Česká geotechnická společnost ČSSI

46. konference se zahraniční účastí
46th Conference with international participation

ZAKLÁDÁNÍ STAVEB BRNO
FOUNDATION ENGINEERING 2018

19. – 20. 11. 2018

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INNOVATIVE AND SUSTAINABLE STEEL SHEET PILE SOLUTIONS FOR UNDERGROUND CAR PARKS

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Abstract
Vehicles traffic and lack of parking space is one of the main challenges for big cities. Especially in city centres, land is very expensive, and the trend to increase parking capacities is to build underground structures. In this article, an innovative, economical, and environmentally-friendly solution for underground car-parks built with steel sheet piles is described. Several aspects, like fire safety, impervious walls, vertical bearing capacity, environmental impact and reduction of traffic due to construction vehicles are discussed.

1. INTRODUCTION

Steel sheet piles have been used for over 100 years in permanent and temporary applications. In the early 1910's, steel sheet piles were mainly utilised for temporary cofferdams in water and excavations on land, but a few years later, the first quay walls were executed with steel sheet piles. One of the first structures that was well documented was built in the Port of Rotterdam, The Netherlands. On other continents, the development of steel sheet piles was done concurrently. In the USA, they were used mainly for large cofferdams, for instance to build hydroelectrical power stations in the Mississippi River. In Japan, one of the first innovative applications was a tunnel built in 1927 with steel sheet piles for the national railway company.

Installation techniques, as well as design methods, evolved continuously during the 20th century. A few pilot projects confirmed that new permanent applications, such as bridge abutments and underground structures were cost-effective and durable. Since the 1960's, these structures have gained momentum in several European countries, but in the last years, a surge in these applications has been quite noticeable, especially in The Netherlands, were several large underground car parks (UCP) were built during the last decade with steel sheet piles [1].

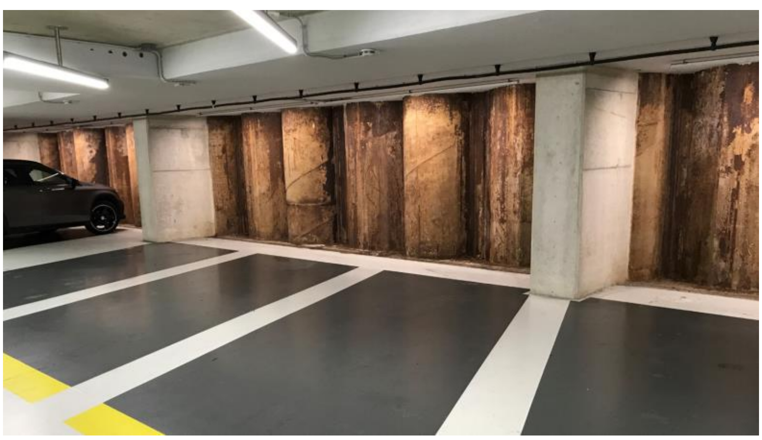

Fig. 1: Markthal, Rotterdam, The Netherlands. 2014

Steel sheet piles are cost-effective solutions for UCP with 3 or 4 levels. So why are they not so widely used in other countries? There are several reasons, most of them are based on a subjective perception. The execution of an UCP in an urban area poses quite a few challenges to the designer and to the contractor. One of the main issues for the design engineer is fire resistance. Other topics can be managed in quite simple ways. These aspects will be explained in the next chapters.

2. DESIGN OF STEEL SHEET PILES

2.1 Design methods

Retaining walls can be designed with relatively simple methods, such as the equivalent beam method (or Blum method), which is a Limit Equilibrium Method. However, most of the walls of UCP's are designed with more than one support, and in that case, elaborate design methods that consider the soil structure interaction are recommended. These methods allow also a better prediction of deformations of the wall. In more sensitive areas, for instance with very soft soils, or complex shapes of the perimeter, the finite element method (FEM) is a better alternative to reduce the risks and to optimize the solution.

In Europe, the geotechnical design shall be done according to EN 1997 – Part 1 [2].

2.2 Design parameters

Soil is obviously the most important parameter for the geotechnical design. It is of utmost importance to start with an extensive geotechnical investigation. The cost of such an investigation will be offset by the savings of construction costs due to the optimization of the solution, and the reduction of risks (and additional costs) during the execution.

There are two different execution methods, which also have an influence on the design: bottom-up (or open cut) and top-down (see below).

The number of supports, either struts or battered grouted anchors, influence the length and the required resistance of the sheet piles. From the execution point of view, anchors are preferred because they do not interfere with the erection of the structure inside the pit, but it is not always possible to install them due to soil conditions, or due to right of way issues.

