Citybanan is a new 6 km (3.7 mi) long double track railway tunnel running beneath central Stockholm and including two new underground stations: Odenplan and Stockholm City. When complete in 2017, commuter trains will have their own tracks through Stockholm, while the existing tracks remain in use, doubling the capacity of the railway traffic through the city. The client is Trafikverket, the Swedish transport administration, and the design/build contractor is German company, Züblin Spezialtiefbau GmbH, together with its Swedish subsidiary Züblin Scandinavia AS.

Because the new Citybanan tunnel is largely situated below the bedrock level, it is being constructed as a rock tunnel using a drill and blast method. The tunnel crosses the Söderström, a branch of Lake Mälaren, between the two inner-city islands Södermalm and Riddarholmen. Here the bedrock descends to a valley more than 40 m (131 ft) deep. To connect the rock tunnels between the islands, a 300 m (984 ft) long immersed concrete tunnel supported on pile foundations was constructed.

The immersed tunnel under the Söderström is the most challenging part of Stockholm’s new underground Citybanan project. The tunnel is subdivided into two tubes: a 12 m (39 ft) wide railway tube and a 5 m (16 ft) wide tube for service and rescue purposes. It has a total width of 20 m (66 ft) and a height of 8.9 m (29 ft). The immersed tunnel consists of three prefabricated tunnel elements. Two elements have a length of 107.5 m (353 ft) and the third slightly curved element is 85 m (279 ft) long.

Foundation of the Tunnel

Where construction is complete, the tunnel forms an underwater bridge with spans of 55 m (180 ft) between each of the four pile foundations. At the north end, called the Joint House, the tunnel is simply supported, but is free to move longitudinally. A fixed restraint is provided at the other end using 50 permanent rock anchors with 19 strands each drilled 40 m (131 ft) deep into the rock. The anchors are distributed conically around the entire cross-section of the concrete tunnel, which

Since a dry dock of sufficient size does not exist in Lake Mälaren, the concrete tunnel elements were built in floating steel shells constructed in a shipyard in Estonia and transported by barge across the Baltic Sea. Prior to starting the reinforcement and concrete works, the steel shells were unloaded from the submersible barges by lowering them to the bottom of the lake. The immersed tunnel section has a constant inclination of 3.07% from south to north. After the tunnel elements were immersed to a depth between 14 and 23 m (46 and 75 ft), they were monolithically connected to each other with cast-in-place concrete and post-tensioning.

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is cast into the rock. The rock anchors overlap with the post-tensioning tendons in the concrete tunnel. To transfer transverse loads into the rock that would occur mainly during the accidental load case “ship impact,” another 25 rock anchors were placed perpendicular to the tunnel axis.

The Joint House is cast directly against the rock and the northern end of the tunnel is on permanent pot bearings within the Joint House. Transverse loads can be transferred through support plates between the tunnel and the Joint House into the rock. The support plates are located at the level of the base and top slab of the tunnel and consist of two stainless steel plates on a concrete socket. As transverse load transfer is only needed for the accidental load case of ship impact, the two stainless steel plates are installed with a 5 mm (0.2 in) gap.

Between the Joint House and the first pile foundation, the tunnel is founded on a raft foundation, directly on the rock. To allow longitudinal movements of the tunnel due to temperature change, creep and shrinkage, a specially-designed sliding bearing was placed between the raft foundation and the concrete slab of the tunnel.

**Immersion of Tunnel Elements**

The three tunnel elements were immersed one after another. First, the southern element was immersed and connected to the concrete tunnel that forms the link between the immersed tunnel section and the rock tunnel sections that continue further south. Next, the northern tunnel element was immersed in front of the Joint House. It was pulled into the Joint House and temporarily set 2 m (6.5 ft) further north than its final position. This was necessary to create space for the middle tunnel element that was immersed last. After the middle element was placed and connected to the southern element, the northern element was pushed 2 m (6.5 ft) southward, closing the last gap between the tunnel elements.

Three ballast water tanks were installed in each tunnel element. The weight of the tunnel elements was increased to 0.4% negative buoyancy at the beginning of the immersion operation by adding ballast water from the outside to all three tanks. The tunnel elements were brought into their exact position in longitudinal direction with two main winches placed on the north and south shores. The steel wires were connected directly to the elements and were kept under constant tension during the whole immersion operation.

A positioning survey was done with a combination of GPS/GNNS and total stations from land. Both GPS/GNNS antennas and prisms for the total station were mounted on the survey tower and the access shaft of each element to sit above water level, even after the elements were lowered to the final depth. The survey data provided the position and inclination of the tunnel elements. Surveyors measured the final position of an immersed tunnel element through survey hatches in the bulkheads of the tunnel elements, which could be opened after the immersion chamber was emptied.

To empty the immersion chamber between two tunnel elements, Gina gaskets were preinstalled on steel frames surrounding the tunnel cross sections. The Gina gaskets only served as a temporary tightening of the immersion chamber. When the final position of an immersed tunnel element was confirmed, the steel shells between the two elements were welded together to create a rigid and permanent water-tight connection. Then the bulkheads at the ends of the tunnel elements could be removed, which created space to build the monolithic concrete.
connection. Finally the northern tunnel element was extended 5 m (16 ft) inside the dry Joint House and the permanent Omega seals were installed.

**Steel Core Pile Foundation**

Between the raft foundation on the north end and the fixed restraint on the south end, the tunnel is founded on four pile foundations. The pile foundations consist of underwater concrete slabs supported by steel core piles. The piles allow load transfer directly into the rock, since the lake bed is soft clay and insufficient for foundation bedding of the tunnel.

