Strategies for Maintenance and Resilience of Aging Critical Infrastructure in the Climate Crisis Era

YUZHUO QIN

National Crisisonomy Institute, Chungbuk National University, 1 Chungdae-ro, Seowon-gu, Cheongju, Chungbuk, 28644, Korea

Abstract

In 2002, with the publication of Human Geography in Nature magazine, Paul Jozef Crutzen proposed the concept of "Anthropocene" in his article. The core of the concept of "Anthropocene" is that the current impact of human activities on the earth far exceeds the impact of natural changes. Since the beginning of the Industrial Revolution, human society has gradually invaded and changed the ecological balance of the earth through landform transformation, land use, mineral mining, surface and groundwater extraction, etc. At the same time, "climate", one of the attributes of the earth, has also gradually undergone irreversible changes. These changes eventually formed the "global climate crisis" we know now. The process of mutual influence can be explained by the "Mobius Strip Theory", that is, humans and the earth's ecology and natural environment are interdependent and influence each other. All influences will act on the time process and gradually expand as time goes by. Eventually, like a boomerang, it will act on human society. This "evil influence" and "global disaster" will once again trigger changes in the infrastructure and living environment of human society, as well as disaster avoidance patterns.

"Critical infrastructure" is the core component of the "urban lifeline" that human survival depends on. In the current global climate crisis disaster, the degree of loss and wear rate continues to rise, so that it enters the "middle-late stage" of its life cycle too early, which will lead to the inability to provide equivalent disaster resistance and shelter capabilities when facing climate disasters that cannot be accurately predicted. At the same time, this process will affect the entire disaster emergency response system, and the city will inevitably be in a state of chaos.

This study will focus on providing timely maintenance and protection strategies for aging critical infrastructure under the global climate crisis. The process is not limited to mechanical structures. The research scope is expanded to maintenance model description, maintenance system analysis, etc., and from the perspective of crisis management scholars, maintenance suggestions are provided for the stability of urban lifeline structures.

Key words: Aging critical infrastructure, critical infrastructure maintenance strategies, urban lifelines, global climate crisis, crisisonomy, disastronomy

I. Introduction

1. Research Background:

The concept of a "global climate crisis" has been developing over the past few decades and even centuries, but there is no clear time point when it was first proposed. Climate change is a long-term change in the Earth's climate and weather patterns. After nearly a century of research and data, the vast majority of researchers in the scientific community believe that human activities can change the climate of the entire Earth. In the 1800s, experiments showed that carbon dioxide (CO2) and other gases produced by humans could accumulate in the atmosphere and insulate the Earth, and human society was more curious than worried at the time. After 1850, human activities had a significant impact on climate change. For example, land use changes caused by deforestation had a significant impact on regional temperatures (Climate Changes over the Past 1000 Years, GOOSSE Hugues and KLEIN François). However, at the time, human activities seemed to have a smaller impact on the global scale, and the main natural driving force of global climate variability over the past thousand years has come from solar activity (DELAYGUE Gilles, Changes in Solar

Activity and Climate Impacts over Centuries). By the late 1950s, carbon dioxide readings would provide some of the first data to confirm the theory of global warming (HISTORY.COM EDITORS, Climate Change History, OCTOBER 6, 2017 (UPDATED: JUNE 9, 2023)). In the late 1970s and early 1980s, scientists began to warn of the impact of human activities on the Earth's climate system and predicted possible serious consequences. In 1988, the United Nations established the Intergovernmental Panel on Climate Change (IPCC) to assess scientific knowledge on global climate change and propose response options (www.ipcc.ch). The first wave of urban action to address climate change was dominated by the activities of a few pioneering cities, mainly in North America and Europe, focusing on the challenge of mitigating climate change (bulkley and Betsill, 2003; bulkley and Kern 2006; Alber and Kern, 2008). Looking back at several cases where global climate change has caused damage and paralysis of national infrastructure, for example, Paris suffered a major flood in 1910, the water level of the Seine-Marne River rose sharply by 8.62 meters, and the flood almost completely paralyzed the city's infrastructure (Wenhui Daily); the Great Hanshin Earthquake in Japan in 1995, more than 500,000 houses and buildings were partially or completely damaged, which also led to a slow start in search and rescue operations, increasing the loss of life and property, including water supply systems and electricity were damaged to varying degrees... (Kawata Y, 1995); Hurricane Katrina in 2005 was one of the most destructive hurricanes in American history. The tsunami and strong winds it caused destroyed infrastructure in New Orleans and other places, including dams, water pumping stations, roads and bridges, etc. Patrick Lagadec (Patrick Lagadec, 2008: 7) describes the complexity of these disasters: "Katrina caused continuous flooding, a series of industrial disasters, critical evacuation challenges, widespread and deadly pollution, the destruction of 90% of basic utility networks (energy, communications, water, etc.), unprecedented public safety issues..." (Moynihan D P, 2009); Typhoon Herrick landed in the Philippines in 2013, causing large-scale damage, including the destruction of infrastructure such as bridges, roads, houses, etc., and triggered landslides and floods; In January 2017, atmospheric high pressure brought extreme cold and snowfall to Italy, the Balkans and Turkey. The temperature in the affected areas was 5-12°C lower than the average temperature in previous years for this season. The extreme weather conditions led to school closures, frequent traffic accidents and flight cancellations; In August 2017, Bangladesh experienced heavy rainfall, and water from upstream India continued to flow into the large river basins of Bangladesh. Most of the water flows into the Jamuna River basin, breaking the riverbank, causing the highest flooding level in history and large-scale floods. The northern part of the country was particularly hard hit. The flood disaster directly affected the homes and livelihoods of nearly 7 million people (extreme weather and climate change report; world weather attribution); in June 2022, continuous heavy rainfall in Pakistan caused serious floods. According to the report of the National Disaster Management Authority (NDMA) of Pakistan: As of November 8, 2022, the floods have caused 1,739 deaths, 12,867 injuries, and more than 33 million people affected; 800,000 hectares of farmland were flooded and crops destroyed; more than 13,000 kilometers of roads were destroyed, 439 bridges were collapsed; about 2.29 million houses were damaged... The direct economic losses caused by this flood disaster exceeded US$10 billion (Top Ten International Natural Disasters in 2022; China Disaster Prevention Information Network). These cases fully demonstrate that there are still obvious deficiencies in countries or regions when responding to climate change or climate crisis on a global scale. These deficiencies in disaster preparedness have nothing to do with the country's land area, national economic strength, combat readiness, etc. In the process of responding to disasters, key infrastructure as a component of the country plays an extremely important role. If the extreme climate response strategy is improperly implemented or delayed, these facilities will be in a state of stagnation during the "critical period". The suspension of operation of these key facilities will have a more serious "impact" on the region, the country and even the world. For a country, important infrastructure such as electricity, water supply, gas supply, roads, transportation, energy, and communications are the "lifeline" to ensure the normal operation of the economy and society; for the whole world, in the era of global interconnection, important infrastructure is the "meridian" to ensure the normal operation of the global industrial chain and supply chain (maintaining the security of important infrastructure should become a global consensus, Wang Hongwei (Director of the National Security Research Center of the School of Public Administration, Renmin University of China), 2022).

Entering the era of the Fourth Industrial Revolution, relying on advanced 4IR (Fourth Industrial Revolution) technology, we can more conveniently collect, analyze and use disaster data to respond to the possibility of natural disasters (hurricanes, earthquakes, floods, blizzards, etc.) and define the scope of impact. At the same time, using 4IR technology, the Chinese government proposed the national construction concept of "new infrastructure" in 2018. Compared with the traditional national core infrastructure elements, "new infrastructure" is guided by the new development concept, driven by technological innovation, based on information networks, and facing the needs of high-quality development. It provides digital transformation, intelligent upgrading, integrated innovation and other services. The infrastructure system has construction goals covering 5G base station construction, ultra-high voltage, intercity high-speed railways and urban rail transit, new energy vehicle charging piles, big data centers, artificial intelligence, industrial Internet and other seven areas (Exploiting the potential and promotion strategies of new infrastructure construction, Sheng Chaoxun, 2022, 10). However, in the context of the current global climate crisis, China's infrastructure still has the possibility of being exposed and vulnerable in the face of extreme climate. According to the 2020 and 2022 Global Natural Disasters Report: In July 2020, a magnitude 6.6 earthquake occurred in Nima, Tibet, China (the highest magnitude in mainland China in 2020), causing damage to more than 50 old houses. From November to December, a large-scale rain, snow and cooling climate occurred in central and eastern China, causing damage to power facilities in seven provinces and regions... In 2022, China suffered a total of 35 cold waves, 5.9 times more than the normal level (29.1 times) in the same period... During the cold wave climate, power supply facilities and communication infrastructure in southwest and central and southern China were damaged (according to: 2020 and 2022 Global Natural Disasters Report). These cases show that when responding to climate disasters, traditional critical infrastructure and aging facilities of varying degrees no longer have the ability to resist adverse climate conditions.

Oxford Dictionary has selected the word of the year for 2019: Climate Emergency. According to statistics from Oxford Dictionary, the frequency of the word "Climate Emergency" increased more than 100 times in 2019 (Wang Jiao, 2020). However, I think a more accurate way to express the climate crisis is "Climate Crisis", because the development of the climate crisis is not a one-time thing, and this extreme climate state will last for years or even decades. Using Google Trends to analyze searches for "Climate Emergency" and "Climate Crisis", it was found that the search volume for "Climate Crisis" has been much higher than that for "Climate Emergency" in the past five years, and the main sources of searches are from the United States, Canada, China, Australia and other regions.

In 2020, a document from the United Nations Industrial Development Organization (UNIDO) on quality infrastructure (QI), "Restarting Quality Infrastructure to Build a Sustainable Future", mentioned: "Quality infrastructure (QI) is a powerful tool to improve people's lives through economic development. In the face of threats such as extreme climate change, pollution, resource scarcity and biosphere destruction, QI needs to continue to develop and keep pace with the times..." This study will focus on how to provide high-quality maintenance management (Maintenance) before the adaptive function of critical infrastructure is updated in response to the global climate crisis, and provide maintenance management solutions and recovery strategies for aging critical infrastructure, so as to ensure that risk resistance and resilience are improved when responding to unpredictable climate crises.

