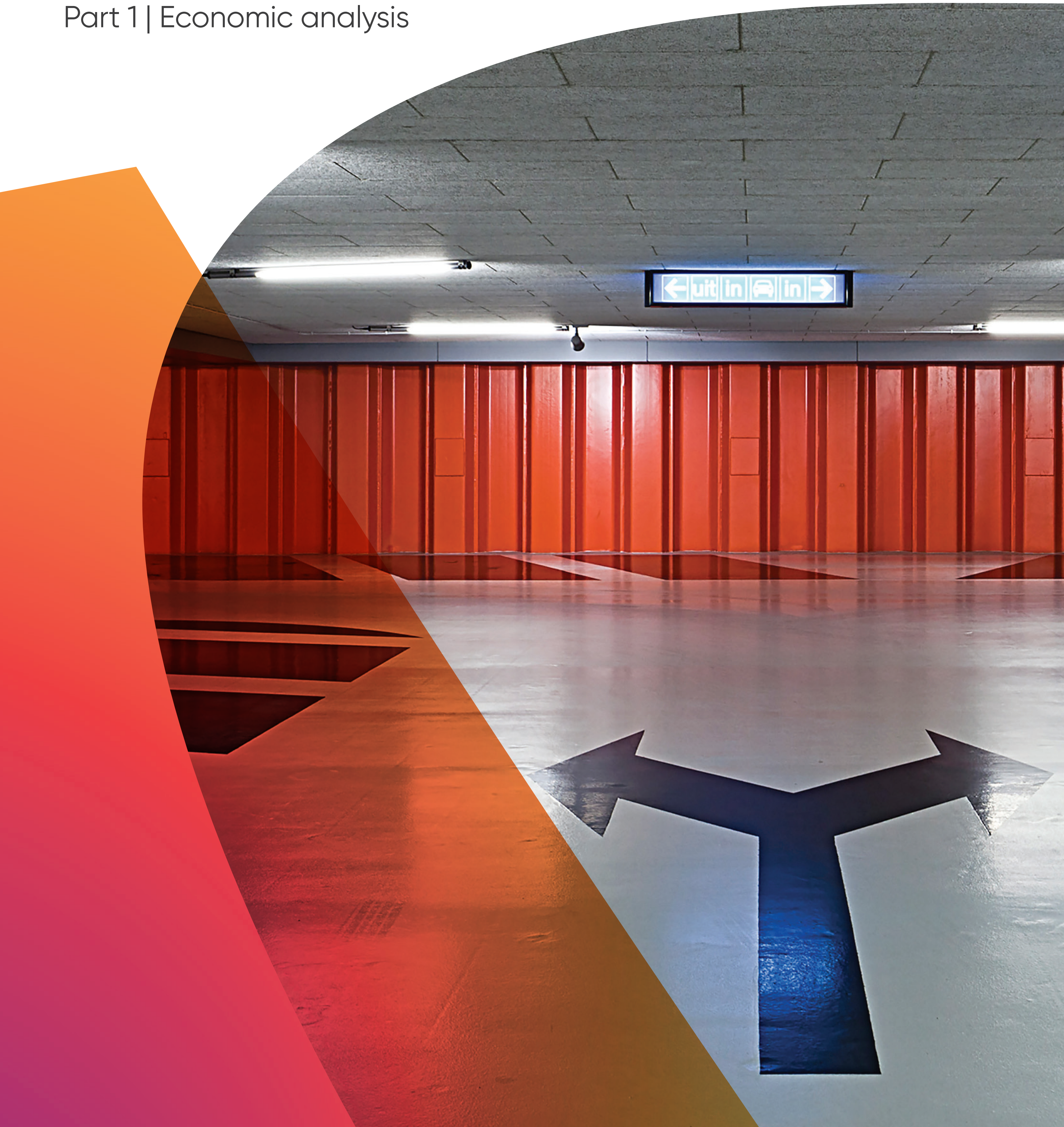
ArcelorMittal Sheet Piling

ArcelorMittal

Underground car parks

Comparative study | Germany

Part 1 | Economic analysis



Note

The economic analysis was performed in 2023 by the German consulting engineer GRBV Ingenieure im Bauwesen on behalf of ArcelorMittal. The design assumptions were determined for an underground car park in soil conditions typical of northern Germany.

ArcelorMittal emphasises that GRBV has carried out an objective and unbiased case study. The analysis is a purely hypothetical case study with limitations in terms of the reliability of costs and procedures, as these aspects can vary (greatly) in different markets and/or subsoils.

This case study is not a project-specific design. Therefore, neither ArcelorMittal nor GRBV engineers can be held responsible for decisions made in specific projects based on the design or conclusions of the report prepared by GRBV.

The text in this brochure is a summary of the report. It has been edited in order to focus on the most important points of the report with a minimum of technical explanations. Although the content and conclusions are consistent with the original report, ArcelorMittal engineers have added some remarks and comments to complement the information contained in the original report. Some figures, tables and sketches have been edited, removed or replaced with new ones prepared by ArcelorMittal. In the case of transcription errors, only the text and other elements from the original report by GRBV are binding.

The original GRBV report is available on request.

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Part 1 - Economic analysis

Urban development faces many challenges, as the population in cities is growing faster than the available (affordable) living space. Large cities are struggling to find a balance between growth and the well-being of their citizens. Noise and traffic jams near job sites are also a negative aspect of construction, so that once a new construction project has started, the execution time is an important indicator that should be taken into account as early as the planning phase. Steel components have the advantage that they are delivered to the construction site as prefabricated elements, can be installed quickly and exposed to loads immediately. Experience shows that the speed of execution for steel elements, such as sheet pile walls, can be twice as high as for other building materials. Nowadays, construction costs are no longer the only factor that needs to be taken into account. In some countries, ecological and social criteria are already being implemented in the tendering process, especially in public tenders.

In 2022, ArcelorMittal commissioned the **German engineering office GRBV Ingenieure im Bauwesen** to look into this issue and compare **several alternatives for the construction of the outer wall of underground car parks** under average ground conditions and with a shallow groundwater table. The case study looks at a two-storey underground car park built using the standard bottom-up method. This involves constructing a supported wall with a concrete floor slab cast under water.

