Deep foundations for large constructions

Fondations profondes pour de grandes constructions

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ABSTRACT: The production of pile foundations for big structures - e.g. bridges, towers and slope stabilization - are a steady challenge for the foundation engineer. This challenge is not only based on the pile dimensions (diameter of 1,20 m up to 2,10 m, pile lengths up to 70 m), but also by the ground conditions and the equipment for constructing in river beds, the onshore areas and in the center of the cities. As the geology is known by the soil report, there is in most cases a difference between the result given by the report and the conditions which are found actuallyduring executing these large piles. Very often additional measures are necessary as: dewatering, cleaning of drilling fluid before concreting, grouting, chiselling and stabilisation of the ground. The report gives explanation to the complicated system of two large foundation jobs: the foundation of the highest office building in Europe - Commerzbank Frankfurt - and the foundation of the world's largest cable stayed bridge 'Pont de Normandie'.

A: DEEP FOUNDATION WITH STEP-TAPERED PILES AT THE „COMMERZBANK" IN FRANKFURT

1 INTRODUCTION

The approximately 300m high tower of the „Commerzbank" is built in the center of Frankfurt and is the highest office building in Europe. Due to the extraordinary difficult geometrical and geological situation the reduction of the settlement is only possible by step-tapered piles in combination with the grouting of the underlaying rocks. Those step-tapered piles carry their load down to the Frankfurt limestone. Executed are 111 piles of this unusual type. One pile carries up to 20 MN with a length up to 45 m. The voids in the soil formations are grouted by the pile skin grouting and additionally borings for grouting up to 10m under the deepest pile base have been executed. By this method a homogenized structural member consisting of soil and and cementgrout was created. In comparison to the foundation of the „Messeturm" in Frankfurt - built 1988 - this foundation is a real pile foundation and not a combined pile/slab foundation. BILFINGER + BERGER sister's company GRUND- UND PFAHLBAU GmbH Frankfurt was responsible for the foundation work starting in June 1994. The foundation itself belong to the biggest pile foundations in Europe.

For design reasons the construction of the piles has been realized by step-tapered borings of Ø 1,80/Ø 1,50m. The design for the foundation was based on the experience of Prof. Dr.-Ing. R. Katzenbach and Dipl.-Ing. H. Quick and among others on the results of the tests of the Research Institute for Soil Mechanics and Geotechnical Engineering of the Technical University of Darmstadt.

Particularities of this foundation are :

- construction of „measurement piles"
- ultrasonic sound tests in the piles
- limited heights for chiseling
- skin grouting
- grouting of limestone up to 10m under the pile base through the installed pipes

Figure 1 Pile installation for the new Commerzbank office in Frankfurt

2 SOIL AND GROUNDWATER

The quaternary deposits of the Main river with sand and gravel layers of a thickness from 5 to 10m characterize the superficial ground conditions. Underneath there are tertiary soils. They consist of the Frankfurt clay followed by the Frankfurt limestone. The Frankfurt clay consists of an alternation of stiff and semisolid clays and hydrobien sand as well as of limestone. The limestone consists of massive lime banks, partly of dolomite brick banks, algae lime riffs, marly lime sand and lime silt as well as of marly clays and claymarls. In the surrounding of the new building there are alternations of layers of the clay and lime in a depth of about 44m under the ground surface. The groundwater was found in a depth of about 5 to 6m. It circulates in the different layers of the quarternary, the pervious zones of the hydrobien sand and the limestone.

