NUCOR®

SKYLINE

Port & Marine Construction

About Nucor Skyline

Rukurt Terminal – Baltimore, MD

Nucor Skyline, your true project partner

We are a premier steel foundation manufacturer and supplier, serving the North American market. Skyline Steel, LLC (doing business as Nucor Skyline) is a Nucor company, North America's most diversified steel and steel products company, and this relationship strengthens our ability to service our customers and the industry.

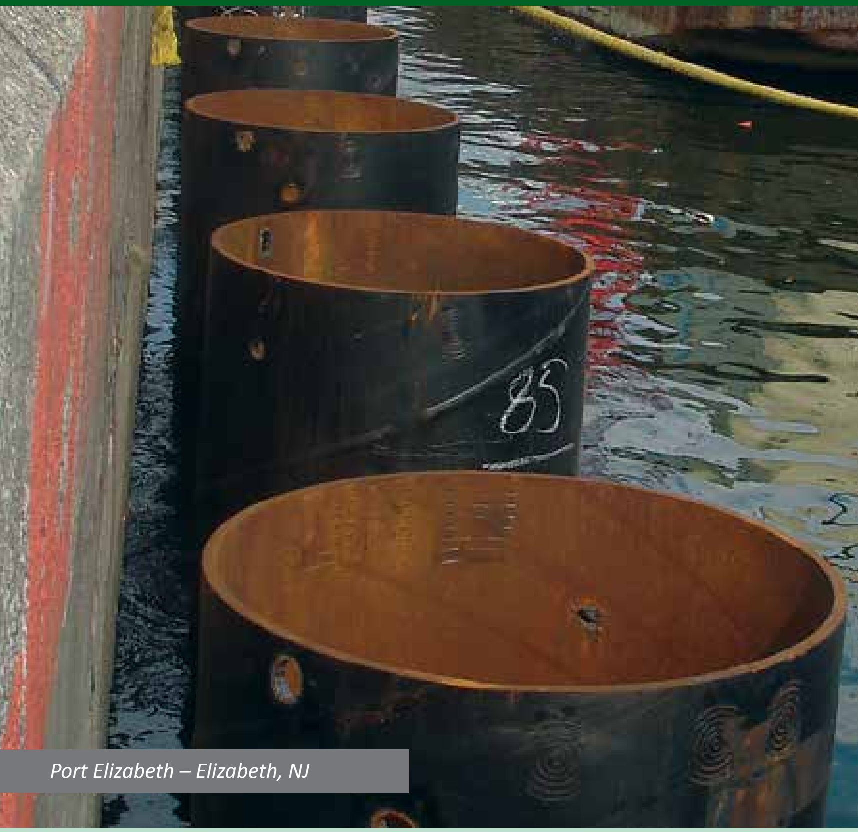
- Over 20 Sales Offices in North America
- Manufacturing, Coating and Fabrication Expertise
- Dozens of Stocking Locations
- Exclusive Engineering Support

Our flagship products include an unparalleled assortment of:

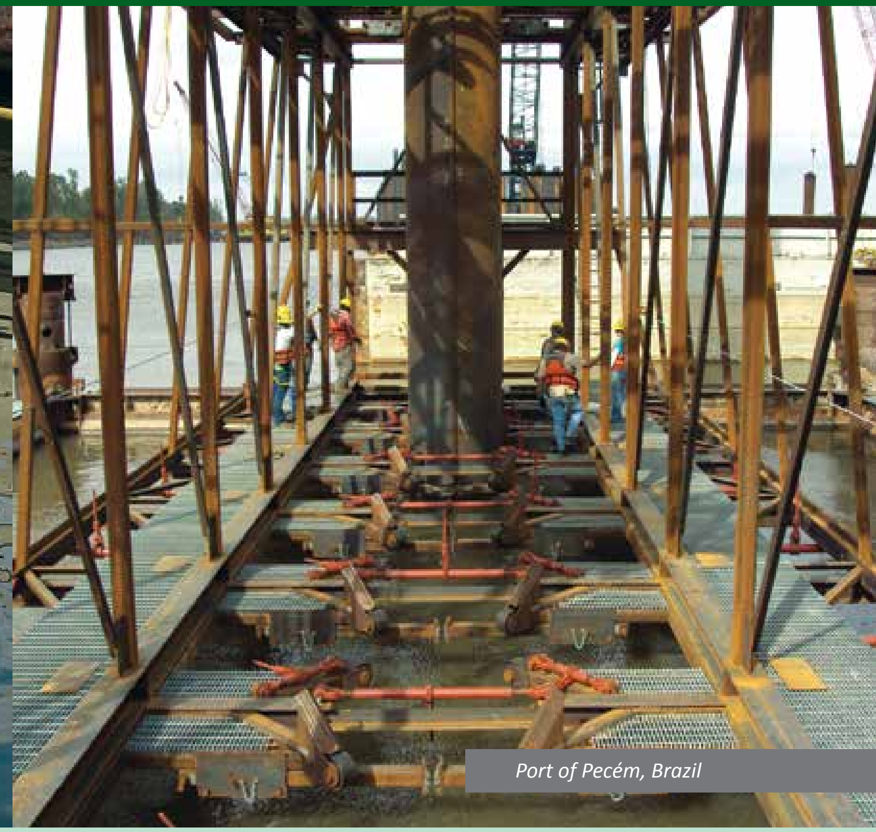
- H-Piles
- Steel Sheet Piles
- Pipe Piles
- Geostructural Products
- Wide Flange and other Structural Sections
- Piling Accessories

Nucor Skyline's knowledgeable engineering team works with owners, engineers, and contractors long before ground is broken. To ensure seamless project coordination and completion, our engineers propose solutions throughout all aspects of design, material selection, installation, and construction sequencing. Nucor Skyline's engineering support is extended even further to include provision of onsite assistance after a project has started. Our relationships extend beyond sales – we are your true project partner.

Port & Marine Solutions from Nucor Skyline



Port Elizabeth – Elizabeth, NJ



Port of Pecém, Brazil

Trade is vital to the economy of the world, and marine infrastructure makes it possible. As container ships and other vessels continue to increase in size, so does demand for port facilities with deeper dredge depths and larger cranes. Taller berthing facilities require large sheet pile combined wall systems to handle the earth pressures and heavy surcharges from stored material and equipment. The increase in crane loads amplifies the size and length requirement of bearing piles under the crane rails. These loading requirements, coupled with aggressive salt water environments, make the design of marine structures a formidable task.

North America also has an extensive network of inland waterways. Fresh water infrastructure is typically designed to accommodate smaller vessels, but these structures still face many challenges. Though the water is not as corrosive, the ice loads can be significant. Additionally, structures in large rivers have to be designed for extreme tidal fluctuations.

Steel sheet piling has been part of the very core of who we are as a company since 1978, when Nucor Skyline transitioned from being a supply center for structural steel to a steel foundation company. Skyline offers an unparalleled level of service and range of sheet pile products, and we are committed to further developments in products, steel grades, and testing.

- Widest Range of Steel Foundation Products and Steel Grades
- Exclusive Supplier of AMLoCor®, a Corrosion Resistant Steel for Sheet Piles
- North America's Only Source for the Unique HZ®-M Combined Wall System

In addition to our sheet pile offerings, Nucor Skyline has a complete range of steel foundation products, including pipe piles and tie rods, available to meet your project's needs.

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Retaining Walls

Retaining Walls

Retaining walls have been constructed along the waterfront for centuries. The main purpose of these structures is to retain or hold back a solid mass, a fluid, or a combination of the two. Retaining walls are made from many types of materials, however this brochure focuses on retaining walls made from steel sheet piles.

A sheet pile is an interlocking, corrugated structural section that is used to form a continuous retaining wall. Each sheet pile section interlocks with the adjacent section as they are driven into the ground.

Retaining walls can be categorized into these groups:

1. Cantilevered walls
2. Anchored or braced walls
3. Combination walls
4. Toe walls

River Walk in Sanford, FL

Cantilevered Retaining Walls

Seawalls, bulkheads, river walk walls, and walls of limited height fall into this category. These walls vary in height up to 15 feet, though some may be as high as 20 feet in good soil conditions. Cantilevered walls are built without an anchor or a brace to support the wall. The exposed portion of the wall is supported by the embedded portion of the wall. The proportion of exposed height to embedded depth is generally 1:2 for cantilevered walls.

