DISPLACEMENT ANALYSIS OF SHEET PILE WITH TIE BEAM ON BREAKWATER CONSTRUCTION BY USING PLAXIS

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ABSTRACT

The breakwater construction usually founded in coastal areas with many public or company facilities. It is very useful to break the ocean waves so it can not reach the shoreline. Furthermore, the breakwater construction is also applied as a barrier of a port for ship docked. One of the breakwater types is a tube column filled with compacted sand reinforced by sheet file and tie beam. This research will discuss the sheet pile displacement in static and dynamic conditions. Plaxis is applied as the main tool to build the 2-D model based on given data from field observation. The input parameter for this model is applied in soil stratigraphy, compacted sand column, sheet pile, tie beam, pseudo-static wave force, sea level, and earthquake acceleration. The running of this model divided into three conditions, namely static condition, static condition with pseu-dostatic wave force, and dynamic condition. The results show different displacement between the conditions. The sheet pile displacement in static condition is 3.35 cm at harborside and 1.91 cm at the open sea. The sheet pile displacement in static condition with pseudo-static wave force is 12.14 cm at harborside and 12.08 cm at the open sea. The sheet pile displacement in dynamic condition has 5 cm peak both harborside and the open sea.

Keywords: Breakwater, sheet pile, displacement, plaxis.

INTRODUCTION

Breakwater construction is one of the water structures that aim to break the waves coming from the sea to the shoreline. Breakwater also becomes the main protector for some harbors if it located near open sea which usually generates higher sea waves. The main purpose of developing a breakwater in harbor is to protect the area of anchor ponds or harbor area by reducing the height of sea waves, so the ships can dock safely to carry out loading and unloading.

Indonesia as an archipelago country uses sea transportation massively to ensure that islands can be connected. Transpacific Petrochemical Indotama, an Indonesian oil and gas company, applied the sea transportation for oil and gas distribution by shipping. The breakwater construction using sand compacted column was their choice to protect the harbor.

Figure 1 shows the breakwater of the harbor. The breakwater located in Tuban, north shoreline of East Java. From the figure, some of the breakwater sections had been broken caused by the cyclic wave from the Java Sea (red circle). The offered alternative choice for this issue is by using sheet pile as a wall protector with tie beam to reinforce the system. The displacement analysis of sheet pile was taken as topic of discussion in this paper. The 2-D model analysis was performed by using Plaxis software.

Figure 1. The location of breakwater (Google Maps, 2020)

BOUNDARY CONDITION

The sheet pile analysis in breakwater model has the same relative condition with a retaining wall model. Azizi (2000) said that for the sheet pile retaining wall for an isotropic homogenous soil, he advised using a model dimensions with a minimum lateral dimension of 2*H* in front of the wall and 3*H* behind the wall. Then the model dimensions should extend in minimum depth of 3*H* or the depth of stiff soil layer, where *H* is the pile length. For more illustration, see Figure 2.
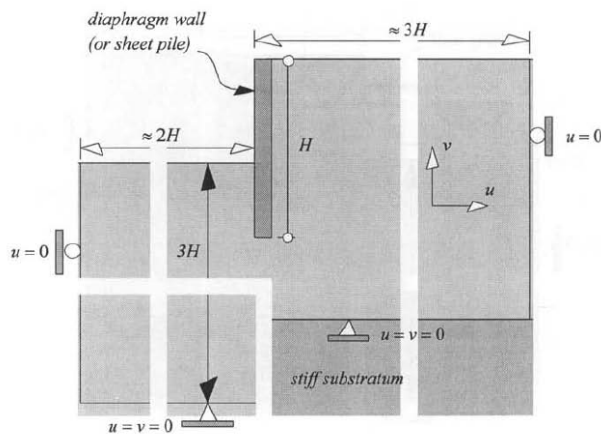

Figure 2. Typical model dimensions of sheet pile retaining wall for an isotropic homogenous soil (Azizi, 2000)

BASIC PARAMETER OF MOHR-COULOMB MODEL

Das (2010) said the Mohr-Coulomb failure criterion can be expressed in Eq. (1).

$$\tau = c + \sigma \tan \varphi \qquad (1)$$

where τ is soil shear strength, c is cohesion, σ is soil stress, and φ is soil friction angle. All these parameters affect the soil strength so the critical point of soil failure can be estimated. Figure 3 shows the parameter relationship in curve based on Eq. (1). Point A means the condition of stress when the soil not fails, point B is the critical condition of the soil to fail, and point C is an impossible event of soil stress because it exceeds the failure border.