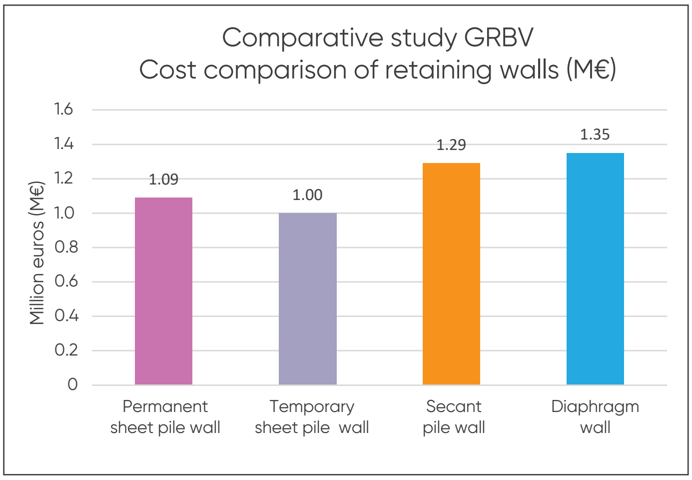
In a second phase, a **life cycle analysis** (LCA) will be carried out on the basis of the results of this case study in order to include the CO2footprint in the selection of the solution that leads to the lowest **total life cycle costs**, including the end-of-life impacts or benefits (demolition, recycling of building components). The LCA will be reviewed by an independent expert. We believe that a Life Cycle Assessment is a fair and transparent method for comparing different solutions and materials, preferably based on specific **environmental product declarations** (EPDs) from manufacturers rather than generic data from databases.

When choosing a solution, several key indicators must be taken into account, the most important of which is the construction cost (including design). The cost indicator from the analysis carried out by GRBV is summarised in the table below. The case study refers to an underground car park with two levels, but the results would be fairly similar for a three-storey underground car park. Please note that the conclusions cannot simply be applied to other situations or countries.

The **sheet pile wall is the most cost-effective solution. The difference is approximately 18%** compared to the bored pile wall and about 24% compared to the diaphragm wall. A temporary sheet pile wall solution was also considered.

Cost	Permanent sheet pile wall	Temporary sheet pile wall	Secant pile wall	Diaphragm wall
M€	1.09	1.00	1.29	1.35
Difference	Referenzwert	- 8%	+ 18%	+ 24%

M€ = Million Euro



In this case study, the steel sheet piling solution for the retaining wall of the two-level underground car park is at least 18% more cost-effective.

1. Introduction

As a rule, an excavation pit with retaining walls is built for the construction of an underground car park. The choice of retaining type normally depends on the given boundary conditions, such as soil conditions, groundwater level, excavation pit depth, logistical conditions and loads. Within the excavation pit, the underground car park is then built with reinforced concrete walls. The selected retaining wall either remains in the ground or is pulled out again if possible (only possible with sheet pile walls/soldier pile walls).

The procedure described is a common method and proven construction technique for the construction of underground car parks under certain boundary conditions. In terms of sustainability, resource conservation, space gain and cost-effectiveness, shoring walls offer further optimisation possibilities as permanent wall systems.

The following wall systems are to be investigated and compared with regard to the points described:

- V1: Sheet pile wall, permanent;
- V2: Sheet pile wall, temporary (only as an excavation pit wall);
- V3: secant bored pile wall, permanent;
- V4: diaphragm wall, permanent.

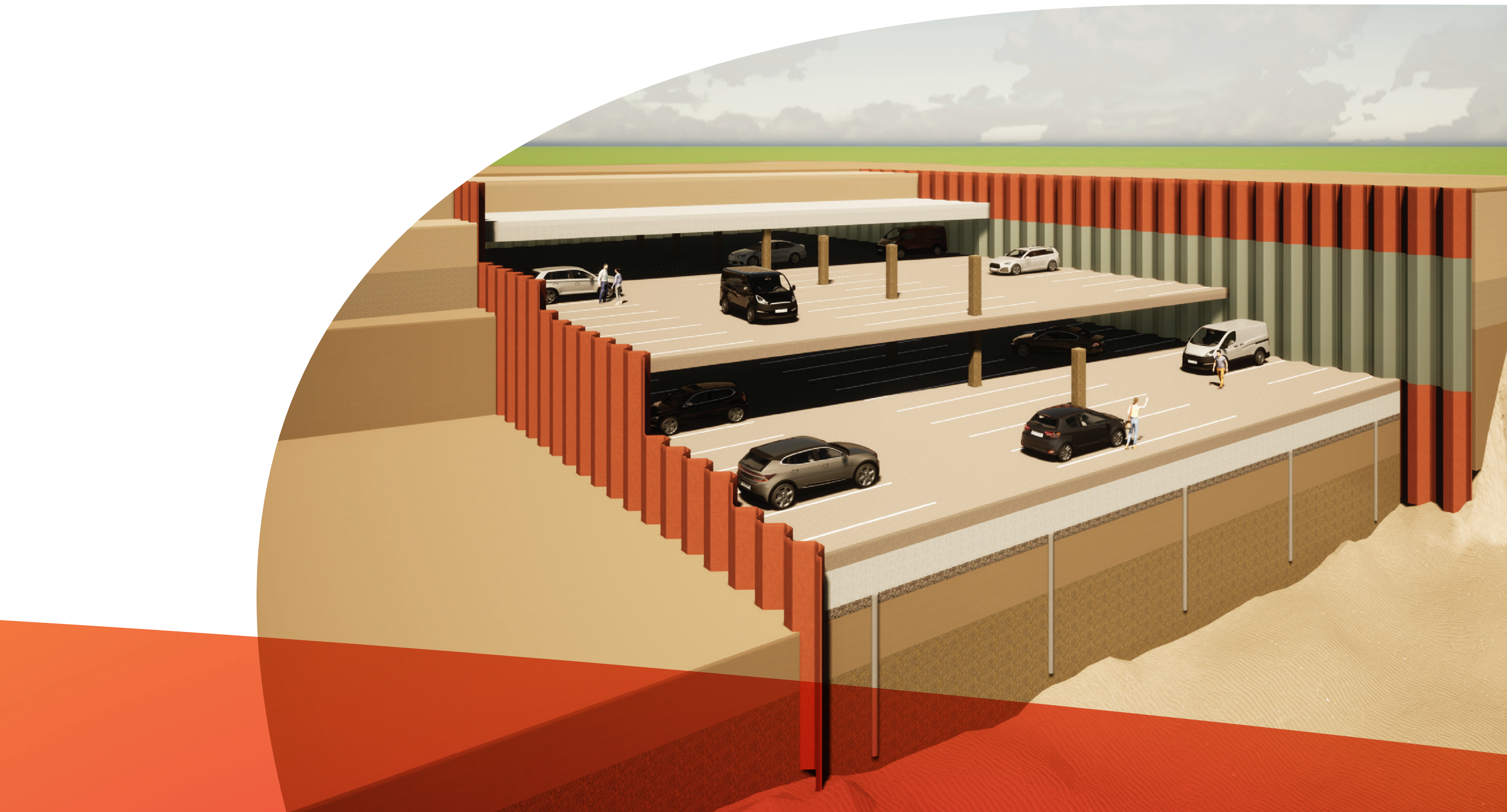
During the study, the boundary conditions such as geometry, soil parameters, water level and excavation pit base are assumed to be the same for all wall systems. An inner-city development with neighbouring buildings is selected as an example project.

