Summary of the Development of New Technologies for Submarine Immersed Tunnel Foundation Reinforcement and Settlement Control

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Abstract. Based on the immersed tunnel foundation improvement modeling and analysis of data through investigations and researches on immersed tunnel diseases at home and abroad, this paper proposes that the adverse loads and poor geology are main causes inducing settlement and diseases. On top of the review on technical innovations in typical immersed tunnel foundation improvement abroad, the innovation and advancement of immersed tunnel foundation improvement of Hong Kong-Zhuhai-Macao Bridge Project is introduced with emphasis and these technical innovations mainly comprise the technology of double-layer bed with both rigidity and flexibility, the technology of SCP(Sand Compaction Piles) plus surcharge loading in ground improvement, the settlement computation method based on CPTU of rebounding and recompression and determination of settlement control criteria and others new development. Furthermore, through analysis the corresponding foundation improvement countermeasures are provided in this paper to meet such construction challenges faced in the immersed tunnel foundation improvement of Shenzhong Link and those challenges are super-wide width varied immersed tunnel element, soft soil ground of sand pit, weathered rock softening in water, sandy soil liquefaction, intense siltation. Finally, as the State key study and development program, it is pointed out that the technical study on diseases inducing mechanism and corresponding pro-active prevention and control of submarine immersed tunnel founded on poor ground conditions shall be carried out based on the full consideration of interactive actions between the structure and its foundation and the technical route and main study contents are further proposed for reference of relevant technical professionals.

1. Introduction
Immersed tunnel as a type of communication infrastructure for river or marine crossing has witnessed development history of over hundred years[1-5]. In China immersed tunnel has development history of over 30 years starting from Yongjiang tunnel and Zhuijiang Tunnel in 1980s. Due to its advantages of shallow burial, small land occupation, high prefabrication quality and water resistance and so on. [6-7], immersed tunnel has been more and more applied in river or marine crossing projects such as Shenzhong Link, Dalian Bay Marine Immersed tunnel, Xiangyang Yuliangzhou Immersed Tunnel,
Shantou Submarine Immersed tunnel and Macao Carvalho submarine tunnel following the immersed tunnel of Hong Kong-Zhuhai-Macao Bridge project and its application develops rapidly[8-11].

After the foundation trench dredging has been done, the foundation bed is executed before the immersed tunnel element installation. In this working process the foundation experienced a rebounding and recompression force course, scholars at home and abroad have carried out a lot of research on this[12-16]. Hence, it was popularly considered that the key issue of immersed tunnel is antiuplifting instead of problem of settlement [17-20]. However, with many projects entering into operation stage. Grants made a statistics of measured settlement actually occurred to large number of immersed tunnels in Europe and America and pointed out that the main causes to the tunnel settlement are excessive settlement or excessive differential settlement and such settlement inducing factors include : backsiltation, soft soil foundation, differential hardness of foundation, over exploration and collection of ground water/gas and oil, uneven backfilling loads, tides variation and so on so forth[21-22]. Junjiang Shao further analyzed the relation between the differential settlement and diseases of the immersed tunnels and pointed out that the differential settlement firstly caused the concrete cracks of the segments adjacent to immersion joints, which led to loosed joint waterstops and then resulted in leaking[23]. Once the cracks became through seepage and leakage might occur thus shortening the element life. The torsion may occur under biased transverse loading thus causing cracking of shear keys. Furthermore, excessive differential settlement may damage performances and functions and cause alignment deviation thus affecting traffic safety.

