0 Wenchuan earthquake (M_w = 7.9, focal depth = 14 km) hit southwestern China, resulting in 69227 deaths, and 17923 missing persons as at Sep. 25, 2008 (ChinaNews, 2008). The earthquake caused enormous building collapse (Yuan, 2008). A survey of 1005 buildings in urban Dujiangyan concluded that 58% buildings built before 1990 were heavily damaged or even collapsed while this ratio was only 18% for post-1990 buildings (Zhang and Jin, 2008). Two years later, on Feb. 27, 2010, on the other side of the Pacific, a M8.8 earthquake hit central Chile. Although the magnitude of this earthquake was much larger than that of the Wenchuan earthquake, the resulting loss was considerably lower. Only four buildings collapsed and approximately 50 were damaged. The human fatality was 525, most of which was due to the induced tsunami rather than the collapsed buildings. Many factors could have contributed to the significant difference between the consequences of these two disasters. For example, the population density of Chile was only approximately one-seventh of that of Sichuan province. The focal depth of the Chile earthquake was also greater than that of the Wenchuan earthquake. Nevertheless, the most important reason for the different consequences of the two earthquakes was the huge difference between the seismic capacities of the buildings at the respective locations. The Chile experience once again proved that an effective means of mitigating earthquake-induced disasters was the enhancement of the seismic capacity of civil engineering works.

It is, however, noteworthy that some building-related disasters are not necessarily civil engineering disasters. Considering building fires as an example, in some cases, the fires may cause the buildings to collapse, resulting in casualties; but the foremost causes of human and property losses in such events are the extreme heat and smoke, rather than the failure of the buildings (Fig. 4). On Dec. 8, 1994, a severe fire broke out in a theater in Xinjiang, China, killing 325. The investigation of the accident revealed that all 325 deaths were caused by toxic smoke, burns, or trampling. The theater did not collapse. On Dec. 25, 2012, another fire occurred in a shopping mall in Luoyang, China, claiming 309 lives, all through toxic smoke (Ren *et al.*, 2014). Although enhancing the fire resisting capacity of buildings is indeed helpful in mitigating the effects of fire disasters, it is hardly possible to avoid either the breakout of a fire or the collapse of a building under fire by increasing the fire resisting capacity of the building. For the case of the World Trade Centre under the terrorist attack, if a more robust gravity system had been used, the progressive collapse of the tower might have been delayed (FEMA 403, 2002), but can not be eventually avoided. For the same reason, in most cases, to increase the fire resistance of buildings is not the most effective way of mitigating fire disasters. Instead, non-civil engineering measures such as smoke detection, fire alarms, and emergency management are much more beneficial to dealing with building fires, which, it should be noted, do not strictly constitute civil engineering disasters.

2.2 Classification

Civil engineering disasters can be classified as natural hazard-related and man-made hazard-related based on the external causes of the failure of the civil engineering work (Fig. 5). In addition to inducement by earthquakes, as discussed above, civil engineering disasters may be related to diverse other natural hazards such as strong winds, floods, landslides, heavy snow, and freezing weather. For example, electricity supply towers may collapse under strong winds, resulting in financial losses through the disruption of power supplies. In 2008, southern China experienced unusually cold weather and heavy snow, which caused the collapse of many industrial buildings, causing human and financial losses. In contrast, civil engineering disasters related to man-made hazards are usually caused by technical inadequacies and mistakes, general human faults, and hostile actions.

2.3 Causes of structural deficiency

Civil engineering works are designed, constructed, occupied, and maintained by human beings. Consequently, the underlying cause of all civil engineering disasters, irrespective of whether they are related to natural or man-made hazards, is structural deficiency in the civil engineering work, and this can always be attributed to human factors such as lack of knowledge or mistakes. In