Anchored Retaining Walls

Anchored walls typically consist of a sheet pile wall that is anchored or braced at one or more levels. The anchors or braces support the wall and reduce the deflection or movement towards the open or exposed side of the wall. These anchored walls generally have an exposed height greater than 15 feet. The exposed portion of the wall is supported through the combined resistance from the anchor or brace, and the embedded portion of the wall. The proportion of exposed height to embedded depth is generally 1:1 for simple anchored walls. Soil conditions, water levels and other loads will have a significant impact on the wall design and will change the 1:1 proportion.

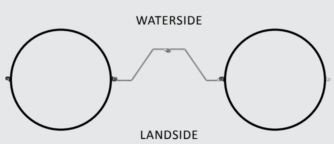
Bulkhead and walers with grouted anchors in Connecticut

Bulkhead and dead man sheeting with walers and tie rods in the Brooklyn Navy Yard

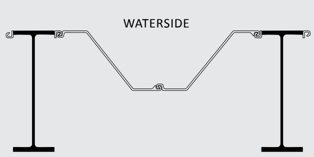
Pipe-Z Combination Wall Construction at Puerto Caucedo, Dominican Republic

Below are examples of single king pile combination wall systems:

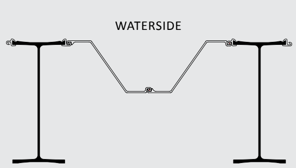
Pipe-Z Combination Wall



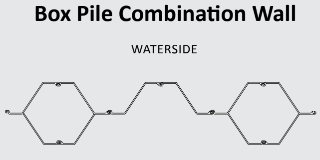
Wide Flange-Z Combination Wall



HZ®-M Combination Wall



Box Pile Combination Wall



Combined Walls

There are times when standard sheet pile sections are not adequate for deep retaining wall applications. In these applications, a combination wall can be used. Combination walls consist of king piles and sheet piles configured to meet the required stiffness and bending capacity. The king pile is the primary structural element in the system, and the sheet pile is the secondary element. A combined wall could consist of a single king pile, double king piles, or in some extreme cases, the wall could consist of only king piles with no intermediate sheet piles.

The king piles are generally fabricated from pipe piles, beams, or sheet pile box piles. Special connectors or flanges cut from sheet piles are attached to the king piles to enable the connection to adjacent king piles or sheet piles. On the left are examples of combined wall systems with single king piles. Similar systems can be designed and built with double king piles or continuous king piles.

Although some king pile walls are cantilevered, most use an anchorage system to help control stresses and deflection. The king piles carry the majority of the load in combined wall systems, therefore tie rods or anchors can be attached directly to the king pile without the need for a waler. The tie rod is then connected to a deadman system, at a specified distance away from the main wall, which usually does require a waler. More information on anchorage systems can be found on pages 14 and 15 of this brochure.

The determination of the properties of combined wall systems is as follows:

Moment of Inertia for System: $$I_{sys} = \frac{(I_{kp} + I_{sp})}{W_{sys}}$$

It is important to note that the offset of the sheet pile from the neutral axis of the system should **not** be included when calculating the sheet pile inertia.

Section Modulus for System: $$S_{sys} = \frac{I_{sys}}{c}$$

Bending Stress in King Pile: $$f_{kp} = \frac{I_{kp}}{(I_{kp} + I_{sp})} * \frac{M_n}{S_{sys}}$$

Bending Stress in Sheet Pile: $$f_{sp} = \frac{I_{sp}}{(I_{kp} + I_{sp})} * \frac{M_n}{S_{sys}}$$

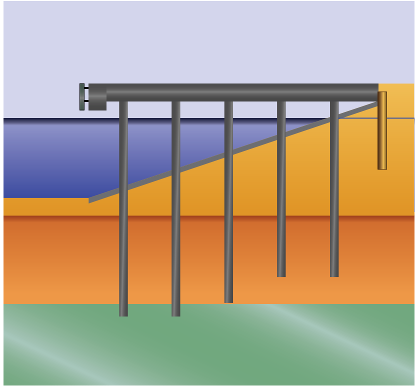
The examples on the left are all for single king pile solutions, but double king pile combination systems can also be made with HZ®-M beams, pipe piles, wide flange beams, or box piles. Each king pile is connected to the adjacent king pile or sheet pile using special connectors that allow free sliding during installation.

Toe Walls

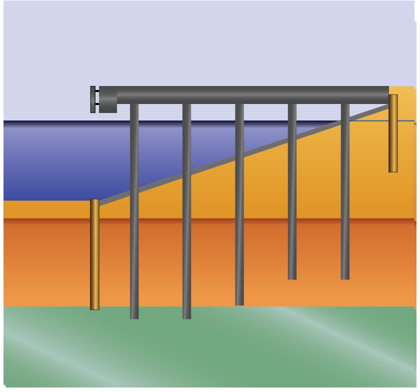
There are occasions when a deeper dredge depth is required at an existing bulkhead to accommodate the berthing of larger vessels. In these applications, a sheet pile wall or combination wall can be driven below the water to accommodate the new dredged depth, stabilize the existing structure, and eliminate the need for an entirely new bulkhead wall. This is referred to as a toe wall because it is driven at the toe or the base of the existing wall. Review the sketches below for more details.

Combined wall before sheet pile is driven to final elevation. Port Authority NY/NJ

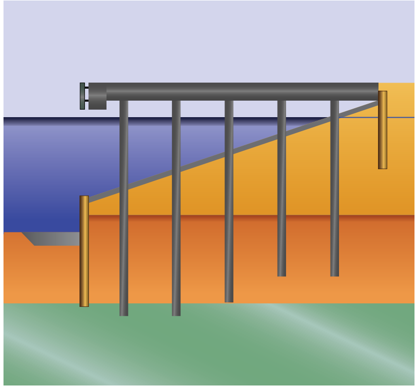
Installation of sheet pile wall underwater



Existing structure: Deck on piles.

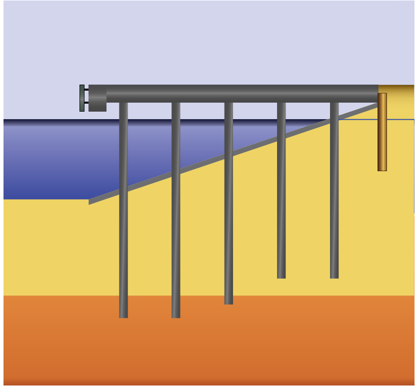


Driving of steel sheet pile down to existing dredge level.

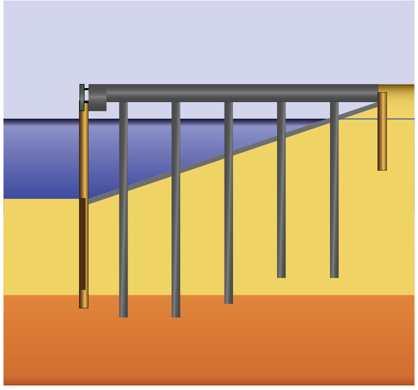


Dredging in front of driven steel sheet pile wall.

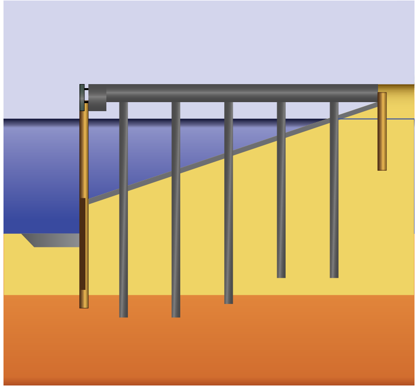
Installation of a combined wall anchored to the deck



Existing structure: Deck on piles.



Driving of king piles, fixed to deck. Driving of intermediary Z sheet piles.



Excavation to final dredge level.

Bearing Piles

Port and marine facilities have many different types of structures that will need to be supported through the weaker upper soil layers down to stiffer soil layers or rock that can safely support the structures from above. Bearing piles are either driven or drilled into the ground. Deciding which type of pile to choose has many parameters (type of structure, loading, soil type, owner and contractor capabilities, etc.) that all have to be addressed for a successful project.

