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RESEARCH ON THE CLASSIFICATION OF LIFE-CYCLE SAFETY MONITORING LEVELS OF SUBSEA TUNNELS

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ABSTRACT

As a traffic engineering project across straits or gulfs, subsea tunnel is one of the oceaneering with great construction difficulties, and the key to the success of subsea tunnel engineering lies in timely and accurate assessment of the structure safety of subsea tunnel engineering construction and life-cycle. Xiang'an Xiamen subsea tunnel is China's first subsea tunnel which crosses complex formation conditions, engineering accidents such as collapse, sudden inflow of water or mud might occur during tunnel construction and operation. Therefore, the concept of subsea tunnel life-cycle monitoring is proposed aiming at the particularity of subsea tunnels. The variation forms of subsea tunnel mainly include large deformation, collapse, primary support cracking, water leakage, water pressure increase, steel arch corrosion, concrete corrosion, longitudinal differential settlement, etc., and classification of the life-cycle safety monitoring levels of the subsea tunnel is conducted based on risk assessment theory and risk level management benchmark to determine the possible variation forms in the monitoring level segments. The research results will provide reference for the subsea tunnel life-cycle monitoring, disaster warning as well as risk management under construction or to be built at home and abroad.

Keywords: Subsea tunnel; Life-cycle; Safety monitoring; Monitoring level; Disaster warning

INTRODUCTION

The life-cycle period of engineering structure mainly includes selection of construction scheme, structure design, construction, operation, aging and abolishment. In recent years, the concept of engineering structure life-cycle is gradually adopted by engineering scholars. American Institute of Architects (1977) proposed the initial concept and thought, research risks and analysis methods of life-cycle economic analysis[1]. Flanagan (1984) made an in-depth discussion of the technical requirements, reasonable cost and other issues involved in life-cycle period cost management starting from the angle of architectural economics[2]. Frangopol (1999) proposed a cost-benefit bridge method combining life cycle reliability and life cycle cost[3]. At present, domestic and foreign researches on project life-cycle are mainly focused on life-cycle cost as well as life-cycle design and life-cycle management of bridge engineering, researches on life-cycle of subsea tunnel engineering are rarely seen, and the concept of life-cycle is merely introduced in tunnel risk analysis[4,5].

In recent years, research on long-term safety monitoring of major projects has attracted more and more widespread attention in engineering circle, long-term safety monitoring system has been effectively implemented in the safety monitoring of long-span bridges in the United States, Canada, Europe, Japan, South Korea and other countries[6,7,8,9,10,11]. For example, long-term structural safety monitoring system has been installed on Confederation Bridge in Canada[12], Commodore Barry Bridge in the US[13], Akashi Kaikyo Bridge in Japan[14], Seohae Bridge in South Korea[15]. In China, structural safety monitoring and working condition assessment system has been installed on Tsing Ma Bridge in

Hong Kong[16], Nanjing Yangtze River Bridge[17] and Wuhu Yangtze River Bridge[18], etc., providing a scientific decision-making basis for the management and maintenance of bridges. However, there is less research on long-term structural safety monitoring system for subsea tunnel engineering.

Since subsea tunnels cross stratums with complex geological conditions and high hydraulic pressure, material performance degradation caused by seawater corrosion, earthquakes and other factors will seriously imperil the safety of subsea tunnels. In case structural damage occurs during tunnel operations, it can easily lead to collapse, sudden inflow of water or mud and other disasters, causing disastrous consequences to the lives and property security of human. Therefore, it is of very important practical engineering significance to ensure the safety and durability of tunnels by establishing life-cycle safety monitoring levels of tunnel structure, real-time monitoring of the safety performance and stress state during tunnel construction, operation and aging maintenance phases as well as health diagnosis and safety assessment.

As China's first subsea tunnel, Xiang'an Xiamen subsea tunnel crosses multiple tectonic fracture zones at different positions, the fracture zones are composed of fully-heavily weathered granite with low rock mass strength and poor self-stability that are prone to seepage failure and other disasters. Thereby, we introduced project life-cycle concept in subsea tunnel monitoring and carried out research on the classification of life-cycle safety monitoring levels of the subsea tunnel by taking Xiang'an subsea tunnel engineering as the research object, the research results will provide valuable reference to similar projects at home and abroad.

RESEARCH BACKGROUND

Located in the northeast part of Xiamen Island, Xiang'an Xiamen subsea tunnel is a high-level highway and city fast track connecting Xiamen Island and the continental shelf of Xiang'an District, see the location map of Xiang'an Xiamen subsea tunnel in Fig. 1.