2. Necessity of research：

Although the research literature on the relevance of "infrastructure" was published as early as around 1950 ("Western Defense Contribution", The Times, 1950), the early Chinese content on "critical infrastructure" came from a Chinese document entitled "The U.S. "Protecting Critical Infrastructure" Plan". The original content of the document quoted "critical infrastructure" was explained as: including telecommunications, power systems, natural gas and oil storage and transportation systems, transportation systems, banking and finance, water supply systems and emergency service systems (including medical, police, fire and emergency, etc.) and the continuation of government services (The U.S. "Protecting Critical Infrastructure" Plan [J]. Foreign Science and Technology Trends, 2000(03):17.). And the factors that may threaten these critical infrastructures are divided into two categories, namely "traditional physical threats" and "computer threats". In the 1960s and 1970s, the technology of analyzing system vulnerabilities was gradually promoted in the United States. Based on this, we can find that the original interpretation of the term "critical infrastructure" in the United States originated from July 1996, when President Clinton signed Executive Order No. 13010, establishing the Presidential Commission on Critical Infrastructure Protection (PCCIP), which explained the critical factors of infrastructure: "Certain national infrastructure is so important that its failure or destruction would have a debilitating effect on the national defense or economic security of the United States," and defined critical infrastructure in the administrative terminology list as: "Infrastructure is so important that its paralysis or destruction would have a devastating effect on national defense or economic security (Moteff JD, Copeland C, Fischer JW, et al; 2003)." In 1998, President Blinken signed Presidential Decision Directive No. 63 (PDD-63, THE WHITE HOUSE WASHINGTON May 22, 2003). 1998), which expanded the definition of critical infrastructure to "physical and network-based systems that are essential to the minimum operation of the economy and government... These include, but are not limited to, telecommunications, energy, banking and finance, transportation, water supply systems, and emergency services (https://irp.fas.org/)", and mentioned "government service continuity" related content. In October 2001, the US government enacted the USA PATRIOT Act. According to the content of the act, the definition of "critical infrastructure" was revised to "physical or virtual systems and assets that are extremely important to the United States, and once their capabilities are lost or destroyed, they will weaken national security, national economic security, or national public health and safety" (Liu, 2016). In July 2002, the Bush administration of the United States issued the National Homeland Security Strategy (National Security Strategy 2002). The "Strategy" pointed out that the federal government should prioritize the protection of critical infrastructure based on a consistent approach, enabling it to balance costs and expected benefits (georgewbush-whitehouse). EU governments believe that the possibility of catastrophic terrorist attacks affecting critical infrastructure is increasing day by day.

Since the 9/11 incident in the United States, the European Commission has put the protection of infrastructure on a par with the protection of borders and citizens. At the same time, it has divided the core factors for identifying potential critical infrastructure into: Scope (the scope of facilities affected by the loss of critical infrastructure), Magnitude (assessment of the impact or degree of loss), Effects of time (at what time the loss of function of a core element will have a serious impact), and formulated the European Programme for Critical Infrastructure Protection (EPCIP) (Critical Infrastructure Protection in the fight against terrorism, 2004). From the above, it can be seen that the threat factors of "critical infrastructure" in the early days of the United States and Western governments were limited to homeland defense, cyber security, and economic and military.

From the perspective of crisis management, critical national infrastructure is defined as "core facilities, systems, and functions that serve as the foundation of national life and property, national sovereignty, and economic, social, and cultural vitality (Jae-En Lee, 2004:80)". Professor Jae-En Lee believes that with the continuous expansion of modern large-scale crises, the importance of protecting various national core infrastructures is second only to traditional military security-level crisis management. These crisis sources include natural disasters and man-made disasters (Source: Crisisonomy). Take natural disasters in the United States as an example. Hurricane Katrina (2005) caused chaos and disorder in the New Orleans area (Boin A, Mc Connell A; 2007), which provides us with a clear example of the impact of natural disasters on critical infrastructure. This emergency is "unforeseeable but predictable, and frequently occurring small-scale events (Perry and Lindell, 2006: 29)". However, in the era of global climate crisis, it is almost difficult to predict extreme climate, and it also greatly increases the possibility of critical infrastructure being fatally hit, because the facilities, systems, and functions that constitute the critical infrastructure network are highly complex and highly interdependent (Jae-En Lee, 2009). In other words, when a core infrastructure is affected, all other facilities that form a functional service network with it will suffer unpredictable damage, and the sustainable service capacity will be severely hit, thereby increasing the possibility of secondary disasters caused by the climate crisis. This critical infrastructure network includes both physical networks such as energy and transportation systems and virtual networks such as the Internet (Bennett, 2007: 9).

The minutes of the 2005 World Conference on Disaster Reduction confirmed the importance of the concept of "resilience" in disaster management (Report of the World Conference on Disaster Reduction 2005), which gave rise to a new disaster response culture, namely "quantitative analysis of disaster resistance" (Cimellaro G P, Reinhorn A M, Bruneau M; 2010). The article mentioned two quantitative analysis elements, "resilience" and "vulnerability". The concept of "resilience" refers to paying attention to and improving the quality of life of people at risk through means, and creating opportunities to provide better response results; "vulnerability" emphasizes that characteristics come from natural carrying, and various natural disasters can be resisted by reducing the possibility of exposure to "vulnerability". The article mentions that in order to facilitate the understanding of the relationship between "vulnerability" and "fragility", a disaster variable - "ground motion intensity" is introduced. "Vulnerability" defines the "loss" caused by an earthquake, while "fragility" provides the "probability" of an adverse event (physical collapse) occurring. In 2009, the American Society of Civil Engineers (ASCE) began to look at safety issues from the perspective of "the overall resilience of infrastructure, or the ability to withstand and recover from natural and man-made disasters" (Report Card for Americas Infrastructure Full Book. 2009). The 2013 report (Report Card for Americas Infrastructure Full Book. 2013) estimated that an investment of $3.6 trillion would be needed over a five-year period to keep the country's infrastructure elements and systems in "good shape." However, the assessment calculations were not included in the standards for assessing infrastructure systems, nor were they assessed as discrete infrastructure systems (Armbruster G, Endicott-Popovsky B, Whittington J, 2013). In other words, this assessment did not find a balance between discreteness and the whole as the basis for the assessment. Holický M, Diamantidis D, Sýkora M, et al. used the Bayesian Networks method to conduct an infrastructure risk assessment of seven dams in central Mexico. During the assessment process, the variables were quantified and analyzed, and then connected through probability distribution. All variables were represented by continuous rather than discrete distributions (Holický M, Diamantidis D, Sýkora M, et al; 2014). The study showed that when dealing with uncertain climate factors, it is more beneficial to use continuous probability distributions than discrete distributions.

Wang Shiying et al. (2016) divided the vulnerability mechanism of critical infrastructure systems (CIS) into three steps: internalization, externalization, and combination, and three risk types: natural fluctuations, human fluctuations, and technical fluctuations. They believe that the failure of critical infrastructure is caused by the fluctuation level exceeding its tolerance, making it unable to maintain normal operation. At the same time, during the fluctuation, due to the correlation between critical infrastructures, unpredictable cascade effects ('Cascade effect', Donald J. Kessler, 1978) may be triggered, that is, the vulnerability exposure of critical infrastructure is combined. For aging critical infrastructure, Jia Jingwen (2024) believes that it is necessary to calculate from eight levels: investment cost, maintenance cost, repair cost, reconstruction cost, depreciation cost, total cost, net present value, and payback period, and implement maintenance strategies from five perspectives: resource assessment, risk assessment, maintenance cycle planning, maintenance cost assessment, maintenance plan execution, and monitoring.

Backwardness and advancement are never absolute concepts. In the current environment, critical infrastructure that is deployed or optimized ahead of time still has major drawbacks when dealing with unpredictable climate crises in the future. Even backward and aging critical infrastructure can still improve the possibility of combating the threats brought by climate crises after professional evaluation and targeted maintenance, thereby ensuring that it can still provide relatively objective continuity functions under extreme conditions. With the continuous expansion of China's urbanization process, the aging core infrastructure in the past has lagged behind the current crisis-ridden era. Therefore, it is extremely necessary to carry out targeted maintenance and upgrades for these aging critical infrastructures, which also meets the current requirements of "big emergency management" in Chinese society.

3. Research objectives and research methods：

The research direction of this study is to enhance the resilience and disaster resistance of China's critical infrastructure, to ensure that it can maintain its current functions and operational capabilities in response to extreme climate conditions, and to reduce the possibility of insufficient infrastructure disaster resistance leading to "secondary disasters", rescue and emergency support and other key function deficiencies, thereby reducing the difficulty of disaster management.

This study will use prior literature surveys, relevant paper readings, questionnaire surveys of experts in related fields, and SWOT-AHP hierarchical analysis methods to complete the construction of the paper content, and provide personal opinions from the perspective of crisis management based on the final analysis results.

II. previous research

1. Aging and maintenance management of critical infrastructure:

As a unitary administrative aggregate of the state, the city's material structure is composed of industrial production facilities and infrastructure facilities. Among them, infrastructure facilities generally do not have direct material product output, but are indeed indispensable material conditions for the production sector (Liu, 1985). Urban infrastructure includes:

1) Productive infrastructure, including departments that provide services for urban production (such as logistics, communications, material and technology supply, production water and electricity supply, etc.)

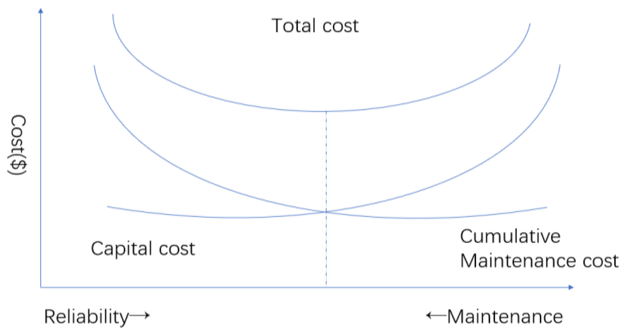
2) Non-productive infrastructure, including social life service facilities, passenger transportation and postal and telecommunications, commerce, public catering, residential shared facilities, as well as medical education, sports and entertainment, etc.