| Tunnel name                   | Brief articlars                                                                 | Main diseases                                                                                       | Causes of adverse soils                                                                 |
|-------------------------------|--------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------|
| Baytown immersed Tunnel, Texas, USA | Immersed tunnel total length of 779m; tunnel elements: 9 Circular shaped structure, external diameter of 10.6m | Total settlement of 45cm occurred in 7 years after completion, one location had leakage, angle tensile strain up to $1.6 \times 10^3$ occurred at the most dangerous joint. | Caused by over exploration and collection of ground water, gas and oil. settlement of 1.5~2.5m of surrounding ground surface occurred in 25 years after tunnel completion and settlement of segments by shore was 30cm higher than that of river central section/ Chemical grouting was carried out as remedy. |
| Tingstad immersed tunnel, Goteborg, Sweden | Immersed tunnel total length 455m; Tunnel elements :5, rectangular section, width 30m, height of 7.3m | Excessive differential settlement; Rump tunnel settlement up to 0.5m, small cracks at side walls and top of some segments | Excessive foundation stiffness variation of rump and immersed sections; Piled foundation + mortar nylon bags were used; No piled foundation was applied in ramp section. |
| Limfjord immersed tunnel, Alborg, Denmark | Immersed tunnel total length: 510m; Tunnel elements: 5, rectangular section, width of 27.4m, height of 8.5m | Excessive settlement; The measured settlement is several times of predicted values, highest settlement value up to 119mm | Soft clay slop stratum caused lateral yield of ground soils Over exploration of ground water caused ground soil consolidation Tide level variation over 4m high |
| Location       | Immersed tunnel total length | Tunnel elements | Shear bolt cracked; The highest differential settlement at ends of the element is up to 60mm | Romaine soil ground, Uneven backfilling load, one sided backfill load upto 160kPa | Vlake Immersed tunnel, Holland |
|----------------|-----------------------------|-----------------|------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------|-------------------------------|
| Elbe           | 1056m; 7 rectangular section, Width of 41.7m, height of 8.4m |                 |                                                                                                |                                                                                |                               |
| Hamberg, Germany |                             |                 |                                                                                                |                                                                                |                               |
| Fort McHenry Immersed tunnel, Maryland, USA | 3292m; 32 rectangular section, Width of 25.1m, height of 12.7m |                 | Excessive differential settlement, the highest differential settlement up to 150mm | One port reconstruction near coastal tunnel section caused surcharge load on the immersed tunnel with soil height over 15m |                               |
| Ted Williams Immersed tunnel, Boston, USA | 1173m; 12 rectangular section, Width of 24.4m, height of 12.3m, double steel shell segment |                 | Excessive differential settlement; Differential settlement of 73mm occurred at East sided longitudinal 93m; Differential settlement of 110m occurred at west sided longitudinal 92m | Caused by transition section from soft clay stratum to hard mud slate on east side (uneven hardness of stratum) Caused by excessive difference of backfill depth on west side |                               |
| Ninbo Yongjiang Tunnel | 420m; 5 rectangular section, Width of 11.9m, height of 7.5m |                 | Differential settlement of immersed tunnel section (maximum settlement up to 90mm), part of element E1 foundation was voided, inclined crack and leaking at bottom slab of side wall, ring cracks occurred near joints, low compression amount of GINA, waterproof performance was reduced | Excessive back siltation (back siltation up to 3m within one month). Ground is soft soil (highly compressive, highly sensitive saturated and flow siltation) |                               |

As the conclusions of all the immersed tunnel diseases the poor soils, adverse loading and back siltation are main causes to tunnel cracking[24-26]. In addition, fine silty sand stratum liquefaction under earthquake added the risk of disease of tunnel element uplifting. The study work on liquefaction under earthquake were carried out in projects of George Massey tunnel, Canada and and Bosphorus tunnel in Turkey but the inducing mechanism and damage modes are not answered[27-28]. T.Casper studied the stability of Busan-Geoje immersed tunnel under attack of tide waves[29]. Xie Xiong Yao[30] based on the Yongjiang tunnel settlement data monitored in 16 years where the sediment is severe and tide variation is large, proposed finite analysis method for long term settlement based on flowconsolidation coupling. For the immersed tunnel of Hong Kong-Zhuhai-Macao bridge...
project to meet the changes of construction constraints of high back siltation, high volume of runoff and deep soft soil ground study works on technical innovation of foundation bed, soft ground improvement, back siltation monitoring and prevention and protection have been carried out[31].