Fig. 1. Schematic diagram of proect location

With a total tunnel length of about 6.05 km, Xiamen subsea tunnel is designed in a 3-tunnel pattern, both sides are the main vehicle cross passageways, the middle is a tunnel for service; wherein the left and right main vehicle cross passageways adopt 6 two-way lanes with design driving speed of 80 km/h, the clear height of construction clearance is 5.0 m, net width is 13.5 m, and the distance between center lines of the main vehicle cross passageways is 52 m, see Fig. 2. There are 2 ventilation shafts, 5 transverse vehicle cross passageways and 12 transverse pedestrian cross passageways along the tunnel. Since Xiang'an subsea tunnel is located in national rare marine life protection zones of Chinese white dolphins and Xiamen amphioxus, the construction scheme of underground subsea tunnel excavation is eventually adopted upon considering marine life protection, port resource protection, geological conditions, engineering technology and cost, natural landscape and other factors.

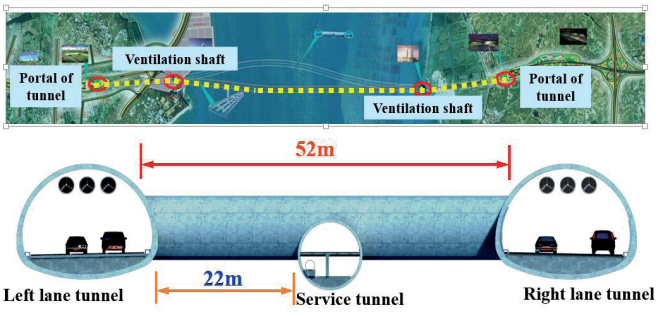

Fig. 2. Schematic diagram of the cross-section of tunnel layout

On account of being the first subsea tunnel on Chinese mainland, the following keys and difficult points were encountered during tunnel construction.

1) Extra large cross-section of tunnel excavation

The main passageway of Xiang'an subsea tunnel adopts a 3-lane highway tunnel, with clear height of construction clearance of 5.0 m and net width of 13.5 m. The maximum excavation span is 16.84 m, the largest excavation height is 12.26 m, and the largest cross-section of tunnel excavation volume reaches 170 m^2.

2) Land and shoal segment crosses a long distance of fully-heavily weathered granite

Xiang'an subsea tunnel mainly crosses fully-heavily weathered granite strata in land and shoal segment, with a total length of 6,244 m, high underground water level and certain hydraulic pressure. Tunnel depth is shallow, which is generally 4-42 m.

3) Seabed segment crosses weakly weathered bladder trough

Xiang'an subsea tunnel mainly crosses F1, F2 and F3 fully-heavily weathered deep troughs and F4 fully-heavily weathered deep bladder, with a total length of 1,121 m, general depth of 21-53.7 m and water depth of 7.8-26.2 m.

4) Crossing a wide range of sand layer

Xiang'an tunnel crosses a sand layer in Xiang'an end, with a total length of 1,721.5 m and general depth from the tunnel vault of 9-36.94 m.

5) Supporting system requires high durability

The design life of Xiang'an tunnel is 100 years, considering primary support, secondary lining as well as waterproof

and drainage system in seawater environment require higher durability, therefore higher concrete durability is required for secondary lining. The level of concrete strength used for structural design shall not be lower than C45, seepage resistance level shall reach P12, and 90 d chloride diffusion coefficient shall be less than 2.0×10^{-12} m^2/s as required by construction requirements.

ANALYSIS OF SUPPORTING STRUCTURE VARIATION FORMS IN SUBSEA TUNNELS

Collapse, large deformation, supporting structure corrosion, primary support cracking, water leakage and other variations appeared in the construction process of Xiang'an subsea tunnel, we obtained factors that influence the safety of tunnel structure through an investigation of these variations.

1) Large deformation

Xiang'an tunnel crosses completely weathered granite, multiple weathered deep troughs, water-rich sand layer and weak surrounding rock segments that have obvious rheological properties, resulting in large deformation of the supporting structure during tunnel construction, and the surrounding rock deformation will be developed due to the "time effect". Upon conducting secondary lining supporting, surrounding rock deformation will also increase over a long period of time.

According to the displacement monitoring results in site construction phase, see the relations of data and reserved deformation in primary support monitoring cross-section that is sandy clay super shallow land segment with left tunnel in Fig. 3.

