Design of a Spun Pile Vertical Wall Breakwater for the Improvement of Damaged Cellular-Cofferdam

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Abstract. A new breakwater is on demand to replace the function of an existing steel sheet pile cellular-cofferdam at TPPI Tuban Port of East Java. The existing breakwater has been partially damaged due to severe corrosion and hard attack by monsoon waves. An open frame structure of spun pile vertical-wall breakwater is proposed as an alternative design. The spun pile is a pre-stressed concrete hollow cylinder pile with outer diameter 1800mm and thickness of 200mm. The spun pile lengths vary between minimum 28m to maximum 33m according to the position of hard soil against seabed. The new breakwater is designed to stand against 100yrs RP wave with Hs = 4.7m. Wave height variations around the structure are simulated using Boussinesq Wave module of MIKE21 software, while SAP2000 is used to calculate the strength of superstructure to withstand existing loads and certain load combinations. Plaxis software is used mainly to analyze substructure using existing soil data. This article describes the design process of spun pile vertical wall breakwater, started from loads calculation, then define load combinations, analyze structure in SAP2000, analyze structure in Plaxis, determination of specification and dimension, to design drawings creation.

Keywords: design, vertical wall breakwater, spun pile, cellular-cofferdam, numerical modeling.

1. Introduction

1.1. Background

Breakwaters are buildings used to protect harbour from wave interference. This building separates the waters of harbour from the open sea, so that they are not much affected by large waves at sea.

TPPI Cellular Cofferdam Breakwater which was built in 2005, is currently damaged. There are seven damaged cell of existing cellular cofferdam breakwater [1], with one cellular cofferdam has been rebuilt. Figure 1 shows location of damaged cells of breakwater
Figure 1. Position of damaged cellular-cofferdam.

The collapse of the six cellular-cofferdam sections of the TPPI Tuban breakwater has reduced the effectiveness of protection from wave in harbour and has become a gap for accelerating the sedimentation rate into the harbour. Likewise, the ongoing damage progress of other cellular-cofferdams is potentially causing total collapse and failure of function in long term. Based on the results of discussions with the TPPI engineering team and the results of the field review it is known that the progress of damage to the existing cellular cofferdams, which is mainly caused by the corrosion process of the cellular-cofferdam steel sheet pile is no longer economical to prevent. Therefore it is necessary to plan and design a new breakwater building as an improvement for the existing breakwater building. This new breakwater building will be made covering the existing cellular-cofferdam, with the layout illustration as shown in Figure 2 below.

Figure 2. Lay out illustration of new spun pile breakwater.

1.2. Purpose
The purpose of this research is to determine maximum moment and deflection due to service loads using SAP2000 and Plaxis software, then designing a new vertical wall breakwater to improve existing damaged cellular-cofferdam breakwater. This design includes specification, dimension, and design drawing.
1.3. Project Location
The location of the project is in the PT. TPPI harbor, Tuban. The coordinates are 49 M605306.13 m 9252435.15 m, which is in the UTM 49M zone.

![Figure 3. Location of existing cellular-cofferdam.](image)

1.4. Software Used
There are four softwares that used in this project:
- MIKE 21- Modul Boussinesq Wave for simulation of wave deformation
- SAP2000 – for calculation of structural analysis
- PLAXIS – for calculation of foundation stability
- AUTOCAD – for design drawing

2. Research Methodology
The work will be carried out by following a certain set of stages where each stage of the work is directed to achieve a clear and precise target, as shown in flowchart in Figure 4.
Figure 4. Flowchart of TPPI Tuban new breakwater design.
2.1. Data Used

2.1.1. Soil Data

In carrying out analytical calculations and modeling of spun pile breakwater, used boring log from Soilens Final Report, June 2003 located at 3 points: B-210, B-211, and B-212 [2].

![Figure 5. Position of B-210, B-211, and B-212 bore holes.](image)

Seabed depth for the open sea area is in accordance with the original bathymetry. Seabed depth for the harbour side area is dredged to -15.5 m for east side of the B-210 and B-211, and dredged to -12.5 m for east side of the B-212.