Brinkgreve et al. (2002) said that the Mohr-Coulomb model in Plaxis requires a total of five parameters. There are Young's modulus (E), poisson's ratio (v), cohesion (c), friction angle (φ), and dilatancy angle (ψ).
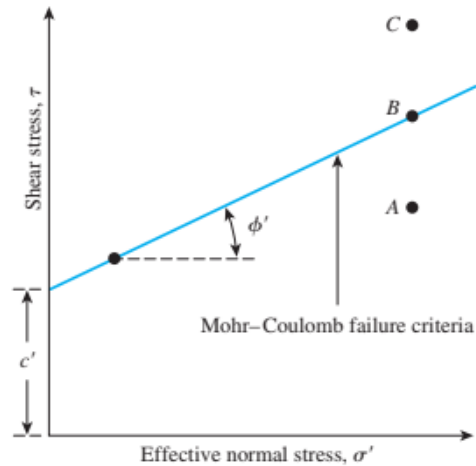

Figure 3. Mohr-Coulomb failure criterion (Das, 2010)

Young's modulus (*E*)

Plaxis uses the Young's modulus as the basic stiffness modulus in the Mohr-Coulomb model. Bowles (1977) proposed the formula for determine the Young's modulus from N-SPT value. Equation (2) is used for clay soil and Equation (3) for sandy soil.

$$E = 300(N+6) \qquad (2)$$
$$E = 320(N+15) \qquad (3)$$

Poisson's ratio (*v*)

Poisson's ratio is a dimensionless parameter. In many cases, Poisson's ratio value ranged between 0.25-0.4. Lower value

of Poisson's ratio means the material is harder, vice versa. Bowles (1977) proposed the poisson's ratio value according to the soil types. See Table 1.

Table 1. Poisson's ratio range value

SOIL TYPE	POISSON'S RATIO
Unsaturated clay	0.1-0.3
Saturated clay	0.4-0.5
Sandy clay	0.2-0.3
Silt	0.3-0.35
Sand	0.2-0.4
Rock	0.1-0.4

Cohesion (*c*)

Cohesion value usually determined in kPa unit. Clayey soil has higher cohesion value because the high cement contain in its grain composition. Table 2 shows the cohesion value according to N-SPT value.

Table 2. Relationship the N-SPT value and cohesion (Kumar et al., 2016)

SOIL CONDITION	N-SPT	COHESION (kPa)
Loose	<10	<5
Medium stiff	10-30	5-48
Stiff	>30	>48

Friction angle (*φ*)

This parameter is entered in degrees. High friction angles value usually obtained from dense sands. Bowles (1984) proposed the friction angle ranged value based on N-SPT value for sandy and clayey soil. See Table 3.

Table 3. Relationship the N-SPT value and friction angle

SOIL TYPE	N-SPT	FRICTION ANGLE (°)
Loose sand	0-10	25-32
Medium sand	11-30	28-36
Dense sand	30-50	30-40
Very dense sand	>50	>35
Very soft clay	<4	<25
Soft clay	4-6	20-50
Medium clay	6-15	30-60
Stiff clay	16-25	40-100
Hard clay	>25	>100

Especially for some types of rock, Goodman (2010) proposed the cohesion and friction angle value. See Table 4.

Table 4. Typical value of cohesion and friction angle for rock

ROCK TYPE	COHESION (MPa)	FRICTION ANGLE (°)
Berea sandstone	27.2	27.8
Muddly shale	38.4	14.4
Stone Mt. granite	21.2	51
Georgia marble	21.2	25.3
Sioux quartzite	70.6	48
Indiana limestone	6.7	42

Dilatancy angle (*ψ*)

The dilatancy angle is specified in degrees. Most soil types tend to show nearly zero dilatancy value. For quartz sands, the dilatancy angle is obtained from Eq. (4).

$$\psi = \varphi - 30^o \qquad (4)$$

where φ is friction angle in degrees.

