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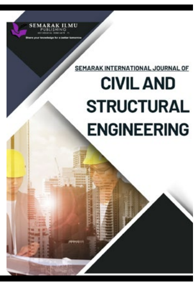

The Effect of Sheet Pile Used for Temporary Work Structure for Excavation Purposes

Melvin Kho Ying Fan[1,*], Daryn Ng Tee Ngi[1], Sim Dong Hao[2], Ng Yen Ying[1], Kok Zi Jie[1], Ho Cheng Jun[1], Muhammad Noor Hisyam Jusoh[1]

[1] Department of Civil Engineering, Faculty of Engineering, Technology and Built Environment, UCSI University, Jln UCSI, Taman Connaught, 56000 Kuala Lumpur, Malaysia
[2] Department of Mechanical Engineering, Faculty of Engineering Sciences, University College London, Gower St, London WC1E 6BT, United Kingdom

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ABSTRACT

It is often challenging to construct temporary work structures for excavation work with temporary structures at coastal areas with soft soil properties and high-water tables. In this project, we simulated the behaviour of soil movements and stresses by finite element analysis method (using PLAXIS 2D) under different types of U- type steel sheet piles. The outcome result is then presented in the form of a table in this paper, for comparison and reference, which promotes better workmanship and quality in selecting the suitable sheet pile used for temporary work structures for excavation purposes at the coastal area. Deformed mesh, Horizontal Displacement, Horizontal Incremental Displacement, Safety Factor, Total Displacement, Total Incremental Displacement, Vertical Displacement as well as Vertical Incremental Displacement for both with groundwater and without groundwater conditions of each option are included in the result and analysis section. In conclusion, the analysis serves as an important guideline and reference before the commencement of work, which is important in the decision-making of future work, especially during excavation.

1. Introduction

The U-type steel sheet pile is often used in construction as a temporary supporting structure for excavation work due to its flexibility of design constructions, fast execution, and high profitability based on full or partial material recovery [40]. On the other hand, the soil in coastal areas normally consists of high content of sand [32], complicating the situation and necessitating a different approach. In such a case, compaction is often needed if the soil has a lower soil-bearing capacity [39].

As suggested by Muhammad Noor Hisyam Jusoh in their previous study, Malaysia is well known for its diverse soil types [26]. And this presents unique challenges in geotechnical work, emphasizing the need to account for variations in soil properties during excavation and construction. While prior

[*] *Corresponding author.*
E-mail address: melvin.kho2002@gmail.com

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research has highlighted these regional complexities, there remains a lack of comprehensive studies focusing on the performance of U-type steel sheet piles in the specific soil conditions, particularly in coastal areas characterized by soft soils and high groundwater tables.

Since the soil at coastal area is mainly soft soil, and the soft soil often brings difficulties for civil engineering works, including the execution of civil engineering structures and geotechnical design due to the fact that the soil is sensitive to deformation and possesses very small shear strength. At such, the usage of Finite Element Method has become increasingly popular and available on market for the analysis of geotechnical problems, including but not limited to the excavation works [28].

On the other hand, in the industry of civil engineering, a U-type steel sheet pile could be used as a temporary work structure for excavation work by providing lateral support to stabilize the structure and prevent erosion of soil, especially during excavation. It is also often used for the construction of marine structures in coastal areas and is an effective way to avoid the movement of soil in deep excavation to ensure the safety of other nearby structures and workers [24].

In our case, we would like to study the movement of different types of individual U-type steel sheet piles as temporary work structures for excavation work in soil, by utilizing the PLAXIS 2D software for simulation, and the data including Deformed mesh, Horizontal Displacement, Horizontal Incremental Displacement, Total Displacement, Total Incremental Displacement, Vertical Displacement as well as Vertical Incremental Displacement under both groundwater and without groundwater condition will be presented in the form of a table in a later section (Results and Analysis).

Despite the growing body of research on U-type steel sheet piles for coastal excavation, significant gaps remain in understanding the specific performance differences under varied soil and environmental conditions, particularly concerning groundwater influence. Previous studies have either generalized soil behavior or lacked comparative analyses of multiple sheet pile types under identical simulation settings. Additionally, while the benefits of finite element analysis (FEA) for pre-construction planning are acknowledged, its application to systematically evaluate different sheet pile configurations for optimal selection in coastal conditions has not been fully explored.

This study addresses these gaps by employing PLAXIS 2D to simulate and compare the deformation and displacement characteristics of three U-type steel sheet piles—YSPIII, FSPIII, and FSPIIIA—under both groundwater and non-groundwater conditions. This study assumes homogeneous soil properties throughout the excavation site.

The findings aim to offer a clearer understanding of the interplay between groundwater and sheet pile performance, contributing valuable insights for decision-making in geotechnical engineering and coastal excavation projects. By utilizing advanced tools like Plaxis 2D or other Finite Element Analysis (FEA) software, stakeholders can conduct comprehensive pre-construction analyses, enabling informed decisions that enhance project planning, structural reliability, and cost-effectiveness.

2. Literature Review

2.1 Soil Properties at Coastal Area

Generally, the coastal zone often refers to a zone or interface between the land and water [37]. It can also be defined as a site of intimate interactions between the land, ocean, as well as the atmosphere [13].

In the coastal area, sands are the main component throughout the beach and offshore deposits, while the back barrier deposits are mainly consisting of clay or clay loams [43]. On the other hand, the Coastal Engineering Guidelines published by Engineers Australia also suggested that the coastal soil in Australia, specifically the presence of acid sulphate soils may cause the rapid deteriorate of concrete and steel foundations or other structures at low lying geologically recent coastal sediments [7]. In such case, a higher factor of safety maybe needed for construction work, especially geotechnical works.

A review paper conducted by University of Tabuk and University of Aswan also suggested that the salt present in the soils at coastal area would generally reduce the plasticity index, soil compressibility, swelling properties, and optimum moisture content, while enhancing the permeability, maximum dry density, shear strength, and bearing capacity of the soil [17]. This indicates it is another variable and factor of influencing the soil properties at coastal area, making it more complex than ordinary soil at non-coastal area.

In addition, the review paper also suggests that the salt present in the seawater, when intruded by seawater, it increases the permeability of soil, resulting in greater settlement, decreased strength or collapse in the worst-case scenario [17]. This clearly indicates that the soil at coastal area possess a weaker mechanical property, and increasing the difficulty level of geotechnical work. In terms of the plasticity of soils, the seawater would have a significant Impact on the clayey soils with liquid limits exceeding 110%, such that it increases the liquid limits when the salt concentration increases but bringing a reverse effect for other types of soil such that their compression index may decreases when the salt concentration increases [17].

Last but not least, the Encyclopaedia of Marine Geoscience also suggests that the main components of coastal area, particularly the sediment type at the site are built up from rock, gravel, sand, clay and muddy soils, while the muddy soils and clays are often treated separately or differently from the other soils and rocks, as they are affected by water in terms of their properties [23].

2.2 Application of Sheet Pile in Excavation and Other Works

Sheet piles come in various forms, each tailored for specific uses. Steel sheet piles are the most prevalent, known for their robustness and adaptability, often employed in retaining walls and cofferdams. Vinyl sheet piles provide excellent resistance to corrosion, making them ideal for marine environments. Aluminum sheet piles are lightweight and offer good corrosion resistance, suitable for waterfront structures. Composite sheet piles combine materials like fiberglass and resin, offering high strength and durability. Timber sheet piles are used in temporary structures or where environmental impact is a concern. Lastly, concrete sheet piles are utilized in permanent structures requiring high strength and durability [36].

According to the Department of Occupational Safety and Health of Malaysia (DOSH) [15], the excavation work can be defined as the process of removing the earth, rock, or other materials during construction or demolition involving or by using tools, machinery, or explosives to create an open surface, hole, or cavity. Works such as earthwork, trenching, cofferdam, caisson, well, shaft, tunnel or underground working are often classified under the excavation work as well.

The method of excavation could generally be classified as trench excavation (used for installing underground utilities such as pipes and cables), basement excavation (creates extra space below ground level for storage or living areas), cut and fill excavation (levels uneven terrain by removing earth from one area and filling another), slope excavation (forms inclined surfaces for roads and embankments), dredging (removes sediment and debris from water bodies), footing excavation (prepares foundations for structures like buildings), pit excavation (creates large holes for foundations or storage), rock excavation (removes rock using specialized equipment), channel excavation (creates channels for water flow), trenchless excavation (installs underground utilities without extensive trench digging), underwater excavation (removes material below the water surface for construction or maintenance) [2].

In the construction project, excavation work can be classified as the most significant hazard, especially at coastal areas with more complex soil properties. On the other hand, the steel sheet piles contribute to the safety of excavation work for its ductility (allowing more time for corrective measures) and reliability (comparatively homogenous and constant properties of the steel), in the way of retaining the soil and water applications. And hence, it is always used as temporary structures especially when the projects involve cofferdams in water, linear excavations, water retention, and complicated utilities installation or repairs [6].

In addition, due to the effectiveness of sheet pile in retaining water, it could also be used in the construction of barriers to groundwater flows, to reduce the effect of groundwater to the surrounding soil, which is significant in excavation work [26]. Furthermore, the sheet pile is used in the coastal area to control and to delay the seepage as well as the transportation of contaminants through soil [5]. It is also often used as a part of earth retaining structure at the water-front structure, with its advantages such that dewatering at the site is not compulsory, and often an ideal option or choice at the sites with groundwater tables or soils with lower bearing capacity [40]. For example, it can be used in the construction of harbor or port, by aligning the sheet pile in the way of connecting to major structures like locks and dams [22].