![Figure 6. Cross section of soil layer based on B-210, B-211, dan B-212 boring log.](image)
Table 1. Detail of soil layers profile.

| Depth (m) | Soil Layer Type | N-SPT |
|-----------|-----------------|-------|
| 0 – 22.5  | Clay            | 2     |
| 22.5 – 39.5 | Limestone     | >60   |
| 0 - 19    | Clay            | 1     |
| 19-20     | Limestone       | 19    |
| 20-21     | Silty Gravel    | >60   |
| 21 - 39   | Limestone       | >60   |
| 0 – 16.5  | Clay            | 1     |
| 16.5 – 37.5 | Limestone   | >60   |

2.1.2 Wind Data
The wind speed used in the calculation is 39 m/s, it is wind speed limit at which the ship or barge is allowed to berth on the TPPI Port.

2.1.3 Current Data

Table 2. Current speed used.

| Return Period [Years] | Wind Speed $U_{10,10}$ [m/s] | Wave Height $H_s$ [m] | Wave Period $T_p$ [s] | Water level (-10 mCD) [m] | Current Speed $V_{10}$ [m/s] |
|-----------------------|-------------------------------|----------------------|----------------------|--------------------------|-----------------------------|
| 1                     | 12.2                          | 3.1                  | 6.9                  | 2.15                     | 0.75                        |
| 25                    | 18.4                          | 3.8                  | 7.8                  | 2.25                     | 0.9                         |
| 100                   | 21.2                          | 4.6                  | 8.7                  | 2.3                      | 0.95                        |

The current speed used is 0.95 m/s with return period of 100 years, based on Tuban Marine Facilities-Meteorological and Oceanographic Feasibility Study Final Report [3].

2.1.4 Earthquake Data
Earthquake load calculation requires $S_s$ and $S_1$ values obtained from the website: http://puskim.pu.go.id/Aplikasi/desain_spektra_indonesia_2011/ [4]. The TPPI Tuban Breakwater Project location is at the Latitude = -6.885842 and Longitude = 112.065433.
Figure 7. The spectral value of acceleration in shallow waters of Tuban.

Table 3. The value of spectral acceleration at ground level .

| Parameter | Value  |
|-----------|--------|
| PGA (g)   | 0.328  |
| PSA (g)   | 0.352  |
| SS (g)    | 0.690  |
| SMS (g)   | 0.776  |
| S1 (g)    | 0.233  |
| SM1 (g)   | 0.365  |
| CRS       | 0.992  |
| SDS (g)   | 0.517  |
| CRI       | 0.935  |
| SD1 (g)   | 0.243  |
| FPGA      | 1.072  |
| T0 (s)    | 0.094  |
| FA        | 1.124  |
| TS (s)    | 0.470  |
| FV        | 1.567  |

From PT Soilens Boring Log at point B-210, at depth below 13.8 m N-SPT>100, then soil type = hard soil (SC), reference of SNI 1726:2012 Table 3 [5].

Earthquake factor = g * Ie/R  

\[ g: \text{Gravity (} 9.81 \text{ m/s}^2) \]
\[ I \text{ from SNI 1726:2012 Table 1 and Table 2} \]
\[ \text{Risk Category} = 1 \text{ (has a low risk to the human soul)} \]
\[ \text{Earthquake Priority Factor (} I_0 \text{) = 1} \]
\[ R \text{ from SNI 1726:2012 Table 9} \]
\[ \text{Response Modification Coefficient (} R \text{) = 8 (Special moment reinforced concrete frame)} \]

So the earthquake factor = 9.81 * 1/8 = 1.23

2.1.5. Design Wave Data (with MIKE 21)
Modeling is done with a 100 year return period simulation resulting:

- \( H_s \) (significant wave height) = 4.7 meters.
- \( T \) (wave period) = 8.7 seconds.
- direction of incoming wave = 315 degrees.
The figure below illustrates the effectiveness of breakwater in absorbing wave energy to maintain the calmness of the harbour. This figure shows some significant wave height values (Hs) at several important locations around cellular-cofferdam breakwater for the return period of 100 years.