3) Other institutions that ensure the operation of the city, such as management agencies, financial credit agencies, insurance agencies, etc.

System theory interprets a system as an organic whole composed of several elements with certain new functions. Once the elements as subunits of the system form the whole system, they have properties and functions that independent elements do not have (the basic principles of system theory, Shanghai Institute of System Science). Regions and cities, critical infrastructure and urban infrastructure are all elements that make up the country. The components in the system have different characteristics and functions. The elements are connected and combined into a critical infrastructure system through interaction. This system will continue to operate as the driving force of the country's basic operation. In other words, if any component element in the system is affected and enters a stagnant state, other elements will be continuously affected by it. According to Long (2007), a country's infrastructure system accounts for about 50% of the country's total wealth. In such a huge infrastructure system, if inappropriate or unsuitable buildings and structures are built, or if the facilities are improperly maintained and renovated, then social and economic life will be damaged (Gann, 2000). How to deal with the ubiquitous aging problem (K. van Breugel, 2014) seems to have become a difficulty in the maintenance of critical infrastructure.

According to the Report Card for America’s Infrastructure released by the American Society of Civil Engineers in 2009, compared with the 2005 report, the US government has made almost no progress in maintaining, repairing and modernizing infrastructure over the past four years, mainly due to huge budget figures, lack of facility reliability assessment and the decline of core government leadership (Infrastructure Age, Security, and Natural Hazards. 2009). The report explains that the maintenance of aging facilities requires a full life cycle cost analysis of all systems, including operation, maintenance, environment, safety and other reasonably expected costs during the life cycle (recovery costs after natural or man-made disasters). There are two basic concepts of crisis management here, namely sustainability and resilience. In the early stage of national critical infrastructure construction, the focus should be on the sustainable operation capabilities of the facilities in response to different and complex extreme environments. These capabilities include risk resistance and disaster response. When these critical facilities are in the middle and late stages of the project life cycle, it is necessary to conduct reliability assessments on their potential risk factors to help implement their subsequent maintenance and reinforcement strategies. Of course, after an unpredictable disaster (natural or man-made) occurs, helping them to restore their operational capabilities in a timely manner through the implementation of recovery strategies is also the key to maintenance management. If a city or region wants to have the ability to survive in the 21st century, new infrastructure and convenience facilities are the key to its future economic development and regional sustainable development (James Carlini, 2009). The investment and research and development of new facilities will inevitably require time investment. How to make a good alternation between the construction of new facilities and outdated facilities requires the management authorities to do a good job in the maintenance and management of aging facilities.

"Maintenance" is often contrasted with "renewal" or "replacement". Infrastructure capital renewal refers to the expansion of the functionality of infrastructure assets by gradually replacing aging or obsolete components, while infrastructure capital maintenance is limited to smaller, more frequent asset operations (Burns P and Hope D and Roorda J, 1999). The reliability of facility operation depends on the initial design decisions of the facility process and the additional operating capital investment. In other words, under the budget constraints after trade-offs, the design phase should solve the problem of optimizing the reliability of facility operation. After the facility is put into operation, it is necessary to achieve high availability in the operation phase through an effective maintenance strategy, as well as to achieve a balance between optimizing maintenance benefits and costs. It can be said that the initial reliability design of critical infrastructure and the maintenance strategy for long-term availability in the operation phase are interdependent (Goel H D and Grievink J and Weijnen M P C, 2003).



(Figure 1: Relationship diagram between reliability, maintainability and cost
Source: Integrated optimal reliable design, production, and maintenance
planning for multipurpose process plants)

The above figure can be expressed as:

Total Cost = (Facility Reliability × Capital Cost) + (1-Maintenance Management Frequency) × Cumulative Maintenance Cost;

The change in total cost is presented as a U-shaped curve. With the lowest point of the total cost curve as the center, we can clearly understand the relationship between reliability and maintenance. The initial capital cost ensures the reliability design of the facility, thereby ensuring a better ability to maintain operation. At this time, the capital cost is positively correlated with reliability. In the middle and late stages of the facility's operating life cycle, additional necessary maintenance and management costs need to be invested to ensure the availability of the facility. The maintainability of the facility (maintenance frequency) and the cumulative maintenance cost are positively correlated. However, it should be emphasized that reliability and maintainability are negatively correlated. The better the reliability design of the facility, the lower the additional cumulative maintenance cost required for the facility during the continuous operation stage, and vice versa.

Operations Research is usually used in the maintenance management process to find performance optimization between operating equipment and systems and predict equipment failures, maintenance requirements, etc., so as to facilitate the derivation of feasible maintenance and repair strategies. Operations Research is defined as "the application of scientific method to operational problems" and was first applied during World War II (quote again: see McClosky and Trefethen, 1954). Sherwin D (2000) believes that early failures after equipment maintenance or PM (Preventive Maintenance) are often misunderstood as "over-maintenance" by industrial statisticians, operational researchers and some engineers. These factors may be negative for the "net benefit (NC)" of maintenance practices because problems are often not analyzed correctly and people are more concerned with numbers than facts themselves.

According to the Department of Defense Reliability, Availability, Maintainability, and Cost Rationale Report Manual published by the U.S. Department of Defense (DoD) in 2009, the manual provides a detailed description of the maintenance strategy. In the manual, Chapter 2 (RELIABILITY, AVAILABILITY, MAINTAINABILITY, AND COST DEVELOPMENT REPORT OVERVIEW), Section 6 (Maintenance Concept and Support Plan Considerations), the maintenance concept is divided into two levels of concepts - "organizational" and "depot" by assuming an environment, that is, the computer maintenance process. The "organizational" maintenance strategy emphasizes the disassembly and replacement of some Line Replaceable Units (LRU) to ensure the integrity and sustainability of the overall operation of the system. This process will transfer faulty parts to the "depot" for repair according to economic standards (repair or discard), or remove or replace faulty parts that are scrapped and can no longer support system operation. Anand et al. (2018) decompose the infrastructure life cycle into "design, financing, completion, maintenance, repair, failure, retirement and destruction." Combined with the above content, I believe that maintenance and repair can be combined into the "maintenance strategy" investment stage. During this stage, the "temporal fragility (Ramakrishnan et al. 2021)" exposed by the facility can be reduced through strategic investment, thereby ensuring that the core infrastructure LRU is repaired and replaced in a timely manner and reducing the possibility of forced downtime.

Forced shutdown can also be regarded as "business continuity interruption (BCI)". Kazantzidou Firtinidou D (et al) demonstrated the relationship between business continuity management (BCM), business impact analysis (BIA) and risk assessment (RA) through the Climate Related Business Continuity Model for Critical Infrastructures (2019). They believe that the concept of "interruption" caused by climate change may be regarded as "reduced efficiency" rather than actual business interruption caused within a certain period of time as is usually considered. At the same time, when studying the business continuity management (BCM) of climate for critical infrastructure, "planning for weather events" should be distinguished from "planning for climate averages", because the latter usually refers to long-term planning with uncertainty.

2. Reliability, Availability, and Maintainability (RAM):

When studying the backward critical infrastructure, it is necessary to consider its inherent key guarantee factors, namely reliability, availability and maintainability. One of the key issues to ensure the reliability of critical infrastructure operation is that leaders and managers need to implement appropriate repair and maintenance strategies (Blokus A&Dziula P, 2021). In this process, the reliability and availability of CI systems are balanced (Fang, Y. P., Pedroni, N., & Zio, E. (2016); Kim, J., Ahn, Y., & Yeo, H.

(2016)). Stenstrom et al. (2016) believe that the implementation of maintenance strategies depends on the reliability of the system. By implementing targeted maintenance based on the current state of the infrastructure, reliability characteristics and expected failure time can be obtained in a timely manner, thereby minimizing the problem of uncertainty. Reliability, availability and maintainability determine the stability of the infrastructure operation life cycle, and the three are mutually influential and inseparable.

Kaur K (2023) describes the concepts and definitions of reliability and availability:

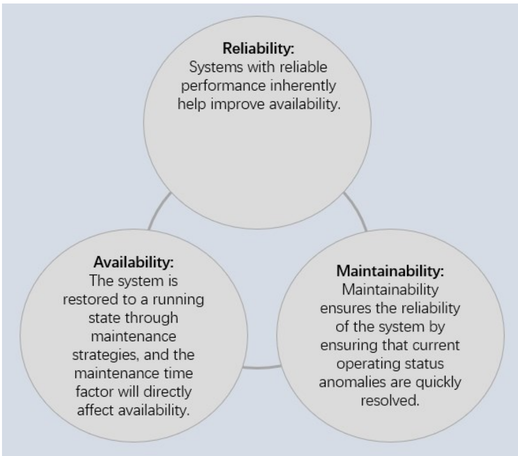
Reliability: Reliability is the probability that a device will operate for a certain period of time without failure. Reliability refers to the ability of modules, devices, components, solutions and projects to complete the required tasks in an ideal time period.

Availability: Availability refers to the probability that a tool can complete the work content within the required working time (i.e., without damage or even repair). More specifically, the probability that the device is ready to work within the tolerance at a certain moment is also described as operational readiness.

Maintainability is defined as "the probability that a given maintenance operation can be performed on an item under given conditions of use within a specified time interval, when maintenance is performed under specified conditions using specified procedures and resources." Maintainability is divided into two categories: 1) maintainability (ease of performing regular inspections and repairs), 2) repairability (ease of restoring service after a failure) (sebokwiki, last viewed: 2024/4/27).

Paul Nation (2024) believes that maintainability is an indicator that measures the speed and effectiveness of a system's recovery to an operating state after a failure or during planned maintenance. Even the most reliable systems may encounter failures or require routine maintenance. Maintenance strategies are used to minimize downtime and ensure that the system can recover quickly from setbacks.

