Circular lining behaviour due to earthquake load in MRT
Jakarta underground tunnel area CP-106

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Abstract. One solution to traffic congestion in Jakarta is to build a mass transportation system in the form of Mass Rapid Transit (MRT), especially the application of underground tunnel structures. This study examines the modeling of tunnel behavior on the effect of earthquake loads. This study calculates circular tunnel behavior in static and dynamic conditions due to earthquake effects. Static condition analysis using Muir Wood's theory and dynamic conditions using the theories of Wang (1993) and Panzien (2000) as well as supported by empiric and numeric calculations. The depth of the MRT tunnel in the CP-106 area is at a depth of 11 meters by diverting by clay with NSPT 3-20. The results show that in static condition has tunnel deformation that works at 8.06 mm in empiric and 15.12 mm in numeric. In the dynamic analysis with earthquake acceleration in 300 cm/s\(^2\) produces oval deformation at 15.95 mm in empiric and 15.20 mm in numeric. The maximum deformation limit given is 20 mm with a maximum earthquake acceleration value of 400 cm/s\(^2\). In conclusion, MRT Jakarta area CP-106 in static condition has a lower deformation than dynamic conditions, but both conditions fulfill the deformation tunnel requirements.

Keywords: Transportation, Static, Dynamic, Earthquake Load, Oval Deformation

1. Introduction

Large cities in developing countries are often faced with transportation problems. Jakarta, the capital of the State of Indonesia, is an example of a large city in a developing country that has problems in the transportation sector. One of the solutions implemented by the Jakarta Government to overcome transportation problems is to build a mass transportation system in the form of Mass Rapid Transit (MRT).

Most of the Jakarta MRT projects especially the tunnel structure are in northern Jakarta. Specifically in the central Jakarta CP-106 area that has already been completed (e.g., [1]). Broadly speaking, the soil base in Jakarta is a volcanic clay deposition that is approximately 2500 years old. The land surface in the northern part of Jakarta consists mostly of soft clay (e.g., [4]). Besides, large-scale earthquakes will also propagate earthquake vibrations so that they experience amplification or magnification of the shock of the structure above or below. According to the Indonesian earthquake threat map published by USGS (2012), the city of Jakarta is in the Peak Ground Acceleration zone between 0.245 g - 0.326 g (Marlihat and Mangape, 2009). Seeing the importance of planning in the construction of earthquake-resistant tunnels in Jakarta, especially in the initial lane of the CP-106 tunnel area, research on modeling the behavior of tunnels to the effects of earthquake loads and the impact on surrounding buildings is needed.
In the first phase, Jakarta MRT construction starts from Lebak Bulus towards the 15.7-kilometer Bunderan HI, including the construction of 13 stations. Figure 1 shows the Jakarta MRT line CP-106 area starts from Dukuh Atas as a research location with a tunnel diameter of 7.3 m which was dug below the surface of the ground using the Tunnel Boring Machine (TBM) using the shield tunneling method. The tunnel consisting of precast segments can be used in single or multiple tunnels to support soil or rock and water pressure. A tunnel construction requires 7 precast lining segments in a full circle. Figure 2 shows the dimensions of the precast segment and the connections between the precast lining segments.

2. Research Method

First of all, this research examines the static and dynamic conditions in the tunnel. This analysis uses several standards to determine the circular tunnel behavior in the Jakarta MRT tunnel and this standard reference has never been used by the Jakarta MRT project. In planning tunnel lining, there are things to consider, namely the behavior of circular tunnel lining. Muir Wood’s (2002) theory provides a method for analyzing static conditions of tunnels by considering Axial Force, bending moment, and lining deformation. Static analysis of circular tunnel behavior can be described in the equation:

\[
N = \frac{r_0(5s_1+2s_2)}{3} \cos 2\theta + p_{ew} + p_r + N_0
\]

\[
M = \frac{r_0 s_1 (2s_0 + s_1)}{6} \cos 2\theta
\]

\[
U = \frac{r_0 s_1 (2s_0 + s_1)}{18} \cos 2\theta
\]

