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A study on the improvement of connection for segment tunnel lining using prestressed steel cable

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ABSTRACT: There has been increasing demand for segment tunnel construction method due to its performance features to meet various requirements of environmental considerations, maintenance and stability of complete structures. In Korea, a new segment fastening system using tensile strength of steel wire is presently being promoted as a part of efforts to develop segment tunnel technologies. Steel wire type-fastening system that integrates segment lining with steel strands, hydraulic jacks and anchorages boasts of its higher fastening force using high pressure of hydraulic jacks and superior tensile strength of steel strands, compared with the existing fastening systems. In this study, we summarized introduction background of steel strands as members for segment assembly, investigated case in which prestress of the steel strands is utilized in construction and introduced the steel wire type-fastening systems of segment tunnels which are currently under development.

1 INTRODUCTION

The saturation of the ground space due to explosive population growth and continuous industrial development led to worldwide efforts to utilize tunnels and underground space, thereby contributing to the rapid development of tunneling method. In recent years, New Austrian Tunnel Method (NATM), segment tunnel construction method and immersed tunnel method have become the preferred method, and in particular, the segment tunnel construction method to be applied to the development of underground space including subway tunnels is currently being highlighted. To cope with global trends, South Korea is developing a new segment fastening system using tensile strength of steel wires as a part of efforts to develop segment tunnel technologies. Steel wire type-fastening system that integrates segment lining with steel strands, hydraulic jacks and anchorages boasts of its higher fastening force using high pressure of hydraulic jacks and superior tensile strength of steel strands, compared with the existing fastening systems. Up to now, a wide variety of approaches to stability analysis, improvement of fastening force, a design for applicable segment, a research on design method and construction methods have been tried in the initial stages of steel wire-type fastening system development. In this study, we summarized introduction background of steel strands as members for segment assembly, investigated case in which prestress of the steel strands is utilized in construction and introduced the steel wire type-fastening systems of segment tunnels which are currently under development.

2 Research Backgrounds

2.1 Paradigm shift in domestic and overseas construction

The entire world has recently been looking for various ways to solve the problems of climate change and depletion of the available fossil fuel, while implementing Bali road map and post-Kyoto protocol, and global construction industry is currently pursuing low-carbon green growth in all areas of construction. As a part of green growth strategy, minimization of environmental damage and preservation of natural environment has been emphasized in planning construction of new roads, railways and tunnels. In this respect, there has been increasing demand for segment tunnel construction method due to its performance features to meet various requirements of environmental considerations, maintenance and stability of complete structures and minimize construction pollution such as noise and vibration and ground subsidence caused by the application of contentional tunneling method (NATM). In Europe, 80% of tunnels have been constructed by segment tunneling method, and the share of segment tunnel construction accounts for 60% in Japan, 50% in the United States, 40% in China and 30% in Taiwan (Korea Institute of construction & Technology 2011). In this connection, researches on the technology development related to segment tunnels have been conducted for the past 30 years in the United States, Europe and Japan. In Korea, application of segment tunnel construction method was limited to underground electric power culvert in the under river tunnels and shallow soft ground in the past, but it is currently being utilized in all geological features due to development of construction equipment and accumulated technologies. As shown in Figure 1, paradigm shift in tunnel construction, superior stability and features to reduce construction period and minimize public resentment through reduction in pollution such as noise and vibration has led to increase in demand for segment tunnel construction method, which is expected to be utilized in the construction of downtown tunnels.

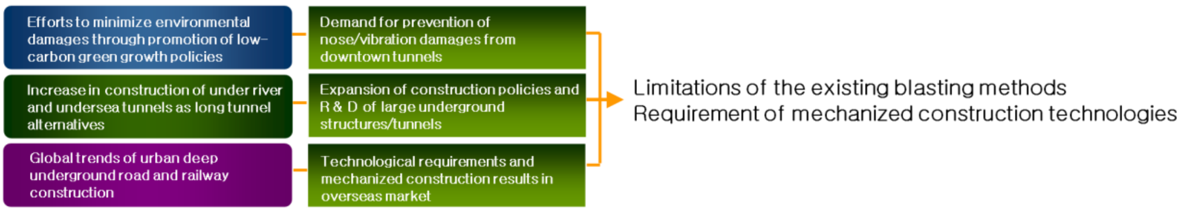


Figure 1. Paradigm shift in construction environment and tunnel construction

2.2 Occurrence of Leaks of Segment Tunnels in Operation

Segments of shield tunnel play an important role in structural function and waterproof function of the tunnel, and waterproof and wastewater treatment has a major effect on the quality of the tunnel structures. In case of shied tunnel, water sealing materials are installed between segments to prevent the influx of ground water. However, due to groundwater residence in the rear surface of the segment lining, water leakage inside a tunnel is occurring in segment tunnel which is actually being operated as shown in Figure 2.

