Recent Highway Bridge Collapses in China: Review and Discussion

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Abstract: The data of 302 highway bridge catastrophic collapses occurring in China between 2000 and 2014 due to human causes were collected and statistical analyses were conducted from various viewpoints including accident stages (during construction or service), casualties (death or injury), location, time, life span, bridge type, and primary causes behind the accidents. Six representative collapse cases were expounded on to find out their individual peculiarities. These cases encapsulated serious problems in Chinese highway bridge engineering, including design, construction, maintenance, and management, among others. A concise review of highway bridge collapses due to human causes in China was presented. Some typical abnormal phenomena, such as those concerning entities involved in the Chinese highway bridge engineering industry, were analyzed and highlighted. Suggestions were put forward to urge all related parties to obey rules and laws to reduce and avoid bridge collapse accidents. The lessons from these bridge accidents should be fully studied to further ensure the safety, durability, and economy of bridges. This study provides a comprehensive reference of the current situation regarding highway bridge collapses in China, which is also useful for ringing the alarm bell to alert bridge owners, designers, constructors, supervisors, researchers, and maintenance crews of potential dangers. **DOI: 10.1061/(ASCE)CF.1943-5509.0000884.** *© 2016 American Society of Civil Engineers.*

Author keywords: Highway bridge; Collapse; Human error; Cause analysis; China.

Introduction

In the 21st century, China has achieved unprecedented advancements in bridge engineering. By the end of 2014, the number of highway bridges exceeded 750,000. Although China is known as a country with massive bridge production, there is still a long way to go before it can be considered a country that produces structurally sound bridges. In recent years, analytical and computational methods have become more advanced, construction techniques have become more proficient, and the societies have become more civilized. Despite these advances, many serious bridge collapses have occurred. This reality is ironic when compared to China's tremendous progress in bridge engineering.

Bridge collapse occurs when an entire bridge or a substantial part comes down, at which point the structure loses its ability to perform its function (Wardhana and Hadipriono 2003). Bridge collapses are induced by functional loss of important members, material deterioration, overloading, and external adverse invasive hazards. Harik et al. (1990) conducted a study on bridge failures in the United States between 1951 and 1988, and found that more than half of the failures were due to collisions. Later, Wardhana and Hadipriono (2003) studied over 500 bridge failures in the United States between 1989 and 2000, revealing that nearly 50% of failed bridges are typical steel beam/girder and steel truss bridges. They also proposed that databases of bridge failures should be established or developed. Subsequently, Biezma and Schanack (2007) reviewed the collapses of steel bridges throughout the world, describing some significant historic cases, and found that the majority of steel bridge collapses (65%) can be mainly attributed to force majeure (avalanche, flood, earthquake, etc.). Nowak and Collins (2012) stated that the bridge failure rate in the United States was between 10^{-3} and 10^{-5} annually. Cook et al. (2015) studied the bridge failure rate based on a regional bridge failure database of the United States and found that the failure rate was approximately 1/4,700 annually and could hardly be reduced significantly by modifying the bridge-design specifications or maintenance regulations.

Generally, the causes behind bridge collapses can be categorized into two types: natural hazards and human errors. The natural hazards include earthquake, hurricane, tsunami, avalanche, volcanic explosion, flood, etc. Once these natural hazards occur, hundreds or even thousands of bridges may be damaged, consequent casualties and economic losses are tremendous, and numerous studies (Hsu and Fu 2004; Padgett et al. 2008; Hong et al. 2012; Ko et al. 2014) have focused on this issue. Although advanced design and analytical approaches have been adopted, as well as the use of high-performance materials that enhance structural capacity and reliability, it is impossible to ensure complete safety given such hazards. Furthermore, the dramatically increasing cost tends to be unacceptable to the public. Finding the balance between risk and cost is an important matter for bridge engineers.

Unlike collapses caused by natural hazards, bridge collapses as results of human errors (Duntemann and Subrizi 2000; Chang et al. 2009) are closely related to irregular actions (e.g., carelessness, oversight, dereliction, malpractice, corruption, or laziness) by people. Typical errors include unfair tendering, unreasonable bidding prices, design deficiencies, mistakes in construction and supervision, lack of maintenance or inspections, vehicle overloading, and ship collisions—with government officials, engineering owners,

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Note. This manuscript was submitted on October 9, 2015; approved on January 4, 2016; published online on March 16, 2016. Discussion period open until August 16, 2016; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Performance of Constructed Facilities***, © ASCE, ISSN 0887-3828.

designers, researchers, builders, supervisors, testers, inspectors, maintenance crews, and vehicle/ship drivers being involved. Some bridges with design or construction deficiencies and material deterioration may be damaged by some natural hazards. For such cases, it is difficult to accurately evaluate what extent should be attributed to human causes. Many bridge collapses are not due to just one cause, i.e., many sectors may be responsible for these accidents. Actually, most incidents due to human causes could be avoided. However, similar mistakes, and even the same ones, are repeated again and again (Pearson and Delatte 2006; Ai and Zhang 2013). Consequently, many people are injured and even lose their lives, with the potential of vast economical losses. Inconveniences relating to traffic and adverse influences on the environment make the matter worse. These social impacts make it significant to comprehensively investigate the human causes behind bridge collapses in order to avoid repetitions of such catastrophes.