3 CONSTRUCTION OF THE PILES

The main part of the foundation work have been the 111 step-tapered piles (∅ 1,80m / ∅ 1,50m). Upfront these works the following had to be completed - in chronological order:
1. installation of a 60m long anchor into layers of „Inflaten“ for the design of the skin friction and grouting of the low-lying layers as an independent first measure in autumn 1993
2. demolition work of existing buildings
3. building pit with sheeting (Berlin method) anchoring, bored pile wall ∅ 0,90m, respectively ∅ 1,50m and
4. dewatering for relief of water pressure
5. bored pile walls for the main building pit and the existing nearby building for settlement shielding

Concerning the construction of the bored piles the first 23,0m under the ground surface have been constructed with a casing diameter of 1,80m. Then the casing of ∅ 1,50m was placed centered into the first casing and was put down to its final depth. The maximum drilling depth was about 50m, the maximum length of the piles was about 46m. The length of the piles were determined and the pile has to be settled on the rock formation. The system of casing of the piles up to the final depth was obligatory for the following reasons:
- cavities exist (known by the preliminary holes by losses of supporting fluid)
- the skin friction had to be guaranteed (difficult if using stabilizing fluids and no casing)
- noncased drillings need supporting fluids, which could lead to a reduction of the skin friction concerning the existing soils

The execution of the piles was carried out by means of four hydraulic oscillators in combination with Liebherr cranes HS 871. As the process of construction is very complex, a short description is given in the following. This process was part of the quality management system:

Pile installation ∅ 1,80m
- insertion of the pile center
- to bring drilling rig into position
- to install 1. casing section
- control of center point
- control of plumbness
- excavation in the casing with grabs
- to add water for overpressure of water surcharge inside

Drilling in limestone
- drill down to the first layer of limestone (note: reduction of chiselling height to < 1,40m because of the vibration)
- excavation with grabs
- permanent control of the water level in the casing to keep water on the level of safety
- puncturing of limestone with the chisel and grab
- further drilling of casing

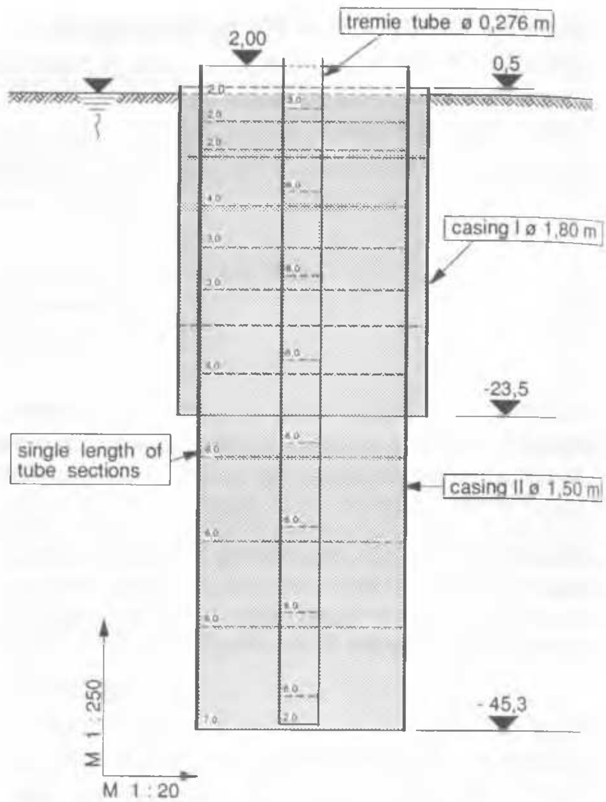

Figure 2 Step-tapered pile execution: sections of inner casing, outer casing and tremie tube

Construction of boring ∅ 1,80m
- drilling of boring ∅ 1,80m down to about 23,0m using alternating grab (clay and sand) and chisel in the limestone layers
- control of water level inside the casing

Installation of casing ∅ 1,50m
- erection of guide ring for the boring ∅ 1,50m in at casing tube ∅ 1,80m
- installation of casing ∅ 1,50m in single sections until reaching the tip of ∅ 1,80m
- application of a distance piece for centering

Construction of boring ∅ 1,50m
- boring ∅ 1,50m down to the final depth of the pile
- cleaning of the bottom by special equipment
- permanent control of water in the casing ∅ 1,50m and ∅ 1,80m (different levels)

Interchange of water in the casing
- by means of an air lift system the dirty water was completely exchanged from the bottom.