With the works commencement of Shenzhong Link project and opening to traffic of Hong Kong-Zhuhai-Macao Bridge the safety guaranty issue of seabed immersed tunnel in poor ground and under adverse loading condition under construction and in operation period are imminent to be solved. Further, such subsequent immersed tunnel projects of Dalian Bay submarine immersed tunnel, Macao Carlsberge submarine immersed tunnel, Shantou submarine immersed tunnel are initiated in succession and safety is highly demanded. Hence in-depth investigation into submarine immersed tunnel foundation improvement and its settlement control technological development history, further in combination with the project features exploration of diseases inducing mechanism and study of pro-active preventive control technology are important to guarantee safety of submarine immersed tunnels.

2. Engineering cases of immersed tunnel foundation improvement abroad

(1) Oresund tunnel[32]

The Oresund tunnel linking Sweden and Denmark is of total length 3510m consisting 26 element with each element 135m long. The tunnel construction was commenced in 1995 and completed and opened to traffic in 2000. In Oresund tunnel gravel placement and leveling innovative technology was developed. The grave bed is of thickness 0.95m, for which multifunction barge with gravel dropping pipe are developed and with the movement of dropping pipe the gravel berm top and grove are formed with highest accuracy up to ±25m. The gravel cushion with groove is of bearing capacity up to 400kPa with internal friction angle of 40°.

The gravel cushion placement and leveling technology before tunnel element installation is featured with rapid construction, high leveling accuracy, high preloading modulus of dropping pipe and high siltation accommodating and discharging capacity and is thus subsequently applied in many well-known immersed tunnels across straits in Holland, South Korea and China. In applications in various countries the groove size and gravel size are slightly different and the parameters applied in different projects in various countries are shown in table 2.

![Figure 1. Illustrative cross section of Oresund tunnel (bottom width 39.75m, height 8.7m).](image)
Figure 2. Gravel placement and leveling technology in Oresund tunnel.

Table 2. Technical parameters of gravel cushion placement and leveling in typical immersed tunnels abroad.

| Tunnel name          | Oresund Tunnel | Busan-Geoje Tunnel | Second Benelux Tunnel | Roer River Tunnel |
|----------------------|----------------|--------------------|-----------------------|-------------------|
| Foundation width     | 42m            | 31.66m             | 47.25m                | 30m               |
| Gravel cushion thickness | 0.5m~1.4m   | 1.5m               | /                     | 0.5m              |
| Berm top width       | 1.65m          | 1.60m              | 1.65m                 | 1.65m             |
| Groove top width     | 1.0m           | 1.0m               | 1.0m                  | 0.85m             |
| Berm centers distance| 2.65m          | 2.60m              | 2.65m                 | 2.5m              |
| Max. gravel size     | 32~64mm        | 75~125mm           | /                     | /                 |
| Max. water depth     | -22m           | -48m               | /                     | -21m              |
| Leveling accuracy    | ±25mm          | ±40mm              | /                     | /                 |
| Building time        | 1995~2000      | 2003~2010          | 1997~2000             | 2004~2007         |

(2) Busan-Geoje immersed tunnel in South Korea[33]

The Busan-Geoje tunnel in South Korea consists of 18 concrete elements with each element 180m long, 26.46m wide and 9.97m high and each 180m long element is made of 8 segments with each segment 22.5m long which are connected by prestressing and this tunnel is segmented type. The deepest part is located at 37m below mean sea level at sea base and tunnel foundation extends to 47m.
below mean sea level and the geological conditions are poor including silt soil and clay stratum of marine sediment. Such technologies of SCP and CDM (Cement Deep Mixing) are imported from Japan for ground improvement. The longitudinal section are illustrated in schematic drawings 3 to 4.

For purpose of marine sediment typed silt and mud stratum SCP and CDM are designed for ground improvement, of which the flow of CDM is illustrated in figure 4. Of the sand compaction piles the upper diameter is 2m and lower diameter of 1.6m and the replacement rate is largely 40% and some location is of replacement of 61% (figure 7). With cement deep mixing pile, pile diameter is 1m and four piles form a cluster with overlapping of 10cm and replacement rate is 30%~50% which is adaptable to upper load size (figure 6).
Figure 6. Layout of reinforcement with CDM.

