1. Introduction

Due to the expansion works for a polish refinery, numerous installations are going to be constructed in the years 2007 to 2010 in order to double the productivity of the refinery in the next years. This is at present the largest petrochemical investment inside Europe. Several international companies, suppliers and consultant engineers are involved in design and construction of the new installations. Buildings, several tanks (max. 50 000 m$^3$), reactors, chimneys (up to 80 m) and numerous steel constructions are to be built. Parts of the new installations are often constructed very near at and between existing buildings, often with very difficult access.

The owner limited the maximum settlement to 25 mm for all sensitive buildings and installations in the tender documents. Since installations are to be realized in difficult ground conditions, several general contractors, construction companies and their consultants had to decide and account for, which foundations are to be executed as shallow or deep foundation.
2. Geotechnical conditions and task

The refinery is situated in an estuary of a river with complicated soil conditions, typical for many cities in the Baltic Sea area. The representative soil profile with some cone penetration logs is represented in fig. 1.

Up to 4 m under the ground surface, medium dense / loose fine sands (S1) were found, sometimes layered with organic silts/clays (C1). Below lays dense fine sand (S2) and further down organic clay (C2, \( c_u \sim 20-30 \) kPa). Deeper medium dense / dense fine sands S3 and S4 are also divided by organic clay (C3, \( c_u \sim 30-40 \) kPa). The lower fine sand (S4) changes into dense medium sand (S5). It can be seen from the CPT profiles that the borders of the soil layers vary partially strongly. Groundwater was found approx. 1,0 – 2,5 m below the surface. The groundwater table has to be lowered in this part of the area.

![Fig. 1](image-url)  
Ground conditions in the area of the refinery
In the existing soil, a shallow footing (in combination with soil improvement) was barely possible for light-weight constructions, smaller single footings and -with the absence of the organic layer C1- for insensitive tanks. For the rest, a deep foundation with piles or similar elements had to be carried out, reaching depths of 21 to 26 meters.

Keller Polska won the geotechnical competition and was awarded with all 20 contracts after a competitor was not able to successfully carry out CFA piles without problems. The final design was prepared and the works were carried out in time successfully.

The executed and assigned works included:
- 3180 piles (64,000 m), thereof 1440 vibrex/ring vibrator piles (406 mm, L = 21 – 23 m, distance 5D)
- 1180 CFA auger piles (430 mm, 630 mm and 800 mm, L = 12 – 26 m) and 560 MESI micropiles with 101 – 127 mm steel pipes (L = 15 – 16 m).
- 3340 vibro replacement columns (26,800 m) for the footing of the 3 tanks and 4 light-weight buildings
- 140 DSM – columns for retaining walls

All pile types (besides the vibrex piles) mentioned above and the vibro replacement technique are well known and executed for years by Keller Polska and are therefore not described here.

3. Vibrex/ring vibrator piles

Vibrex-/ring vibrator piles are in-situ concrete, full displacement piles that -by means of modern drilling equipment- are offered on the German speaking market since 2 years. A first big-sized piling project of that kind, that has been carried out in Domdidier / Switzerland, was described recently (Schmid 2008). Compared to Domdidier, different load conditions (compression/tension with high horizontal loads) and different soil conditions were obtained in Poland.

3.1 Piling procedure

A piling pipe (L = 30 m, D = 406 mm) and a ring vibrator 32 VMR was attached to the Liebherr LRB 255 (see fig. 5). That 100 t – rig with adjustable momentum and frequency regulated vibrator was able to create a 400 kN compression/tension load during driving/extraction to achieve an optimal piling process.

Situated at the application point, the piling pipe is being closed with a dead nose cone (see fig. 3) and vibrated to the design depth (see fig. 2, left side). In order to penetrate dense sands (S2 - S4), to shorten the penetration time and to minimize vibrations in the vicinity, low pressure flushing was used during driving. This flushing process started from the surface and stopped 2 m above the design depth. Two rotary pumps delivered tap water out of a flushing container into two irrigation tubes, creating a pressure of 20 bars and a flow rate of 2x2 l/s (see fig. 4).
After reaching the design depth, a two-piece reinforcement cage was put together and inserted into the piling pipe (see fig. 2 second step, fig. 7). The piles were reinforced completely with 13 – 18 kg/m (5 rebars with 16 mm or 20 mm and a 8 – 10 mm helix. In fig. 6 two steel pipes for crosshole sonic logging can be seen.

