Oldie but Goldie – Bi-directionally tested foundation piles with base enlargement as a smart and economical alternative to conventional piles at Geneva, Switzerland

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ABSTRACT

Foundations in Geneva are difficult and expensive due a large overlayer of clay and silt above competent bearing material in the moraine. Common foundation schemes use deep barrettes or bored piles, first passing large, weak layers of soil before finally reaching acceptable, solid moraine with reasonable values of skin friction and end bearing resistance, thus requiring further deep penetration for the necessary length for load transfer in the moraine. Depths of more than 60 m (200 ft) in Geneva are common in this region.

At the Onyx-Project Geneva Implenia Foundation Company also encountered these circumstances.

Despite usual solutions Implenia referred to an old and well known, but still intelligent and in today's words smart, efficient and economical solution. Using small shafts, passing the large layers of clay and silt, ending with the pile toe in the underlaying moraine with a belled or underreamed base was the technic adopted to save drilling time, reduce spoil and concrete, so finally reducing the CO_2 footprint.

Piles with enlarged base ("belled" or "underreamed") are reported at the beginning of the 20th century, for example at Chicago, which has a quite similar geotechnical structure as Geneva with the need of deep foundations. The first pile base enlargements were built in hand-dug caissons with wood lagging and steel ring bracing. In the 50s and 60s piling works were more and more mechanized, driven by the development of more powerful cranes and specialized drill rigs. Additionally the first tools for mechanized base enlargement were invented around that period.

This report describes the project situation at Geneva, the drilling and enlargement technique of the pile base, the verification of the design values with an in-situ bi-directional load test and the smart execution by reduction of CO_2 and costs.

Keywords: underreamed piles, enlarged base, belled piles, foundation, bored pile, O-cell test, Osterberg-cell test, skin-friction, end-bearing, ecological footprint, bi-directional load testing

INTRODUCTION PROJECT

The extension of the Rolex Factories at Geneva, Switzerland envisaged a new building with 6 stories above and 3 levels below surface. The construction pit with a base area of 3500 m^2 (4200 yd^2) was designed 13 meters (42 ft) deep, supported by a circumferential diaphragm-wall with maximum depths reaching down to 48 m (160 ft).
The foundation of the building inside the pit were designed with cased piles of 800 and 1500 mm (31 – 60 in) diameter.

GEOLOGY

The geology is characterized by post-glacial layered deposits of the last glacial period “Würm” in this region.

Preliminary core hole drilling and cone penetration tests were undertaken on site, additional information were given from the investigations of the recent built neighboring subway line extension.

1. Filled ground, silt and clay 0 - 2 m (0 – 6 ft)
2. Glacial deposits, gravel clay 2 – 6 m (6 – 20 ft)
3. Glacial deposits, clay 6 - 8 m (20 – 26 ft)
4. Glacial deposits, silt 8 - 30 m (26 – 100 ft)
5. Moraine > 30 m (> 100ft)