The steel sheet pile is often used and preferred, for its shorter time for installation (does not required curing as reinforced concrete), lighter weight than reinforced concrete, easier for transportation and also homogeneous material (less deterioration of material quality than reinforced concrete) [18].

In simpler language, the sheet pile is often used as an earth retaining wall as temporary excavation protection, and to mitigate the rapid seepage of groundwater into the site. The sheet pile is often made by steel, for its workability and properties mentioned in upper section [18].

2.3 Geotechnical Design and Environmental Interactions of Steel Sheet Piles

Conventional design method of steel pile wall construction is based on limit equilibrium approach, which ignores the construction method used. The conventional methods consider active and passive earth pressure that is based on the Mohr-Coulomb failure criterion [31].

The Mohr-Coulomb failure criterion is expressed as:

$$\tau = \sigma \, tan \, (\phi) + c$$

where τ is the shear strength, σ is the normal stress and c is the intercept of the failure envelope with τ axis, also known as the cohesion. ϕ is the angle of internal friction.

The use of finite element analysis allows the identification of stresses and displacement and creates a vector field for the soil-structure interaction. Therefore, this opens the possibility of discovering the effects of surrounding environment and construction process on the steel sheet pile [11].

The interaction with the surrounding is an important factor when it comes to the study of steel sheet pile as the stability of the sheet pile walls can be heavily affected by the presence of the groundwater flow. The presence of groundwater reduces the passive earth pressure behind the sheet pile and increases the active earth pressure. This reduction of the passive earth pressure stops when the soil is no longer able to withstand any lateral pressure due to loss of strength.

Based on the study conducted [42], the presence of groundwater has no absolute effect on the stability as it may either stabilise or destabilise soil particles, depending on the direction of the flow. The first situation takes place where the resultant of the gravity force and the seepage force is (nearly or completely) downward and the second takes place when this resultant force is (nearly or completely) upward.

The understanding of the interactions of steel pile and the environment has also led to better design of U-shape steel pile. For instance, the study conducted by Zhao *et.al.*[44] has proposed new steel pile with more outward expansion alongside hydrophobic coating and reverse hooks. These modifications provide better anti-seepage performance which will improve practicality and structural integrity as aforementioned in other literatures.

Besides the groundwater, the actual flexural stiffness of sheet piles greatly depends on the shear force transmission between corresponding sheet piles. The sheet pile can have 0% transmission when not connected with any sheet pile; or 100% transmission when welded to the corresponding sheet pile. In most real-life cases, the results should lie between these two extremes as the sheet piles connects with friction in the interlocks [16].

A similar study to this research had been done by Kim *et.al.* [29] where the strain on the steel sheet pile is investigated. The properties of a single sheet pile and coupling mated joint specimen is analysed when interpenetrating into the soil where a V-shape strain-interpenetration graph is observed. In all cases, the strain did not exceed the yield strain, proving the feasibility of re-using sheet pile for construction. Another practical implication of the finite element analysis study on sheet pile is to derive seismic fragility curves, which can provide invaluable information for disaster prevention. [30] In Singapore, Moriyasu *et.al.* [34] researched on the flexural stiffness of U-type steel sheet pile with PLAXIS excavation simulation model under different soil conditions. This research investigated the reduction in flexural stiffness due to the lack of shear force transmission in U-type steel sheet pile and compared it with other type of sheet pile. It is also important to note that FEA may not fully represent real-life scenarios. In a numerical modelling done for sheet piles behavior [16], the standard values for flexural stiffness for a single U-Pile is largely overestimated. In the worst-case scenario, the effective stiffness of an individual U-pile is only 32% of the full wall stiffness.

2.4 Introduction to Finite Element Analysis (FEA)

According to Flaherty and Eaton in their book titled “Finite Element Analysis”, the Finite Element Method is commonly used as a computational technique in engineering and scientific fields to obtain approximate solutions to partial differential equations [25].

In addition, according to the official website of Ansys, 1 of the most used finite element analysis software, Finite Element Analysis (FEA) is the application of the Finite Element Method (FEM) which utilizes mathematical equations to further break down the complex problems or systems into smaller pieces of elements by using the computer, which is always used to validate and test designs. In Civil Engineering, FEA is often utilized to conduct the evaluation of the safety and integrity of structures, including but not limited to the construction of dams, commercial buildings as well as bridges by optimizing the engineering design to meet safety standards and to predict the needs of maintenance work [4].

For example, the FEA software such as Ansys could be used in the analysis and calculation of stress intensity factors of an edge crack, in a function of time, crack length, and thickness ratio for 2 types of different material systems, as what Basheerali, Hrairi, and Jaffar Syed did in their research of Thermal Stress Intensity Factors for Cracked Bimaterial System Under Convective Cooling [9].

Also, the official website of AutoDesk [8], one of the biggest engineering software providers nowadays suggests that the advantages of using FEA software include:

i. Accurate performance modeling and simulation
ii. Enable prototype virtually
iii. Accurate Analysis (Predictive)

On the other hand, Mustafa Seif, a senior civil engineer suggests that the limitations of FEA software come in a way such that it is highly complex and difficult especially for new users, as it involves various steps and sub-steps including pre-processing, processing as well as post-processing. In addition, the accuracy could be low and unreliable due to errors and uncertainties in modeling such as human errors, numerical errors, discretization errors, and modeling errors [35].

The software used in this research, the PLAXIS 2D, is one of the products under the Bentley system, another popular engineering software provider. According to the official website of Bentley Systems, it is a commonly used software in the civil engineering and geotechnical engineering industry due to its efficiency and user-friendliness. It is often applied in simulating the deformation in excavation works and conducting safety analysis in the work [10].

The elements in the system during simulations consist of nodes and beam. These connected elements can be described with the formula $F^e = K^e\, d^e$, which can also be written in the matrix form.

$$[F_1^e\ F_2^e\ ] = [k^e\ -k^e\ -k^e\ k^e\ ]\ [u_1^e\ u_2^e\ ] \quad (1)$$

Based on the Figure 1, the force and displacement acting on a section of a pile can be represented by a component consisting of 3 nodes and 2 beams. The force acting on node 2 of the first beam is equivalent to the force acting on node 1 of the second beam. Therefore, it is possible to conclude $F_2^{(1)} = F_1^{(2)}$ and $u_2^{(1)} = u_1^{(2)}$, where $F_1^{(1)}$ and $F_1^{(2)}$ are related to the matrix above. Hence, the software calculates the parameters by propagating the forces and displacements acting on the nodes based on the boundary conditions [12].

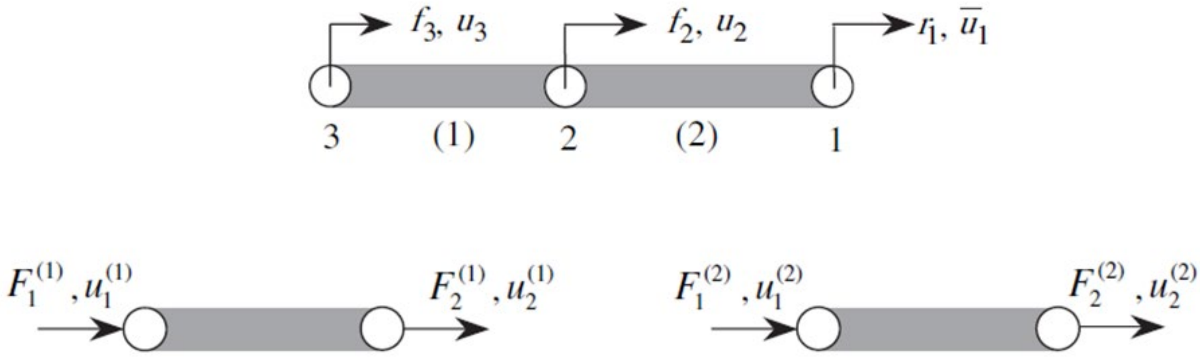


Fig. 1. The force and displacement acting on pile represented in beams and nodes

2.5 Equation to Estimate the Settlement of Pile in Clay

Generally, the Poulos and Davis Equation could be used for the estimation of pile settlement considering both pile-soil interaction and pile group effects, and it has been widely adopted in geotechnical engineering for estimating the settlement of piles.

In the Malaysia's Public Work Department or the JKR (Jabatan Kerja Raya) Geotechnical Design Guideline [38], they also suggested the Poulos and Davis Equation to estimate the settlement of an individual pile in clay, such that:

$$\rho = \frac{Q}{L.E_S}.I_p \tag{2}$$

whereby the
$\mathrm{Q} = \text{Load on the pile}$
$\mathrm{L} = \text{Length of Pile}$
$\mathrm{Es} = \text{Young'smodulus of the soil for long term settlement}$

$$Es = (1 + \nu)(1 - 2\nu) / Mv\,(1 - \nu) \tag{3}$$

$\mathrm{Mv} = \text{Average value of Coefficient of Compressibility}$
$\mathrm{V} = \text{Poisson's ratio}$

The Poisson's ratio can be taken as 0.4 for over consolidated clays, firm or stiff normally consolidated clays, 0.2 for soft to firm normally consolidated clays.
Ip = influence factor from the Figure 2 and Figure 3:

