Research on Risk Evaluation of Flooding in Immersed Tunnels During Operation

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Abstract: As more and more immersed tunnels are built in China, due to the characteristics of closed space, long-term structure in deep water, and complicated surrounding environment, if an accident occurs during the operation period, it will cause immeasurable losses. The safety risks faced during the period must also be taken seriously. This paper analyzes the causes of flooding risks and identifies the sources of flooding risks for the flooding risks faced during the operation of the immersed tunnel. Based on the scenario design and simulation analysis, the impact on the tunnel structure at different depths of flooding and the consequences of flooding on immersed tunnels are proposed. Based on this, anti-flooding measures and related suggestions for immersed tunnels during operation are proposed.

1. Introduction

Immersed tunnels have many excellent features such as shallow burial depth and strong adaptability to strata. Owing to it, immersed tunnels have been widely used in the construction of underwater tunnels in China. Although the amount of immersed tunnel construction is small, more and more cross-river and cross-sea channel projects are giving priority to immersed tunnels [1-2].

Immersed tunnels are laid underwater, sealed off, and waterproofing. Once an accident occurs, the damage will be incalculable. Besides, their operational safety risks have their characteristics, such as fire, earthquake, explosion, flooding, traffic accidents, shipwreck. This paper discusses the risk of flooding in the operation of immersed tunnels as follows [3].

(1) Analysis of flooding risks in immersed tunnels to determine the causes of flooding in immersed tunnels.

(2) Numerical analysis of the impacts of different depths of the flooded section on the structure of the immersed tunnel through scene simulation.

(3) Obtain the consequences of the impacts of the immersed tunnel under flooding conditions and propose flooding prevention measures and recommendations based on the calculation results.

2. Analysis of Flooding Risks in Immersed Tunnels

By analyzing and identifying the risk sources of flooding in immersed tunnels during operation, the key flooding risks in immersed tunnels during operation are obtained, which can be divided into five major categories: severe weather; vehicle accidents in tunnels; earthquakes; war and terrorist attacks; and other accidents [4].
Figure 1. Key risks of flooding of immersed tunnels

(1) Severe Weather

According to the analysis of severe weather, tunnel flooding is mainly caused by heavy rain and strong wind and rainstorm.

In coastal areas of China, each heavy rain generally lasts less than one day, and only torrential rain can cause tunnel flooding accidents. In addition, some urban tunnels have experienced tunnel flooding accidents of varying severity during severe weather conditions. This kind of severe weather mainly refers to heavy rain, including pure heavy rain and strong wind and rainstorm accompanying typhoons and other severe weather. The latter has a greater impact on tunnel flooding. Generally, in the tunnel design stage, the tunnel's drainage capacity should be calculated according to the local rainstorm recurrence period, and a certain design margin should be left. When the volume of torrential rain exceeds the drainage capacity of the tunnel drainage system, the tunnel may be at risk of flooding. Also, the lower drainage capacity of the surrounding areas of the tunnel will increase the risk of tunnel flooding.

(2) Vehicle Accidents in Tunnels [5-8]

According to the structural form of the immersed tunnel, the fire mains of the immersed tunnel are generally arranged in the middle of the tunnel or the pipe gallery below the tunnel. There is a partition wall between the middle pipe gallery and the vehicular space, which can well protect and prevent the vehicle collision from damaging the fire mains. The side of the vehicular space is arranged with a firebox and a fire branch pipe. The firebox can provide some protection for firefighting facilities, to prevent minor vehicle collisions from damaging fire hose. But for serious collision, the protection ability is still not enough.

(3) Earthquakes

According to the seismic design, the tunnel itself can withstand a certain degree of an earthquake disaster. When the degree of earthquake disaster exceeds the seismic design value, the tunnel structure may be damaged to some extent. For flooding accidents, this kind of damage is generally caused by a crack in the structure, which results in the surrounding seawater entering the tunnel through the crack. But it generally occurs in more severe earthquake disaster situations. Another form of tunnel flooding resulted from earthquakes is that the earthquake triggers a tsunami or an unusually high tidal level. Although the tunnel does not have a crack where the seawater can enter, the seawater will flow into the tunnel from the holes at the tunnel ends or the artificial island in case of a high water level, resulting in flooding.

(4) War and Terrorist Attacks

War and terrorist attacks will have an impact on the tunnel structure. For tunnel flooding, one possible impact is that they cause a crack on the tunnel and may even lead to the collapse of the top structure of the tunnel. Seawater pours into the tunnel from the crack or the collapse section, resulting in flooding.
accidents. This kind of damage is similar to that caused by earthquakes, which result in structural cracks, further leading to tunnel flooding accidents.

(5) Other Accidents

Other accidents that may cause tunnel flooding mainly refer to ship collision. The impact of ship accidents on the tunnel mainly includes the following aspects: the impact of ship grounding on the shallow buried section of the tunnel; the pressure of sunken ships on the tunnel; the impact of anchor dropping on the tunnel; the impact of dredging anchor on the tunnel; the impact of the flow field around the propeller of super-large ships on the protection layer structure of the tunnel.

