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Evaluation of Surface Settlement and Lateral Displacement During Tunnel Construction Using 3D Numerical Modelling

A. Fahmi[1], Desyanti[1], I. Masyhur[2], H. Bigman[2], S. Endra[2], M. Riska[3] and M. Weni[3]
[1]*Institute of Road Engineering (IRE), Bandung, Indonesia*
[2]*Bandung Institute of Technology, Bandung, Indonesia*
[3]*Mass Rapid Transit Jakarta Project, Jakarta, Indonesia*
E-mail: fahmi.aldiamar@pusjatan.pu.go.id

ABSTRACT: Shield tunnelling construction in urban area could influence surrounding structures. Several empirical equations and laboratory testing using centrifuge model already published to determine effect of tunnel excavation, especially due to the shield loss and tail loss effects. Gap between shield machine and tunnel segment lining is the main subject that determine the amount of surface settlement and lateral displacement. In this study, case study for evaluating ground deformation during tunnel construction is located in Mass Rapid Transit Jakarta project around diaphragm-wall Bendungan Hilir station. Evaluation consists of comparison between prediction analysis using 3-dimensional finite element numerical model and actual deformation from surface settlement and inclinometer are conducted to evaluate the modelling effectiveness.

Keywords: shield tunneling, ground loss, surface settlement, lateral displacement and mass rapid transit Jakarta

1. INTRODUCTION

Mass Rapid Transit Jakarta is the first shield tunnelling using Earth Pressure Balance (EPB) method constructed in Indonesia. EPB method are commonly used for fine grained soils (<0,06 mm) such as clay-silt and silt-sand soft to stiff consistency and active support pressure control conducted to ensure low influence to settlement and lateral deformation (B. Maidl, et al., 2012). Anticipation of possible problems especially to surrounding structure due to excessive settlement, cave in and building damage should be considered during design and construction phase. According to Mair and Taylor (1997) and Nagen Loganathan, et al (2011) deformation due to tunnel construction mainly caused by face loss, over cutting, shield loss and tail loss. Even though gap usually determined by effectiveness of shield machine, soil condition could also influence displacement that happened. In this study, case study for evaluating ground deformation during tunnel construction is located in Mass Rapid Transit Jakarta project around diaphragm-wall Bendungan Hilir station. Surface settlement marker and inclinometer were placed above tunnel alignment and near the tunnel cross section to measure surface settlement and lateral displacement. Evaluation consists of comparison between prediction analysis using 3-dimensional finite element numerical model and actual deformation from surface settlement and inclinometer are conducted. Since tunnel in this location constructed into hard silty sand material, two constitutive models using Mohr-Coulomb and hardening-soil model were evaluated to determine which of the following constitutive model best suit the actual deformation occur on the field during construction.

2. METHODOLOGY

Numerical modelling 3-dimension finite element method using Midas Gts Nx software is conducted to predict and simulated excavation phase in stage construction. Deformation acting around tunnel excavation then compared with surface settlement and lateral deformation measured using digital waterpass combined with robotic total station and inclinometer that placed 5 m from outer tunnel cross section. Ground condition that modelled in this paper based on primary borehole, in-situ test and laboratory test also secondary data collected by MRT project. All of the data then review to gain soil parameter that suitable for Mohr-Coulomb and hardening-soil modelling. Actual and numerical matching method then conducted to evaluate best fit result between predicted and actual measured deformation.

