In a class of its own

Irina Melzer

Project data

<table>
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<tr>
<th>Employer</th>
<th>Emschergenossenschaft (Emscher Water Board)</th>
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<td>Contractor</td>
<td>Consortium Emscher BA 40 (Emscher Construction Stage 40) – PORR Bau GmbH. Infrastructure Tunnel Construction and PORR Germany GmbH.</td>
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<td>Project type</td>
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<td>Project scope</td>
<td>Mechanised Tunnelling, Civil Engineering, Pipe Jacking, Specialist Civil Engineering</td>
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<td>Construction Start Date</td>
<td>December 2013</td>
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<td>Construction End Date</td>
<td>April 2018</td>
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In the course of restoring the Emscher to its natural state, a system of sewers totalling 51 km in length will be constructed.

General information

In 2013, PORR Bau GmbH, Infrastructure Tunnel Construction, together with PORR Deutschland GmbH, won the contract to build construction stage 40 of the new Emscher sewer. This 10 km long section consists of two parallel tunnel bores, constructed by the segmented method. The tunnelling employed two earth pressure balance shields, and was completed in June 2017. In addition to the tunnel boring, the PORR consortium is constructing fourteen shafts, and fitting out twelve of these for the operation of the sewer. This involves building complicated underground civil engineering structures in these construction pits, which are up to 45 m in depth.

Background

The Emscher is an approximately 85 km long tributary of the Rhine river which, as a result of the historical development of the Ruhr region, came to be used as an open sewer. In the course of restoring the river to its natural state, a 51 km long system of sewers is being constructed to carry the wastewater of approximately 2.2 million residents. The waters of the Emscher and its tributaries will thus be restored to as near their natural state as possible. The future Emscher sewer (Abwasserkanal Emscher, AKE) will run from Dortmund to Dinslaken, and carry wastewater to the sewage treatment plants at Bottrop and the mouth of the Emscher.

In construction stage 40 (Bauabschnitt 40, BA 40), the sewer will be constructed in a twin bore configuration for a length of circa 10 km. In addition, nine main and five secondary shaft structures will be constructed, and four secondary inlets will be excavated by means of pipe jacking.

Part 1: Tunnel construction

Unlike many other projects, the challenge in this tunnelling project lay not in the ground in which it was to be built, which despite exploratory drilling always remains an unknown element, but in the small diameter of the tunnel bores. At 2.6 m, these are at the lower limit of what is possible with segmented tunnel construction. The resulting spatial constraints had massive implications for the overall mechanical engineering, the design of the tunnel segments, the logistics of the excavation, and safety during the works.

Technical challenges

The most difficult task in setting up the tunnelling equipment was arranging the components without compromising functionality or safety considerations. Components such as conveyor belt bearings, switch cabinets and pumps had to be easily accessible and could not be blocked by other components, in order to allow maintenance and repair works to be completed quickly and effectively. A two-floor arrangement, as is usual with larger shield machines, was not possible due to the limited height of 2.6 m. Therefore, all components had to be constructed one behind the other.

Although some components in a small-diameter machine can also be made smaller, other components cannot be changed in proportion to this. For instance, the length of the auger in an earth pressure balance shield depends largely on the required operating pressure. This decreases along the length of the auger, and should reach atmospheric pressure at the exit of the auger, in order to make sluice-free jacking possible. The theoretically estimated pressure for this project was 3.6 bar. This resulted in an auger length of 8.8 m. The shield casing of the boring machine was already nearly 15 m long, about five times as large as the diameter of the cutting wheel. The total length of the machine, including all the trailers, reached 90 m. For comparison, the largest earth pressure balance shield machine in the world, with a diameter of 15.5 m, is 130 m long.

Tunnel segment design

The narrow diameter of the tunnel also had an impact on the design of the tunnel segments. As in all tunnelling machines,
the width of the segments, and therefore the jacking length, is dependent on the width of the trailer structure, which in this case was 1.3 m. After deducting tolerance dimensions, the width of the segments was chosen as 1.18 m. The specifications of the machine also had to be considered in dividing the rings. A division of the rings into only four pieces would have required a larger height clearance for the segment feeder in the first trailer. That would not have been possible with the steering position for the machine operator and the conveyor belts lying directly above. Due to these and other geometric requirements, each ring was made in six equally sized segments with a thickness of 25 cm and a weight of 1.1 t.