Installation of pile reinforcement
The reinforcement cage was installed in 3 different sections. The connection of the different cages have been realized with cable clamps. All pre-assembled grouting tubes had to be connected for the following skin grouting, the ultrasonic mearurement and the grouting underneath the pile bottom as well as the cables for the different measuring equipment in the pile.

Installation of the tremie tubes and concreting
After the installation of the reinforcement the tremie tube was

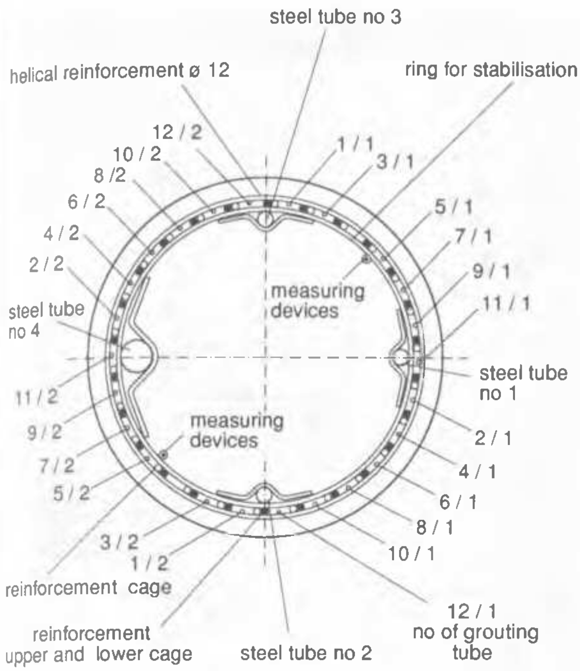

Figure 3 Reinforcement cage

fixed to the very end of the pile bottom. The specially designed concrete was placed in several sections by pumping. The tremie tube was always embedded 4 to 6 m in the fresh concrete.

This a.m. method demonstrates the difficulties of the production. For each element the Engineer prepared a pile history diagram with - as an example - the embedment of the tremie pipe after each concrete delivery. Apart from this the following particularities are remarkable:

Drilling system

In the neighbouring building „Commerzbank" there are highly sensitive electronical equipment and the center of the computer system. While using a special grab or chisel for the soil excavation inside the casing the non-allowable vibration was leading to an alarm sign. The permitted height of the grab/chisel was determined during measuring tests in advance. This height was permanently controlled.

During the boring the water level in both casing tubes have been permanently measured to guarantee the overpressure of water inside the system.

Changing and cleaning of the drilling fluid

After drilling down to the final depth the bottom was cleaned by a special pump. Before concreting the complete water in the casing was changed to guarantee a area free of sediments at the pile bottom. The amount of fresh water corresponds to the triple of the pile volume. The cleaning resp. regeneration was realized by regeneration plant, sewage purification plant and band filter press.

Reinforcement cage

The reinforcing cage always consisted of 3 single sections. Its maximum weight was 10 t as a complete cage. Due to the tubes for the ultrasonic testing and the measuring systems a high precision of the single cages was necessary. The pile had always to be settled on solid rock, therefore prolongations of the cages have been partly necessary.

