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Steel Sheet Piles – Applications and Elementary Design Issues

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Abstract. High-intensity housing having been carried out in town's centres causes that many complex issues related to earthworks and foundations must be resolved. Project owners are required to ensure respective number of parking bays, which in turn demands 2-3 storeys of underground car parks. It is especially difficult to fulfil in dense buildings of old town areas where apart from engineering problems, very stringent requirements of heritage conservator supervision are also raised. The problems with ensuring stability of excavation sidewalls need to be, at the same time, dealt with analysis of foundations of neighbouring structures, and possible strengthening them at the stages of installing the excavation protection walls, progressing the excavations and constructing basement storeys. A separate problem refers to necessity of constructing underground storeys below the level of local groundwater. This requires long-term lowering of water table inside excavation while at possibly limited intervention in hydrological regime beyond the project in progress. In river valleys such "hoarding off" the excavation and cutting off groundwater leads to temporary or permanent disturbances of groundwater run-off and local swellings. Traditional way to protect vertical fault and simultaneously to cut-off groundwater inflow consists in application of steel sheet pilings. They enable to construct monolithic reinforced concrete structures of underground storeys thus ensuring both their tightness and high rigidity of foundation. Depending on situation, steel sheet pilings can be in retrieving or staying-in-place versions. This study deals with some selected aspects of engineering design and fabrication of sheet piling for deep excavations and underground parts of buildings.

1. Introduction – traditional solutions for deep excavations or trench shoring with sheet piling

Technological progress of recent years concerns both the steel sheet piles themselves („efficient" large-width profiles – Figure 1) and the methods of pushing them into ground (reducing the dynamic effects by application of static embedding the sheet piles – Figure 2) [1]. This study deals with some selected aspects of engineering design and fabrication of sheet piling for deep excavations and underground parts of buildings formerly presented in work [2][1].

It is impossible to list all important implementation of deep excavations over downtown areas. It has to be noted that construction boom from late 90-ties coincided with introducing modern methods of steel sheet pile embedding in Poland, which allowed to run works within inner core of city centres (Fig. 3) where the deep excavations always bring a risk of negative influence on neighbouring structures [3], [4]. The features offered by steel sheet piles are: flexibility of design constructions, fast execution, and in general, high profitability basing on full or partial material recovery.