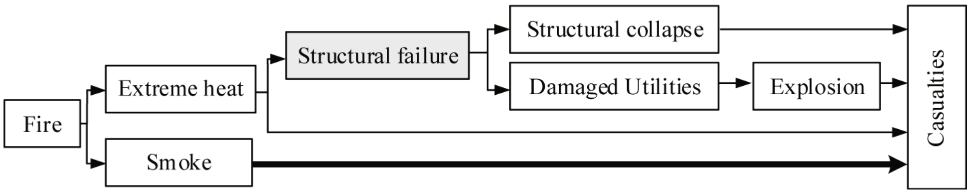


Fig. 4 Evolution of fire disaster

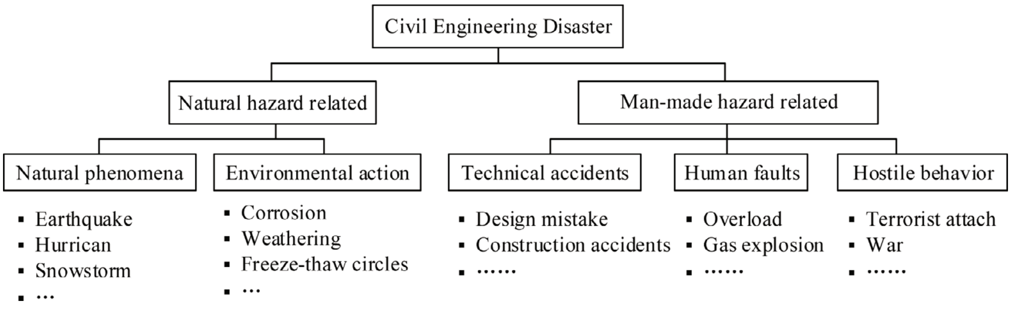


Fig. 5 Classification of civil engineering disasters

this context, the reasons for structural deficiency in civil engineering works can be summarized as follows.

2.3.1 Improper site selection

Sites that are located on active faults, exposed to landslides or debris flows, or vulnerable to non-uniform settlement are a few examples of sites that are improper for civil engineering constructions. It is presently either technically impossible to achieve adequate disaster resistance in buildings and infrastructure on such sites, or the cost of doing so would be unreasonably high. A practical strategy is thus to avoid such improper sites. In the region affected by the aforementioned Wenchuan earthquake, the town of Beichuan was located in an area that is highly vulnerable to landslide and debris flow—a typical example of an improper civil engineering construction site. During the earthquake, 15646 were killed and 1023 went missing from Beichuan alone. This constituted approximately 20% of the total human loss to the disaster. The mountainous town of Beichuan was completely destroyed and buried by not only the quake, but also the landslides, floods, and debris flows that followed (see Fig. 6).

The suitability of a site for construction is changeable. On Dec. 20, 2015, 33 buildings in an industrial park in Shenzhen, China were buried or damaged to different extents by a landslide that affected an area of 380000 m^2, killing 69 people (Fig. 7). Investigations showed that the landslide was not from the original mountain behind the industrial park, but from mountains of constructional debris that had been dumped there beginning in 2014. The deadly debris did not exist when the industrial park was constructed but was created by human behavior, which exposed the site to a landslide hazard.

2.3.2 Improper hazard assessment

Effective mitigation of civil engineering disasters can be achieved by designing the construction for an appropriate hazard level. Owing to the neglecting of potential earthquake hazard in its urban area since its establishment, the city of Tangshan, China was entirely unprepared for the earthquake that struck it in 1976. None of the civil engineering works in the city, including the buildings and infrastructure, was seismically designed and constructed. Most of the buildings thus collapsed during the earthquake and the city was entirely destroyed. Port-au-Prince, the capital city of Haiti, was also unprepared for the 2010 Haiti earthquake, which claimed several tens of thousands of lives. What these two disasters had in common was the failure of a large amount of non-seismically designed civil engineering works, which constituted the primary hazards for the disasters, although the earthquakes received greater attention (Fig. 8).

Even if hazards are taken into consideration in the design of civil engineering works, improper assessment of the hazard levels may lead to the construction of inadequate structures. In Dec. 2005, many industrial buildings in the Shandong province of China collapsed under a once-in-a-century snowfall (Fig. 9). In the Chinese load code for building structures (GB50009, 2001), the standard load of a 50-year reoccurrence snow for the local area is 0.4–0.45 kN/m^2. Between Dec 3 and 17, 2005, the accumulated snow was 80.2 mm thick, which corresponded to a load of 0.8 kN/m^2, a value that is almost double the design value. This was the direct

Fig. 6 Beichuan County after debris flows in September 2009

Fig. 7 Buildings in Shenzhen buried by landslide in December 2015 (Source: Baidu Baike)

cause of the collapse of the steel portal frame factories.