Figure 1. Occurrence of leaks of the existing segment tunnels

In particular, more than 60% of the leakage occurred in the segment tunnel occurs in bolt joints connecting segments as shown in Figure 3. The array of the water sealing materials installed between segments varies depending on the fastening methods due to limitations of segment thickness measuring about 35cm. In case of bolt box, it is possible to install water sealing materials in a double line, but only single line array is allowed in case of inclined bolt method, Pin method and bent bolt method due to a large area of assembly part. In case of bent bolt method, it has a relatively higher fastening force, thereby preventing water leaks efficiently, but inclined bolt method and pin method are applied in most segment tunnels, resulting in a lot of leaks. As waterproof measures on the bolt joints, packing materials are currently being installed in between bolt washer and holes, but since long-term wear of the packing materials and volume expansion of the bolt due to long-term water leaks, crack occurrence in bolt holes and gap/offset of bolt connections can cause water leaks continuously, the occurrence of leakage is inevitable unless the development of a new fastening method is made.

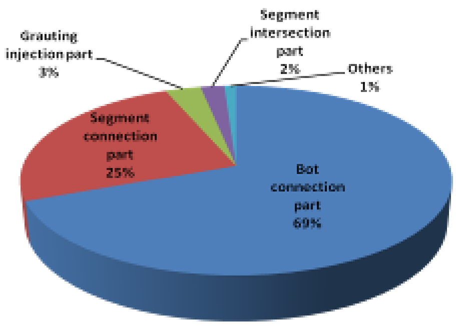


Figure 1. Distribution of leakage occurred in the segment tunnel

2.3 Existing Segment Fastening Methods

Shield segment is composed of several segments, and each segment forms a single unified ring through various fastening methods. Accordingly, a method for fastening segment and ring is one of the major elements in structural stability of the shield segment. In particular, as connections in the shield segment constitutes 30 to 40% of the total cost, simplification of the connections and development of connecting members has a huge effect on the economical efficiency of the segment tunnel. A method for fastening segment and ring is being developed into a variety of methods from conventional bolt method(Jeong 2004).

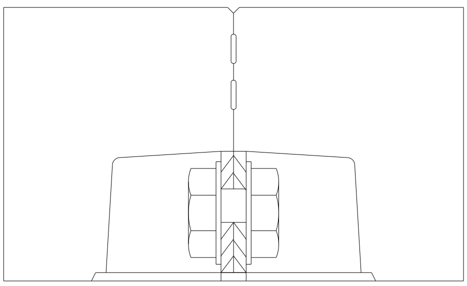


Figure 4. Box bolt fastening method

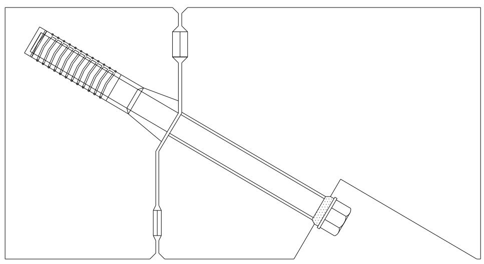


Figure 5. Inclined bolt fastening method

Figure 4 shows the bolt box fastening method which constitutes most of the segment fastening method constructed until now. Bolt box type-method has fewer assembling errors due to excellent constructability and easiness of assembly and disassembly operations of segments and can suppress leakage to the maximum through installation of box bolt inside the double line of the water expansional sealing material. On the other hand, bolt embedment is structurally vulnerable and can cause corrosion problems, and the box bolt type has its disadvantages in that separate filling operation are required when considering secondary lining in case of raceway, and the production cost is a little more expensive than that of inclined bolt type. Figure 5 shows the inclined bolt type, the second-highest applied method. The inclined bolt type requires shorter assembly time compared to bolt box type and has its advantages of fewer corrosion problems and low cost, but it can cause cracks in segment edges and has possibilities of corrosion of bolts exposed on the outside and a water leakage around the bolt since water sealing materials are installed only in a single line on the outside. In addition, it has its disadvantage in that even minor errors occurred in segment assembly can make bolt embedment difficult.

