Static and Seismic Design Approach for Underground Station Structure for the case of Jakarta MRT

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The first Metro Project in Indonesia has commenced finally and half of the packages are underground structure. The civil packages have been achieving some significant progress in construction where the majority of underground stations are under construction now together with the progress of tunnel. The station structure is designed and constructed with Diaphragm Wall (D-wall) system, while tunnel is the segmental lining to connect each station.

In this occasion, the authors would like to present the design approach of underground station structure that has been applied for Jakarta MRT by considering static and seismic case. The static loading is primary coming from soil condition surrounding the structure by considering the condition during the construction and final including the residue force. The seismic loading for underground structure is due to relative displacement of soil surrounding the structure due to seismic wave propagation. By the fact Jakarta is located in the high risk zone of earthquake; hence the resistance of the structure under seismic load is really an important issue. Since there is no actual major record for dominant earthquake, thus the development of site specific seismic analysis will be required to get the corresponding ground motion by Shake Analysis in order to determine the displacement of surrounding soil around the underground structure.

By this paper, the authors try to describe the approaches used by structure engineer in quantifying the soil loading surrounding the location and seismic approach. This contribution has been applied in the case of the first MRT Underground in this country.

Keywords: Underground structure, Static Design, Lock-in force, Seismic Design

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1 INTRODUCTION

The first Metro project in Jakarta and also in Indonesia will be constructed at South – North corridors (Lebak Bulus – Kampung Bandan) with distance of ± 23.8 Km. Phase I construction will connect Lebak Bulus to Bundaran Hi with distance of 15.7 km. which is divided into 6 (six) civil works packages with total of 13 stations and consist of 7 elevated stations (CP 101 – CP 103) and 6 underground stations (CP 104 – CP 106). All civil work packages have been awarded and in detailed design stage now.

Instead of those civil work packages, there are also 2 (two) packages i.e. CP 107 for Signalling System and CP 108 for Rolling Stock.

In the recent time during the paper produced, the current status of the project itself is in detailed design stage. However, the construction of D-wall for underground station is already finished and continuing with the installation of two tunnels.

As known, the problem of traffic is the major topic in Jakarta nowadays. The need of massive public transport is unquestionable; also when one considers the loss of fuel, time and expenses. Therefore,
the needs for massive public transport such like MRT is obviously needed for such a big metropolitan city like Jakarta.

In this occasion, the authors wish to explain briefly the “state of the art” of design procedure for underground structure such as station and tunnel by considering static due to soil pressure and seismic load case as can be seen in the approach below.

2 UNDERGROUND STRUCTURE FOR MRT

Talking about the underground MRT, one should refer to Underground Station and Tunnel structure itself. Although the influence of soil surrounding the structure plays dominants, the structural engineers plays important role in determining the type of the structure and how to get the more efficient structure that governs the overall cost.

STATION

The stations are underground boxes comprising of main sections, the deep station box with D-wall and the shallow entrance and ventilation shafts that utilize soldier pile and lagging as temporary earth retaining wall and permanent reinforced concrete as permanent works.

D-walls for the deep station box are a proven earth retaining system that has been used extensively around the world. This system provides a robust earth retaining system that is then reused for the permanent structure enabling advantages in construction program. A top down construction method is used for this deep station box. This method involves installing diaphragm walls to form the station box followed by excavation and construction of the slabs from roof slab downwards as excavation progresses. These slab diaphragms act as a strut to keep the diaphragm wall propped and is a robust construction method proven to reduce ground movement.

For entrance and ventilation shafts, a cast in-situ reinforced concrete will be used as the permanent structure. This method is a more effective than diaphragm walls for shallow excavations. Entrances and ventilation shafts meanwhile will be constructed using bottom up construction method. This method is suitable for the smaller and shallower entrance and ventilation shaft excavations. Steel struts and walers are then used to prop open the excavation.

The material for concrete and steel rebar will be C40 (40 MPa cube characteristic strength at 28 days equivalent with approx. 35 MPa for cylinder test) and 390 MPa respectively.