The plot to be developed has a rectangular layout measuring 28 x 50 m. The new building is planned as a 4-storey building with a 2-storey underground car park.

The service life for buildings and underground car parks made of reinforced concrete is 50 years. The selected permanent wall systems must meet this requirement as a minimum.

The scope of the work consisted of designing various alternatives and comparing the construction costs of the walls, taking into account financial aspects related to the speed of execution.

The quantity determination obtained in this project serves as input for a subsequent life cycle analysis (part of another project).



2. Boundary conditions

2.1. Geometry/components

The construction site to be planned has an area of 28 x 50 m. The new building is to be constructed on an area of 28 x 28 m. The underground car park comprises two floors, each with a clear room height of 2.70 m.
In this example, the groundwater table is assumed to be just below ground level. This means that an underwater concrete base is required for the excavation pit and the construction of the underground car park. The underwater concrete base ensures that that no water can penetrate the excavation pit from below during construction work.
In addition, the base and the the micro-injected piles integrated therein absorb the uplift pressure caused by the drainage of the excavation pit. For the design, a 1.40 m thick concrete base plus a 30 cm levelling/drainage layer is assumed. To allow for tolerances during excavation, another 30 cm is deducted. For the calculation of the individual systems, the underwater concrete base and the grouted piles have no influence on the results (boundary conditions are assumed to be the same for all systems).
See Figure 2-1: Schematic section of the of underground car park.

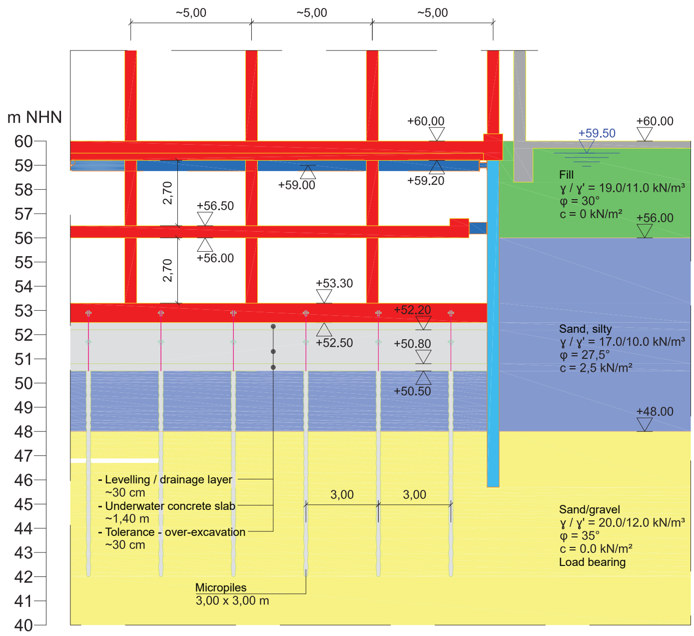


Figure 2-1: Schematic section of the of underground car park.

2.2. Construction phases

The following sequence of execution is specified for the construction work:

1. Construction of retaining wall depending on the selected construction method
   a. V1 - Permanent sheet pile wall:
      i. Predrilling along the pile driving line
      ii. Pressing/vibrating the sheet pile walls
   b. V2 - Temporary sheet pile wall:
      i. Predrilling of the pile driving route
      ii. Pressing/vibrating the sheet pile walls
   c. V3 - Bored pile wall:
      i. Construction of bored piles including concreting and reinforcement (further steps only after the concrete has hardened)
   d. V4 - Diaphragm wall:
      i. Construction of the diaphragm wall including concreting and reinforcement (further steps only after the concrete has hardened)
2. Installation of strutting system at +59.00 m above sea level (preceded by: preliminary excavation to +58.50 m above sea level + parallel lowering of groundwater to +58.00 m above sea level)
3. Underwater excavation to +50.50 m above sea level
4. Installation of underwater concrete slab including levelling layer, buoyancy piles and drainage layer+ Draining of the excavation pit to +50.50 mNHN
5. Concreting of basement floor U2, columns, ceiling above U2, temporary strutting of ceiling above U2 to retaining wall (→ not for «V2 sheet pile wall temporary»), removal of temporary strutting layer
6. Concrete pouring of columns, ceiling above U1 including reinforced concrete connection to sheet pile wall (→ not for «V2 temporary sheet pile wall») removal of temporary sheet pile walls (V2).

2.3. Subsoil conditions

A standard, average soil profile with the following layers is selected for the building site:

1. Fill
2. Silt layer, non-load-bearing
3. Sand/gravel mixture, load-bearing

The soil parameters for the individual layers are specified in Table 2-1.

Layer	Nbr.	Tip of layer	Weight		Friction angle	Cohesion	Peak resistance cone penetration
			[kN/m³]		$\varphi_{k'}$	$c_{k'}$ / $c_{u,k}$	q_c
		[mNHN]	γ	γ'	[°]	[kN/m²]	[MN/m²]
Fill	1	+56.00	19	11	30	-	5
Silty layer	2	+48.00	17	10	27.5	2.5	5
Sand-gravel mix	3	from +48.00	20	12	35	-	15

Table 2-1: Soil parameters.

2.4. Hydrological data

The design water level is +59.50 m above sea level and must be lowered in the excavation pit. The lowering will take place in phases during the individual construction steps.

After the underwater concrete slab (UWS) has been constructed, the excavation pit water level is at the level of the bottom of that slab at +50.50 mNHN.

2.5. Design assumptions

2.5.1. Loads

After completion of the underground car park, the 4-storey building will be constructed. The resulting vertical loads are transferred to the subsoil via the external walls and columns. This means that the retaining will also be subject to vertical loads in its final state, with the exception of the temporary sheet pile wall. The vertical load is specified as a distributed load with N_k = 350 kN/m.

Due to the nearby neighbouring buildings, the retaining is directly adjacent to the existing structure. The neighbouring buildings are built on shallow strip foundations.

The bottom of the strip foundation is at +58.00 mNHN and has a width of 1.0 m. The top of the floor of the neighbouring building is at +60.00 mNHN.

The foundation load was determined assuming the dimensions and materials of the existing building with G_k = 350 kN/m.

In addition, a load of p_k = 5 kN/m² is applied at ground level from the rear edge of the existing neighbouring foundation. This covers the load from the dead weight of the floor slab and other surcharge loads.

2.5.2. Technical regulations

The standards, recommendations and guidelines used can be found in Chapter 7 «References».

2.5.3. Partial safety factors

The partial safety factors for the design of the retaining walls are taken from EC7 (DIN EN 1997-1), Tables A 2.1 and A 2.3 or the EAB, Tables A 6.1 and A 6.2.

According to EC7-1 and DIN 1054 (2010), temporary structures are to be classified in the design situation BS-T and permanent structures in BS-P. For the present investigation, the diaphragm wall and bored pile wall are examined as permanent structures. The sheet pile wall is examined as both a permanent structure and a temporary structure.