2.3.3 Improper design

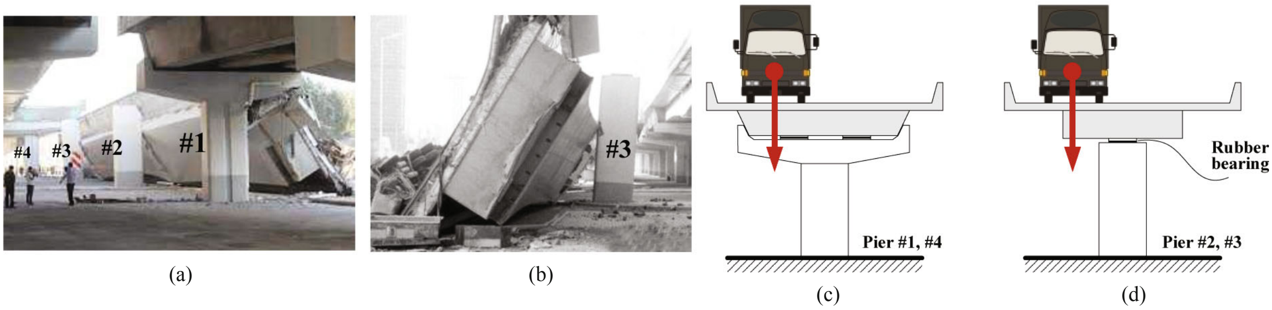
Proper hazard level assignment during the design of a structure requires comprehensive understanding of the hazard. In addition, the appropriate design of a structure for a given hazard level requires sound knowledge of the hazard-bearing body. In 2012, a ramp of the Yangmingtan Bridge in Haerbin, China fell when four heavy trucks were simultaneously driven along the same outside lane. Although the event was officially concluded as a traffic accident caused by overloading of the trucks, the deficiency of the structural design of the ramp should not be overlooked. The fallen segment was a three-span segment supported by four single piers (Figs. 10(a) and (b)), with the two middle piers having caps very different from those at either end of the segment. At both ends of the segment, the bridge deck rested on bracket beams rigidly connected to the top of the piers (Fig. 10(c)). The deck within this segment was simply supported by the two piers through a single rubber bearing located mid-

(a) (b)

Fig. 8 Unprepared cities damaged by earthquakes: (a) Tangshan city and (b) Port-au-Prince after earthquakes

(a) (b)

Fig. 9 Steel structures that failed under heavy snow: (a) industrial buildings covered by snow and (b) collapsed steel frame buildings



(a) (b) (c) (d)

Fig. 10 Design defects of fallen segment of Yangmingtan Bridge (Qu, 2014)

width, with the configuration providing little resistance to the overturning of the deck (Fig. 10(d)). When the four trucks were driven along the same outside lane at the same time, the deck was subjected to a large overturning moment by the eccentric load. The resultant falling of the segment was very likely due to the inadequate overturning resistance of the bridge deck (Qu, 2014).

Design deficiency is also often due to inadequate knowledge or experience in the civil engineering community as a whole. For example, seismic design has gradually evolved over the last century as the civil engineering community gained knowledge from each major earthquake that caused huge losses. After the 1968 Tokachi-oki earthquake in Japan, during which many reinforced concrete (RC) frame structures suffered from brittle failure of their columns (Aoyama, 2010) (Fig. 11), Japanese engineers recognized the importance of transverse reinforcement to achieving ductile yielding of RC members. In the revision of the Japanese seismic provisions in 1971, the use of more densely placed hoops in certain segments of RC columns was stipulated. This has since become standard practice in the design of ductile moment-resisting RC frames, and has been adopted in the seismic codes of many countries. The 1994 Northridge earthquake also revealed the problematic brittle fracture of beam-to-column joints in steel moment-resisting frames, which were previously believed to be very ductile. This finding stimulated continuous efforts in the earthquake engineering community to develop new beam-to-column joints that do not suffer brittle failure (Bruneau *et al*., 2011). The 2008 Wenchuan earthquake in China caused the collapse of many RC moment-resisting frames with a weak-story pattern, including those that were designed with the latest seismic provisions. This drove the Chinese civil engineering community to reconsider the code measures for ensuring a strong column-weak-beam mechanism in RC frames (Ye *et al*., 2008; Ye *et al*., 2010; Wang, 2010). The observed damage to steel space structures during the 2015 Lushan earthquake also indicated possible improvement in the seismic analysis and design of such structures (Dai *et al*., 2013). It should be emphasized that the improvement of structural design is a gradual long-term process, and civil engineering disasters put the latest innovations to real tests, while also providing clues for further design improvements.