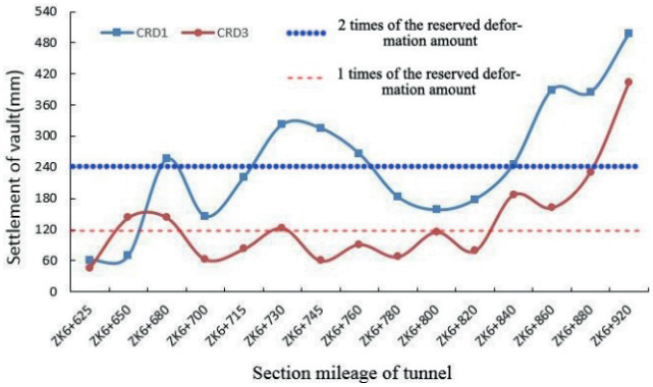

Fig. 3. Settling volume of sandy clay super shallow buried monitoring cross-section in the left tunnel

AS seen from Fig. 3, the maximum settling volume of the primary support CRD1 vault in sandy clay super shallow buried land segment is about 480.9 mm, and the minimum settling volume is about 62 mm, part of the segments occur large deformation that is greater than 2 times of the reserved deformation amount, causing variations of the supporting structure. Since the surrounding rock and supporting structure occur large deformation, severe consequences caused therefrom are shown in Fig. 4, such as the intrusion of surrounding rock in tunnel lining clearance limit, concrete cracking or peeling, steel support distortion, etc., seriously affecting construction safety, lining quality and construction period of the tunnel.

Fig. 4. Concrete peeling and steel arch distortion of primary support in subsea tunnels

2) Collapse

Subsea tunnel structure collapse will cause voids behind the lining and changes in the stress field of surrounding rock, upon conducting backfilling of the collapsing segments, the surrounding rock on tunnel crown will form loose pressure, which can cause severe stress abnormalities in lining structure, and a strong impact on the long-term safety performance of structure. During tunnel construction, collapse incidents occurred many times, see Fig. 5.

Fig. 5. Intrusion of surrounding rock and primary support in clearance limit of subsea tunnel

3) Primary support cracking and water leakage of tunnel

Water leakage of the structure will affect the durability of structural materials, in particular, under the special hydrological and geological environment between the sea and tidal tunnel segments, seawater corrosion on tunnel

structure can not be ignored, lining cracking and water leakage will seriously affect the life of tunnel structure. The primary support cracking and water seepage on Xiang'an Xiamen subsea tunnel site are as shown in Fig. 6.

(a) Cracking and water seepage of primary support

(b) Cracking and water seepage of primary support

Fig.6. Schematic diagram of cracking and water seepage of primary support on site

4) Water pressure increase

The total head of the seawater is 50-65 m and the maximum hydrostatic pressure of the crown is 0.65 MPa in the ground where Xiang'an tunnel crosses, since the subsea tunnel is located under the underwater rock, its top seawater can be infinitely supplied. With the passage of time, due to the serious corrosion of seawater on grouting water shutoff materials and advanced support, the permeability coefficient of surrounding rock around the tunnel will increase and infiltration volume will also gradually increase. On account of the limited emission principle, water pressure will gradually increase and eventually reach the maximum water pressure in case the drainage system is blocked by silt, thus posing a strong impact on the long-term safety of tunnel structure.

See the water plugging effect before and after whole cross-section grouting of Xiang'an tunnel F1 weathered trough segment in Fig. 7.

(a) Large amount of water in tunnel before grouting

(b) Tunnel water disappeared after grouting

Fig.7. Grouting and water plugging at whole cross-section of F1 weathered trough

5) Steel corrosion of primary support and advanced support

Compared with general tunnels, the biggest characteristic of subsea tunnel is the corrosion of seawater on supporting structure. Primary support corrosion results from the intrusion of electrochemical ions and chloride ions as well as concrete carbonization, the corrosion rate in lining cracking and water leakage area increases since the steel support or advanced support are directly exposed in seawater, in addition, concrete cracking occurs due to corrosion expansion, severely reducing the material strength of primary support and advanced support, eventually resulting in the loss of bearing capacity. Serious corrosion of primary support was found in field research, which is mainly in sea area segment,

especially in weathered bladder trough, corrosion situation is shown in Fig. 8.