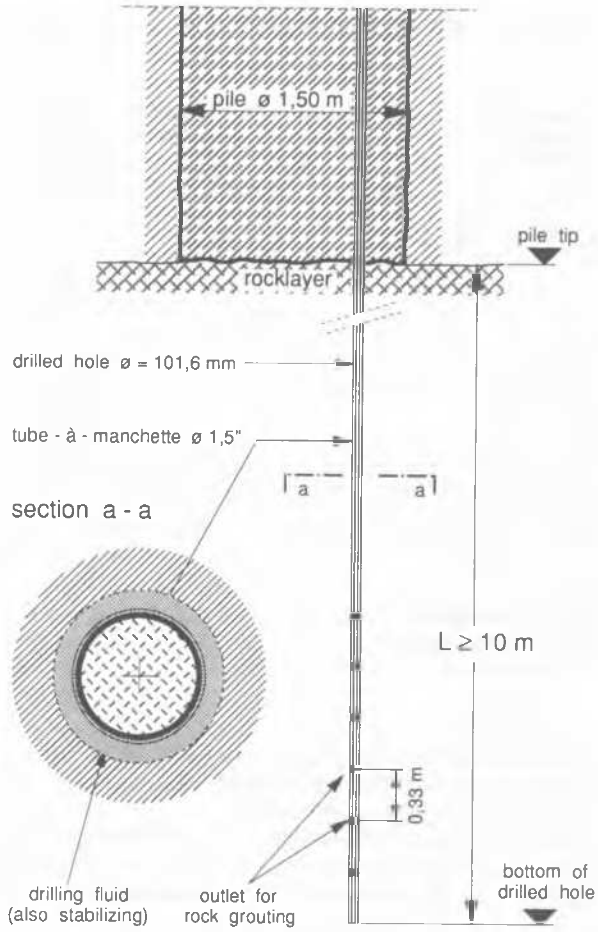

Figure 4 Grouting under the pile bottom

Concreting

After the installation of the reinforcement the tremie pipe (Ø 256mm) was settled down to the pile bottom. The haulage of concrete was realized by a concrete pump. Up to 4 concreting sections had been necessary for the production of the 46m long piles (up to 100m^3 concrete). The drilling water was conducted back to the cleaning plant and was prepared for another drilling procedure. The concreting procedure took up to 8 hours. For this a concrete quality B 35 was used. This concrete had a retardation time of up to 15 hours.

Skin grouting of the piles shafts

For increasing the skin friction grouting was necessary at each pile in the certain areas of soil layers. The grouting has been realized by a central grouting station. About 30 hours after the end of the concreting the grout-tubes have been „blasted" with water under a pressure up to 80 bar. After this the grouting was realized by a suspension of a water cement mixture.

Grouting under the pile bottom

For the grouting of the soil formations under the pile aa additional drilling was executed through one of the steel pipes. This core drilling was run app. 10m into the soil formation. A plastic pipe has been installed into this drilling. The grouting was realized by steps of about 0,33m in heights with a pressure up to 30 bar - if necessary.

Measuring program for the piles

As for the measuring program 30 of 111 piles have been

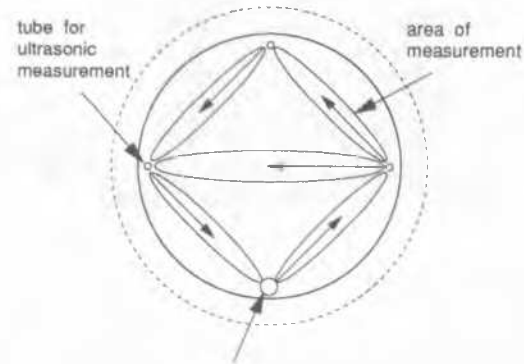

Figure 5 Ultrasonic measurement for the foundation piles

restricted to the installation of
- concrete stress in the concrete
    - pile bottom
    - pile shaft
    - pile head
- extensometer, down to about 100m
- inclinometer for the walls of the building pits
- ultrasonic tests by installed steel pipes

The tests of the pile shaft was realized by the steel pipes by means of ultrasonic measurings. Due to the extensive installations, this pile could be defined as measuring pile.

Ultrasonic measurings in the pile shaft
According to the experiences concerning the production of foundation piles of the „Pont de Normandy" ultrasonic measurings were executed for the first 37 piles and then in each 5th pile to test the concrete quality. The measuring was realized in 4 steel tubes in each pile. This way 6 measuring paths were checked in each pile.