The relationship between reliability, availability, and maintainability can be more easily understood by referring to the following figure:



(Figure 2: Paraphrasing and References: The Symbiotic Trio: Reliability, Availability and Maintainability)

Refer to the following figure to understand the interaction between reliability, availability and maintainability:

Availability	Reliability	Maintainability

↑ Increases	←→Constant	↑ Increases
↑ Increases	↑ Increases	←→Constant
↓ Decreases	←→Constant	↓ Decreases
↓ Decreases	↓ Decreases	←→Constant

（Table 1:References: The Symbiotic Trio: Reliability, Availability and Maintainability）

Paul Phister and David Olwell visualized the ARM index through formula calculation:

	Metric defined	Metric describe
Reliability: mean time to failure (MTTF)/mean time between failures (MTBF)	$\{MTTF \mid MTBF\} = \frac{T_{op,Tot}}{n_{fails}}$	T_{op}, T_{ot} :the total operating time n_{fails} :the number of failures
Maintainability: the exponential distribution and the mean time to repair (MTTR)	$MTTR = \frac{T_{down,Tot}}{n_{outages}}$	$T_{down,Tot}$:the total down time $n_{outages}$:the number of outages
Availability: calculated from the total operating time and the downtime, or in the alternative, as a function of MTBF and MTTR	$A = \frac{T_{op,Tot}}{T_{down,tot} + T_{op,tot}} = \frac{MTBF}{MTBF + MTTR}$	**Refer to the table above**

（Table 2:References: System Reliability, Availability, and Maintainability，Lead Authors: Paul Phister, David Olwell）

It is extremely important to maintain the good operation of critical infrastructure. The aging critical infrastructure in its life cycle gradually wears out over time and in response to various situations, which leads to the degradation of infrastructure capital and higher estimated reconstruction costs. Because compared with optimizing or upgrading assets, the maintenance of outdated infrastructure emphasizes how to protect assets in their current state and have a certain ability to resist unknown risks. In other words, how to ensure that the outdated infrastructure can maximize its benefits in its current state is one of the key factors in the implementation of maintenance strategies. These maintenance strategies include small repairs (routine maintenance) and improvement operations (basic maintenance), as well as timely detection and elimination of the causes of defects to avoid excessive repetition of routine maintenance work in the future (Why Maintaining Public Infrastructure is So Important. Willie du Preez, May 28, 2019).

Of course, the infrastructure system has a complex structure, and many of its indicators cannot be calculated directly. They are usually estimated using simulations. Since other indicators are not included in the scope of this study, no separate prior research will be conducted.

3. Aging critical infrastructure and climate resilience:

Critical infrastructure plays an important role in disaster reduction, because the stable operation of critical infrastructure systems is essential to reducing disaster risks and improving society's resilience to disasters. Looking back at the < Sendai Framework for Disaster Risk Reduction 2015-2030 > issued in 2015, disasters have seriously hindered the process of achieving sustainable development in regions and countries, and global climate change has exacerbated the severity of disasters, as well as the frequency and intensity of disasters. In the early, mid-term and long-term of a disaster, the impact of a disaster affects regions and communities covering the economy, society, health, culture and environment, and these disaster-affected areas include critical infrastructure, which is the "lifeline" of a region or city.

City lifelines include urban infrastructure such as transportation, energy, communications, and water supply and drainage, which are important living facilities that maintain the daily functions of the city and the normal operation of urban life (CHEN&YAN, 2020). Urban design principles define the form of the city. Some principles are cultural, defining the style, scale, and characteristics of the public domain; while others are practical, reflecting the requirements for urban transportation, infrastructure, and architecture. According to forecast reports, by 2050, the global urban population is estimated to reach 6.3 billion, almost twice the 3.5 billion urban residents in 2010. The high degree of urban saturation and the carrying capacity of key infrastructure will face increasing risks, most of which come from natural and climate disasters (storms, floods, wildfires, tornadoes, earthquakes, etc.) (Urban lifelines to achieve climate resiliency [M]. Watson D. 2017).

Transportation infrastructure, including roads and bridges, railways, ports and airports, connects major independent entities in a city through transportation hubs such as roads and bridges, and plays an important role in residents' lives and the economy. Take the United States as an example. According to a 2017 document from Zurich North America titled ‘Challenges of our nation’s aging infrastructure’, as of 2017, about one-ninth of the bridges in the United States were rated as ‘structurally deficient’, with a total of 614,387 bridges with an average age of more than 50 years. These aging bridges cannot avoid disasters, such as the collapse of the eight-lane I-35W Highway Bridge in Minneapolis, which killed 13 people and injured 145 people. The collapse of the I-10 bridge in California on July 20, 2015 (I-10 in California closed after bridge collapses, USA TODAY) caused the highway to be closed, hundreds of vehicle drivers were trapped, and the storm exacerbated the disaster (Photos of I-10 bridge collapse, Arizona Republic).

The July 18 torrential rain disaster in Jinan, Shandong Province, China fully demonstrated the inability of aging facilities to cope with abnormal climate disasters. The incident was caused by the inability of Jinan's drainage system to withstand heavy rainfall, resulting in serious loss of life and property. According to the accident cause analysis report, at that time, the urban water supply and drainage system in Jinan was composed of drainage pipelines that were hundreds of years old. The diameter of the main pipeline was 300 mm, which was different from the design standard of more than 500 mm for smooth sand discharge. At the same time, the moat sluice system was closed and disrepaired for many years, and it was not opened in time when the rainstorm occurred, which led to the further spread of the disaster (LU, 2014). This incident caused more than 30 deaths, more than 170 injuries, and about 330,000 people were directly or indirectly affected by the disaster (baike.baidu).

Natural gas is a key energy source in the primary energy composition. According to the <2023 Statistical Review of World Energy> released by Energy Institute (EI) in 2023, the global demand for natural gas in 2022 will account for about 24% of the primary energy, second only to oil and coal. As a gas pipeline system that carries natural gas transportation, it is an important infrastructure to ensure people's livelihood. Based on the time node of 2022, the number of people using natural gas in China will reach 667 million. With the increase in the urbanization rate, the penetration rate of urban gas use is as high as 97.87% (Gas Pipelines Enter Aging Cycle, Ministry of Housing and Urban-Rural Development of the People’s Republic of China, 2022-07-18).

As a key component of the city's lifeline, the aging of natural gas transportation pipelines means the occurrence of major accidents and disasters. On September 9, 2010, a natural gas pipeline in San Bruno, a town near San Francisco International Airport, exploded due to a fire. The accident caused 8 deaths, at least 66 injuries, 37 houses burned down, and 18 houses and many cars were affected (Global Disaster Event Book). After the accident, it was found that the pipeline was built in 1956 and lacked maintenance and repair, and could not withstand the new pipeline test pressure. The above cases all show that backward infrastructure lacks absolute climate resilience when dealing with unpredictable extreme conditions and climate disasters.

Resilience was first used in physics, meaning the ability of a system to return to its original state after being stressed. In 1973, Holling introduced the concept of resilience into ecosystem research and defined it as ‘engineering resilience (Holling CS, 1973)’. After 2000, the concept of resilience was gradually extended to the socio-economic system, and concepts such as economic resilience, infrastructure resilience, and urban resilience emerged accordingly (Walker B, Holling CS, Carpenter SR, et al. 2004; Gunderson LH, Holling CS. 2002). The concept of resilience associated with key infrastructure as a basic component of the city has also been separated with continuous academic exploration. Jah believes that the definition of urban resilience consists of infrastructure resilience, economic resilience, institutional resilience, and social resilience. These resilience concepts cover the emergency response capabilities of lifeline projects and communities (Building urban resilience, 2013). SHI et al. (2022) regard urban resilience as a complex concept, that is, when the urban system faces disturbance, it integrates and exerts the functions of various urban elements, mobilizes the participation of multiple subjects, and responds through prevention, resistance, recovery, learning adaptation and transformation, so as to achieve the ability of the city to autonomously realize and optimize resilience in the whole area, including economic, social, organizational, ecological and infrastructure aspects. The 2022 IPCC AR6 (The IPCC produced the Sixth Assessment Report) proposed the definition of climate resilience, that is, the adaptive capacity of social-ecological systems:

(1). Absorbing external pressures imposed by climate change and maintaining functions;

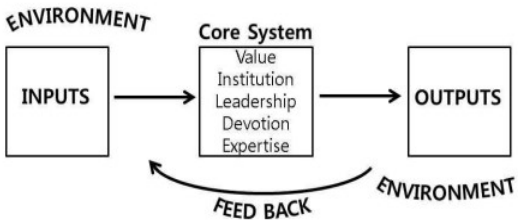
(2). Adapting, reorganizing and evolving into a more ideal configuration to improve the sustainability of the system (YANG et al. 2024).

The methods and implementation paths of climate resilient development (CRD) are integrated into AR6 Chapter 18 (Climate Resilient Development Pathways), where CRD implementation policies are described as stemming from daily formal and informal decisions, actions, and adaptation or mitigation policy interventions, including system transformation, enhancing resilience, and reducing vulnerability. In the current global climate crisis, acute risk monitoring and timely countermeasure investment are the key to measuring the strength of climate anomaly response and national critical facility protection capabilities. In certain environments, "informal decisions" have a higher priority than formal decisions. Formal decisions ensure that the operation of the organization has compliance and legitimacy; while "informal decisions" have more flexibility, which can respond to the anomalies and challenges in frequent daily management in a timely manner.

AR6 Chapter 6 Figure 6.2 (Cities, Settlements and Key Infrastructure) describes the impact of climate on infrastructure. Climate crisis, energy supply and social infrastructure form a closed loop under extreme conditions, and the occurrence of extreme climate events will cause damage to the energy supply system. As a key component of the city's lifeline, the interruption of energy supply directly affects the city's public service system (transportation, finance, IT, etc.), thereby causing the entire social infrastructure system to be interrupted. If the maintenance strategy and backup plan are not put into use in time, the exposure of the vulnerability of the entire region or city will be further aggravated. The factors in the entire closed loop affect each other, increasing the possibility of "compound disasters (secondary disasters)".