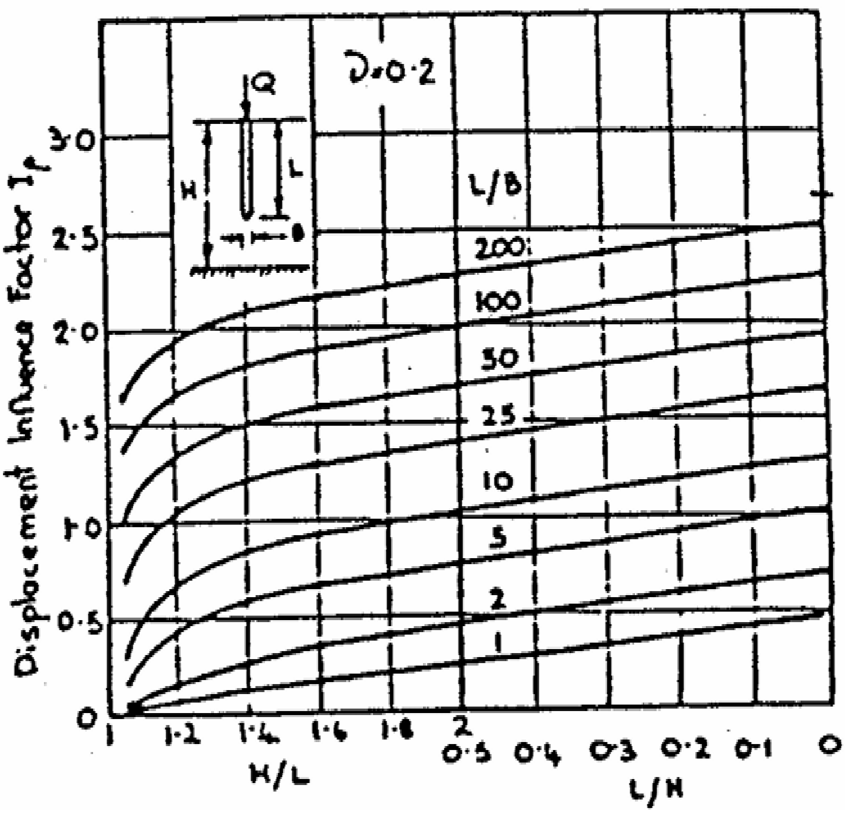


Fig. 2. values of influence factor when Poisson's ratio = 0.2

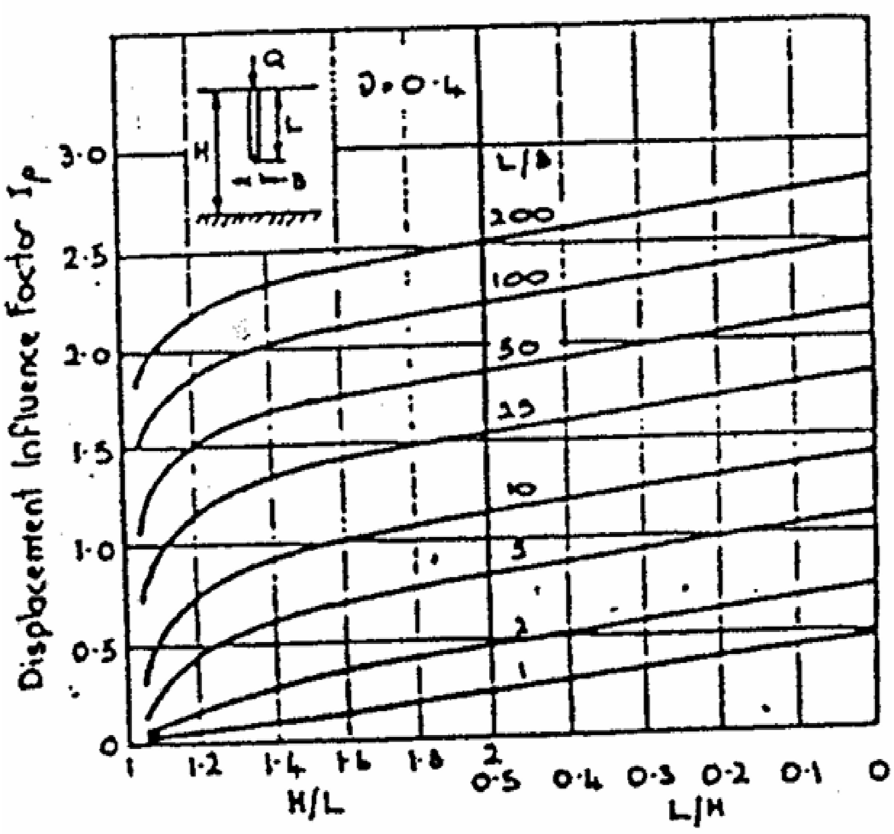


Fig. 3. values of influence factor when Poisson's ratio = 0.4

The equations and formulas above show a straightforward, quick and simple way in giving rough estimation of the settlement of pile, but it should not be relied on to give accurate values according to JKR, as it is often complex to fully understand the relationship and interaction between surrounding soils and the pile [38].

At such, finite element analysis which can be used for complex and detail analysis is hence more preferred. On the other hand, the method above does not outline the effect of presence of groundwater to the settlement of pile. In addition, the estimation of settlement does not outline all of the movement, such as horizontal movement of soil.

3 Methodology

The literature review has been done by reading relevant articles and journals covering different topics, including geotechnical engineering, finite element analysis, and soil mechanics. This included but not limited to research papers available online.

Some of the official websites of software providers such as Bentley are also referred, for the discussion and literature review of the Finite Element Analysis Method software.

The simulation of soil behaviour to obtain the data of Deformed mesh, Horizontal Displacement, Horizontal Incremental Displacement, Total Displacement, Total Incremental Displacement, Vertical Displacement as well as Vertical Incremental Displacement under both groundwater and without groundwater conditions is done by PLAXIS 2D, a well-known finite element analysis software.

To enhance the credibility and accuracy of the study, a team member with a Mechanical Engineering background was deliberately included to provide a multidisciplinary perspective. This addition ensures a broader analysis of the results by integrating expertise from a distinct engineering discipline, offering insights that might not be apparent from a single-field approach. Furthermore, this collaboration facilitates more thorough oversight of the case study, helping to identify potential gaps or improvements in methodology. The inclusion of diverse skill sets and viewpoints strengthens the overall rigor and integrity of the research process.

The input values for FEA by Plaxis 2D will be discussed in detail in the next section (3.1)

3.1 Input Values for Modelling and Settings

The following values are used as input into PLAXIS 2D for simulation, which are relatively conservative values deduced from experience in coastal areas. The values are as follows:

In this pit excavation scenario, the excavation depth is 4 m and the width is 8 m, while the soil model extends to a depth of 12 m and a width of 24 m. The pit walls are vertically cut, supported by sheet piles with a total length of 10 m (4 m exposed above ground and 6 m inserted into the soil for stability). A surcharge of 20 kN/m² (2 tonnes/m²) is applied on both sides of the pit, considering the potential impact of heavy vehicle movement. The surcharge is a conservative value considering the weight from heavy vehicles, scaffolding, construction material and soil. Besides, the soil properties used in our research are assumed to be as follows:

Table 1
Input of soil parameters

Material	Unit Weight, $\boldsymbol{\gamma}$	Saturated Unit Weight, $\boldsymbol{\gamma}_{sat}$	stiffness, E_{ref}	Void Ratio, V	Reference Cohesion, C_{ref}	Friction angle, $\boldsymbol{\phi}$
Soft Silty Clay	15kN/m^3	18kN/m^3	1800kN/m^2	0.35	10kN/m^2	15°

All the soil parameters are taken from a soil investigation report, from coastal area at northern Malaysia. The values from the soil investigation report are also cross checked with the suggested soil parameters available in Geotech data and other references.

As discussed in the previous section (2.1, soil properties at coastal area), considering the moist soil unit weight (referred as “unit weight” in the later section) is often greater than the dry unit weight (11.5 kN/m^3-14.5 kN/m^3) [14], unit weight with a value of 15 kN/m^3 is then considered logic, which indicate that the soil condition is less ideal in the way that it contributes less to the bearing capacity of pile and increase the risk of settlement. The void ratio is also ranged from 0.25 to 1.8, and a value of 0.35 in our cases which we assume the soil has been slightly compacted due to the machineries and human activities [20]. The cohesion is also suggested ranged between 10 to 20 kN/m^2, with the fact that the soil is less cohesive, it is also an acceptable value within suggested range (as it is closer to the sand at coastal area, assume the clay near to the boundaries) [19].The stiffness of soil is suggested to be 0.5 Mpa to 5 Mpa (500 kN/m^2 to 5000 kN/m^2) for very soft to soft clays with low-medium plasticity, 0.35 Mpa to 4 Mpa (350 kN/m^2 to 4000 kN/m^2) for very soft to soft clays with high plasticity, a value of 1.8 Mpa or 1800 kN/m^2 in our case, which is within both ranges [21]. On the other hand, the friction angle of clay may range from 6°to 24°, depending on the plasticity of the clay [1]. A value of 15° is a moderate and medium value in this case.

For the project, the water table level is set as 1 m below the surface, and the excavation is planned in four layers, each with a depth of 1 m, which can help to manage the soil pressures. Struts will be installed at 1.2 m from the top to provide additional lateral support to the sheet piles during the excavation.

The recommended steel pile is a U-type YSPIII, FSPIII, and FSPIIIA, Use 200×10^6kN/m² as the Young Modulus of Steel to provide the necessary strength to withstand the soil pressure. The elastic modulus of steel is taken as 200×10^6kN/m², which is a widely accepted conservative value for young modulus of steel, given that the young modulus of steel normally ranged between 190

$\times$ 10^6kN/m² to 210 $\times$ 10^6kN/m² [3]. While the other properties of sheet pile are listed in the next section (section 3.2, figure 5 and 6).

