

# Analysis on Methods of Guaranteeing the Safety of Civil Structures in Traffic Systems during Long Service Lives

Qian Yongjiu<sup>1</sup>, Du Yanliang<sup>2</sup>

1. Southwest Jiaotong University, Chengdu 610031, China

2. Shijiazhuang Tiedao University, Shijiazhuang 050043, China

**Abstract:** China has built the largest traffic infrastructure in the world. Owing to many factors, the security of major structures is becoming extremely challenging. This paper analyzes the current development of China's transportation infrastructure, reviews the research progress of the related fields at home and abroad, discusses methods to guarantee the safety of the major civil structures during long service lives, and proposes the implementation objectives of a safety plan and key issues to be resolved.

**Keywords:** civil structure; long life; safety; evaluation; management

## 1 Introduction

Transportation infrastructures such as roads, railways, bridges, tunnels, subways, and airports are important components of the social transportation system; additionally, they are large fixed assets of the society with basic attributes of social public welfare, economical precursor, network economy, economy of scale, and military strategy. To support the sustained development of economic construction, guarantee the order and safety of people's life, assist the national security and social stability, it is of strategic significance to ensure the service safety and prolong the service life as much as possible of transportation infrastructures and major structures to adequately exert their fundamentality, pioneering ability, and service ability.

After years of development, the construction of national transportation infrastructures has achieved remarkable heights. Generally, the construction of transportation infrastructures in China shows the characteristics of late starting, fast development, and great intensity compared with that of other industrialized countries. However, owing to factors such as the natural

deterioration of structures of the transportation infrastructure, severe service conditions, and insufficient maintenance and repair, some structures have experienced the insufficiency of security, reduction of durability, and vulnerability of usability far earlier than expected, thereby resulting in the actual service life far shorter than the expected years of usage. As time progresses, the aging phenomenon of a large number of engineering structures of China has become more prominent, and the designed service life of some major structures is depleting. The method to scientifically decide the ascription of those nearly retired structures or reasonably use them will become a major problem for China. Meanwhile, the fast developing speed and great intensity in constructing the structures will undoubtedly reflect the maintenance and consolidation of the structures, thereby causing great pressures to their maintenance and repair, pressures of traffic and transportation, and of social life.

In the coming years, China will systemically solve the common fundamental theories and methodological problems in the realm of long-period safety of civil transportation structures using technological innovation, system of organization, and mech-

**Received date:** November 17, 2017; **Revised date:** November 22, 2017

**Corresponding author:** Qian Yongjiu, Southwest Jiaotong University, Professor. Major research fields include assessment and diagnosis of existing engineering structures, reinforcement theory, and design theory of bridge structure. E-mail: yjqian@sina.com

**Funding program:** CAE Advisory Project "Strategic Studies on Safety of Major Structures of Transportation Infrastructure" (2015-XZ-28)

**Chinese version:** Strategic Study of CAE 2017, 19 (6): 006–011

**Cited item:** Qian Yongjiu et al. Analysis on Methods of Guaranteeing the Safety of Civil Structures in Traffic Systems during Long Service Lives. *Strategic Study of CAE*, <https://doi.org/10.15302/J-SSCAE-2017.06.002>

anism; promote laws and norms with respect to design, construction, management, operation, and maintenance etc.; systemically develop research in the areas of new material, new technology, new structure, new equipment, and new constructing method; raise new industrial systems of the construction of transportation infrastructures and management-maintenance work that fit China; fully exert the efficiency of major transportation infrastructures; serve the national economic construction; enhance China's international influence and competitive ability in the related fields.