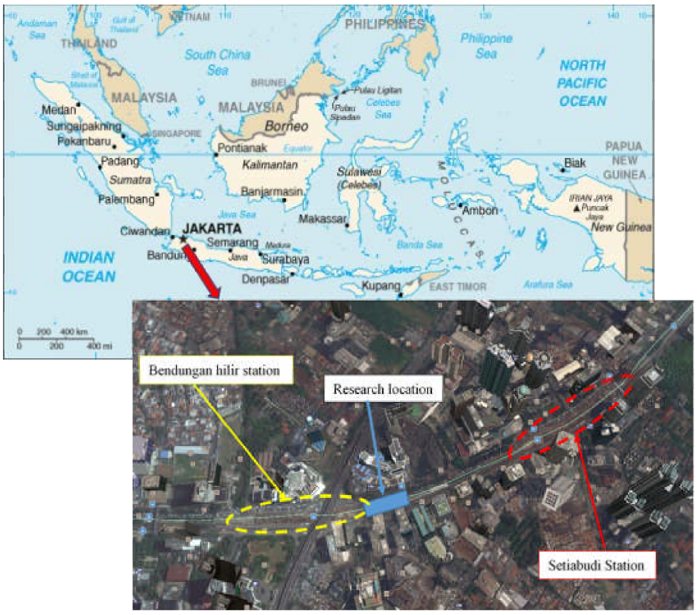

Figure 1 Location of monitoring site

2.1 Soil Parameter

There were 3 borings conducted in the tunnel section at Bendungan Hilir station, with distance range from 50 m to 92 m from diaphragm-wall (D-wall). First boring was conducted during design stage on 2010, while the other boring conducted in 2016 and 2017. According to the evaluation from all of the field testing, tunnel construction was predicted going through hard silty sand and below ground water level. According to ASTM D2487-17, soil at project location mostly have liquid limit more than 50% and plasticity index plots below "A"-line which can be defined as elastic silt (MH) as seen in Figure 2, while prediction of Young's modulus according to pressuremeter test can be seen in Figure 3. Soil parameter used in the modelling can be defined in Table 1 and Table 2.

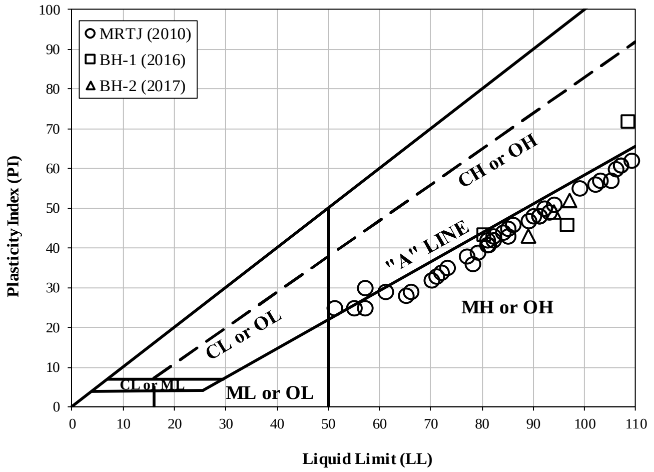

Figure 2 Plasticity chart data

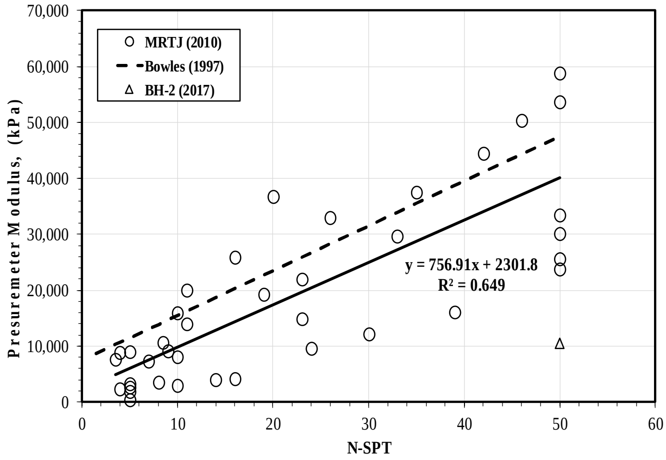

Figure 3 Elastic modulus from Pressuremeter test

Table 1 Mohr- Coulomb Soil Parameters

Name	Description	γ kN/m^3	c' kPa	Ø' deg	E kN/m^2
Layer-1	Stiff silty clay	15.68	5	25	7,600
Layer-2	Stiff clayey silt	15.54	10	27	9,114
Layer-3	Very stiff silty sand	15.50	1	30	17,440
Layer-4	Hard silty sand	16.00	1	30	47,716
Layer-5	Very hard clayey silt	16.00	15	27	47,716

Table 2 Hardening Soil Parameters

Name	Description	Secant stiffness, E_{50} (kPa)	Tangent stiffness, E_{oed} (kPa)	Unload/reload stiffness, Eur (kPa)	K0	Shear modulus at small strain (kPa)
Layer-1	Stiff silty clay	4,180	4,180	12,540	0.58	31,660
Layer-2	Stiff clayey silt	5,013	5,013	15,038	0.55	24,713
Layer-3	Very stiff silty sand	9,592	9,592	28,776	0.50	18,957
Layer-4	Hard silty sand	26,244	26,244	78,732	0.50	14,217
Layer-5	Very hard clayey silt	26,244	26,244	78,732	0.55	23,822

2.2 Numerical modelling

Numerical modelling using finite element method is usually used for evaluating soil structure interaction between tunnel boring machine and the surrounding soil, complex model also to estimate deformation around tunnel on design stage. German Tunneling Committee (ITA-AITES, 2016), recommended 3 dimensional (3D) numerical modelling with stage construction to evaluate tunnel excavation phase. 3D model can give a more thorough information not only deformation around tunnel excavation, also face stability each step of excavation progress. In this paper, thickness of ground loss is according to site project information as seen in Figure 4 and modelled as soil interface that reduced in term of strength.

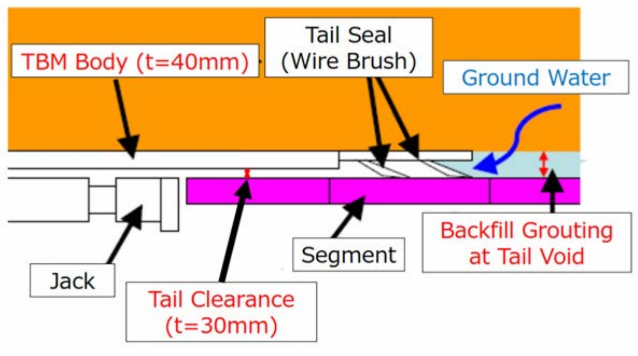

Figure 4 Shield loss and tail loss at MRT Project (Shimizu-Obayashi-Wijaya-Jaya,SOWJ, 2015)

Surface elevation in tunnel modelling are according to topography at site to evaluate influence of overburden height (H), diameter of tunnel (D) is 6.55 m and advance of excavation (d) is 1.50 according to lining segment placement as illustrated in Figure 5.

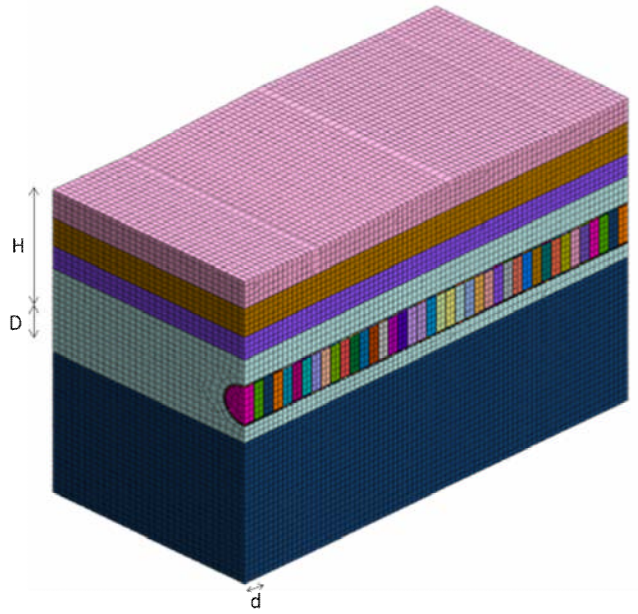

Figure 5 Numerical modelling scheme

3. RESULTS AND DISCUSSION

3.1 Surface settlement measurement

According to average value of surface settlement monitoring for 10 cross section, daily measured starting from November 21, 2016 until April, 9 2017 as seen in Figure 6, it is shown that at every section trend of surface settlement curve is quite different. 0 number in x-axis is denote centreline of tunnel section position which shown largest surface settlement (until -1.39 cm) occurred during monitoring time frame. In some position of surface settlement marker section, heaving occurred, nevertheless average displacement from all of 10 sections show that the trend is displaced and the value decline along with the distance away from tunnel cross section. This trend is relatively similar with previous researcher (Sven Moller, 2006), and (Loganathan, et al, 2011).

Surface settlement that occurred are relatively small. This is possibly due to the high overburden above tunnel construction and less disturbance of ground loss from shield and tail loss. Empirical approach as mentioned in (JSCE, 2006) describe that minimum overburden that could cause large surface settlement is less than 1.5 times tunnel diameter.