Preparation of the pit
For the pit the *Berliner Verbau* was realized. Inside this a second pit was installed by a soldier pile wall ∅ 0,90m resp. ∅ 1,50m.

Drilling-out of existing piles
In some areas there were found piles (1,20m) which had to be removed for the foundation piles. These piles have been cored inside the pile shaft and then destroyed by overdrilling with a special tool with a diameter of 1,50m.

B. CONSTRUCTION OF PILE FOUNDATIONS 'PONT DE NORMANDY'

During the time of construction for this extraordinary bridge many publications have been presented (Arz/Seitz 1992). The following summary gives an impression of the construction method and the difficulties during drilling.

1 CONSTRUCTION OF PILE FOUNDATIONS

The concept recommended by BILFINGER + BERGER involved using the company's own Hochstrasser-Weise (HW)

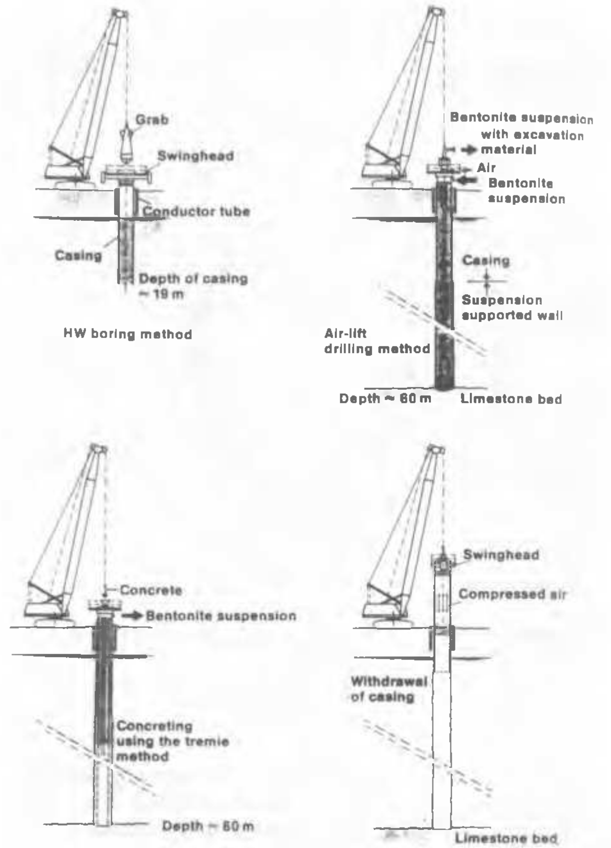

Figure 6 Pile installation scheme for the foundation of the Pont de Normandy

boring method or the hydraulic boring method, with cased boreholes, combined with air lift drilling using a rock roller bit. The basic steps in the construction of one the north tower piles is shown in Fig. 1. The sequence can be summarized as follows:

Installation of casing using the HW method or hydraulic boring method:
- sinking of guide casing, excavation of soil
- installation of temporary casing with a length of 19 to 22m, using either the HW or the hydraulic method,
- excavation under bentonite suspension.

Air lift drilling method with rock roller bit:
- erection of drilling platform, assembly of rock bit with stabilizers and air lift system, drilling to prescribed penetration depth in limestone.

Replacement of slurry, reinforcement and concreting:
- replacement of bentonite slurry with fresh slurry
- insertion of reinforcement cage sections, constructed of up to 50 double-stranded, 40mm thick reinforcement bars and double-stranded, 25mm thick helical bars, d = 25cm.

The reinforcement cages were constructed in a frame to simplify insertion of the lengths over the casing.
- insertion of tremie pipes for replacement of bentonite slurry using air lift system, after the cage had been fitted into place
- placement of concrete, with up to 220m^3 of B 35 grade concrete for each pile
- removal of casing
- removal of guide casing and aligning of pile head reinforcement.

