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SEISMIC DESIGN FOR IMMERSED TUBE TUNNEL AND ITS CONNECTION WITH TBM TUNNEL IN MARMARAY PROJECT

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ABSTRACT

In Marmaray project in Istanbul, Turkey, railway tunnel has been constructed beneath the Bosphorus strait. Since Istanbul is located in a highly seismic area, seismic design is one of the most important factors for the tunnel design. Right under the Bosphorus, immersed tube tunnel was selected, and TBM (shield) tunnel, which was directly connected to the immersed tube tunnel, was selected for land portion.

In this paper, characteristic seismic issues for the tunnel especially under the Bosphorus strait are presented, such as site response analysis, tunnel longitudinal design including connection portion between immersed tube tunnel and TBM tunnel, design of seismic joint and design for liquefaction induced ground improvement.

INTRODUCTION

Asia and Europe has been connected under the Bosphorus strait (Fig.1). Marmaray project had realized such a dream which had been imagined since 150 years ago.

In Marmaray project, about 13km railway tunnel has been constructed. As for the types of tunnel structure, immersed tube tunnel is selected under the Bosphorus strait and TBM type tunnel is selected mostly for the land portion (Fig.2). Since large earthquake is expected to hit the region around Istanbul with a recurrent interval of about 250 years, seismic design is one of the most important factors in the structural design of the tunnels. The nearest fault is located about 16 km away from the tunnel location of the Bosphorus strait, and the magnitude of earthquake is expected to be 7.5.

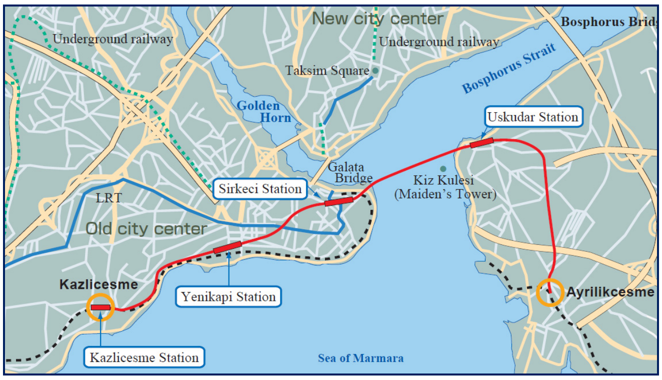

Figure 1. Plan of Marmaray Project (in the vicinity of Bosphorus strait)

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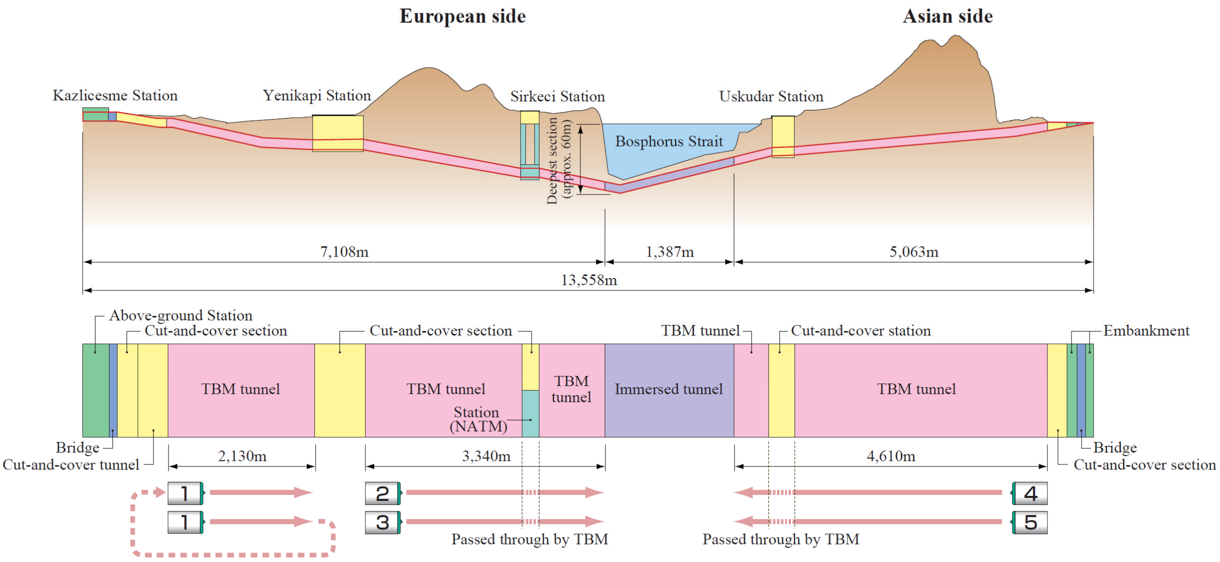


Figure 2. Section and tunnel type of Marmaray Project (in the vicinity of Bosphorus strait)

Immersed tube tunnel is placed relatively shallow part of the ground under the sea bed of the Bosphorus strait (Figs.3&4). The immersed tube tunnel section is composed of 11 tunnel elements made by reinforced concrete which are rigidly connected one by one. Therefore, the tunnel structure is highly affected by the seismic movement and the liquefiable soil beneath the tunnel. In general, at the ends of immersed tube tunnel, vertical shaft exists in order to connect between immersed tube tunnel and land tunnel. However, in this project, TBM tunnels are directly and rigidly connected to the immersed tube tunnel. Furthermore, since the connection location is just outside of the rock bed, seismic joints are needed to be placed near the connection location.

As for liquefaction, ground movements, such as floatation and lateral movement due to liquefaction and post-liquefaction settlement, are required to be considered in the design in order to keep the tunnel alignment within the allowable tolerance of the railway alignment. Structural design of the tunnel is also conducted in consideration of both liquefaction-induced settlement and lateral movement.