In this study, the information and data of highway bridges with total collapses (bridges on which all primary members of a span or several spans dropped such that no travel lanes are passable) resulted from human causes in China over the past 15 years (2000–2014) were extensively collected. Then, statistical analyses were comprehensively performed on the collected data. Moreover, several representative failure events were introduced and demonstrated, by which the corresponding main causes were then revealed and highlighted. In the end, some concluding remarks were summarized. Many of the issues and suggestions described in this study are not unique to China, but are applicable to some other Third-World and developing nations.

Overall Statistics on Highway Bridge Collapses in China from 2000 to 2014

Data Collection

Highway bridge collapse occurrences in China spanning from 2000 to 2014 were collected from civil engineering journals, magazines, web sites, and newspapers. Although many incidents of bridge distress and minor partial collapses (with no injuries or lives lost) have not been publicly reported or contained in this study, the information compiled here is sufficient to summarize some lessons and raise awareness, with the goal of drawing beneficial conclusions.

Collapses during the Construction and Service Stages

The overall statistics on bridge collapses caused by human errors are summarized in Table 1. The data of 302 bridge collapses were collected; the numbers of collapses occurring at the construction and service stages were 131 and 171, respectively. One collapse occurred while the completion check test was being conducted and 15 collapses occurred in the course of demolishing operations. The aforementioned 16 cases were considered as construction failures. Compared to the service stage, the construction stage had more casualties. Two causes were included. First, bridge construction in China is a labor-intensive industry; people working on these sites number in the dozens or even hundreds. Most people who work on site are migrant workers with low safety awareness. Once accidents occur, the loss of life can be significant. Second, one construction collapse (Tuojiang Bridge) had particularly high casualties: 66 deaths and 23 injuries. Details of this accident will be introduced later.

Table 1. Overall Statistics of Bridge Collapses

Item	Construction stage	Service stage	Total
Total collapses	131	171	302
Annual collapses	8.7	11.4	20.1
Fatalities	399	165	564
Injuries	694	223	917

Service Time Analyses

For the 171 bridges collapsed at the service stage, the service ages of only 133 bridges were available. Study of these 133 bridges revealed an average service age of 18.7 years, with a standard deviation of 15.7 years. It can be concluded that the service ages varied greatly among different bridges. Some bridges served no more than 5 years. As a comparison, the mean age of collapsed bridges is 54.8 years in the United States (Cook et al. 2015). The bridge numbers and percentages in different life durations are shown in Fig. 1. The service ages of 40, 36, 21, 24, and 10 for bridges fall in the intervals of (0, 10], (10, 20], (20, 30], (30, 40], and (40, 50] years, respectively. In addition, one bridge served 69 years, and the longest-enduring bridge served 101 years. Most bridges served no more than 30 years, which is far shorter than the designed life span of 50 years or 100 years.

Because bridges benefit the public, not only direct economic benefits of the structures shall be considered, but also social benefits. The authorities should take effective and rigorous measures to prolong the service ages of bridges.

Life Casualty Analyses

For bridge collapses, the casualty distribution intervals are summarized in Table 2. It is almost impossible to study all bridge collapses, especially those with no or low casualties. Although these accidents indeed occurred, they were unreported and excluded in this study. Usually, serious accidents with large casualties would attract public attention more easily, and related information could be readily collected. It was indicated that there were 116 (38.4%) collapses with no casualties and 102 (33.8%) collapses with casualties fewer than 5. The above two proportions might be further increased if unreported small accidents were included. In addition, 84 (27.8%) collapses had casualties greater than 5, one of which had an amazingly high number of 89. Five dramatically serious collapses had more than 30 casualties, respectively.