Bearing Pile Types

There are two types of driven steel bearing piles: pipe and H-piles. Pipe piles with an attached end plate are considered displacement piles, and pipe piles without an end plate are considered non-displacement piles. In general, pipe piles are advantageous due to the fact that they are available in a nearly limitless number of sizes, allowing the designer to optimize their project solution. The most common steel grade for pipe piles is ASTM A252 Gr. 3 with 50 ksi minimum yield, but can be produced up to 80 ksi depending on the diameter to thickness ratio. H-piles are low displacement piles and can be driven into very hard soils. The standard grade for H-piles is ASTM A572 Gr. 50, but they are available in grades up to 70 ksi.

H-pile Bearing Piles

Pipe Bearing Piles

Bearing Piles

Every project is unique, due to the owner's needs and requirements. At Nucor Skyline, we have the ability to supply many different types of products to support these structures. The following is a breakdown of the different types of structures that utilize bearing piles for port and marine facilities.

Pile Supported Docks

For most vessel loading or unloading platforms, docks provide ample space for movement of materials and offer the owner more flexibility when adjustments to operations is required. They also allow the owner to continue the structure over water to the vessel berthing area. When the upper soil levels near the mud line are very weak, these docks must use a deep foundation system. Using piles to support docks offers many advantages including speed of construction, minimal ground modification, and project cost over other methods of dock support.

Floating Dock, Charleston, SC

Crane Rails

Due to the size of cranes used in port facilities, most crane rails have their own foundation system, separate from the rest of the port structure. Designers must take into account the static loads of supporting a crane that may extend beyond the dock to load or unload ships as well as the dynamic loads generated while the cranes are in motion. Proper crane rail installation is paramount in the longevity and operation of the cranes. Piles used to support crane rails are usually steel pipe piles or H-piles that are uniformly spaced. Specific areas of the crane rail may be designated for jacking the crane off the rails for maintenance, which would require larger foundation elements.

Port Authority NY

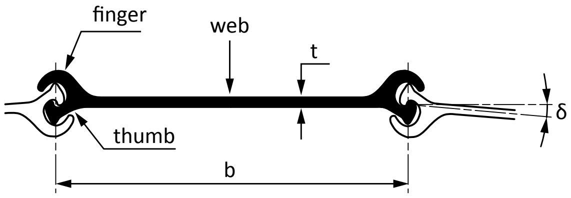
Dolphins

The two primary uses of structural dolphins are to protect waterfront structures, and to berth and moor ships. Breasting dolphins are used to secure ships and protect other port structures, while mooring dolphins are used only for securing ships. For liquid and dry bulk facilities, a series of dolphins can be more cost effective than building a dock or pier. Dolphins that are designed as a crash barrier are considered sacrificial and are usually designed as a "flexible" system to absorb the impact loads induced from vessels, ice, waves, or other environmental forces.

Kinder Morgan Terminal, Dock 4, Charleston, SC

Cellular Structures

Cellular structures are made up of cells constructed from flat sheet piles (also referred to as straight web sheet piles). This type of sheet pile is designed to resist large tensile loads from the granular fill, and the surcharge live and dead loads. The interlocks can resist 20 to 34 kips per inch of sheet pile length. This is key to the overall structural stability and load resistance of the cells.



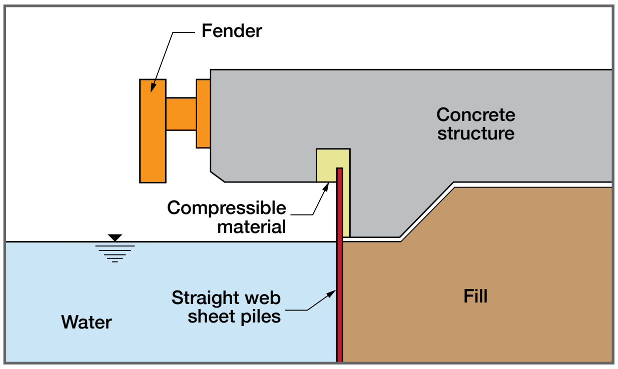
Width (b) = 19.69 in. / 500 mm
Thickness (t) = 0.375 in. – 0.512 in.
(9.5 mm – 13.0 mm)

Cellular structures are unique for several reasons:

Cellular structures can be constructed in shallow or deep water, or on land, to resist huge loads for deep excavations or large retaining structures. For example, cellular structures formed the cofferdams in water depths of 26.7 m for the Seo-Hae Grand Bridge piers as shown on the right.

The next unique feature of these structures is that they are gravity structures. The force of gravity on the mass of the fill, inside the cells, provides the stability of the structure. As a result, cells can be constructed on shallow bedrock (as shown on the right) or embedded deep into soils, depending on site conditions.

Cellular structures can be built to withstand heavy surcharge loads. The force of the surcharge load is distributed through the concrete slab and cap, into the fill, and is resisted by the interlock tension and the surrounding soil layers.



Types of Cellular Structures

Cells can be arranged in many different ways:

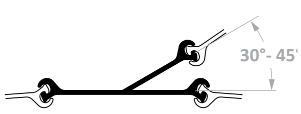
1. Combinations of main circular cells with connecting arcs
2. Connecting arcs with straight walls called diaphragm cells or OPEN CELL™ structures.

These structures are defined in further detail below:

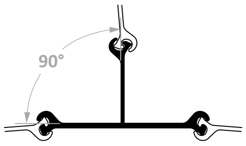
Circular Cells

These are retaining wall structures made with flat sheet piles consisting of main cells (complete circles) and connecting arcs (partial circles between the main cells). Sometimes the arcs are constructed on both the front and back sides of the wall; other times the arcs are placed only on one side. The junction piles enable the connection between the main cells and the arcs.

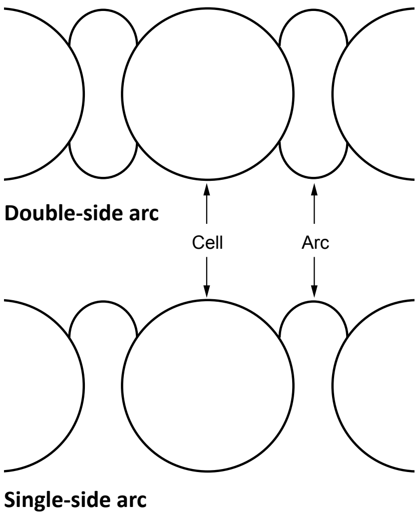
JUNCTION PILES



Y pile

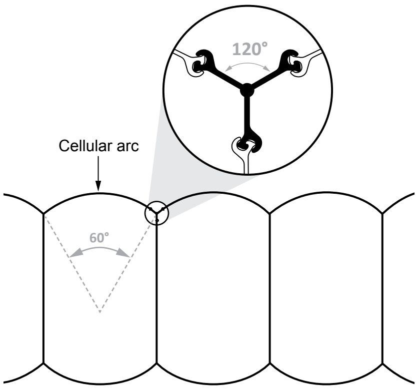


90° T pile



Diaphragm Cells

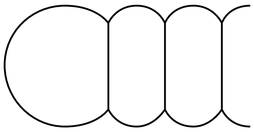
These structures consist of two arcs connected by 120° junction piles and straight transverse sheet pile diaphragms.



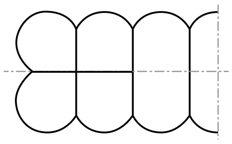
Diaphragm structures have two major advantages:

1. The length of the straight wall within each box does not impact the tensile force in the sheets, so the length of each transverse wall is not restricted. As a result, diaphragm structures can be built to resist much higher loads. This is an alternative to circular cells when the maximum interlock resistance is exceeded.
2. The tensile forces in the 120° junction piles are equally balanced once the cells are installed and backfilled with soil.

The ends of the diaphragm wall must be closed off with a closure cell or with a clover leaf closure cell.