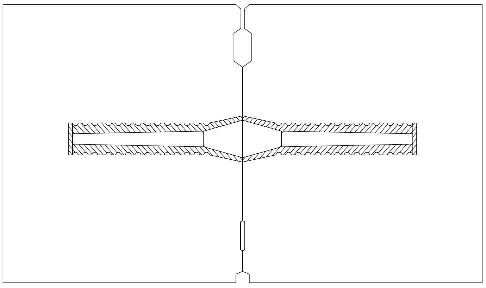


Figure 6. Pin fastening method

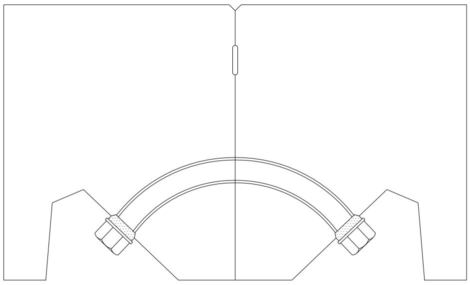


Figure 7. Bent bolt fastening method

Figure 6 shows pin-type fastening method, which boasts of fine look of inner segment after assembly due to fewer bolt grooves. This method has advantages of the lowest production cost and availability of automatic assembly, but has disadvantages in that a lot of assembly time is required since it is difficult to select pin fastening locations when assembling rings, and there is a danger of leakage as water sealing material is to be installed in the a single line on the left, and fastening force is weak due to the fluidity of embedment part made of urethane. Figure 7 shows bent bolt-type joints most preferred in recent years. The bent bolt type-method has high structural stability as joints are strongly tightened by bolts and boasts of excellent adaptability to the thrust of a jack according to shield propulsion. In addition, this method has its advantage of a relatively simple process since segments and rings are assembled by using insert nuts and bolts, but it has disadvantages of requiring more complex operations compared to inclined bolt type and high risk of water leaks around bolts since water sealing materials are to be installed in a single line on the left.

3 Development of Steel-wire Fastening Systems

3.1 Overview

With increased demand for structures which requires large section, prestress has been applied to construction materials to improve structural performance in the construction sector. For the prestressed structures, deformed reinforcing steel bars were mostly used as tendons, but steel strands have mainly been used in recent years. In case of using deformed steel bars, it is difficult to manufacture hooks and anchorages and conduct reinforcement work when large-diameter reinforcing bars are required, and compactability of the concrete are also degraded. In addition, the excessive stress concentration of the hook part can lead to localized destruction of a ground pressure and slip. On the other hand, the use of wire strands can simplify the complexity of reinforcement inside joints, remove the need for reinforcement process of connecting materials and help to achieve superior constructability(Yoon 2007). In addition, since steel strands have greater ductility compared with general reinforced steel bars, ductility behavior of the structures is expected if the steel strands are used as connection members. For this reason, steel strands in which prestress is applied are widely being used as structured cabling of PCS structures such as cable-stayed bridges, suspension bridges and Nielsen arch bridges.

Figure 8. front jacking method

Figure 9. PSM method

Figure 8 shows front jacking method, a construction method to apply the prestress of the steel strands to structures, which is being used in the construction of crossing tunnels in the lower part of roads and railways. The front jacking method in which shear-plane precast box manufactured in the field is drawn in the ground using PC wire strands and hydraulic jacks after minimizing earth pressures and friction with structures through indentation of small-diameter steel pipes makes sustainable construction possible regardless of sectional size of the box, extension and soil conditions. Figure 9 shows PSM method, which completes the upper structures through connection of segments by mounting post-tention using steel strands, and this method is widely being used in the construction of the upper structures of bridges. Furthermore, the wire strands are widely being used in many construction projects such as high-pressure waterway, pipe, a railroad tie, dam, nuclear power plant dome, LNG gas storage tank, building, beam and earth anchor.

3.2 Concept of Steel-wire Fastening System

The steel-wire fastening system currently under study is a method for connection of segment tunnel lining through injection of prestress using wire strands, hydraulic jacks and anchorages, and it helps to obtain higher fastening force compared to the existing segment fastening systems due to the utilization of high pressure of the hydraulic jacks and superior tensile strength of the wire strands. The steel strands are made of several strands of circular steel wires with diameter of 2.9 to 9mm twisted together, and they are divided into 2, 3, 7 and 19 wire-strand according to the number of strands. Figure 9 shows the shape of 7 wire-strand applied in this study.