## 2 Analysis of current status

### 2.1 Analysis of current status of national transportation infrastructure

At the end of 2015, China's "five vertical and five transverse" large comprehensive transporting channels had been linked through. The scale of the already constructed major transportation infrastructure is listed below: The total mileage of the national highway was  $4.6 \times 10^6$  km, in which the mileage of the expressway was  $1.3 \times 10^5$  km; the mileage of the nationally operated railway was  $1.24 \times 10^5$  km, in which the mileage of the operated high-speed railway had exceeded  $2.2 \times 10^4$  km; the length of the national urban roads was  $3.65 \times 10^5$  km, the pavement area was  $7.18 \times 10^9$  m<sup>2</sup>, and the urban pavement area per capita was 15.60 m<sup>2</sup>; the length of county-town roads was  $1.34 \times 10^5$  km, the pavement area was  $2.49 \times 10^9$  m<sup>2</sup>, and the urban pavement area per capita was 15.98 m<sup>2</sup>; the total number of highway bridges was  $7.79 \times 10^5$ , and China had already built a group of super bridge constructions that had significant international influence; the total number of railway bridges had reached  $6.5 \times 10^4$ , where middle-long bridges, viaducts, and large-span bridges of high-speed railways were multitudinous, and the proportion of these bridges to the route exceeded 50%; the number of operated highway tunnels was 11 359, of which the total length was 9605.6 km (including 562 super-long tunnels with a length of 2500.69 km); the number of operated railway tunnels was 11 074, of which the total length was 8938.78 km; the rail transit system was constructed in 24 cities, of which the whole route length was 3069 km, and the number of stations was 2008 [1].

In general, China has built a transportation infrastructure whose scale was at the world's front rank. However, owing to a variety of factors, the problem in guarantying the safety of major structures is confronted with increasing severe challenges.

Significant discrepancies and uncertainties exist between the designed service life and actual service life of major structures of transportation infrastructures of China. Taking bridge engineering for example, the designed service life of a grand bridge, large bridge, and major middle bridge is 100 years (special bridges can be designed as 120 years); the designed service life of a middle bridge and a major small bridge is 50 years; the designed

service life of a small bridge and culvert is 30 years. During the serving years, however, the actual service life is shorter than the designed service life owing to a variety of factors that threaten the normal and safe usage of the bridges. Additionally, affected by the limitations of national conditions and economic circumstances in different periods, large discrepancies exist regarding the construction standard and quality of many bridges built after the establishment of new China, of which the general tendency is that the actual load grade is still increasing but the original bridges cannot adapt well to the current transporting requirement.

As time progresses, large numbers of major structures of the transportation infrastructure will successively reach their designed serving life; thus, a significant amount of fixed asset with "problems" will remain. It is economically unfeasible to completely replace these structures, in which some of the methods are technologically difficult to achieve. For instance, even if the service life of some important urban subway systems and major bridges and tunnels have exceeded their designed service life, these structures are difficult to be replaced or reconstructed, and will still serve for a relatively long period of time and exert huge social benefits and economic welfare, provided that their safety of use is ensured. Thus, the method to guarantee the reliability and safety of these aging structures (including structures that have arrived or will soon arrive to their designed service life) in terms of theory, technology, specification, policy, and management system is a serious subject that we are facing.

Long-period capability degradation, material aging, and material deterioration significantly affect the safety of major structures of China's transportation infrastructure. Taking bridges and tunnels for example, according to the statistics, the number of dangerous bridges in the national highway network indicates an increasing tendency year after year. In 2014, the total number of dangerous bridges was 79 600, which occupied 10.5% of the number of total highway bridges. According to the statistics of the 2009 autumn inspection by the Ministry of Railways, railway bridges that attained a deterioration grade of A class (grievous) or above constituted 24.8% of the total railway bridges. Among more than 5200 operated railway tunnels of China, more than 2000 tunnels exhibited detriments such as water leakage, serious lining cracking, ballast damage, etc.; the length of the detrimental tunnels were approximately 10% of the total tunnel length [1]. Erosive substances in the groundwater around the tunnels, and exhaust gas released by vehicles will lead to the corrosion of the adopted materials of tunnel structures such as concrete or reinforced concrete. Chemical and physical destructions and multiple forms of electrochemical corrosions such as chloride ion erosion, reinforcement corrosion induced by concrete carbonization, sulfate attack, alkali aggregate reaction, and freeze-thaw and salt crystallization damages cause severe cracks and damages to China's railway tunnels.