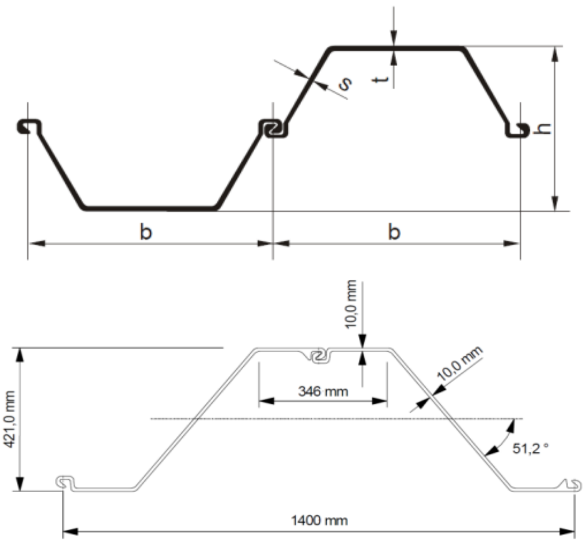


Figure 1. U-profiles and Z-profiles

Figure 2. Press-in method

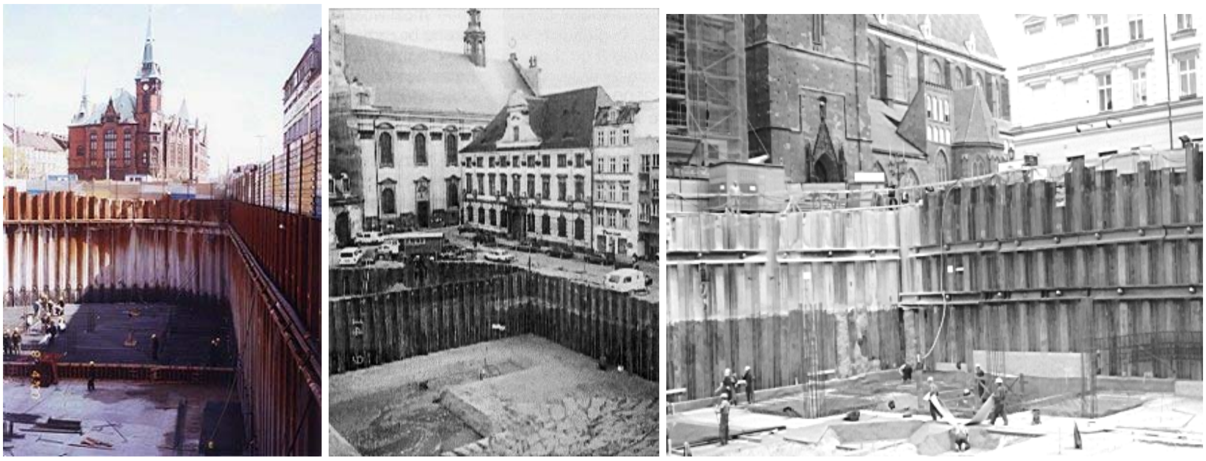


Figure 3. Wroclaw experience – deep excavations in historical city centre

2. Modern methods of steel sheet pile applications

Though one of the main tasks of sheet piles was, is now and will be to withstand the earth pressure, they can be also used, in some situations, to transfer vertical loads. At present an explicit trend is observed that sheet pile walls are used as foundation elements which transfer loads from structure to subsoil. Many bridge structures have been completed so far where the steel wall of abutment transfer the loads from travelling beams. The methods of calculating and controlling the vertical bearing capacity of sheet piles were developed [5].

There are some cases (which become more and more frequent) that piles and steel sheet piles are used in other durable structures. These are, to name a few, the following:

- footbridges founded on bulkheads out of flat steel sheet piles;
- tunnels and semi-tunnels (Fig. 4) where steel sheet piles in a cantilever arrangement, anchored or expanded, are the element of steel/concrete tunnel shoring united with its bottom;
- tunnels and semi-tunnels where steel sheet piles in single- or double-row, of cantilever, anchored and/or expanded arrangement are used as a permanent final shoring of communication excavations, or at the same time as excavation shoring and support/abutment of overbridges;

- embankments of approaches to engineering structures in enclosure out of steel walls, either cantilever or braced;
- railway and road overbridges with various static schemes, which abutments and possibly the piers are constructed out of steel sheet piles as palisades (combination of H-type profiles and steel sheet piles – Fig. 5).

Figure 4. Railway tunnel opening in Lipsk

Figure 5. Sheet piles as foundation elements – overbridge in Swarzędz

Even more radical idea is to use sheet piling as final underground walls of buildings. Such solution frequently used in tunnel works (entrances), now due to developments in sheet pile fabrication technology, is used in construction of basement car parks. However, due to the pushback of design engineers, there are a small number of such implementations, nevertheless the facilities completed so far behave well and they do not give rise to any objections and are a good reference and a source of inspiration for the future.

Walls out of steel sheet piles as permanent shoring and for foundations of various structures are generally much more used over the world than in Poland. It is greatly dependent on local tradition. For example:

- steel sheet pilings are used as a shoring for most excavations in Holland, Germany and Denmark, i.e. in countries which also lead in development of design methods for such type of construction,
- pressed-in steel sheet piles are used on a massive scale (much higher than that in Europe) in Japan – the country haunted by earthquakes where impact and vibrating methods for sheet pile seating are not socially acceptable.

The above, inevitable very short, presentation clearly shows the potential still existing in Poland for wide and various applications of steel sheet pilings as walls and foundations of permanent structures, especially in areas of limited access, so mainly in urban conditions.

Table 1. Thickness reduction in steel profiles, in mm acc. to Tables 4.1 and 4.2, EN 1993-5 (2003).