Figure 7. Layout of reinforcement with SCP.
3. Innovation and upgrading of the immersed tunnel of Hong Kong - Zhuhai - Macao Bridge project[34]

The immersed tunnel of Hong Kong - Zhuhai - Macao Bridge project is of total length of 5664m and is the longest submarine immersed tunnel ever completed worldwide up to date and this tunnel consists of 33 elements with each standard element 180m long, 37.95m wide and 11.4m long. Compared with other foreign submarine immersed tunnels following construction constraints challenged the immersed tunnel of Hong Kong-Zhuhai-Macao bridge project.

(1) Distance from shore: the distance from shores is 29km, maximum depth of 45m, complex wind, wave and current conditions

(2) 40m thick soft soils: soft soils depth up to 40m

(3) 1cm/d high back siltation: maximum back siltation upto to 23m deep and 3km long, back siltation intensity within foundation trench reached 1cm/d.

(4) 5.664km super long: the longest immersed tunnel worldwide with immersed tunnel section up to length of 5.664km.

(5) Large variance of ground: muck, mucky clay, clay, sand, sand which are distributed unevenly and longitudinally.

(6) High seismic intensity, with life span of 120 year (10%) seismic acceleration up to 0.175g.

On top of learning from experiences of foreign countries following innovations and improvements have been achieved in the immersed tunnel of Hong Kong-Zhuhai-Macao Bridge.

(1) With the application of foreign traditional prior placement of gravel cushion 2m thick blocky stone layer is placed additionally and compacted and leveled.

(2) On top of the SCP method applied in Busan-Geoje project surcharge loading procedure is increased to eliminate main consolidation settlement.

(3) Site in situ CPTU is carried out extensively and new method of settlement calculation by rebounding and recompression is raised based on in situ test data and high quality inhouse consolidation test.

(4) The analysis method of immersed tunnel structure ground interactive action based on rigidity impact line is proposed and the method is established to determine the criteria for longitudinal settlement control by parameter of shear resistance of segment joint.

Figure 8. Longitudinal profile of immersed tunnel of Hong Kong-Zhuhai-Macao Bridge.
4. Challenges and countermeasures for Shenzhong immersed tunnel

The immersed road tunnel of dual 8-lane is first time used in Shenzhong Link Project worldwide and steel shellconcrete immersed tunnel structure is applied first time in China and the main construction constrains comprise following challenges:

(1) Super wide, deep burial, varied width: 8 lane, the largest width in excess of 56m, maximum water head of -38m, varied width section length of 615m

(2) Large scaled steel shell concrete immersed tunnel is applied first time: complex forces to be sustained, unclear mechanism, lack of design criteria and assessment and evaluation standard

(3) Complex geological conditions: high challenges in respects of 1.4km sand pit range, weathered rock softening, sandsoil liquefaction, high siltation in foundation trench, seabed evolution, tunnel foundation type variety, deep trench construction technique applied.

The use of sections to divide the text of the paper is optional and left as a decision for the author. Where the author wishes to divide the paper into sections the formatting shown in table 2 should be used.

For the west island tunnel ramp section founded on sand pit disturbed and thick soft foundation in Shenzhong Link project the key problems in need of solutions involve foundation formation, adaptability of SCP and DCM solutions meanwhile coordination transition of bedrock stiffness of middle section shall be handled properly. For the intermediate tunnel sections founded on bedrock ground with high back siltation key problems to be solved are to improve the muck accommodation capacity of foundation bed. The foundation improvement scheme for the whole line of tunnel are illustrated in table 3 and figure 12 respectively.
Table 3. Immersed tunnel longitudinal foundation improvement solution of Shenzhong Link Project