The segments were to be installed by conventional means, with a vacuum segment erector. However, in the process of qualifying the vacuum plate, it became apparent that because of the small surface area of the segments and their relatively heavy weight, it was not possible to produce a sufficient vacuum for safe installation. The same was true for the segment crane, which is why the segments without openings and depressions desired by the client were not feasible. The segments were therefore produced with a plastic sleeve, into which a steel bolt was screwed for unloading the segments onto the segment feeder, and for the ring construction. To this, a mechanical erector plate was clamped. This construction also required a change in the installation procedure; now every segment had a steel bolt screwed into it, which had to be removed after the ring construction, and every plastic sleeve then closed with a plastic cap. Sealing the sleeves, which was necessary in the case of this particular project due to the eventual use of the tunnel as a sewer, could probably have been avoided with the use of a vacuum erector.

The pressure on the logistics was further relieved by the use, for the first time in Germany, of a two-component mortar for the gaps between the rings. Rather than the usual method of carrying the mortar in a mortar tank on the machine, in this case it is pumped via a transfer line from the mortar mixing equipment directly to the mortar tank on the tunnelling machine. To avoid the mortar hardening in the transfer line, it is separated into two components. The so-called “A-components” consist of water, cement, powdered rock, bentonite and a stabiliser. With this composition, the mortar is very fluid and can be pumped easily. During the tunnelling process, the mortar is pumped to the end of the line in the shield tail, where the B-components are added as it passes through the so-called grout injection line into the annular space. The B-components consist of soluble alkali silicates and serve as an accelerator, so that the liquid mortar hardens quickly, guaranteeing the necessary ballast for the segment ring. In order to avoid segregation of the A-components and resultant blockages in the mortar transfer line, as high a flowrate as possible in the small cross section had to be achieved. The usual pressure in the mortar transfer line was circa 10 bar at a flow of some 3 m³ per hour. With increasing lengths of up to 4,100 m, the pressure increased significantly, and the installed system nearly reached the limits of its performance capacity.

**Workplace health and safety**

Safety is a particular concern in all tunnelling operations. After all, there is always only one escape route, and the length of the escape or rescue route increases with every drive forwards. In the case of BA 40, the small internal diameters brought further difficulties. The fire protection and rescue plans originally envisaged starting the three tunnelling sections each as one piece, so that the maximum escape and rescue route corresponded to the longest section at 4,100 m. The other shafts along the route were to be driven through in an unexcavated state, and only be excavated and fitted out after the tunnelling works were completed. In order to ensure a speedy rescue despite the long rescue route, a team of paramedics would be contracted to accompany the tunnelling works. With the help of technical rescue equipment, victims of accidents in the tunnelling machine could be rescued within a short time frame, transported to the shaft, and there transferred to the local fire brigade. However, before the start of the tunnelling work, a revision of the fire protection and rescue plans was requested.
by the responsible fire brigade. The escape and rescue routes were deemed too long considering the small cross section of the tunnel, and the construction process had to be significantly modified. The intermediate shafts were now to be converted into rescue shafts immediately after the equipment had passed through. This meant that, first of all, the shafts had to be excavated and the floor slabs installed, before the tunnelling machine could enter. The shafts were then filled with “liquid soil”, a type of lean concrete, so that the tunnelling machine could drive through the shaft. After the machine, including all the trailers, had driven through the shaft, the tunnelling work was paused, and the shaft excavated once more. The segment rings were subsequently removed from the shaft, and the shaft was converted into a rescue shaft. This included, for example, a rescue stair tower, as well as an electrically driven lift with emergency back-up power. Only after the rescue shaft was commissioned could the tunnelling work continue. This rebuilding phase took place for every intermediate shaft.