TUNNEL

The running bored tunnels have the internal diameter of the bored tunnels is 6.05m. The distance between the tunnel axis and the rail level will be considered as 2.085m while the type of rail track is
fixed concrete slab track with embedded sleepers. The thickness of the segment lining will be 250mm and width of each section will be 1500mm.

The lining will consist of 3 standard segments, 2 top segments and a key. The bolts will be straight type (spear bolts) and typically four number per segment. Top segments will have a central grout hole. Hydrophilic seal and caulking grooves will be provided in the segments to deal with ground water. Concrete grade shall be grade C60 (60 MPa cube characteristic strength at 28 days equivalent with approx. 50 MPa for cylinder test) and steel reinforcement grade to be in compliance with fy = 390 MPa. All bolts, nuts and washers to be galvanized.

Two numbers of Earth Pressure Balance (EPB) Tunnel Boring Machines (TBM) are proposed to construct the two running tunnels.

3 STATIC LOADING FOR UNDERGROUND STRUCTURE

Underground MRT Station is an underground structure that uses diaphragm wall system as temporary wall for excavation purpose and for permanent also. The excavation stage will be done stage by stage, and every certain of depth excavation the slab will be cast and act as a strut. By this method the diaphragm wall will never be act as free cantilever. Diaphragm wall will be used as a permanent structure as well after all excavation work has been done. The depth of the excavation is around 14 m depth, and the width is more than 20 m. The structure has 3 floor, roof floor, concourse floor and base floor. The approach here is basically pure soil structure interaction, that simplified 2D analysis can be regarded as a box analysis.

STATION MODELING

As first step, one must have Geotechnical Interpretative analysis as input from Geotechnical Engineer. They will determine the type of soil parameter for each station and if necessary, could be more than one type of soil in each station. Then, the cross section will be chosen for each type of soil to be analysed by using 2D model by taking into account the temporary, static and seismic condition and finally getting the reinforcement design.

The station is modelled as 2D plane frame rectangular box section. All elements including the diaphragm walls at the external sides, internal walls/columns and slabs are modelled as frame elements with unit width in the longitudinal direction of station box. Soil subgrade is modelled as stiff vertical springs and assigned to base slab and diaphragm wall as shown in Figure 5 below. Stiffness of the vertical springs is derived using numerical solution through iteration between geotechnical and structural modelling.

The first stage is to perform an initial 2D linear static plane frame analysis of the station box structure while in parallel 2D geotechnical finite element analysis is then carried out to considering the
construction sequence of the station box. This will provide the envelope of temporary stage forces on the diaphragm walls and slabs.

A 2D plane frame analysis is then carried out for the permanent stage station box including the locked-in forces from the final stage of construction. This will provide the forces on the diaphragm walls and slabs due to permanent stage forces. In order to account for the locked-in forces in the wall during construction, forces on the wall resulting from the lateral pressure equal to at rest minus active soil pressure applied on 2D plane frame model is added to the geotechnical numerical result forces and compared with forces in the wished-in place model.

The lock-in force procedure itself is to get the envelop of internal forces by considering the construction stages, wished in placed (long term loading of the permanent stage of the structures) and using the appropriate lateral earth pressure as required in each of the load combinations. The procedure can be figure as below:
The result of envelop can be seen below:

![Figure 8 Envelop of Moment Internal Forces](image)

**TUNNEL**

Lining design models will be based on the continuum mechanics principles based on continuum model by AM Muir Wood (cf. Zhao et al, 2000). The precast concrete segments will be subject to short term and long term loads. Handling, stacking, erection and TBM shove forces are short term loads. To resist these loads, two layers of reinforcement will be provided along the intrados and extrados of the tunnel lining. Reinforcing bars are provided along the circumferential joints to take the TBM shove forces.