Closure cell



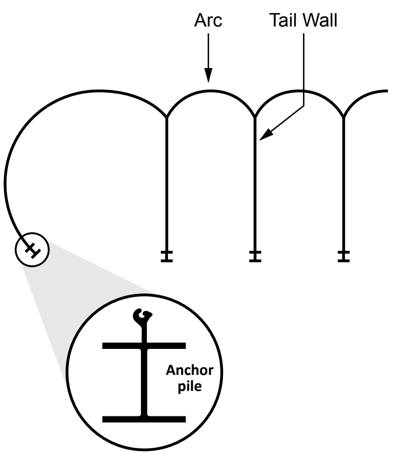
Clover leaf closure cell

OPEN CELL™ Structures

These structures are similar to diaphragm structures, but instead of two rows of arcs to create a closed and contained structure, OPEN CELL structures have only one row of arcs and are less complicated to construct and backfill than closed structures. The arcs (face of sheet pile wall) are interconnected by fabricated junction piles and straight transverse sheet pile walls. See sketch on the left.

America's Cup Village

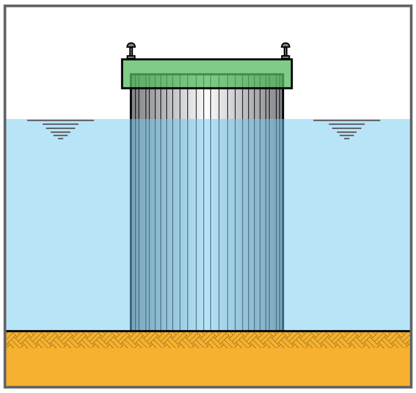
OPEN CELL SHEET PILE™ bulkheads use the transverse sheet pile walls or tail walls to provide the resistance needed to support the load applied to the arcs. A special fabricated H-pile is installed at the end of each transverse wall to anchor the end of each wall into the backfill soil. OPEN CELL structures, like the diaphragm walls are self-supporting, can resist very high loads/tall walls, can be used as retaining walls for very deep excavations and can be designed to accommodate soft soils, shallow bedrock or seismic conditions.



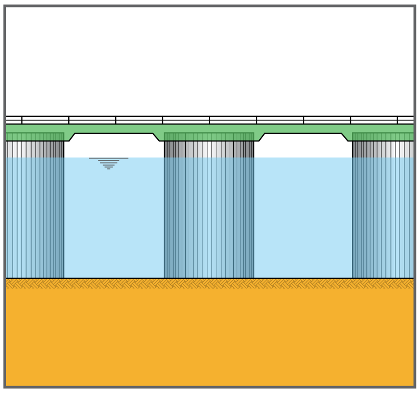
OPEN CELL SHEET PILE bulkhead technology is proprietary to PND Engineers, Inc.™ and is patented. Contact Nucor Skyline or PND Engineers, Inc. for additional information.

Mooring Dolphin, Jetty, and Quay

Circular cells are designed to be stable structures when filled with granular soil. In deep waters, these individual cell structures have been used as mooring dolphins for ships. A series of individual cells can also be connected or linked together with a platform to make a jetty or quay wall. These structures provide a robust support structure when a standard pipe pile or other solution is insufficient.



Mooring Dolphin



Jetty or Quay

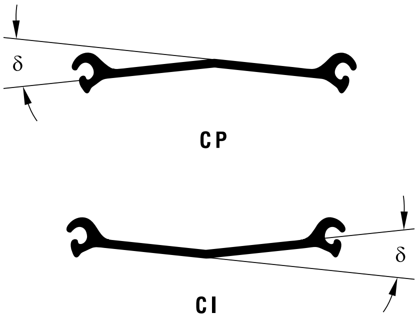
Interlock Rotation (Swing Angle)

The amount of rotation in the interlocks of flat sheet piles, sometimes referred to as the swing angle, is an important consideration in circular cell design. The amount of interlock rotation impacts the allowable range of diameters of a cell. The table below highlights the minimum diameter for the PS and AS sheets based on the swing angle in each joint.

Sheet Piles	Swing Angle (degrees)	Lengths* (ft)	No. of Pieces	Circumference (ft)	Min. Diameter (ft)
PS Sheets	7.0	< 65	58	95.2	30.3
AS Sheets	4.5	< 65.6	80	131.3	41.8
AS Sheets	4.0	< 65.6	90	147.7	47.0

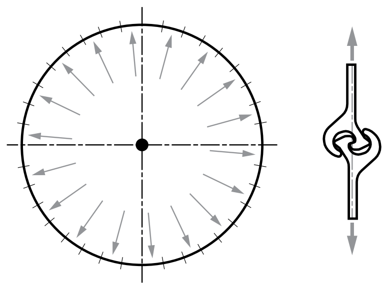
*The maximum length at which the mill will guarantee the listed swing angle. For longer lengths, please inquire.

In some cases, the swing angle is not sufficient to meet the required diameter for a given project. In these applications, a small bend (usually up to a maximum of 12°) can be made in a selected number of sheets, in form CP or CI as shown to the right. The pre-bent sheets should be evenly spaced around the cell to ensure the cell closes and that the shape of the cell remains as circular as possible.



Interlock Strength inside the Cells

Another key component in the design of cellular structures is interlock tension. The pressure on the inside of cellular structures creates radial tension around the cell. Flat sheet pile interlocks are designed to take tension in this direction. In addition to checking the capacity of the interlock, the tensile strength of the web must also be checked.



Radial pressure or hoop stress inside the cells

Interlock Tension = Maximum Pressure * Radius of Main Cell

Where Maximum Pressure refers to the design value of the internal pressure acting in the main cell at the governing horizontal plane due to water pressure and the at-rest pressure of the fill.

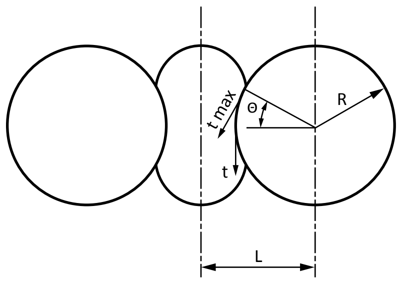
For example:

Maximum Pressure = 2,500 psf
Radius of Main Cell = 30 feet
Interlock Tension = 2,500 psf * 30 feet = 75,000 lbs/ft = 6.25 k/in

The taller a cell is, and the larger the radius, the greater the interlock tension. Manufacturers of flat sheet piles publish maximum interlock strengths, and the capacity of the web is determined by the thickness of the web and the steel grade. Appropriate factors of safety or reduction factors should be applied to these values.

Tension in Cells

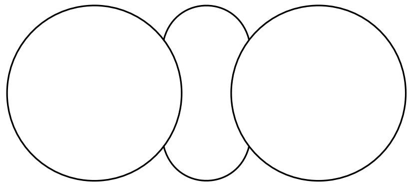
The structural capacity of the sheet piles, and the stability of the cells, are the two main components of the design of sheet pile cellular structures. Information on the structural aspects of the flat sheets is covered below.



The first step is to determine radial tension in the cell. The radial tension, or interlock tension, is equal to the pressure multiplied by the radius of the cell or arc. The pressure value is the maximum differential between internal and external pressure.

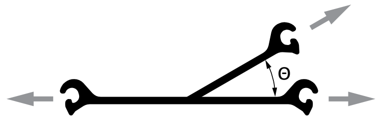
tension = pressure * radius

The tension value is most commonly expressed in kips/inch or kN/m. The interlock tension needs to be checked against the interlock strength of the sheet pile, the strength of the web, and the capacity of the junction piles.



The interlock strength of a flat sheet pile is a published value. Appropriate factors of safety or reduction factors should be applied. The calculation of the strength of the web is also quite simple.

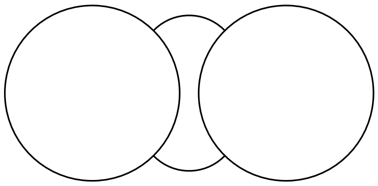
web strength = web area * yield strength

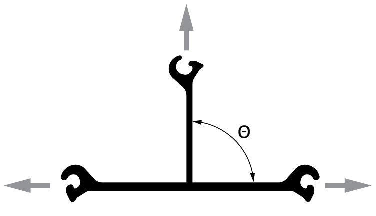


Y Pile

Interlock Strength of the Junction Pile

The final structural check is for the junction pile. There are multiple ways to determine the capacity of the junction pile, and some designers choose to ignore it. One methodology as outlined in ArcelorMittal's, "Design & Execution Manual AS500 Straight Web Steel Sheet Piles" is based on the ratio of the radius of the arc and cell and the internal friction angle of the soil.