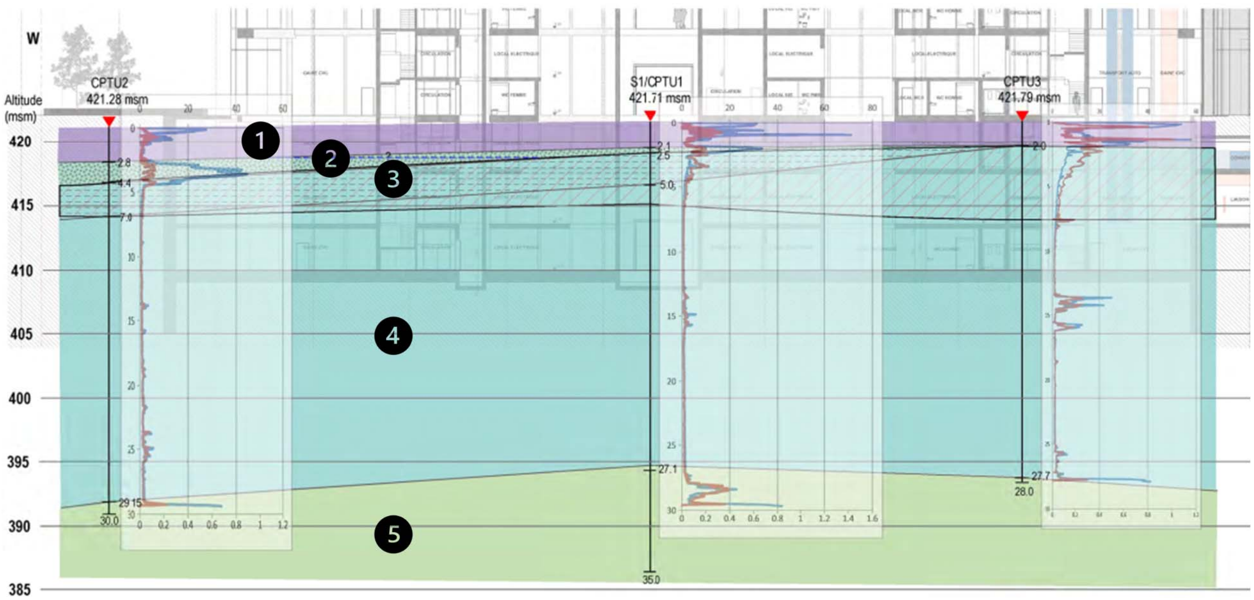


Figure 1. Geological section (Geotechnical Report, De Cérenville Géotechnique)

According to the geological probes and CPTU the geotechnical design engineers supplied the following resistance values:

Table 1. Characteristic soil resistance anticipated for bored piles

Geological formation	Skin friction $q_{s,k}$ [kPa]	End bearing resistance $q_{p,k}$ [kPa]
Fine deposits	-30 (negative)	-
Moraine < 35 m (115 ft)	90	1000
Moraine > 35 m (115 ft)	150	1750

It was recommended to found the building on foundation piles into the loadbearing moraine layer. Differential settlements of the building should be minimized. Furthermore, additional negative skin friction of the weak overlayer was to be anticipated and its effect on the foundation element had to be respected.

FOUNDATION VARIANTS

The initial foundation concept by the engineer was a plan to construct the new building on piles of 800 and 1500 mm (31 – 60 in) diameter, drilled down and anchored into the competent moraine layer at approx. 30 –35 m (100 - 115 ft) depth. With the additional necessary pile length for load transfer by skin friction and end bearing it was obvious that this would be an expensive scheme in terms of time, equipment and material. Handling the anticipated temporary 1500 mm casing down to 50 m (165 ft) would demand an additional oscillator, thus reducing again the execution time. Excavation deposits and concrete quantities would rise due to the large distance between the subsequent building and load transfer zone.

At this stage the alternative solution of piles with enlarged base was proposed by Implenia to reduce the spoil and concrete, avoid additional equipment and save time and money.

Some of the early applications of pile base enlargement with extensive testing programs in London clay specifically can be found in the reports from Whitaker & Cooke (1966)

Implenia have at their disposal several pile enlargement tools for casing diameters of 750 mm to 1300 mm (30 – 51 in) and can provide maximum enlargement diameter of 3000 mm (10 ft) from which the most appropriate can be selected. In this case a guide was attached to fit the special swiss casing diameter 800°mm (31 in).

DRILLING TECHNIQUE

Sequence pile installation

The technique for pile base enlargement requires a special procedure and tool, added to the standard sequence of rotary drilled cylindrical piles, either cased or uncased.

The construction sequence is illustrated in Fig. 2: set up on pile location, then start drilling with conventional auger or bucket and -if necessary- sinking the temporary casing sections (step 1, 2). At the final depth, the base is cleaned and the specialized tool is used to excavate the base enlargement (step 3). A reinforcement cage may then be installed (step 4), before pouring the concrete with the aid of a tremie concrete pipe (step 5). Simultaneously with the rising concrete level the casing sections are withdrawn and removed as are the concrete tremie pipe sections.