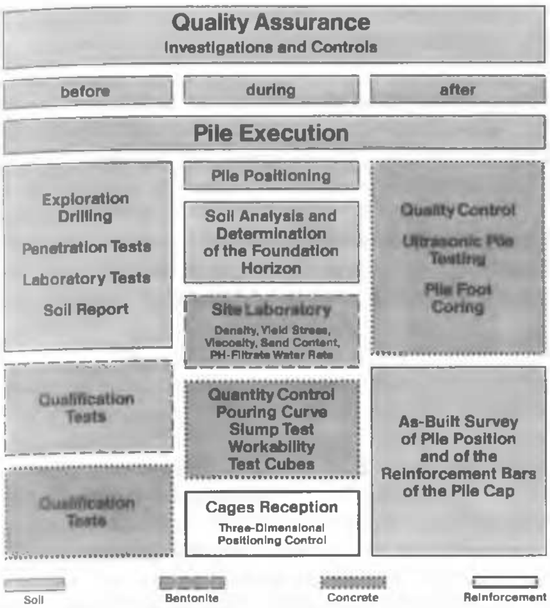

Figure 7 Quality assurance system for the pile execution

A special feature of the construction of the piles is the reinforcement. Besides the very high vertical forces, the towers of the bridge also transmit bending moments and horizontal loads, and these are conducted through those piles located around the sides. The degree of reinforcement required for the piles varies considerably, therefore, due to the load differences between corner piles and those in the middle. The reinforcement used in piles constructed for the north tower has a cross section of $350cm^2$ for a pile in the middle and for a corner pile roughly $600cm^2$/pile section. For the corner pile, therefore, a double-stranded reinforcement is required using 40mm thick longitudinal bars and 25mm thick horizontal bars. A cage approaching 60m in length weighs roughly 30t when assembled, and must be carefully inserted to ensure precise alignment, a maximum deviation of ± 5cm being allowed in both the horizontal and the vertical. For piles d=1.50m, cages weighing up to 15t were required.

Whereas a roughly 20m long temporary casing had been used for the piles constructed on land for the southerly foreshore bridge, it was decided that, for reasons of safety and stability, a permanent casing would be employed for the piles of the northerly foreshore bridge, which stood in water. The length of these pipes was initially limited to 5 - 11m. From what had been learned about the structure of the gravel bed encountered while constructing the piles for the southerly foreshore bridge and the towers, it was necessary, for safety reasons, to install permanent casing right down to the secondary clay. This involved inserting steel pipe segments with graded wall thicknesses of 12, 15 and 18mm and 30mm for the casing shoe, into each borehole to a depth of 35m.

2 DIFFICULTIES DURING DRILLING

The soil investigation reports contained information on the 12 to 15m thick gravel horizon, suggesting that it contained cobbles and rocks with lengths of up to 150mm. the frequency and the location of the rocks was not indicated. The presence of these silica rocks required that no vibrations result from the drilling so as to minimize soil collapse. This was one of the factors that led to the choice of BILFINGER + BERGER's recommended method of drilling, as the temporary casing was scheduled to end above this layer of gravel.

Difficulties began to appear, however, as soon as drilling started, caused by the presence of cobbles and boulders with lengths far exceeding those expected from the soil reports. These irregularly distributed boulders of 700mm to 1200 mm arris lengths were extremely difficult to crush with the rock bit, as they were loosely embedded in the gravel. Cobbles and boulders of medium to large size were presumably being „dragged down“ further into the clay with the rock bit during drilling and were acting like a millwheel. This led to considerable „erosion“ of the clay, with the result that an excessively high consumption of concrete was observed in the clay layer, which is most uncommon in such soil. In addition to this, the clay was being kneaded by the action of the boulders during the drilling, lost its excellent drilling characteristics through the combination of this kneading process and the presence of the bentonite slurry, so that it became impossible to cut through it cleanly with the rock bit and remove it. What resulted was a conglomerate of large boulders, cobbles and - originally hard - clay. Since it was now taking longer to drill through the clay, this tended to increase the effect of the slurry, and this led to more swelling and softening of the clay.