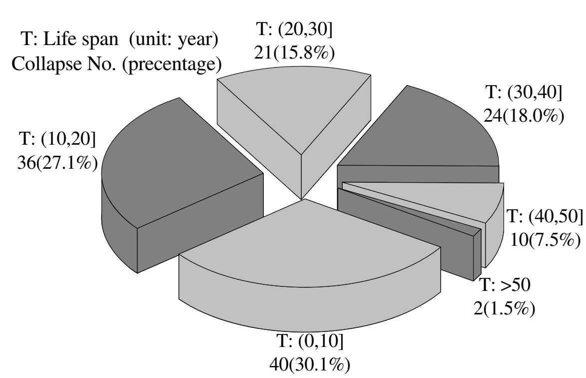

Fig. 1. Life span distribution of collapsed bridges

Table 2. Statistics of Casualty Distribution

Casualty	Construction stage	Service stage	Total
None	16	100	116
(0, 5]	53	49	102
(5, 10]	30	12	42
(10, 15]	11	4	15
(15, 20]	8	2	10
(20, 25]	6	2	8
(25, 30]	3	1	4
(30, 35]	1	0	1
>35	3	1	4

Table 3. Collapses Listed by Bridge Type

Type	Construction stage	Service stage	Total
Beam	73	96	169
Arch	34	47	81
Cable-stayed	6	1	7
Suspension	2	3	5
Unknown	16	24	40

Collapses of Different Bridge Types

Table 3 shows the collapse occurrences of four different bridge types: beam, arch, cable-stayed, and suspension. Forty of the collapsed bridges could not be classified (from public sources); consequently they were classified as unknown. Table 3 shows that beam bridges were the dominant type of collapsed bridges, with 169 (56.0%) occurrences. This phenomenon was closely related with the wide applications of beam bridges. The arch bridge collapses ranked second, representing 81 (26.8%) occurrences. Collapses of cable-stayed bridges and suspension bridges were lower in comparison to the former two types. On one hand, the total percentages of cable-stayed bridges and suspension bridges were relatively lower. On the other hand, the span lengths of cable-stayed bridges and suspension bridges were comparatively longer; they were also more significantly used in highway networks. Consequently, bridges with stricter design, construction, supervision, and management become safer.

Bridge Collapses and Casualties in Each Year

Collapse distributions with respect to time are shown in Fig. 2. From 2000 to 2014, each year experienced bridge collapses. Seven collapses occurred in 2000 and 10 in 2001. In comparison, 29 collapses occurred in 2007 and 2012, respectively, both ranking first in number of collapses during the investigated period. Fig. 2 shows an apparent bias in the number of bridge collapses with respect to time. The following four actualities might contribute to this observation:

- A large number of bridges were built in recent years, resulting in more construction collapses (2012–2014). According to the Ministry of Transport of the People's Republic of China (MOT 2007–2014), from 2007 to 2014, the new highway bridges increased with an average of about 28,000 each year.
- With the rapid development of China's economy, the problem of vehicle overloading has become more and more serious in recent years;
- The conditions of some bridges built in the 1970s and 1980s are getting worse. If the inspection, maintenance, and rehabilitation are inadequate, the deteriorating bridges are prone to fail. In recent years (2009–2014), the collapses at the service stage were much more than those in 2000–2006; and

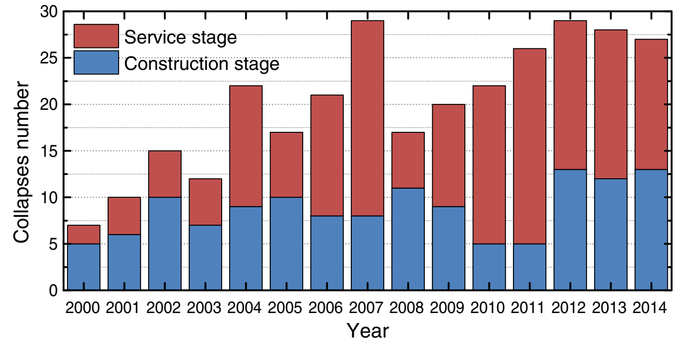

Fig. 2. Bridge collapses in different years

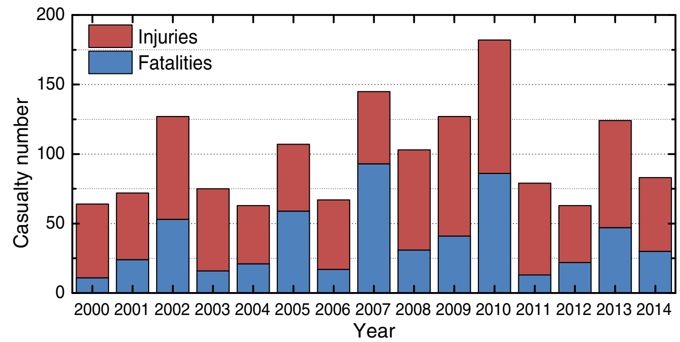

Fig. 3. Human casualties caused by bridge collapses in different years

- In China, the mass media tend to be more and more open. Contrarily, some bridge collapses in early years of the investigated period may not have been publicly reported, and cannot be included.