Figure 10. steel strand

Figure 11 shows sectional shape of the segment newly devised in this study for application of steel-wire fastening system. there are 4 penetrating passages for steel-wire injection inside each segment, and shear key of trapezoidal shape is formed in traverse direction. After segment assembly, 4 shear keys in both sides of the ring perform stress distribution function to segments through generation of shear resistance to the vertical loads, and shear keys in top and bottom exert shear resistance to horizontal stress. Figure 12 shows mechanism in which stress is distributed through shear keys when vertical loads are applied to segment tunnels. In addition, since the shear keys resist to the power of all angles in the direction of the ring due to array characteristics of the segment, they are expected to contribute to increased stiffness and stress redistribution of the segment tunnel after completing assembly.

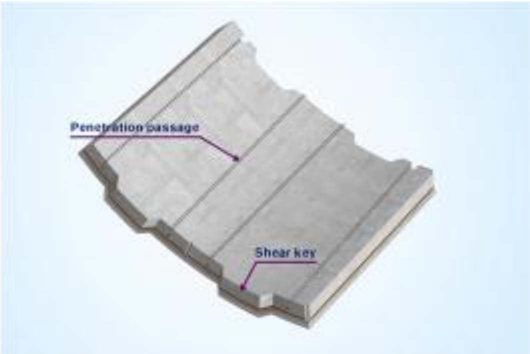


Figure 11. Segment cross-section schematic diagram

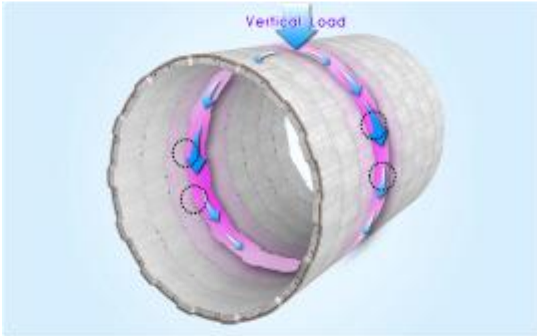
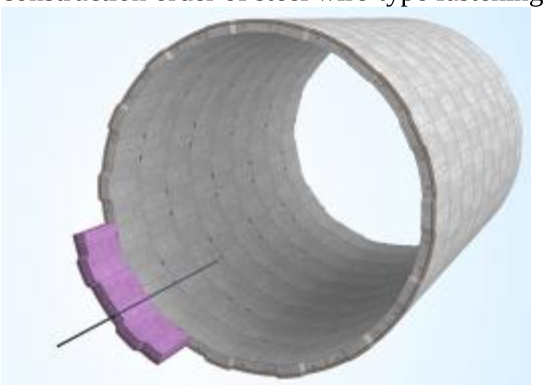
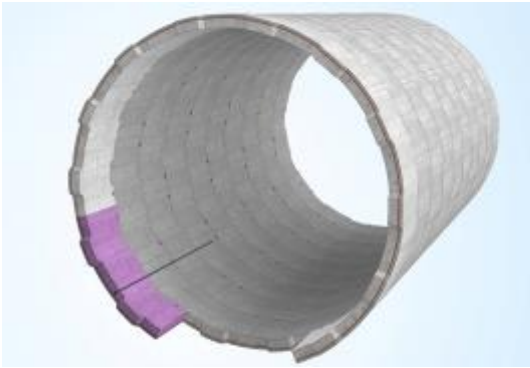


Figure 12. Stress redistribution through shear keys

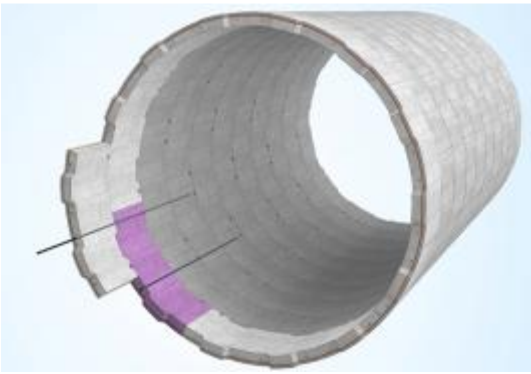
In case of steel wire-type tightening method, segments are attached to the ring in the circumferential direction, and they are combined by fixing the prestressed steel strands carried into penetration passage inside the segment with anchorages after prestressing steel strands using hydraulic jacks. When the devised segments are tightened by steel wires, one tensile force per 4 segments is applied through injection of the steel strands, and since there are 2 center-penetration passages and 2 end-penetration passages inside the each segment, 4 steel strands are carried and 4 tensile forces are applied. As segment tunnel is composed of 5 to 7 segments per one ring, and segments in each row are placed in a zigzag shape when they are tightened longitudinally, effects of increase in lining stiffness resulting from superposition of the stiffness and structural stability through unified maintenance of the tunnel behavior are expected. Figure 13 shows schematic diagram representing construction order of steel wire-type fastening method.