Steel core piles are a common Swedish pile system developed to take advantage of the hard rock, which is often found in Scandinavia. The piles are designed as end bearing and embedded into the solid rock a minimum length of 1m (3 ft). To utilise their full bearing capacity, each pile is driven with a weight of 1.8 tonnes (2 tons) into the rock until settlements have stopped. To define the stopping criteria a shock wave measurement is executed on the first pile of each group.

The steel core piles consist of a casing drilled into the rock with an outer diameter of 273 mm (10.7 in) and a wall thickness of 5.6 mm (0.2 in). The steel core placed inside the casing has a diameter of 180 mm (7 in) and lengths of 6 m (20 ft) with threaded API joints. The annular gap between the casing and the steel core is filled with cement grout to provide permanent corrosion protection.

To ensure a minimum grout cover, centralizers were mounted to the steel cores. For vertical bearing capacity, only the steel core is taken into account. For calculation of the stiffness and horizontal bedding of the piles in the soft soil, the casing and grout were also considered.

The number of piles for the four pile foundations ranged between 34 and 46, with lengths between 15 and 30 m (49 and 98 ft). The piles were concentrated below the two outer walls and the inner wall of the tunnel. The concrete pile caps, with a minimum thickness of 1.5 m (5 ft), were also divided into three sections below the tunnel walls.

Installation of Steel Core Piles

The piles were installed in a water depth of about 20 m (66 ft) and were driven through layers of clay and moraine into the bedrock, requiring a total casing length of more than 40 m (131 ft). Drilling, grouting and installation of the steel core were executed from pontoons secured in position by winches. The pontoons were assembled as moon pool working platforms with rectangular 3 m by 12 m (10 ft by 39 ft) openings in the middle. The pontoons were fixed with anchors at all four corners to ensure sufficient stability of the working platforms during the drilling operation despite impact from wind and waves. The pontoon positions were continuously monitored with help of a GPS system and moved as needed using hydraulic winches.

Drilling was performed with an air-driven down-the-hole hammer with a pilot bit and a ring bit mounted to the casing. The overburden drilling system allowed penetration through boulders, which were encountered in the soft clay layers as well as in the deeper moraine. After the casing had been drilled into the bedrock the inclination was measured. Divers then cut off the casing underwater to the correct length to embed 5 cm (2 in) into the pile caps. The exact length of the steel core was calculated based on the drilling protocols. This permitted prefabrication of the entire steel core to the correct length prior to installation including all welding works for the pile head. The execution and testing of the welding works could be performed above water under workshop conditions, with corresponding good quality.

Prior to the installation of the steel core, the grout was poured into the casing from the bottom up. The theoretical volume of the annular space plus 20% extra was used; filling the casing roughly halfway before the installation of the pile. During installation, divers observed the grout flowing over the edge of the casing. The grout level was checked again afterwards and if necessary the grout was refilled. The site engineer on the pontoon observed all
the concrete pile caps was filled with cement grout using grout bags. The gap between the tunnel and the pile caps was around 300 to 400 mm (12 to 16 in). Prefabricated grout bags 3 m by 5 m (10 ft by 16 ft) were fastened on steel frames before lowering the tunnel elements. The

**Temporary Support of Tunnel Elements**

During the immersion process, the tunnel elements were supported by hydraulic jacks mounted on the pile caps. The jacks were placed in steel housings and fixed in recesses in the underwater concrete pile caps. Each tunnel element was supported on four jacks with a load cell at each jack. The actual jack loads were displayed on a screen in the command unit and allowed the immersion engineer to control the final height and the pitch and roll of the tunnel.

When the immersion operation for one tunnel element was finalised, the ballast tanks inside the element were filled to achieve a negative buoyancy of 3%. The increased weight was needed to secure the tunnel element in its position. Also during the filling process, the jack loads were controlled continuously and compared with the design values. As long as the tunnel elements were supported on the temporary jacks, the vertical loads were limited to 250 tonnes (276 tons) per jack to avoid overloading the pile caps.

The friction between the tunnel elements and the jacks had to be reduced to allow for movements of the tunnel after it was placed on the jacks. This was done using a combination of stainless steel and Teflon plates, which ensured that only minor horizontal forces were introduced into the jack housings and the pile caps.

**Permanent Support of Tunnel Elements**

The hydraulic jacks acted as temporary support for the tunnel elements. After the elements were adjusted to the correct height, the space between the tunnel and grout bags were made from porous fabric, which was grout tight but water permeable. Nonshrink grout was pumped through filler sleeves sewn to the grout bags. To ensure complete filling, side vents were sewn to the grout bags and used to control and limit the grout pressure. The grout bags provided a permanent and uniformly loaded bearing connection between the tunnel and the foundations.

**Conclusions**

The Söderströmstunneln project required a unique solution for design and execution of the immersed tunnel and its foundation. A close and open relationship between the client, Trafikverket, and the contractor, Züblin, together with an experienced team of designers and consultants, made it possible to successfully complete the tunnel immersion during the summer of 2013. The remaining works are ongoing and should be completed by the end of 2014.

For additional details on this project, please refer to the May 2014 DFI/EFFC International Conference on Piling and Deep Foundations proceedings for the complete paper. Printed proceedings are available at www.dfi.org/publications.asp?goto=100&P100 and are $145 for members or $195 for nonmembers.