The software settings are as follows, with assumptions that for the entirety of the excavation, installation of sheet piles, struts, and waler beams, the soil type remains unchanged and of Soft Clay and utilizing Mohr-Coulomb's material modeling type (refer to appendix for example of PLAXIS 2D rendition) with an Unit Weight, γ= 18kN/m^3 and saturated Unit Weight, γ_{sat} = 15kN/m^3, stiffness, E_{ref} of 1800kN/m^2, a void ratio, V of 0.35, Reference Cohesion, C_{ref} of 10kN/m^2 , Friction angle, ϕ of 15°.

With the specifications of the Struts being calculated as followed, by obtaining all the necessary data from figure 5 and 6 at the next section (3.2), such that :

YSP III and FSP III:

$$\mathrm{EA} = 200\mathrm{x}10^6\mathrm{kN/m^2\ x\ 76.42cm^2\ (per\ pile)\ x\ 1}\ \frac{\mathrm{m^2}}{\mathrm{1x10^4cm^2}} = 1.53\mathrm{x}10^6\mathrm{kN},$$

FSP IIIA:

$$\mathrm{EA} = 200\mathrm{x}10^6\mathrm{kN/m^2\ x\ 74.40cm^2\ (per\ pile)\ x\ 1}\ \frac{\mathrm{m^2}}{\mathrm{1x10^4cm^2}} = 1.49\mathrm{x}10^6\mathrm{kN},$$

For struts of sheet piles with a spacing of 1.2m between each strut. The specifications for sheet piles used are calculated as follows:

For YSP III

$$\mathrm{EA} = 200 \times 10^6\,\frac{\mathrm{kN}}{\mathrm{m^2}} \times 191 \times 10^{-4}\,\frac{\mathrm{m^2}}{\mathrm{m}} = 3.82 \times 10^6\,\frac{\mathrm{kN}}{\mathrm{m}}$$

$$\mathrm{EI} = 200 \times 10^6\,\frac{\mathrm{kN}}{\mathrm{m^2}} \times 16400 \times 10^{-8}\,\frac{\mathrm{m^4}}{\mathrm{m}} = 32.8 \times 10^3\,\frac{\mathrm{kNm^2}}{\mathrm{m}}$$

$$\mathrm{w} = 150\,\frac{\mathrm{kg}}{\mathrm{m^2}} \times \frac{9.81\mathrm{m}}{1000\mathrm{s^2}} = 1.47\,\frac{\frac{\mathrm{kN}}{\mathrm{m}}}{\mathrm{m}}$$

For FSP III

$$\mathrm{EA} = 200 \times 10^6\,\frac{\mathrm{kN}}{\mathrm{m^2}} \times 191 \times 10^{-4}\,\frac{\mathrm{m^2}}{\mathrm{m}} = 3.82 \times 10^6\,\frac{\mathrm{kN}}{\mathrm{m}}$$

$$\mathrm{EI} = 200 \times 10^6\,\frac{\mathrm{kN}}{\mathrm{m^2}} \times 16800 \times 10^{-8}\,\frac{\mathrm{m^4}}{\mathrm{m}} = 33.6 \times 10^3\,\frac{\mathrm{kNm^2}}{\mathrm{m}}$$

$$\mathrm{w} = 150\,\frac{\mathrm{kg}}{\mathrm{m^2}} \times \frac{9.81\mathrm{m}}{1000\mathrm{s^2}} = 1.47\,\frac{\frac{\mathrm{kN}}{\mathrm{m}}}{\mathrm{m}}$$

For FSP IIIA

$$\mathrm{EA} = 200 \times 10^{6}\,\frac{\mathrm{kN}}{\mathrm{m}^{2}} \times 186 \times 10^{-4}\,\frac{\mathrm{m}^{2}}{\mathrm{m}} = 3.72 \times 10^{6}\,\frac{\mathrm{kN}}{\mathrm{m}}$$

$$\mathrm{EI} = 200 \times 10^{6}\,\frac{\mathrm{kN}}{\mathrm{m}^{2}} \times 22800 \times 10^{-8}\,\frac{\mathrm{m}^{4}}{\mathrm{m}} = 45.6 \times 10^{3}\,\frac{\mathrm{kNm}^{2}}{\mathrm{m}}$$

$$\mathrm{w} = 150\,\frac{\mathrm{kg}}{\mathrm{m}^{2}} \times \frac{9.81\mathrm{m}}{1000\mathrm{s}^{2}} = 1.47\,\frac{\frac{\mathrm{kN}}{\mathrm{m}}}{\mathrm{m}}$$

Whereby:
EA = Elastic Modulus multiplied by Sectional Area (per unit width)
EI = Elastic Modulus multiplied by Moment of Inertia (per wall width)
W = Unit Weight of Sheet Pile

and with a Poisson ratio, v of 0.2 for FSPIII as an example. The following conditions are for both drained (without groundwater) and undrained (with groundwater).

In addition to the information that was already provided, we took advantage of PLAXIS 2D 8.6 Professional to generate the Deformed mesh, Horizontal Displacement, Horizontal Incremental Displacement, Total Displacement, Total Incremental Displacement, Vertical Displacement as well as the Vertical Incremental Displacement for both with groundwater and without groundwater conditions. As the excavation site is in a coastal area, we assume the results from ‘with groundwater’ to be more practical as it is unpractical to drain all the water off before excavating, but both conditions were considered as draining the groundwater is a plausible action that can be taken by site engineers and contractors.

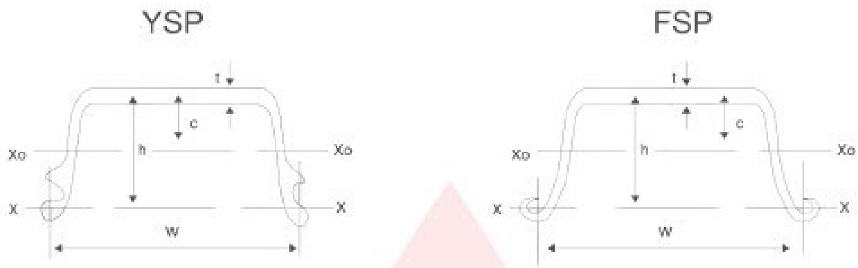
Sheet piles and struts were requested for the excavation pit, therefore, we referred to the Steel Sheet Pile – U Type table to obtain the specifications as well as the dimensions. Furthermore, we also referred to various online resources such as geotechdata.info, a platform that collected all the basic soil parameters based on different standards and manuals that provided us with the specifications of the soil type selected, which is Soft Clay for both ‘with groundwater’ and ‘without groundwater’ conditions.

Within Plaxis 2D, we divided the construction phases into 6 phases. In the first phase, we established that the surcharge of 20kN/m^2 was applied to both sides of the excavation pit surface and the sheet piles were installed before the excavation began for ease of excavation. Phase 2 involves the 1st excavation of the pit with a depth of 1 meter, Phase 3 involves the installation of the strut before the 2nd excavation begins to provide rigidity to the structure to prevent it from collapsing into itself and closing the excavated pit. Phase 4 involves the excavation of the 2nd pit of 1 meter, Phase 5 the excavation of the 3rd meter, and Phase 6 with the excavation of the 4th meter.

3.2 Parameter for Piles

Figure 4 and Figure 5 are the parameters of the 3 piles used in the simulation as discussed in the previous section (section 3.1), which is relatively common in industry for reference.

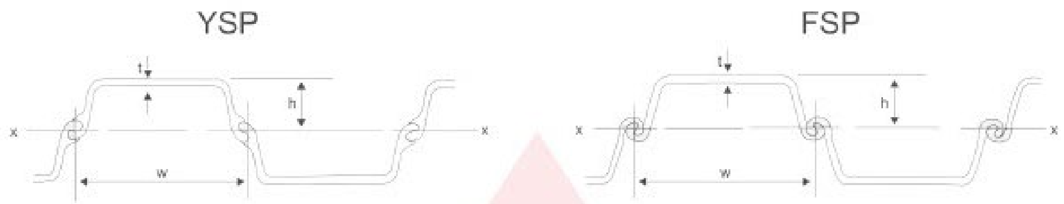
Steel Sheet Piles - U Type



Designation	Dimensions						Sectional Area				Surface Area			
	W		h		t		per pile		per wall width		per pile		per wall width	
	mm	in	mm	in	mm	in	cm²	in²	cm²/ m	in²/ft	m²/m	ft²/ft	m²/m²	ft²/ft²
YSP I	400	15.7	75	2.95	8.0	0.315	46.49	7.206	116.2	4.589	1.15	3.77	1.44	1.44
YSP U-5	400	15.7	80	3.15	7.6	0.299	45.21	7.008	113.0	5.338	1.17	3.84	1.47	1.47
FSP IA	400	15.7	85	3.35	8.0	0.315	45.21	7.008	113.0	5.338	1.21	3.97	1.51	1.51
YSP II	400	15.7	100	3.94	10.5	0.413	61.18	9.483	153.0	7.228	1.24	4.07	1.55	1.55
FSP II	400	15.7	100	3.94	10.5	0.413	61.18	9.483	153.0	7.228	1.33	4.36	1.66	1.66
YSP U-9	400	15.7	110	4.33	9.3	0.366	55.01	8.527	137.5	6.496	1.29	4.23	1.61	1.61
FSP IIA	400	15.7	120	4.72	9.2	0.362	55.01	8.527	137.5	6.496	1.34	4.40	1.68	1.68
YSP III	400	15.7	125	4.92	13.0	0.512	76.42	11.85	191.0	9.022	1.33	4.36	1.66	1.66
FSP III	400	15.7	125	4.92	13.0	0.512	76.42	11.85	191.0	9.022	1.44	4.72	1.80	1.80
YSP U-15	400	15.7	150	5.91	12.2	0.480	74.40	11.53	186.0	8.788	1.43	4.69	1.78	1.78
FSP IIIA	400	15.7	150	5.91	13.1	0.516	74.40	11.53	186.0	8.788	1.44	4.72	1.80	1.80
YSP IV	400	15.7	155	6.10	15.5	0.610	96.99	15.03	242.5	11.46	1.47	4.82	1.84	1.84
FSP IV	400	15.7	170	6.69	15.5	0.610	96.99	15.03	242.5	11.46	1.61	5.28	2.01	2.01
YSP U-23	400	15.7	175	6.89	14.7	0.579	94.21	14.60	235.5	11.12	1.56	5.12	1.94	1.94
FSP IVA	400	15.7	185	7.28	16.1	0.634	94.21	14.60	235.1	11.11	1.57	5.15	1.96	1.96
YSP V	420	16.5	175	6.89	22.0	0.866	134.0	20.77	319.0	15.07	1.59	5.22	1.99	1.99
FSP VL	500	19.7	200	7.87	24.3	0.957	133.8	20.74	267.6	12.64	1.75	5.74	1.75	1.75
FSP VIL	500	19.7	225	8.86	27.6	1.09	153.0	23.72	306.0	14.46	1.83	6.00	1.83	1.83