![Wave Height Map](image)

**Figure 8.** Extract model results from several locations.
(Hs at 100 years return period - wave numeric result with MIKE 21 Buisinesq wave modul)

3. Result and Discussion

3.1. Load Calculation for Structural Analysis with SAP2000

The results of the recapitulation of structural loads based on the rules and standards mentioned below can be seen in Table 4.
Table 4. Recapitulation of structural loads.

| No  | Workload                        | Value                                                                 |
|-----|---------------------------------|-----------------------------------------------------------------------|
| 1.  | Active Earth Pressure Rankine’s Theory (1857) : Active Lateral Earth Pressure [6] |
|     | \( P = \rho * H * K_a \)       |
|     | \( H = 0 \text{ m} \rightarrow P_{top} = 0 \text{ kg/m}^2 \) |
|     | \( H = 3.13 \text{ m} \rightarrow P_{middle} = 1810 \text{ kg/m}^2 \) |
|     | \( H = 10.39 \text{ m} \rightarrow P_{bottom} = 6001 \text{ kg/m}^2 \) |
|     | \( H = 16.07 \text{ m} \rightarrow P_{bottom} = 9281 \text{ kg/m}^2 \) |
| 2   | Live Load                       | SNI 1727-2013 Table 4-1 [7]                                           |
|     | P = 200 kg/m² (capping beam)    |
|     | P = 200 kg/m² (tie beam)        |
| 3   | Hydrostatic Pressure            | P = \( \rho * h \)                                                     |
|     | P = 0 kg/m² (water level)       |
|     | P = 10,648 kg/m² (sea bed)      |
|     | P = 16,468 kg/m² (sea bed)      |
| 4   | Wave Pressure                   | Goda (1973) and Takahashi (1994) [8]                                   |
|     | \( P_1 = 7009 \text{ kg/m}^2 \) |
|     | \( P_2 = 5174 \text{ kg/m}^2 \) |
|     | \( P_4 = 4967 \text{ kg/m}^2 \) |
| 5   | Current Pressure                | OCDI Technical Standards and Commentaries for Port and Harbour Facilities in Japan 2009 Subchapter 6.5 [8] |
|     | \( F_D / A_n = 0.5 * C_D * \rho_w * V^2 \) |
|     | \( F_D = 47.1 \text{ kg/m}^2 \) |
| 6   | Wind Pressure                   | BS 6349-2:1988 part 2 subchapter 6.11.3.1 Wind [9]                    |
|     | \( F_v / A = q * C_D \)         |
|     | \( F_v / A = 241.77 \text{ kg/m}^2 \) (spun pile) |
|     | \( F_v / A = 175.64 \text{ kg/m}^2 \) (capping beam) |
| 7   | Earthquake Load                | Response Spectrum                                                      |
|     | \( S_1 = 0.69 \) and \( S_1 = 0.233 \) |
|     | http://puskim.pu.go.id/Aplikasi/desain_spektra_indonesia_2011/ [4] |
|     | SNI 1726:2012 Table 3 [5]      |
|     | Soil Type = Hard Soil (SC)      |
|     | SNI 1726:2012 Table 1 dan Table 2 |
|     | \( I_e = 1 \)                   |
|     | SNI 1726:2012 Table 9           |
|     | R = 8                          |
|     | Earthquake Factor = \( g * I_e / R \) |
|     | Earthquake Factor = 9.81 * 1/8 = 1.23 |

3.2. Loads Combination Calculation
Calculation of loads combination refers to SNI 1727: 2013 subchapter 2.3.2 basic combination [7].
Table 5. Unfactored loads combination.

| Comb No. | Loads Combination |
|----------|-------------------|
| Comb 1   | 1D                |
| Comb 2   | 1D + 1L           |
| Comb 3   | 1D + 1L + 1H + 1F|
| Comb 4   | 1D + 1FWY + 1FCY + 1H + 1F |
| Comb 5   | 1D + 1L + 1WY + 1FWY + 1FCY + 1H + 1F |
| Comb 6   | 1D + 1L + 1EX + 1EY + 1H + 1F |
| Comb 7   | 1D + 1EY + 1EX + 1FWY + 1FCY + 1H + 1F |

D : Dead Load  
L : Live Load  
H : Cofferdam Soil Load  
WY : Y-Direction Wind Load  
F : Sea Water Hydrostatic Load  
FWY : Y-Direction Wave Load  
FCY : Y-Direction Current Load  
EX : X-Direction Earthquake Load  
EY : Y-Direction Earthquake Load

Moment resulted from unfactored load combination is $M_a$, will be compared with $M_{cr}$ (cracking moment of the table of spun pile cracking bending moment from the manufacturer), and the following inequality is required [7]:

$$M_a < M_{cr}$$  \hspace{1cm} (7)

Where:

- $M_a$ = Unfactored moment or maximum moment in structural components due to service loads (ton.m)
- $M_{cr}$ = Cracking moment (ton.m)

3.3. Calculation of Soil Spring Stiffness

The breakwater structure is modeled by idealizing the Open Frame Structure. Modeling of soil spring stiffness to the spun pile due to influence of interaction between soil and structure.