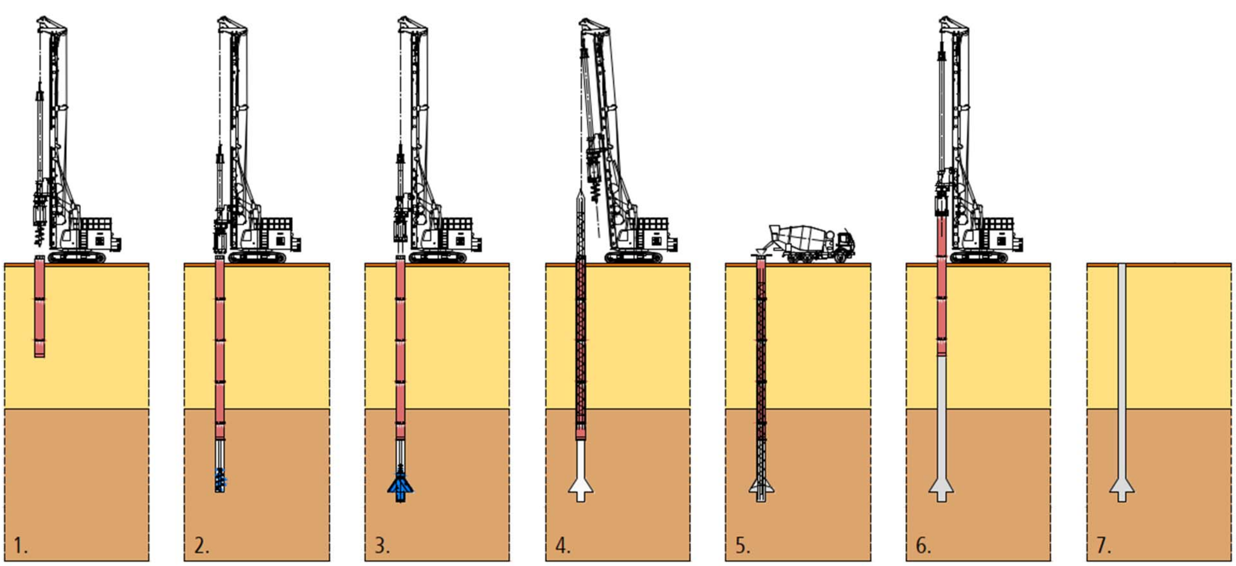


Figure 2. Drilling sequence pile with enlarged base (Implenia)

Base enlargement tool

The purpose-built extension tool is equipped with lateral cutting wings, which can be mechanically unfolded and be extended in a very controlled manner. The tool is designed so when the Kelly-bar pushes at the top of the tool, the wings are operated and unfolded. Rotating the tool creates the conical enlargement. The debris is collected in a bucket, arranged underneath the wings of the tool.

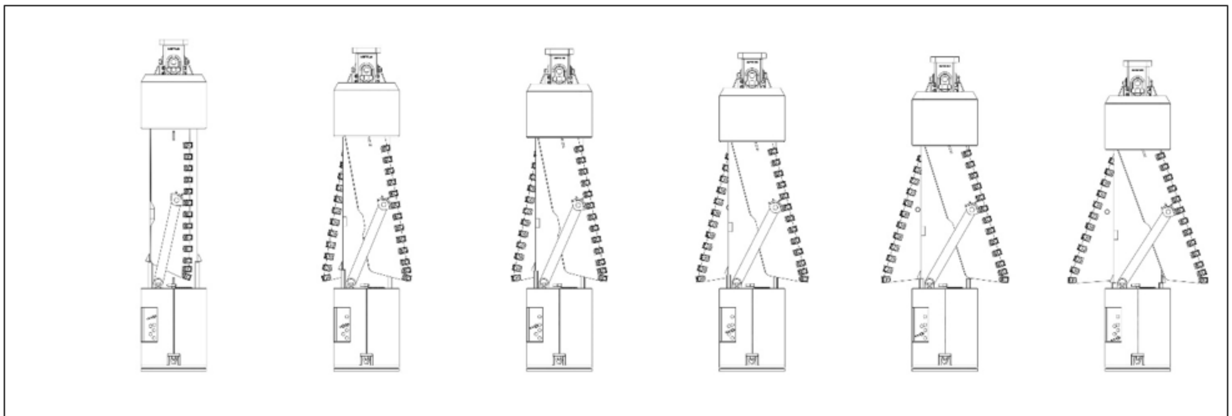
The cutting diameter of the lateral unfolding wings may be controlled by the vertical movement of the kelly-bar. Due to the short vertical movement of approx. 10 to 30 cm (4 – 12 in) this demands a high attention and accuracy of the rig operator. A more advanced and reliable method is the control of the lateral movement of the cutting wings with a "stop bolt". This bolt restricts further lateral extension of the wings even if the Kelly-bars still pushes vertically on the tool.