90° T Pile

$$\text{Interlock Strength Reduction Factor} = 0.9 * (1.3 - 0.8 * r_a/r_c) * (1 - 0.3 * \tan(\phi))$$

r_a: radius of arc
r_c: radius of cell
ϕ: internal friction angle of soil

The ratio of the radius of the arc to the radius of the cell is crucial in the verification of the capacity of the junction pile. Utilizing junction piles with lower angles, such as 30°Y piles, as opposed to 90°T piles will naturally lead to a smaller radius arc and a higher reduction factor.

Anchorage Systems

Steel sheet piles are often cantilevered for lower retained heights, but for walls taller than ~15 feet a support system is usually required. On tall cantilevered walls, it is very difficult to control deflections without using a very large combined wall system. For marine structures, the most common options are tie rods, grouted anchors, and battered piles.

Tie Rods

Tie rods are the most common and most efficient form of support for waterfront walls and are usually made from threaded bar. Threaded tie rod systems can be easily installed on backfilled walls, but are not practical for cut or excavated walls. The tie rod connects the main wall to a secondary structure, which could be a pile, buried deadman wall or another exposed wall. Bars are available in a wide variety of steel grades and diameters to accommodate your needs and are also available with upset ends to reduce weight. Clevis systems and spherical hardware is the best way to reduce bending in the tie rod caused by settlement.

Grouted Anchors

Grouted anchors are different from tie rods in that instead of connecting to a second structure, they are grouted to the soil or rock. Anchors are usually used on cut or excavated walls, rather than backfilled walls, and are also drilled into place. One of the biggest benefits of grouted anchor systems is that every anchor is loaded to 120% of their design load, making them one of the most thoroughly tested elements in the entire construction industry. Most grouted anchors are made from either high strength threaded bar or strand. Strand is especially useful for very long anchors or load distributive compression anchors. Smart jack systems can be used to ensure proper tensioning of complex anchor systems.

Battered Piles

Battered pile systems are built with bearing piles driven at a steep angle behind the wall. The piles work in tension (skin friction) and are connected to the top of the main sheet pile wall. As with most support systems, the load is distributed to the wall through a waler system. Battered piles are usually H-piles or pipe piles and can take larger loads because of the size of the elements. They are also installed using the same equipment that is used to install the sheet pile wall. The steep angle of installation makes battered piles useful for sites that don't have enough room for tie rods or grouted anchors.

A-frames

A-frame systems are a type of deadman structure for walls using tie rods. The tie rod is connected to a horizontal waler system, which in turn is supported by battered piles. The battered piles take load in tension and compression and form a triangular or A shape in the soil. A-frame systems are especially useful in very soft soils, where traditional deadman may not be stable, or for very heavy loads.

Walers

Walers are used to distribute the load on the sheet piles to the support system. Walers are most commonly made from double channel systems, but can be made from a variety of sections and can take compression loads in addition to the bending loads for which they are most often designed. The waler system is one of the least expensive components of an anchored sheet pile wall, but it is critical to the entire system and should be well protected from corrosion. It is easier to install walers on the front of the wall, but they are then exposed to the elements. Walers installed on the back of the wall require a tension connection to the wall, but are well protected once they are buried in the soil. Tie rods, anchors, and battered piles are usually connected directly to the waler, but this is not required. If the supporting elements (tie rods, anchors, or battered piles) are spaced at less than the width of a double sheet pile, the waler is not required. Walers are also not needed on combined wall systems.

Corrosion Protection

Steel durability is critical to the design process. As a steel section corrodes, it loses strength and the designer must ensure that the section can safely carry the design loads at the end of the design life. Determining the design life of a port or marine structure is a straightforward process of understanding the corrosion rate and mitigating its effects through utilization of corrosion protection measures.

Understanding the corrosion rate of a particular environment is critical when calculating the design life. Different soils and types of water will have varying influences on the corrosion rate.

There are tables on the following page which provide average values for the loss, in thickness, in varying soils and water conditions. These measurements were collected from actual jobsites and can be used for preliminary guidance. If there is historical information available locally, that information should be used instead. The designer should determine the rate for all sides of a steel section, as they are usually subjected to different corrosion environments. It should be noted that soil resistivity is sometimes used to determine the corrosiveness of a soil sample. This method for determining the corrosion rate does not take into account the level of oxygen in the soil and should not be used. The steel will not corrode without oxygen or extremely acidic soil.

Once the corrosion rate has been determined, the reduced section properties and design life can be calculated. Increasing the design life of a steel section can be done in a variety of ways. Most of these will fall under three main categories: over-design, corrosion rate reduction and steel protection.

Over-design is most often done by selecting a larger section, therefore increasing the thickness or steel grade. This method will reduce the stress in the steel section. Although increasing the yield strength will not change the corrosion rate, it allows the steel section to carry the same loads with a lesser thickness.

Corrosion rate reduction can be achieved through the use of specialty steel grades, such as ASTM A690 or AMLoCor®. ASTM A690 is a high-strength low-alloy nickel, copper, phosphorus steel grade used for improved atmospheric corrosion resistance in marine environments. It generally performs two to three times better than traditional carbon steels in the splash zone, which is typically the zone of highest corrosion.

AMLoCor® is a "low corrosion" steel grade developed by ArcelorMittal for improved corrosion resistance in the low water zone (LWZ) and the permanent immersion zone (PIZ) in marine environments. It reduces corrosion by a factor of 3 in the LWZ and by a factor of 5 in the PIZ, compared to traditional carbon steels.

Another method used to reduce the corrosion rate is cathodic protection. Cathodic protection involves either sacrificial anodes or an impressed current system. Both systems create a battery cell to prevent the loss of material from the exposed steel.

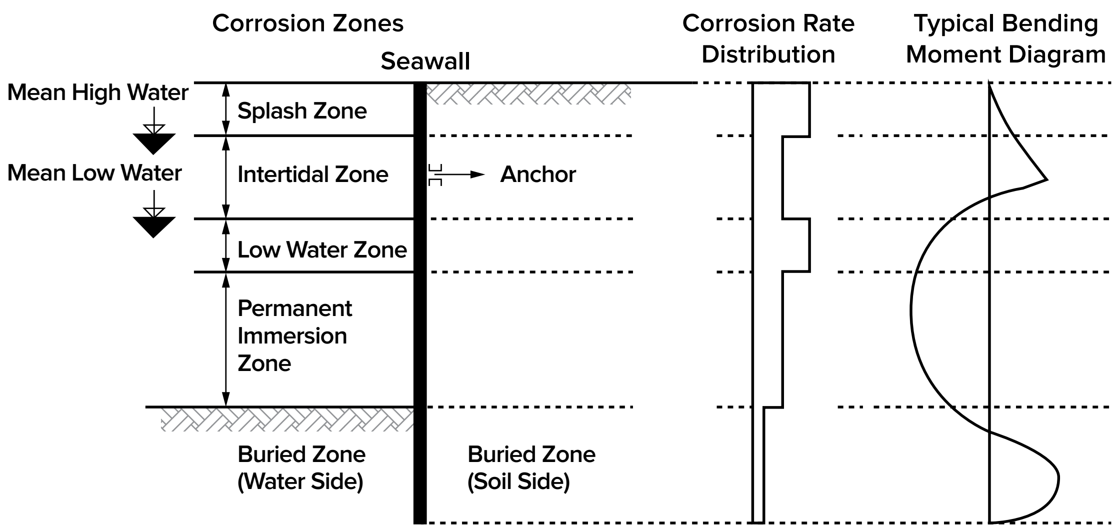
Protecting the steel by a coating or galvanization is another method to increasing durability. Galvanization is commonly used for atmospheric protection, but should not be used in the permanent immersion, tidal, or splash zones. Coating is very common and relatively inexpensive. It works well on exposed steel, but it can be damaged during transportation, installation, or by debris in a marine environment. Once the steel is exposed, it will corrode at the normal rate. Other methods for protecting steel include using concrete encasement, jackets, or sleeves.

