Innovative Positioning System Integration for Immersed Tunnel Construction

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INTRODUCTION

A road connection was constructed in the south eastern part of South Korea between Busan, the country's second largest city, and Geoje Island. The Busan-Geoje Fixed Link (BGFL) crosses the Jinhae Bay and reduces the travel time from 3 hours to 40 minutes. The BGFL has a total length of 8.2 km, consisting of 3.2 km of immersed tunnel and two cable-stayed bridges of 2 km length. The 2x2 lane immersed road tunnel is one of the longest and deepest in the world, having a maximum depth of 48 m. In total, 18 tunnel elements of 180 m (Figure 1) were immersed in a crossing directly connected to the Eastern China Sea and the Pacific. Significant wave heights of 8 m, due to typhoons, are not an exception. Moreover, a current velocity of up to 2.0 m/s make the marine circumstances challenging.

Figure 1. Immersed tunnel longitudinal section

Performing the immersion of tunnel elements in these extreme conditions would appear impossible. Especially considering the maximum allowable deviation in the final position of no more than 0.050 m from the longitudinal tunnel axis. Both the length and depth of this immersed tunnel imposed great challenges and required 'out of the box' positioning solutions. Since the contract was awarded in March 2007 and the first immersion was scheduled for January 2008 the development and implementation time were very short. Main contractor Daewoo Engineering and Construction chose Strukton Immersion Projects for the immersion of the tunnel elements with its subsidiary Geocon taking care of the immersion survey.

TUNNEL IMMERSION PROCESS

In case it is not possible to build a tunnel at its final location an immersed tunnel can be the solution. Therefore the tunnel is divided in tunnel elements with a manageable length. These elements are built in a temporary precast yard. When ready the tunnel elements are floated and temporary stored at a mooring location. The tunnel elements are transported to their final location just before immersion. For the BGFL tunnel the conditions and phasing were as follows.

Precast yard and mooring location

The construction of the tunnel elements was carried out in a temporary precast yard (Figure 2) on the western side of the Jinhae Bay, about 40 km from the immersion area. The casting of the tunnel elements was carried out in two batches of four and two

Figure 2. Temporary precast yard

batches of five tunnel elements. The first 16 tunnel elements are 180 m long, 10 m high, 26 m wide and each weigh about 48,000 tons. The final two tunnel elements are equipped with a climbing lane and are 2 m wider. The tunnel elements were equipped on both ends with steel, reusable bulkhead panels.

After finishing each batch, the precast yard is flooded and the construction dock door is removed. The tunnel elements are floated up and trimmed one by one with the ballast water system inside the tunnel element. The transport inside the precast yard is carried out by a fixed winching system. Once the tunnel element has been moved through the dock gate, four tugs are used to transport the tunnel element to the nearby mooring location. A maximum of six tunnel elements at one time are stored at the mooring location. The tunnel elements are stored in floating conditions. Due to the sheltered area of the mooring location, the tunnel elements are not affected by swell waves and can be stored there throughout the year.

Immersion preparation and transport

The tunnel elements are prepared for the immersion operation at the mooring location (Figure 3). Prior to the transport, two immersion pontoons are positioned over the tunnel element. The pontoons are of the catamaran type and consist of a main deck (42.5 m x 24 m x 2.5 m) and two floaters (36 m x 6 m x 6 m). The pontoons are each designed for at least 1000 ton pulling force.

Figure 3. Immersion pontoons at mooring location

On the tunnel deck, bollards, lifting lugs, sheaves and a landing tower are installed, as well as guide beams on the primary side (bow) and catches on the secondary side (stern) of the tunnel element. The guide beams and catches are used to guide the tunnel element sideways during the immersion process. Equipment for the remote-controlled ballast water system and the immersion survey system are installed inside the tunnel element.

As soon as the predicted weather and wave conditions are within the limits and provide a weather window of 3 days, the final go decision was made. The combined system of tunnel element and pontoons is towed by four tugs to the immersion location.

Immersion

A spread consisting of 18 winch wires is used in order to be able to carry out a controlled and secure immersion operation. Four mooring wires per pontoon for positioning the immersion pontoons above the target position of the tunnel element, three contraction wires per pontoon for positioning the tunnel element and two suspension wires per pontoon to carry the weight of the tunnel element.

Figure 4 Immersion spread

As soon as the tunnel element arrives at the immersion location, the winch wires are connected one by one to seabed anchors. The mooring and contraction wires are installed in a taut configuration in order to reduce the motions influenced by waves to a minimum (Figure 4).

