Simplified Failure Mechanism for the Prediction of Tunnel Crown and Excavation Front Displacements

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1. Introduction

With over 200km (125miles) of rail and nearly 4million daily passengers Mexico City Metro is one of the world's largest underground transportation systems. A 25.4km (15.8mi) long route was proposed as part of the expansion project of the Mexico City metro system. The new line (L-12) was planned to pass through 22 new stations between localities Tlahuac and Mixcoac. The 7.7km (4.8mi) long tunnel represents the capital's first new route in a decade, and service thousands of passengers on a daily basis.

Because of Mexico City's difficult subsoil formation, this project was considered one of the most challenging projects for all fields of engineering, especially for geotechnical engineers. The L-12 was planned to connect Southeast Mexico City to West of Mexico City. The new L-12 was designed to be part underground and part above ground. The underground construction techniques encompassed Tunneling using a TBM (Tunnel Boring Machine) and the NATM (New Austrian Tunneling Method), and cut-and-cover using braced Diaphragm walls. The above ground structures consisted of superficial and elevated sections. The above ground sections were selected to avoid construction and excavation difficulties due to the presence of high plastic clays.

This paper presents details regarding Mexico City's geotechnical aspects including a preliminary crown deformation calculation for a tunnel section using the simplified method for tunnel stability. Although, advanced tools and software such as FLAC3D were implemented during the design phase, for purposes of this paper the discussion has been limited to the simplified design method only.

2. Mexico City Metro System

With 195 stations, 12 lines, and approximately 227km (141mi) of route, Mexico City's Metro system is the second largest in North America and 5th largest in the world, (APTA 2014). The public transportation system Mexico City, added its first Metro system line in 1969 serving 16 stations and ever since it has been expanded based on the City's population demand. Due to the regional subsidence and the high deformability of Mexico City's clay layers, the train carts are rubber–tired–based system on rolling pads instead of traditional steel–wheel based system with flanges on steel tracks, (SCT 2016).

The Metro construction took place in different historic times in Mexico City starting in 1967. Between 1967 and 1972 lines 1, 2, and 3 were constructed. During these years the 1968 summer Olympics, 1968 Tlatelolco massacre, and the 1970 World Cup were debuted in Mexico. Between 1977 and 1982 expansions to line 3 and the construction of lines 4 and 5 took place. From 1983 to 1985 when the earthquake occurred, lines 1, 2, and 3 were significantly expanded, and the construction of lines 6 and 7 started. On the morning of 19 September 1985, an 8.1 magnitude in the scale of Richter, hit Mexico City. Majority of buildings and streets were significantly damage. Due to its geometry, the Metro underground structures did not suffer major damage proving a safe mean of transportation during the time of crisis in Mexico City. Between 1985 and 1987 and 1988 and 1994 line 7 was completed, and lines 8 and 9 were constructed, respectively. Also, in 1988 a new line referred to as Line A (with fewer stations) was introduced to leverage the eastern suburbs of Mexico City. Between 1994 and 2014, Line B and Line 12 were added to the Mexico City metro system.

Each line is identified with color and numbers, and each station has been named after historic figures, locations, and events in Mexico. With 24 stations serving as connecting stations, the Metro system covers the majority of the downtown (El Centro) and suburbs of the city, Figure 1. Line 12 was proposed to connect the west and southwest location of the city to the Mexico City's southeast. Considering new residential developments in the southeast region, the need for transportation systems other than local bus routes resulted in the planning and design of the Line 12, (SCT 2016). Line 12 was planned to connect the station Mixcoac (an existing station corresponding to the Orange line 7) to a newly planned station, Tlahuac. The route will include three connecting stations with lines 2, 3, and 8 to provide direct access to the north, Center, and east of the city, Figure 1.

〈Figure 1〉 Mexico City Underground Map (Retrieved from SCT 2016)

## 3. Mexico City Soil profile and Geology

The Valley of Mexico (El Valle de Mexico) is located at the southern part of the Mexican plateau with an average altitude of 4650m (15256ft) above sea level. It has the shape of an extended bowl spreading in a

north-south direction. The Valley is surrounded by the Pachuca range in the north, the Ajusco range in the south, the Sierra Nevada in the east, and the Sierra Madre Occidental in the west. Two mountain ranges known as Guadalupe and Santa Catarina are extending into the basin creating two curtains in the central-north and south of the Valley and Mexico City is located in the middle of these ranges. The lowest elevation in the Valley is approximately 2200m (7220ft) above sea level which is the final destination of many small rivers flowing into the Valley.

During a 17th century excavation for the Mexico City's deep sewage system, a large accumulation of fossils and sediments were encountered. This finding suggested that this path was part of the outlet in the north side of the basin during the early Pleistocene which was blocked by fossils and sediments. In the south a heavy volcanic activity mainly from Popocateptl created another block to the southern outlet, (Zeevaert 1983), explaining the high-water elevation in the valley during the Pleistocene and further clarifying how the deepest part of the Valley was filled with water-transported materials. Furthermore, high water elevation caused the disintegration of andesitic rocks of the surrounding hills represented by accumulation of residual clays, pyroclastic materials, gravel, and sands at the bottom of the basin which created layers of gravel, sand, and silty clays with hundreds of meters in thickness. In the center of Mexico City, the upper surface of these layers is encountered at the depth of approximately 35m (115ft) below the ground surface. Above these layers, fine-grained lake sediments are located which it is believed to be the product of the volcanic effusion containing fine fractions of basaltic lava and very fine water-transported materials. