Proceedings of the Transport and Immersion Operations of the N31 Aqueduct in Harlingen, The Netherlands

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ABSTRACT

The article describes the Scope of Work of Tunnel Engineering Consultants (TEC) for the N31 Aqueduct Harlingen project. The Works included all work preparations, immersion engineering, construction engineering and guidance for transport and immersion operations of the aqueduct, up to and including operational management of the transport, immersion, sand flow foundation and backfill operations of the aqueduct. Specialists of Tunnel Engineering Consultants were requested to guide main contractor Ballast Nedam Infra through the process of preparatory works and execution of all works related to installation of the aqueduct, all within a very tight construction schedule.

Key Words: Aqueduct, Immersion, Transport, Operations, Immersion Engineering

1. INTRODUCTION

The Harlingen Aqueduct is part of the new N31 roadway connecting Leeuwarden with Amsterdam. The new alignment of the N31 provincial road at Harlingen, Friesland, goes around the city centre of Harlingen in a largely deepened road and crosses the Van Harinxma canal, parallel to the old bridge in the existing N31 road. Due to the number of recreational (sailing) vessels passing the existing moveable bridge in the N31 being the cause of usual traffic delay, the new crossing has been designed as an aqueduct under the canal.

Construction of the tunnel element started in August of 2016 next to the canal in which later the North ramp to the aqueduct is constructed. In March 2017 the concrete works of the aqueduct where finished and the building pit was flooded. A few weeks later, 31 March, the immersion operation started.

The design of the aqueduct and design of immersion provisions is described in chapter 2. The immersion operation itself is described in chapter 3.

Figure 1. Final situation
2. DESIGN

The length of closed section of the aqueduct in the final phase amounts 63 m with a 51 m long immersed section. The width of the tunnel is 24.30 m and contains two lanes per tube. The top of the roof of the aqueduct in immersed position is 4.20 m below average water level.

Figure 2. Top view of aqueduct

Figure 3. Cross-section (left) and longitudinal section (right) of aqueduct in final situation

Figure 4. Start of construction (left) and aqueduct during transport (right)
2.1. Buoyancy

At 2 kilometres from the aqueduct a sluice is located separating the canal from the Wadden sea and therewith controlling the water level in the canal. At low tides water from the canal is discharged by opening of a sluice gate resulting in a decrease of salinity levels and temporary lowering of the water level by 30 cm. During closure of the discharge sluice salinity levels tend to rise due to drainage from both farmland and construction activities, and of course the passage of ships through the ship locks increases salinity in the neighbouring part of the Harinxma canal. Salinity levels in a period of one year prior to immersion varied between 100 mg/l and 7700 mg/l. Three weeks before the immersion operation the trench was dredged in which salinity levels were built up far exceeding the previous measured levels. To limit salinity effects during the immersion operation the canal was drained by the discharge sluice in the day before the immersion operation reducing as much as possible the salinity level in the immersion trench. During the weekend discharge of water from the canal to the sea and passage of ship was prohibited.

The element is transported with a freeboard of 0,15 m. As the bulkheads are located in front of the quay walls a relatively large area remains above the water line at all times and delivers additional buoyancy when lowering the element, even when the roof is already submerged. This buoyancy of the quay walls and the volume of bulkhead enclosed space provides the buoyancy required as lifting capacity for the vertical control of the element during the immersion operation. 185 m3 of ballast water shall be taken in to lower the element the first 0,15m with the roof through the water line, then another 480 m3 is required to lower the element to its final position. After touch down a final 500 m3 of ballast water is taken in to ensure the elements vertical position during succeeding sand flow operations.

![Image](image.png)

**Figure 5. Salinity levels as a function of the depth (left) and water volume in ballast tanks during immersion (right)**

2.2. Roll stability and transversal guidance

During transport the element is stable, meaning that a roll will always turn the element to its stable position. However, as soon as the roof goes through the waterline the meta centric height becomes negative meaning that the element will roll along its longitudinal axis (the quay walls protruding the waterline are not large enough the ensure stability).
To prevent the element from rolling a guidance structure is applied at the 4 corners of the element at the north and south transition structures. At the final stage of transport, with 1,00 m to go in longitudinal direction, the element is positioned in a sort of catch lowering the transverse misalignment from 0,30 m to 0,10 m on both the north and the south side. When positioned correctly in longitudinal direction the element is positioned between the 4 guidance structures. By extending the two times two hydraulic push-pull cylinders located on the two eastern guidance structures, the element is pushed against the two guidance structures located on the west side. The western guidance structures have been constructed exactly on As-built correct position within 10 mm tolerance. During the entire immersion operation this fixation is maintained. Only after ballasting, just prior to the sand flow operation, the cylinders were withdrawn. To limit friction between the element and the guidance structure during immersion 6 teflon pads are located between the western guidance structure and the element. On the eastern guidance structure tank rolls were positioned on the push-pull cylinders.

The hydraulic push-pull cylinders where pushed against the element after which they were retracted a bit (=5 mm) to release the pressure to minimize friction. During immersion the force in the jacks was constantly monitored with a maximum of 15 tons per jack. Most likely those forces where not the result of the element willing to roll but due to imperfections in the concrete surface.

![Guidance structures in cross-sectional view (left) and schematic view of hydraulic push-pull cylinder (right)](image)

**Figure 6. Guidance structures in cross-sectional view (left) and schematic view of hydraulic push-pull cylinder (right)**

![Teflon pad mounted on the element (left) and hydraulic cylinder with tank roll pushed against a steel plated mounted on the element (right)](image)

**Figure 7. Teflon pad mounted on the element (left) and hydraulic cylinder with tank roll pushed against a steel plated mounted on the element (right)**
2.3. Longitudinal guidance

The position of the element in longitudinal direction is ensured by two steel stopper/bumper structures at the primary side; the south transitions structure. The two steel bumper structures are used as a first stopper for the element during transport at their top level, and guide the element from an initial longitudinal positioning tolerance of 100 mm to the exact As-built determined position of the immersed element at the bottom level. With the winch wire on the primary side the element is pulled against the two steel structures. The two smaller steel structures at the secondary side of the element are only for back-up purposes (in case of failure of the longitudinal wire). During immersion a constant tension on the longitudinal wire was maintained (≈15 tons).

![Figure 8. Guidance structures in longitudinal view](image)

2.4. Ballast system (safety against uplift)

4 ballast tanks with a total capacity of 1,800 m3 are installed in the aqueduct. The ballast tanks where filled through ordinary drainage pipes connected with two remotely controlled valve racks located in the element. Ballasting of the element is done by pumping in water rather than letting in water, so that the filling speed can be configured more accurately. In every ballast tank a single pressure sensor with an accuracy of 1 cm was located at the bottom of the tank to determine the water levels. Two of the four tanks where equipped with an additional sensor to measure tilting. The drainage pipes where connected with a total of 6 pumps to control the capacity and pumping speed between 50 m3/hour and 400 m3/hour.

![Figure 9. Empty ballast tank (left) and full ballast tanks (right)](image)
2.5. Temporary support (jacks)

The element is immersed and positioned on temporary supports consisting of 10 jacks. 4 pieces of 100 ton jacks where installed at the primary (South) side transition structure and 6 pieces of 90 ton jacks where installed at the secondary (north) side transition structure. The jacks at the primary side where coupled and the jacks on the secondary side where divided in two groups effectively creating a 3 point support. The chosen bearing capacity of the jack configuration takes into consideration the contingency scenario of one failing jack per support that cannot be exchanged by divers during the operation.

![Figure 10. Location of temporary support jacks (left) and theoretical jack forces during sand flow (right)](image)

2.6. Transition structures

After immersion the ramps are casted against the aqueduct and water tightness is maintained by water stops connecting both the ramps and the aqueduct. Before the final situation is reached a temporary water barrier between the canal and the dry ramps is required. A temporary water barrier on the bottom is created with a rubber profile. The top of the profile is a few centimetres higher than the bottom of the element in immersed position such that the profile is compressed by the element.

At the 4 corners of the aqueduct concrete panels, functioning as stop-logs, are lowered in concrete recesses.

![Figure 11. Rubber profile mounted on a horizontal sheet pile to guarantee a water barrier during constructing of the ramp sections](image)
The entire transport, immersion, sand flow and locking fill operation has been planned and executed within a shipping and discharge closure period of the Harinxma canal of 82 hours. In the period of 3 weeks before the planned shipping closure, all marine works preparations in the dredged trench and the casting basin of the aqueduct were finalised, including inundation of the casting basin, float up and mooring of the element, final preparations of the element, removal of the front combi walls of both the casting basin and the other cut and cover ramp and the final inspections and preparations of the transition structures, temporary supports and guidance structures for the transport and immersion of the element. The provisions for the temporary supports, temporary water retaining structures for the closure joints in the North and South transition structures and all the guidance structures required for transport and immersion of the element, were constructed, finalised and surveyed As-Built in the weeks before inundation of the dry dock. These activities were carried out in parallel to the installation of all immersion provisions in and on the aqueduct element before inundation.

3.1. Float-up

Remarkable for this project is that the aqueduct element has been constructed on a sand layer bottom within a casting basin inside the northern cut and cover ramp leading to the aqueduct. As typical potential sticking of the concrete element to the bottom of the casting basin was a point of concern, the basin was filled to a level below the minimum water depth required for float up 24 hours before the scheduled float up operation. The sandy bottom was thus saturated with water and when the basin was finally filled up to the water depth required for float up, the element floated up gradually and evenly with only several centimeters of vertical difference between the corners of the North and South quay walls before full floatation. The element was secured by wooden fenders and a mooring configuration with winches on the element roof towards mooring bollards at one side of the casting basin. The mooring configuration was mainly designed to with stand suction forces of ships passing the casting basin, once the water retaining front wall was to be removed. In secured floating position, the element was balanced and ballasted to a minimum operational freeboard of 15 cm by pouring ballast concrete in between the ballast
tanks within the element. After ballasting for transport, the element was moored tightly and the front combi-wall of the casting basin, separating the basin from the Harinxma canal, was cut off by divers.

3.2. Transport

After both water retaining front walls in front of the North and South transition structures had been removed, all As-Built Surveys finalized, the transport winch wire configuration had been installed and all dive inspections of element, transition structures, temporary supports and trench had been carried out and a last silt removal/cleaning activity had been completed, transport of the floating element could be begun by warping/hauling the element with the southern winches through the northern transition structure into the Van Harinxma canal.

The main points of attention during transport were the wind load working on the quay walls of the floating element, which had to be balanced out by the transversal winch pontoons positioned in the Harinxma canal, and the passage of the element of the northern transition structure and its transversal guiding structures at the end of the casting basin with a sufficient transversal transport tolerance of As-Built 80 mm.

Figure 13. Aqueduct during transport with winch wire configuration
Figure 14. Aqueduct during transport

Figure 15. Aqueduct during transport

Figure 16. Aqueduct positioned between transition structures

Figure 17. Aqueduct lowered through water line (left) and floating pipe to pontoon during sand flow operations (right)
The transport winch configuration was based on a two-step system of accuracy of transversal steering of the element into the catch of the southern transversal guidance system. Once the floating element has been steered into the transversal catch at the primary side, the element could be positioned longitudinally into the immersion position.

The South longitudinal guidance structures have been designed to take the load of collision of the floating element being hauled forward towards the immersion location, followed by the tensioning of the element by the longitudinal pulling winch against the bumper structure for maximum accuracy of positioning of the element during immersion.

### 3.3. Immersion

The immersion operation procedure of the aqueduct was based on the following concepts:

- Vertical lift/buoyancy control during immersion solely by quay wall volume and enclosed space by bulkheads
- Positioning of element and guiding element in steps to correct immersed position by guidance structures in both longitudinal and transversal direction
- Roll movements of the floating element with the roof through the water line to be prevented with the vertical guidance structures

In order to correct the negative GM once the roof of the element goes through the water line, it has been chosen to devise a set of equipment and facilities to keep the element upright in vertical position and to not allow roll movement, rather than to allow the element to roll towards either the East Or West guidance structures and design these to bear the accidental load of collision due to roll movement. As this collision load will increase with the allowed rotation around the longitudinal axis of the element, it has been a starting point to keep these loads small and decrease any occurring roll to an absolute minimum. This has been achieved by the application of hydraulic push-pull cylinders mounted on the transversal guiding structures, forcing the element in an upright position during the entire immersion procedure.