Climate-resilient infrastructure is defined as planning, design, construction and operation in a way that can predict, prepare for and adapt to changing climate conditions. Climate-resilient infrastructure can withstand and respond to damage caused by extreme weather conditions and recover quickly from damage to ensure climate adaptability (Climate-resilient Infrastructure, OECD). LI (2023) describes the four core components of resilient cities as "carrying capacity", "resilience", "reliability" and "degree of intelligence". As an important component system of the current resilient city, the climate-resilient infrastructure cluster plays a key role in reducing unpredictable future losses and reducing the possibility of vulnerability exposure caused by high urbanization. Therefore, I believe that "adaptability" needs to be added to the four core components of resilient cities to emphasize the importance of climate-resilient infrastructure clusters in responding to climate crises.

Aging critical infrastructure has shown obvious lack of climate adaptability in response to the current global climate crisis. How to provide and improve extreme climate adaptability for the aging critical infrastructure currently in operation has become the key to the formulation of maintenance and recovery strategies. I believe that the "Core System" described by Lee (2014) provides a new research idea when establishing and formulating maintenance strategies for aging critical facilities. The Core System is defined as a network hub that guides and coordinates the entire system, and the core hub completes the entire process from element input to output. The Core System is the key to explaining and in-depth research on social and political systems. The main elements that constitute the Core System include "values", "institutions", "leadership", "dedication" and "professionalism". Bringing them into the management process of aging infrastructure can help policymakers and administrative experts understand how these core factors guide the formulation of maintenance strategies.



(Figure 3: Source: Components of Core System. Lee(2014: 23))

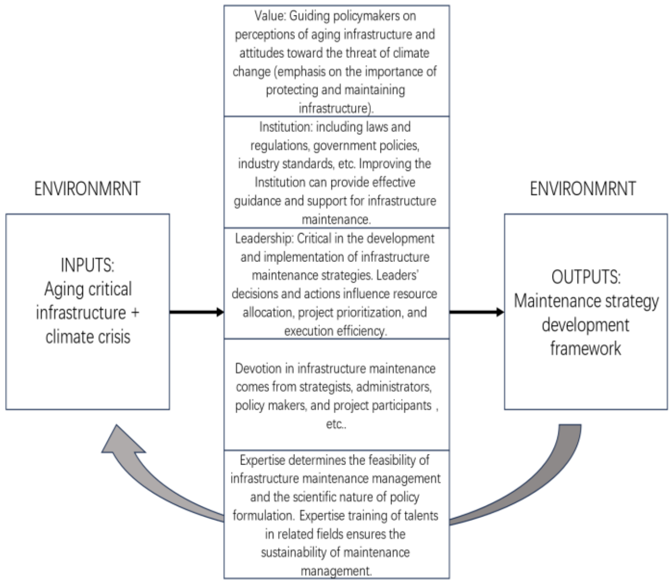
Values guide the degree of attention that administrators pay to aging infrastructure. If the decision-makers generally believe that it is important to protect and maintain aging infrastructure, they will invest maintenance capital and energy to ensure the smooth operation of the facilities during their life cycle. If the decision-making is oriented to short-term interests, it will lead to infrastructure maintenance defects, which will not be able to avoid major losses that may occur in the future.

System improvement includes the completion of the current infrastructure protection system, relevant laws and regulations, and the formulation and improvement of construction industry standards. Having a sound system can provide effective support for the infrastructure maintenance process. The system also includes disaster management for climate crises and the improvement and monitoring mechanism of the maintenance management system to ensure that risk factors are captured in time and that maintenance management operations are standardized and procedures are effective.

Leadership and dedication are equally important. Leadership is crucial in the decision-making and implementation process. At the same time, policymakers and implementers with leadership also need to have dedication. These factors affect the allocation of maintenance resources, project priority differentiation, and the efficiency of action execution.

The maintenance of aging critical infrastructure requires the professional skills and management capabilities required for maintenance management (maintenance operations, project management, risk monitoring and assessment, etc.). At the same time, investment in maintenance management professional talent training programs is also very important. The training of professional talents determines the sustainability of subsequent maintenance management and the expansion of the expert team.

Based on the above summary, the author describes a model for the core framework of infrastructure maintenance strategy formulation, which will be used for subsequent research on maintenance strategy focus:



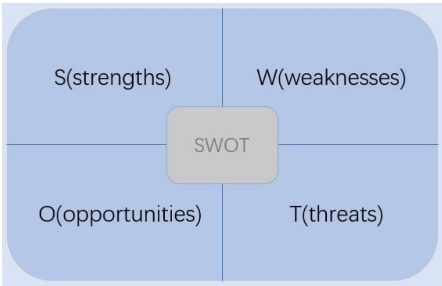
(Figure 4:Paraphrasing and References: Components of Core System. Lee(2014: 23))

III. Empirical analysis and model building

1. SWOT-AHP Model:

The SWOT analysis method is a strategic analysis method derived from the concept proposed by Heinz Weihrich, a professor of management at the University of San Francisco, and G. A. Steiner in 1980 (https://pride.stpi.narl.org.tw/index/graph-world/detail/4b1141ad870eff16018721393a745160). It is a method that can objectively and accurately analyze and study the actual situation of a unit. The SWOT analysis method is based on the situation analysis under internal and external competitive environments and competitive conditions. It is to list the internal advantages, disadvantages, external opportunities and threats related to the research object through investigation, and arrange them in the form of a rectangular array. Then, using the idea of system analysis, various factors are matched and analyzed, and a series of corresponding conclusions are drawn from them, and the conclusions usually have a certain degree of decision-making. In SWOT analysis, S (strengths) stands for advantages, W (weaknesses) stands for disadvantages, O (opportunities) stands for opportunities, and T (threats) stands for threats (https://www.itheima.com/news/20230403/182442.html).

The analytic hierarchy process (AHP) was formally proposed by American operations researcher T.L. Saaty in the mid-1970s. AHP is a systematic, hierarchical analysis method that combines qualitative and quantitative methods. Because of its practicality and effectiveness in dealing with complex decision-making problems, it quickly gained attention worldwide (wiki.mbalib.com/wiki/The analytic hierarchy process). This method combines quantitative analysis with qualitative analysis, uses the decision maker's experience to judge the relative importance of the standards that can be achieved between the various measurement goals, and reasonably gives the weight of each standard of each decision-making plan, and uses the weight to find the order of advantages and disadvantages of each plan, which is more effectively applied to those topics that are difficult to solve with quantitative methods (https://spssau.com/helps/weights/ahp.html).



(Figure 5: SWOT analysis model)

The SWOT-AHP analysis model forms a comparison matrix of research elements through SWOT analysis, and makes questionnaire content based on it. After determining the hierarchical relationship, experts compare the indicators of the same level in pairs. The matrix is assigned values and weight relationships are obtained through the comparison results (Zhou et al. 2021). Finally, a strategic quadrilateral is drawn through consistency test to obtain the core description of the strategy.

Rajput T S et al (2021) used SWOT-AHP analysis to conduct decision analysis on urban development planning during the research process. Guo et al (2019) used SWOT-AHP analysis to finally determine the development strategy of rural areas in China. Kurttila M et al (2000) applied SWOT-AHP analysis to the strategic decision-making of Finnish forestry certification. Guo (2011) established a strategic analysis of China's ecological industrial park enterprises based on the SWOT-AHP model. Zhang et al (2020) used SWOT-AHP to analyze the development trend of the marine cultural industry. Song et al (2023) used a SWOT-AHP analysis model to study the strategy of China's grain inspection and monitoring agencies.

2. Empirical analysis:

2.1 SWOT Analysis of Maintenance Strategies for Aging Critical Infrastructure:

The key infrastructure that constitutes the lifeline of a city is generally divided into two categories, namely engineering infrastructure (also known as physical infrastructure) and social infrastructure. The core subject of this study, namely municipal management infrastructure, belongs to social infrastructure (https://baike.baidu.com/item/). Yang (2019) divides the core of the social public service system into economic infrastructure and social infrastructure. He believes that infrastructure and public services are two aspects of the same object, that is, infrastructure provides public services to society, and the supply of public services is inseparable from infrastructure (Yang KaiYue, 2019. The main connotation, common characteristics and government responsibilities of infrastructure, China Information Technology Research). Wang and Gu and Xuo (2024) concluded in their research on the allocation of key infrastructure protection-maintenance resources that China's current public safety governance model is transforming towards pre-emptive prevention. The resilience improvement effect brought by pre-emptive prevention is better than post-event maintenance, and the effect is more obvious if the budget is sufficient.

After searching for relevant papers on "critical infrastructure + maintenance + climate", combined with SWOT analysis elements, a list was made to facilitate the design of subsequent questionnaires. The questionnaire survey targets municipal management departments and construction industry experts, etc., and the key factors of the main SWOT elements are evaluated for priority. If the score rate of the element selection in the SWOT matrix is 50% or above, it is determined to be a key factor, and subsequent analysis and conclusions are drawn in turn.

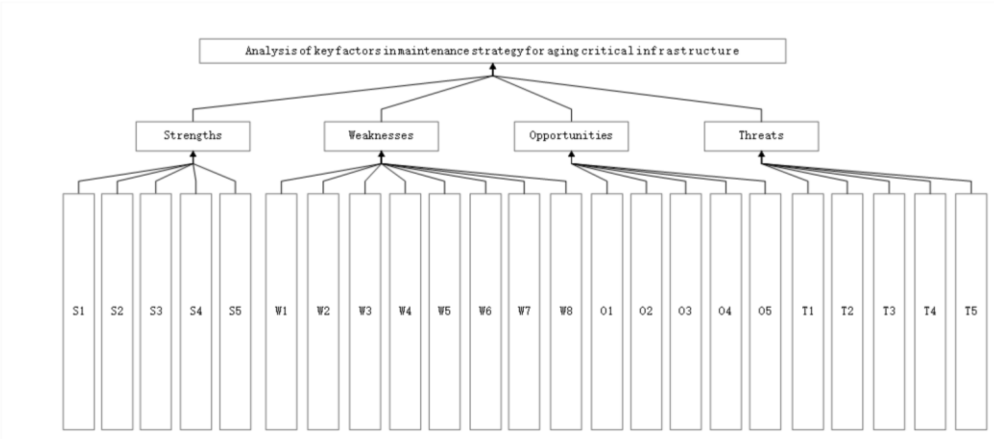
2.2 SWOT Analysis:

This SWOT analysis was constructed through literature survey and analysis of relevant papers. The target literature was searched by querying keywords such as "critical infrastructure", "infrastructure resilience", and "critical infrastructure maintenance", and the literature was used to construct a SWOT analysis framework.