As described above, there are several features regarding seismic design of the tunnels. In this paper, following topics are mainly described. Firstly, site response analysis which is the basis of seismic design of the tunnels is presented. Three dimensional finite element analyses have been conducted. Secondly, modelling and analysis of the tunnels including connection portion are described. Dynamic response analysis in tunnel longitudinal direction has been conducted. Although tunnel transverse section has been designed by using seismic response analysis, it is omitted in this paper. Thirdly, design of seismic joint is described. And finally, immersed tube tunnel movement due to liquefaction induced ground movement is presented. Design of liquefaction countermeasure is also be presented.

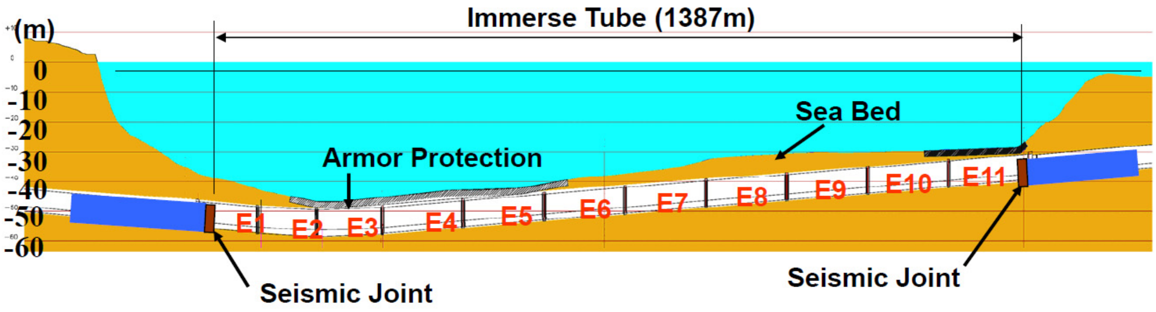


Figure 3. Longitudinal section of immersed tube tunnel

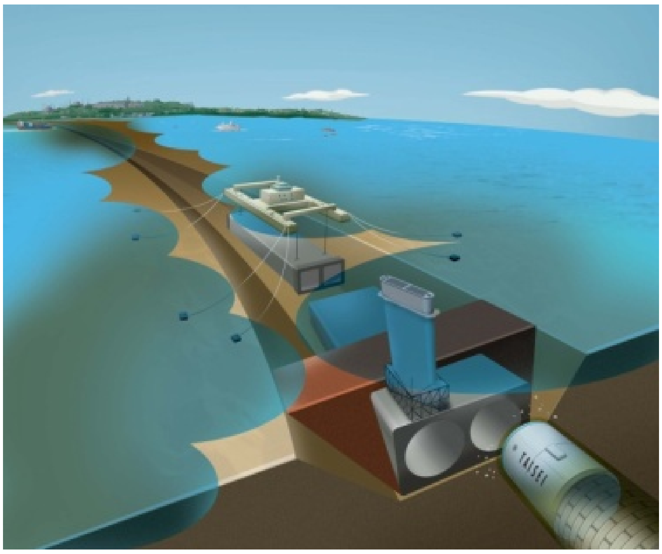


Figure 4. Conceptual image of tunnel construction and connection between immersed and TBM tunnels

GROUND CONDITIONS AND SITE RESPONSE ANALYSIS

Fig.5 shows the geological profile under the Bosphorus strait. Maximum 80m sedimentary layers, alternating sandy stratum and clay stratum, exist. Right under the tunnel, liquefiable loose sandy soil exists on the Asian side, and clay stratum exists on the European side.

Seismic waves to be considered in the design are presented by the Employer. The nearest fault, which is North Anatolian fault in Marmara Sea, is located about 16 km away from the tunnel, and the magnitude of earthquake is expected to be 7.5. Three components of ground motion, such as longitudinal, transverse and vertical directions, are presented. Fig.6 shows one example of the seismic waves and the acceleration response spectrum considered in the design.

Site response analysis was conducted by using non-linear finite element method in time domain with consideration of those waves, because large shear strain was anticipated in loose sandy soil and soft clay. Fig.7 shows the schematic models for site response analysis.

Phase shifts, both from the European side to the Asian side and the reverse, were also considered in the input seismic waves.

Figs.8a and 8b show typical results of the maximum acceleration response and the maximum shear strain. Maximum acceleration response at the sea bed is amplified about twice of the acceleration at the bed rock. About 1% maximum shear strain appears at the shallow part near the sea bed.