3. Immersed Tunnel Flooding Accident Scenario Design and Simulation Analysis

According to relevant information and analysis, tunnel flooding caused by severe weather and vehicle accidents in tunnels is generally not very serious, while tunnel flooding caused by earthquakes, war, terrorist attacks, and shipwrecks is relatively more serious. The consequences of flooding caused by water infiltration from tunnel openings are generally less severe than those caused by structural damage of tunnels. In this paper, the consequences of tunnel flooding are divided into three conditions for separate consideration, namely one-third tunnel section flooding, half tunnel section flooding, and full tunnel section flooding [7].

3.1. Transversal Calculation Analysis of Flooding Conditions

For the calculation part, this paper selects the section with poor geological conditions and analyzes the structural deformation and internal force changes of the tunnel during 1/3 flooding, 1/2 flooding, and full flooding, respectively.

When 1/3 of the tunnel is flooded, the calculation model and mesh division are shown below.

![Calculation model at 1/3 of flood](image1)

Figure 2. Calculation model at 1/3 of flood

![Additional displacement cloud map of soil around 1/3 of flood](image2)

Figure 3. Additional displacement cloud map of soil around 1/3 of flood
Figure 4. Additional deformation and internal force diagram of 1/3 immersed tube structure under water flooding

When 1/2 of the tunnel is flooded, the analysis are shown below.

Figure 5. Additional displacement cloud image of soil around flooded 1/2
When the tunnel is fully flooded, the analysis are shown below.

Figure 6. Additional deformation and internal force diagram of flooded 1/2 immersed tube structure

Figure 7. Additional displacement cloud map of surrounding soil
Figure 8. Additional deformation and internal force diagram of immersed tube structure when fully flooded

Table 1. Summary of additional displacements and internal forces of immersed tunnel structures under various conditions

|            | Additional Bending Moment (kN·m) | Additional Shear Force (kN/m) | Additional Axial Force (kN/m) | Additional Settlement (mm) |
|------------|----------------------------------|-------------------------------|-------------------------------|---------------------------|
|            | M+                               | V+                            | F+                            |                           |
| 1/3 Flooding | 419.7                            | 204.9                         | 180.5                         | -30.4                     |
| 1/2 Flooding | 329.2                            | 170.4                         | 249.8                         | -49.8                     |
| Full Flooding | 591.2                           | 464.3                         | 601.8                         | -99.3                     |

3.2. Longitudinal Calculation Analysis of Flooding Conditions
In this paper, the additional longitudinal deformation and internal force changes of the tunnel structure are analyzed for the 1/3 flooding, 1/2 flooding, and full section flooding conditions respectively. Longitudinal calculation model and cloud map of the immersed tunnel when 1/3 of the tunnel is flooded.
Figure 9. Longitudinal calculation model of immersed tunnel at 1/3 water flood

Figure 10. Longitudinal displacement cloud image of immersed tunnel at 1/3 of flood

Figure 11. Shear cloud diagram of immersed tube tunnel at 1/3 of flood

Figure 12. Moment cloud diagram of immersed tube tunnel when flooded by 1/3

Longitudinal calculation model and cloud map of the immersed tunnel when 1/2 of the tunnel is flooded.

Figure 13. Longitudinal and vertical displacement cloud image of immersed tube tunnel when flooded 1/2

Figure 14. Shear cloud diagram of immersed tube tunnel at 1/2 flood
3.3. Impacts of Flooding on the Immersed Tunnel

According to the calculation analysis, for the immersed tunnel method, because the tunnel is set in a shallow layer, the tunnel can be seriously affected by the soft soil layer, and the deformation generated under flooding conditions is larger.

(1) When 1/3 of the tunnel is flooded, for the burial depth of the immersed tunnel is shallow, resulting from the impact of the deep soft soil on the surface, the additional deformation and internal force are relatively large after flooding. But according to the longitudinal calculation, the internal force of the joints is still basically within a tolerable range of the structure and will not cause obvious damage to the tunnel structure.

(2) When 1/2 of the tunnel is flooded, for the burial depth of the immersed tunnel is shallow, resulting from the impact of the deep soft soil on the surface, the additional deformation and internal force is relatively large after flooding. But according to the longitudinal calculation, the internal force of the
joints is still basically within a tolerable range of the structure and will not cause obvious damage to the tunnel structure.

(3) When the tunnel is fully flooded, for the burial depth of the immersed tunnel is shallow, resulting from the impact of the deep soft soil on the surface, the additional deformation and internal force is relatively large after flooding. But according to the longitudinal calculation, the internal force of the joints is beyond the tolerable range of the structure in regular operation but still within the acceptable range of abnormal load. Therefore, if the water is emptied as soon as possible after the tunnel is flooded, it will not cause serious damage to the tunnel structure.