2.3 Sheet pile sections

According to the new design rules of Eurocode 3 Part 5 [3], sheet pile sections may be classified in 4 classes. Class 1 and 2 can be designed with the plastic section modulus W_{pl}, which depending on the section, is 10 to 25% higher than the elastic section modulus W_{el}. Thus savings of up to 25% of steel can be achieved by simply using the Eurocode.

Generally speaking, the optimum choice of a sheet pile section considers a light section with a high yield strength (steel grade). For permanent structures, Z-type piles are preferred, because in some specific cases, reduction factors applied to the resistance of U-type piles make these solutions less efficient.

Note that driveability may be the governing factor. For instance, installation in very compact soils may require a heavier or thicker section than the one selected based on the statical design.

2.4 Vertical loads and bearing capacity

Retaining walls are predominantly submitted to horizontal pressures and loads from the soil and water. However, underground car parks, basements and bridge abutments can be submitted to significant vertical loads from the superstructure. The transfer of vertical loads to the sheet pile through a concrete capping beam needs special detailings: reinforcing of the concrete above the sheet pile top is indispensable. The design can be done according to the Eurocodes, but for the sake of simplification, manufacturers developed alternative design methods based on extensive laboratory testing. ArcelorMittal developed its design method for the 'knife edge' resistance ("*Schneidenlagerung*" in German) and submitted it for a German National Technical Agreement, which was granted in 2016 [4]. To ease the rather complex calculations, they also developed *VLoad*, a free software.

Vertical loads from the superstructure and / or from battered anchors have to be transferred from the sheet pile to the soil, either by friction or by point resistance. In some cases, it is necessary to increase the embedment depth to resist these additional vertical loads. The bearing capacity can be assessed according to EN 1997 – Part 1. Note that NF P94-262: 2012 [5], the French national application document of EN 1997 - Part 1 for bearing piles, proposes more realistic and more cost-efficient methods than the basic method proposed in the standard. In the past, French authorities made extensive in-situ tests to measure the friction and the plug effect of steel sheet piles, in order to be able to optimize the design.

2.5 Fire resistance

This is a crucial issue for any steel structure. Tests on steel structures for car parks above ground were made more than two decades ago, and the results were used also for the elaboration of a fire design concept for underground car parks. Several parameters that will impact the evolution of a fire inside a closed environment: ventilation, type of material and mass that can burn (i.e. fuel, number of cars that burn concurrently,…).

In some countries, the ISO 834 fire curve is mandatory for the design of the structure. This fire scenario is quite conservative for UCP, because it does not mimic a real fire in an UCP.

There are other scenarios, based on more realistic fire curves (called also "natural fire") that can be considered for the design of the sheet pile wall. Laboratory tests were performed in order to assess the behaviour of a sheet pile in a realistic condition, with several saturated and non-saturated soils behind the sheet pile [6].

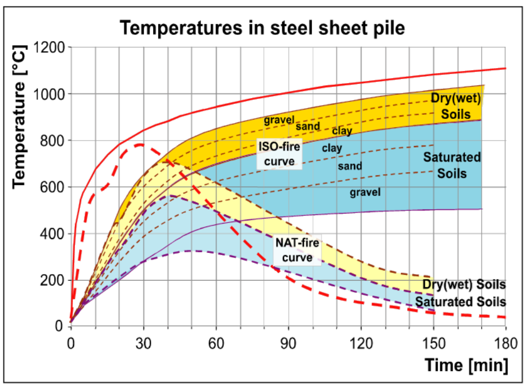

Fig. 2: Temperatures in steel sheet piles based on different fire design curves.

One of the conclusions of this R&D project was that groundwater had a positive influence on the performance of the wall, reducing the increase of temperature inside the steel, or at least delaying the increase of temperature in the steel by a certain time.

The design in itself is quite complex and should be made by specialists in fire engineering. For instance, SARI is a finite element software developed by ArcelorMittal that can simulate the behaviour of a sheet pile retaining wall in a fire scenario. It considers the soil and water behind the wall, as well as any fire curve on the inside of the car park.

It should be noted that above 400°C, the resistance of steel diminishes, but on the other hand, in case of a multi-strutted structure, redistribution of the bending moments can occur, which offsets partially the reduction of the resistance of the wall.

Basically, the fire protection concept for UCP is to protect human lives, and to prevent the collapse of the structure, but large deformations of the wall are an acceptable risk. It is also clear that the wall might have to be repaired after the fire incident.