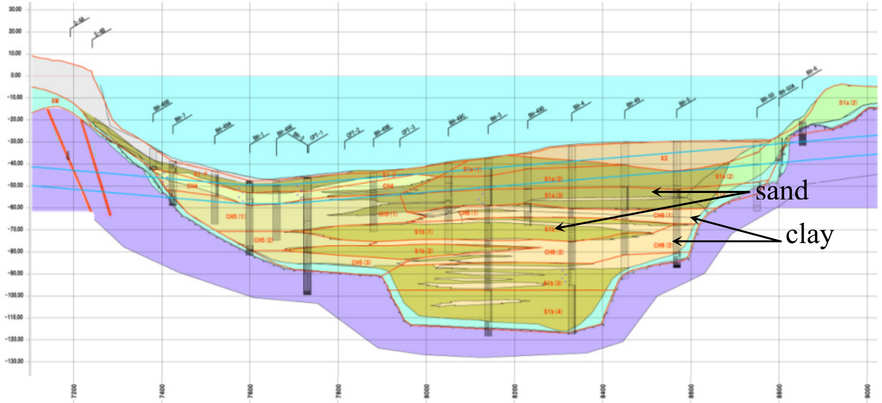


Figure 5. Geological profile of Bosphorus strait

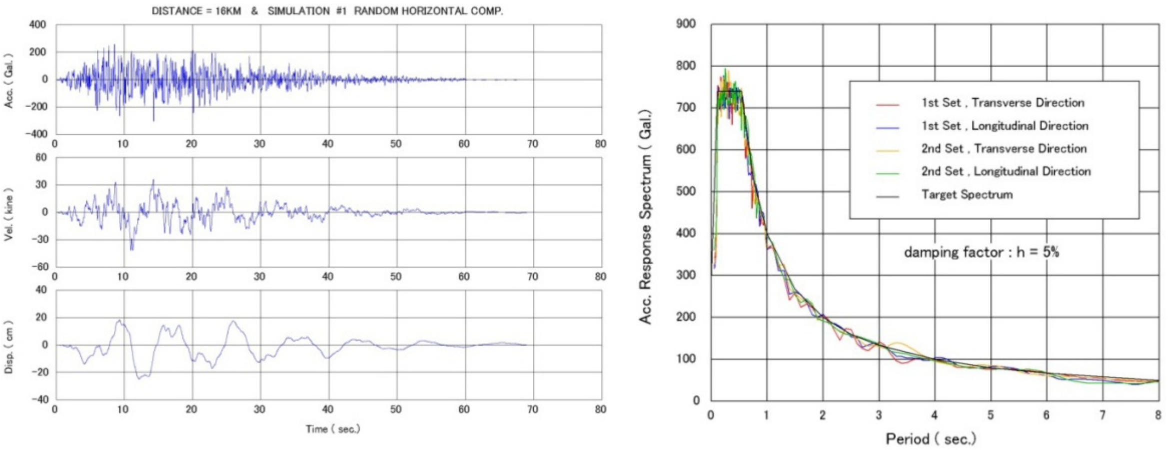
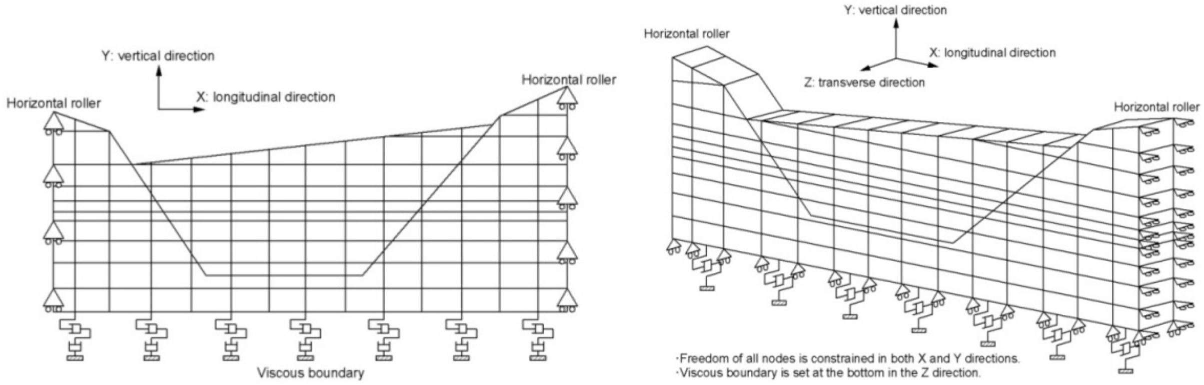


Figure 6. One example of horizontal seismic waves and acceleration response spectrum (shortest fault distance of 16km)



longitudinal direction transverse direction

Figure 7. Schematic image of site response analysis modelling

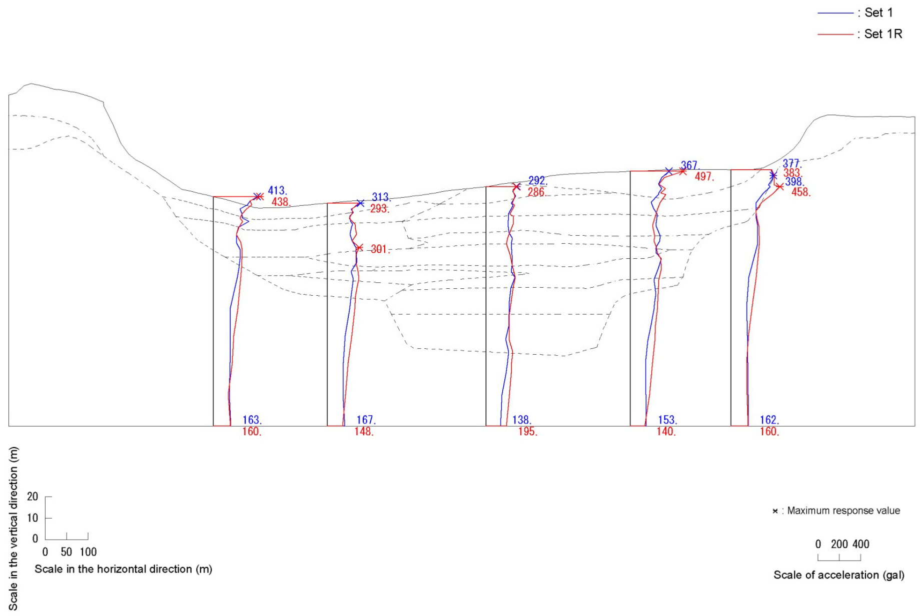


Figure 8a. Site response analysis result (maximum acceleration)