After taking in the necessary water for the 2% overweight, the tunnel element is lowered to the gravel bed. The immersion pontoons fully bear the immersion loads during the immersion process. The connection with the previous tunnel element is carried out by the Gina gasket, a water tight seal between two tunnel elements. After connection of the tunnel element the immersion joint between the newly immersed tunnel element and the previously installed tunnel element is emptied. An Omega Gasket is mounted at a later stage for extra safety with regard to water tightness. Divers remove the deck layout from the tunnel deck. This equipment is returned to the mooring location where immersion preparations for the new tunnel element commence.

TRADITIONAL IMMERSION SURVEY SYSTEM

The survey of an immersion operation is usually carried out by a tacheometric system consisting of three total stations on shore, measuring four survey prisms mounted on an access shaft and an alignment tower (Figure 5). An inclinometer is used to measure the roll of the tunnel element. Before immersion the position of the prisms is measured and related to the tunnel geometry by known points on the deck of the tunnel.

Figure 5. Traditional survey system

This traditional system uses land survey techniques and functions appropriate up to a distance of +/- 800 m offshore, at greater distances the accuracy deteriorates. Also the greater depth of the tunnel restricts the use of the access shaft and alignment tower as result of the current forces. Therefore a new underwater survey system had to be developed.

SURVEY SYSTEM USED FOR THE BGFL PROJECT

The BGFL Survey System consist of a combination of new and existing techniques, with an increasing accuracy from the transport phase up to the joining of the tunnel elements. In total four new survey systems are used for the immersion. For the first tunnel elements the traditional survey was used as well for verifying the newly developed systems.

Transport and positioning above immersion trench

Figure 6. RTK-GPS at immersion location

The first system, an RTK-GPS system on the immersion pontoons, was used for the transport phase and for the positioning of each tunnel element above the immersion trench. On both of the pontoons a GPS receiver was installed. Near the immersion location a GPS base station was placed which provided RTK-GPS accuracy for the positioning (Figure 6). The accuracy of the system is +/- 0.03 m. in XY and 0.1 m. in Z.

Immersion survey

Approach

Figure 7. Tautwire system

For immersing the tunnel element to a distance of 0.5 m towards the previous one a custom made 'light tautwire' system (Figure 7) was designed, the second survey system. The tautwire is an instrument running a tensioned steel wire up and down on a drum. The tautwire unit is attached to the primary bulkhead of the tunnel element; the wire is connected to the secondary side of the previously immersed tunnel element. The tautwire measures the length of the wire, as well as the angles of the arm guiding the wire. The accuracy of the tautwire increases the closer the tunnel element gets to its final position. Information about the secondary side, referenced to the primary side, was provided by a Fiber Optic Gyroscope (FOG). The accuracy of the tautwire system is ± 0.03 m in X,Y and Z in the final and most critical stage of immersion.

The third system, a USBL system, was used as a backup of the tautwire. This acoustic survey system consists of a transducer and several transponders. The transducer, mounted on the primary side of a tunnel element, transmits an acoustic signal. This signal is received by the transponders mounted at known positions on the previously immersed tunnel element. The transponders reply to the transmitted signal with their own acoustic tone which is subsequently received at the transducer. A sound velocity sensor is mounted near the transducer. The speed of sound is frequently updated in the USBL software. This software outputs forward, starboard and depth values for each transponder. The Geocon immersion software processes these values to an actual position of the tunnel element. The accuracy of this system is ± 0.15 m.

Final immersion phase

In the final phase of the immersion process, the Gina gasket is pulled against the steel end frame of the previous tunnel element to obtain the initial water tightness, necessary to empty the immersion joint. For this phase, distance sensors (Figure 8) were developed to provide accurate measurements. With their range of 0.4 m, the four distance sensors are extended just before the moment the Gina gasket touches the previously immersed tunnel element. The submillimeter accurate readings of these sensors are used in several ways. The reading of the stroke is a direct indication of the distance. Using the four distance sensors on each corner of the primary side of the tunnel element, a conclusion can be drawn about the position of the secondary end from the differences in the readings of the sensors. The accuracy of this forth immersion survey system is ± 0.005 m at the primary side, and ± 0.02 m at the secondary side.

As immersed survey

To determine the final position of the tunnel element after immersion a final survey is performed. Traditionally this is done with laser-plummet measurements through the access shaft to confirm the final position of the tunnel element. For the BGFL-project most tunnel elements were not equipped with an access shaft and the end survey was done by tacheometric measurements through the bulkhead doors. The accuracy of this final measurement is ± 0.005 m.

Figure 8. Distance sensor

IMMERSION SURVEY PREPARATIONS

Precast yard

The immersion survey preparations start in the precast yard where the tunnel elements are built. The tunnel element geometry is verified by means of total station measurements. Survey points are created in and on the tunnel element. The steel end frame on which the Gina gasket is mounted needs to be flat within ± 0.003 m and facing in the right direction. An as-built check on this plate is performed as deviations in its position may compromise the water tightness of the immersion joint.