When segments are in the good ground as a complete ring, the concrete is mostly in compression and the segments are designed as short columns subjected to axial forces and small bending.
moments. The Muir Wood method (cf. Zhao et al, 2000) will be adopted in the design of the linings. Expected rotations from the elliptical mode deformations under design loading are taken into account as shown below.

The bolt shall be designed to cater for all temporary load conditions during construction stage and satisfy the requirements of tunnel analysis in seismic condition. Bolt sockets are to be installed at 11.25° intervals at the middle of each tunnel segment for the fixing of cable brackets and other attachment. M12 bolt sockets will be used. The clear distance between socket and any reinforcement shall not be less than 40mm after making full allowance for inaccuracies in the position of the reinforcement.

3 SEISMIC LOADING FOR UNDERGROUND STRUCTURE

By the fact Jakarta is located in the high risk zone of earthquake; hence the resistance of the structure under seismic load is really an important issue. However, unlike the elevated structure, the seismic design of underground structures is unique in several ways. For most underground structures, the inertia of the surrounding soil is large relative to the inertia of the structure.

It is understood that the first evaluation of the ground response shaking can be divided into two groups i.e. ground failure and ground shaking and deformation. In the case of Jakarta particularly in South location, the authors focussed on the ground shaking and deformation, which assumes that the ground does not undergo large permanent displacement, following the approach from Hashash (2001). Another notice that the measurements of the seismic response of an immersed tube tunnel during several earthquakes show that the response of a tunnel is dominated by the surrounding ground response and not the inertial properties of the tunnel structure itself (Hashash, 2001). The focus of underground seismic design, therefore, is on the free-field deformation of the ground and its interaction with the structure. The emphasis on displacement is in stark contrast to the design of surface structures, which focuses on inertial effects of the structure itself. This led to the development of design methods such as the Seismic Deformation Method that explicitly considers the seismic deformation of the ground. Hashash (2001) clearly presents a review on the seismic behaviour and design of underground structures in soft ground with an emphasis on the development of the Seismic Deformation Method.

SEISMIC HAZARD ASSESSMENT

Seismic hazard assessment is required in this project since the facilities is categorized as an important structure that affect a lot of people. By the requirement of the project, it is decided that the lifetime of structure is 100 years is chosen. Moreover, the project also considers two levels of seismic: Maximum Design Earthquake (MDE) and Operating Design Earthquake (ODE).

Seismic hazard assessment had been conducted (cf. Irsyam et al, 2014) with the objectives to obtain the level of ground motion and develop design response spectra at bedrock for two levels of design, Operating Design Earthquake (ODE), and Maximum Design Earthquake (MDE) and to develop time histories at bedrock for those two levels of design.

Maximum Design Earthquake (MDE) in this case is the earthquake with return period of 1000 years; while the damage is considered as level 2 in accordance with DSRSC-SD (see Figure 10) while Operating Design Earthquake (MDE) in this case is the earthquake with return period of 100 years; while the damage is considered as level 1.
In Level 1 earthquake (ODE), structure is designed to ensure that it still perform in elastic range, confirm that the rebar stress is under yield point and no damage happened (Damage Level 1). In Level 2 earthquake (MDE), structure is designed to satisfy strength within ultimate limit state, repair may be required, but function of structure can be restored within short period (Damage Level 2).

9 (nine) motions are selected for ODE and MDE level. The selected motions are based on the period at PGA and 0.2s.

**SITE SPECIFIC RESPONSE ANALYSIS**

When ground motions have been obtained, the next phase is to use it as an input of wave propagation analysis. In this project, we utilized software so called Nonlinear Earthquake Response Analysis (NERA) which was developed by J. P. Bardet and T. Tobita of University of Southern California (NERA, 2001). This software adopts a nonlinear behaviour of soil during earthquake, damping also considered as a nonlinear to the strain.

Bedrock depth is considered as 350 meters depth, although there were such discussions of the true depth of bedrock which should be applied for Jakarta. Careful study has been conducted to examine the sensitivity of soil response regarding bedrock depth. We found that bedrock depth is one of the important parameter that affect the soil response, and concluded that in terms of displacement of ground (one of the important parameter required for the design of underground structure) shallower bedrock depth will result bigger relative displacement for underground structure. Another conclusion also can be obtained, acceleration with deeper bedrock will result smaller ground acceleration.