2.3.4 Improper construction

Appropriate construction management and the use of construction materials of the proper qualities are essential to effectively realizing a structural design. Unfortunately, civil engineering disasters are often caused by improper construction. On June 27, 2009, a 13-story residential building in Shanghai suddenly collapsed during construction (Fig. 12). An investigation concluded that the collapse was initiated at the foundation piles, which were sheared off by the large difference in soil pressure on either side of the building. The south side of the building foundation was weakened


(a) (b)

Fig. 11 School building in Hachinohe, Japan damaged during 1968 Tokachi-oki earthquake (Aoyama, 2010)


(a) (b)

Fig. 12 Collapsed high-rise apartment building—result of improper construction

by an underground garage under construction, while a large amount of soil was piled up on the north side of the building. The high soil pressure on the foundation on the north side eventually broke the piles, causing the foundation to slide toward the low pressure south side.

Poor construction quality also frequently causes civil engineering disasters. On Jan. 22, 2008, a stone bridge under construction in the Hunan province of China suddenly collapsed, resulting in 64 deaths and 22 injuries (Fig. 13). The 328.45-m-long bridge was supported by a series of stone arches—a structural system that is poor in robustness and highly dependent on the construction quality. An inspection revealed that the material used to construct the main arch was of inadequate quality, and that the construction quality did not satisfy the requirements of the relevant codes.

2.3.5 Improper maintenance and management

After the completion of a civil engineering work, proper occupancy, maintenance, and management are important to avoid a civil engineering disaster. On June 15, 2007, a cable-stayed bridge in the Guangdong province of China was hit by a 2000-ton sand carrier, resulting in the fall of an approximately 200-m-long deck (Fig. 14). Four cars on the bridge fell into the river, nine people went missing, and local transportation was greatly affected. A post-event inspection found no deficiency in the design and construction of the bridge. Mis-operation of the sand carrier was concluded to be the primary cause of the accident.

It should be noted that many civil engineering disasters cannot be attributed to a single cause. For example, the collapse of the steel portal frames under heavy snow shown in Fig. 9 could also be partially attributed to the poor robustness of the structural system and low stiffness of the roofs, which are related to improper structural design. The causes of civil engineering disasters can sometimes be interrelated. Taking the Shenzhen industrial park landslide as an example, although the sliding of the dumped debris was obviously the hazard, it was not as unpredictable as natural events like earthquakes. The cause of the disaster was rather human behavior because, if the risk of the construction debris had been properly assessed and prevention measures taken, the disasters could have been avoided. The disaster was thus due to a combination of improper site selection and improper management after the construction of the industrial park.

Fig. 13 Collapsed bridge over Dixituo River

Fig. 14 Collapsed Jiujiang Bridge under ship impact (Photo by CFP)

Despite the significantly varied potential causes of civil engineering disasters, they can only be prevented or mitigated through civil engineering measures. Good civil engineering practice particularly guarantees the avoidance of the five aforementioned causes of structural deficiency. In other words, civil engineering disasters can be mitigated if the sites are properly selected, the hazards are properly assessed, and the civil engineering works are properly designed, constructed, maintained, and managed. It is noteworthy that, as mentioned earlier, losses due to a building fire cannot be reduced solely by civil engineering measures that strengthen the structures, and fire disasters are therefore not civil engineering disasters.

3 Research on civil engineering disasters and their mitigation

3.1 Goals

A study of civil engineering disasters and their mitigation not only involves civil engineering disciplines, but also significantly draws on many emerging scientific fields. There are nevertheless two main goals of such a study, namely, to understand the scientific and technical mechanism of civil engineering disasters, and to mitigate the occurrences of the disasters in cities and rural areas.