4. Control of Flooding Risks in Immersed Tunnels

4.1. Principles of Flood Prevention Measures
Flood prevention in tunnels mainly depends on active flood prevention, especially for tunnel flooding caused by structural cracks, which is usually destructive. Therefore, it is necessary to consider the problem of tunnel flood prevention in the planning and design stage and take flood prevention into consideration in the design of standards and plans so as to design a series of components and measures to avoid tunnel flooding.

4.2. Current Status and Importance of Flood Prevention Design
At present, there are no special regulations on flood prevention in China, but the National Flood Control Standard and other industry standards have some special regulations regarding flood prevention, which are available for reference. There are no specific flood protection design standards for tunnels in China, and most of the flood protection involved is based on the requirements of the Code for Design of Metro (GB50157-2013).

When the tunnel is under construction and normal operation, and when it is damaged by explosions, earthquakes, war, or other unexpected accidents during the flood season, the seawater will no longer be blocked and can be quickly diffused into the tunnel, endangering people's lives and properties. In order to prevent the risk of flooding in the tunnel under this special condition, flood prevention doors are designed at both ends of the water, so that in case of emergency, the flood prevention doors can be closed quickly to prevent seawater from invading and ensure the safety of the tunnel, people's lives, and properties. According to the experience of the river-crossing subway tunnel, the flood prevention door system is installed in a special location, the construction cycle is short, and it is closely related to civil construction, power supply, and other specialties. Therefore, it is necessary to make careful consideration during design and construction.

4.3. Other Flood Prevention Measures
(1) Severe Weather
Tunnel flooding caused by severe weather can only be prevented by the tunnel's own drainage facilities and flooding prevention structure, such as strengthening the power of drainage pumps, setting up backup pumps, setting up flood prevention doors.

(2) Vehicle Accidents in Tunnels
Flooding prevention measures for tunnel flooding caused by vehicle accidents in tunnels mainly include setting up anti-collision protection measures for fire hoses. It should be specifically noted that fire mains should not be set in the vehicular space as far as possible. Good anti-collision protection measures should also be conducted for fire branch pipes in the vehicular space. Foam water spray pipes and other pipes must be equipped with certain protection measures when they pass over the tunnel. Meanwhile, management in tunnels should be strengthened. Illegal overtaking and ultra-high and over-limit vehicles shall be prohibited in tunnels to ensure the arrangement of traffic in the tunnels, thus reducing the probability of tunnel flooding caused by vehicle accidents.

(3) Earthquakes
Earthquake-induced tunnel flooding cannot be reduced in terms of the likelihood of occurrence but can only be controlled in terms of reducing the consequences of tunnel flooding. The main measure is to strengthen the seismic capacity of the structure, which needs to be considered in conjunction with the seismic standards and design flooding standards of the project.

(4) War and Terrorist Attacks

For tunnel flooding caused by war and terrorist attacks, on the one hand, we can strengthen the explosion resisting capability of the tunnel so that the tunnel can withstand the impact of man-made explosions. On the other hand, we can strengthen the tunnel management to prevent vehicles with dangerous goods from entering the tunnel. Explosion-proof checking can be set in front of the tunnel entrance to prevent the explosive source from entering the tunnel, thus reducing the possibility of tunnel flooding caused by this situation. For war-induced tunnel flooding, as the war attack is usually relatively clear, the attack may be made within the island or outside the tunnel. For this situation, the attack cannot be avoided through technical and management measures, and we can only strengthen the explosion resisting capability of the tunnel.

(5) Other Accidents

Other accidents mainly refer to shipwreck collision. For the prevention of shipwreck collision, on the one hand, we can strengthen the anti-collision ability of the outer protective layer of the tunnel, and on the other hand, we can strengthen the promotion and management of the vessels in this area. Meanwhile, we shall strengthen the rescue capability in the ship accident-prone areas so as to minimize the occurrence of shipwreck accidents.

5. Summary

Through the transversal and longitudinal calculation analysis of the immersed tunnel under flooding conditions, the following conclusions can be initially obtained.

(1) Flooding in immersed tunnels is mainly caused by five factors: severe weather, which results in rainwater entering the tunnel from the openings; vehicle accidents in the tunnel, which lead to the rupture of fire hoses in the tunnel, causing the fire water into the tunnel; earthquakes, which result in the tunnel cracks so that the seawater pours into the tunnel from the cracks, or lead to a tsunami and high tidal level so that the seawater pours into the tunnel from the openings; war and terrorist attacks, and other explosion-related situation, which lead to structural cracks in the tunnel so that the seawater pours into the tunnel; other reasons such as sunken ship collision, which lead to structural cracks in the tunnel so that the seawater pours into the tunnel.

(2) According to the simulation of flooding accident scenarios, the structure of the tunnel is not seriously damaged when one-third or one-half of the tunnel is flooded. When the tunnel is fully flooded, the structure may reach its bearable limit, but if the water in the tunnel can be drained off as soon as possible so that the flooding is only a short condition, the structure of the tunnel can also be not seriously damaged through structural strengthening measures.

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