The originally planned construction process...
Image: Emschergenossenschaft

...had to be changed due to a reworking of the fire protection and rescue plans.
Image: Emschergenossenschaft

In addition to these measures, a variety of safety technologies were employed. PORR installed an employee tracking system, fire alarms and extinguishing systems, smoke bulkheads to stop the spread of smoke in case of fire, and a communication system. Furthermore, intensive training and instruction were provided, and regular rescue drills were performed in order to familiarise all parties concerned with the special circumstances, and to ensure things would run smoothly in case of an emergency. Apart from the special requirements for the fire protection and rescue plans, even regular operation was a borderline case from a workplace health and safety perspective. The height clearance in the trailer area was around 1.6 m, whilst the passage height on the catwalk was just 1.2 m. This meant that a person of average height could only stand upright behind the last trailer, or in the area of the shield tail. Upright movement was impossible for those employed in the tunnelling operation.

Because of the extremely cramped conditions, the number of employees in the tunnel was kept to a minimum.
Image: PORR AG

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It was impossible to walk upright in the tunnel.

Image: PORR AG

A container to serve as a break room, which is usual on larger machines, could not be included because of the geometric conditions. Even the installation of a construction site toilet was impossible given the small cross section. Therefore, since neither the tunnel cross section nor the size of the tunnelling machine could be changed, other measures had to be taken to reduce the physical toll of the work. First and foremost, the number of employees in the tunnel was kept to a minimum. Only a shield driver, a ring builder and a post-drive metalworker stayed permanently on the tunnelling machine. In order to keep working times within an eight-hour limit, the work was conducted in three shifts, instead of the two-shift schedule usually used in tunnel construction.

As after the first few weeks of tunnelling it became clear that employees with normal hard hats regularly hit their heads, the helmets worn in the tunnel were replaced with impact caps, after consultation with the responsible authorities. As a further measure, all employees were put through several weeks of a “construction fitness” programme. Here, a sports scientist intensively followed the tunnelling work in particular, and gave the employees advice on working movements, in order to prevent damage to the musculoskeletal system.

### Facts and figures

<table>
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<tr>
<th>Description</th>
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<td>Tunnel Length</td>
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<td>Tunnelling Technology</td>
<td>Earth pressure balance shield with segmented construction</td>
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<td>Inner Diameter</td>
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<td>Cutting Wheel</td>
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<td>Outer Diameter</td>
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<td>Number of</td>
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<td>Number of fully fitted out shafts</td>
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<td>Depth</td>
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<tr>
<td>Geology</td>
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### Part 2: Civil engineering

As with the tunnelling work, the current shaft construction is also taking place under special conditions. Both the spatial limitations and the complexity of the construction works pose a number of challenges. Although the shafts are quite wide, with an inner diameter of 12.5 m, the space required for the formwork and auxiliary construction such as falsework and work platforms is so great that these must be planned precisely, so that the works do not impede each other, and safe working conditions can be maintained.

#### Technical challenges

Basically, one outer wall and two separating or partition walls must be built in each shaft construction pit. Additionally, in some shafts, one or even two swirl chambers must also be built. Once in operation, the wastewater from the inlets above will flow through these down to the main sewer. When in use, the shaft structures may be subject to increased acid attack, so the shafts are constructed from acid-resistant concrete. Shafts into which the wastewater will flow via a swirl chamber must be clad in polyethylene slabs in addition to acid-resistant concrete.