Just before immersion, the tautwire and distance sensors are mounted on base plates. These base plates are mounted on the bulkhead and measured in the precast yard (Figure 9, marked) at the primary side of the tunnel element. During immersion the distance sensors are extended to reference plates that are mounted at the secondary side of the previously immersed tunnel element.

Figure 9. Baseplates on bulkhead

Before an immersion all survey equipment is transported to the mooring location where the tunnel elements are temporarily parked. The next element to be immersed is fitted with all necessary sensors required for the immersion.

A GPS compass is used for the alignment of the FOG inside the tunnel element as well as for the tunnel element position and heading during the transport phase. It is mounted on the two catamaran pontoons. After connecting these pontoons to the tunnel element the position of the GPS antennae is measured with a total station. With the known position of the antennae and the heading from the GPS compass, the heading of the tunnel element is calculated.

The FOG is used to measure the roll, pitch and heading of the tunnel element. The heading misalignment which is introduced due to the mounting of the sensor is dynamically determined by simultaneously measuring the heading of the tunnel element with the GPS compass and comparing it with the output of the FOG. After approximately 30 minutes of data collection the Geocon software calculates the best fit of the two data sets resulting in a C-O value.

Figure 10. Mounting the USBL system

Since the elements are floating at the mooring location, the roll and pitch C-O's need to be determined in a dynamic environment. An automatic levelling instrument is set up above a known point on the tunnel element deck. A rod is placed above another known point and is observed through the levelling instrument. The rod is observed while it goes up and down behind the instruments crosshair as the levelling instrument compensates for the motion of the tunnel element. With the radio open the observer behind the instrument and the online surveyor take a reading of both the levelling rod and the inclinometer roll at the same time. After some 10 readings a reliable C-O for the roll, and likewise for the pitch is determined.

At the mooring location the USBL transducer is mounted (Figure 10) and surveyed with land survey equipment. Also an "as-mounted" check on the guidebeams and catches is performed. The Geocon immersion software is configured with all latest survey data and maps and the remaining checklist items are completed. The element is now ready to be immersed and awaits its final go decision.

IMMERSION

After leaving the mooring location the tunnel element starts a 36+ hour journey to its final position. Crews of winch operators, hydraulic engineers, divers, surveyors, immersion commanders and other engineers work in 12 hour shifts until the immersion operation is successfully completed. The data coming from all sensors finds its way through the integrated systems to the immersion command unit from where the operation is lead. As no access shaft is used in this project all equipment inside the tunnel element such as valves of the ballast tanks, the dome cameras, the tautwire and distance sensors are remotely controlled. All the data from these systems is transmitted through an umbilical, running from the secondary bulkhead to the umbilical winch on the secondary immersion pontoon.

The Geocon software displays and also logs all received data. After each immersion all logged data is reviewed, analyzed and reported.

Visualisation

Figure 11. Immersion command center

All immersion survey data is presented in a sober yet adequate data screen providing the immersion commander with no more information than necessary. Simultaneously, all immersion survey data is uploaded to a computer server. This data is directly available for the web application www.geocon3d.com which displays the immersion process in real time in a virtual environment. Management, client, engineers, relatives and all those interested can log on to this website and follow the immersion process through webcams and the virtual 3D model.

Geodetic alignment control

After immersion the position of the tunnel element is verified with a total station measurement through the tunnel gallery. As the tunnel is getting longer, the accumulated total station data results in a declining accuracy as a result of poor geometry and poor survey conditions. Large variations in humidity, temperature and line of sight due to construction works inside the tunnel influence the survey conditions considerably. The angular reliability of the geodetic network inside the tunnel decreases with the tunnel length. Therefore the geodetic network inside the tunnel is strengthened using land survey gyroscope observations. This instrument measures the true heading at several chords throughout the tunnel with an angular accuracy of 0.001° , equal to 0.015 m / km . The headings measured with the total station are dependent of the accuracy of the preceding survey points that are used in the tunnel. The gyroscope headings on the other hand are independent. The total stations measurements are corrected with the gyroscope observations. With this corrected data the as built tunnel alignment is determined.

CONCLUSIONS

The existing Geocon Immersion Software Package required to be re-written in order to cope with the input of data from sensors like remote controlled winches, CCTV, ballast water systems and the new survey systems. Struktons in-house software engineers managed to successfully deliver this new software prior to the first immersion in January 2008. The integrated survey system approach by Geocon proved to be successful for the Busan Geoje Fixed Link immersed tunnel project. During the first immersion, all new positioning systems were mirrored against the traditional total station system. The accuracy and the reliability of the new systems proved to meet the requirements to position 3.2 km of immersed tunnel within just 0.05 m from its intended position. The 18th and final tunnel element was immersed in June 2010. The south Korean president proudly opened the tunnel for public in December 2010.

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