The casualties in each year are shown in Fig. 3. Although collapse occurrences did not peak in 2010, the maximum casualties of 182 occurred in this year as a result of several high-casualty collapses. The chart also reveals that in recent years casualties have not increased along with the increase of collapse occurrences, and the average casualty rate of each collapse during the most recent four years has dropped. This could be ascribed to the advancements in technology, strictness in management, and improvements in safety awareness.

Bridge Collapses in Different Regions

The statistics on the regions with most collapses and the five regions with the fewest collapses are listed in Table 4. The three provinces with the most collapses were Zhejiang, Jiangsu, and Guangdong, all of which have well-developed economies. They had more bridges in service and under construction, and their information was more transparent, making their statistics more complete. Regions with fewer collapses were either highly developed areas (Beijing, Tianjin, etc.) because of better construction technology and advanced management, or underdeveloped areas (Ningxia, Qinghai, Xizang, etc.) because there were fewer bridges and some information about the bridge collapses might not be open to the public.

Typical Bridge Collapses

The data and information regarding some representative bridge collapses that occurred during the construction and service stages are

Table 4. Collapses Listed by Region

Region	Construction stage	Service stage	Total
Zhejiang	17	18	35
Jiangsu	3	24	27
Guangdong	13	12	25
Beijing	1	3	4
Tianjin	1	3	4
Xizang	1	1	2
Ningxia	0	1	1
Qinghai	1	0	1

listed in Tables 5 and 6, respectively. Detailed causes relating to each collapse (e.g., details of deficiencies in design and construction, steel bars or concrete corrosion for lack of maintenance, overloading) might not be readily apparent and so it was difficult to make an explicit summary or classification. Hence, only the most principal causes were considered herein and the related detailed causes could be discussed later for specific cases. The two tables reveal several conclusions, as follows:

- All collapses during the construction stage were blamed on construction mistakes (the construction teams), whereas only a few could be blamed on the supervision teams, designers, engineering owners, or the authorities;
- Some bridge collapses (e.g., Shenzhen Viaduct, Tonganwan Bridge) during the construction stage were directly related to the falsework or scaffold. The falsework/scaffold is a temporary facility and if not enough attention is received, an accident could potentially occur during the system transformation (removing the falsework/scaffold);
- Many collapsed bridges during the construction stage were not long-span cases; the construction techniques were not complicated and the construction difficulties were not high. The collapse causes could be attributed to the inadequacy of numerical and experimental analyses and the poor construction management;
- The principal causes of collapses at the service stage included design and construction deficiencies, performance degradation of materials, accumulated damages by earthquake and other dynamic actions, lack of appropriate and sufficient maintenance, overloading and ultrahigh of trucks, ship collisions, and foundation scours. These causes were comparatively complicated when compared to those at the construction stage;
- Almost half of the collapses during the service stage were (partially) attributed to overloading. A number of heavy trucks were overloaded by 200% and even 300% and kept running on highways and bridges. Fines were used to restrict this phenomenon. However, it was proved to be insufficient for effectively solving this intractable problem; and
- Most collapses during the service stage could not be simply attributed to design and construction deficiencies, poor maintenance, accidental overloading, ship collisions, or another single reason, which means the involved entities need to cooperate positively to ensure the bridges are serviced in good condition.

In different countries/regions, the percentages of bridge-collapse causes may be distinct, which are closely related to national conditions. For instance, in the United States, with respect to China, the degree of industrialization is higher; the workers are more experienced; the construction time duration is longer; the construction quality is comparatively higher; and fewer collapses occurred during the construction stage. In addition, vehicle overloading is not as serious as in China, and the maintenance and inspection conditions are better, so the service ages of bridges are relatively longer. According to the study made by Wardhana and Hadipriono (2003), the leading causes of bridge failures in the United States were flood/scour and collision.

In the following section, six typical collapse cases will be expounded for their individual peculiarities, and their detailed causes