Fig. 4. Parameter for Piles page 1

Steel Sheet Piles - U Type



Centre		weight				Moment of Inertia				Radius of Gyration		Section Modulus			
C		per pile		per wall width		per pile		per wall width		per pile		per pile		per wall width	
cm	in	kg/m	lbs/ft	kg/m²	lbs/ft²	cm⁴	in	cm⁴/m	in⁴/ft	cm	in	cm³	in³	cm³/m	in³/ft
2.64	1.04	36.5	24.5	91.2	18.7	429	10.3	3,820	28.0	3.04	1.20	66.4	4.05	509	9.47
2.78	1.09	35.5	23.9	88.8	18.2	454	10.9	4,220	30.9	3.17	1.25	64.7	3.95	527	9.80
3.45	1.36	35.5	23.9	88.8	18.2	598	14.4	4,500	33.0	3.64	1.43	88.0	5.37	529	9.84
3.62	1.43	48.0	32.3	120	24.6	986	23.7	8,690	63.6	4.01	1.58	121	7.38	869	16.2
4.04	1.59	48.0	32.3	120	24.6	1,240	29.8	8,740	64.0	4.50	1.77	152	9.28	874	16.3
3.86	1.52	43.2	29.0	108	22.1	1,070	25.7	9,680	70.9	4.42	1.74	120	7.32	880	16.4
4.72	1.86	43.2	29.0	108	22.1	1,460	35.1	10,600	77.6	5.15	2.03	160	9.76	880	16.4
4.72	1.86	60.0	40.3	150	30.7	1,920	46.1	16,400	120	5.01	1.97	196	12.0	1,310	24.4
4.90	1.93	60.0	40.3	150	30.7	2,220	53.3	16,800	123	5.39	2.12	223	13.6	1,340	24.9
5.71	2.25	58.4	39.2	146	29.9	2,700	64.9	22,800	167	5.12	2.02	238	14.5	1,520	28.3
5.84	2.30	58.4	39.2	146	29.9	2,790	67.0	22,800	167	6.12	2.41	250	15.3	1,520	28.3
5.85	2.30	76.0	51.1	190	38.9	2,690	88.7	31,900	234	6.15	2.42	311	19.0	2,060	38.3
6.45	2.54	76.1	51.1	190	38.9	4,670	112	38,600	283	6.94	2.73	362	22.1	2,270	42.2
6.51	2.56	74.0	49.7	185	37.9	4,380	105	39,400	389	6.81	2.68	330	20.1	2,250	41.8
7.45	2.93	74.0	49.7	185	37.9	5,300	127	41,600	305	7.50	2.95	400	24.4	2,250	41.8
6.15	2.42	105	70.6	250	51.2	5,950	143	55,200	404	6.67	2.63	433	26.4	3,150	58.6
6.94	2.73	105	70.6	210	43.0	7,960	191	63,000	461	7.71	3.04	520	31.7	3,150	58.6
8.09	3.18	120	80.6	240	49.2	11,400	271	86,000	630	8.63	3.40	680	41.5	3,820	71.1

Fig. 5. Parameter for Piles page 2

4. Results and Analysis

Theoretically, the pile settlement should not exceed 1% of the pile lateral dimension [33]. In other words, the maximum limit for settlement is 60mm (if only considering the 6m insertion of pile in soil) or 100 mm (considering 10m of total pile length) in our cases, such that only the YSPIII pile fulfill the conditions for not exceeding the 100mm limit, leaving a factor of safety of 1.44 in both condition with groundwater and without groundwater, but failed to comply with the limit of 60mm maximum settlement.

Table 2
Quick Summary of Data Generated from PLAXIS 2D for 3 U-type Steel Sheet Piles under Different Conditions

Parameters	YSPIII		FSPIII		FSPIIIA	
	With Groundwater	Without Groundwater	With Groundwater	Without Groundwater	With Groundwater	Without Groundwater
Deformed Mesh	69.55mm	69.55mm	93.1mm	128.2mm	34.34mm	126.33mm
Horizontal Displacement	41.49mm	41.49mm	53.46mm	39.42mm	20.68mm	55.06mm
Horizontal Incremental Displacement	0.0023mm	0.00225mm	2mm	1.22mm	1.83mm	1.31mm
Total Displacement	69.55mm	69.55mm	93.07mm	128.15mm	34.34mm	126.33mm
Total Incremental Displacement	0.063mm	0.0627mm	4.28mm	3.28mm	2.85mm	1.86mm
Vertical Displacement	69.55mm	69.55mm	93.07mm	128.15mm	34.34mm	126.33mm
Vertical Incremental Displacement	0.061mm	0.061mm	4.22mm	3.1mm	2.39mm	1.63mm

Such that the factor of safety discussed above is quantified as:

$$\text{Factor of Safety, Fs} = \text{Total Displacement} \,/\, 0.01 \times \text{Total Length of Pile} \quad (4)$$

Overall, the pile of YSPIII demonstrates a most consistent performance, with a minimal level of deformation as well as displacement across all the mentioned parameters in the table above, under the condition of both with and without groundwater. This has highlighted its highest stability and suitability for its implementation in coastal areas that require stronger structural performance and stability.

On the other hand, the FSPIII shows significant deformation and displacement especially when without the presence of groundwater which implies its lower stability and higher stress levels, resulting in it being a less ideal choice. FSPIIIA demonstrates moderate levels of deformation and displacement, providing a balanced performance suitable for moderate conditions.

In other words, the YSPIII maintains the highest stability under varying conditions. Consequently, YSPIII is recommended for scenarios requiring high stability, FSPIII for conditions where movement is tolerable, and FSPIIIA for moderate requirements. This comparative analysis serves as a guideline for selecting the most appropriate sheet pile type for temporary work structures in coastal areas.