After installation of the reinforcement, the concrete C25/30 is pumped by a CIFA concrete pump via a hose and a swivel head directly into the piling pipe (see fig. 2 right side and fig. 8). Since the vibrex piles in Poland were carried out without a geotextile encapsulation as it was carried out in Switzerland, the concrete consumption exceeded the theoretical diameter of the piling pipe by 40 – 50 %.

Ahead of the first piling works, penetration tests and test piles, accompanied by vibration measurements, had been carried out. The awarding authority wanted to verify the compatibility and the bearing capacity of the new technology. At a distance of 20 – 60 m to critical installations, penetration tests with vibration measurements were carried out every 10 m. Even at a minimum distance of 20 m, the maximum particle velocity measured at foundations and installations did not exceed 2 mm/s, which was still far below the permitted value of the client.

During the piling process, the following data were monitored and logged via a PDE – system into the piling protocols: penetration depth and –speed of the piling pipe, frequency and amplitude of the vibrator, compression and tension applied, oil pressure of the vibrator and concrete consumption.
Fig. 5 LRB 255 with 30 m piling pipe and ring vibrator
Fig. 6 reinforcement cage with spacers and two pipes for crosshole sonic logging (upper right side)
Fig. 7 installation of part 2 of the reinforcement cage (middle right side)
Fig. 8 casting of the pile inside the pipe above the swivel head (lower right side)
4. Quality control and pile tests

Besides the logging of each pile’s process data, the following tests were performed:

- quality tests of the concrete from each delivery (cube samples)
- integrity tests via PIT and CSL for 50% of the piles
- 250 % service load tests on the test piles via load tests
- 150 % service load tests on the regular piles. 1 % of the regular piles had been loaded with a static load.

For long full displacement piles (with D/L > 30 : 50), the reflected signal at the low strain integrity test (PIT, SIT) is sometimes difficult to evaluate. For that reason, an ultrasonic pile integrity test is carried out as shown in fig. 9.

![Fig. 9: Results of an ultrasonic pile integrity test carried out with the CSL-method: intact pile on the left hand side, defective pile on the right hand side (courtesy PMC).](image)

5. Comparison of load tests and static calculations

The load – settlement curves of the vibrex and CFA test piles with compression load allow the following conclusions:

- vibrex piles with a length of 21 m, 23 m and 25 m showed a similar, almost linear behaviour up to a maximum load of 3000 kN. The maximum settlement measured was 6 – 8 mm respectively 1,5 – 2,0 % pile diameter. The permanent settlement of the vibrex piles was 1,4 – 2,2 mm. The maximum stress inside the theoretical pile diameter was 23 MPa with an allowed compressive strength in the reinforced concrete C25/30 of 16,7 MPa (according to polish Standard PN-B-03264:2002)

- CFA-piles with a length of 21 m and 25 m showed a similar behaviour up to a maximum test load of 3500 kN. Maximum settlements measured were 12 – 14 mm respectively 20 – 22 % pile diameter. The permanent settlements of the CFA-piles were 7,2 – 8,5 mm. The maximum stress inside the theoretical pile diameter was
11.2 MPa with an allowed compressive strength in the pure concrete C25/30 of 13.9 MPa (CFA-piles were reinforced only down to a depths of 12 – 15 m)

- At high loads (2500 – 3000 kN), vibrex piles (D = 406 mm) showed a stiffer behaviour and smaller permanent settlements compared to CFA auger piles (D = 630 mm). The skin friction limit of the CFA-piles has been already exceeded at the maximum load of 3500 kN. This did not happen with the vibrex-piles at their maximum load of 3000 kN.

- No test pile reached the limit load at 3000 – 3500 kN. The geotechnical pile bearing capacity could be estimated to 80 % of the maximum test load, that is ~2400 kN for vibrex and ~2800 kN for CFA-piles, according to the polish pile standard.

![Fig. 10: load-settlement curve of three vibrex 406 mm and two CFA 630 mm test piles](image)

The load displacement curve of the vibrex piles loaded with static tension force allow the following conclusions (see fig. 11):

- The load displacement behaviour of the vibrex piles under tension load was characterized by the resistance of the reinforcement. After exceeding the allowed stress in the reinforcement cage (for instance 422 kN at 5 rebars Ø16 mm), the displacement increased clearly. The remaining permanent displacement after unloading was 1.5 – 2.2 mm.