Table 5. Overview of Bridge Collapses during the Construction Stage

Date	Name	Place	Structure type	Fatalities/injuries	Main causes
November 27, 2000	Shenzhen Viaduct	Shenzhen, Guangdong	Reinforced concrete beam	0/33	Construction mistakes and falsework design deficiencies
August 15, 2002	Wangou	Nanyang, Henan	Arch bridge	10/7	Construction mistakes
November 5, 2005	Pearl	Zhunyi, Guizhou	Reinforced concrete arch	16/3	Construction mistakes, low-quality facilities
December 14, 2005	Xiaojianshan	Guiyang, Guizhou	Reinforced concrete beam	8/12	Construction scheme deficiencies, low capacity of falsework
August 29, 2006	Tonganwan	Xiamen, Fujian	Five-span continuous arch	0/17	Construction scheme deficiencies, unqualified full scaffold
August 13, 2007	Tuojiang	Fenghuang, Hunan	Masonry arch bridge	66/23	Construction mistakes, supervision malpractice, owner interference
November 26, 2010	Viaduct	Nangjing, Jiangsu	Curved steel-box girder	7/3	Construction mistakes, overturning of steel box girder
October 12, 2013	Fengdu Yangtze 2nd	Chongqing	Cable-stayed bridge	11/2	Construction mistakes, steel cofferdam was broken by crane arm
May 3, 2014	Gaozhou	Maoming, Guangdong	Stone arch bridge	11/16	Construction mistakes, supervision malpractice
November 19, 2014	Jinshan	Enshi, Hubei	Extradosed cable-stayed bridge	1/10	Construction mistakes, supervision malpractice
December 9, 2006	Shunyi	Beijing	Suspension bridge	0/3	Low quality of construction, design deficiency
March 11, 2006	Tongyang	Yangzhou, Jiangsu	Reinforced concrete beam	4/5	Demolition risk
December 9, 2008	Xiaozhuang	Kunming, Yunnan	Reinforced concrete beam	2/4	Construction mistakes, supervision malpractice
May 17, 2009	Hongqilu	Zhuzhou, Hunan	Prestressed concrete beam	9/16	Construction mistakes, low quality of management
July 2, 2012	Xingfulu	Hangzhou, Zhejiang	Continuous beam	1/3	Crane cable broke

Table 6. Overview of Bridge Collapses during the Service Stage

Year opened	Name	Place	Date	Structure type	Fatalities/ injuries	Main causes
1990	Xiaonanmen	Yibin, Sichuan	November 7, 2001	Concrete arch bridge	3/3	Hangers erosion due to poor inspection and maintains
1977	Tiantaizhuang	Panjin, Liaoning	June 10, 2004	Beam bridge	0/0	Overload, poor maintenance
1988	Jiujiang	Jiujiang, Guangdong	June 15, 2007	Cable-stayed bridge	9/2	Ship collision
1980s	Dumu Reservoir	Qujing, Yunnan	January 13, 2008	Continuous beam bridge	3/1	Poor maintenance
1973	West	Yichun, Heilongjiang	June 29, 2009	Cross curved arch bridge	4/4	Overload and scour
2002	Highway ramp	Shanxi	July 15, 2009	Reinforced concrete beam	6/4	Overload and resonant oscillation
1996	Gongguan	Wuyishan, Fujian	July 14, 2011	Steel-frame arch bridge	1/22	Some hangers broken due to erosion and bad maintains
2011	Yangmingtan	Harbin, Heilongjiang	August 24, 2012	Continuous beam bridge	3/5	Ramp bridge overturn induced by serious overload of four trucks, design deficiencies, poor management
2011	Yichang	Sanmenxia, Henan	February 1, 2013	Continuous beam bridge	10/11	A truck of fireworks exploded, not terrorist attack
2008	Jingong	Guiyang, Guizhou	May 23, 2013	Beam bridge	0/1	The central pier was collided to be broken by a tank truck
2000	Tongmai	Linzhi, Tibet	August 2, 2013	Suspension bridge	4/0	Overload and anchor failed

will be revealed. The first event occurred on a continuous arch bridge during the construction stage, which was very close to completion. The second event occurred during the process of a completion test on a suspension bridge. The third case was the collapse of a beam bridge after the collision of a sand carrier on the pier. The fourth event was the overturning of a beam bridge that lasted no longer than three years as a result of vehicle overloading. The fifth catastrophe was the complete collapse of a serving arch bridge due to countless errors. The last event was a case of unexpected collapse of a viaduct in the course of a demolition operation. These cases were the height of serious problems in Chinese bridge construction industry. Each collapse had various causes, with one or two causes dominating.