Design time of structure usage [years]	5	25	50	75	100
	Thickness reduction of steel profiles [mm]				
Undisturbed natural soils (sands, clays)	0.00	0.30	0.60	0.90	1.20
Normal fresh water: water table line	0.15	0.55	0.90	1.15	1.40
Sea water: full submersion & rippling zone	0.25	0.90	1.75	2.60	3.50
Sea water: splashing and low water level zone	0.55	1.90	3.75	5.60	7.50

In relation to steel walls as the permanent construction elements, often the problem of sheet pile durability is raised. In general, durability is affected by environmental conditions (corrosion-related), which need to be reviewed as compared with design durability of the whole structure.

Figure 6. Steel sheet piles in foundation of a bridge in Poland (beginning of XX century structure)

As early as at design stage, it is possible to envisage: zinc coatings; paint coats; „duplex" coating, and use corrosion-resistant steels or to provide respective allowance for possible corrosion. Existing structures are properly maintained, at accessible areas by maintenance operations such as sealing, coatings. Corrosion losses in natural soils are negligible and corrosion of steel submersed in sweat water is at low level (Fig. 6). The issues can be with steel corrosion in sea water, especially in variable water level zone, however such phenomenon is absent in deep excavations.

3. Main design issues

This text of limited volume is just an introduction to the subject dealing with application of steel walls in town centre areas, hence the most difficult problems related to design work will be barely mentioned and shortly commented basing on experience. In order to design sheet pile walls we need to determine the necessary depth of penetration, maximum bending moment (i.e. to select proper profile of steel sheet pile) and to calculate the forces in anchorages or struts, in so far as they are present. The known and common methods used to calculate pressure on retaining structures fixed in soil are based on vary different assumptions and usually lead to divergent results. For example, in traditional design methods for sheet pilings, generally no their distortion is analysed, neither the effect of excavation on surroundings. Numerical methods provide better overview of soil-structure interaction. Already the first computer programs based on solutions of beams on elastic supports enabled to estimate horizontal displacements of walls. Further on, specialist geotechnical software based on Finite Element Method (FEM) and other ones (like MEB, MRS) enabled full analysis of excavation shoring distortion and the land surface behind retaining wall [6]. For various reasons, these are however not in common use because advanced calculation procedure does not provide results of higher credibility level than the data applied. Hence, designing the excavation shoring with sheet piling needs experience while a series of risk factors causes that current coordination is needed for work execution so as possibly changes can be introduced to design documentation.

There is now a separate group of methods supporting design work like so called observation method [7]. It consists in application of quite simple solutions and models, which however are accompanying by current correction of design assumptions basing on deformation observed during project progressing [7]. In this way we avoid dramatic discrepancies between forecast and real behaviour of the structure. This design method is also not free of disadvantages. Due to unforeseen situation, planning and arranging the building process are here hindered, e.g. preparing the reliable time and payment schedule, not to mention the procedural requirements of construction law.

In each case, a continued communication between supervision, management at site and design agency is necessary to allow current updating the project assumptions. In case of large geotechnical contracts, the best solution is to make use of a design team of experienced contractor (design-and-construct system). The competence injunctions are thus reduced and the responsibility clearly established. It is of great importance as there are no design (calculation) standards for sheet pile shoring. Excavation safety, at design stage, depends on the following:

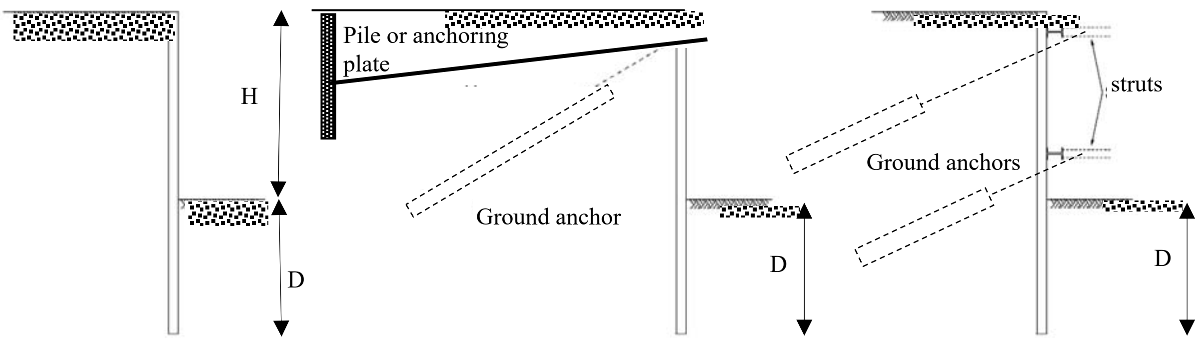
- proper selection of static scheme and determination of the excavation affected zone,
- properly determination of geotechnical characteristics used to calculate earth pressures and passive pressures, and safe estimation of surcharge load from construction site arrangement or from adjacent buildings,
- proper selection of shoring elements (indicators, steel grades, type of sheet piles) – due to their loading capacity (also in vertical direction), flexibility, expected deformations (including possible slip on interlocking joints) and chance to be built-in.
- forecast of short and long-term phenomena related to works progressed and – ultimately – related to presence of the building under design.