After cutting the actual ream, the tool wings are retracted and the reamer extracted back to the working platform and the bucket emptied. The "stop bolt" then will be gradually moved to the next position step by step, thus ensuring the quantity of fresh drilled debris fits in the volume of the debris bucket in every single step.

The final actual ream diameter per step is additionally controlled by a mechanical indicator within the mechanism of the tool. This supports the control of real enlargement in hard layers, when in hard layers the tool does not open easily. When the indicator matches the nominal "stop bolt" enlargement, the next step can proceed.

The drilling and evacuation of debris and repositioning of the "stop bolt" is continued by several steps until the final enlarged diameter is achieved.

This base enlargement is applicable either for cohesive soils or -with support fluid- for non-cohesive soils.



Position	Pos. 1	Pos. 2	Pos. 3	Pos. 4	Pos. 5	Pos. 6
Ø max. base enlargement	700 mm	1200 mm	1280 mm	1500 mm	1680 mm	1850 mm
Volume / step	0 m^3	0,44 m^3	0,15 m^3	0,38 m^3	0,39 m^3	0,34 m^3
Volume total	0 m^3	0,44 m^3	0,59 m^3	0,97 m^3	1,35 m^3	1,69 m^3
single steps	---	3	1	3	3	2

Figure 3. Drilling tool for base enlargement Onyx, Geneva (courtesy of Hartfuss Stahlbau GmbH)

FULL SCALE BI-DIRECTIONAL LOADING TEST

In 2020 Implenia executed with Fugro Loadtest a bi-directional load test on a test-pile of a shaft diameter of 800 mm and base enlargement to 1,85 m (6 ft) over a ream length of 4 m length (13 ft) to verify the design values and the execution process of a pile with base enlargement. Performing a bi-directional loading test was significantly more efficient than deploying nominally cylindrical anchor piles for a traditional top down loading test.

The principle of a bi-directional load test is to split the pile in two sections and test both with the assistance of the reaction forces induced by the other section. This test was invented in the 80s by Dr. J. Osterberg in the US and is widely known as an Osterberg-test, or O-Cell test.

The tests consist of one or more hydraulic cylinders normally fixed between steel bearings plates. It is located at a predetermined elevation, in this case immediately above the start of the ream and fixed within the upper and lower test pile reinforcement cage sections before pouring concrete. After concrete curing the O-cell assembly will be expanded by hydraulic pressure, pushing both sections of the pile upwards and downwards respectively and in effect performing two traditional static load tests simultaneously against each other. Strain gauges at different levels give information of load distribution and tell-tales indicate the movement of the upper and lower pile section. Measurements are also made of the pile head movement, compression and the pile base separately during the loading to reveal the load displacement behavior in each direction.

In this rare case of testing a pile with an enlarged base bi-directionally the O-cell was placed directly above the enlargement cone to distinguish directly the behaviour of the whole reamed base and its base resistance together with the skin friction at the pile-shaft above.

Using 4 levels of strain gauges allowed to the distribution of load in the different soil layers to be estimated.