Tuojiang Bridge, Hunan (Xu et al. 2007; Ai and Zhang 2013)

Tuojiang Bridge is a six-span ($34.25 + 4 \times 65 + 34.25 = 328.5$ m) stone arch bridge with a width of 13 m. It was scheduled by government officials to be opened to the public at the end of August 2007, to salute the 50th anniversary of the Xiangxi Autonomous Prefecture. However, this bridge catastrophically collapsed (Fig. 4) on August 13, 2007, resulting in 66 fatalities and 23 injuries. Regarding maximum casualties, it was the most serious bridge catastrophe in China during the past 15 years. The direct cause can be explained as follows. The main arch ribs were built with inferior masonry materials. The superstructure's construction procedure was unreasonable: templates were removed too early to enable the arch with enough integrity and strength. The spandrel arch collapsed because the concrete on the arch foot reached its ultimate strength, and the whole bridge collapsed rapidly due to a continuous arch effect. According to the official report on this catastrophe, the mistakes and responsibilities of each sector were summarized as follows:

- Engineering owner: Indications of unfair tendering were found in this project. They gave orders beyond their authority and prevented the supervision unit from checking up the construction. They blindly urged the construction unit to shorten the construction period;
- Designers and geology explorers: The geological survey was illegally subcontracted to a private individual. The depth of the geological survey was not thorough enough and failed to find the karst cave. The design scheme was not clearly expressed to engineers and workers on site;

Fig. 4. Collapse scene of Tuojiang Bridge (image courtesy of Long Xiao)

- Construction company: The construction company seriously violated the construction regulations of bridge engineering. The masonry of the arches was extremely low quality. They changed the construction scheme of the main arches without any authority or permission. The superstructure's construction procedure was unreasonable; the templates were removed too early (19 days, although the standard curing period is 28 days). The supervision unit was not informed of the changes made by the construction company. The falsework had sunk about 10 cm before the whole bridge collapsed, which did not draw enough attention. Construction was conducted in extremely dangerous conditions; and
- Supervision: The supervision engineers failed to prevent the construction unit from changing the construction scheme of

the arch ribs and were willfully blind to the quality problems during construction. The completion acceptance was signed without testing the strength of the arch.

Recently, the numbers of design, construction, and supervision units in China have been far more than the market demands. Competition for expensive projects like Tuojiang Bridge could be intensely fierce. Regarding the economic benefits, ethical issues might exist in every aspect. Apart from the ethical aspects, the collapse of this bridge could be traced back to the following technical factors:

- Selection of bridge type should take into consideration the geological conditions of the bridge site. A stone arch bridge with large self weight has higher requirements for geological conditions and might be not the best scheme for this case;
- Tuojiang Bridge failed to install braking piers, which are indispensable for arch bridges with multiple spans. Once a span is collapsed, braking piers could support the thrusts of arches, and the security of other spans could be consequently ensured; and
- Numerical analyses and construction control during the construction stage should be improved and strengthened.

As a traditional bridge type, the stone arch bridge remains competitive in China for its aesthetic and economic benefits. With the development of analytical theories and construction technologies, the stone arch bridge will provide increasing benefits.

Shunyi Bridge, Beijing (Xu and Ma 2007)

Shunyi Bridge in Beijing is a suspension structure with a span length of 120 m. It completely collapsed on December 10, 2006, during the static tests for completion acceptance. Ten trucks with total loads of about 100 t dropped off with a fallen girder, and three people were injured. From the collapse scene, it could be seen that the concrete in the south anchorage zone cracked, and the main cable was pulled out. In addition, the south pylon was bent and twisted. A worker recollected that there had been a crack on the south anchorage, which had been artificially covered by a layer of cement prior to the completion test. As a result, the main cable could not be safely anchored, and collapse occurred.

According to the design scheme, the design load was almost three times that of the testing load. Normally, when the overloading factor attains 1.2 or even 1.5, the structure should not completely fail. Furthermore, the test load could be regarded as static, and the dynamic impact was almost negligible. Hereby, it could be speculated that the ultimate bearing capacity could not attain one third of the design target. It is unclear whether the designers, builders, supervisors, or testers were responsible for the collapse. The main technical causes and the responsible person(s) have not been publicly revealed. Integrity and responsibility of all entities are key supports to bridge quality. To avoid bridge collapse, engineers should actively analyze and examine the primary causes during bridge construction and maintenance. Construction projects should be strictly examined and supervised. Based on the comprehensive investigations of bridge collapses, the technical reports should be opened to the public to improve the level of bridge design, construction, and management, and to further to avoid repetitions of similar disasters.

Jiujiang Bridge, Guangdong (Liu 2009; Ai and Zhang 2013)

Jiujiang Bridge was completed in 1988, with a full length of 1,370 m. On June 15, 2007, a sand carrier about 70 m long and weighing 2,000 t, deviated from its normal navigational channel and collided with the bridge on its pier. Three piers and 200-m-long girders collapsed. Nine lives (seven of whom were drivers or conductors on the carrier) were lost, and two people were injured. The downfallen portion (4×50 m) was a continuous girder bridge, adjacent to the main bridge (a single pylon cable-stayed bridge, the span arrangement was $160 + 160$ m). Piers of this bridge were highly flexible without enough anticollision ability. All three piers collapsed when only one was hit, which was likely caused by the unbalanced thrust that occurred when one side of the girder fell down. Another possible cause was that under the scouring actions of flowing water, the buried depth of the foundation was largely reduced, and the piers' ability to withstand collision was then weakened. The sand carrier and the service management department were judged to be responsible for this collapse.