STRUCTURE MODELS AND PARAMETERS

Sheet pile in Plaxis is considered as a plate in plane strain condition because of the two-dimension analysis. There are some parameters input for plate analysis such as *EA*, *EI*, *d*, *w*, and *v*. Where *EA* and *EI* are sheet pile Young's modulus multiply with its cross-section area and its inertia. The diameter (*d*) will be determined automatically after the *EA* and *EI* value input based on the Eq (5). The *E* value obtained from Eq (6) where *f'c* is the concrete compressive strength.

$$d = \sqrt{\frac{12EI}{EA}} \qquad (5)$$

$$E = 4700\sqrt{f'_c} \qquad (6)$$

In this case, the tie beam in Plaxis is considered as an anchor because they have the same force behavior. The benefit of this choice is to approach the real condition for the model especially for the tie-beam spacing. For anchor, there are fewer parameter input than

plate model that is only *EA* and $L_{spacing}$ where each value represents the individual anchor.

METHOD AND ANALYSIS

Numerical modeling using Plaxis is the method of this research. The analysis flow outline started by preparing the model, running the calculation, and result. The data used in this study obtained from soil laboratory analysis results. Drilling data also used to describe the subsurface and the soil layer condition below the seabed.

Model Preparation

Geometry and boundary condition

The determination of the geometry model is based on the field condition and the proposed schematic dimension from Azizi (2000). The model laterally has a 160 m length. The different elevation between harborside and the open sea about 5.5 m where the seabed from the open sea is -10 m and the seabed in harborside is -15.5 m. The seawater level is 0 m.

The soil stratigraphy condition from the top are soft clay and limestone layer. Soft clay has a thickness of 15 m at the open seaside, and 9.5 m at the harborside The limestone layer start from -25 m depth. Sheet pile total length is 36 m and tie-beam is 24 m. See Figure 4 for further details.

The boundary condition of the model was made based on the proposed schematic dimension from Azizi (2000) also. The left and right sides determined as roll because the vertical deformation of the model is allowed. Different from the left and right side, the bottom side determined as fixed because there is considered no deformation at the bottom.
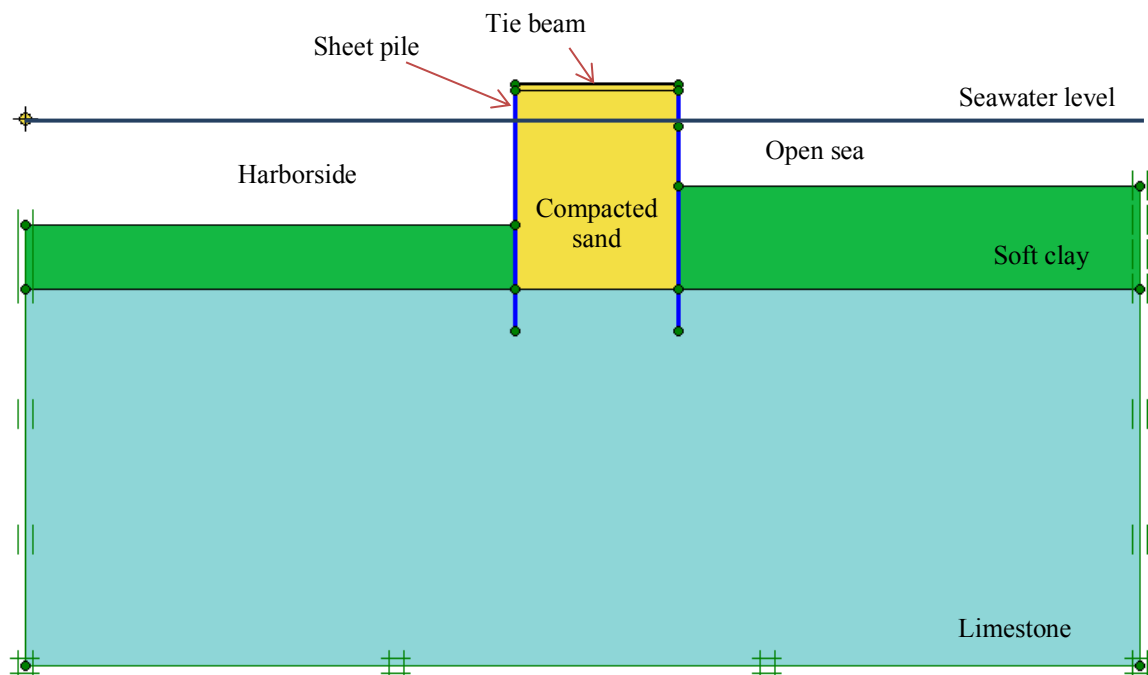

Figure 4. Geometry model and boundary condition

Parameter input of model elements

According to Figure 4, the model consists of some elements. There are *cluster* element for modeling the soil, *plate* element for modeling the sheet pile, and *anchors* element for the tie-beam. Table 5 shows the soil input parameter for the Mohr-Coulomb model taken from laboratory data and parameter relationship formula. Plate element and anchors element are used for modeling the structure during this analysis. The plate element described as a blue line on the model and anchors element as a black line on the top of the compacted sand cell. Table 6 shows the parameter input for the sheet pile and tie-beam. For anchors element, in reality, it actually used for anchor reinforcement. But in this case, tie beam is considered to have the same function and behavior as the anchor. Because there is a spacing between the tie beam and difficult to equivalent the parameter for 2-D analysis, so it was selected as the model element for tie beam.