SWOT	SWOT Factors(Key words)	Reference
Strengths	S1. Aging Community Resilience Maintenance Plan S2. Infrastructure informatization continues to advance S3. Core city infrastructure services and quality S4. Integrated development of China's industry and information (2%~3% development rate maintained) S5. Government-led urban resilience infrastructure construction	Zhang (2024), Tang(2022), Han (2021), Analysis based on China's Integrated Development of Industrialization and Industrialization Data Map (2020), Hu(2024), Yao and Li(2024), Gu(2018), Zhang(2011), Wan and Guo(2018), Bi et, al(2021), Ma(2021), Ge(2022), Yang(2022), https://www.gov.cn/, Nie(2023), Fang(2023), Wang and Gu and Suo(2024), Fan(2021), Tang(2021), Liu et, al(2022), Wang et,al(2023), Zhang et, al(2013), Liang(2021), Zhang and Khor(2024) et, al.
Weaknesses	W1. Maintenance capital does not match maintenance needs W2. Poor detailed maintenance management system W3. Local government debt risks increase W4. Lack of climate resilience monitoring technology W5. Resilient maintenance standards for critical infrastructure are vaguely described W6. Insufficient maintenance and management data statistics W7. Insufficient municipal infrastructure and supporting facilities W8. Autonomy of key technologies and core equipment for facility maintenance	
Opportunities	O1. Infrastructure dividend O2. Structural health monitoring	

	mechanism O3. Transformation of public security governance model O4. Infrastructure digitalization based on the fourth industrial revolution O5. Improve the maintenance management system through "digital government"	
Threats	T1. Social awareness of the climate crisis T2. Crisis of public opinion and lack of trust T3. Risk perception based on climate crisis T4. Maintenance strategy implementation capital gap T5. Infrastructure Capital Negative Externality Consideration Missing	

（Table 3: A SWOT analysis framework for maintenance strategies for aging infrastructure）



(Figure 6: SWOT analysis model of Analysis of key factor in maintenance strategy for aging critical infrastructure)

2.3 AHP Analysis:

A total of 20 experts participated in this questionnaire survey. The questionnaire survey used the 1-9 scale method to assign weights to the SWOT group matrix, and then assigned weights to the key elements in the SWOT matrix. The experts independently thought about and selected the corresponding values to form the final evaluation indicators.

First, the questionnaire survey content was distributed to the targeted expert group through an electronic questionnaire survey. After the expert group review process was completed, the completed questionnaires were collected and sorted and revised. The sorted questionnaires were analyzed using AHP analysis software to calculate the maximum eigenvalue (λ_{max}) and normalized eigenvector (W) of the judgment matrix, that is, the relative weight analysis of each indicator. After obtaining the maximum eigenvalue of the matrix, the corresponding matrix was tested for consistency, and the consistency index CI value and the consistency ratio CR value were obtained. When the CR value is less than 0.1, the judgment matrix consistency test passed, otherwise a questionnaire survey or correction of the judgment matrix is required (Yu and Chen, 2016).

Calculated as follows:

$$CI = \frac{\lambda_{max} - n}{\mathrm{n}-1} \quad CR = \frac{CI}{\mathrm{R}I}$$

Through the assembled SWOT judgment matrix, we can see that S (strength) has a priority weight of 60%, which is greater than the other three groups of factors. The priority order is S (strength) > W (disadvantage) > O (opportunity) > T (threat). The matrix CR value is 0.04, which is less than 0.1, that is, the aggregate matrix passes the consistency test. The table is as follows.

SWOT set matrix	S	W	O	T	Weights	CR
S	1.00	3.99	5.00	5.76	0.60	0.04
W	0.25	1.00	2.56	3.09	0.22	
O	0.20	0.39	1.00	2.15	0.12	
T	0.17	0.32	0.47	1.00	0.07	

(Table 4: SWOT set matrix)

According to the analysis results of each factor matrix, 'S1-Aging Community Resilience Maintenance Plan' in the S (Strengths) matrix has the highest priority weight, accounting for 43% (Table);

Strengths	S1	S2	S3	S4	S5	Weights	CR
S1	1.00	2.35	4.36	3.44	4.24	0.43	0.07
S2	0.43	1.00	2.96	3.02	3.34	0.26	
S3	0.23	0.34	1.00	2.39	2.89	0.14	
S4	0.29	0.33	0.42	1.00	2.73	0.10	
S5	0.24	0.30	0.35	0.37	1.00	0.06	

(Table 5: S (Strengths) matrix)

The weight value of 'W1-Maintenance capital does not match maintenance needs' in the W (Weaknesses) matrix is significantly higher than that of other factors, with a weight value of 21% (Table);

Weaknesses	W1	W2	W3	W4	W5	W6	W7	W8	Weights	CR
W1	1.00	1.84	1.63	1.95	2.38	2.08	3.29	1.67	0.21	0.03
W2	0.54	1.00	1.24	2.48	1.69	2.35	3.21	1.54	0.17	
W3	0.61	0.81	1.00	2.07	2.05	2.42	3.50	1.64	0.17	
W4	0.51	0.40	0.48	1.00	1.41	2.53	3.45	1.78	0.13	
W5	0.42	0.59	0.49	0.71	1.00	2.03	2.96	2.23	0.11	
W6	0.48	0.43	0.41	0.40	0.49	1.00	2.34	1.48	0.08	
W7	0.30	0.31	0.29	0.29	0.34	0.43	1.00	0.74	0.05	
W8	0.60	0.65	0.56	0.56	0.45	0.68	1.35	1.00	0.08	

(Table 6: W (Weaknesses) matrix)

The 'O1- Infrastructure dividend' priority weight value in the O (Opportunity) matrix is the highest, at 40% (Table);

Opportunities	O1	O2	O3	O4	O5	Weights	CR
O1	1.00	2.46	2.64	3.11	3.50	0.40	0.03
O2	0.41	1.00	1.04	2.35	3.06	0.21	
O3	0.38	0.96	1.00	2.75	3.69	0.22	
O4	0.32	0.42	0.36	1.00	2.20	0.11	
O5	0.29	0.33	0.27	0.45	1.00	0.07	

(Table 7: O (Opportunity) matrix)

The priority weight value of 'T1- Social awareness of the climate crisis' in the T (threat) matrix is significantly higher than other elements in the same matrix, with a weight value of 41% (Table).

Threats	T1	T2	T3	T4	T5	Weights	CR
T1	1.00	2.33	3.21	3.23	3.76	0.41	
T2	0.43	1.00	2.04	3.04	2.92	0.25	
T3	0.31	0.49	1.00	2.15	2.69	0.16	0.04
T4	0.31	0.33	0.46	1.00	2.22	0.11	
T5	0.27	0.34	0.37	0.45	1.00	0.07	

（Table 8: T (threat) matrix ）

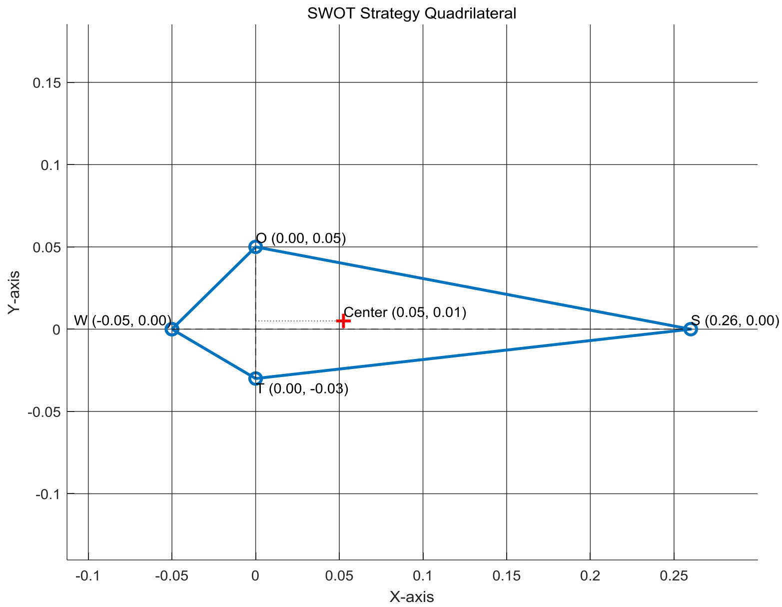
According to the total ranking table of the SWOT matrix, it can be seen that the priority weight elements in each matrix are ranked from high to low in the total ranking: ‘S1- Aging Community Resilience Maintenance Plan’, ‘W1- Maintenance capital does not match maintenance needs’, ‘O1- Infrastructure dividend’, and ‘T1- Social awareness of the climate crisis’.