Hereunder, there are some detailed notes dealing with aforementioned issues.

3.1. Static schemes of sheet pilings

Depending on excavation depth, possible immersion of the wall below the designed bottom of excavation, possibility of using struts of anchorages, assumed limitations as concerns wall displacements and, finally, the necessity to cut off water inflow into excavations, various static schemes are assumed (Figure 7). In case of cantilever scheme, we always must expect that the wall must be embedded deeply below final bottom of excavation. Cantilever walls subject to strong bending and are experienced by considerable horizontal displacements, hence they are rarely used close to other structures or installations. For the sake of operating principle, they are extremely sensitive to their insufficient embedding (when it is impossible to immerse the sheet piles to the required depth) or to excessive depth of excavation. These two situations result in reduction of fixing depth being the only factor which makes the wall stable.

Publications often provide experience that cantilever walls or cantilever stages of walls, which finally are anchored or provided with struts, suffer breakdowns. In case of cantilever walls, the preliminary excavations and temporary earth slopes inside the excavation are often used. Such solutions can be used only when the work progressing is ensured strictly in line with the design (phased execution, geometry of slopes). Unfortunately, there are numerous cases of failures when earth works inside excavation are run inconsistently with design (reduction of earth slopes, steep and loaded slopes of preliminary excavations).



Cantilever scheme – wall secured in soil | Single anchorage or strut (various levels of immersion D below excavation bottom) | Walls with multiple anchorages or struts

Figure 7. Static schemes of sheet pile walls

Figure 8. Steel walls with single strut (final wall of tunnel) and anchored (excavation shoring)

Single anchored or strut walls (Figure 8) are designed by calculating the necessary depth below excavation bottom, required strength of sheet pile to bending force and the forces in anchors or struts. Traditional approach to designing the sheet pilings, not covered by any standard, provides a difficult-to-read picture of static calculations and the scale of simplifications made. The reason is the change of physical quantities – more or less subjective:

- reduction of passive earth pressure,
- neglecting the friction at wall-to-earth contact,
- increasing the depth of wall embedding,
- assuming the force in anchorage higher than that resulting from calculations.

Furthermore, we need to take into account the fact that quantities given for execution are frequently much higher than those calculated. This can result from:

- extending the wall below excavation bottom forced by necessity to limit water inflow under the wall and to eliminate depression around the excavation,
- application of steel profile which is dependent of embedding it to the design depth but not the bending strength,
- application of steel with relatively low strength, which forces that higher bending factor need to be assumed and also ensures higher rigidity of wall (it is not "economical" approach but light sheet piles out of good steel may lead to excessive wall deformation),
- application of struts or anchorages with strength much higher than those from calculations (to reduce displacements).

Designing the walls with multiple anchors or struts requires specialist software, experience and a skill of evaluating the safety of excavation shoring at all stages of execution. In case of walls with multiple anchorages, the conditions of total stability and schemes of soil displacement at excavation bottom are of large importance.