Table 5. Parameter input of Mohr-Coulomb model material

MATERIAL TYPE	γ_{unsat} (kN/m³)	γ_{sat} (kN/m³)	k_x (m/s)	k_y (m/s)	E (kN/m²)	v	c (kN/m²)	φ (°)	ψ (°)
Soft clay	13.34	16.67	10^{-10}	10^{-10}	3000	0.3	5	1	0
Compacted sand	14.7	18	10^{-3}	10^{-3}	40000	0.3	1	34	0
Limestone	22.5	25	10^{-12}	10^{-12}	30000000	0.23	1	37	0

Table 6. Parameter input of structure

STRUCTURE	EA (kN/m)	EI (kNm²/m)	d (m)	w (kN/m/m)	v	$L_{spacing}$
Sheet pile	23800000	7050000	1.886	16.848	0.15	-
Tie beam	33700000	-	-	-	-	4.2

Initial condition

The initial condition of the model include the initial pore water pressure and initial stress of the soil. The initial condition will be the beginning condition before starting the phases of model analysis. The inital condition of the model seen in Figure 5.
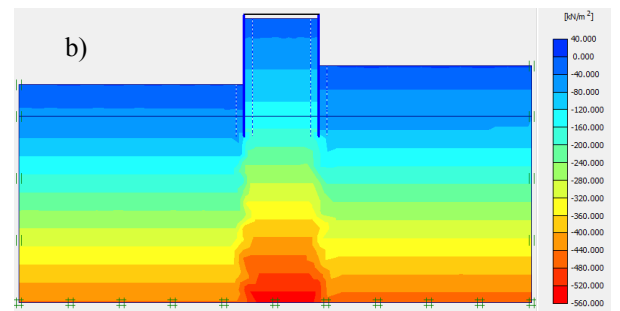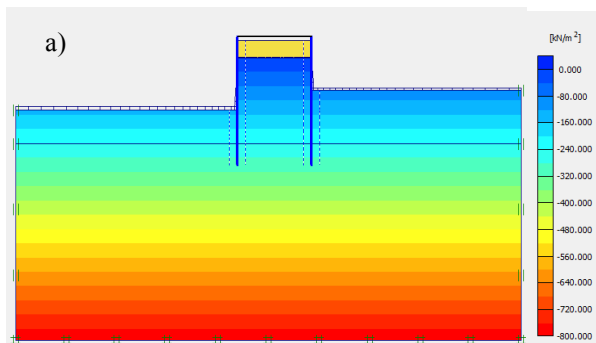
Figure 5. a) Initial pore water pressure, b) initial stress

Model Analysis

After generating the initial condition, the model is ready for running. The running analysis divided into three conditions, there are static condition, static condition with pseudo-static sea wave force, and dynamic condition.

The static condition conducted in plastic analysis calculation. The initial condition directly analyzed by the calculation program. One of the outputs from the calculation is the maximum displacement of sheet pile

The second condition is an additional of pseudo-static sea wave force through the sheet pile on the open seaside. Pseudo-static force is the maximum force taken from the cyclic force because of the limitation of modeling. There are three different pseudo-static force values from top, middle, and bottom of sheet pile above the seabed. See Table 7.