There are alternative methods to protect the steel from reaching high temperatures. They consist typically in adding a protection in front of the wall, for instance a brick wall, or concrete facing poured in front of the steel surface.

3. PERMANENT VS TREMPORARY USE

Land property is quite expensive in the centre of most cities. Hence, any additional space that can be effectively used is very valuable.

Steel sheet piles are sometimes used for temporary retaining walls, that retain soil (and water), so that the car park can be erected inside a healthy and safe environment. This method wastes a valuable surface due to the work area required to build a concrete structure inside the excavation.

Consequently, rather than leaving the sheet piles in the ground, which still happens, and which in addition is a waste of natural resources, or rather than extracting the sheets after the erection of the building, the most cost-efficient solution is to use the sheet piles as a permanent wall. It saves times and increases the available surface inside the car park (see option c in *Fig.3*).

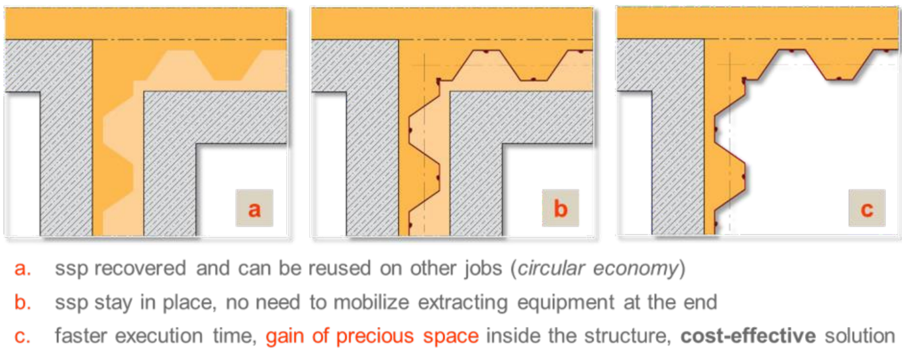

Fig. 2: Execution options for a UCP. Plan view.

4. EXECUTION OF THE UNDERGROUND STRUCTURE

The execution of a sheet pile wall is much faster than any other alternative. However, installation of permanent walls require more care because of the required accuracy (verticality, watertigthness,…). Two methods can be used, each having its advantages, so that the choice must be made on a project basis.

4.1 Bottom-up

The bottom-up is the classical methods, also called open cut. The main advantage is the easiness to execute. The contractor installs the sheet piles, excavates inside the pit to the first anchor / strut level, lowers down the water inside the excavation (if applicable), installs the anchor / strut, and so on for each additional support, until the final excavation level elevation. After that, he erects the structure inside the dry pit.

For deep excavations under the groundwater, an alternative is to excavate under water (wet excavation), pour a thick bottom slab in concrete (with vertical anchors if needed), then lower progressively the water inside the pit while installing the supports.

4.2 Top-down

This alternative is faster in execution. The concept consists in working above and below ground concurrently, thus saving a large part of the period required to erect the structure below ground.

The contractor installs the sheet pile wall, and all the steel or concrete columns inside the perimeter of the building. Columns are founded on piles (deep foundations). Then the contractor pours a concrete slab on the ground level, the slab acting also as a strut.

From that moment on, the contractor can work on the structure above and below ground.

Excavation under a concrete deck, with low headroom, takes more time and is slightly more expensive than in the open cut method, but the time saved with this method can offset this disadvantage: the building is ready weeks or even months faster, so that the return on investment is faster.

4.3 Watertightness

Permanent retaining walls need to be watertight. No building owner accepts significant water ingress through the wall into the building. Steel sheet piles are per se impervious, so the only way water can find to pass through the wall is to percolate through the interlocks.

Larssen type interlocks are quite tight and impervious. In most situations, the gap inside the interlocks will fill up with thin particles and after a few weeks, the interlocks are almost 100% watertight.

However, for underground car parks and basements, it is advised to use an additional sealing system, so that the wall is impervious right from the beginning.

Several sealing systems exist [7]: bituminous fillers, compressive joints, waterswelling joints,… For underground structures reaching below groundwater level, the most efficient solution is to choose very wide sheet piles, install them as double piles with the common interlock seal-welded, and to seal-weld the threaded interlocks on site after excavation. It is more expensive than other sealing systems, but less risky. The other acceptable solution are compressive joints, such as the Akila® system, which are more robust and less prone to damage during handling and installation.

Using wider piles reduces the amount of interlocks per running meter of wall, thus reducing the water seepage into the excavation.

When an a quite impervious layer is quite shallow, it is reasonable to lengthen the sheet piles so that they penetrate the impervious layer. This can reduce drastically the amount of water seeping into the pit through the soil between the sheet pile walls.