There were some other bridge collapses due to ship collisions. In 1980, the Sunshine Skyway Bridge over Tampa Bay, Florida, was struck by a marine vessel, resulting in 35 fatalities (Wuttrich et al. 2001). In most cases, the piers or pylons were hit, and in other cases, the decks were hit by ships. Another case occurred on January 27, 2012, in Kentucky. There, a large span steel bridge deck was hit by a large cargo ship transporting a space rocket (Christina 2012). The incident occurred at dusk with good visibility. Thus, preventive management is as important as improving a bridge's ability to withstand ship collision.

With the increase of new bridge projects and waterway traffic demands, the rationality of existing channels needs to be reevaluated. Line selections of new bridge projects should not diminish the navigation capacity of existing channels. Traffic flows of important channels crossed by bridges should be under constant supervision. Warning signals should be installed on piers in case of poor visibility. It is obvious that the Jiujiang Bridge failed to achieve this essential requirement.

Yangmingtan Bridge, Heilongjiang (Luan 2014)

Yangmingtan Bridge was opened to the public on November 6, 2011, and its full length and width were 6,464 m (main span: self-anchored suspension bridge, 248 m in length) and 41.5 m, respectively. Under the static actions of four overloaded trucks, one span of the approach bridge (continuous beam bridge) was overturned (Fig. 5) on August 24, 2012, resulting in three fatalities and five injuries. The direct cause can be explained as follows: Four overloaded trucks stopped on the right side of a 122-m-long beam, all at the same time; the excessive load induced the composite beam to overturn. The official report attributed the collapse to two aspects: The overloaded truck drivers definitely should be responsible for the accident, and the service management department should

Fig. 5. Collapse scene of Yangmingtan Bridge (image courtesy of Xiaojiang Zhang)

also be criticized and penalized for their nonfeasance on controlling the traffic flow on bridge.

In addition, some experts doubted the rationality of the bridge design. Bridges with single column piers have natural limitations on their ability to resist overturning. The designers regarded the bearings as being completely rigid in their design calculations, which proved to be a dangerous method of evaluating the bridge's ability to resist overturning. The failure mode of overturning was not considered in the design.

Overloading is a difficult problem to prohibit, which has already caused many bridge collapses or weaknesses accumulated in bridges. The vehicle load specified by China's design code (MOT 2004) is 55 t. However, countless vehicles weighing more than 100 t are running on bridges. The overloading phenomenon in China is trapped in a vicious cycle: overloading vehicles in the pursuit of profit, spending more money to pay for fines or bribes, then continuing to overload to make up for any loss. The question then is why so many vehicles overload regardless of the punishment. The main reason is poor freight because of market competition. Overloading could save transportation expenses, but the fines increase the cost, which further results in more overloading. Nowadays, vehicle overloading is one of the most critical problems to be solved. If overloading vehicles are not well controlled, no matter how excellently the bridges are designed and built, their safety cannot be effectively ensured.

Caihong Bridge, Chongqing (Xu et al. 2007; Ai and Zhang 2013)

Caihong Bridge is a concrete-filled steel tubular arch bridge, with a span length of 140 m and width of 6 m. It was opened to the public in 1995 and collapsed on January 4, 1999, resulting in 40 fatalities. Although it did not collapse between 2000 and 2014, it is introduced here for its striking social impact. Numerous human errors contributed to this full collapse. At the moment of failure, about 30 citizens were on the bridge, and a troop of policemen and soldiers (fewer than 40) were crossing the bridge.

Prior to the collapse, there were some indications of the latent danger. Four examples are offered:

- Cracking sounds had been heard on the suspenders during construction. The chief designer claimed the sounds were results of stress adjustments, and considered them to be normal phenomena. Subsequently, the construction was carried on despite problems.
- A retired welder proficient in his craft doubted the welding method of steel pipe, though his warnings were ignored.
- Cracking sounds had been heard on the bridge during the Dragon Boat Festival in 1996. Later, the authority explained that the sounds had been made by a loosened board on the deck.
- A pupil noticed the cracks on the bridge (in 1998) and wrote in his composition, "there are cracks on the iron bars [in fact, he referred to the hangers of the bridge], it seems so dangerous that the bridge may collapse anytime." The pupil was definitely not an expert, but even he could notice the danger of collapse.

The local construction committee submitted a report to the county government, intending to halt the service of this bridge. However, the report was ignored, and Caihong Bridge fully collapsed seven days later. The mistakes and responsibilities of each sector officially reported are summarized as follows.