Calculating the Required Section Properties of a Steel Structure

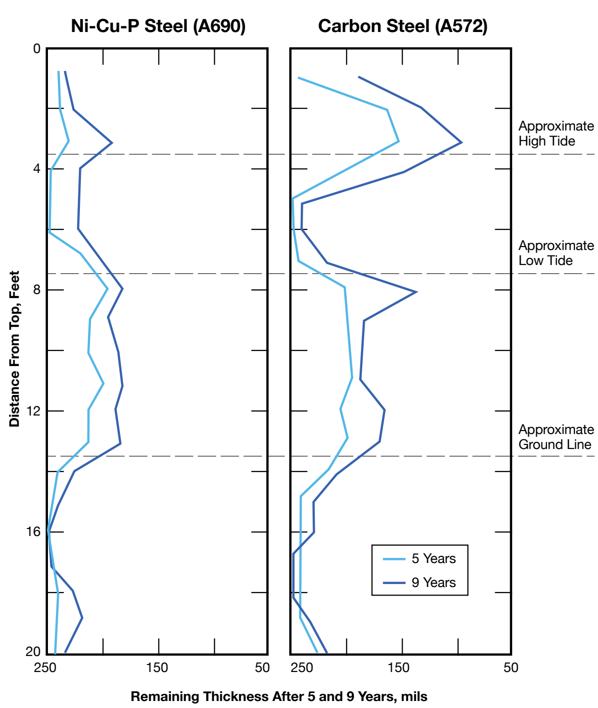
1. Design structure for all induced loads (axial, moment, shear, thermal, seismic, etc.).
2. Select a steel section to start, this is an iterative process.
3. Determine maximum allowable stress for each corrosion zone.
4. Determine corrosion rates for all sides.
5. Calculate the total section loss in each zone for the desired design life, taking into account any corrosion mitigating measures such as varying steel grades, coatings, or steel protection methods.
6. Calculate the reduced section properties of the selected steel section.
7. Compare the reduced section properties to the maximum allowable stresses required for the design.
8. If the reduced section properties are sufficient, proceed with that steel section. If they are not, select a new larger or thicker steel section and repeat the steps.

Corrosion Calculation Example

Example of corrosion rate distribution



NOTE: Corrosion rate distribution and zones may vary considerably from the example shown depending upon the conditions prevailing at the location of the structure.



Comparative corrosion of Ni-Cu-P steel and carbon steel in marine environment. Test strips exposed for 5 and 9 years at Wrightville Beach, North Carolina. [Schmitt, R. J. and Phelps, E. H., "Corrosion Performance of Constructional Steels in Marine Applications", talk prepared for presentation at the First Offshore Technology Conference, Houston, Texas, May 1969.]

Loss of Thickness Due to Corrosion for Piles in Soil with or without Groundwater

Required design working life	5 Years	25 Years	50 Years	75 Years	100 Years
	in / mm				
Undisturbed natural soils (sand, clay, schist, ...)	0.000 0.00	0.012 0.30	0.024 0.60	0.035 0.90	0.047 1.20
Polluted natural soils and industrial grounds	0.006 0.15	0.030 0.75	0.059 1.50	0.089 2.25	0.118 3.00
Aggressive natural soils (swamp, marsh, peat, ...)	0.008 0.20	0.039 1.00	0.069 1.75	0.098 2.50	0.128 3.25
Non-compacted and non-aggressive fills (clay, schist, sand, silt, ...)	0.007 0.18	0.028 0.70	0.047 1.20	0.067 1.70	0.087 2.20
Non-compacted and aggressive fills (ashes, slag, ...)	0.020 0.50	0.079 2.00	0.128 3.25	0.177 4.50	0.226 5.75

Notes:
1. Corrosion rates in compacted fills are lower than those in non-compacted ones. In compacted fills, the figures in the table should be divided by two.
2. The values given are only for guidance. Local conditions should be considered because they may affect the actual corrosion rate, which can be lower or higher than the average value given in the table.
3. The values given for 5 and 25 years are based on measurements, whereas the other values are extrapolated.

Loss of Thickness Due to Corrosion for Piles in Fresh Water or in Sea Water

Required design working life	5 Years	25 Years	50 Years	75 Years	100 Years
	in / mm				
Common fresh water (river, ship canal, ...) in the zone of high attack (water line)	0.006 0.15	0.022 0.55	0.035 0.90	0.045 1.15	0.055 1.40
Very polluted fresh water (sewage, industrial effluent, ...) in the zone of high attack (water line)	0.012 0.30	0.051 1.30	0.091 2.30	0.130 3.30	0.169 4.30
Sea water in temperate climate in the zone of high attack (low water and splash zones)	0.022 0.55	0.074 1.90	0.148 3.75	0.220 5.60	0.295 7.50
Sea water in temperate climate in the zone of permanent immersion or in the intertidal zone	0.010 0.25	0.035 0.90	0.069 1.75	0.102 2.60	0.138 3.50

Notes:
1. The highest corrosion rate is usually found at the splash zone or at the low water level in tidal waters. However, in most cases, the highest stresses are in the permanent immersion zone.
2. The values given are only for guidance. Local conditions should be considered because they may affect the actual corrosion rate, which can be lower or higher than the average value given in the table.
3. The values given for 5 and 25 years are based on measurements, whereas the other values are extrapolated.

Steel sheet pile, and many other steel products, are often over-designed because we assume that the maximum bending load in the wall occurs at the same location as maximum corrosion. We can optimize the solution by analyzing corrosion and bending on a zone by zone basis. The following examples use this methodology.

Example 1: Low Water Zone & AMLoCor®

In this example, the maximum bending occurs in the low water zone and the required design life is 50 years. From the bending moment diagram produced in our design model, the maximum bending in each zone can be identified as well as the required section modulus based on the grade of steel.

$$\text{Minimum Section Modulus} = \frac{\text{Maximum Ultimate Bending Moment}}{\text{Yield Strength}}$$

Zone	Depth	Maximum Ultimate Bending Moment kip-ft/ft	Minimum Section Modulus* in^3/ft	Minimum Section Modulus** in^3/ft
Splash	5	25	6.00	5.00
Intertidal	10	100	24.00	20.00
Low Water	13	170	40.80	34.00
Permanent Immersion	20	140	33.60	28.00
Buried	60	130	31.20	26.00

* 50 ksi steel ** 60 ksi steel

The next step is to determine what steel sheet pile section will meet these section properties at the end of the design life. The total corrosion will depend on what type of steel is used.

- For ASTM A572, the Eurocode corrosion rates will be used for the appropriate zone and a non-compacted and non-aggressive fill.
- ASTM A690 is known to significantly reduce the corrosion rate in the splash zone. For this example and the following examples, it is assumed that the corrosion is halved in the splash zone.
- AMLoCor® reduces the corrosion rate in the low water zone by 3 and in the permanent immersion zone by 5.
- It is assumed that coating will protect the steel for 10 years, delaying the start of corrosion.
- It is assumed that galvanizing will protect the steel for 8 years, delaying the start of corrosion.

Zone	Corrosion Rates				
	ASTM A572	ASTM A690	AMLoCor	ASTM A572 – Coated	ASTM A572 – Galvanized
Splash	0.195	0.097	0.195	0.156	0.164
Intertidal	0.116	0.116	0.116	0.093	0.098
Low Water	0.195	0.195	0.065	0.156	0.164
Permanent Immersion	0.116	0.116	0.023	0.093	0.098
Buried	0.094	0.094	0.094	0.076	0.079

From this point, it is an exercise of trial and error. Select a sheet pile section, reduce the section properties by the proportional thickness loss, and check against the required section modulus for each zone.

$$\text{\% Steel Remaining} = \frac{\text{Original Flange Thickness} - \text{Total Corrosion in Zone}}{\text{Original Flange Thickness}}$$

$$\text{Reduced (Corroded) Section Modulus} = \text{(\% Steel Remaining)*Original Section Modulus}$$

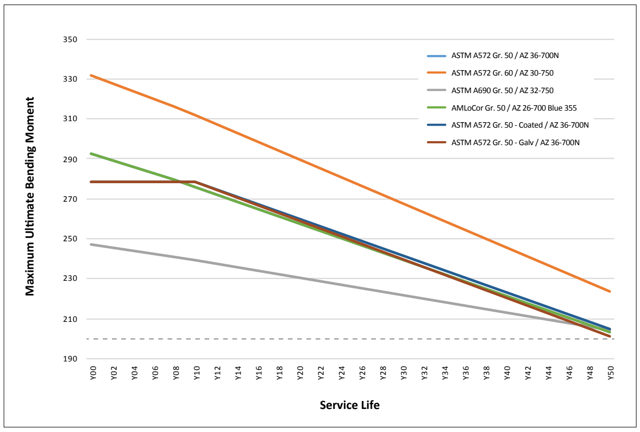
For typical ASTM A572 Gr. 50 steel, the AZ 36-700N was checked and confirmed as the optimal option.