Fig. 8. Steel corrosion in primary support of subsea tunnel

RESULTS AND DISCUSSION

CLASSIFICATION OF SUBSEA TUNNEL SAFETY MONITORING LEVELS BASED ON RISK LEVEL STANDARD

Classification of subsea tunnel safety monitoring levels based on risk level standard

At present, the safety monitoring level of subsea tunnels is mainly determined as per the classification of surrounding rock, however, tunnel risks are not only related to the level of surrounding rock, but also the buried depth of tunnel, construction method, management level of the construction unit and other factors, risk analysis theory is introduced to establish the life-cycle safety monitoring levels of tunnels.

Determination method of risk level

The measurement of risk requires indexes, and the current commonly used international risk rating method mainly measures via the product of risk occurrence probability and risk consequences [19], see formula (1).

$$R = P \times C \tag{1}$$

Where:
R – risk level;
P – risk occurrence probability;
C – risk consequences.

Classification of risk probability levels and risk consequence levels

Since risk is mainly determined via the product of risk probability and risk consequences, hence risk level is jointly determined by risk probability level and risk consequence level, and level classification is required.

1) Classification of risk probability levels

There are many uncertain factors in the probability of risk accident occurrence during construction, the occurrence time, location, form and scale are all undetermined, probability or probability level are used to describe the uncertain events in mathematics. Risk events are classified into five levels according to the different probability, and the risk probability of uncertain factors is converted into risk probability index to facilitate quantitative analysis, see Table. 1.

Tab. 1. Probability Level Standard

Probability range	Center value	Probability level description	Probability index
>0.3	1	Frequently occurs	5
0.03-0.3	0.1	Probably	4
0.003-0.03	0.01	Accidentally	3
0.0003-0.003	0.001	Rarely occurs	2
<0.0003	0.0001	Impossible	1

2) Classification of risk consequence levels

Different assessment levels of consequence levels are adopted according to different risk consequences, but the losses or adverse consequences caused by the accident under the same level are divided into 5 levels, uncertain factors that might cause risk consequences are converted into consequence index to facilitate quantitative analysis, see Table. 2.

Tab. 2. Classification of risk consequences

Event definition	Consequence description	Consequence index
A large area of damage, the whole or part needs to be rebuilt; serious environmental damage; casualties.	Disastrous consequences	5
Endangering the main project; a lot of repair work is required, environment is damaged, traffic roads are blocked; personnel are injured.	Serious consequences	4
Emergency handling is required, property damage, delays in construction, interference in services; minor injuries.	Less consequences	3
Emergency handling is not required, the loss is small; service is not disturbed; personnel are slightly injured.	Light consequences	2
Slight effect.	Consequences can be ignored	1

Risk level standard

ALARP (As Low As Reasonably Practicable) is the most commonly used risk acceptance criteria, also known as the lowest feasible criterion, which means any engineering activity has risks that can not be eliminated via preventive measures, instead, balance between the risk level and interests must be made, see Fig. 9. In Fig. 9, risks are divided into three regions, if the assessed risk level is in an unacceptable

region, it must be rejected or reduced by taking mandatory measures; if the risk level is in an acceptable risk region, there is no need to take any corresponding measures since the risk level is very low; if the risk level is in the maximum feasible reduction region, the effects after the implementation of various risk level reduction measures need to be examined and a contrast analysis shall be made to determine whether the risk is acceptable.

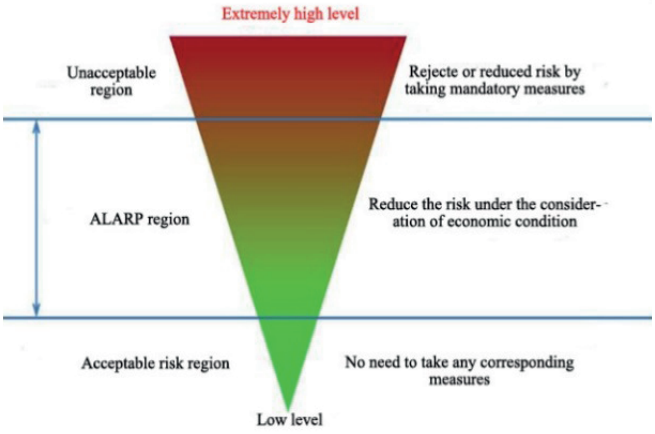

Fig. 9. ALARP risk management criteria

Based on ALARP criteria, the probability of accidents and the corresponding consequences are placed in a risk matrix, which is shown in Table. 3.