2.5.4. Toe support

The toe support of the wall is determined within the design software depending on the selected length and the structural requirements.

2.5.5. Deformation

During the construction of retaining walls, system-related deformations in the ground behind and in front of the wall are to be expected.

According to EAB, sheet pile walls are considered to be flexible and bored pile walls and diaphragm walls are considered to be rigid structures. The rigid structures are also considered to have low deformation.

Experience shows that approximately 50% of the horizontal deformations indicated in the static calculation occur. Horizontal deformations in the ground always result in vertical deformations.

For the flexible construction (permanent and temporary sheet pile wall), the critical design sections are additionally calculated with the partial safety factor γ = 1.0 to determine the realistic deformation.

Results with high deformation are referred to as critical design sections. The deformations in the area of the existing foundations up to approx. 0.5 m below the lower edge (+57.50 mNHN) are limited to a maximum of 30 mm in order to prevent damage to the neighbouring building.

2.5.6. Durability

In order to be able to use the excavation pit walls as exterior walls in the basement, the individual types of retaining walls must meet the requirements for permanent structures depending on their use.

In addition to stability and load-bearing capacity, the durability of the chosen solution must also be ensured over the planned service life of 50 years for underground car parks in accordance with DIN 1045 and DIN EN 1990.
In general, durability describes the resistance of components to external influences in order to ensure their load-bearing capacity during the required service life. External influences include, for example, heat, cold, moisture and chemical or microbiological attacks. The durability requirements for steel wall types differ fundamentally from those for reinforced concrete.

2.5.7. Software

The computer calculation is performed using the GGU-Retain software, version 11.21, by Prof. Dr.-Ing. Johann Buß and various Microsoft Excel tables. The geotechnical verifications are carried out within the software and are not shown separately.

2.6. Constructive measures

2.6.1. Waterthightness

Due to the presence of groundwater, measures are required to drain the excavation pit. Either groundwater can be lowered or the excavation pit must be constructed as a watertight trough excavation pit. In inner-city areas, groundwater lowering is out of the question due to neighbouring buildings and the associated risks, such as settlement. In a trough excavation, the water is pumped out of the pit, which is why almost watertight walls and a watertight base with a sealed connection are required. If the walls are imbedded into a watertight soil layer, a sealing base is not necessary. Sheet pile walls, secant bored pile walls and diaphragm walls are used as watertight excavation walls. The critical points of the watertight walls are the connection points between the wall elements used or the connection points between the walls and slabs and other horizontal structural elements.

Sheet pile wall

In a sheet pile wall, several sheet piles are connected to each other by interlocks. To ensure a watertight excavation pit wall, it is necessary that these interlocks are watertight. There are various options for this:

- Filling products such as bitumen or polymer seals into the Interlocks
- Seal-welding the interlocks
  - in the factory as double or triple piles (additional sealing or welding required on site; pressing method not possible)
  - on site (difficult to carry out below water)

Other possible sealing methods involving the filling of bentonite, injections or suspensions are not suitable for temporary shoring.

Bored pile wall

If a bored pile wall is designed with overlapping piles, it must be considered watertight. To this end, the overlap of the piles must be sufficiently large to compensate for tolerances during execution. DIN EN 1536 specifies the permissible deviations in the execution of bored piles. A distinction is made between deviations in position and inclination. To limit the deviation in position more strictly, a drilling template can be used as an aid. In the case of very deep excavation pits and therefore long piles, the deviation in inclination is of great importance. If the permissible deviations mentioned above are taken into account at the selection of the overlap, no further measures are required to ensure tightness. Local defects can be repaired with injections. Since the wall is to serve as a basement wall later on, attention must also be paid to aesthetics when filling defects.

Diaphragm wall

Diaphragm walls are also constructed with an overlap. However, the number of joints in a slotted wall is significantly lower than in a bored pile wall. This also reduces the number of possible defects, which can also be sealed with injections. Additional sealing measures are not necessary for a diaphragm wall.

Sealing base

In addition to vertical sealing, horizontal sealing of the excavation pit must also be taken into account. The connection between the wall and the base in particular offers an increased risk of defects and water ingress. When constructing the base, care must be taken to ensure that the concrete flows into the wedges or valleys in the case of sheet pile walls and bored pile walls. In contrast, with a diaphragm wall, the straight front edge of the wall means that the geometry does not complicate construction. In terms of the tightness of the individual wall types with a sealing base, concrete walls offer a better bond between the wall and the base than steel sheet pile walls. In comparison, bored pile walls and diaphragm walls are less prone to deformation and have a lower risk of cracking.

2.6.2. Connection underwater concrete slab

The connection between a retaining wall and an underwater concrete base is often necessary in construction pits in water to ensure a stable and safe structure.

Depending on the specific requirements of the project and the geological conditions on site, the connection between the shoring wall and the underwater concrete base can be achieved using various methods. Some common methods for establishing the connection are listed below:

Welding

Cleats can be welded on sheet piles take up forces in the area of the planned concrete base. This requires precise welding procedures and qualifications to ensure a strong and durable connection. Welding work is difficult to carry out underwater.

Prefabricated connecting elements

In some cases, prefabricated connecting elements such as bolts, plates, reinforcing bars or other mechanical connections can be used to connect the shoring wall to the underwater concrete base.

Without elements

The connection between the base and the shoring wall can also be made without additional elements. However, this requires careful cleaning of the contact surfaces under water. With this method, the vertical loads are transferred via friction between the concrete slab and steel or concrete wall.

2.6.3. Fire protection

For buildings and their construction materials, a distinction is made between building material classes in terms of their fire behaviour and fire resistance classes. Building material classes generally indicate whether the material is combustible or flame-retardant. The fire resistance class, on the other hand, indicates the minimum number of minutes that the component can withstand fire. The three performance criteria of load-bearing capacity, room closure and thermal insulation are taken into account.

To increase fire resistance, a coating system is available for steel components. The coating foams up in the event of a fire, delaying the transfer of heat to the sheet pile wall. The coating offers high durability and can also be selected in the desired colour. To protect the coating, the layer should only be applied after the sheet piles have been installed and the excavation pit has been drained. The cost of the coating depends on the desired fire resistance class.

For reinforced concrete components, the fire resistance class is measured based on the concrete cover and the concrete composition. The minimum concrete cover required by DIN EN 1992-1-1 is sufficient to achieve the highest fire resistance class. For diaphragm and secant pile walls, a higher concrete cover is selected compared to standard exterior walls. As a result, no further measures to increase fire resistance are necessary.

3. Construction methods investigated

3.1. Sheet pile wall, permanent

The sheet pile wall is a wall made of steel sheet piles that are vibrated, driven or pressed into the ground. The installation method depends on the nature of the soil. In stiff and hard soils, predrilling can reduce the resistance to driving. The sheet piles are connected to each other via an interlock and can be manufactured in various steel grades and geometries. In areas with limited space and groundwater, sheet pile walls are used as excavation pit walls due to the small cross-sectional area and watertightness of the sheet piles.