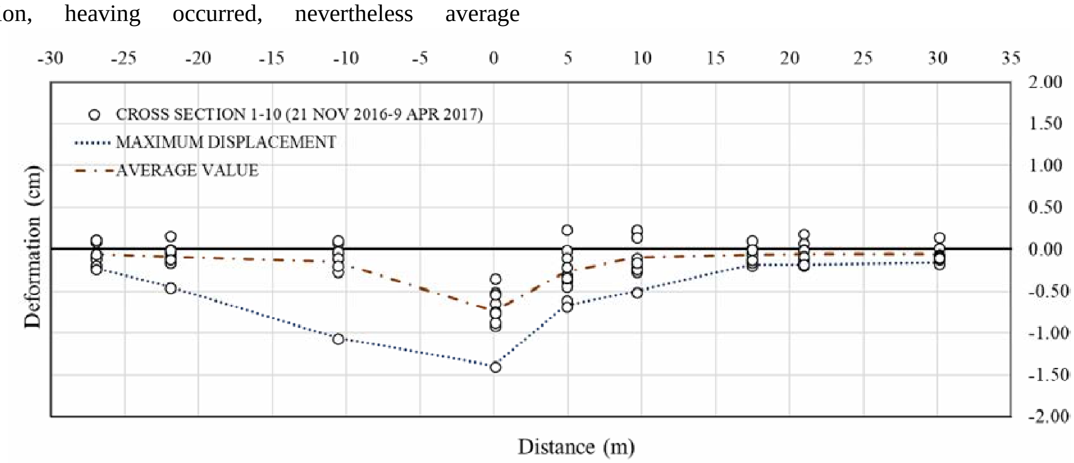

Figure 6 Result of surface settlement measurement

3.2 Inclinometer measurement

Inclinometer position are set into four direction i.e. Meridien Building to HSBC Building for cross sectional evaluation and D-wall to Setiabudi Station for longitudinal evaluation of tunnel construction influence as seen in Figure 7. Shield tunnel position is passing through inclinometer position at December 8, 2016 and inclinometer indicate lateral displacement (2.6 mm) perpendicular to the tunnel direction or to direction A. Lateral displacement increasing until 3.15 mm on December 10, 2016 and reduced until 0.6 mm on April 06, 2017 as seen in Figure 8. This behaviour indicate ground loss during passing through of tunnel construction and application of grouting radial to the tunnel surrounding that filling void around tunnel excavation and reduce lateral displacement.