| Location | Geology condition | Improvement solution |
|----------|-------------------|----------------------|
| East island tunnel, cofferdam reclaimed section | Fully and highly weathered residual soil deposits | Plain concrete bed of thickness 30cm, Locally replacement /DCM |
| Airport branch channel and east side tunnel section of elements E22–E32 | Fully and highly weathered residual soil deposits | Mucky soil, silty clay and sand stratum |
| Middle section with shallow burial E13–E21 | Mucky soil, silty clay and sand stratum | 1m thick gravel cushion +1.1m thick vibratory compacted block gravel cushion 5-6m long DCM (locally 2~3m compacted and leveled block stone) |
| Bilateral sides of Fanshi waterway E6–E12 | Fully and highly weathered and moderately weathered | 1m thick gravel cushion +1.1m thick vibratory compacted block stone layer |
| West island ramp section E1–E5 | Mucky soil | 1m thick gravel cushion +1.1m thick vibratory compacted block stone layer DCM pile E1 with locally high pressure inject grouting |
| West island cut and cover section | Island surcharge loading mucky soil | Compound foundation with PHC pile of diameter 0.6m |

Figure 11. Longitudinal section division of immersed tunnel foundation improvement of Shenzhong Link Project.

Figure 12. Schematic drawing of combined impacts of adverse geology and adverse loading.
5. Future study direction

On top of existing study work done for purpose of submarine immersed tunnel, those disease inducing
mechanism and their prevention and control technology study ideas and methods for the submarine
immersed tunnels located in adverse geological conditions are elaborated and the inducing mechanism
of excessive deformation of submarine immersed tunnel under comprehensive impacts of various
adverse geological conditions and adverse loadings and the structural diseases and damage modes are
exposed and unveiled. Thus the difficult problems in respect of deformation control and structural
disease prevention and control of immersed tunnel with super width and with varied sectional width
have been cracked and solved. Ultimately the safety guaranteeing capacity of submarine immersed
tunnel has been improved within its life span.

The key scientific and technical issues of study comprise the following items:
(1) The foundation deformation calculation method considering the bed silt accommodation, soft
soil accumulated deformation effect and weathered rock softening
(2) Seismic response analysis method for immersed tunnel considering transverse additional torsion
shear effect
(3) Disease inducing mechanism and damage mode of submarine immersed tunnel under combined
impacts of adverse geology and adverse loading
(4) Disease classification criteria, assessment system and pro-active prevention and control
technology for submarine immersed tunnels.

6. Main study contents

(1) Foundation bed sedimentation mechanism and prewarning and forecasting technology for
submarine immersed tunnel

The study scope comprises the following respects: to study the foundation bed sedimentation
physical mechanism of immersed tunnel under multidynamic forces general impacts, to establish site
oceanic environmental monitoring system, to study the complex ring current forming evolvement
process within foundation trench based on site observation and lab. Testing, to analyze 3D features of
flow field and vortex field, to reveal adding and mixing mechanism of currents from upper main flow
and lower secondary ring flow and to define the physical mechanism of backsiltation formed by muck
and sand movement driven by current in the foundation trench.

To study accurate and fine numerical alerting and forecasting technology and system for water
dynamic force caused sedimentation in foundation bed of immersed tunnel. To establish an accurate
and fine sea wave forecasting system and 3D alerting system and forecasting system for sea current in
the foundation trench and the adjacent sea current forecasting system. to develop an accurate and fine
numerical alerting and forecasting technology and system for water dynamic force induced
sedimentation on the foundation bed in foundation trench and finally to accurately forecast the
window for tunnel installation.

To study the impacts of sedimentation on foundation bed deformation and the calculation method.
Based on the silt accommodating gravel cushion deformation modulus testing to study the silt
accommodation capacity of foundation bed and impacts of muck backsilt on the foundation bed and
thus elaborating the quantitative relation between the back silt strength and bed deformation modulus
and finally to establish the calculation method for silt contained bed settlement deformation.

(2) Deformation mechanism and calculation method for submarine immersed tunnel under soft soil
and weathered rock softening conditions

To study the deformation mechanism of soft ground reinforced by DCM for submarine immersed
tunnel to reveal the soft foundation deformation law for immersed tunnel; to analyze deformation
mechanism of ground improved by DCM to establish a calculation method for compound foundation
deformation reflecting soft ground characteristics and improving media parameters; to analyze
characteristics of trench bottom highly and fully weathered rock stratum softening in water in
combination with in place testing and laboratory tests to gain weathered rock softening characterists
and deformation mechanism for submarine immersed tunnel, to establish a settlement and deformation
calculation method with comprehensive consideration of weathered rock softening and unloading effect of dredging; to study differential settlement development mechanism of transition tunnel section from different hardness grounds for submarine immersed tunnel, to establish mathematical model to simulate adverse soils of transition section from different stiffness, to study longitudinal and transversal differential settlement evolvement mechanism at interfacing sections between bedrock with various weathering degrees and soft ground to reveal the law how the soft and hard stratum space distribution features may impact differential settlement.