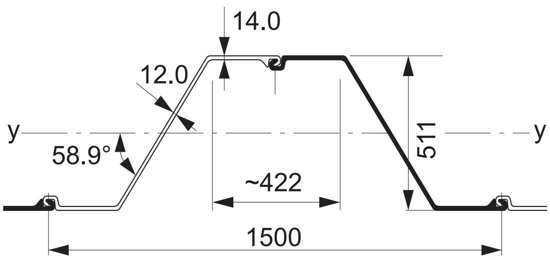


Figure 3-1: Section AZ 32-750 with dimensions in mm.

The design is based on sheet pile section AZ 32-750. To take into account the specified clear distance between the existing structure and the shoring walls, the width of the sheet pile wall and the width of the vibrodriver result in a distance of a_{Sp} = 0,90 m for the design in GGU-Retain (see Figure 3-2).

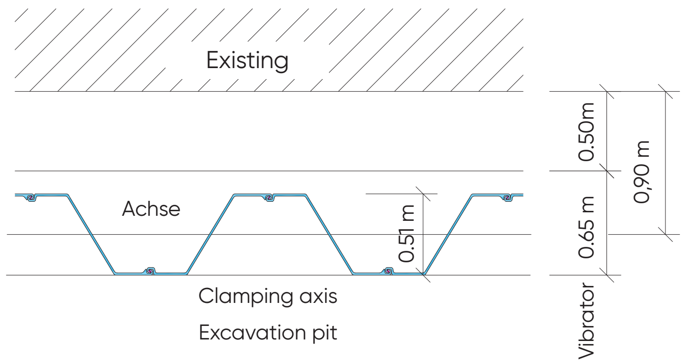


Figure 3-2: Distance between sheet pile wall axis and outer edge of existing structure.

The sheet pile wall is a flexible structure in which system-related deformations are to be expected. This must be taken into account when selecting the sheet pile profile in the area of structures that are sensitive to settlement. The durability of the sheet pile wall depends on its corrosion resistance. If required by boundary conditions, the corrosion resistance can be increased by coatings. In the soils in question, a very low abrasion rate of 0.01 mm/year is to be expected on both sides. With a service life of 50 years, this results in total corrosion of 1.0 mm. This corresponds to a loss of section modulus of approx. 7%. Under the selected boundary conditions, the reduction in this case does not affect the load-bearing capacity and serviceability of the structure. The specified service life of 50 years for underground car parks can therefore be achieved by the sheet pile wall as an external wall.

The sheet pile wall offers a number of advantages, such as a short construction time, a small site installation surface, maximum space utilisation, manageable construction risks and low cost. However, there are also disadvantages such as larger obstacles in the building ground that could interfere with installation, noise emissions and vibrations caused by impact driving and vibration. However, these can be avoided by pressing in the sheet pile wall.

An AZ 32-750 in steel grade S 355 GP with a length of L = 14.50 m was selected as the sheet pile profile. In addition to the selected section, other sections with equivalent cross-sectional values (W = 3,200 cm^3 /m) can also be selected. When selecting the sheet pile wall section, the limiting deformation is decisive and not the utilisation of the cross-section. The length of the sheet pile wall is determined by the verification of the vertical load-bearing capacity.

Tubes with a cross-sectional area of 660.4 x 20 mm were selected to brace the excavation pit. Equivalent stiffeners (W = 6,250 cm^3) from other section series are also possible here. The tube section was selected for all variants to ensure comparability. Only the spacing and thus the required number of struts is different and adapted to the respective load.

The connection between the sheet pile wall and the reinforced concrete intermediate floor or base in the ground floor can also be made using mechanical elements, as with the underwater concrete slab. However, compared to the underwater concrete slab connection, it is much easier to fix the elements as it is done in dry conditions. Since the intermediate floor serves as bracing, the connection must be force-fit so that the forces can be transferred. The connecting elements do not reduce the load-bearing capacity of the sheet pile wall.

3.2. Sheet pile wall, temporary

Sheet pile walls can be removed after the building has been constructed and reused for other projects. However, compared to permanent sheet pile walls, this requires the construction of a basement wall, which results in a reduction in usable space of around 7% compared to option 1.

Unlike the other construction methods, the temporary sheet pile wall does not require a connecting structure between the wall and the intermediate floor.

The temporary wall is dimensioned in the same way as the permanent wall using section AZ 32-750. The distance between the wall and the existing foundation is also a_{Sp} = 0.90 m (see section 3.1). Compared to the permanent wall, the temporary sheet pile wall does not receive any surcharge loads from the new building.

The use of sheet pile walls as temporary excavation walls has established itself as an effective method for the realisation of construction projects. Various technical aspects must be carefully evaluated to ensure successful implementation. In this context, the flexible design of the sheet pile wall is of particular interest, as system-related deformations are to be expected.

Since the sheet pile wall is only used as a temporary excavation wall, it is not necessary to investigate its durability and thus its corrosion resistance. Another aspect is fire resistance, which is not required due to the temporary use of the sheet pile wall, as this function is performed by the surrounding basement wall.

The chosen construction method offers various advantages, such as a short construction time, a small site installation space and low maintenance costs. In addition, the system is characterised by sustainability, as by reusing the sheet piles after pulling out. However, pulling can only take place once the ground floor has been completed and it takes over the bracing of the walls. Compared to the other variants, the temporary sheet pile wall is the most cost-effective design variant according to the total production costs (see Chapter 4.2).

The logistical and geometric challenge of pulling the sheet piles alongside existing structures also poses a challenge. The construction equipment must be placed on the already constructed underground car park. To transfer the loads of the construction equipment, bracing must be provided in the basement floors. When pulling sheet piles, settlement is to be expected in the immediate vicinity and thus in the area of the existing foundations.

The choice of section AZ 32-750, S 355 GP, L= 14.50 m, or an equivalent section from another series (W = 3,200 cm^3/m) was made due to the limit deformations and load-bearing capacity aspects. With regard to the cross-section utilisation, a weaker section would also have been possible.

The calculation of the sheet pile length is based on the verification of the vertical load-bearing capacity in order to ensure the stability of the excavation pit.

3.3. Secant bored pile wall, permanent

A bored pile wall usually consists of bored piles made of in-situ concrete. Various drilling methods are available for the production of the piles, which can be selected according to the boundary conditions. The wall system can also be selected according to the conditions between a contiguous or secant pile wall. The bored piles can be reinforced or unreinforced, depending on the selected system and load-bearing behaviour.

The bored pile wall is considered a very robust and deformation-resistant construction method. Robust means that the system can activate load-bearing reserves through redistribution in the event of overload. The bored pile wall is particularly suitable as a rigid shoring method in areas with settlement-sensitive components.