For the formworking of the outside walls, PORR relies on climbing and sliding methods. In these approaches, the formwork is hoisted by means of a special lifting apparatus. Fabrication by the climbing formwork method proceeds in sections; every section is individually reinforced, and then concreted. This has the advantage of allowing every section to be manufactured in a controlled manner, and no time pressure arises. The disadvantage is that a construction joint must be made after every section. In the sliding method, a construction-joint-free construction is achieved, as the reinforcement and concreting work runs continuously in 24-hour operation. The disadvantage here is that the work cannot be interrupted. This places high demands on the supply of concrete, the general logistics, as well as the organisation of the works. The advantage of the sliding method is fast completion. For comparison: the fabrication of a shaft by the sliding method takes around nine days, but by the climbing method would require around 28 days.
The civil engineering works of the project involve three different types of shaft. In most shafts, the outside wall of the shaft is concreted against the existing diaphragm wall. In this case, a dimpled drainage layer must be installed first. Because of the large depth of the shafts, this is conducted from a work basket, as the construction and deconstruction of scaffolding would incur long lead times. Therefore, the reinforcements are brought in piecewise. The installation of the reinforcements is clearly complicated by the limited accessibility, since the rear rows of reinforcement must be installed over the reinforcement joint at the front. In the shafts where cladding with polyethylene slabs is not necessary, the sliding method is used. Shafts with polyethylene cladding can only be fabricated by the climbing method, since this step can not be incorporated in the sliding approach for one-sided formwork. If polyethylene panels are to be installed, they must be subsequently welded together, in order to provide the necessary water tightness. To do this, work platforms from which the welding work can take place are mounted underneath the climbing formwork. Thus the work takes place on two levels above the platform; whilst the next section is being concreted above, the polyethylene slabs for the previous section are being welded on the level below.

After the outer walls, the fabrication continues with the inner walls, also clad with polyethylene slabs, including the swirl chambers. For this, a support structure is necessary; this will later be modified to create the support structure for the ceiling formwork. Because of the complicated construction of the swirl chambers and space limitations, it is not technically feasible to fabricate all the inner walls at the same time. Therefore, the walls comprising the swirl chamber are “tightened up”, or finished off, later.

The next steps of the work involve the construction of the ceiling, including superstructures and the assembly of various built-in elements, and the building of gutters and clinker brickwork in the shaft. The clinker bricklaying and installation of all the built-in elements are particularly complex and very time consuming. Many of these works take place at different heights, so again support scaffolding will be necessary for the subsequent operation of the sewer. In this case, the existing diaphragm wall is not concreted, but the outer walls of the shaft are instead fabricated by means of two-sided formwork. Unlike the single-sided formwork, this is accessible from both sides. Therefore, in this case, the formwork can proceed by the sliding method, even though polyethylene slabs must also be incorporated.
needed. The built-in elements can also differ from shaft to shaft, and must therefore be fabricated and installed accordingly.

The many different construction processes and subsections require precise organisation and planning of the works. Also, high demands are placed on the quality of the work – not only in the terms of the contract. Reworking defects would entail a heavy work load and long delays. For example, a work platform would have to be set up for the retrospective welding of polyethylene slabs in the upper section. To reduce the occurrence of any such faults in the construction, the site management employees carry out regular checks and maintain thorough documentation.

Furthermore, the location of the shaft construction works complicates the organisation of the construction process. Twelve shafts are to be fitted out, each one currently in a different stage of construction, spaced along the 10 km route. Driving from the first shaft to the last can take up to 45 minutes in rush hour traffic. Therefore, the works must be well organised, with the timings and assignment of employees carefully worked out, so that as few extra journeys as possible are required. Also, since failure of construction equipment can lead to long waiting times and accompanying delays, regular testing and maintenance of the equipment is essential.

**Workplace health and safety**

As in the tunnelling works, workplace safety is also top priority in the construction of the shafts. Since the access routes to individual work areas change regularly as the construction progresses, it is important, particularly during the fabrication of the external walls, to adapt these access routes in the course of the works. That is why PORR moved and rebuilt the stair towers over the course of the works to ensure safe access routes in every phase. After the work on the outer wall, work progresses on several subsections at the same time; good coordination of subcontractors is essential to guarantee workplace safety, as up to 20 people can be working in a shaft at one time. Employees take part in regular courses and are given frequent instruction in the correct usage of personal protective equipment.

**Summary**

The Emscher sewer is in a class of its own. Currently, there is no comparable project in the whole of Europe. The engineering, logistics and, last but not least, workplace safety, posed enormous challenges for PORR.

In the tunnelling work, the small inside diameter of just 2.6 m is particularly noteworthy. This is right at the limit of what is possible not just technically, but also in terms of workplace health and safety.

The civil engineering works are characterised by their high degree of complexity and stringent quality demands. Because of the many different subsections and procedures involved, the works require precise planning and coordination.