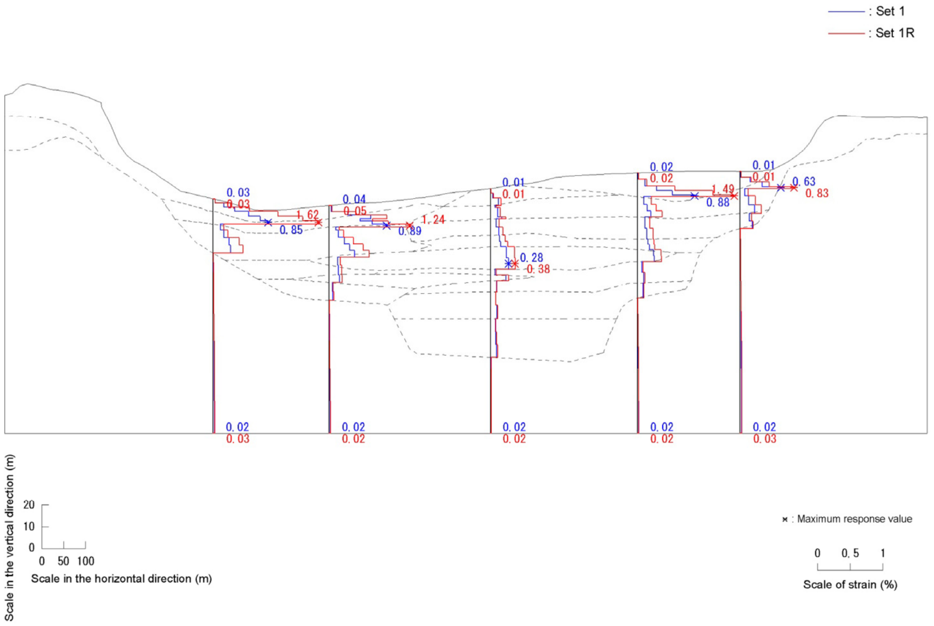


Figure 8b. Site response analysis result (maximum shear strain)

SEISMIC ANALYSIS FOR IMMERSED TUBE TUNNEL AND ITS CONNECTION WITH TBM TUNNEL IN LONGITUDINAL DIRECTION

The response analysis of the immersed tunnel in the longitudinal direction is performed through the step-by-step seismic deformation method. In the response analysis, the tunnel is modeled with a three-dimensional beam element and the ground with a spring element. Fig.9 shows schematic image of the modelling for the analysis. The displacement of the ground that is obtained from the site response analysis is imposed step-by-step on the node of spring element opposit side of beam element.

The analysis model consists of three sections, the immersed tunnel section, the TBM tunnel section, and the connecting section located between the immersed tunnel section and the TBM tunnel section. The immersed tunnel section is modelled with a three-dimensional fiber model that represents the nonlinearity of the reinforced concrete structure. The TBM tunnel section is composed of segment rings and inter-ring joints that are modelled using a combination of a three-dimensional beam element having equivalent flexural rigidity and a spring element having different equivalent axial rigidities under compression and tension. The connecting section is composed of cast-in place concrete lining that is modelled using a three-dimensional fiber model. The joint between the immersed tunnel elements is rigid, and the joint between the immersed and connecting sections is also rigid. The seismic joints (flexible segments) are installed in the TBM tunnel section outside of the bedrock on both the European and Asian sides. In the analysis, the seismic joints are set to be free.

The ground spring constants in the longitudinal, transverse and vertical directions are calculated using a finite element model of the cross section of the tunnel (Fig.10). In calculating the ground spring constants, the equivalent shear rigidity is determined as being 65 percent of the maximum shear strains that are obtained from the site response analysis. The ground displacement time histories along the tunnel axis are applied as a seismic action in the longitudinal, transverse and vertical directions, simultaneously.

The site response analyses include a case where the ground displacement takes into consideration the wave propagation in the horizontal direction of the input earthquake motion, and a response analysis of the tunnel is conducted by applying the ground displacement obtained from the site response analyses of the wave propagation in the horizontal direction.

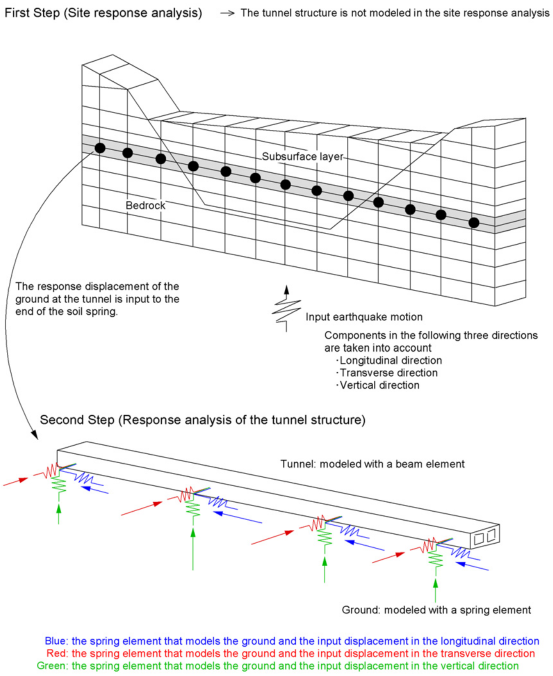


Figure 9. Schematic image of tunnel modelling

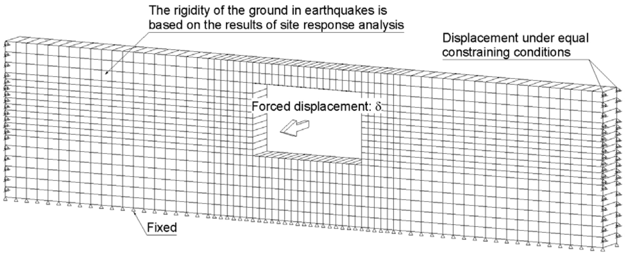


Figure 10. Schematic image of ground spring calculation modelling using FEM (ex. longitudinal direction)

The immersed tunnel is modelled with 11 tunnel elements and each element is composed of several beam elements. The TBM tunnel and the connecting sections are modelled with both inbound and outbound lines. The joint between the immersed tunnel elements is rigid as is the joint between the immersed and connecting sections. The flexible segments are installed in the TBM tunnel section outside of the bedrock on both European and Asian sides. And in the analysis, the flexible segments are set to be free. The horizontal and vertical alignments of the tunnel structural model are shown in Fig. 11. Fig.12 shows the detailed elevation view of the connecting section at the European and Asian sides for modelling the tunnel. Enlarged views of the connecting sections of the analysis model are also shown in Fig.12.