For the analysis of lateral soil resistance which is linearly elastic, the soil is modeled as a spring with each distance in the vertical direction is 1 m. From the soil N-SPT value, will be obtained the value of coefficient of subgrade reaction ($k_{ch}$) and the value of soil spring stiffness ($k_h$). Based on OCDI 2009 [8], the relationship between $k_{ch}$ value and N-SPT value is formulated as follows:

$$k_{ch} = 3910N^{0.733} \text{kN/m}^3$$  \hspace{1cm} (8)

With the $k_{ch}$ value known, then the value of $k_h$ can be determined with formula:

$$k_h = k_{ch} \times A$$  \hspace{1cm} (9)

in which,

- $A$ = Surface area of the vertical plane structure elements
Table 6. Soil spring stiffness (B-210).

| No. | Depth (m) | N-SPT | k_{ch} (kN/m^3) | k_{h} (kN/m) |
|-----|-----------|-------|-----------------|-------------|
| Seaed |           |       |                 |             |
| kh1  | 1         | 1     | 3,910           | 3,519       |
| kh2  | 2         | 1     | 3,910           | 7,038       |
| kh3  | 3         | 1     | 3,910           | 7,038       |
| kh4  | 4         | 1     | 3,910           | 7,038       |
| kh5  | 5         | 1     | 3,910           | 7,038       |
| kh6  | 6         | 1     | 3,910           | 7,038       |
| kh7  | 7         | 1     | 3,910           | 7,038       |
| kh8  | 8         | 2     | 6,499           | 9,368       |
| kh9  | 9         | 2     | 6,499           | 11,698      |
| kh10 | 10        | 2     | 6,499           | 11,698      |
| kh11 | 11        | 2     | 6,499           | 11,698      |
| kh12 | 12        | 3     | 8,748           | 13,722      |
| kh13 | 13        | 3     | 8,748           | 15,746      |
| kh14 | 14        | 28    | 44,972          | 48,348      |
| kh15 | 15        | 50    | 68,789          | 102,385     |
| kh16 | 16        | 50    | 68,789          | 123,820     |
| kh17 | 17        | 65    | 83,376          | 136,949     |
| kh18 | 18        | 65    | 83,376          | 150,077     |
| kh19 | 19        | 65    | 83,376          | 150,077     |
| kh20 | 20        | 65    | 83,376          | 150,077     |

Figure 9. Illustration of soil spring stiffness.
3.4. SAP2000 Modeling Results

SAP2000 modeling results in the form of a summary of analysis results of the maximum moment, cracking moment, deflection due to service loads, and allowable deflection can be seen in Table 7.

Table 7. Summary of analysis results of maximum moment and deflection due to service loads.

| Bore Hole | $M_d$ (ton.m) | $M_{cr}$ (ton.m) | $\Delta s$ (cm) | $\Delta_{allow}$ (cm) | Control $M_d < M_{cr}$ | Control $\Delta s < \Delta_{allow}$ |
|-----------|---------------|------------------|-----------------|---------------------|------------------------|-------------------------------|
| B-210     | 313           | 520              | 7.7             | 22.3                | OK                     | OK                            |
| B-211     | 318           | 520              | 7.1             | 21.4                | OK                     | OK                            |
| B-212     | 347           | 520              | 6.3             | 18.6                | OK                     | OK                            |

Note:
- $M_{cr}$ : 520 ton.m (prestressed concrete post tension spun piles - cylinder piles - specification 1800 mm class C)
- $\Delta_{allow}$ : L/150 (SNI 2847-2013 subchapter 14.8.4) [10] (10)
  - 33.48 m/150 = 0.223 m → Point B-210
  - 32.16 m/150 = 0.214 m → Point B-211
  - 27.88 m/150 = 0.186 m → Point B-212

3.5. Structure Modeling in Plaxis

3.5.1. Soil Input Parameter

The soil layers are modeled as a cluster in Plaxis. Each cluster is given an input parameter according to the soil data. The correlation results used as input parameters in the Plaxis software are listed in Table 8.