Failing to reach the standard of design and construction

quality is the major hidden danger affecting the long-life safety of China's current transportation infrastructures, and is one of the primary causes of grave accidents. It is a long-term as well as arduous task to scientifically diagnose, evaluate, and execute such hidden dangers. Since China's reform and opening, the extraordinary development of the national infrastructure construction and the lack of the corresponding technological cultivation of constructors have resulted in deficiencies such as a short designing period and the incompetency of quality-supervising measures, short period of construction and the insufficiency of exerting supervising function, varied quality of materials and nonrigorous examining measures, and different degrees of defects in constructed structures. Taking tunnels for example, lining cracks and damages resulting from nonstandard construction constitute 80% of the total lining cracks of the tunnel structure, and cracks resulting from poor quality of material or irrationality of mixing ratio constitute 15%, and those by inappropriate design constitute approximately 5% [1].

Overload, and the lack of daily repairing and management are key factors affecting the damage state and actual service life of major structures. In recent years, with the substantial growth in transporting volume and the increasing trend in the size and weight of vehicles, the phenomena of overload and over-limit transportation becomes severely common; the transit load far exceeds the designed load and bearing capacity of structures; long periods of structural overload operation leads to cracks and damages, which severely curtails the service life and threatens the safe usage of the structures. According to statistics, the annual economic loss of overload and over-limit transportation of vehicles on China's highway is approximately 30 billion yuan; the number of annual fatalities from traffic accidents induced by overload is 100 000 in China. Taking Sichuan for example, 90% of 400 000 freight cars have over-limit or overloading problems, in which the overloading degree is 50% to 200% of the approved tonnage, and that of some freight cars even reaches 300% of the approved tonnage or above [1].

Natural disasters and man-made damages are the primary threats of the safe usage of the major structures. China has a vast territory, of which the geographical environment and climatic condition are complex; the types of natural disasters are varied and their occurrences are frequent. Many built major structures of the transportation infrastructure suffer great loss from natural disasters such as typhoon, earthquake, debris flow, and landslide. Meanwhile, structural safety affected by man-made damages such as explosion, crashing, and conflagration are not negligible.

Currently, China is still in the fast-developing period of transportation infrastructure construction; the safety guarantee of the transportation infrastructure shows new content, new form, and new characteristics. Thus, to assure the structural safety during operation, a rational evaluation and prediction mechanism of safety risks must be established to improve the structural risk resistance.

## 2.2 Relevant research and current development in other countries

In the United States, the highway transport is highly developed; the country has 600 000 highway bridges. Since the collapse of the Silver Bridge in 1967, the United States has focused strongly on the inspection and maintenance of bridges; currently, it has formed relatively perfect systems of inspection, evaluation, maintenance, and reinforcement of bridge, and has been gradually decreasing the number of defective bridges. In 2008, the infrastructure research and development agency of the Federal Highway Administration of the United States (FHWA) once again launched the long-term bridge program (LTBP), which planned to systemically collect the relevant data of highway bridges in America within 20 years, establish detailed and instantaneous database of bridge health, develop studies of applied technology and performance theory of bridge structures, and finally improve the safety, reliability, and service life of American highway bridges [2].

In Japan, the capital high-speed line constructed during the Tokyo Olympics in 1964 and other transportation infrastructures constructed in its rapid economic growth period will enter the aging period. For example, in the subsequent 20 years, the proportion of roads and bridges that are older than 50 years will increase from the current 16% to approximately 65%, and the increase in the aging ratio of these bridges and roads is accelerating. Structures with unidentified maintenance-management information (such as infrastructure elements of established year and structural form, etc., and progress of deterioration status and damage, etc.) exist in Japan; meanwhile, the standard for maintenance and management, and the regulating system and policy are not complete [3].