The three-dimensional fiber model is used to calculate the stress and the tangential rigidity corresponding to strain under the assumption that the plane of a cross section is held. This is done by dividing the cross section of a structural member into elements, and giving each element the cross-sectional areas and the constitutive models of rebar and concrete. Accordingly, the fiber model is capable of taking into account the nonlinearity of the structural member by considering the axial force and the bending moments simultaneously. Sectional image of fiber model is shown in Fig.13. The stress-strain characteristics of concrete and steel reinforcement are set in accordance with the Standard Specifications for Concrete Structures, JSCE (2002) as shown in Fig.14.

The TBM tunnel section is modeled by combining a three-dimensional beam element having equivalent flexural rigidity and a spring element having different equivalent axial rigidities under compression and tension. The equivalent rigidities for the TBM tunnel section are determined in accordance with Design Standard for Railway Structures (Shield-driven Tunnel) Railway Technical Research Institute (RTRI) (2002).

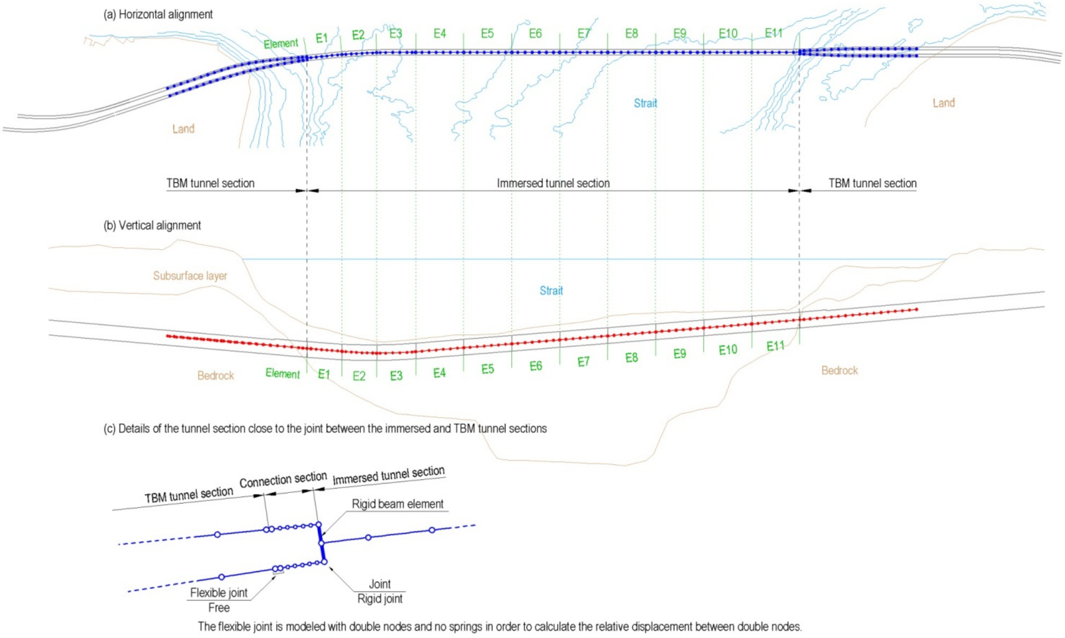
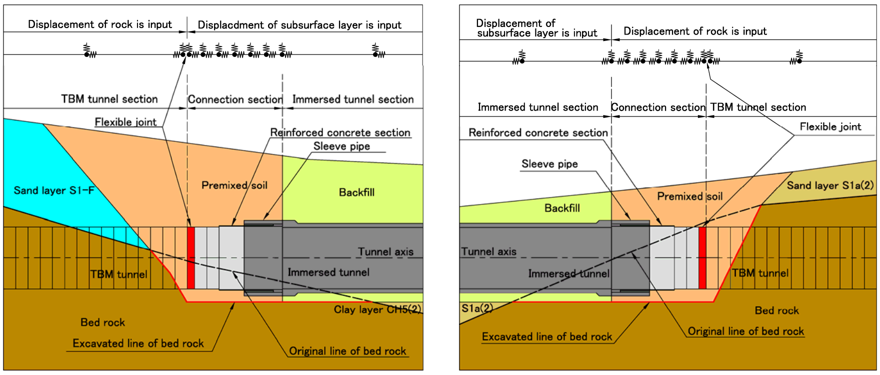
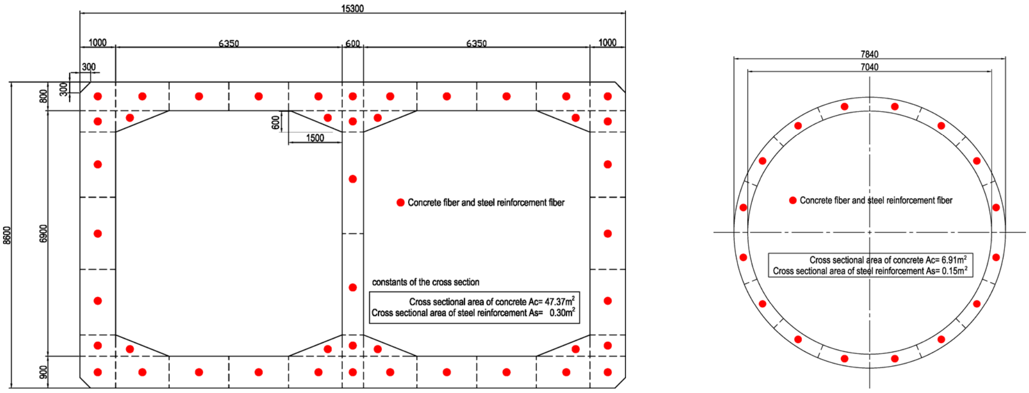