Classification of life-cycle safety monitoring levels

In the actual tunnel engineering, the importance degree of safety monitoring of tunnel segments is related to the risk occurrence probability and risk consequences of the segments, sometimes the risk probability is big but the consequences are light, in this case monitoring can be lessened; however, sometimes the risk probability is less but the consequences are disastrous, in this case monitoring shall be strengthened; hence the importance degree of life-cycle safety monitoring can be determined as per the monitoring level.

Based on the determination method of risk level and aiming at the particularity of subsea tunnel engineering, life-cycle safety monitoring level is mainly assessed according to the product of risk probability index and risk consequence index of the tunnel, see formula (2).

$$M = P_1 \times C_1 \tag{2}$$

Where, M – life-cycle safety monitoring level index; P_1 – risk probability index of the tunnel; C_1 – risk consequence index of the tunnel.

Based on the risk level management standard and the assessment method of monitoring level index, see Table. 4, the life-cycle monitoring levels of the subsea tunnel are divided into levels A, B, C and D from low to high according to the range of monitoring level index. Monitoring levels and measures are determined on the basis of tunnel risk acceptance criteria.

Tab. 4. Classification table of life-cycle monitoring levels of the tunnel

Risk level	Acceptance criteria	Monitoring level index	Monitoring levels	Monitoring measures
Low level	Negligible	1-2	Level A	This level has low risks, monitoring can be neglected
Moderate level	Acceptable	3-6	Level B	This level has moderate risks, monitoring can be carried out only in construction period
High level	Not expected	8-12	Level C	This level has high risks, monitoring needs to be strengthened, monitoring during construction period must be carried out, monitoring during operation period may assist
Extremely high level	Unacceptable	15-25	Level D	This level has extremely high risks, monitoring must be strengthened, life-cycle monitoring shall be carried out

Tab. 3. Risk level standard

Consequence level / Probability level		Slight	Great	Serious	Very serious	Disastrous
1		2	3	4	5	
Very likely	5	High level	High level	Extremely high level	Extremely high level	Extremely high level
Probably	4	Moderate level	High level	High level	Extremely high level	Extremely high level
Accidentally	3	Moderate level	Moderate level	High level	High level	Extremely high level
Impossible	2	Low level	Moderate level	Moderate level	High level	High level
Very unlikely	1	Low level	Low level	Moderate level	Moderate level	High level

VARIATION FORMS AND MONITORING LEVELS OF THE SUBSEA TUNNEL

Through an investigation and analysis of the variations occurred in Xiang'an seabed construction stage, collapse, large deformation, cracking and water leakage, reinforcement and concrete corrosion at primary support, hydraulic pressure increase and other variation phenomena appeared in the construction process of tunnel, wherein some variation forms directly affect the safety of the tunnel in the short term of construction stage, while some will affect the safety over a long period of operation. Thus, the tunnel variation forms possibly corresponding to each monitoring level are shown in Table. 5.

Tab. 5. Variation forms of each monitoring level segment of the tunnel

Monitoring levels	Variation forms	Variation consequences
A	Water leakage, reinforcement corrosion, shotcrete corrosion	Slight
B	Collapse, cracking and water leakage at primary support, steel arch corrosion, concrete corrosion	Moderate or serious
C	Large deformation, collapse, cracking and water leakage at primary support, steel arch corrosion, concrete corrosion, vertical uneven settlement	Very serious
D	Large deformation, collapse, cracking and water leakage at primary support, water pressure increase, steel arch corrosion, concrete corrosion, vertical uneven settlement	Disastrous

CONCLUSIONS

In this paper, China's Xiang'an Xiamen subsea tunnel is taken as the research object, and the following main results are obtained through classification of the life-cycle safety monitoring levels of the subsea tunnel:

1) Classification of the life-cycle safety monitoring levels of the subsea tunnel is made on the basis of risk assessment theory and risk level management benchmark, the life-cycle monitoring levels of the subsea tunnel are divided into levels A, B, C and D from low to high according to the range of monitoring level index;
2) Through an investigation of the surrounding rock of Xiang'an subsea tunnel and variations of its primary support as well as an analysis of the monitoring data, we found that the main variation forms of the subsea tunnel are large deformation, collapse, cracking and water leakage of primary support structure, water pressure increase, steel arch corrosion, concrete corrosion, etc., and the possible variation forms, influence factors and indexes of structure safety in each monitoring level segment are further determined.
3) By applying the research findings into life-cycle monitoring system of subsea tunnels, we can solve the assessment and segmenting issue of life-cycle safety monitoring levels of subsea tunnels, thus providing a basis for determining life-cycle monitoring projects and their layout of measuring points in the future.

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