3.2. Data for static calculations of shoring out of sheet pile walls.

Static calculations of sheet pilings are run basing on values of pressure and passive earth pressure depending on geotechnical characteristics, wall geometry and surcharge loading conditions. Thus, proper geotechnical identification is a key factor for safety of calculations. The purposes of geotechnical investigations specify how accurate they should be. The range of identification was regulated by ordinance of the Minister of Internal Affairs and Administration (1998) which introduced the notion of geotechnical category. In case of deep excavations this is most often the second (or third) category. Paradoxically, the full range of identification cannot be determined prior initial determination of the scope of protecting works (wall depth, locations of anchorages). Therefore, subsoil identification works are made in stages. Initial testing is to determine the static scheme and conception of wall-relate and anchorage-related works. Detailed testing is crucial for designing the foundation for the structure and for selecting the method of execution (machines to be used). Unfortunately, geotechnical documentation to be used in design of excavation protection wall is often excluded from the responsibility of structural engineer and entrusted to geologists. This leads to a series of errors in programming the subsoil investigations. The most flagrant deficiencies are:

- restricting the scope of field works to the minimum, which leads to over-interpreting the information gained and to geotechnical omissions,
- large number of shallow holes on the object projection (useless for designing the shoring),
- bad arrangement of holes over the object projection (e.g. omission the area beyond foundation contour, in the zone where earth anchorages will be made),
- omitting in laboratory testing the soils regarded as weak, for which no detailed description is provided and no geotechnical characteristic are determined (such soils are indeed removed from excavation, but remain behind the wall and give pressure which are difficult to estimate).

Errors in carrying out field testing are generally the following:

- clutching tightly the scope of work as contracted, which often restricts the chance to determine accurately the reach of weak soils both in plane and in depth,
- finishing drilling in weak soils, thus making the investigations useless in designing or leads to considerable over-dimensioning for the foundation elements,
- improper execution of boreholes – making the boring without piping, which gives a false image of water relations and condition of soils (especially cohesive ones).

Errors occurring at the stage of laboratory testing and workshop work result from:

- executing laboratory tests which do not correspond to the needs of standards,
- omitting determination the features of soils recognized as weak: fills, silts, peats, which makes impossible to design their strengthening and to calculate the earth pressures.

3.3. Considering the influence of wall flexibility.

Extensive review and discussion about various designing methods for sheet pile walls, considering their flexibility, was published by Bjerrum, Frimann-Clausen and Duncan over 40 years ago [9]. It was a presentation of history and current status of knowledge in this field. They draw attention to large discrepancies between bending moments calculated by commonly used methods due to assuming extremely different design assumptions. Model testing shows occurrence of so called spanning – concentrations of pressures at points of anchorages and below excavation bottom while simultaneously the pressure is reduced along wall length, where its deflection is possible.

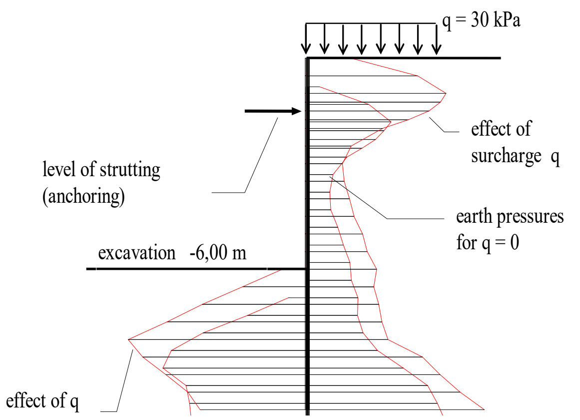


Figure 9. Concentration of soil pressures at the level of strutting or anchorage specific for walls with low rigidity (sheet pilings).

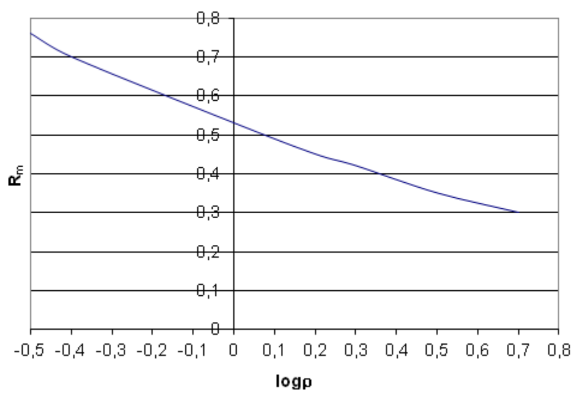


Figure 10. Reduction factor R_m for moments from soil pressures.