Sheet Pile Section	Original Section Modulus in³/ft	Flange Thickness in	Thickness Loss in	% Remaining	Reduced Section Modulus in³/ft	Required Section Modulus in³/ft	Design Check
AZ 36-700N ASTM A572 Gr. 50	66.8	0.591	0.195	67.0%	44.76	6.00	OK
	66.8	0.591	0.116	80.3%	53.66	24.00	OK
	66.8	0.591	0.195	67.0%	44.76	40.80	OK
	66.8	0.591	0.116	80.3%	53.66	33.60	OK
	66.8	0.591	0.094	84.0%	56.11	31.20	OK

Next, other steel grades or corrosion protection methods can be considered and compared. For example, if AMLoCor steel is used, the required steel sheet pile section is reduced to AZ 26-700N, providing more than 20% in weight savings and, therefore, cost savings.

Sheet Pile Section	Original Section Modulus in³/ft	Flange Thickness in	Thickness Loss in	% Remaining	Reduced Section Modulus in³/ft	Required Section Modulus in³/ft	Design Check
AZ 26-700N Blue 355 (51 ksi min yield)	48.4	0.480	0.195	59.4%	28.76	6.00	OK
	48.4	0.480	0.116	75.8%	36.70	24.00	OK
	48.4	0.480	0.065	86.5%	41.85	40.80	OK
	48.4	0.480	0.023	95.2%	46.06	33.60	OK
	48.4	0.480	0.094	80.3%	38.88	31.20	OK

The figure on the right summarizes the results of all of the various steel grades. Due to the fact that AMLoCor® corrodes at a much slower rate in the low water zone, the critical zone for this example, we can start with a much smaller sheet pile section and end up with the same design life. This amounts to significant project cost savings at the start of the project and over the life of the wall.



Summary of Steel Grades and the Optimal Section for Each Grade

Example 2: Splash Zone

In this example, the maximum bending occurs at the splash zone. The required design life is 50 years. From the bending moment diagram produced in our design model, the maximum bending in each zone can be identified as well as the required section modulus based on the grade of steel.

Zone	Depth	Maximum Ultimate Bending Moment kip-ft/ft	Minimum Section Modulus (50 ksi steel) in³/ft
Splash	5	200	48.00
Intertidal	10	175	42.00
Low Water	13	150	36.00
Permanent Immersion	30	100	24.00
Buried	60	75	18.00

For this example, ASTM A690 Gr. 50 steel will be used. A690 has been shown to reduce corrosion in the splash zone by 2 to 3 times, 2 will be used for the following analysis.

Zone	Corrosion Rate
	ASTM A690
Splash	0.097
Intertidal	0.116
Low Water	0.195
Permanent Immersion	0.116
Buried	0.094

As with the previous example, it is an exercise of trial and error from this point. Select a sheet pile section, reduce the section properties by the proportional thickness loss, and check against the required section modulus for each zone.

For typical ASTM A572 Gr. 50 steel, the AZ 38-700N was checked and confirmed as the optimal option.

Sheet Pile Section	Original Section Modulus in³/ft	Flange Thickness in	Thickness Loss in	% Remaining	Reduced Section Modulus in³/ft	Required Section Modulus in³/ft	Design Check
AZ 38-700N ASTM A572 Gr. 50	70.6	0.630	0.195	69.1%	48.76	48.00	OK
	70.6	0.630	0.116	81.6%	57.58	42.00	OK
	70.6	0.630	0.195	69.1%	48.76	36.00	OK
	70.6	0.630	0.116	81.6%	57.58	24.00	OK
	70.6	0.630	0.094	85.0%	60.01	18.00	OK

Using ASTM A690, the sheet pile section can be reduced to AZ 32-750, providing more than 13% in weight savings and, therefore, cost savings.

Sheet Pile Section	Original Section Modulus in³/ft	Flange Thickness in	Thickness Loss in	% Remaining	Reduced Section Modulus in³/ft	Required Section Modulus in³/ft	Design Check
AZ 32-750 ASTM A690 Gr. 50	59.5	0.551	0.097	82.3%	48.98	48.00	OK
	59.5	0.551	0.116	78.9%	46.96	42.00	OK
	59.5	0.551	0.195	64.6%	38.46	36.00	OK
	59.5	0.551	0.116	78.9%	46.96	24.00	OK
	59.5	0.551	0.094	82.9%	49.30	18.00	OK

Example 3: ASTM A572 Gr. 60

With or without corrosion, higher steel grades should always be considered. In this example, simply choosing Gr. 60 over Gr. 50 steel provides significant savings.

From the bending moment diagram produced in our design model, the maximum bending in each zone can be identified as well as the required section modulus based on the grade of steel.

Zone	Depth	Maximum Ultimate Bending Moment kip-ft/ft	Minimum Section Modulus (50 ksi steel) in^3/ft	Minimum Section Modulus (60 ksi steel) in^3/ft
Splash	5	25	6.00	5.00
Intertidal	10	100	24.00	20.00
Low Water	13	170	40.80	34.00
Permanent Immersion	30	140	33.60	28.00
Buried	60	130	31.20	26.00

For typical ASTM A572 Gr. 50 steel, the AZ 36-700N was checked and confirmed as the optimal option.

Sheet Pile Section	Section Modulus in^3/ft	Required Section Modulus in^3/ft	Design Check
AZ 36-700N ASTM A572 Gr. 50	70.6	48.00	OK
	70.6	42.00	OK
	70.6	36.00	OK
	70.6	24.00	OK
	70.6	18.00	OK

Using ASTM A572 Gr 60, the sheet pile section can be reduced to AZ 30-750, providing more than 14% in weight and, therefore, cost savings

Sheet Pile Section	Section Modulus in^3/ft	Required Section Modulus in^3/ft	Design Check
AZ 30-750 ASTM A572 Gr. 60	55.9	5.00	OK
	55.9	20.00	OK
	55.9	34.00	OK
	55.9	28.00	OK
	55.9	26.00	OK

Installation

The two things critical to the installation of steel sheet pile systems are wall alignment and equipment selection. Good alignment reduces friction in the interlocks and keeps the wall straight. The right equipment ensures the piles can be installed without being damaged.

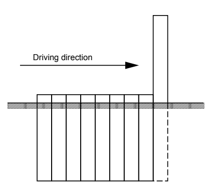
Alignment

To ensure good alignment of a sheet pile wall, attention needs to be given to the template and the driving method.

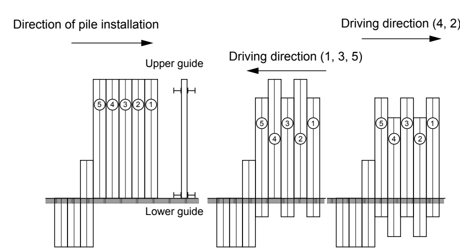
Templates vary from a single beam laying on the ground to complex structures for combined walls and circular cells. For a normal Z-pile wall, double sided templates work better than single sided templates, and double tiered templates work better than single tiered systems. Although more complicated templates are more expensive, and take longer to setup and move, they pay for themselves by reducing installation problems and producing a straighter wall. This is especially true for walls with long piles and difficult soil conditions.

One of the most common methods for driving sheet piles is called the pitch and drive method. This method involves setting the sheet pile and driving it to grade before the next sheet pile is set. This works fine with short sheet piles and easy driving conditions, but it is difficult to maintain alignment with longer sheets and harder driving conditions. In more difficult conditions, it is better to use panel or staggered driving. Both of these methods involve setting multiple piles and working the group down rather than one pile at a time. Since the piles help support and guide one another, this makes it easier to keep the wall straight, horizontally and vertically.