SWOT	Each matrix weight value	Matrix components	The total weight of each matrix component
S	0.60	S1	0.26
		S2	0.16
		S3	0.09
		S4	0.06
		S5	0.04
W	0.22	W1	0.05
		W2	0.04
		W3	0.04
		W4	0.03
		W5	0.02
		W6	0.02
		W8	0.02
		W7	0.01
O	0.12	O1	0.05
		O3	0.03
		O2	0.02
		O4	0.01
		O5	0.01
T	0.07	T1	0.03
		T2	0.02
		T3	0.01
		T4	0.01
		T5	0.01

（Table 9: The total ranking table of the SWOT matrix ）

2.4 Draw a ‘strategy quadrilateral’ based on the SWOT-AHP analysis results:

Based on the weight values of the priority weight factors in the above list, the strategic quadrilateral is drawn using the MATLAB image drawing function, where the corresponding coordinates of S1, W1, O1, and T1 on the coordinate axes of the quadrilateral are S1 (0.26, 0), W1 (-0.05, 0), O1 (0, 0.05), and T1 (0, -0.03), respectively. The center point is in the first quadrant of the quadrilateral with coordinates (0.05, 0.01). It can be concluded that the SO strategy (developmental) should be adopted at the current stage to protect and maintain aging critical infrastructure. Through the current strategic advantages, actively matching external opportunities, coordinating the process of critical infrastructure through strong government leadership, and using technologies such as the "digital revolution" to iteratively improve the monitoring mechanism and structural stability of backward infrastructure.



(Figure 7: SWOT Strategy Quadrilateral)

IV. Conclusions

The above SWOT-AHP analysis results show that my country should adopt a SO development strategy to deal with the maintenance of aging critical infrastructure. Thanks to the reform of infrastructure management informatization, maintenance plans for backward infrastructure have been gradually carried out, and the ability to actively meet future opportunities has also been gradually strengthened. At present, China's social public security governance model has also changed from the early "post-disaster governance type" to the "pre-disaster prevention type", and the potential risks carried by aging infrastructure have been paid attention to. Under this state, the optimization of aging infrastructure protection and maintenance strategies focuses on ensuring the current implementation status of strategies while seizing opportunities, using the advantages of the maintenance strategy group to form a "leverage principle", actively driving and meeting future opportunities in critical infrastructure management, thereby generating the possibility of optimizing government structure and "electronic government management" capabilities. The specific strategy optimization implementation is as follows:

(1) From the perspective of the current maintenance strategy, the resilient maintenance strategy for aging facilities is relatively stable in the short term, but from the perspective of time nodes, the current definition of backward infrastructure is relatively vague. Infrastructure built before 2000 is generally defined as aging infrastructure, because these infrastructures have been in use for more than 20 to 30 years since the initial construction, and are generally in the middle and late stages of their entire life cycle. As the world enters the era of climate crisis, the "sensitivity" of critical infrastructure to extreme climate change is obvious. In other words,

climate change factors have accelerated the "loss" of critical infrastructure, shortening the overall operating life cycle of infrastructure that lacks resilient transformation or maintenance management. The author believes that in the context of the climate crisis era, optimizing the aging assessment standards of different infrastructures has become one of the goals that need to be considered, and the traditional assessment system is no longer applicable to the current climate crisis environment.

(2) The resilience monitoring mechanism for critical infrastructure structure and stability cannot be limited to the outside of the facility. The internal stability of the facility and the facility operation system should be divided into the monitoring area. The internal structural stability of the facility determines its climate resilience. The critical infrastructure maintenance management model in the context of the climate crisis is described as follows:

Urban critical infrastructure + digital city management platform (E-Government) + IoT sensing equipment + Critical Infrastructure Structural Health Monitoring (CI SHM)

Establish a regional digital city management platform through regional e-government, integrate the infrastructure status data in the city, set up IoT devices outside the facility to integrate monitoring data in real time and provide feedback, and use the SHM monitoring system inside the facility to digitally quantify the changes inside the facility, and finally form a digital three-dimensional monitoring system to improve the digital archives of urban management.

(3) Due to China's land area, population and geographical location, the impact of the climate crisis on different regions is different. Local governments should optimize infrastructure resilience maintenance strategies based on the characteristics of climate disasters within their jurisdiction. At the same time, through internal and social climate disaster education, they should improve and enhance the professionalism of disaster management practitioners and citizens' awareness of the climate crisis, so as to achieve the goal of optimizing the joint governance of climate disasters and timely feedback, and reduce the possibility of exposing the vulnerability of critical infrastructure.

（4）Compared with the past, disaster factors in the era of climate crisis are more complex, that is, when climate disasters occur, they are diverse and occur at the same time. When these disaster factors overlap, the vulnerability of infrastructure becomes particularly prominent. This situation often occurs in non-first-tier cities or non-central cities. We can use high-quality infrastructure management strategies to gradually radiate to surrounding areas with weak infrastructure, use our own management advantages to drive surrounding areas to reduce problems such as insufficient resilience to climate disasters under extreme climates, and build a common climate disaster defense system through the infrastructure maintenance system in core advantage areas, weakening the differences in disaster resistance in areas where key infrastructure is poorly maintained.

References

https://www.history.com/topics/natural-disasters-and-environment/history-of-climate-change

https://www.ipcc.ch/

Bulkeley H, Schroeder H, Janda K, et al. 2009. Cities and climate change: the role of institutions, governance and urban planning[J]. Change. 28: 30.

https://www.encyclopedie-environnement.org/zh/climat-zh/climate-variations-last-millennium/

https://www.worldweatherattribution.org/

https://zaihaifangyu.cn/

https://opinion.huanqiu.com/article/4A2seCI9o2Y

Moynihan D P. 2009. The response to hurricane Katrina[J]. *Geneva (Italy): International Risk Governance Council*. 27-45.

Kawata Y. 1995. The great Hanshin-Awaji earthquake disaster: damage, social response, and recovery[J]. *Journal of natural disaster science*. 17(2): 1-12.

https://www.preventionweb.net/publication/2022-global-natural-disaster-assessment-report

https://www.preventionweb.net/

Wang Jiao. 2020. From climate change to climate crisis[J]. *World Environment.* (01):19-22.

https://hub.unido.org/

The US "Protecting Critical Infrastructure" Plan[J]. *Foreign Science and Technology Trends*. 2000(03):17.

Liu Jinrui. 2016. Basic ideas and institutional construction of my country's critical network infrastructure legislation[J]. *Global Legal Review*. 38(05): 116-133.

https://georgewbush-whitehouse.archives.gov/nsc/nss/2002/

Moteff J D, Copeland C, Fischer J W, et al. 2003. Critical infrastructures: What makes an infrastructure critical?[C]. Washington, DC, USA: Congressional Research Service, Library of Congress.

https://irp.fas.org/offdocs/pdd/pdd-63.htm

Boin A, McConnell A. 2007. Preparing for critical infrastructure breakdowns: the limits of crisis management and the need for resilience[J]. *Journal of contingencies and crisis management*. 15(1): 50-59.

Lee J E. 2009. Comprehensive Security and Crisis & Emergency Management for Protecting Critical Infrastructure[J]. *International Journal of Contents*. 5(3): 71-78.

EU Commission. 2004. Critical Infrastructure Protection in the fight against terrorism[J].

Aradau C. 2010. Security that matters: Critical infrastructure and objects of protection[J]. *Security dialogue*. 41(5): 491-514.

Cimellaro G P, Reinhorn A M, Bruneau M. 2010. Framework for analytical quantification of disaster resilience[J]. *Engineering structures*. 32(11): 3639-3649.

https://www.coe.int/t/dg4/majorhazards/ressources/Apcat2005/APCAT-2005-26-e-rapport-kobe.pdf

Zio E. 2016. Challenges in the vulnerability and risk analysis of critical infrastructures[J]. *Reliability Engineering & System Safety*. 152: 137-150.

Report Card for Americas Infrastructure Full Book. 2009

Report Card for Americas Infrastructure Full Book. 2013

Armbruster G, Endicott-Popovsky B, Whittington J. 2013. Threats to municipal information systems posed by aging infrastructure[J]. *International Journal of Critical Infrastructure Protection.* 6(3-4): 123-131.

Holický M, Diamantidis D, Sýkora M, et al. Methods for the risk assessment and risk-based management of aging infrastructure[J]. 2014.

Jia Jingwen. 2024. Analysis of life cycle maintenance strategy of port infrastructure based on cost assessment model[J]. *Sichuan Cement*.

(02):63-65.

Liu Tielian. 1985. On the content, characteristics and benefit evaluation of urban infrastructure[J]. *Quest*. (06):49-51.

The basic principles of systems theory https://sass.usst.edu.cn/2021/1103/c12540a258365/page.htm

Long A. 2008. Sustainable bridges through innovative advances[C]//*Transport Research Foundation, Fellowship Lecture*.

D.M. Gann. 2000. Building innovation: Complex constructs in a changing world. *London, Thomas Telford*. 5p.

Van Breugel K. 2017. Societal burden and engineering challenges of ageing infrastructure[J]. *Procedia Engineering*. 171: 53-63.

Zimmerman R, Restrepo C E, Simonoff J S. 2009. Infrastructure Age, Security, and Natural Hazards[J].

Burns P, Hope D, Roorda J. 1999. Managing infrastructure for the next generation[J]. *Automation in construction*. 8(6): 689-703.

Goel H D, Grievink J, Weijnen M P C. 2003. Integrated optimal reliable design, production, and maintenance planning for multipurpose process plants[J]. *Computers & chemical engineering*. 27(11): 1543-1555.

Sherwin D. 2000. A review of overall models for maintenance management[J]. *Journal of quality in maintenance engineering*. 6(3): 138-164.

Department of Defense Reliability, Availability, Maintainability, and Cost Rationale Report Manual. United States Department of Defense(DoD). 2009.

Anand, Nikhil, Akhil Gupta, and Hannah Appel, eds. 2018. The promise of infrastructure. *Duke University Press*.

Ramakrishnan, Kavita, Kathleen O'Reilly, and Jessica Budds. 2021. "The temporal fragility of infrastructure: Theorizing decay, maintenance, and repair." *Environment and Planning E: Nature and Space*. 4.3: 674-695.

Kazantzidou Firtinidou D, Gkotsis I, Eftychidis G, et al. 2019. Climate Related Business Continuity Model for Critical Infrastructures[J]. *Annals of Disaster Risk Sciences: ADRS*. 2(1-2): 11-27.

Blokus A, Dziula P. Relations of imperfect repairs to critical infrastructure maintenance costs[J]. *Sustainability*, 2021, 13(9): 4917.