Model tests show reduction of bending moment, which can be as low as 30% of the value calculated on the basis of limiting pressures. What need to be stressed, possible reduction of bending moment can be accompanied by essential growth of force in anchorage and therefore – in economic terms – they should be jointly examined. The discussion about the effect of wall stiffness on determined bending moments (so consequently on the protection costs) was given in publications of Rowe [10] who dealt with single-anchored walls. The measure of wall rigidness is $log(\rho)$, where the parameter $\rho = H^4/EI$ is expressed in m^3/kN (H – wall length). The moment which is considered in calculations of necessary wall factor is $M=R_m \cdot M_{max}$. For the most frequent values of parameter $log\rho = log(H^4/EI)$ equal from -0.5 to 1.3 (in International System of Units, where H [m], EI [kNm^2/m]), the reduction of wall bending moments with respect M_{max} (for the scheme with wall not fixed in soil) can be estimated to 25-70%. Example of the diagram for reduction factor R_m for pressures from non-cohesive soils is given in the figure 10.

In case of cohesive soils, such redistribution of pressures on flexible structures leads to reduction of bending moment by up to 40%. Reduction refers to the moments from soil pressure only (pressures from water are not reduced). If wall flexibility is taken into account during calculations, more accurate determination is possible for bending moments and designing process is more cost-effective.

3.4. Selecting the sheet piles – problem of low rigidity of sheet piles out of high-strength steel.
A successive way to reduce the cost of shoring composed of sheet pilings is to use the sheet piles made of higher-strength steel. They allow to use lighter profiles. However, each time they should be examined for possible embedding and estimated for deformations of unearthed wall (also as concerns redistribution of soil pressures towards struts and anchorages.

3.5. Calculating and verifying the bearing capacity to pressing.
Vertical load bearing capacity of sheet piling (to pressing) depends on resistances generated at the basis and on the side surface of sheet piles. Here, we need to mention that the soil ground cork is created between arms of sheet piles immersed. For this reason, type Z sheet piles should be immersed with hammer or vibrating hammer in pairs. This is clearly shown in figure from „Fascicule 62 Titre V" – the publication of LCPC in Paris.

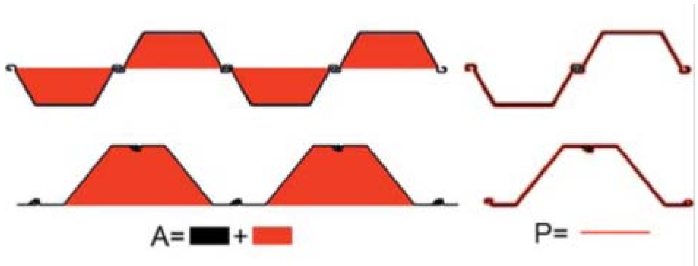


Figure 11. Surface area of base A and side surface P (measured along the circumference) assumed for calculations, sheet piles type U in upper row and type U in lower row

An important factor affecting the piling capacity is the embedding technology. Coefficients considered in calculating the vertical capacity given in French recommendations were determined for walls immersed with pile-driver as this document is the result of correlation between trial loads of so immersed sheet piles and in-situ tests made at point of immersion. In 2002, trial loads were carried out for walls being vibration-immersed and driven. The largest differences of vertical capacity were about 50% in favour of driving method. Hence, proposal was made to reduce the bearing capacity for base and side surface of vibration-immersed sheet piles calculated on the basis of „Fascicule" by 50% and 30% respectively. The vertical bearing capacity of sheet piles embedded by means of vibrating hammer can be increased by driving them in for the last 2 or 3 metres of the pile. Worth mentioning is that the sheet piles immersed by means of static pressing have the vertical capacity comparable with that of being driven in. This is the result of mobilizing friction at side surface during pressing in the sheet piles. The most credible way to estimate the vertical bearing capacity of vertical sheet pilings is to carry out trial load. It should be borne in mind to load the sheet piles which are not connected with adjacent ones via interlocking joints. The point is that the effect of friction in interlocking joint of loaded and unloaded sheet piles does not affect the results of trial loading. Hence, it is recommended to immerse additional sheet piles at the same soil conditions, i.e. close to the wall which will be a part of the structure under construction. The other solution (which is a little more complicated in technical aspects) is to tear out the adjacent sheet piles for the time of trial loading, and the re-immerse them again after trial load testing.