In the coming years, Japan will authentically respond to the problem of infrastructure aging, of which the economic scale is 800 trillion yen. It schemed and formulated the "Basic Plan for Infrastructure Longevity" by referring to all the infrastructures managed by the country, local public communities, and private entrepreneurs as objects, demanding all provincial governments and autonomous agencies in Japan to draft the general maintaining-management systems and the necessary middle-long term plans for the funding cost, etc., and formulate plans of inspection and repair of facilities of schools, roads, sewer systems, etc., to gradually realize the expected targets of constructing a safe and stable infrastructure system, achieving a comprehensive and integrated management, as well as reinforcing the competitive power in the maintenance industry [3].

Recently, the British government announced the largest engineering scheme of road construction in the past 50 years by managing the properties of development, the infrastructure maintenance of highway agencies, and developing the corresponding management system, i.e., investing 15 billion pounds to ameliorate more than 100 domestic trunk roads [4].

### 3 Major problems faced by long-life safety of traffic and civil structures

The problem of longevity safety and the guarantee of traffic and civil structures primarily involves two aspects: one is to ensure the reliable and safe service of the existing transportation infrastructure with a large scope and wide range within the expected design service life; the other is to prolong the service year and ensure a safe operation after a major or important structure arrives at or exceeds its designed service life. The guarantee of longevity safety of a major structure is a systemic project that involves policy and laws, designing theory, evaluating and diagnosing theory, problem monitoring and inspection, theory and technique of structural repair and reinforcement, construction craftwork, material and equipment, etc. However, this project currently lacks the necessary and sufficient studies. From the current engineering practice, the paper concludes the existing key problems in the field of long-life safety of major structures.

(1) The existing designs are short of systemic considerations of structural longevity, including the juvenility of the relevant designing theories and construction methods, which forms the hidden dangers of structural longevity safety.

(2) Defect in design and construction quality menaces the safety of many existing serving structures.

(3) The phenomena of emphasizing construction but despising management or maintenance in the field of transportation infrastructure construction has existed for a long time; the deficiency in maintenance, repair, or systemic care of the existing structures may sharply shorten the actual service life of the structure.

(4) The overload phenomenon existing universally in highway systems exacerbates the injury of structures, and curtails the structural service life simultaneously.

(5) Structures that suffered from various types of disasters will generate different degrees of injuries; although reinforcements might be conducted, these damages to the safety of long-term use of structures necessitate further research and evaluations.

(6) The theoretical foundation for evaluating the remaining service life of major structures is lacking.

(7) For major structures reaching their designed service year, theories and methods to assess their continuing safe-service feasibility remain to be researched.

(8) The existing technology, means of monitoring, and health inspection still require further studies.

(9) The durability results obtained by fast experiments in laboratory are not sufficient to assure the long-term capability of real structures.

(10) Systemic works developed in the realm of the longevity safety of structures are insufficient, thus not beneficial to the management and maintenance of the existing structures, and challenges the design of new structures.

### 4 Analysis approach to guarantee longevity safety of transporting and civil structures

Based on the situation analyses of the related fields domestically and abroad, to better exert the function of transportation infrastructure whose stock is gigantic and property huge in China to serve the national economic construction, considering the severe situations concerning the safety of major structures of the transportation infrastructure, and being aware that the long-term programming and top-class design of structural safety assurance as a systemic project is lacking at the moment, this paper recommends the development of the “Plan of Long-Life Safety Assurance of Major Structures of Transportation Infrastructures.”