Fang Y P, Pedroni N, Zio E. 2016. Resilience-based component importance measures for critical infrastructure network systems[J]. *IEEE Transactions on Reliability*. 65(2): 502-512.

Kim J, Ahn Y, Yeo H. 2016. A comparative study of time-based maintenance and condition-based maintenance for optimal choice of maintenance policy[J]. *Structure and Infrastructure Engineering*. 12(12): 1525-1536.

Stenström C, Norrbin P, Parida A, et al. 2016. Preventive and corrective maintenance–cost comparison and cost–benefit analysis[J]. *Structure and Infrastructure Engineering*. 12(5): 603-617.

Kaur K. 2023. System Reliability, Availability, and Maintainability[J]. *Availability, and Maintainability* (September 23, 2023)

https://sebokwiki.org/wiki/System_Reliability,_Availability,_and_Maintainability#Maintainability

https://www.linkedin.com/pulse/symbiotic-trio-reliability-availability-paul-nation-yaa6c

https://blog-pfm.imf.org/en/pfmblog/2019/05/why-maintaining-public-infrastructure-is-so-important

Chen Tan, Yan Yan. Theoretical propositions and practical paradigms of urban lifeline management (http://gupa.gzhu.edu.cn/info/1086/12862.htm)

Watson D. 2017. Urban lifelines to achieve climate resiliency[M]//*Growing Compact. Routledge*. 51-63.

https://www.usatoday.com/story/news/nation/2015/07/19/i-10-collapse-california/30399815/

https://www.azcentral.com/picture-gallery/news/local/arizona/2023/08/18/i-10-bridge-collapse-joins-arizona-and-california-photos/70627675007/

https://baike.baidu.com/item/7%C2%B718%E6%B5%8E%E5%8D%97%E7%89%B9%E5%A4%A7%E6%9A%B4%E9%9B%A8/19838671

Lu Huapu, 2014, 9. Case and Strategy Study of the Influences of Abnormal Weather and Natural Disasters on Transportation. Institute of Transportation Studies, Tsinghua University.

Energy Institute. 2023. Statistical Review of World Energy[J].

https://www.mohurd.gov.cn/xinwen/gzdt/202207/20220715_767202.html

https://den.ncdr.nat.gov.tw/1132/1188/1205/14621/20191/

Holling C S. 1973. Resilience and stability of ecological systems[J]. *Annual Review of Ecology and Systematics*. 4(1): 1-23.

Walker B, Holling C S, Carpenter S R, et al. 2004. Resilience, adaptability and transformability in social–ecological systems[J]. *Ecology and society*. 9(2).

Gunderson L H, Holling C S. 2002. Panarchy: Understanding transformations in human and natural systems[M]. *Island press*

Jha, Abhas K., Todd W. Miner, and Zuzana Stanton-Geddes, eds. 2013. Building urban resilience: principles, tools, and practice. *World Bank Publications*,

Shi L, Zheng Q, Yang M, et al. Sin, 2022. A review of definitions, influence factors and assessment of urban resilience[J]. *Acta Ecol*. 42(14): 601-6029.

Yang Xianhu, Yao Yuanyuan, Zhang Yuyu, Liu Xingrong. 2024. Visualization analysis of climate resilience research: based on CiteSpace and VOSviewer[J]. *Science Observation*. 19(01): 31-38.

https://www.ipcc.ch/report/ar6/wg2/chapter/chapter-18/

https://www.oecd.org/environment/cc/policy-perspectives-climate-resilient-infrastructure.pdf

https://news.jnu.edu.cn/content/202311/30/c1981.html(Li Weiquan: Resilient cities have four core characteristics: carrying capacity, resilience, reliability and intelligence)

Lee J E. 2015. 코어 시스템 (Core System) 과 국가위기관리시스템의 개선 방향[J]. *한국위기관리논집*. 11(8): 1-18.

The main connotation, common characteristics and government responsibilities of infrastructure (https://www.sohu.com/a/313776536_828724)

Wang Lin, Gu Shenghui, Suo Weilan. 2024. Research on the protection and repair resource allocation of urban key infrastructure considering multiple connections under the guidance of resilience[J/OL]. *Chinese Journal of Management Science*: P1-P15.

https://wiki.mbalib.com/wiki/%E5%B1%82%E6%AC%A1%E5%88%86%E6%9E%90%E6%B3%95

https://pride.stpi.narl.org.tw/index/graph-world/detail/4b1141ad870eff16018721393a745160

Zhou Zhenyu, Chen Yu, Li Liangping, et al. 2021. Research on the evaluation of state-owned forest tourism landscape based on SWOT-PEST and AHP method[J]. *Journal of Central South University of Forestry and Technology (Social Sciences Edition)*.

Rajput T S, Singhal A, Routroy S, et al. 2021. Urban policymaking for a developing city using a hybridized technique based on SWOT, AHP, and GIS[J]. *Journal of Urban Planning and Development*. 147(2): 04021018.

Guo X, Yan H, Yuan W. 2019. Research on China's Rural Development Strategy Based on SWOT-AHP Analysis[J]. *International Research in Economics and Finance*. 3(1): 10.

Kurttila M, Pesonen M, Kangas J, et al. 2000. Utilizing the analytic hierarchy process (AHP) in SWOT analysis—a hybrid method and its application to a forest-certification case[J]. *Forest policy and economics*. 1(1): 41-52.

Guo Yun, Gao Li, Feng Nanping. 2011. Strategic analysis of my country's ecological industrial park enterprises based on SWOT-AHP[J]. *Science and Technology Progress and Policy*. 28(1): 63-67.

Zhang Y, Yuan L, Ye T. 2020. Management Innovation of Marine Cultural Industry Based on SWOT and AHP[J]. *Journal of Coastal Research*. 112(SI): 199-202.

Song Xiaojie, Han Yitao, Li Chunhua, An Chunmei, Xie Gang. 2023. Strategic selection of my country's grain inspection and testing institutions based on SWOT-AHP[J]. *Chinese Journal of Food Hygiene*. 35(03): 416-421.

https://www.gov.cn/lianbo/bumen/202307/content_6892957.htm

https://pic.bankofchina.com/bocappd/rareport/202107/P020210728580173029135.pdf

https://www.thepaper.cn/newsDetail_forward_26427482

Yu Shunkun, Chen Li. 2016. SWOT analysis and development strategy selection of food safety testing intellectual property alliance[J]. *Chinese Journal of Management Science*. 24(2): 169-176.

Zhang Chengcheng. 2024. Research on infrastructure renovation of old urban communities from the perspective of resilience[J]. *Engineering Economics*. 34(02): 72-76.

Tang Renmin. China's infrastructure development has achieved historic achievements since the 18th National Congress of the Communist Party of China[J]. *China Economic and Trade Guide*, 2022(11):29-36.

Han Hongwei. *Juye*, 2021. Analysis on strategies for optimizing municipal street lamp management and daily maintenance[J]. (07):114-115.

https://www.cics-cert.org.cn/web_root/webpage/articlecontent_102005_3275.html

Hu Mengzhu. 2024. Infrastructure resilience: a new perspective on understanding urban spatial risk governance[J]. *Local Governance Research.* (02):40-52+79.

Yao Tianxiang, Li Wanlian. 2024. Accelerate the construction of high-quality, resilient and safe cities. China Social Sciences Network - *China Social Sciences Daily*.

Gu Changping. 2018. Research on Problems and Countermeasures in Urban Infrastructure Maintenance and Management[J]. *Shanghai Construction Science and Technology*. (04):97-99+103.

Zhang Xiuwei. 2011. On the necessity and measures of implementing precise and detailed management in the construction and maintenance of urban municipal public infrastructure[J]. *Friends of Science*. (09):118-119.

Wan Xiaomeng, Guo Yanan. 2018. An empirical analysis of local government debt risk assessment: from the perspective of infrastructure maintenance costs[J]. *Journal of Jiangsu Normal University (Philosophy and Social Sciences Edition)*. 44(05): 135-143.

Bi Wei, Tang Yuchun, Mao Tingting, Sun Xinhong, Li Qiming. 2021. A review of resilience management of urban infrastructure systems[J]. *China Safety Science Journal*. 31(06): 14-28.

https://www.gov.cn/lianbo/bumen/202307/content_6892957.htm

Ma Shuting. 2021. Research on the maintenance and management of public infrastructure in L city ports[D]. *China University of Mining and Technology, Master of Public Administration.*

Yang Guoliang. 2022. Research on the digital transformation of traditional infrastructure: Taking agriculture and industry as examples[J]. *Science and Technology for Development*. 18(03): 401-407.

https://h5.drcnet.com.cn/docview.aspx?version=gov&docid=7227171&leafid=3003&chnid=1013

Fang Zhuo. 2023. Structural health monitoring and maintenance technology based on civil infrastructure[J]. *China Building Metal Structure*. 22(07): 72-74.

Wang Lin, Gu Shenghui, Suo Weilan. Research on the protection and repair resource allocation of urban key infrastructure considering multiple connections under the guidance of resilience[J/OL]. *Chinese Journal of Management Science*: 1-15

https://www.workercn.cn/c/2021-03-02/6544824.shtml

TANG X. 2021. Function of New Infrastructures on National Governance Modernization[J]. *Bulletin of Chinese Academy of Sciences (Chinese Version)*. 36(1): 79-85.

Ulrich Brand, Gold Steinfens, Liu Lingyu, Liu Jingjiao. 2022. Climate crisis and social learning[J]. *Journal of Nanjing Tech University (Social Sciences Edition)*. 21(05): 60-69+116.

Wang Yang, Gong Ruoyan, Xu Peizhi, Sun Xueliang, Tang Yufei. Evolution of public opinion crisis of infrastructure trust under extreme climate[J/OL]. *Complex Systems and Complexity Science*: 1-12

Zhang Hui, Xu Fuming, Li Bin, et al. Risk perception based on climate change[J]. *Advances in Psychological Science*, 2013, 21(9): 1677.

https://pic.bankofchina.com/bocappd/rareport/202107/P020210728580173029135.pdf

https://www.thepaper.cn/newsDetail_forward_26427482