Testing the vertical bearing capacity of sheet piles, type AZ37-700 D, in construction of retain wall RC21 at construction site of the S8 throughway, Armia Krajowa Route, in Warsaw. The trial load of the separate sheet pile, type AZ37-700D, gave the design capacity for pressing of 1212 kN what means that the admissible load for pressing in the sheet piling is about 866 kN/m. In fact, the bearing capacity of continuous wall is higher due to higher capacity of the base (soil spanning). The settlement corresponding to the design vertical capacity of paired sheet pile was 2.80 mm.

4. Summary: Advantages and limitations of sheet pile walls.

Steel sheet piles are commonly used to protect deep excavations. Modern methods of designing and monitoring the quality of works are available now. The advantages of steel sheet piles worth to emphasise are as follows:

- they can be easily transported and installed using up-to-date and highly efficient equipment for driving them in, vibration pressing and pressing; (reduction of work scope at foundation construction area – starting from the moment when material unloading is completed, the construction site is occupied just by pile driver or pressing machine with a crane which handle the sheet piles;
- sheet pilings have quite flexible work schedule – there is no risk related unplanned downtime; sheet piles can be pulled out and driven in again;
- when the steel sheet piles can be retrieved, the costs are substantially reduced and the project impact on environment is limited as the water relations can be regenerated totally or to considerable extent (limitation of damming);
- they can be easily joint together; the profiles, length, level of wall crown and the shape of footprint of future excavation can be flexibly selected;
- when transfer of vertical forces is planned, they have high bearing capacity at low settlement; after they are driven in immediate loads can be applied;
- they have high durability, proved in practice, also under severe conditions of use; observations made for over a hundred-year-old embankments or equally old communication structures allow to say that steel elements in soil ensure sufficient durability in adverse environmental conditions, often without proper maintenance;
- they ensure clean site area, and – what is important – limit traffic of heavy vehicles (concrete mixer vehicles) because steel sheet piles are delivered with one transport.

Application of steel sheet piles have also some constraints:

- Steel sheet piles have limited length, which results both from transportation reasons and from limited height of pile-driver masts. In special cases, this may cause necessity to “lengthen” the wall of sheet piles by means of palisade of injection piles. Such solutions have already been successfully implemented.
- Occasionally, it is impossible to immerse the sheet piles with conventional methods. Then, drilling or water jetting is necessary to assist in immersing. Such actions reduce soil strength at contact with the wall and can cause higher pressures than those in design assumptions.
- Steel sheet piles can, when they encounter obstacles in soil, be destroyed or partially disconnected in interlocking joints. When the wall shall pay the role of sheet piling, a “window” is then created and the ground water will flow into the excavation.

In congested housing, deep excavations may adversely affect close surroundings by:

- lowering the land adjacent to excavation and settlement resulted from possible depression cone when walls protecting deep excavation did not reach non-permeable layers (affected are buildings and infrastructure),
- dynamic effects transmitted to neighbourhood during works,
- soil distressing due to unloading the excavation bottom level.

These last phenomena are described in detail in Polish ITB Instruction No. 376/2002 [10]. All available techniques of steel piles and sheet piles embedding in towns (also by means of driving in and vibration driving) are possible provided the surroundings subjects to continuous monitoring referring the impact of the works, and provided the project progressed is accompanied by a proper information action. Commonly available measuring instruments with recorders and fast analysing method for measurement results enable to run measurements continuously, and they frequently allow to ensure automatic work suspension if the acceptable vibration level is exceeded. The aforementioned issues do not fully exhaust the subject of designing and executing steel sheet pile walls. The author is going to provide a review of problems, which need to be taken into account by a cognizant design engineer dealing with shoring of deep excavations.

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