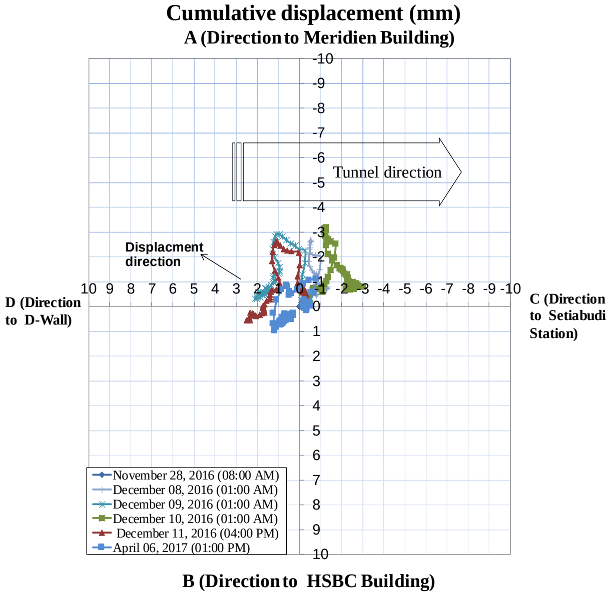

Figure 7. Result of top view cumulative displacement

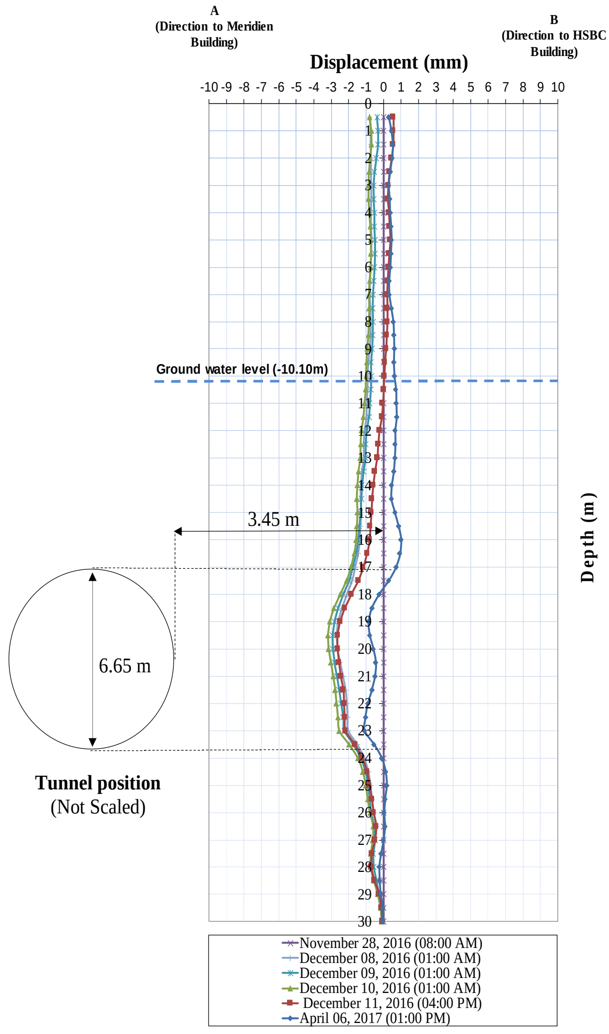

Figure 8. Result of lateral displacement during tunnel construction

3.2 Numerical simulation result

Numerical modelling using Mohr-Coulomb and hardening soil model give a different result as seen in the total displacement Figure 9 and Figure 10. Mohr-Coulomb model give a smaller displacement at ground surface while hardening soil model give the opposite result.

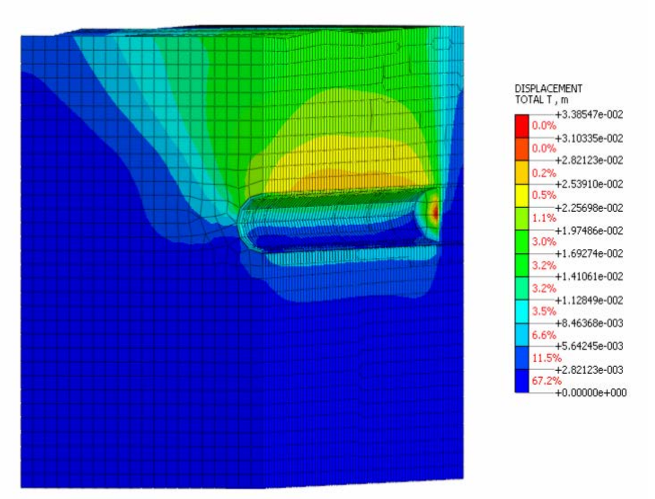

Figure 9. Numerical simulation result using Hardening soil Model

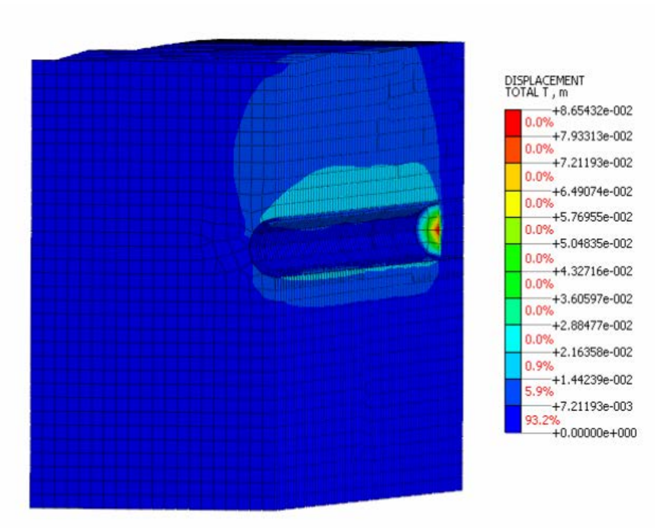

Figure 10. Numerical simulation result using Mohr-Coulomb model

Comparison between numerical and actual deformation according to measured instrumentation result are describe in Figure 11 and Figure 12. Mohr-Coulomb model fit in great correlation with average surface deformation result, while hardening soil close match with the maximum surface ground deformation. Opposite result shown in the lateral displacement, i.e. Mohr-Coulomb model fit in great correlation with maximum lateral displacement, while hardening soil model give a smaller result.