Shear wave velocity parameter was taken from correlation of the N–SPT to velocity obtained from the relation between seismic down-hole tests which were carried out independently.

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**Figure 10 Load Displacement Relation of Reinforced Concrete Members (ref. DSRSC-SB)**

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**Figure 11 N-SPT vs Shear Wave Velocity correlations for Sand and Clay**
9 (nine) motions are selected for ODE and MDE level. The selected motions are based on the period at PGA and 0.2s.

**RESPONDED DISPLACEMENT METHOD**

The model of cross sectional analysis is shown in Figure below. The horizontal and vertical stiffness of seismic springs are derived based on the simplified dynamic properties as a function of shear modulus of soil (ref. DSSRC-SD). The model is set up to get the moment and shear forces are then super positioned, hence, the result forces are the sum of load according to ground displacement, inertia forces, peripheral shear forces and hydrodynamic water pressure.

![Figure 12 2D frame model of cross sectional analysis & Responded Displacement Method (according to DSRSC-SD)](image)

**TUNNEL ANALYSIS**

The behavior of a tunnel is sometimes approximated to that of an elastic beam subject to deformations imposed by the surrounding ground (Hashash, 2001). Three types of deformations express the response of underground structures to seismic motions i.e. axial compression and extension, longitudinal bending; and ovaling/racking. Axial deformations in tunnels are generated by the components of seismic waves that produce motions parallel to the axis of the tunnel and cause alternating compression and tension. Bending deformations are caused by the components of seismic waves producing particle motions perpendicular to the longitudinal axis. Design considerations for axial and bending deformations are generally in the direction along the tunnel axis (Wang, 1993).

**Cross Sectional**

Ovaling or racking deformations in a tunnel structure develop when shear waves propagate normal or nearly normal to the tunnel axis, resulting in a distortion of the cross-sectional shape of the tunnel lining. Design considerations for this type of deformation are in the transverse direction. The general behavior of the lining may be simulated as a buried structure subject to ground deformations under a two-dimensional plane strain condition.

![Figure 13 Ovaling of tunnel section (cf. Hashash, 2001)](image)
Longitudinal Analysis

Longitudinal Analysis is governed by the condition beam in elastic foundation with the simplified harmonic wave shear.

Simplified, closed-form solutions are useful for developing initial estimates of strains and deformations in a tunnel. These simplified methods assume the seismic wave field to be that of plane waves with the same amplitudes at all locations along the tunnel, differing only in their arrival time. Wave scattering and complex three-dimensional wave propagation, which can lead to differences in wave amplitudes along the tunnel are neglected, although ground motion incoherence tends to increase the strains and stresses in the longitudinal direction. Results of analyses based on plane wave assumptions should be interpreted with care (Power et al., 1998).

![Beam in elastic foundation as model for longitudinal analysis](image]

Kuesel (1969) proposed a simplified method for calculating free-field ground strains caused by a harmonic wave propagating at a given angle of incidence in a homogeneous, isotropic, elastic medium. The most critical incidence angle yielding maximum strain is typically used as a safety measure against the uncertainties of earthquake prediction.

![Simple harmonic wave and tunnel](image]

4 CONCLUSION AND PERSPECTIVE WORK

The material presented in this report describes the current state of knowledge for the design of underground structures for the case of Jakarta MRT. Many issues require further investigation to enhance our understanding especially regarding the seismic response of underground structures and improve the design procedures. Some of these issues include:
1. Instrumentation of tunnels and underground structures to measure their response during ground shaking during earthquake
2. Development of improved numerical models to simulate the dynamic soil structure interaction problem of underground station included tunnels structures. These models will be useful in studying the effect of high velocity pulses generated near fault sources on underground structures.
3. Development study about the ductility of the structure of underground structure.

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