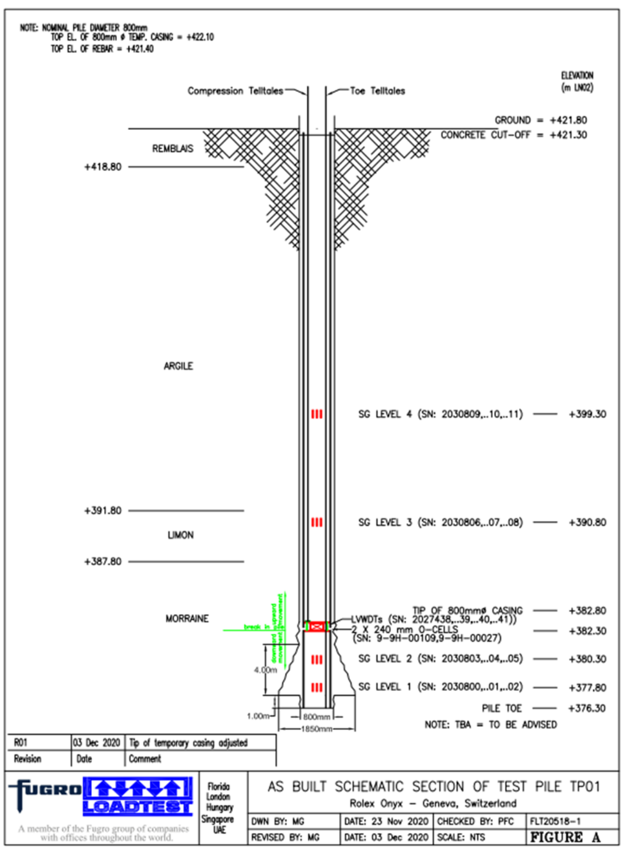


Figure 4. Schematic section test pile (Fugro Loadtest)

PILE TEST RESULTS

The key movements are shown in the following Figure 5 below, which shows the upward movement from the top of the O-cell assembly and upward compression together with the downward O-cell assembly movement and calculated pile toe movement. The load was applied in steps up to a maximum of 3.85 MN in each direction.

The maximum displacement upwards was approximately 5.8mm with enough geotechnical movement to be able to assess the asymptotic capacity to be around 5 MN.
The downward displacement shows a typical point of inflexion where the skin friction is fully mobilized and the end bearing dominates the behavior at subsequent loads. The estimated friction downwards (using the Cemsolve analysis, Fleming, 1992) is approximately 1 MN and the remaining load mobilizing 1 MN/m^2 at a displacement of around 33 mm over the full base diameter. The asymptotic estimate of the end bearing capacity is 10 MN.
An additional observation and advantage of the specific tool used for this project is that the friction in the section below the ream will often exhibit even higher unit friction due to the increased lateral earth pressures developed by the ream itself, so not only can one capitalize on the additional end bearing surface area, but one can also gain some additional friction.

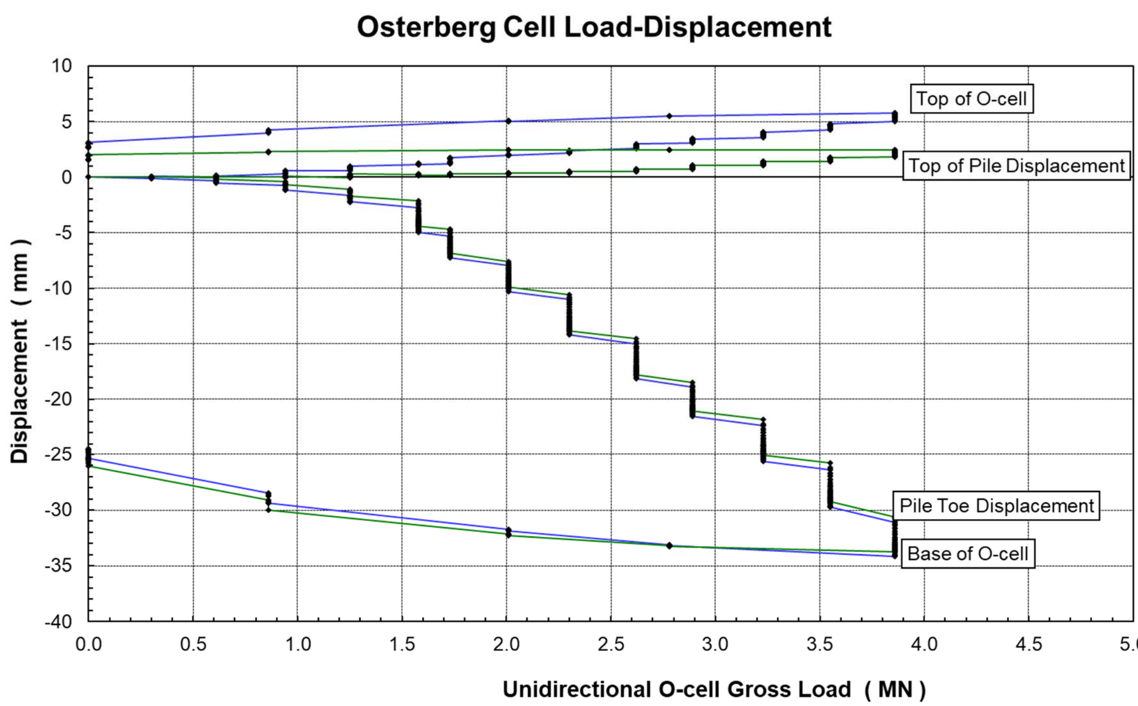


Figure 5. Graph Load – Displacement (Fugro Loadtest)