Due to the water present in this example, the bored pile wall must be constructed with secant piles. It is constructed using the rotary drilling method with casing and in-situ concrete, which is a low-vibration method. The wall is constructed using the pilgrim step method, with every second pile reinforced, see Figure 3-3.

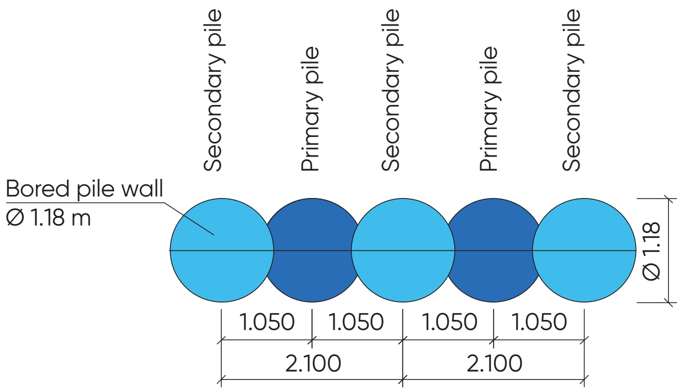


Figure 3-3: Schematic diagram of an secant bored pile wall.

The pile diameter is set at d= 1.18 m. No additional space is required for the equipment beyond the clear distance of 0.50 m. This results in a distance from the shoring to the existing structure of a_B= 1.09 m for dimensioning in GGU.

Durability is ensured by the concrete cover and thus the protection of the reinforcement rebars, but the load-bearing capacity and serviceability are limited by corrosion of the steel reinforcement. The service life is approximately 50 years.

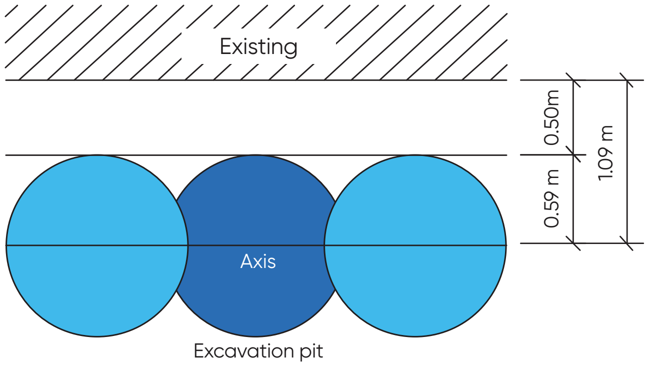


Figure 3-4: Distance between bored pile wall axis and outer edge of existing structure.

The concrete cover can be increased to improve durability. Compared to the temporary sheet pile wall with basement wall, the bored pile wall is thicker and more robust.

The bored pile wall offers various advantages, such as the robustness of the construction, the ability to efficiently transfer vertical loads into the ground, suitability for deep inner-city excavation pits, low-vibration construction and low wall deformation. The bored pile wall is an effective solution for minimising settlement, particularly in existing buildings.

However, there are also disadvantages, such as a longer construction time compared to options 1 and 2, higher construction costs of around 10% compared to option 2, more complex connection of the base and ceiling, and around 9% less usable space compared to option 1.

For the secant bored pile wall, a pile diameter of d = 1.18 m with a spacing of a = 1.05 m and a concrete grade of C25/30 was selected. Every second pile is unreinforced. The statically required length is 13.90 m for the relevant section and is selected as L = 14.50 m. Due to the robust construction, the deformation in relation to the wall height is very low at max. 9.3 mm.

A bored pile wall can be connected to an intermediate floor using mechanical elements such as bolts or reinforcing bars. An alternative method is to use a wailing, but this may not be aesthetically pleasing. It should be noted that the integration of such elements can influence the load-bearing capacity of the piles.

3.4. Diaphragm wall, permanent

Diaphragm walls are retaining walls made of concrete or reinforced concrete, which are concreted into a liquid-supported earth trench or filled with precast concrete elements. The trenches are excavated using diaphragm wall cutters or diaphragm wall grabs. Concrete guide walls must be constructed in advance to support the upper trench area. When constructing the wall, a choice can be made between the continuous method and the pilgrim step method. The joints are sealed using a special joint construction.

The diaphragm wall provides a robust and watertight excavation pit wall. High loads from neighbouring buildings can be absorbed without any problems and with minimal deformation.

The width of the slot is set at t = 1.00 m. No additional space is required for the equipment beyond the clear distance of 0.50 m. The 0.50 m wide strip can be used for any necessary guide walls. This results in a distance from the the shoring to the existing structure of a_S = 1.00 m for dimensioning in GGU.

Like the bored pile wall, the diaphragm wall is considered an extremely robust, rigid and deformation-resistant construction method. Its durability is ensured by the protection of the reinforcement, although the load-bearing capacity and serviceability may be compromised due to the risk of corrosion of the steel reinforcement. The service life is approximately 50 years until renovation, for which increased concrete cover serves as a protective measure.

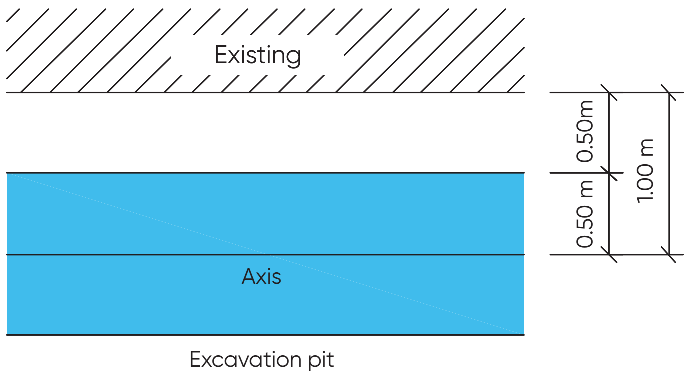


Figure 3-5: Distance between diaphragm wall axis and outer edge of existing building.

The advantages of diaphragm walls include their robustness, suitability for transferring vertical loads, the possibility of constructing deep excavation pits in inner-city areas, low-noise and low-vibration construction and low deformation. Due to the low deformation, the diaphragm wall is very well suited for use close to existing structures.

However, there are also some disadvantages to consider. These include a longer construction time compared to options 1 and 2, higher construction costs of approx. 15% compared to option 2, a more complex connection between the base and ceiling, and a reduction in usable space of approx. 6% compared to option 1.

The following values were selected for the design of the diaphragm wall: width t = 1.0 m, concrete grade C25/30 and length L = 16.00 m.

The connection of a diaphragm wall to an intermediate ceiling is similar to the procedure for a bored pile wall and can be achieved using mechanical elements such as bolts or reinforcing bars. An alternative method is to use a wailing, but this may not be an aesthetically pleasing solution. It should be noted that the integration of such elements can impair the load-bearing capacity of the wall. By planning for the reinforcement to protrude, it is possible to connect the ground floor slab to the diaphragm wall.