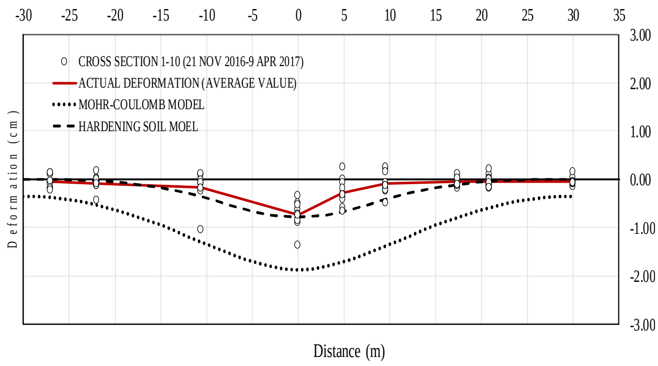

Figure 11. Comparison between numerical and actual surface settlement

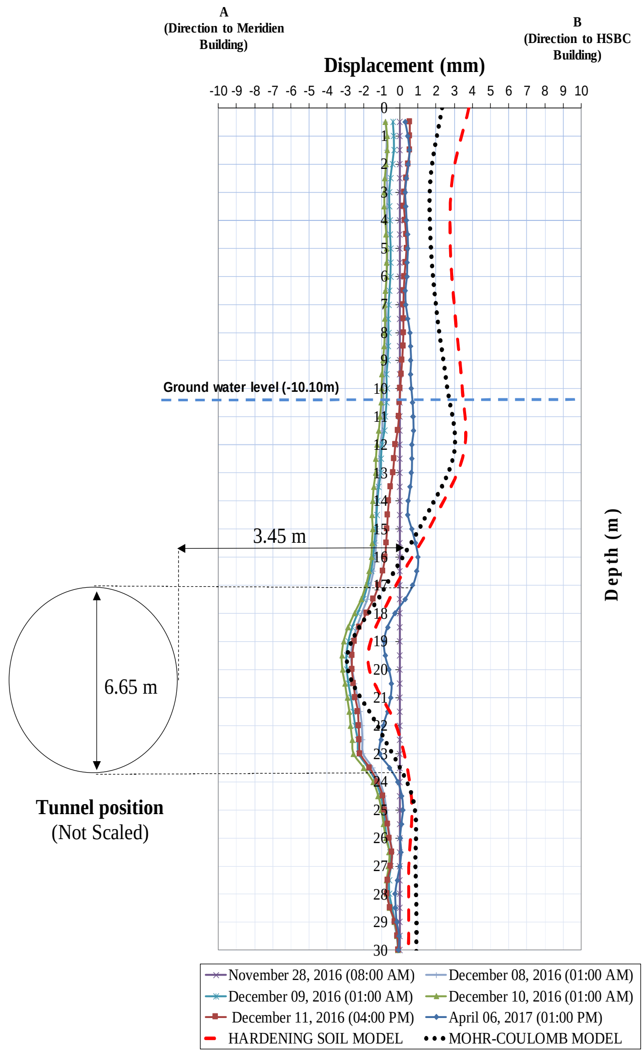

Figure 12. Comparison between numerical and actual lateral displacement

4. CONCLUSIONS

In this study, numerical analysis compared with actual measurement data from instrumentation of surface ground settlement and lateral displacement. The main results can be summarized as follows:

(1) Mohr-Coulomb model give a good result to evaluate lateral displacement on tunnel construction but give a less conservative result on the surface ground settlement.

(2) Hardening soil model give a smaller lateral displacement on tunnel construction but give a more conservative result on the surface ground settlement

This study was collaboratively carried out based on “Agreement on Research Exchange and Cooperation between Institute of Road Engineering and MRT Jakarta in order to develop technical guideline for shield tunnelling using earth pressure balance method.

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