STANDARDS AND RECOMMENDATIONS

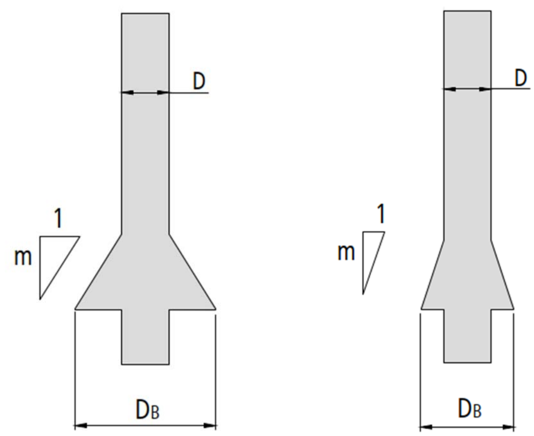
The design and execution of piles with base enlargements is regulated in different European standards.

The “SIA 267:2013 Geotechnical Design” (Swiss Standard) has no special information regarding base enlargement.

In the “European standard DIN EN 1536:2015 Execution of special geotechnical work – Bored piles” the enlargement of pile bases is properly regulated.
This standard determines several aspects:

The maximum diameter of enlargement and the cone geometry are determined according the soil type cohesive or granular, so supporting the stable excavation.

Table 2. Dimensions criteria DIN EN 1536:2015 (Implenia)



Criteria DIN EN 1536:2015	D_{base} / D_{shaft}	Cone inclination 1/m	Max. cross section
Cohesive soils	≤ 3	≥ 1,5	Max. 15 m^2
Non cohesive soils	≤ 2	≥ 3	

No base enlargement is allowed in sensitive soils as
- Sand with low density
- Uniformly graded sand under groundwater
- Soft and sensitive clay

The maximum cross-section of the enlarged base is limited to 15 m^2 (18 yd^2).

In the “Recommendations on Piling, EA Pfähle 2. Edition 2012”, available in German and English some further important determinations and advice for piles with enlarged base is given:

The recommendations confirm, that there is no need for additional reinforcement in the base cone. The vertical loads will be transferred from shaft to the base aside by shear stresses. This is the reason for the geometrical restrictions of allowable enlargement and the ratio height to enlargement.

Base enlargement is allowed in stable soils or in soils, which can be stabilized by support fluids like bentonite or cement slurry.

For piles with base enlargement the end bearing design values have to be reduced to 75%. This is to reduce the settlements under the base induced by the effect of influencing greater depths by the greater diameter cross section.

At least the "ICE Specifications for piling and embedded retaining walls", 3rd edition, 2017 proposes remote camera inspections to assess and control the stability and effectiveness of the enlargement and cleanliness of the base of the underream. Additionally, it describes sampling or test by penetrometer to ensure no remoulding of the material.

FOUNDATION WORKS

After the O-Cell test has proven the suitability and performance of piles with base enlargement, the design was revised. The foundation design for the new building was adapted to the anticipated loads; piles dia. 800 mm as standard piles, or with enlarged base for higher loaded barrettes originally specified.
All piles with initial dia. 1500 mm could be replaced by piles dia. 800 mm with an enlarged base 1850 mm; in total 41 piles with a total of nearly 1.750 linear meters (1900 yds).

The piles were drilled with an 800 mm temporary casing to the required depth into the moraine to approx. 40 to 50 meters. The casing was then retracted just above the start of the ream and locked in position. The enlargement-tool was then attached to the drill-rig and the base enlargement was cut in several steps to the final diameter 1850 mm. If debris were to fall down the center core at the base, the rig operator could identify this situation with the depth measuring device installed inside the cabin. If any debris is detected, the cleaning bucket tool is reconnected and used to clean the central base to the initial depth before continuing the reaming process.

The process of completing each base enlargement took about 90 – 120 minutes. Subsequently, installation of the reinforcement cage and tremie pipe followed before finally concrete pouring and retracting of the temporary casing could be executed.