#### 4.1 Target to achieve by the “Plan of Long-Life Safety Assurance of Major Structures of Transportation Infrastructures”

Based on the specific national condition, it utilizes a method that combine system innovation, mechanism innovation, technology innovation, and production-learning-research, to fulfill the objective of economic and social development as well as the security requirement of the people’s life and property. Further, it fully explores the potential of the national economic development served by the existing infrastructures, retains the balance between longevity safety and comprehensive cost control of transportation infrastructures of major structures, initiates the deep amalgamation of infrastructure construction with information and industrialization, widely practices green construction that promotes the safety, applicability, reliability, and longevity of the national major transportation infrastructures, cultivates innovative industrial systems that fits the national construction of transportation infrastructures and maintenance management, which improves the national comprehensive ability in aspects such as design, construction, building, and management in the field of long-life safe security of major structures of the national transportation infrastructure to reach the advanced level worldwide, assures the safety of the major structures of the national transportation infrastructure, and protects the national security and the people’s life and property security.

By developing studies and practices in the domain of long-life safe security of the major structures of the transportation infrastructure, it sets up a whole-life information file and management system based on survey, projection, design, construction, operation maintenance, and management, to adapt to the monitoring system of the modern operating organization and management, new engineering structural systems that improve and ameliorate the structural capability of major structures, systems that handle emergent-critical repair and reconstruction of large structures under different natural disasters, equipment research, and development, and organization managements of emergency rescue; based on the whole process of projection, design, con-

struction, operation, management maintenance, and dismantling, a system of design, construction, and management of transportation infrastructure of major structures is realized with respect to the optimization of the overall performance (function, cost, culture, environment, etc.) in the structure's whole-life period, which ensures no occurrence of significant safety accidents in the major structures of the national transportation infrastructure, and provides powerful support in the national economic construction and development.

Specifically, three steps can be divided to achieve our expected target.

(1) Comprehensively master the constructing situation of the national major structures of the transportation infrastructure and predict the developing future tendency. According to the classification of major structures of the transportation infrastructure, the required collected data are to be studied and determined, the standard of data sampling, collection, and quality assurance are to be formulated, and the relevant data are to be systematically collected. The detailed and instantaneous database of the structural health and the corresponding open, upgrade available, and extensible system of data management and analysis are to be established. The relevant data are to be collected via the system to determine the typical form, number, and location of the major structures that are required in the future study, monitoring (detection) and evaluations are to be conducted, and the corresponding research projects are to be formulated. This series of work is to be finished within approximately five years.

(2) Systemically develop the research works in the field of key technology including studies in the common fundamental theory and method of long-life safety, evaluate the structural longevity safety and early-warning platform, establish the preventive maintenance–repair strategy of the major structure system, establish innovative practical technologies of structural inspection and health monitoring, develop the long-life safety guarantee technology of major structures, research and apply the emergent technical equipment, new material, new technology, and new equipment, and establish the policy and laws of long-life safety guarantee, etc. Achieve breakthrough in technology and obtain the corresponding technical regulations and specifications. This work is to be finished within 10 years.

(3) Establish a long-life safety guarantee system for the major structure of the transportation infrastructure that fits the China's national condition; popularize and spread the corresponding new materials, new technologies, new structures, new equipment, new techniques, new specifications, and new institution; build a standard system of the large structure's management and maintenance; gradually cultivate innovative industrial systems and new growth points of the national economy; realize measuring applicable, inspection applicable, controlling applicable, repair applicable, and emergent handling applicable; and fully exert the significant function of major structures of the transportation infrastructure to serve the national economic construction, and

embody great economic benefits. This work is to be finished within 20 years.

By implementing this project, the following objectives can be obtained: ① All transportation infrastructures should establish a longevity safe guarantee plan that is practicable in the daily management works; ② develop an industrial system for the long-life safety guarantee of major structures, and achieve an industrialized output value that is 50% of the new output value of the major structures; ③ all transportation infrastructures can use new types of sensors, robots, and nondestructive inspecting technologies to highly execute inspection, detection, evaluation, repair, or consolidation by combining big data and modern information technology such as cloud computing; ④ significantly decrease the probability of severe accidents during the service life of major structures of the transportation infrastructure by performing the works above; ⑤ combine the Belt and Road Initiative to spread the relevant achievements and technologies to other countries.