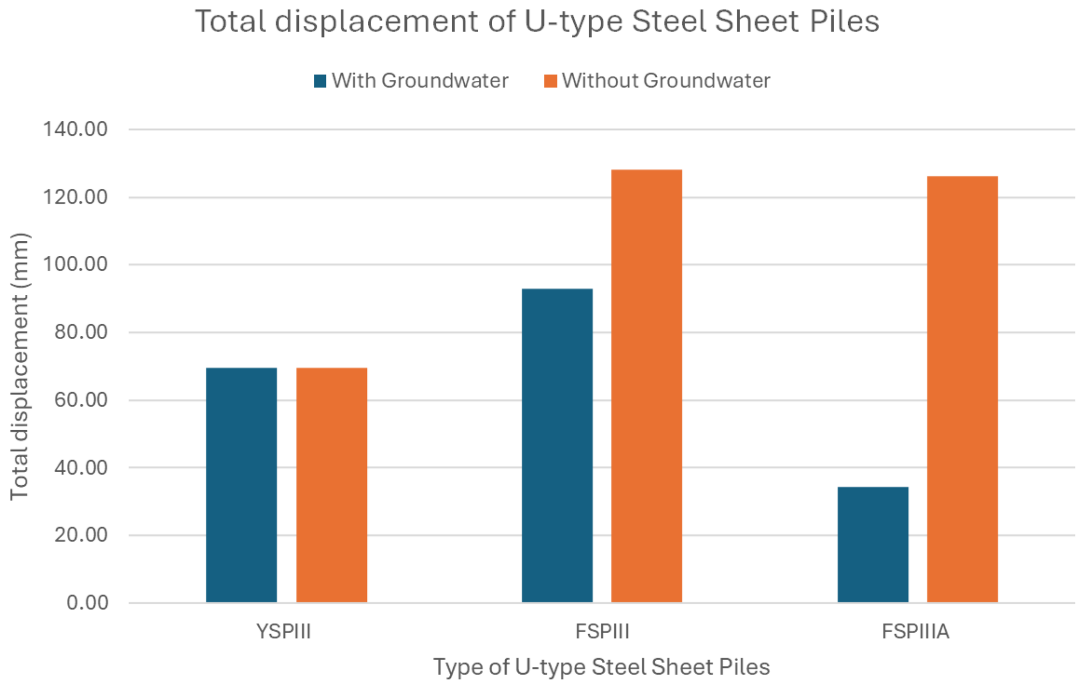


Fig. 6. Total displacement of U-type Steel Sheet Piles generated from PLAXIS 2D

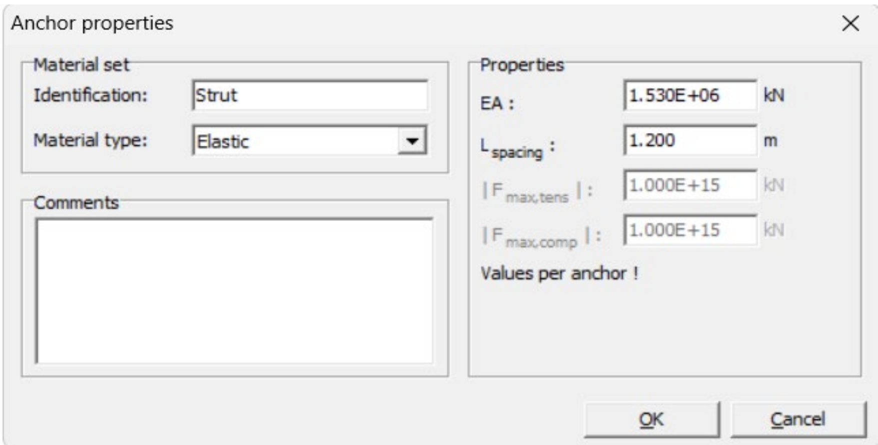


Fig. 7. Anchor Properties for FSPIII

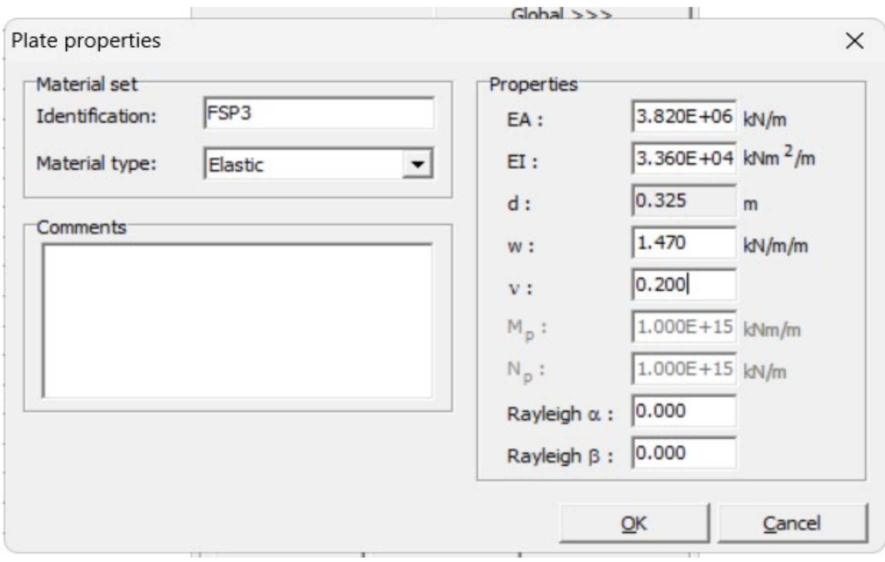


Fig. 8. Sheet Pile Specifications for FSPIII

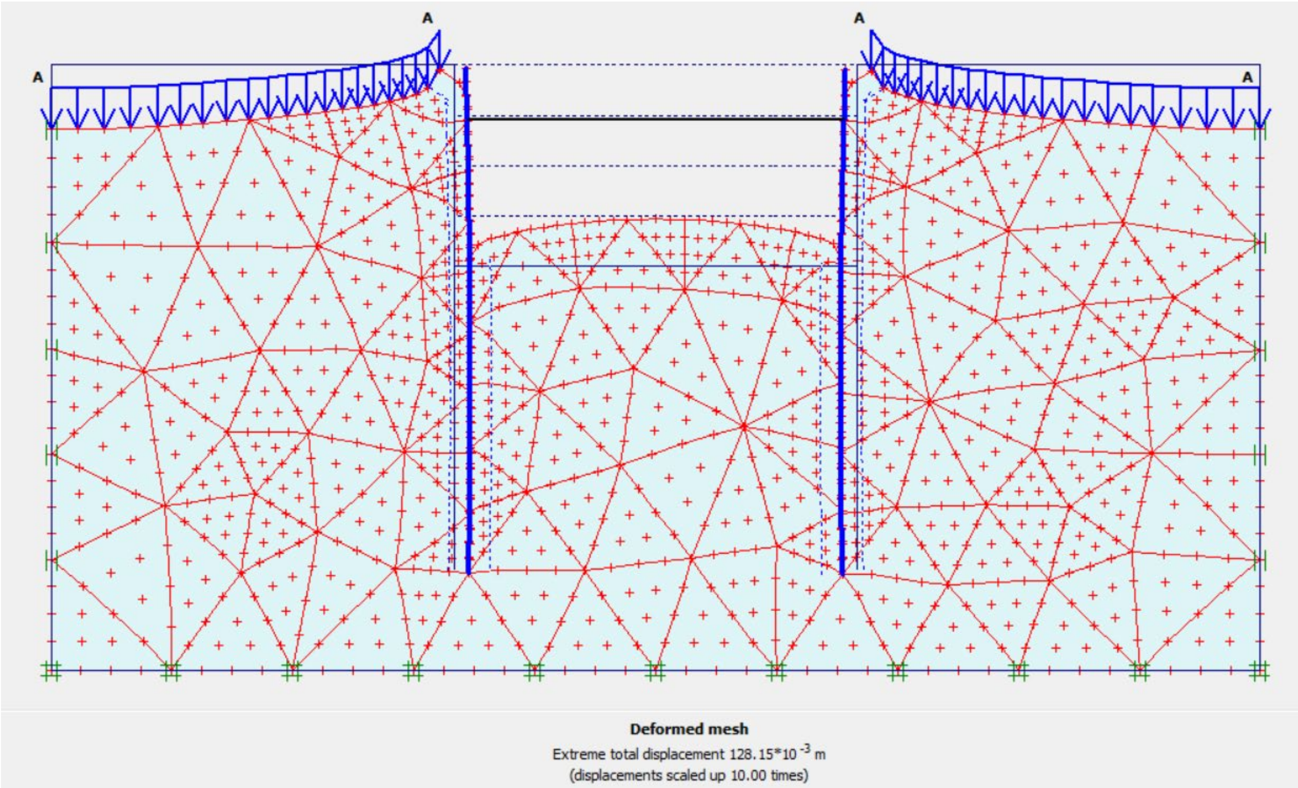


Fig. 9. Deformed mesh for FSPIII

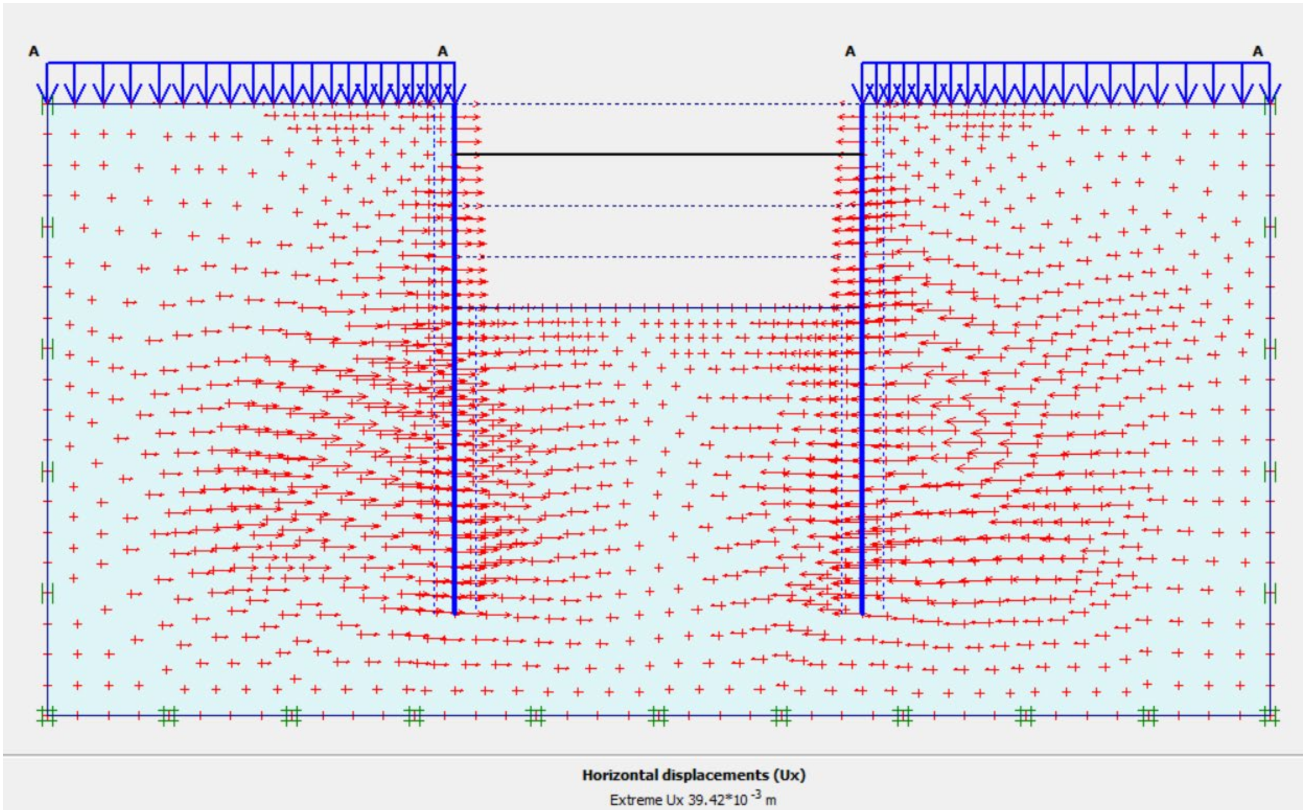


Fig. 10. Horizontal Displacement for FSPIII

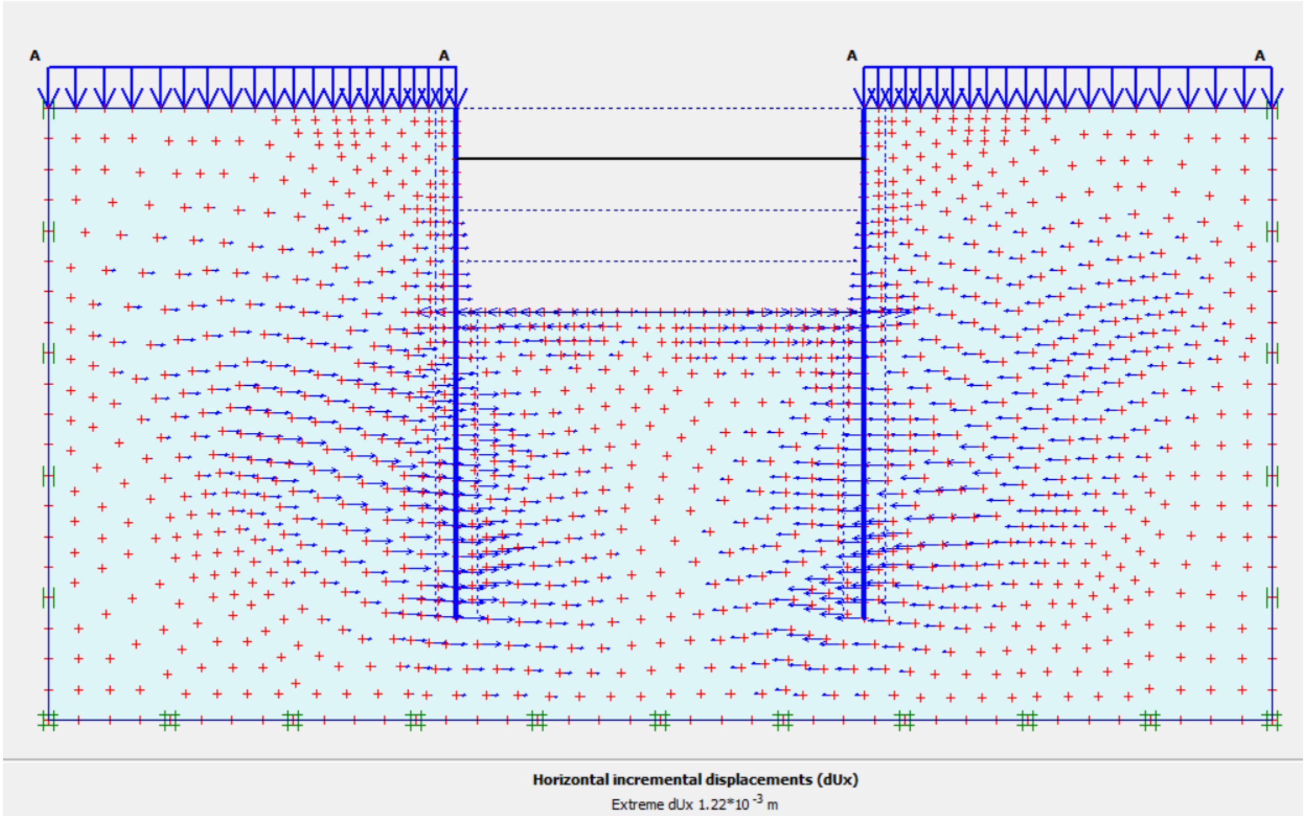


Fig. 11. Horizontal Incremental Displacement for FSPIII

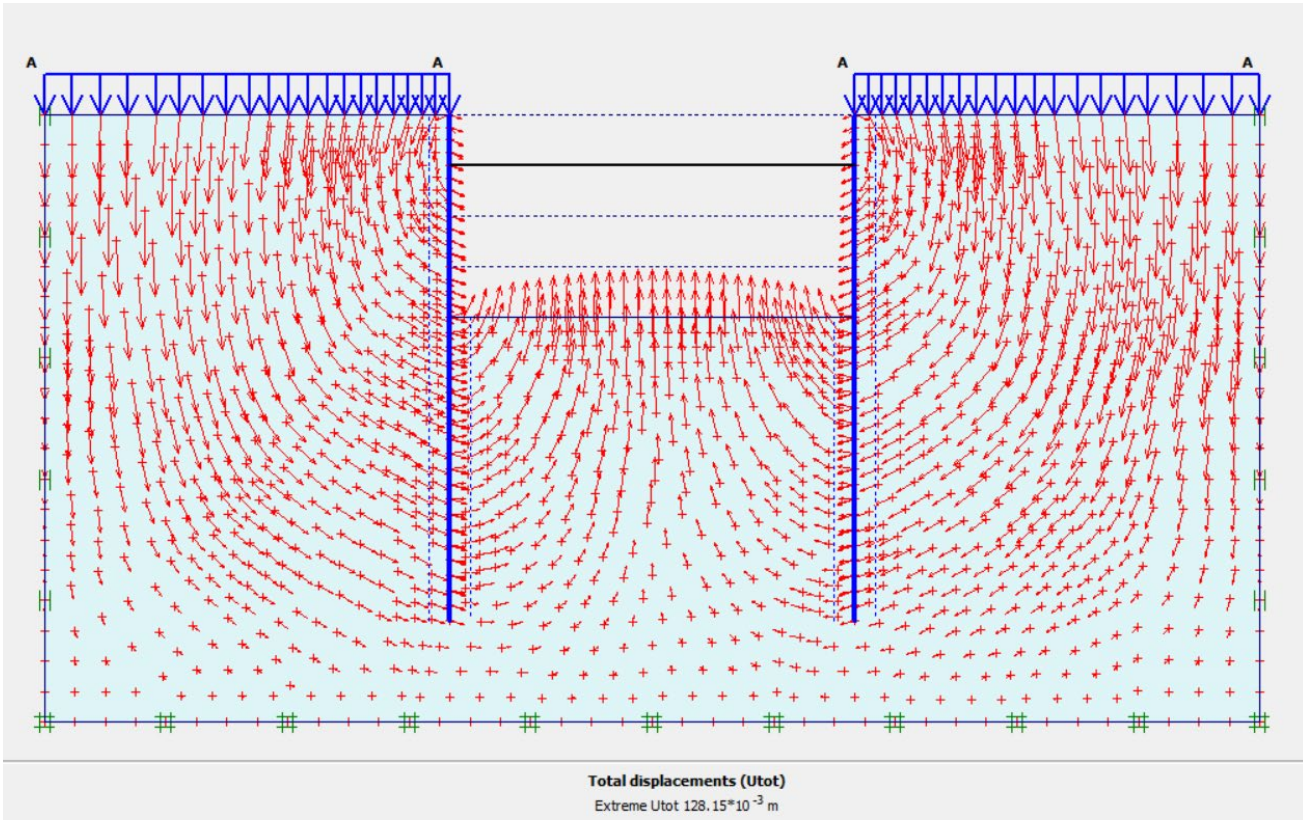


Fig. 12. Total Displacement for FSPIII

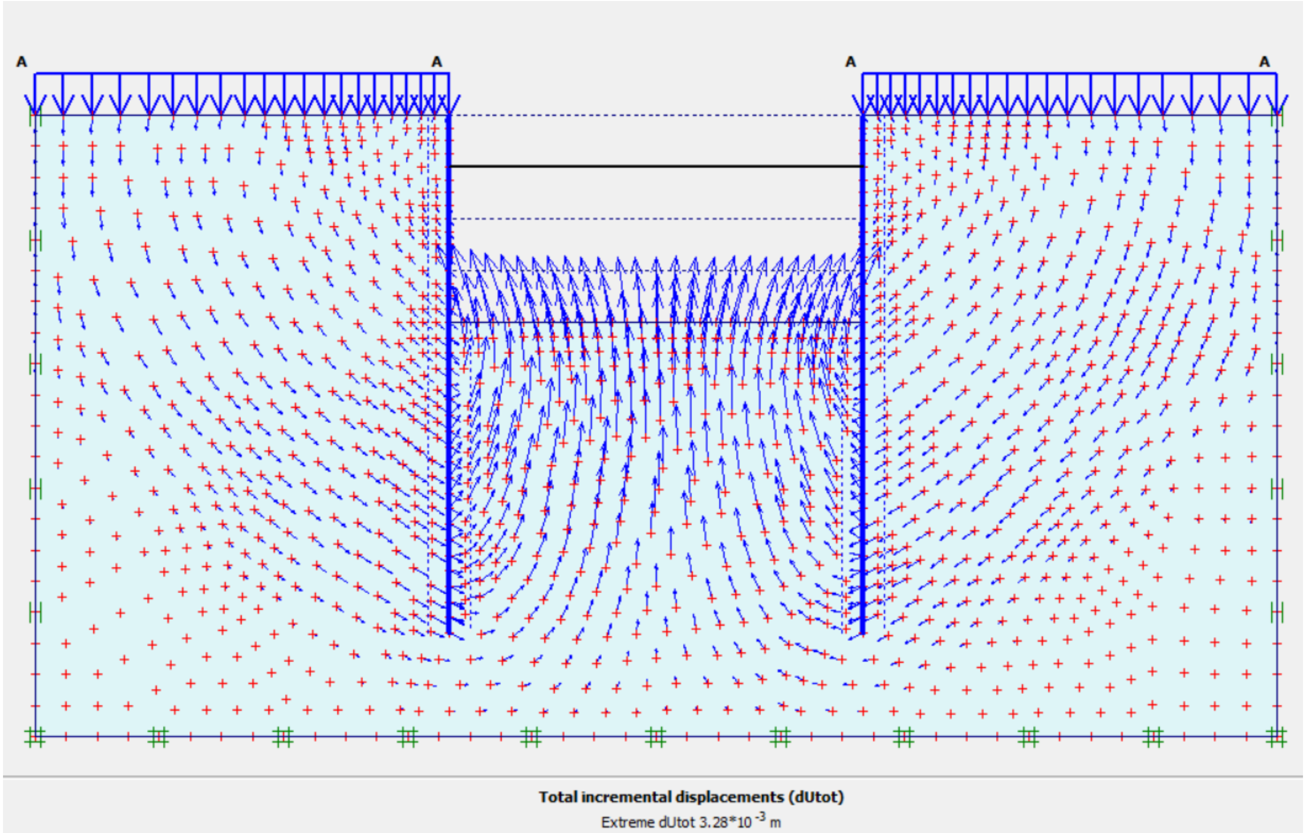


Fig. 13. Total Incremental Displacement for FSPIII

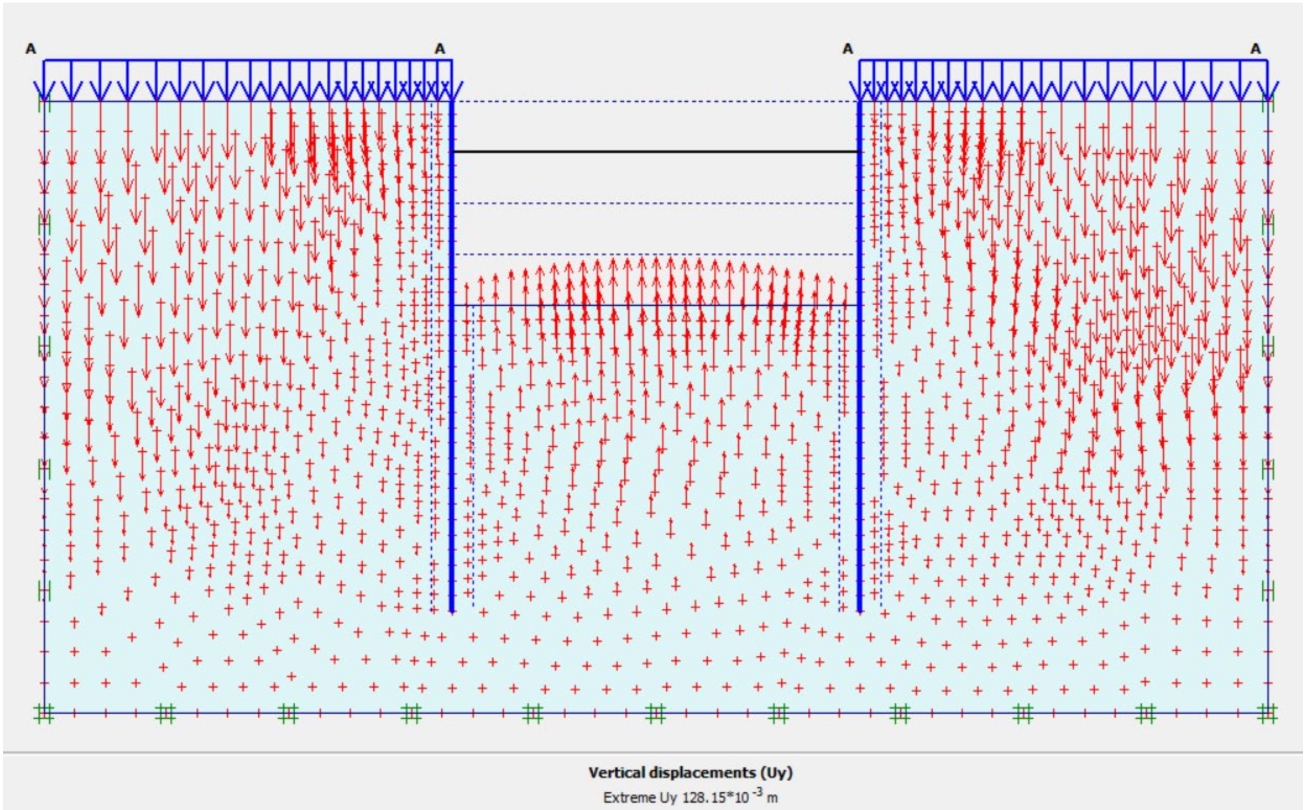


Fig. 14. Vertical Displacement for FSPIII

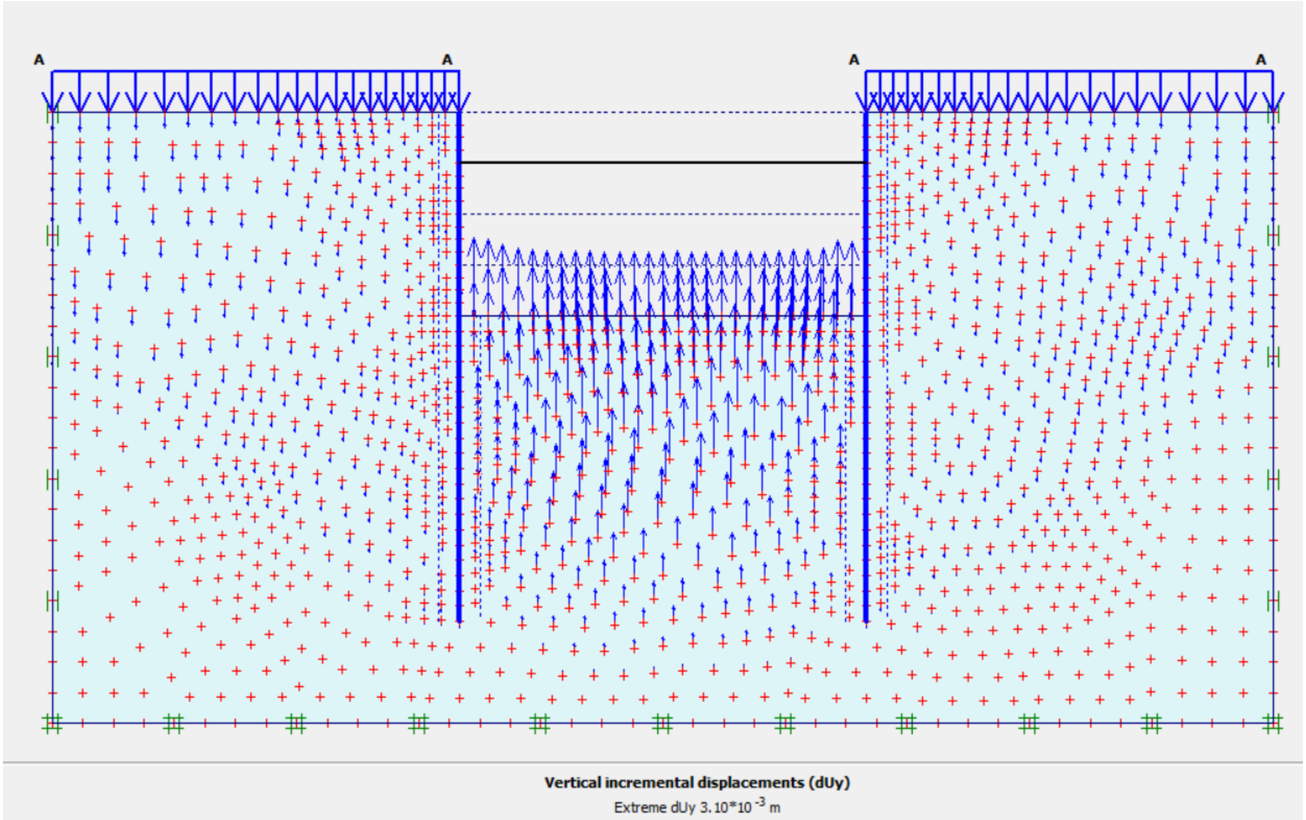


Fig. 15. Vertical Incremental Displacements for FSPIII

However, this study assumes homogeneous soil properties across the entire excavation site, even though excavation sites often exhibit diverse soil types. The void ratio of the soil is determined under the assumption that the soil has been