No one had been aware of these processes and problems at the beginning, and they were finally understood only after the boulders had been removed and investigations had been carried out on the clay. Neither the size of the boulders nor their location and frequency had been mentioned in the original soil report. Quite the contrary, in fact, as it had been stated that the maximum size would be 150mm. the extremely unfavourable drilling characteristics of the overconsolidated secondary clay had also not been indicated and this presumably, therefore, was also not known to the client's consultants. They were first discovered by IGW, Lahmeyer International, German specialists who had been called in by BILFINGER + BERGER following an unfortunate incident that triggered off the whole thing, which then proceeded to get worse.

As a result of the partial collapse of a completed borehole within the gravel horizon at a depth of 30 to 35m, with the drill string still in the hole, the extreme danger facing the entire foundation engineering concept of the north tower became clear (unstable gravel layer, ground fracture, collapse of north tower and loss of artificial island). The risk of a further collapse and the possibility of having to abandon the piling concept and install additional piles, which, due to the limited space on the artificial island, would not have been an easy solution, seemed, under the circumstances, the least of the problems that were to be expected. The possibility certainly existed, after all, that the stability of the entire cofferdam had been affected. After weeks of deliberation, the client finally decided to pregrout the 15m thick gravel horizon below the towers.

3 STABILIZING METHOD 1: GROUTING

Remedial grouting was scheduled to be carried out below each of the towers, with injection points around the pile boreholes. Also included were special cases, such as whenever a large obstruction was removed from the side wall of a borehole, this too was to be grouted. Other proposals - such as installing casing down to the clay - were rejected by the client, due to the amount of time required to obtain the relevant pipes, tools and equipment. On the other hand, 12 of the 28 piles for the north tower had already

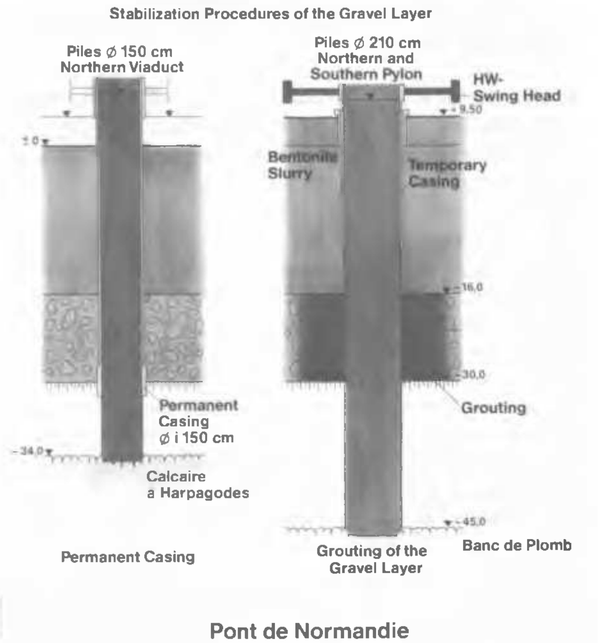

Figure 8 Stabilization procedures for the gravel layers

been completed, and the only point that needed to be considered, as far as the permanent casing of the remaining piles was concerned, was the different load-settlement behaviour.

Remedial grouting of the gravel layer was required to accomplish the following:
- individual cobbles and boulders around the rim of the borehole and those near the injection points were to be linked up in a matrix, allowing them to be crushed druing drilling or preventing them from falling into the borehole.
- excessive hardness was to be avoided, in view of the amount of drilling to be done and the
anticipated wear on drilling tools.

