1. Abstract

The execution of foundations in maritime environments often involves important temporary works, in order to provide a safe workplace, comply with environmental requirements and achieve high quality standards.

This paper presents the design, construction and installation of the steel cofferdams used for the execution of the N1 and S4 piers at the Forth Replacement Crossing (Edinburgh, Scotland), currently under construction.

The cofferdams consist on manufactured steel corrugated plates welded to each other and strengthened with two waling levels. The bottom part of the cofferdam would be embedded up to one meter into ‘Burdiehouse Limestone’ which according to boreholes would be expected twelve meters below water level. The overall height of the structure was almost 15 metres.

The cofferdam was manufactured in a steel mill in Seville (Spain) and transported to site by means of a towed pontoon. The loading-out manoeuvres were a challenging part of the works due to the dimensions of the structure itself.

Key words: Volcanic Tuff, cofferdam, welding, foundation, trench

2. Introduction

N1 Pier is the one located just adjacent to the northern tower being part of the cable-stayed section of the Firth of Forth new bridge main crossing. It is located close to the northern shoreline and consists of a massive reinforced concrete direct foundation, 26m x 29m and 5.5m deep, and is founded on Volcanic Tuff bedrock of the Sandy Craig Formation.

This foundation is to be built in the dry. For making this possible, a temporary works structure had to be built in order to resist the hydrostatic thrust forces.

Figure 1: Bridge location (left). Current view from North Tower (right)
Given the relatively shallow water depth and depth to the rockhead underneath, prefabricated cofferdams were decided to be installed.

Prefabrication of the cofferdam as opposed to the more conventional form of cofferdam construction by driving sheet piles has the benefit of avoiding the creation of airborne and underwater noise. The method of pre-excavation also removes the risk of encountering obstructions.

The temporary works structure consisted of a number of corrugated plates welded side-by-side, arranged so the pier foundation could be fit inside. The overall plan dimensions were 30m by 27m (transverse x longitudinal). Two levels of frames provide the required stiffness to withstand the horizontal thrust forces.

The cofferdam rest on four bearing plates located at each corner at a level below the foundation bottom level. For achieving this, a trench was excavated along the sides of the cofferdam prior to the cofferdam installation, which were filled with concrete later on. This was required to provide the foundation of the cofferdam with the corresponding water tightness, once it was dewatered.

The uplift forces were counterweight by a concrete plug beneath the foundation bottom level. Destressing wells were also installed to minimize those forces.

Both cofferdams were constructed in Seville (Spain) and transported to site by means of a towed pontoon. Once there, they were installed at their final position by means of a barge crane.

3. Design

Although Pier N1 cofferdam was initially conceived as driven sheet piles in the tender design, it was decided to use a prefabricated structure instead. The reasons were, among others, the relatively shallowness of the foundation, as the pier was close to the shoreline, and the reduced risk associated to this solution, given the excavation took place before placing the structure. There would also have benefits from the environmental perspective, as airborne and underwater noise would be prevented during the cofferdam installation.

The following figure shows a sketch of the adopted solution.

The cofferdam had to be designed to withstand a pressure corresponding to a 15m water column. The corrugated plates would be embedded in a concrete trench along the contour of the cofferdam. This plug would act as sealant in the joint to prevent leaking.
The structure had to be checked for two different scenarios:

1. Before foundation execution: corrugated plates would have be supported on the concrete trench, as well as in two intermediate points located at level +3.25m and -2.35m, materialized by two levels of frames and struts

2. After foundation execution: corrugated plates would be supported on the concrete plug and the foundation itself, as well as the upper strut level. It is to be noted that the lower strut level would be removed during construction

The following figures show the two structural schemes adopted for the corrugated plates design, as well as the structural model used to check the top frame.

![Figure 4: Models used during design](image)

Reactions of each model would be used to design the propping system (frames) and concrete plug at the lower part of the cofferdam.

Accordingly, bending moments and shear forces in each case would be used for checking the corrugated plates. Also pressure on bearing plates as well as lifting lugs were important elements to be checked.

4. **Construction**

Both cofferdams were manufactured in Seville (Spain) by two important steel mills MEGUSA and TECADE. Once constructed, they would be shipped to Edinburgh and installed at their final position.

Given the size of the structures, they were built in smaller sizes and assembled at the Port of Seville, where they would be load-out on a pontoon.

The manufacturing process followed was:

1. Plate reception: Quality Control compliance
2. Plate preparation: plates were then cut to their final dimensions and edges prepared for welding
3. Plate bending: geometry control was very important in this phase: if bends were not perfectly parallel, it would have impacted the total cofferdam geometry
4. Welding of plates: all welds were executed using Submerged Arch welding (SAW) process
5. Frame assembly: frames were typically compound sections connected with intermediate plates. Sections were whether standard sections or welded beams
All welds in the steel mill were performed using SAW. Whenever this was not possible, Shielded Metal Arch Welding (SMAW) process was used. Plates and beams were welded so elements were transportable to the assembly yard.

6. Cofferdam walls assembly: the cofferdam’s shorter walls were welded to form one piece, whereas the longer walls were split in four and connected to the shorter to for a half cofferdam

7. Cofferdam assembly: both halves had to be turned and welded together

8. Cofferdam finishes: weld of rest of plates, props, etc.

9. Load-out onto pontoon: to load them out, Self-Propelled Modular Transporters (SPMT) were used. The number of axles was chosen so the total weight of the cofferdam was spread according to the wharf allowable bearing pressure. Also, the cofferdams themselves needed to be strengthened to prevent the corrugated plates from buckle

10. Once on the pontoon, the cofferdam needed to be secured to prevent it from sliding/falling during the haulage

11. Shipping

It was essential to accomplish the construction of the cofferdams on time, given the overall programme depended on it. Along with the construction itself, it was essential to assure a quality level for the cofferdam. As it was classified as Execution Class 2, this required a minimum number of inspections to be performed on the welds, including visual inspection as well as NDT’s.