Table 7. Input value of pseudosatic force

POSITION	Pseudo-static force (kN)
Top	45.7
Middle	71.2
Bottom	54

The dynamic condition analysis also conducted as an illustration of sheet pile displacement during earthquake occurrence. The additional prescribed displacement on the model is needed to run the dynamic analysis. Figure 6 shows the *.smc* file of the Mentawai 2007 earthquake with 12.8 cm/s^2 maximum acceleration used for earthquake acceleration input. The epicentral distance is about 142.7 km.
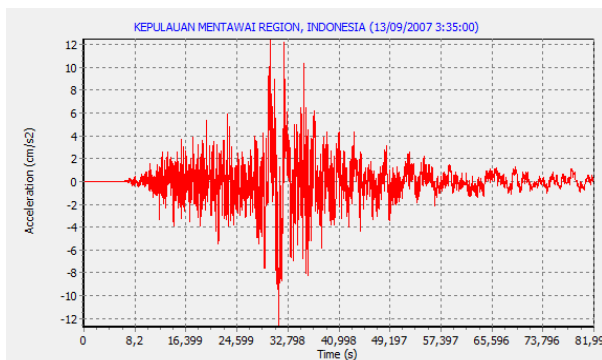

Figure 6. the *.smc* file data of the Mentawai 2007 earthquake

RESULT AND DISCUSSION

Static condition

The sheet piles displacement in the static condition is 3.35 cm at harborside and 1.91 cm at the open seaside. The displacement mainly caused by the lateral pressure of compacted sand from the cell. The harborside has greater displacement than the open seaside because the thickness of soft clay is different on both sides. The thicker soft clay layer at the open seaside makes it has more passive lateral pressure of soil that reduces the displacement. Figure 7 shows the result of static condition analysis.

Static condition with pseudo-static wave force

The additional of pseudo-static wave force make the sheet pile displacement of both sides are greater than before. The sheet piles displacement is 12.14 cm at harborside and 12.08 cm at the open seaside. The pseudo-static force impacts the displacement of sheet pile almost four until six times greater than before. See Figure 8 for further details.

Dynamic condition

The earthquake event affects sheet piles displacement. Various displacement values occur during the earthquake. According to Figure 9, the red line and blue line are sheet pile displacements at open sea and harborside during the earthquake. There is no significant contrast of displacement between the open sea and harborside indicated by the coinciding curve.

The maximum displacement is 5 cm. From the curve, the rapid rising of displacement appears at 32 seconds of 80 seconds dynamic time. This is caused by the peak of earthquake acceleration occur at that time.
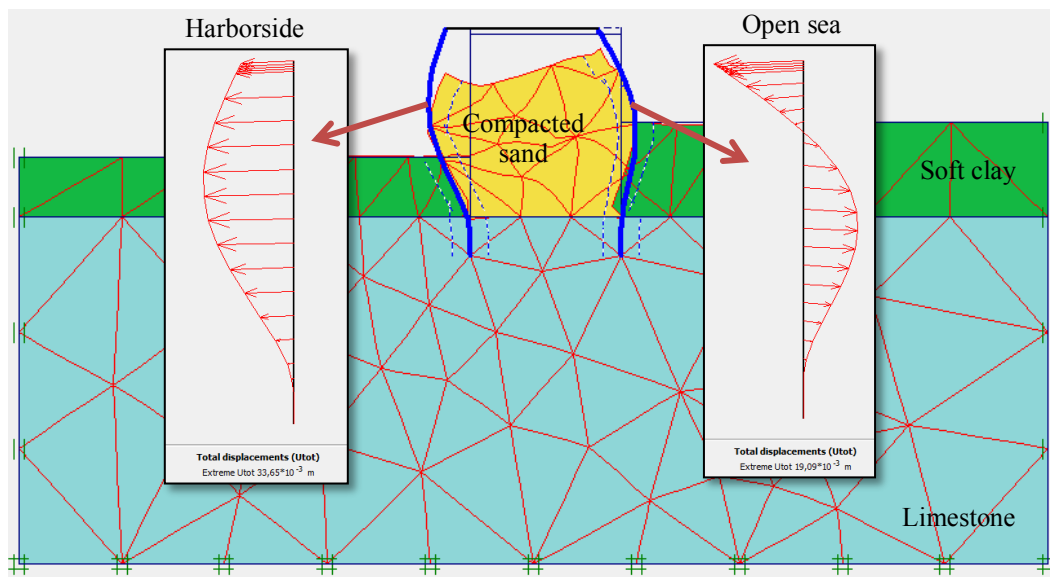
Figure 7. Sheet pile displacement in static condition
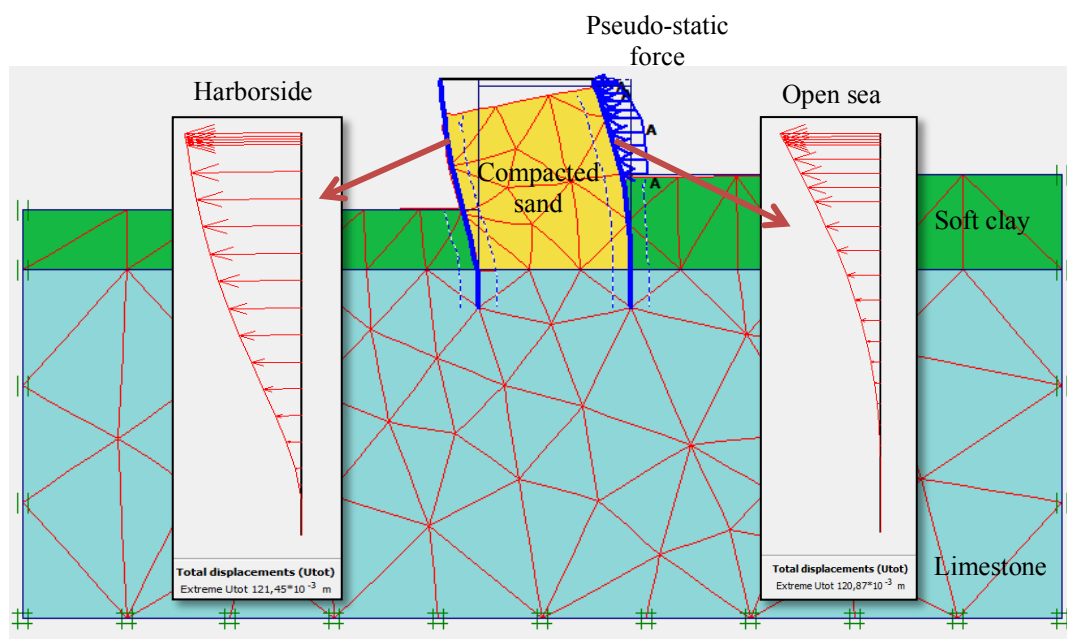