- At a tension test pile with a reinforcement of 7 rebars Ø25, no limit load could be obtained up to 1400 kN. The remaining permanent displacement after unloading was only 2.4 mm.
Vibrex/Ring vibrator piles - experiences in Poland
Dr.-Ing. Jerzy Świniański    Dr.-Ing. M.Sc. Jimmy Wehr

Fig. 11: load displacement curves of the vibrex piles resulting from static compression and tension tests

Allowed maximum loads [kN] ¹

<table>
<thead>
<tr>
<th>Pile length</th>
<th>PN -83/B-02482 ²</th>
<th>LCPC B&amp;G ²</th>
<th>LCPC B&amp;G ³</th>
<th>Load test ⁴</th>
</tr>
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<tbody>
<tr>
<td>21 m</td>
<td>790</td>
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<td>1690</td>
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<tr>
<td>23 m</td>
<td>1000</td>
<td>1330</td>
<td>1750</td>
<td>2400</td>
</tr>
<tr>
<td>25 m</td>
<td>1210</td>
<td>1380</td>
<td>1940</td>
<td>2400</td>
</tr>
</tbody>
</table>

Auger pile - CFA 630 mm

<table>
<thead>
<tr>
<th>Pile length</th>
<th>PN -83/B-02482 ²</th>
<th>LCPC B&amp;G ²</th>
<th>LCPC B&amp;G ³</th>
<th>Load test ⁴</th>
</tr>
</thead>
<tbody>
<tr>
<td>21 m</td>
<td>1260</td>
<td>1380</td>
<td>1950</td>
<td>2800</td>
</tr>
<tr>
<td>23 m</td>
<td>1450</td>
<td>1610</td>
<td>2270</td>
<td>--</td>
</tr>
<tr>
<td>25 m</td>
<td>1660</td>
<td>1840</td>
<td>2400</td>
<td>2800</td>
</tr>
</tbody>
</table>

Legend:
1. factored pile loads without group effects and negative skin friction
2. bearing layer: Sands S4 and S5, beneath the organic clay C3
3. bearing layer: Sands S3, S4 and S5, including sand layer above the organic clay C3
4. bearing capacity of a single pile: according to PN -83/B-02482 as 80% of the maximal test load

Tab. 1: admissible pile loads calculated after PN-83/B-02482 and LCPC-method, together with estimated pile loads resulting from test loadings.

The polish standard for pile calculations PN-83/B-02482 recommends in layered soils (see fig. 1) only the sand layers S4 and S5 as bearing layers. This classic and conservative assumption leads to very low pile bearing capacities or to very long piles (see tab. 1, col.2).

By means of the LCPC-method of Bustamante & Gianeselli based on results of the CPT penetration tests, higher allowed maximum loads with the same assumption are obtained (see tab 1, col. 4).

Caused by the allowed concrete C25/30 compression strength with an additional partial safety factor of 1.5 and 2.0, the admissible maximum pile loads were limited to 1460 kN (factored load) for vibrex piles and 2170 kN for CFA 630 mm at the final design.
6. Summary

For the expansion of a refinery, vibrex-/ring vibrator piles were used for the first time in Poland. Hence this refinery is located in the estuary of a river, complicated soil conditions existing the whole area. Sandy soils with three layers of organic sediments in depths up to 18 to 22 m were found. Because the client limited the settlements to 25 mm, all sensitive and heavy buildings had to be founded deeply on piles.

Prior to the pile execution works, pile tests accompanied by vibration measurements have been carried out. Static tests at 21 to 25 m long piles with 406 mm diameter showed an almost linear stiffness. Up to 3000 kN, only negligible settlements and no limit load could be reached. The bearing capacity of the piles exceeded the estimated loads by far (according to polish standard and LCPC method with CPT – tests)

Over all, 3180 piles (vibrex-, CFA piles and MESI micropiles) with a length of 15 to 27 m had been carried out, of them ~1440 vibrex piles with ring vibrator. Compared to CFA piles, vibrex piles could be reinforced over the total length. This was very important for buildings with high tension loads like chimneys.

Over 30 load tests (tension/compression) and many integrity tests have been carried out. Soil conditions, the piling process and the results of the load tests of the vibrex and CFA piles were compared with the static calculations.

7. Literature

Ortbeton- Verdrängungs-Pfahl, Einführung eines neuen Gründungselement am Beispiel Sonderfundierung ALDI, CH-Domdidier, 7268 Pfähle a 35 m Länge. 6. Kolloquium, Bauen in Boden und Fels, Technische Akademie Esslingen, Jahr, 571-578.

BVV / Liebherr, Technische Beschreibungen und Dokumentation

PN-83/B-02482. Fundamenty palowe. Nośność pali i fundamentów palowych.