Table 8. Soil input parameter in Plaxis.

| Soil Type   | $\gamma_{unsat}$ (kN/m$^3$) | $\gamma_{sat}$ (kN/m$^3$) | $k_x$ (m/day) | $k_y$ (m/day) | $E$ (kPa) | $\nu$ | $c$ (kPa) | $\phi$ (°) |
|-------------|-------------------------------|---------------------------|----------------|---------------|-----------|-----|-----------|-----------|
| Fat Clay    | 13.34                         | 16.67                      | $8.64 \times 10^{-6}$ | $8.64 \times 10^{-6}$ | 3000      | 0.3 | 5         | 0.5       |
| Limestone   | 22.5                          | 25                         | $8.64 \times 10^{-8}$ | $8.64 \times 10^{-8}$ | 3 $\times$ 10$^7$ | 0.23 | 1         | 37        |
| Cell Fill   | 14.7                          | 18                         | $8.64 \times 10^{-4}$ | $8.64 \times 10^{-4}$ | 40000     | 0.3 | 1         | 32        |

3.5.2. Breakwater Input Parameter

Relationship between concrete modulus of elasticity and concrete compressive strength can be expressed in equation below [11].

$$E = 4700 \sqrt{f'c}$$

In which,
- $E$ : Concrete Modulus of Elasticity (MPa)
- $f'c$ : Concrete Compressive Strength (MPa)

The spun pile component can be modeled as plates. For tie beam component, it can be modeled as an anchor due to its behavior as a spun pile reinforcement. The input parameter which is used for designing breakwater model can be seen in Table 9.

Table 9. Breakwater input parameter in Plaxis.

| Structure Type   | Structure Components | $EA$ (kN/m) | $EI$ (kNm$^2$/m) | $d$ (m) | $w$ (kN/m/m) | $v$ | $L$ (m) |
|------------------|----------------------|-------------|------------------|---------|---------------|-----|---------|
| Breakwater       | Spun Pile (D=1.8 m)  | $3.407 \times 10^7$ | $1.107 \times 10^6$ | 1.8     | 16            | 0.3 | -       |
|                  | Tie Beam (1x1 m)     | $2 \times 10^7$ | $1.67 \times 10^6$ | 1       | 16            | 0.3 | -       |
3.6 Spun Pile and Tie Beam Structure Geometry in Plaxis

The geometry of the spun pile and tie beam structures in Plaxis can be seen in figure 10 below.

![Geometry of spun pile and tie beam in plaxis.](image)

**Figure 10.** Geometry of spun pile and tie beam in plaxis.

3.7. Analysis Stages

This analysis stages using static and dynamic analysis method to determine deflection, bending moment, and axial of spun pile and tie beam components. Besides using static analysis, this analysis stages also using dynamic analysis to assess the strength of spun pile breakwater when the earthquake load is applied according to earthquake factor and earthquake map of Indonesia. The stages of analysis can be seen in Table 10.

| No | Analysis Stages | Output |
|----|----------------|--------|
| 1  | Static analysis 1: Dead Load, Hydrostatic Load | Deflection, bending moment, axial |
| 2  | Static analysis 2: Dead Load, Hydrostatic Load, Wave Load, Current Load, Wind Load | Deflection, bending moment, axial |
| 3  | Static analysis 3: Dead Load, Live load, Hydrostatic Load, Wave Load, Current Load, Wind Load | Deflection, bending moment, axial |
| 4  | Dynamic analysis: Dead Load, Live load, Hydrostatic Load, Wave Load, Current Load, Wind Load, Earthquake Load | Deflection, bending moment, axial |

3.7.1. Result of Deflection Analysis on Spun Pile Breakwater Model

The result of deflection analysis on spun pile and tie beam on cross section A, B, and C with various analysis stages, can be seen on Table 11.