#### **4.2 Strategic task and emphasis of “Plan of Long-Life Safety Assurance of Major Structures of Transportation Infrastructures”**

Specifically, the strategic task and emphasis of “Plan of Long-Life Safety Assurance of Major Structures of Transportation Infrastructures” includes the following:

(1) Based on the database establishment of large engineering projects in information technology and big data, construct a whole-life information file and management system from survey, programming, design, and construction to operation maintenance and management; establish a structural deterioration and predicting model of the remaining service life based on the database and modern experimental technologies; construct the long-life safety theory and method for major structures, realize the scientific maintenance–repair of major structures, and scientifically formulate the reinforcing strategy.

(2) Based on the health monitoring of large structures and the construction of a safety controlling system by modern sensing technology, information technology, and structural evaluation strategy, as well as the construction of point-line-surface-volume monitoring system fitting modern operating organizations and management, the research and industrialization of modern sensing and monitoring equipment that is suitable for large engineering structures are to be established.

(3) Based on the performance improvement of large structures and the promotion of engineering development and industrialization via new material, new structure, and new craftwork, the service life is to be prolonged and the bearing capacity is to be increased to form a new structural force system.

(4) Establishment of emergent-critical repair and construction of large structures, equipment research, and development and organization of management system of emergent assistance for different natural disasters.

(5) Information, network, intelligence-based modern operation–organization management, whole-life predicting mode of maintenance–repair, research–development of automatic maintenance machinery, equipment that foster new industry of maintenance–repair, and reinforcement of major structures of the transportation infrastructure.

(6) Policy, law, and technology standards and specifications that adapt to the whole-life period management of modern large engineering structures.

## 5 Recommendation

Constituting a huge amount of the society’s fixed asset, the transportation infrastructure is critical in the national economic construction. In China, large numbers of existing major structures of transportation infrastructure has been generating different degrees of, and even severe potential safety hazards in their service life. With time progressing, the phenomena of aging and capability degeneration of many engineering structures are becoming increasingly obvious, and some major structures will successively reach their designed service life. Currently, China is still in the fast development period of traffic and transportation; many newly built transportation infrastructures have huge volumes and complex structures, and their safety, durability, and management–regulation problems will become more difficult with the continuous increase in service year; further, the problem of longevity safety guarantee will become more prominent.

Owing to lack or deficiency of theory, technology, and management system in the relevant territory, countries, especially advanced countries have been paying great attention to and been actualizing the theory and technology research of major structures of the transportation infrastructure in the long-life safety

domain; further, these countries have been investing a significant amount of money to formulate new policies to guarantee the related jobs and careers to occupy the commanding elevation of this field.

It is suggested that the “Plan of Long-Life Safety Assurance of Major Structures of Transportation Infrastructures” should be implemented immediately in China. By comprehensively occupying the constructing status of the transportation infrastructure in China, research works in the key technology can be systemically developed, and the corresponding technical systems and technical standards that are suitable to national conditions of China is to be constructed. To ensure the safety of major structures of China’s transportation infrastructure, to assure the national security and the security of people’s life and property, to guarantee the transportation infrastructure as a huge amount of fixed asset serving the national economic construction and benefiting the people, and to foster innovative industrial systems and new economic growth points, this work is highly significant.

## References

- [1] Ministry of Transport of the PRC. Statistics report on transportation industry development in 2016[R]. Beijing: Ministry of Transport of the PRC, 2017. Chinese.
- [2] Zhu C M, Zhang Y F, Dai Y F. American bridge long term performance research and its enlightenment [J]. *Modern Transportation Technology*, 2012, 9(2): 18–21. Chinese.
- [3] Basic plan for long-life infrastructure [R]. Ministry of the Environment Government of Japan, 2013. Japanese.
- [4] Huang W J, Zhao W. Brief introduction of road asset management system [J]. *Journal of China & Foreign Highway*, 2012, 31(1): 253–258. Chinese.