Figure 6. Expanded drilling tool diameter 1850 mm (6 ft) attached to drill rig (Implenia)

The Table 3 below compares the initial plan and later realized alternative solution. It highlights the reduced quantities and savings of drilling spoil, concrete as the reduced truck loads for transport offered with the alternative solution. Debris quantity is calculated - on the safe side - only below the later excavation level. The concrete volume is calculated with an 1,5 m overpour above final pile for trimming

Roughly summarized only 30% of the original material is required and similarly 30% debris are generated, in a reverse view a remarkably reduction of 70%.

Table 3. Comparison initial pile foundation plan and alternative solution, quantities and savings

Comparison average values: - drilling depth 42,19 m - pile length 31,84 m	**Quantity**	**Pile Diameter**	**Shaft volume**	**Volume Base En-largement 1850 mm**	**Debris** (only below cut off level)	**Concrete**	**Temporary backfill**	**Debris** (only below cut off level)	**Concrete**
	[pc.]	**[mm]**	**[m3/m]**	**[m3]**	**[m3/pc]**	**[m3/pc]**	**[m3/pc]**	**[m3]**	**[m3]**
Initial Plan	41	1.500	1,77	---	56,3	58,9	15,6	2.307	2.416
Alternative Solution	41	800	0,50	1,7	17,7	18,5	4,4	726	757
Difference			**-1,26**		**-38,6**	**-40,5**	**-11,2**	**-1.581**	**-1.659**
% of initial plan			**28,4%**				**28,4%**	**31,5%**	**31,3%**
Truck load capacity	**[m3]**							15	7
Nos. Trucks savings	**[pc]**							**-106**	**-237**

COMPARISON CO_2 FOOTPRINT

The alternative solution with execution of foundation piles with enlarged base offers a sharp reduction of drilling debris and concrete. This simultaneously reduces the CO_2 emissions significantly.
A simple comparison of emissions for different foundation techniques and variants can be made using the EFFC / DFI Carbon Calculator. It is available for download on the homepage and free to use.
The main advantage of this calculator is the focus on the foundation industry. Typical foundation techniques and materials and their equivalent CO_2 emission (CO_2eq) are prepared in sheets and ready to easily use. For instance, for piling works, concrete and reinforcement are the primary sources of CO_2 emissions. Transport for material, equipment and staff, waste, and at least depreciation of equipment are secondary sources and may be neglected for a first approach, they contribute typically less than 10% to the total emission of pile foundations. Other foundation techniques may be different due to their own type of work and demand of material.

The initial plan demanded 59 m^3 concrete per pile, thus emitting 14 tons of CO_2eq per pile, mainly resulting from the production of cement (CEM II B) with already reduced CO_2eq-footprint in comparison with CEM I types. The alternative variant, in technical terms proven equally, demands only 19 m^3 concrete and emits 5 tons CO_2eq per pile. For the relatively small amount of only 41 piles at this site the total emissions of 420 tons CO_2eq were avoided as well as the monetary savings for concrete and debris removal.
Additional reductions may calculated by more detailed input regarding less transports, less equipment demand and fuel usage, less refilling of empty boreholes, less pile head trimming etc. Similarly, using the bi-directional loading method the additional transport and erection for kentledge or for the installation of anchor piles and mobilization of reaction piles is avoided completely
A further way to reduce the CO_2 footprint for piling works may be also change of cement type to low emotion types, if available and applicable.

SUMMARY

The efficiency of underreamed bored pile solutions have been acknowledged previously but somehow, they do not find their way into common practice.

This site report illustrates the real potential by use of this technic to reduce equipment and fuel, construction materials and debris, simultaneously saving time, money and protecting the environment by reduced CO_2 footpath.

The summarized possible advantages of piles with enlarged base are

- Higher vertical load bearing capacity
- Enhanced rate of capacity utilization of concrete shaft
- Fewer piles under concentrated loads
- Reduced pile diameter
- Reduced drilling depths
- Reduced rig dimension
- Reduced material, reduced debris
- Reduced transports
- Reduced impact on environment

Pile foundations with base enlargement have to be designed and planned properly. In difficult situations a pile test provides security in design, offering further optimization and more economical and ecological solutions.
Experienced contractors and staff with good workmanship are advised for proper execution quality.

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