Figure 11. Structural model of the tunnel



a) European Side b) Asian Side

Figure 12. Detailed elevation view of the connection location

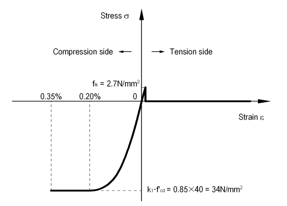


a) Immersed tube tunnel b) TBM tunnel

Figure 13. Three-dimensional fiber model of the tunnels divided into elements

(a) Concrete

Specified design strength f'_{ck}	N/mm^2	40
Tensile strength f_{tk} (= $0.23f'_{ck}{}^{2/3}$)	N/mm^2	2.7
Modulus of elasticity E_c	kN/mm^2	31



(b) Steel reinforcement

Yield strength f_{yd}	N/mm^2	500
Modulus of elasticity E_s	kN/mm^2	200

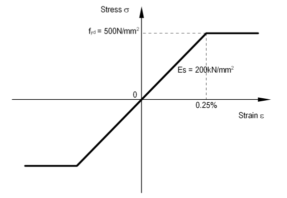


Figure 14. Constants of physical properties and constitutive models of the materials

DESIGN OF SEISMIC JOINT

When the TBM tunnel is subject to large displacements due to differential settlement or earthquakes, the joints with other structures and the lining joints will be damaged and water-tightness lost. In addition, the expansion and contraction of the immersed tunnel due to temperature variations need to be taken into account. In order to absorb such harmful displacements, seismic joint are installed at the joints.

The required displacement of the seismic joint is determined by considering the expected displacement of the tunnel due to differential settlement and earthquakes, and the expansion and contraction of the immersed tunnel due to temperature variations. The expected displacement is calculated for both the longitudinal direction and transverse direction. The seismic joint is also analyzed in both directions.

The seismic joint are composed mainly of main beams, a water cutoff gasket, a skin plate, and a jack thrust force support. The main beams are made of steel and connected to the adjoining segment with ring connection bolts. The skin plate prevents the backfill grout from touching the water cutoff gasket, thereby allowing the gasket to remain flexible. The jack thrust force support protects the gasket from damage due to the forces induced by the thrust jacks during construction and is removed when it has been confirmed that the gasket is no longer in danger of being damaged.

The main girders are made of steel and designed to withstand water and earth pressures. In this project, about 50m water pressure is considered. The stresses are calculated using a model in which the segments are assumed to be rings having uniform stiffness. The details of the main girder and segment joints are designed using the stresses obtained from the calculation.

The water cutoff gasket is designed to accommodate the design displacement and to withstand a water pressure corresponding to the maximum possible groundwater level. The thrust force support is a temporary structure that is designed to withstand forces induced by the thrust jack. Since the jack is pressed against a location that is off the centroid of the support, the section forces induced in the support are calculated taking into consideration the eccentricity.

Proving tests had been conducted under the design load conditions, with regard to the directions of compression, tension, and shear. It is confirmed that the rubber rings provide adequate waterproofing performance and deformation performance under hydrostatic pressure.

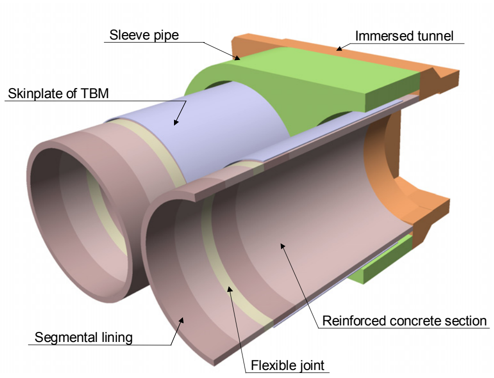


Figure 15. Schematic view of connection portion

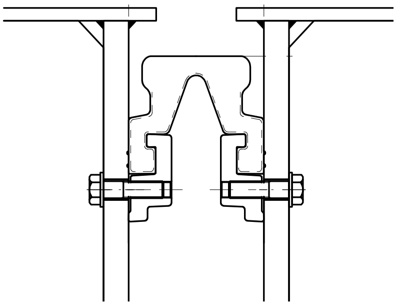


Figure 16. Sectional image of seismic joint

LIQUEFACTION INDUCED GROUND MOVEMENT AND COUNTERMEASURES

The study of the effect on the flotation and lateral spread due to liquefaction was conducted by using the program ALID which was developed by Yasuda et al. (1999). ALID can accommodate the calculation of residual ground displacement by using static FEM analysis in consideration of the reduction of the ground stiffness due to liquefaction.

Since the maximum inclination of the sea bed of Bosphorus strait is about 3% in transverse direction of the tunnel, about 1000m area of analysis model is used.

Fig.17 shows one of the analysis results. In this result, lateral spread at the subsurface layer due to liquefaction was induced, but the displacement around the tunnel was not so significant because the backfilling material around the tunnel was non-liquefiable. Fig.18 shows the horizontal and vertical displacement of the ground at the tunnel. Significant horizontal displacement of about 500 mm appears on the Asian side.