4. Summary

4.1. Design results

The results of the design are summarised in the following tables:

Variant	Solution	Ground level	Dredging level	Wall type	Length according to design	Top level	Tip level*)	L_{Wall} (Top-Tip)	Selected L_{Wall}	Selected tip of wall
[-]	[-]	[mNHN]	[mNHN]	[-]	[m]	[mNHN]	[mNHN]	[m]	[m]	[mNHN]
V1	Sheet pile wall permanent	60.00	50.50	AZ 32-750; S 355 GP	14.30	60.00	45.50	14.50	14.50	45.50
V2	Sheet pile wall, temporary			AZ 32-750; S 355 GP	14.30	60.00	45.50	14.50	14.50	45.50
V3	Secant bored pile wall, permanent			Ø 1.18 m	13.90	60.00	45.50	14.50	14.50	45.50
V4	Diaphragm wall permanent			t = 1.00 m	15.99	60.00	44.01	15.99	16.00	44.00

* Tip of wall: minimum 2.5 m embedded in the sand/gravel layer.
* Top of sand/gravel layer: 48.00 mNHN.

Table 4-1: Summary of geometric results for retaining variants.

Variant	Solution	Max. deformation		Reinforcement content	Max. utilisation	Strut, tube 660.4 x 20			
		ULS[1]	SLS[2]			Max. load $N_{(g+q),h,k}$	Max. design load $N_{(g+q),h,d}$	Distance	Max. utilisation
[-]	[-]	[cm]		[cm²] /[cm²/m]	[-]	[kN/m]	[kN/m]	[m]	[-]
V1	Sheet pile wall permanent	7.3	5.8	-	0.74	403	472	3.75	0.97
V2	Sheet pile wall, temporary	7.3	5.8	-	0.74	318	368	4.50	0.94
V3	Secant bored pile wall, permanent	0.9		84.3 cm²	0.85	323	378	4.20	0.92
V4	Diaphragm wall permanent	0.6		26.1 cm²/m	0.78	354	409	4.00	0.87

[1] ULS: ultimate limit state.
[2] SLS: service limit state.

Table 4-2: Summary of design results for retaining variant.

4.2. Costs

The component dimensions, designs and quantities underlying the cost estimates are based on the preliminary structural analysis in Section 3.

The costs include the pure manufacturing costs of the excavation pit construction plus the costs for the necessary earthworks and shell construction work for the underground car park.

This results in the following total manufacturing costs for variants 1 to 4:

V1 SPW	V2 SPW t.	V3 BPW	V4 DW
3,193,575 €	3,100,475 €	3,390,185 €	3,584,875 €
103%	100%	109%	116%
4,080 €/m²	3,960 €/m²	4,330 €/m²	4,580 €/m²

Table 4-3: Comparison of manufacturing costs for construction variants 1-4.

The total costs of the variants refer only to the present example and the selected boundary conditions. The costs may vary if the boundary conditions differ. For similar boundary conditions, the costs in €/m² can be used as a reference value.

As can be seen from Table 4-3, the costs of variant 2: temporary sheet pile wall are the lowest. In contrast, the additional costs for the sheet pile wall as a permanent solution (V1) are slightly higher by 3%. Option 3 is 9% more expensive to manufacture than option 2, and option 4 is 16% more expensive.

The total costs do not include the loss of income due to a smaller usable area, as the total costs are the pure manufacturing costs. However, the proportion is not insignificant and should be taken into account when choosing the type of shoring. The usable floor space is taken into account in the evaluation of the variants by comparing the floor space provided.

5. Evaluation

5.1. Evaluation criteria

The different retaining wall types are evaluated according to the agreed criteria. Different weightings are assigned to the criteria to emphasise their relevance. The following evaluation criteria are applied:

1. Investment costs
2. Provision of space, usable space
3. Maintenance costs
4. Construction time
5. Construction logistics, disruption to the construction environment
6. Execution risks
7. Sustainability

Definition of individual criteria :

Investment costs

→ The total costs incurred for the construction of the building

Provision of space

→ Actual space available for the planned use, in this case underground car park/parking spaces

Maintenance costs

→ Operating costs or running costs to maintain the use of the building

Construction time

→ Time required for completion of the building

Construction logistics

→ Coordination of material flows, labour, machinery and other resources to ensure the sequence of execution and the schedule

Execution risks

→ Risks that may arise during the execution of individual tasks and the probability of their occurrence

Sustainability

→ Consideration of long-term positive effects on the environment, society and the economy without compromising the needs of future generations

Criterion	Weighting	V1 Permanent sheet pile wall	V2 Temporary sheet pile wall	V3 Bored pile wall	V4 Diaphragm wall
Investment costs	20%	+	+ +	–	– –
Provision of space usable space	15%	+ +	–	+	+
Maintenance costs	10%	+ +	(+ +)	+	+ +
Construction time	10%	+ +	+ +	+	–
Construction logistics, disruption to the "construction environment"	10%	+ +	+ +	+	– –
Execution risks	10%	–	–	+ +	+
Sustainability	25%	+ +	+	–	–

\+ + = Very good   + = good   – = less good   – – = not good

5.2. Assessment

5.2.1. Results of the evaluation

The evaluation of the variants according to the criteria described in section 5.1 can be found in the table on the previous page.

5.2.2. Reasons for the evaluation

Investment

Compared to the other criteria, investment costs are the second most important criterion with a weighting of 20%. The costs determine whether a project is implemented or not. If the project proves to be uneconomical, it will not be implemented. The investment costs are assessed on the basis of the cost calculation for the example project (see section 4.2).

Provision of space

In inner-city areas in particular, it is essential to utilise every last centimetre of available space. Buildings should make optimum use of the available space and offer the largest possible usable area by using slim supporting structures. In addition, the usable area provides a source of income over the service life of the building. The weighting of the criterion «usable area» is 15%.

The largest usable floor space can be achieved with variant 1. The slim section and the use of the construction pit wall as an exterior wall save on construction space. The other three variants, on the other hand, have a larger cross-sectional area or require an additional reinforced concrete exterior wall. Compared to variant 1, variants 2, 3 and 4 offer approx. 6-9% less usable floor space.

Maintenance costs

The criterion of maintenance costs was weighted at 10%. Costs play an important role in the maintenance of a building and its service life. A distinction must be made between maintenance costs for purely aesthetic purposes (renovation) and costs for maintaining the structure (refurbishment). Within the planned service life of 50 years, it may be necessary to renovate the reinforced concrete walls and also the steel walls 1 to 2 times. In order to maintain the external appearance of the walls, cleaning and renewal of the surfaces may be necessary for all wall types. The geometry of the bored pile wall and the sheet pile wall can make the work more difficult compared to the diaphragm wall and the classic reinforced concrete outer wall.