| No | Cross Section | Analysis Stages | Deflection of Spun Pile (cm) | Deflection of Tie Beam (cm) |
|----|---------------|----------------|-----------------------------|-----------------------------|
|    |               |                | Open Sea | Harbour Side |                |                    |
| 1  | A             | Static analysis 1 | 1.7      | 5.5          | 3.7            |                      |
|    |               | Static analysis 2 | 2.7      | 3.9          | 2.7            |                      |
|    |               | Static analysis 3 | 2.7      | 4            | 2.7            |                      |
|    |               | Dynamic analysis | 2.8      | 4.1          | 2.9            |                      |
| 2  | B             | Static analysis 1 | 1.5      | 4.8          | 3.4            |                      |
|    |               | Static analysis 2 | 2.4      | 3.4          | 2.5            |                      |
|    |               | Static analysis 3 | 2.4      | 3.4          | 2.6            |                      |
|    |               | Dynamic analysis | 2.5      | 3.5          | 2.8            |                      |
| 3  | C             | Static analysis 1 | 3.3      | 1.2          | 1.4            |                      |
|    |               | Static analysis 2 | 1.2      | 1.2          | 1              |                      |
|    |               | Static analysis 3 | 1.2      | 1.2          | 1              |                      |
|    |               | Dynamic analysis | 1.3      | 1.3          | 1.2            |                      |
3.7.2 The Result of Bending Moment and Axial Force Analysis on Spun Pile Breakwater Model

The result of bending moment and axial force analysis on spun pile and tie beam on cross section A, B, and C with various analysis stages can be seen on Table 12.

Table 12. The result of bending moment and axial force analysis on spun pile breakwater model.

| No | Cross Section | Analysis Stages | Bending moment (ton.m) | Axial (ton) |
|----|---------------|-----------------|-----------------------|------------|
|    |               |                 | Open Sea | Harbour Side | Tie Beam | Open Sea | Harbour Side | Tie Beam |
| 1  | A             | Static analysis 1 | 367.5   | 342.8       | 125.8   | 93.2     | 133.7       | 29.3     |
|    |               | Static analysis 2 | 293.3   | 274.2       | 97.7    | 76.8     | 148.3       | 15.3     |
|    |               | Static analysis 3 | 294.4   | 274.2       | 100.9   | 79.2     | 150.6       | 15.8     |
|    |               | Dynamic analysis  | 294.4   | 274.2       | 100.9   | 79.2     | 150.6       | 15.8     |
| 2  | B             | Static analysis 1 | 345.0   | 312.4       | 116.9   | 89.3     | 127.0       | 27.9     |
|    |               | Static analysis 2 | 273.1   | 256.2       | 92.1    | 73.4     | 131.5       | 16.2     |
|    |               | Static analysis 3 | 274.2   | 256.2       | 95.4    | 75.6     | 132.6       | 16.7     |
|    |               | Dynamic analysis  | 274.2   | 256.2       | 95.4    | 75.6     | 132.6       | 16.7     |
| 3  | C             | Static analysis 1 | 118.0   | 119.1       | 63.9    | 57.2     | 75.5        | 7.0      |
|    |               | Static analysis 2 | 122.5   | 104.5       | 10.5    | 45.4     | 82.1        | 34.0     |
|    |               | Static analysis 3 | 120.2   | 110.3       | 110.3   | 48.3     | 84.9        | 34.5     |
|    |               | Dynamic analysis  | 120.2   | 110.3       | 110.3   | 48.3     | 84.9        | 34.5     |

3.8. Result of Specification and Dimension of Spun Pile Breakwater

- Spun pile: Prestressed Concrete f_c' = 52 Mpa D=1800 mm t=200 mm cracking bending moment 520 ton.m.
- Capping Beam: Reinforced Concrete f_c' = 35 Mpa B=2.5 m H=1.5 m.
- Tie Beam: Reinforced Concrete f_c' = 35 Mpa B=1 m H = 1 m.

3.9. Design Drawing

Design drawing of spun pile vertical wall breakwater can be seen in figures below:
Figure 12. Plan view STA 1-3 of spun pile breakwater.

Figure 13. Cross section A-A of spun pile breakwater.
4. Conclusions
The results of analysis using SAP2000 obtained a maximum moment value of 347 ton.m. On the other hand using Plaxis, the analysis results obtained a maximum moment value of 367.5 ton.m. Both of these results are still below the cracking moment limit value, which is 520 ton.m.

The results of analysis using SAP2000 show deflection due to service loads is 7.7 cm. While using Plaxis the deflection due to service loads is 5.5 cm. This result is still below the deflection limit value, which is 22.3 cm.

All of dimension of spun pile, capping beam, and tie beam analysis results meet specified design requirements.

5. References
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