(3) Dynamic force response analysis technology and silty sand stratum liquefaction uplifting mechanism of submarine immersed tunnel under seismic effect.

To study the inducing uplifting mechanism of submarine immersed tunnel founded in silty sand stratum due to seismic uplifting. To establish silty sand dynamic force liquefaction analysis method, to study the law of super pore water pressure rise of silty sand stratum under seismic, to evaluate the impact of tunnel foundation bed, backfill cover on disperse of super pore water pressure, to reveal the inducing mechanism of uplifting of immersed tunnel elements due to liquefaction of silty sand stratum and its damage mode.

To study the pressure-torsion-shear force composite actions mechanical property analysis method for immersion joint. To study the immersion joint deformation mode under coupling effects of seismic loads and sand soil liquefaction and to establish a mechanical property analysis method for immersion joints with consideration of composite effects of pressure-torsion-shear forces combined so as to provide basis for joint design parameters and reveal joint bearing damage modes.

To study the immersed tunnel seismic response analysis method with consideration of transverse additional torsion and shear effects. To propose immersed tunnel-foundation system multiparticle systemspring-shell structural mechanical model, to propose immersed tunnel seismic response analysis method with transverse and shear force effects consider, to study the such impacts of coupled effects on tunnel dynamic response as the foundation differential deformation on poor ground, construction errors, seismic dynamic inclined incidence and so on other impacts.

(4) Disease evolvement and damage mode of submarine immersed tunnel under coupled effects of adverse geology and adverse loads.

To study the composition of typical adverse geological conditions, to establish a foundation stiffness analysis method under adverse geological compositions, to propose a foundation stiffness distribution mode intended for incremental damage analysis of submarine immersed tunnel. To study hazard causing and effect mode of typical adverse loads and mathematical model, to analyze the such long term variable loads as vehicular load and temperature variation and disease causing mode of such extreme loads as alluvial silts, channel dredging and abrupt muck deposits and to establish a numerical model of describing adverse loading effect manners.

To establish a immersed tunnel diseases evolvement mechanical model with initial defects considered. ①-bearing capacity and stiffness of shear resistant connections under concrete casting defect impacts ; to study impacts on shear resistant connections of different types under concrete cast voided of steel plate and concrete composite immersed tunnel with emphatic concern on the impacts on tunnel extreme bearing capacity and stiffness so as to further study the design method of shear resistant connections as member with defects considered and to consider the member stiffness design method with connection sliding considered. ② to study the member bending resistance bearing capacity design method with consideration concrete cast defects effect. To study the impacts on voided concrete cast on bending resistant bearing capacity of key members in steel plate concrete composite immersed tunnel, including short term impact and long term evolvement so as to raise bending resistant bearing capacity reduction design method for different degrees of avoid and to propose construction control parameters for concrete casting errors. ③ to propose member shear capacity design method under impact of concrete casting defects. To study the impacts of concrete void on shear capacity of key members in steel plate concrete composite immersed tunnel including short term impact and long term evolvement and to raise shear capacity calculation model and bearing capacity
reduction design method with void considered and finally to raise construction control parameters for concrete cast defects control.

To study incremental damage mode of submarine immersed tunnel under combined impacts of multiple factors. To establish a 3D elastic-plastic numerical analysis method for submarine immersed tunnel which shall reflect joint GINA nonlinear effects, shear key force characteristics, initial defects, disease evolvement mechanical model, coupling with adverse ground stiffness changes and adverse loading effects, reveal incremental damage course mode of any submarine immersed tunnel starting from excessive deformation → waterstop opening/rotation → shear key damage → joint leaking which forms an incremental damage mode from clear disease causes→ evolvement and development→ occurrence of damages.