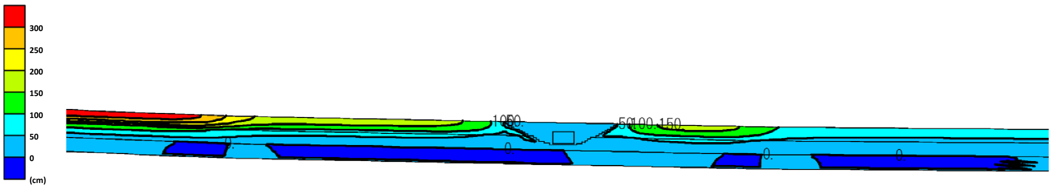


Figure 17. Analysis result of ground floatation and lateral spread by ALID

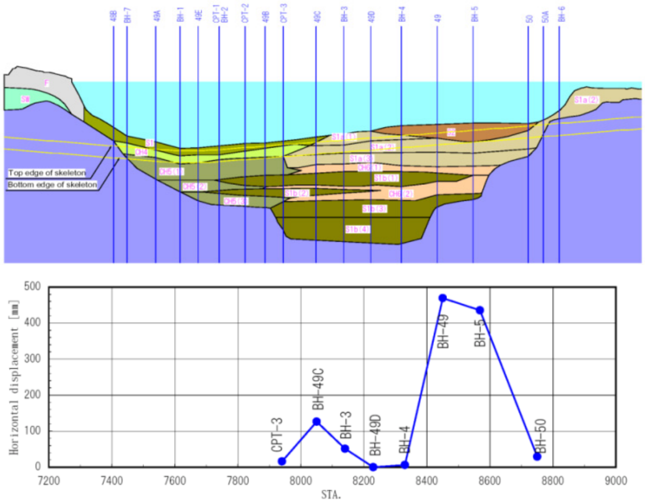
Post liquefaction settlement due to dissipation of the excess pore-pressure was assessed by using the method proposed by Ishihara and Yoshimine (1992), in which volumetric strain ε_v was obtained from the chart. ε_v at each depth can be obtained by using the normalized cone resistance q_{c1} and the liquefaction safety factor F_L at the corresponding depth, and the total settlement value can be calculated by accumulation of ε_v multiplied by the corresponding layer thickness. Fig.19 shows the settlement distribution along the tunnel. Similar to the result of horizontal displacement due to lateral spread, significant maximum settlement of 300 mm is occurred in the Asian Side.

Structural safety and functional soundness of the tunnel in longitudinal direction are checked by using the liquefaction induced ground movement described above. Fig.20 shows the schematic model for tunnel analysis after liquefaction induced ground movement.

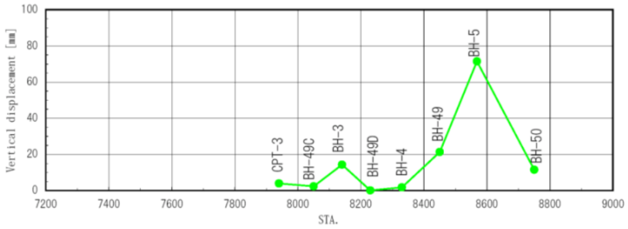
From the analysis results above, liquefaction countermeasures needed to be considered in two areas. Fig.21 shows the necessary improvement areas. Compaction Pile Grouting (CPG) method, which is one of the compaction methods used for ground improvement, was selected for the ground improvement under the Bosphorus strait especially in the Asian side. In the other area, replacement method was selected because thickness of liquefiable soil was small.

In the design for CPG, F_L values, ground displacements and settlements are calculated in accordance with improvement factor, and then improvement factor of 13.3% was obtained in order to keep the tunnel functional. Fig.22 shows analysis results after improvement. Structural safety and functional soundness of the tunnel in longitudinal direction are also checked by using the calculated results of ground displacement and settlement after improvement.

After completion of piling, CPT was conducted to check whether the necessary improvement being obtained. Calculated from the CPT results, it was found that F_L values in all blocks were greater than the required value of 1.3 and that the settlements in all blocks were less than the design settlement.

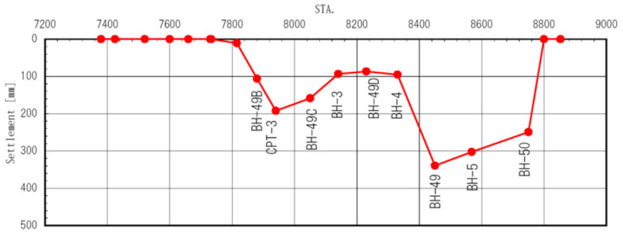


Horizontal displacement



Vertical displacement

Figure 18. Horizontal and vertical displacement distribution



Settlement

Figure 19. Settlement distribution

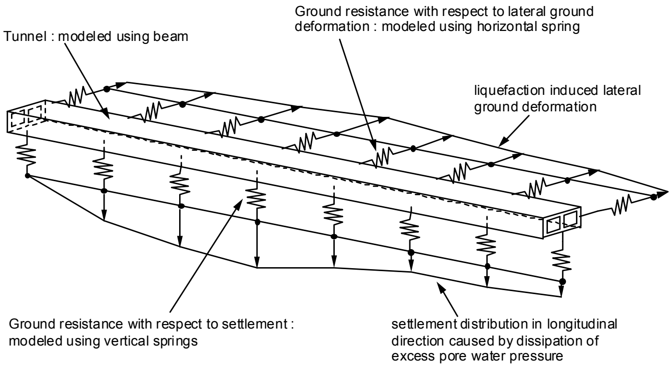


Figure 20. Schematic model for tunnel analysis after liquefaction induced ground movement