Construction time

A shorter construction time also means lower costs, as the building can be occupied sooner, and equipment and fewer workers are required for a shorter period of time. The weighting of the construction time criterion is also set at 10%. Due to the preparatory work required for the construction of the diaphragm wall (construction of the guide wall), the construction time for option 4 is the longest. The bored pile wall also requires preparatory work, such as the production of a drilling template, which means that this option also has a longer construction time than options 1 and 2. No preparatory work is required for the construction of the sheet pile wall. Without taking into account the execution risks involved in the construction of the individual walls, the construction time for the sheet pile wall is the shortest. In the case of the temporary solution, the time required for pulling the sheet piles must also be taken into account.

Construction logistics

There is a particular lack of necessary space for the construction site facilities in inner-city areas. A large construction site facility has a greater impact on the construction environment than a small one. A small construction site facility can possibly be accommodated on the existing construction site, whereas a larger one requires road closures or neighbouring areas. The criterion of construction logistics is weighted at 10%. The construction site facilities for diaphragm walls require large amount of space for the necessary additional equipment (separation plant, pump, mixing plant for concrete suspension, piping system if required). In contrast, the space required for the construction site facilities for cast-in-place concrete bored pile walls is smaller. For production, it is necessary for the concrete mixer to be able to drive right up to the pile. No additional equipment is required for the sheet pile wall and, unlike with bored pile walls, no additional access route needs to be kept clear.

Execution risks

The greatest risk with shoring walls is posed by obstacles in the ground. Even with prior close-meshed probing of the ground, obstacles can never be completely ruled out. Whether an obstacle poses a risk to the execution depends on the choice of shoring type, the installation method and the type of obstacle (large stone, old concrete, wooden piles, etc.).

Any kind of obstacle is disruptive when sheet pile walls are driven or pressed into the ground. The sheet piles may then either not be able to be driven to the planned final depth and/or may bend and become unusable when they encounter an obstacle. The interlock could also declutch if the sheet pile wall hits an obstacle. However, if the subsoil is suitable for driving or pressing and an obstacle still appears, there are several ways to solve the problem. The options are either to check retrospectively whether the depth reached by the sheet pile wall is sufficient, adjust the position of the sheet pile, which changes the geometry of the usable areas (costs), or drill holes to remove the obstacle. However, the latter option increases the cost of the structure due to the use of a drilling rig and also extends the construction time.

Obstacles in the ground can also be a hindrance when constructing diaphragm walls. In comparison to sheet pile walls, the type and location of the obstacle determines whether it can be removed or causes problems. If a large stone, concrete chunk or wooden pile is located in the centre of the trench, the grab can lift the obstacle out. Removing an object at the edge of the trench is more difficult. In addition to an obstacle in the ground, the joint tapes can be damaged when inserting the basket of a diaphragm wall, thereby compromising the watertightness of the excavation pit. Unlike sheet pile walls and diaphragm walls, obstacles are less of a risk when constructing a bored pile wall. In most cases, obstacles can be drilled through. This increases wear on the drill bit (costs increase minimally) and reduces the drilling speed. Compared to sheet pile walls, however, no additional equipment is required, the geometry does not need to be changed, and no additional verification is necessary.

Sustainability

In the construction industry, sustainability can be achieved by considering the service life of structures, reusing resources and minimising resource consumption, with a particular focus on raw materials that are in short supply and non-renewable (e.g. sand for concrete production).

As a building material, steel is well suited for sustainable construction due to its high strength and the possibility of being reused after dismanteling. In addition, steel scraps can be recycled into high-quality steel.

Reinforced concrete, on the other hand, is not sustainable enough due to the limited availability of concrete aggregates and the need for concrete cover (increased material consumption) to protect the reinforcement. In the future, it will also be necessary to act sustainably in the construction industry. The weighting of the sustainability criterion is considered the most important criterion, accounting for 25%. The most sustainable solution for the choice of a retaining wall in this project is the permanent sheet pile wall. The sheet piles are made of steel and the wall also serves as an external basement wall in its final state. The steel can be reused when the entire building is dismantled. The steel can also be reused for temporary sheet pile walls. The piles can be removed after the underground car park has been constructed and used for other projects. However, compared to option 1, a reinforced concrete exterior wall is required. Concrete is used as the building material for the bored pile wall and diaphragm wall. Both options serve as exterior basement walls, eliminating the need for an additional basement wall. Compared to a conventional basement wall as in variant 2, however, the shoring walls are more solid and therefore require a higher content of reinforcement and concrete.

6. Conclusion

According to the evaluation matrix, the permanent sheet pile wall proves to be the preferred option. It achieves excellent results in most criteria, especially in terms of sustainability. The permanent sheet pile wall is designed as a long-term structure, which means that there is no need for an additional exterior wall. Furthermore, steel is lighter and easier to recycle than reinforced concrete in the event of subsequent demolition. The sheet pile wall performs slightly worse only in terms of execution risks, as it can be difficult to overcome obstacles in the ground compared to bored pile walls and diaphragm walls.

In conclusion, this study lays important foundations for future projects. Looking ahead, there is a growing need in the construction industry for new and more efficient solutions to conventional designs. The study has shown that a rethink is possible and that other designs may offer better options for the construction of underground car parks in the future.

7. References

German standards (including national annexes), recommendations and guidelines used in this case study by GRBV.

Standards

DIN 1054	Subsoil - Verification of the safety of earthworks and foundations - Supplementary rules to DIN EN 1997-1.
DIN 4020	Geotechnical investigations for civil engineering purposes – Supplementary rules to DIN EN 1997-2.
DIN 4084	Ground – Calculation of embankment failure and overall stability of retaining structures.
DIN 4085	Building ground – calculation of earth pressure.
DIN 4124	Excavations and trenches - Slopes, planking and strutting breadths of working spaces.
DIN EN 1990	Eurocode 0: Basis of structural design.
DIN EN 1991	Eurocode 1: Actions on structures.
DIN EN 1992	Eurocode 2: Design of concrete structures.
DIN EN 1993	Eurocode 3: Design of steel structures.
DIN EN 1997	Eurocode 7: Geotechnical design.
DIN EN 12063	Execution of special geotechnical works - Sheet pile walls.
DIN EN ISO 14688	Geotechnical investigation and testing - Identification and classification of soil.

Literature

[1] Recommendations of the Working Group «Building excavations», EAB, 6th German edition, 2021.

[2] Recommendations of the Working Group on Piling, EA Pfähle, 2nd German edition, 2012.

[3] Recommendations of the Working Committee for Waterfront Structures, Harbours and Waterways, EAU, 12th German edition, 2020.

[4] Eurocode 7 Handbook – Geotechnical Design – Volume 1: General Rules, 1st edition, 2011.

[5] Eurocode 7 Handbook – Geotechnical Design – Volume 2: Investigation and Assessment, 1st edition, 2011.

[6] Schneider Construction Tables for Engineers, 21st edition, 2014.

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