To fully understand the evolution mechanism of a civil engineering disaster, it is essential to quantify the effects of the hazards on the civil engineering work. It is equally important to determine how the civil engineering work is damaged or fails under the action of the hazard. However, these goals can only be achieved by proper numerical simulation of the failure of the civil engineering work.

The ultimate goal of a study on civil engineering disasters and their mitigation is the protection of human life and property. This can only be achieved by comprehensive enhancement of the resistance capacity of civil engineering works to hazards. It must nevertheless be conceded that its full attainment is beyond the ability of natural science and technology. Socioeconomic development, education, regulations, and local customs are all pertinent factors in this regard.

3.2 Important research topics

From a scientific and technological viewpoint, the following issues are essential to accomplishing the ultimate goal of studies on civil engineering disasters.

3.2.1 Characteristics of hazardous actions

Taking earthquakes as an example, the hazardous action is the shaking of the ground. There has been gradual improvement in the understanding of earthquake actions over more than the last 100 years. At the beginning of the 20th century, earthquake actions were considered as being equivalent to the application of horizontal static forces on buildings. This laid the foundation for the seismic design of buildings. It was later recognized that an earthquake action was dependent on the dynamic properties of the buildings. The current use of response spectrum analysis, time history analysis, and nonlinear dynamic analysis has greatly extended the understanding of earthquake actions. Studies on earthquake actions have also progressed rapidly by exploiting the fast growing database on real earthquake ground motion records. Tens of parameters for quantifying earthquake actions have been proposed by researchers worldwide, who have demonstrated the complexity of the problem and contributed to the improved understanding in the earthquake engineering community.

3.2.2 Zonation of hazardous actions and risk analysis

The objective of hazard zonation is the provision of the time and spatial distributions of hazards for engineering design. Although much effort has been made along this line, the task is very challenging. In the case of earthquakes, the zonation of the ground motion parameters is the basis of seismic design and involves many scientific processes and factors related to seismic hazard analysis, ground motion attenuation modeling, and local site effects. Large scatterings and uncertainties still exist in dealing with these issues. Along with the continuous effort to reduce the uncertainties, more efforts are needed to understand the inherent uncertainties of many hazardous actions and risks and to develop robust civil engineering solutions to minimize the influence of such uncertainties.

3.2.3 Response characteristics and damage mechanism of civil engineering works under hazardous actions

There has been an improvement in the understanding of the response characteristics and damage mechanisms of civil engineering works, the behaviors of which range from linear elastic to nonlinear. Many parameters based on force, displacement, energy, or combinations of these have been proposed to quantitatively describe the failure mechanism and dynamic behavior of civil engineering works under hazardous actions. In the process, many physical and numerical models have been developed, with the latter having obvious advantages and showing promise for application to the simulation of the damage of civil engineering works.

3.2.4 Engineering measures and design codes for enhancing hazard resistance capacity of civil engineering works

New technologies and design codes are the most important basis for increasing the hazard resistance capacity of civil engineering works. Differing from scientific research, engineering practice gives consideration to safety, cost, simplicity, effectiveness, and standardization. The provision of effective solutions to civil engineering problems at a reasonable cost is sometimes more important than the scientific quantification of the detailed parameters. In addition, research findings need to be implemented in civil engineering constructions for them to be of any benefit to the community. To this end, design codes and standards are developed for the use of scientific and technological innovations to protect civil engineering works under hazardous actions. However, additional effort is required in the directions of management and regulation, which are beyond the scope of this paper.

4 Conclusions

Among the different types of disasters, civil engineering disasters are the most closely related to human beings and have constituted an important stimulus for civil engineering development. Many scientific and technological topics are relevant to the understanding and mitigation of civil engineering disasters, the concept of which emphasizes the transformation of civil engineering works from hazard-bearing bodies into hazards when they fail. Unlike disasters caused by natural hazards, which often cannot be predicted or controlled, civil engineering disasters can be effectively mitigated based on a thorough understanding of the associated failure mechanisms and by enhancement of the resistance capacity of engineering works.

The two goals of studies on civil engineering disasters are to understand the evolution mechanisms of the failure of the civil engineering works and to mitigate the disasters to protect human communities. The former goal can only be accomplished by accurate reproduction of the failure of the engineering works, while the latter requires comprehensive enhancement of the engineering works.

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