Figure 8. Sheet pile displacement in static condition with additional of pseudo-static wave force
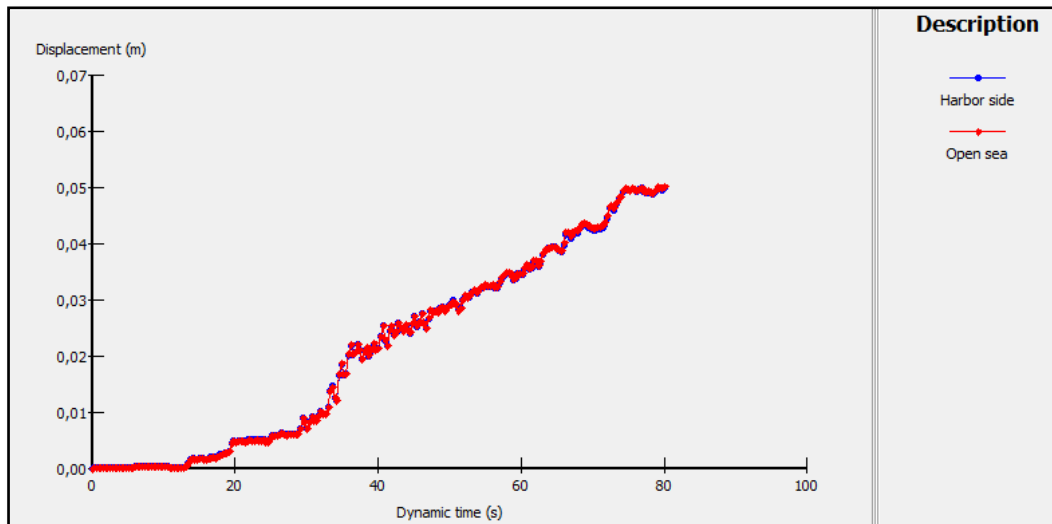
Figure 9. Curve of dynamics of sheet pile displacement during earthquake acceleration

CONCLUSION

According to the analysis results of each condition, the various displacement values of sheet pile obtained. In the static condition, the sheet pile displacement at the open seaside is 1.91 cm and the harborside is 3.35 cm. This is influenced by the differences in seabed elevation in which the open seaside is higher than the harborside. The existence of thicker soft clay also affects the sheet pile more stable caused by the passive lateral pressure of soil. The additional pseudo-static force affects the displacement of sheet pile become four to six times higher than before where the displacement in the open sea is 12.08 cm and the harborside is 12.14 cm. In dynamic condition, the acceleration of earthquake influence the stability of sheet pile marked by the displacement up to 5 cm during the earthquake.

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