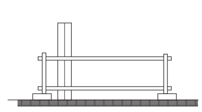
Pitch and Drive Method



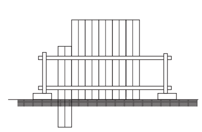
Staggered Driving Method



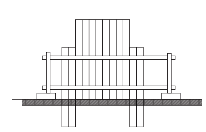
Panel Driving Method



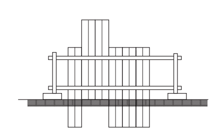
1. Pitch, align, & plumb 1st pair



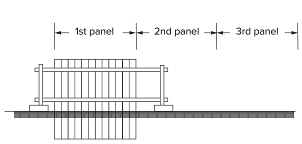
2. Drive 1st pair – carefully & accurately pitch remainder of panel



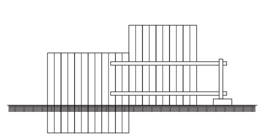
3. Ensure last pair is accurately positioned & plumbed, drive last pair



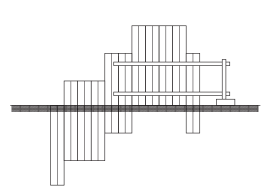
4. Drive remainder of panel – working backwards toward 1st pair



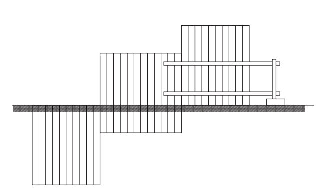
5. 1st panel part driven



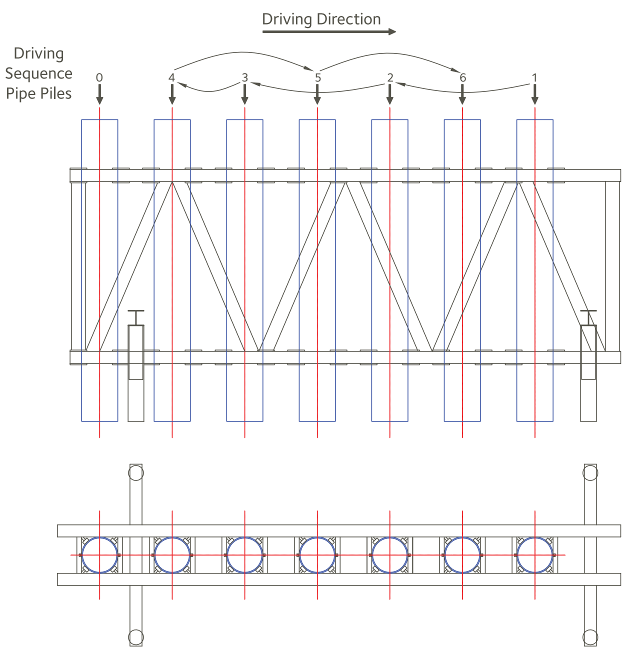
6. 2nd panel pitched. Last pair of 1st panel becomes 1st pair of 2nd panel.



7. 1st panel driven to final level in stages. Last pair of 2nd panel plumbed & driven accurately



8. 1st panel completed. 2nd panel partly driven. 3rd panel pitched. Last pair of 2nd panel becomes 1st pair of 3rd



Double sided, double tiered king pile template

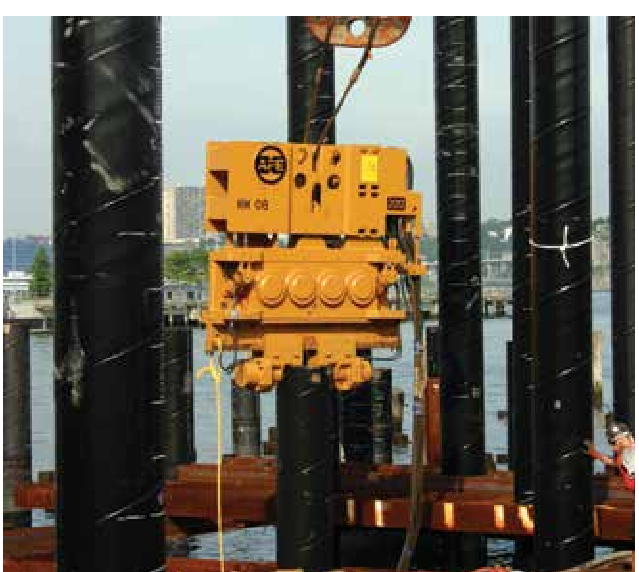
For combined wall systems made up of beams or pipes and sheet piles, it is essential to have a good template. The template should have pockets for the king piles to ensure the spacing of the king piles is as close to theoretical as it can be. For king pile walls, the beams or pipes are driven first and the sheet piles are installed after the template has been moved. Driving the sheet piles between two sets of king piles requires that the king piles be almost perfectly vertical. The two tiered, double sided template controls this to ensure verticality and reduce the driving stress in the intermediate piles.

Equipment

Vibratory hammers are the most common method for driving sheet piles. They work by clamping the top of the sheet and quickly vibrating the pile in a vertical direction. The vibration coupled with the self-weight of the pile and the hammer allow the pile to penetrate the soil. Vibratory hammers work best in loose sands and silts, but have difficulty in very dense granular material and stiff clays. The vibration of the pile does little to move cohesive material and makes it more difficult for the pile to advance. If the pile does not move for an extended period of time, the friction in the interlock can create enough heat to melt the steel.

Impact hammers are less common and slower than vibratory hammers, but are sometimes necessary. The falling weight of an impact hammer strikes the cap, which is placed over the top of the pile to protect it. The hammer has to have enough energy to install the pile, but has to be limited so the pile is not damaged. Ram weight should be at least the weight of the pile, plus the cap. Generally speaking, a heavier ram with a lower stroke works better than a light ram with a long stroke. Impact hammers can be used to finish piles a vibratory hammer started and can be used to verify the vertical load capacity of a sheet pile, just like any other bearing pile.

When noise and vibration are an issue, presses can be used to push the sheet piles into the soil. Press equipment is not as common as vibratory and impact hammers, so care should be taken to ensure equipment is available if low noise/vibration is specified for the installation. The noise and vibration levels can be reduced to the point where they are no longer an issue on the project. The types and capacities of presses can vary widely and they cannot all handle every type of sheet pile. Most presses do not have the capability of handling large combined walls. Some presses have the ability to load test the piles as they are being driven.



Vibratory Hammer

Impact Hammer

Driving Aids

Sometimes the ground is too hard to install the piles without assistance. There are various ways to help drive the piles down and/or reduce the probability of damage.

Low or high pressure water jetting can be used in granular and lightly cohesive soils. The jets of water coming out of tubes at the toe of the piles help to reduce toe resistance and skin friction near the bottom of the pile.

Augers can be used to break up hard layers of soil and make the pile easier to drive. If the piles need to be toed into rock, it might be necessary to remove rock, install the pile and then replace the voids around the toe of the pile with fill or concrete.

If the bedrock is too high to ensure stability of the wall, the pipe piles and/or sheet piles can be pinned to the rock. The pipe piles can be anchored to the rock by drilling out the inside of the pipe, while the sheet piles would need additional tubes. Geotechnical and structural engineers must evaluate the wall requirements and the strength of the bedrock before attempting to anchor any piles to it.

Blasting can also be used to fracture rock when pre-drilling is not sufficient, but this method requires certain precautions. It is critical to make sure that there is enough soil above the explosion to contain all of the energy from the blast. Also, keep in mind that explosives create powerful vibrations in the soil which could affect surrounding structures. Consult an explosives expert before blasting to be sure that the grade, direction and magnitude of the explosion is properly designed.

In cohesive soils, the skin friction between the pile and the soil can make installation more difficult. Adding cutting shoes, driving points or plates to the toe of the pile will help temporarily reduce the skin friction on the rest of the pile. The additional steel will also reduce the likelihood of damage to the toe of the pile. Under hard driving conditions, steel plates can be added to strengthen the top of the pile. These plates will reinforce the pile around the clamps of the vibratory hammer or the top of the pile, just below the driving cap.

Hydraulic press with auger assist

Sheet Pile Protector

TECHNICAL/SALES
866.875.9546
engineering@nucorskyline.com

www.nucorskyline.com

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info@nucorskyline.com

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04/21 Edition