The combination of two- to three-step guidance structures in both longitudinal and transversal direction was developed to decrease transport tolerance into a catch, followed by a stepwise decrease in immersion positioning tolerance. The combination of said guidance structures with the application of a very accurate ballast system and the push-pull cylinder system to keep the floating element upright, ensured a more accurate and careful immersion configuration and procedure for this floating element with limited floating stability than traditionally applied.

The immersion procedure was carried out as follows:

1. Positioning of floating element into guidance structures for correct immersion position
2. Send out hydraulic push-pull cylinders on eastern transversal guidance structures with tank rolls to steel vertically mounted plate on element. Push element towards western transversal guidance structures and retract cylinders to a gap of around 5 mm
3. Ballast floating element slowly in steps of 5 cm water in internal ballast tanks at lowest pump speed to immerse roof through water line.
4. Once roof has gone through water line, increase ballast steps and pump speed for immersion process.
5. Immerse in steps to 4.00 m depth and decrease ballasting speed to arrive on temporary jack supports; last longitudinal and transversal winch correction to immersed position of element towards As-Built Best-Fit position.
6. Land element on jacks at level of 5 cm above preset level for sandflow to not damage watertight rubber gasket on support transition structure (temporary water retaining structure for closure joints).
7. Ballast element to operational level for jacks.
8. Lower jacks 5 cm to pre-set level for sand flow and compress the rubber gasket on the transition support structure (temporary water retaining structure for closure joints).
9. Ballast the element to the required uplift safety for successive sand flow operation.

The aqueduct was immersed within 1 cm longitudinal tolerance and 2 cm transversal tolerance to the determined Best-Fit position of the As-built situation in between the North and South transition structures.

3.4. Closure joint

After immersion and positioning on the jacks and ballasting of the element, the temporary water retaining structures at the four corners of the aqueduct could be lifted into position. These interconnecting concrete panels positioned in a clamp construction form the temporary water retaining structure between the Harinxma canal and the cut and cover ramps, where the concrete closure joints on both sides of the aqueduct element will be constructed in the dry. The retaining structures at the four corners had a split of function between water retaining and ground retaining structure; the last being required as a temporary retaining structure for the sand flow operation, consisting of sheetpiles.

3.5. Sand flow

When the concrete panels water retaining structure and the sheetpile ground retaining structure were in place at all four corners of the aqueduct, the sand flow operation could start to construct the foundation bed of the aqueduct. After completion of the sand flow operation, the jacks were released and the element was set down on the created sand bed, after which locking fill and back fill to the sides of the element within the dredged trench could start. From the moment of retraction of the jacks, the position of the element was monitored to keep track of the settlement developments.

3.6. Transport and Immersion Survey

The Transport and Immersion survey was based on the As-built survey of the permanent concrete works of the aqueduct element and the transition support structures. The element was modelled 3D and a Best-Fit position was determined in between the transition structures to ensure a maximum water tightness of the clamping water retaining structures at the four corners of the aqueduct, forming the connection between the element and the transition structures with the cut and
cover ramps towards the aqueduct. All guidance structures were surveyed As-built as well, to determine the minimum free space between the element and transition structures and guidance structures during passage of the northern transition structure during the transport operation. The element was followed live on screen in the command cabin and on the element during the transport operation, so that the element could be steered in between the boundary conditions and towards the catch of the primary guidance structure. During the entire immersion operation the element was followed live on screen and the position, roll, pitch and yaw of the element were monitored during ballasting and at landing on the jacks. The height of the element was monitored at every corner during lowering of the jacks to final pre-set position for sandflow. The 3D visualization and the graphics of the live position data of the element at every moment during the operations provided a very good tool and overview for management of the complete operations.

Figure 18. Aqueduct Immersion Survey; View of 3D model during transport towards best fit position in between As-Built models of North and South transition structures.

Figure 19. Aqueduct Immersion Survey system overview during transport and positioning of aqueduct in between North and South transition structures.
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- Tunnel Engineering Consultants (Immersion Engineering and Management of Transport and Immersion Operations)
- MHPoly (design of Immersion provisions and Temporary Structures)
- Tenwolde marine & transport services (Marine Equipment and Transport)
- Geovisie land & marine (Transport and Immersion Survey)
- Aquatech (Diving Works)
- Van Tongeren (Ballast System construction and operation)

Figure 20. Immersion team