The following photos show each of the steps described above.

Figure 5: Plate bending machine (left). Inspection after bending to guarantee the lack of cracks on the outer face (right)

Figure 6: Automated process to weld the sheet plates
Figure 7: Frame assembly

Figure 8: Sheet pile assembly in assembly yard

Figure 9: Cofferdam turn for assembly

Figure 10: Load-out manoeuvre onto pontoon
5. **Installation**

Once on site, the cofferdam were to be installed. The general sequence of construction was:

1. Form a perimeter trench cut into the bedrock with a raised plinth area in the centre

   This required excavating the foundation pocket underwater through the superficial deposits down to formation level. Deeper trenches were locally excavated around the perimeter of the foundation to allow the cofferdam box to be placed. The figure on the right shows schematically the foundation. The photo besides it shows the final bathymetric survey which shows the as-built perimeter trench and raised plinth areas.
2. Installation of the bearing plates

Once the excavation was completed, it was ready for the installation of the corner bearing plates on which the cofferdam would temporarily be supported. It was important to make sure this plates were correctly installed and levelled so the cofferdam would be properly placed.

3. Lower the cofferdam into the perimeter trench and onto the bearing plates.

Figure 14: Cofferdam foundation trench. Scheme (left) and bathymetric survey once executed (right)

Figure 15: Placement of Pier N1 Cofferdam was computer assisted

Figure 16: Installation of Pier N1 Cofferdam
The next step was to lift the cofferdam off the supply barge and transfer it from the quayside to the location of Pier N1. The lifting operations were carried out using the crane barge made up for this type of operations. It was one of the largest lifts on the project by floating plant. Given the weight of the cofferdam (567 tonnes approx.), four tugs were required as well as two multicat work vessels in addition to the crane itself.

The crane then required to be winched into position, so the cofferdam could be carefully lowered down into the perimeter trench, and the four corners would rest in the bearing plates located under the water.

It took 24 hours to place the cofferdam on the corner bearing supports.

4. The next step was to pour the concrete into the trench to provide a bearing support to the cofferdam, and a seal between the cofferdam and the bedrock.

Once the temporary access platforms have been installed and prior to pouring the underwater concrete, it was required to clean the trench both inside and outside the cofferdam, as the internal trench was beneath part of the foundation formation. Following cleaning and inspection by divers, the trench was filled with underwater concrete to create a seal.

This was done following the next steps: install temporary formwork in positions 1 and 4 (in the form of one tone bags with smaller sand bags used to fill the gaps) to control the placement of underwater concrete and to provide temporary lateral support to the cofferdam.

Place under water concrete in area 2, remove the formwork from position 1 and place the underwater concrete in areas 3 and 5 to form a water tight seal between the steel cofferdam and the bedrock.

The following figure shows the sequence how the trench was filled with concrete.
5. Internal de-stressing wells are then installed into the bedrock to lower the groundwater pressures below cofferdam and the formation area.

The foundation formation level is approximately 12m below sea level. Therefore, to allow the cofferdam to be dewatered, a de-stressing system had to be installed to prevent any damage to the rock formation by relieving the water uplift pressure beneath the formation. A total of 12 de-stressing wells and four piezometers were installed deep into the rock formation and a series of de-stressing trials/tests were undertaken.

6. Finally the cofferdam is dewatered to allow formation inspection and foundation construction in the dry.

The cofferdam was then dewatered using a large submersible pump. This allowed the volcanic tuff formation to be exposed for the first time.
7. Cleaning of the formation

The rock formation was then cleaned and inspected to ensure compliance with the geotechnical design. During the inspection works there was a steady flow of water coming up through the rock formation on the south side of the cofferdam. The cause of the water was found to be a crack within the perimeter trench concrete which was then appropriately sealed which stopped the flow of water.

![Figure 22: Formation cleaning prior to concrete blinding](image22.png)

![Figure 23: Geotechnical inspection (left). Exposed volcanic Tuff (right)](image23.png)

The rock formation was blinded in a number of pours in order to allow an area of the formation to be clean and inspected and then immediately concreted to prevent the tuff for being disturbed and deteriorating. The bed was then ready for the execution of the reinforced concrete foundation.

![Figure 24: Progressive blinding operation at Pier N1](image24.png)
6. Conclusions

The construction of some pier foundations for the Forth Replacement Crossing in Edinburgh, required the use of prefabricated cofferdams. These structures were to be built off site and installed into position with marine means.

Two of them, N1 and S4 were constructed in Seville and shipped to site. They consisted of rectangular structures made of corrugated plates welded to each other and stiffened by frames and props. The total weight was 550 and 240 tones respectively.

Two major challenges needed to be addressed during the design phase. These were the huge horizontal thrust forces due to the water pressure on the outer side of the cofferdam and the bottom seal required along the perimeter of the cofferdam to avoid the water to leak through it.

They were manufactured in Seville. Being relatively simple structures, their overall size made it difficult to handle during construction. Also, the load-out manoeuver was specially challenging because of the size and weight of both structures.

The installation of the cofferdam required the excavation of a trench below the existing seabed reaching the Sand Craig Formation laying underneath. After placing the cofferdam, the trench was filled with concrete to create a seal that would prevent the water from entering the dry side of the cofferdam, once dewatered. Also, some de-stressing wells were installed to relieve the rock from the pressure that would be built up inside the cofferdam. Despite this, water leaked through various cracks that had to be resealed.

Once the cofferdam was dewatered, and the formation inspected, the rock was blinded to prevent it from further deterioration. The execution of the foundation could then commence.