(5) Disease grading criteria, evaluation system and pro-active prevention and control technology for submarine immersed tunnels

To study the disease grading criteria and evaluation system for submarine immersed tunnels. To analyze the immersed tunnel disease types and damage extents and establish a submarine immersed tunnel deformation monitoring system and based the monitored data to establish a disease grading criteria and alerting threshold value based on the parameters of total settlement value, differential settlement, joint openings and crack width so as to raise disease quantitative evaluation method and to form a disease judgment, alerting and handling evaluation strategy system.

To study the pro-active disease prevention and control technology for submarine immersed tunnels. To raise systematically a pro-active prevention and control technology based on disease evolvement process within full life span based on the disease inducing and causing mechanism including technologies as advanced reinforcing and adjusting technology during construction period, such as DCM ground improvement technology, weathered rock softening in water reducing and elimination technology, transition section stiffness smooth adjusting technology from soft ground to stiffener ground, shear key size and installation time optimization technology, safety rick assessment and rick control measures during construction stage, pro-active prevention and control technology during operation period such as element top load adjustment technology, element bottom pressurized grouting technology, rapid remedy technology to stop leaking joint. By taking technical measures in advance the potential structural hazards and risks are eliminated and pro-active alerting and prevention of diseases can be achieved.

7. Technical route of study work

Site survey and observation and case investigation methods are to be used in the study and external boundaries as adverse ground conditions and adverse loads shall be defined clearly. The study follows the technical route: to study muck silt mechanism in the foundation trench, to develop foundation bed muck back silt alerting system by combing assimilation and multiple dimensional coupling calculation technology; to establish muck contained stratum settlement deformation calculation model based on silt accommodating bed modulus test; to analyze immersed tunnel differential settlement evolvement mechanism by in place test and laboratory consolidation test; to raise immersed tunnel seismic response calculation method with transverse addition torsion and shear forces considered based on coupling effect theory and numerical simulations; to study the immersed tunnel uplifting mechanism due to sandsoil liquefaction under seismic effect, to set up immersed element elastic-plastic analysis model and to elaborate the structural performance deteriorating mechanism and damage mode; by means of generalization and integration and system configuration to set up disease grading criteria and evaluation system and finally to develop a pro-active prevention and control technology. The technical route is illustrated in charge 13.
Figure 13. Proposed technical route to be applied in study work.

### 8. Conclusion

In this paper, based on the investigation of the foundation treatment forms of the Oresund tunnel and the Busan-Geoje immersed tunnel in South Korea, the feasibility of the first-laying gravel cushion is verified. This method has fast construction speed, high leveling accuracy, and high accuracy. The pipe has the advantages of large precompressed modulus, strong silt drainage capacity, and for soil layers with poor geological conditions, it is proposed that SCP and CDM can be used for reinforcement. On this basis, the foundation treatment of the Hong Kong-Zhuhai-Macao Immersed Tunnel is summarized, the settlement of the main consolidation of the SCP method, the calculation of the rebound and recompression settlement of the tunnel, and the longitudinal differential settlement using the shear capacity of the segment joint as an indicator. The innovation and improvement of the determination methods of control standards, etc., combined with the characteristics of the Shenzhong immersed tunnel, summarized the challenges encountered in the construction of the immersed tube tunnel of the Shenzhong immersed tunnel and the countermeasures.

Based on the above investigation, analysis, induction, and summary, the research directions for foundation treatment of immersed tunnels in the future are proposed: (1) the foundation deformation calculation method considering the bed silt accommodation, soft soil accumulated deformation effect and weathered rock softening. (2) seismic response analysis method for immersed tunnel considering transverse additional torsion shear effect. (3) disease inducing mechanism and damage mode of submarine immersed tunnel under combined impacts of adverse geology and adverse loading. (4) disease classification criteria, assessment system and pro-active prevention and control technology for submarine immersed tunnels. The main research contents of each research direction are analyzed in detail, and the technical route of the research work is given, and scientific suggestions are proposed for the future development and innovation of the immersed tunnel.
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