Additionally, the connection of the bottom slab to the sheet pile wall has to be watertight. Typical details can be found in the literature, using either studs or steel rebars welded to the sheet piles, injection pipes around the perimeter of the wall, steel plates and membranes,…

The water seepage through sealed interlocks can be estimated quite accurately with a simple method that was developed by the laboratory of a Dutch university.

5. INSTALLATION

Installation of steel sheet piles in an urban area should avoid as much as technically feasible nuisances to the surroundings: vibrations and noise should be kept within a reasonable limit.

Another constraint in urban areas are settlements: foundations of adjacent buildings may be sensitive to large settlements, but it is also clear than any type of retaining wall leads to settlements.

5.1 Driving equipment

There are two efficient methods to install steel sheet piles in a city centre, but the best option depends on the soil conditions: resonance free – high frequency vibratory hammer and hydraulic presses. Hydraulic presses are usually limited to 15 to 20 m long sheet piles, whereas vibratory hammers can handle longer piles.

The advantage of hydraulic presses is that they do not generate any vibrations. Disadvantage is that the installation is more expensive, and the process less fast.

Additional aids can be used to reduce vibrations and noise, or to speed up installation: water-jetting and pre-drilling are quite proven aids, even in relatively compact soils. First tests with these methods were already completed in Europe in the 1970's.

The final choice of the driving equipment shall take into account all the constraints mentioned above.

5.2 Driving method

For permanent walls, the architect or the owner will regard aesthetics as a key parameter. In those cases, panel driving is the recommended installation method, using preferably the staggered sequence (see Chapter 11 of the *Piling Handbook* [8]).

First, a panel of a few sheet piles is threaded above ground, inside a two level rigid template. Then each sheet pile is driven in a specific sequence a few meters into the ground, in one direction, then the same procedure is repeated, but in the opposite direction, and so on until the sheet piles reach the final elevation. With this method, the sheet piles are guided on both sides, and never penetrate very deep into the ground without a lateral support. This improves drastically the installation accuracy of the wall: position and verticality.

6. SUSTAINABILITY

Sustainability considers three different aspects: financial, environmental and social. The overall cost of the structure will most often be the main criteria, but the trend is to add environmental and social criteria into the decision-making process. It is already the case in many tenders prepared for public authorities. The goal is to achieve a solution with the lowest possible negative environmental impact. The difficulty is to elaborate a fair system that weighs all the criteria. In some countries, environmental criteria can be monetized (transformed into a bonus or credit), so that the overall financial cost can be reduced by a certain amount of money. This final tab will be used to choose the most sustainable bid, and not the lowest bid as it used to be in the past.

6.1 Environmental impact

Most of the time, people talk and compare only carbon footprint, but it is clear that more elements have a negative impact on the environment, for instance energy consumption and water consumption. Additionally, the use of natural resources and the capability of reusing and recycling needs to be accounted for when comparing different solutions.

Steel can be either reused or recycled. Ideally, a steel product should be reused as many times as possible before being recycled.

The advantage of steel sheet piles is that they can be recycled at 100%, and when used only as a temporary element, they can be re-used up to 10 times before being scraped and recycled.

A Life Cycle Analysis (LCA) offer the opportunity to compare different solutions in a fiar manner, but it is important to compare the same functional unit of a structure. An LCA should be based on ISO standards, which define clearly how to calculate the environmental footprint of a product, a service or a solution. However, several software and databases can be used for this analysis, hence different results may be obtained for similar analysis.

A LCA should consider the manufacturing processes, transport, installation, use and maintenance phases, as well as deconstruction, re-use and recycling phases.

An Environmental Product Declaration (EPD) is an official document that provides reliable, peer-reviewed data that can be used in an LCA. An EPD should be worked out according to international standards, for instance ISO 14025 and EN 15804. The EPD can cover one or more products, produced in one or more facilities. It is always recommended to use the EPD from the manufacturer of the product that is purchased rather than a generic EPD. However, not all products are covered by specific EPD’s.

For steel sheet piles, similarly to most steel products, the major contribution to the environmental impact comes from the production phase. The contribution of all the other modules (transport, use, …) is rather small. It should be noted that re-use and recycling should in any case be considered in any LCA!

The findings of recent LCA’s made by ArcelorMittal were that for permanent retaining structures, provided the sheet piles are recycled at the end of the service life, their environmental impact is in most cases far below any other equivalent alternative. For temporary applications with reused sheet piles, this advantage is even stronger.