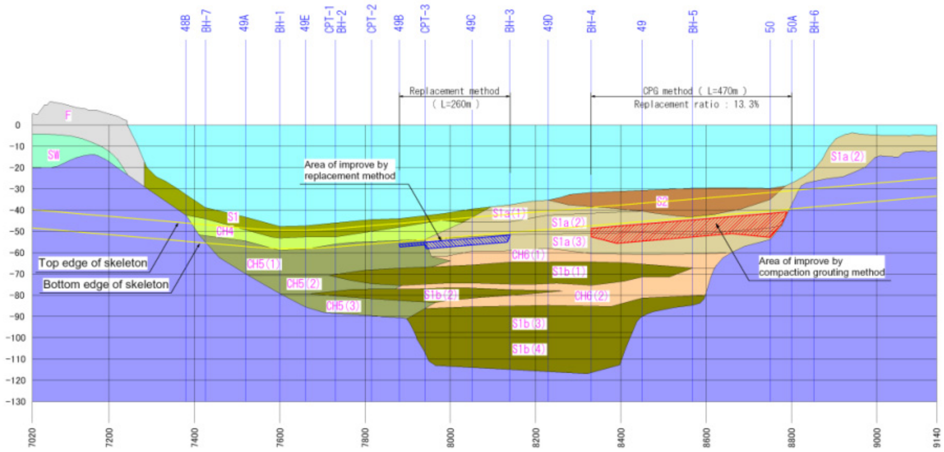
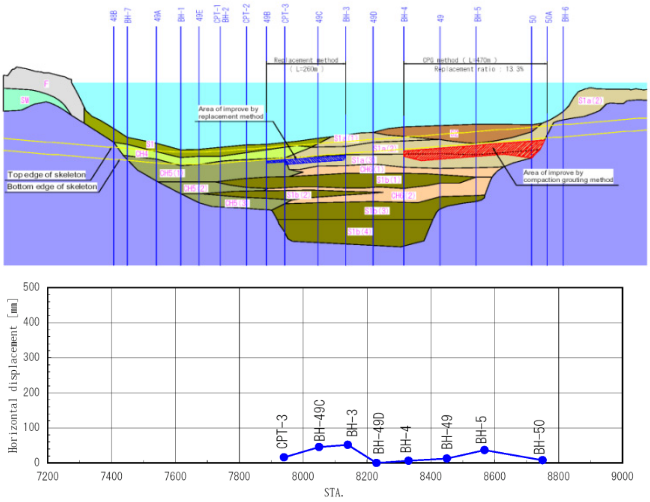
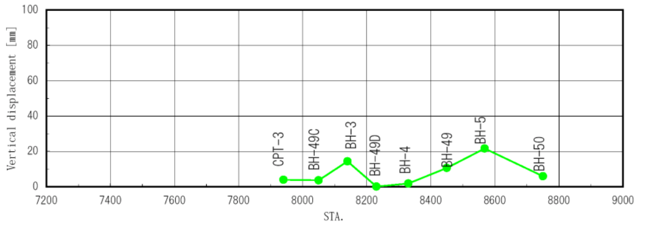


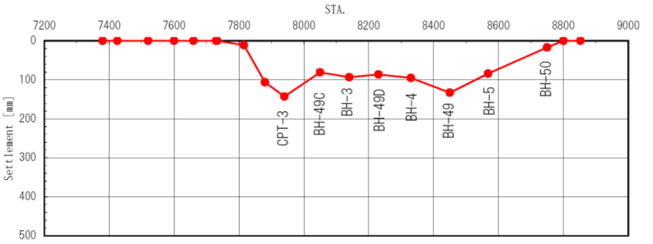
Figure 21. Necessary improvement areas



Horizontal displacement



Vertical displacement



Settlement

Figure 22. Analysis results after improvement

CONCLUSION

Characteristic seismic design issues in Marmaray project are presented in this paper. Since immersed tube tunnel and TBM tunnel are directly connected which is uncommon type of connection, various ideas for modelling are adopted. As a result, seismic joints are installed at the connection portion between immersed tube tunnel and TBM tunnel, and ground improvement against liquefaction is conducted under the immersed tube tunnel. Then, structural safety and functional soundness of the tunnel are finally confirmed for both during and after seismic event.

Opening ceremony for Marmaray project was held on October 29th, 2013, and commuter train services are currently under operation.

REFERENCES

"Technical Manual for Immersed Tube Tunnels", Coastal Development Institute of Technology, Japan (2002)

"Standard Specifications for Concrete Structures", Japan Society of Civil Engineers (JSCE) (2002)

"Design Standard for Railway Structures (Shield-driven Tunnel)", Railway Technical Research Institute (RTRI), Japan (2002)

Ishihara K, Yoshimine M (1992) "Evaluation of settlements in sand deposits following liquefaction during earthquakes", Soils and Foundations, Vol.32, No.1, pp.173-188.

Yasuda S, Yoshida N, Adachi K, Kiku H, Gose S, Masuda T (1999) "A simplified practical method for evaluating liquefaction-induced flow", Japan Society of Civil Engineers Papers, No. 638/III-49, 71-89

Youd TL, Idriss IM, Andrus RD, Arango I, Castro G, Christian JT, Dobry R, Finn WDL, Harder LF, Hynes ME, Ishihara K, Koester JP, Liao SSC, MarcusonIII WF, Martin GR, Mitchell JK, Moriwaki Y, Power MS, Robertson PK, Seed RB, StokeII KH (1997) "Summary report of the 1996 NCEER Workshop on Evaluation of Liquefaction Resistance", Salt Lake City, Utah.