Tests with tube à manchette grouting turned out to be unsatisfactory and far too time consuming, due to the high permeability and absorptive capacity of the soil. It was therefore decided to carry out the grouting while the drill string was being drawn back. Tests began with 14 injection points spread around the pile shaft in two concentric rings and, due to the excellent results obtained in these first tests, the number of injection points was then reduced to 10, and these were now arranged in one ring. The method of monitoring involved automatically recording the measured values for each of the points (grouting pressure, quantity and depth). In addition, about 30 % of the grouted areas were subjected to filtration tests carried out with a gauge placed in the centre of the piles to determine the success of the grouting from the level of permeability of the gravel.

The quantities of cement slurry injected at each point was between 34 and 63m^3, which represents a theoretical grout volume in the gravel layer of about 1600m^3 for each pile.
Once work started up again, in order to make up for lost time, both the grouting work - which had a lead time of 4 weeks - and the piling work for the north tower and the south tower now continued day and night without a break.

4 STABILIZING METHOD 2: 1,50 M DIAMETER PERMANENT CASING

In the case of the 1,50m diameter piles of the southerly foreshore bridge, for which the client had rejected implementing stabilization measures for the gravel horizon for cost reasons, after calculation of a possible soil collapse, a restricted area was set up for the drilling personnel and a stable, transportable platform was built for the excavators. The client had accepted the risk of furher collapse with the construciton of additional piles. No other additional safety measures were taken for these piles.

This concept could not be applied to the southerly foreshore bridge, as a soil collapse there would have led to considerable settlement of the piles supporting the temporary bridge, and possibly to their complete collapse, with the serious consequences this would produce. Settlements permitted for the temporary bridge were limited furthermore to 1cm, as a 40m high gantry crane was to be used in the production of the piers and approach roads, which, under the prevailing ciurumstances, would have had a fairly limited usefulness anyway.
Stabilization of the gravel bed for the piles of the northerly forehore bridge was carried out, therefore, using permanent steel pipes with stepped wall thicknesses of 12, 15 and 18mm, and a casing shoe of 30mm.

The permanent steel casing had the sole task of preventing a collapse of the deep-lying gravel into the bentonite supported borehole. Pre-grouting from the temporary bridge was rejected for reasons of time and cost, and also due to the presence of some risk still remaining regarding the stability of the temporary bridge leading to the tower.

The ideal approach for the installation turned out to be the HW method, a technique which was introduced by BILFINGER + BERGER several decades ago for use in special applications.

The temporary bridge that provided access to the tower had been erected in 1989. It was supported on temporary driven piles with a diameter of d = 0,812 m and penetration lengths of up to 14m, and had been designed to support the weight of the 100t excavator, with drilling equipment and HW swinghead attached. The production of the piles for the northerly foreshore bridge was done in the following way:

The construction of these temporary piles was carried out from the temporary bridge. Even at this stage, the work required very high levels of accuracy, and a template had to be used. The temporary piles had penetration lengths of up to 14m and a diameter of 0,80m.

The drilling platform itself was mounted on temporary piles, to which it was firmly anchored. Then followed the sinking of the permanent casing with the HW method. The entire operation of transporting the 18m lengths of piping to the site, including placing and sinking of each pipe section, cutting off the HW guide casing head, positioning and welding on a second or third section, required working three shifts. Logistics had to be precisely coordinated, as the temporary bridge was the eye of the needle through which all traffic passed to reach the tower.
As a precautionary measure, the casing shoe had been given a wall thickness of 30mm and a length of 2m. During drilling operations, it turned out, in fact, that boulders of up to 1m arris length were encountered. This reinforced casing shoe was

depended on, therefore, to ensure that no deformation of the piping occurred, that might jeopardize the subsequent piling operation.

The remaining piling work continued as described above, with the air lift method employed within a 34m long protective casing.
After piling had been completed, the prefabricated concrete slabs used for the pile caps were added and secured in place employing a special technique. This was followed by ultrasonic testing, core drilling at the base of the piles, backfilling of the ultrasonic pipes and cleaning the pile heads.

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