The effects of earthquakes on underground structures can be grouped into two categories, namely ground vibration and soil failure. Ground vibration refers to the deformation of the soil produced by seismic waves that propagate through the earth's crust. The main factors affecting ground vibration are soil shape, dimensions and depth of the structure, the nature of the surrounding soil or rocks, the nature of the structure, and the weight of the soil under review (Zahrah, 1987). The tunnel behavior approach refers to the elastic beam model for deformation caused by the surrounding soil. Three types of seismic
response deformation in underground structures are axial compression - extension, longitudinal moment, and ovaling. Axial deformation of the tunnel resulting from seismic waves produces motion parallel to the axis of the tunnel and causes compression and stress. The tunnel deformation mode due to seismic waves can be seen in figure 3 (Wang, 1993).

![Figure 3](image)

**Figure 3.** Mode of deformation of a tunnel due to seismic waves (Owen and Scholl, 1981)

The equation to determine the ground shear strain caused by dynamic loads is as follows:

$$\gamma_{\text{max}} = \frac{c_{\text{max}} (P_{\text{GM}} \sigma_v)}{G_m E_m (1 + \nu_m)}$$

(4)

with,

- $P_{\text{GM}}$ = the acceleration of the peak land adjustments influences the site class
- $\sigma_v$ = earth vertical stress (kN/m²)
- $c_{\text{max}}$ = earth shear stress (kN/m²)
- $R_d$ = stress reduction factor
- $E_m$ = modulus of soil elasticity (kN/m²)
- $G_m$ = earth shear modulus (kN/m²)
- $\nu_m$ = soil Poisson ratio

The forces and moments on a tunnel caused by seismic waves act on the axis of the tunnel. Maximum friction between the tunnel wall and the surrounding soil results in axial strain on the tunnel wall. The lining response coefficient can be obtained using a graph between the compressibility ratio and the flexibility ratio. Lining resistance response due to ground pressure with earthquake load is calculated by Equation (4) - (6).

$$C = \frac{E_m (1 - \nu_m)}{E_m (1 + \nu_m) (1 - 2\nu_m)}$$

(5)

$$F = \frac{E_m (1 - \nu_m)^2}{6E_m (1 + \nu_m)}$$

(6)

$$K_j = \frac{12(1 - \nu_m)}{2F + 5 - 6\nu_m}$$

(7)

with,

- $C$ = compressibility ratio (response due to soil pressure)
- $F$ = ratio of replacement (response layer to withstand soil pressure) $I$ = moment of inertia (m²)
- $r$ = lining radius (m)
- $t$ = lining thickness (m)
For the bending moment equation, axial force and oval deformation due to earthquake loads on the cross-section of the tunnel as a function of maximum flexural strain are described as follows:

\[
M_{\max} = \frac{1}{6} K_f \frac{E_m r^2 \gamma_{\max}}{1 + v_m}
\]

(8)

\[
N_{\max} = K_1 \gamma_{\max} \frac{r}{2(1 + v_m)}
\]

(9)

\[
\Delta d = \frac{D K_f F_\gamma \gamma_{\max}}{3}
\]

(10)

The underground construction research site is located on the CP 106 section which is viewed from the Upper Dukuh pedestrian bridge (STA 13k + 000) to the Upper Dukuh Station (STA 13k + 916). In this study, primary and secondary data are used as input data in the modeling of circular lining tunnel behavior analysis in the Jakarta MRT tunnel construction project. Primary data in the form of results of land investigations that have been carried out previously as well as the results of surveys and documentation. Secondary data in the form of soil layers interpretation and tunnel design.

3. MRT Jakarta Tunneling Result

In this study, the soil layer in the Jakarta MRT tunnel from Upper Dukuh Bridge to Upper Dukuh Station were taken in one section is BR 21. Soil conditions at the construction site are dominated by soft clay at a depth of less than 10 m from the ground surface and silt layer to sand with medium density at a depth of 15 to 20 m.