Indications of illegal tendering were found in this project. Phenomena of corruption and dereliction of duty existed in the local authorities. This bridge was designed by a retired engineer and several college teachers instead of a qualified design company. Suspenders, welding joints, and even concrete-filled steel tubes of the main arch were of poor construction quality. The project did not have a supervision unit and the bridge was opened to the public without a completion acceptance test. Nearly 20 people were sentenced and imprisoned for corruption and negligence of duties in this case.

The phenomena of corruption and negligence of duty are definitely not unique to China. According to ASCE, corruption accounts for an estimated \$340 billion in worldwide construction costs each year. The Institution of Civil Engineers (United Kingdom) estimates that the corruption affects 5% of the consultancy world (Sohail and Cavill 2008). Such cases are more common in developing countries (Maarten and William 2009). Sometimes, the most serious problem in bridge construction may not be ascribed to technical deficiency but inadequacy of the industry system. The authorities or engineering owners should not be the chiefs of projects. Instead, they should provide services to other entities involved in the bridge construction (design, construction units, etc.). All entities involved in the bridge lifecycle (design, construction, management, and maintenance, etc.) should be familiar with the knowledge of bridge engineering, which is really hard to actualize in remote regions.

Hongqi Road Viaduct, Hunan

Hongqi Road Viaduct was a simply supported reinforced concrete beam bridge with a total length of 2,920 m and width of 16 m (four lanes). It was a landmark building in Zhuzhou City, Hunan Province, with a design service life of 50 years. It was opened to the public in 1995, but in 2009 it was decided to schedule it for demolition by blasting on May 20. The blasting test was conducted on May 15, 2009; however, a portion of about 160 m long collapsed abruptly on May 17, 2009, resulting in 9 fatalities and 16 injuries. In addition, 24 cars, minivans, and/or buses were damaged. Three government officials were dismissed, and nine individuals (mainly the demolition company members) were arrested and imprisoned in this case. The main causes of the failure cannot be found in public reference. The experts and public proposed the following five questions, which remain unanswered:

- Should the viaduct be demolished after such a short time (<15 years)? The media revealed that the government officials and the citizens had distinct opinions on this issue, and most citizens thought that this viaduct should not be demolished;
- The demolition company was a unit without qualification for blasting demolition work. It is unclear how they could defeat other qualified companies to be awarded the job;
- During the period from the blasting test to the complete demolition, the demolition company drilled holes on piers and stuck explosives inside. It is unclear why vehicles and pedestrians were still permitted to pass under the viaduct afterward;
- Prior to the catastrophic accident, three piers were manually or mechanically demolished. The weight of steel bars in the demolished piers was estimated to be just 50% of the design value. This provides at least an impression of cheating on materials; and
- Was the demolition scheme fully verified by analysis and calculation?

Concluding Remarks

An overview of catastrophic highway bridge collapses caused by human mistakes in China (2000–2014) was presented in this study. Significant lessons were learned from these collapses, relating to design, construction, supervision, and maintenance practices, etc. The following list summarizes the primary observations and conclusions that were drawn:

- The data of 302 bridge collapses were collected and statistically analyzed, of which 43% occurred at the construction stage and 57% appeared at the service stage. In these bridge collapses, the total fatalities and injuries were 564 and 917, respectively. For the bridges that failed at the service stage, the average service age was about 18.7 years, which was far shorter than the design life of 50 or 100 years;
- Most collapsed bridges were beam bridges, which accounted for about 56% of all occurrences. Arch bridge collapses represented about 26.8% of occurrences. Cable-stayed bridges and suspension bridges with longer span lengths and prior social impacts received more attention in design, construction, supervision, and management. Therefore, the percentages of occurrences of these two types were relatively lower;
- Six typical collapse cases clearly revealed both technical and ethical problems in China's bridge-engineering industry. The flaws include inadvisable management of the engineering owner, design deficiency, poor construction practice, dereliction of supervision, vehicle overloading, vessel collision, and lack of maintenance and inspection, among others. The experiences and lessons from bridge collapses provide useful references for current and future bridge engineering, especially for some Third-World and developing nations; and
- In the bridge-engineering industry there must be laws/regulations to follow, the laws must be observed and strictly enforced, and those who break the laws must be prosecuted. Only by raising awareness, perfecting institution, strengthening supervision, urging entities perform their duties, and ensuring enough investments, can accidents be greatly reduced.

Acknowledgments

The research is jointly supported by the National Program on Key Basic Research Project (973 Program, 2015CB057705) and National Science Foundation of China (51478087), both of which are gratefully acknowledged.

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