compacted through human activities and that groundwater is present. Additionally, the finite element analysis presumes that the mesh size is sufficiently refined to ensure convergence of results. While this methodology provides a reasonable prediction of sheet pile displacement under conditions akin to those described in the model, it is important to acknowledge that real-world excavation complexities may exceed the model's assumptions, potentially undermining the validity of its predictions, and the value obtained from the simulation should only be taken as one of the references.

5. Conclusion

Concluding the result analysis, the performance of each pile could be arranged in the following order, from the most preferred choice with best performance to the least preferred with the poorest performance in this study:

YSPIII > FSPIIIA > FSPIII

The limitations of the study include that the simulation is fully conducted on the finite element software, and heavily relies on the simplified single parameters of soil provided in the previous section by assuming the soil is homogeneous. The soil parameters in coastal areas may be much more complex than in the study above. In other words, the geotechnical works may require background knowledge in coastal engineering, which is not covered in this paper. Site visit would be required if possible.

In addition, the studies only involve 3 types of piles which are commonly used as temporary work. It is recommended that the studies should cover more types of pile to provide a more comprehensive and clearer view in the usage of U-type steel sheet pile as temporary work.

The study aims to offer alternative perspectives and valuable insights to the industry by recommending the use of Plaxis 2D or other relevant Finite Element Analysis (FEA) software for pre-construction assessments during excavation projects.

This approach serves as a valuable reference for decision-making, particularly when comparing and selecting the appropriate specifications for sheet piles. By leveraging the insights provided through pre-construction analysis, stakeholders can make informed choices that align with project requirements, ensuring structural stability, cost efficiency, and compliance with industry standards.

Acknowledgment
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