**Figure 4. Interpretation of the Jakarta MRT tunnel layer CP 106 section**

For numerical calculations using Plaxis-2D, earthquake loads are given in the time acceleration calculation format. In this study, variations in earthquake load applied at 300 cm/s² at Southern Sumatra, Indonesia obtained from USGS. Soil movements that occur in the subsoil or solid layer, its characteristics are regulated using the maximum soil acceleration parameters. The maximum value of
ground motion for dynamic analysis is more effective using the initial earthquake record (Nuttli, 1979). In table 1 the parameters of the earthquake data are described in the analysis and the acceleration of Southern Sumatra can be seen in figure 5.

| Acceleration (cm/s²) | Earthquake Source                  | Magnitude | Peak time (s) |
|----------------------|------------------------------------|-----------|---------------|
| 300                  | Southern Sumatra, Indonesia, 2007  | 8.4       | 36.80         |

Figure 5. Southern Sumatra earthquake acceleration recording (USGS, 2012)

3.1. Calculation Phase
The analysis phase carried out in this study was 3 stages. In general, the analysis phase can be seen in figure 6. For more details, the analysis phase will be described as follows.

3.1.1. First Phase (Surcharge Load)
The first phase applies static loads to the ground before tunnel excavation is carried out. This type of calculation in this phase uses plastic calculations by loading the input construction stage. The static load
application is set from the sheet tab-define parameter. The structural model in the first phase calculation can be seen in figure 7.

![Figure 7. Structure model in the first phase calculation](image1)

3.1.2. Second Phase (Tunnel Excavation)
Behavior applied to the model in the second phase is by activating cluster tunnels and soil excavation. This type of plastic analysis calculation by loading input stage construction is still used in the second phase. The structural model in the second phase calculation can be seen in figure 8.

![Figure 8. Structure model in the second phase calculation](image2)

3.1.3. Third Phase (Application of Earthquake Load)
In the last phase or third phase, dynamic load in the form of an earthquake load is given to the tunnel model. Setting the type of dynamic analysis calculation, by loading the input total multipliers. On the parameters tab, the settings are performed on an iteration procedure using a manual system with dynamic sub-steps of 3. Earthquake load is entered by opening the multiplier -SMdispl tab sheet. The earthquake load format used uses the SMC (Strong Motion CD) data format from USGS. The data chosen in this analysis is the acceleration type of data. The last place is to set the dynamic time of earthquake load. For more details, can be seen in figure 9.
3.2. Static Load Analysis
The final result of static load analysis based on empirical analysis refers to Muir Wood's theory in the Land Transport Authority (2002) and numerical analysis using Plaxis-2D. Overall lining strength based on the interaction diagram is still within safe limits, with a deformation lining tunnel below 20 mm (Mott Mc Donald, 2013). For an overall comparison of the deformation analysis, axial forces and bending moments can be seen in figure 10 in the diagram of internal forces.

![Figure 9. Application of earthquake loads in the spent phase calculation](image)

**Figure 10.** Comparison of the behavior of circular tunneling static load analysis tunnel. (a) Bending Moment, (b) Axial Force, (c) Deformation.

3.3. Dynamic Load Analysis
For dynamic load analysis, the calculation of the empirical method uses the methods of Wang (1993) and Panzien (2000) as well as numeric using Plaxis-2D. This method is valid and has a high level of accuracy if the results are the same. Circular tunnel behavior in overall dynamic load analysis can be seen in figure 11.
Figure 11. Comparison of the behavior of circular tunneling dynamic load analysis. (a) Bending Moment, (b) Axial Force, (c) Deformation.

The largest oval deformation is based on the empirical method of 15.95 mm and based on the numerical method of 15.20 mm. From the deformation graph, dynamic analysis produces the largest deformation value due to the earthquake acceleration of 300 cm/s², but the deformation of the lining tunnel is still within the given limit.

4. Conclusion
The lining ability which is assessed based on axial force, bending moment, and oval deformation due to static and dynamic loads is carried out in section BR 21 in the CP-106 area. Deformation values in the analysis of static conditions have smaller results than dynamic conditions due to dynamic conditions considering the peak ground acceleration (PGA) value of 300 cm/s² and do not consider friction between the lining and the ground. So this can make the tunnel deformation greater than the static condition which only considers overburden loads and surcharge loads. But from these two conditions, tunnel deformation is still within the safe limits because it has a deformation value below 20 mm.

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