As an example, the EPD from ArcelorMittal’s sheet piles assumes that 30% of its production is reused five times, and that 99% of all sheet piles are recycled. Only 1% ends up in a landfill.

6.2 Durability

Steel in contact with water or humidity corrodes. Generally speaking, corrosion rates in a marine environment are higher than in natural soils.

Corrosion reduces the steel thickness, thus leading to a reduction of the section properties. Nevertheless, in natural soils, this reduction is quite small.

It is almost impossible to predict exact corrosion rates because these are influenced by the environment, which can also change during the service life. In some ports, corrosion rates have been monitored for years, so that it might be possible to take into account local conditions. Otherwise, it is advisable to consider corrosion rates from the literature, or to estimate them based on standards. There is a German standard that can be used for soil corrosion, but most often, required data to perform the assessment is not available, or not reliable enough.

Corrosion rates of standard soil and water environments are covered in Table 4.1 and 4.2 of EN 1993 – 5. Below an extract for natural soils.

Tab.1: Extract of EN 1993 – Part 5: 2007. Table 4.1 Loss of thickness (mm) per face due to corrosion of bearing piles and sheet piles in soils, with or without groundwater

Required design working life	5 years	25 years	50 years	75 years	100 years
Undisturbed natural soils (sand, silt, clay, schist…)	0.00	0.30	0.60	0.90	1.20
Non-compacted and non-aggressive fills (clay, schist, sand, silt…)	0.18	0.70	1.20	1.70	2.20

Note that corrosion rates in compacted fills are lower than those in non-compacted fills. In compacted fills the figures from *Tab.1* should be divided by a factor two.

The reduction of the section properties due to the loss of steel thickness can be estimated with a simple rule: it is proportional to the initial thickness. However, this rule is too conservative for Z-type sheet piles; the manufacturer can give more realistic values. A few design programs have implemented the simplified rule in their code, but for a design according to EN 1993 - 5, the software *Durability* [9] is quite convenient and user-friendly and considers more realistic values.

Coatings can be used on the interior to protect the steel surface from corroding, but coatings are mostly employed to improve the aesthetics of the wall. It is a fact that the rusty appearance of raw steel is quite often not well perceived by most persons, but there are some structures where the architect insisted on keeping the clean rusty surface visible.

6.3 Deconstruction

The total cost of ownership of a structure takes into account not only financial costs (interest rates), the cost of the design and execution, but also maintenance and deconstruction. After the service life, steel elements can be recycled, as it is nowadays the case. Remember that scrap has a non-negligible value. But if deconstruction is born in mind already during the design phase, then after the service life of the structure, most steel elements can be simply detached and reused in other buildings, before being eventually recycled at a later stage.

Steel sheet piles are the product per excellence for deconstruction and reuse: it can be easily extracted from the ground with vibratory hammers or hydraulic presses, and driven again and again on the same project, or in other locations.

6.4 Recycling

Steel can be recycled at 100% indefinitely. In fact, many steel products sold nowadays are already the fruit of one or more recycling processes. The quality of the steel is not negatively impacted by the recycling process. Actually, the steel quality of long steel products improves with each recycling process (production technology is much more efficient nowadays), and the yield strength of new steels is higher than it was a few decades ago.

Recycling also preserves our natural resources, by using scrap rather than iron ore and coke. Finally, steel is recycled in an electric arc furnace which consumes less energy than a blast furnace (for producing the same quantity of steel). Materials resulting from the recycling process, such as slags, can be used in different applications.

6.5 Traffic of construction vehicles

Congestion in city centres is a plague that many cities have not been able to solve yet. Steel sheet piles are prefabricated elements that are produced to length, and although they are quite heavy, their volume is relatively small compared to other alternatives. For the same retaining wall, alternative solutions need much more raw material (in volume), which are transported by trucks, hence they generate more traffic of trucks.

Additionally, steel sheet piles can be produced and delivered to the job-site on a just-in-time basis, reducing the amount of storage area at the job-site. Besides, installation does not require the replacing of soil by concrete, nor any treatment of spoiled soil. This in turn reduces again the traffic to and from the job-site, and its impact of the environment and traffic flow.

7. CONCLUSION

Steel sheet piles have been used for decades in underground car parks all over the world. One of the main hurdles to a broader use is fire design and potential nuisances, such as settlements, noise and vibrations during installation. Current innovative installation techniques, fire design methods, design software, sealing systems, etc offer new opportunities to overcome the bad perception of a permanent sheet pile retaining wall.

More and more underground car parks will be built in the future in very densely populated areas. Steel sheet piles walls are sustainable solutions for underground car parks up to 3 or 4 levels below grade.

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