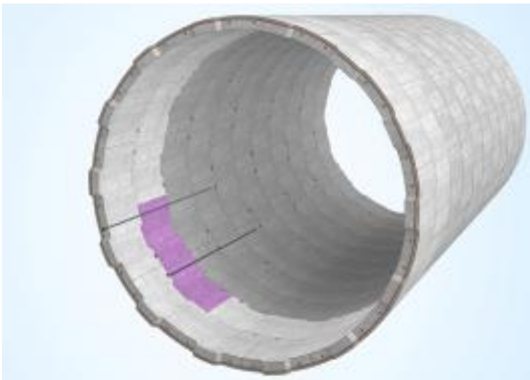
(a) First segment connection



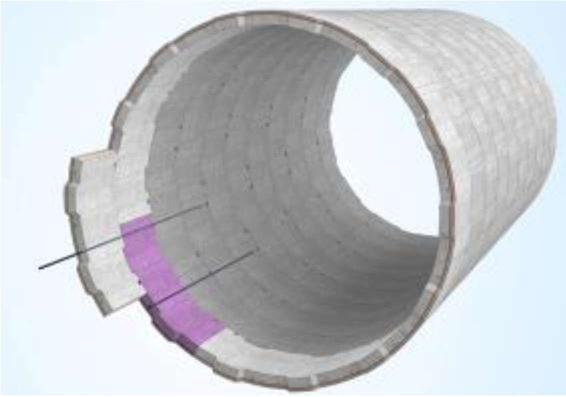
(b) Circumferential segment connection



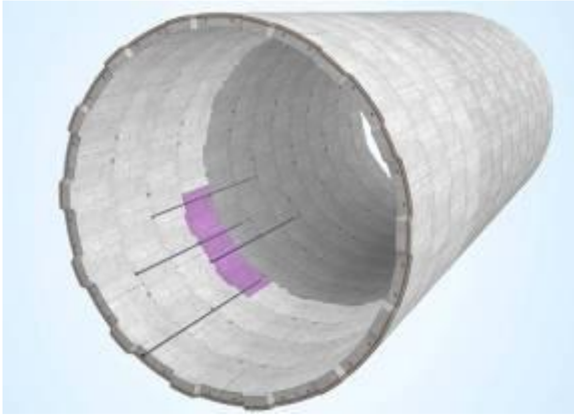
(C) Additional installation of lateral segment



(d) Second segment connection with circumferential 1-ring



(e) Third segment connection with circumferential 1-ring



(f) Fourth segment connection with circumferential 1-ring

Figure 13. Sequent order of segment connection

In case of the existing segment fastening methods, it is inevitable to increase section to make space for installation of water sealing materials, but steel wire-type fastening method only requires the minimum diameter to pass through the steel strands, thereby contributing to reduction in the segment lining section. In addition, the application of steel wire-type fastening method can lead to reduction in water leaks through reduced cross-sectional area of connections. In the initial stages of steel wire-type fastening system development, various approaches to review on the structural stability, plans to improve fastening force, development of applicable segment design, design method and construction method have been tried as a part of researches conducted for national development project. If steel wire-type tightening system is completed through this research development, it can increase segment tunnel stability through higher fastening force compared with the existing bolt fastening method and contribute to material cost savings. Furthermore, it is expected to contribute to the enhancement of segment tunnel technologies with expected demands for segment tunnels in the near future.

4. Conclusion

In this study, we investigated methods for segment connection, presented problems of segment tunnels in operation, and introduced steel wire-type fastening systems currently under study. The research contents are summarized as follows.

1. The connection methods used in segment assembly of the existing segment tunnels have problems resulting from water leaks through connections and requirement of a large area in assembled parts.

2. Due to its material advantages, steel strand has been used in a lot of construction sites as construction material, and the range of its uses is on the rise.

3. Through shear keys of the segment devised in this study, tangential load resistance can be achieved, and after the completion of tunnel construction, effects of increased stiffness and stress redistribution of segment tunnels are expected.

4. The steel wire-type fastening system boasts of its higher fastening force in comparison with the existing segment fastening devices by injecting prestress into steel strands through pressure of hydraulic jacks using steel strands, hydraulic jacks and anchorages. In addition, its application can lead to reduction in water leaks through connecting members since the area of connections is relatively small.

ACKNOWLEDGEMENT

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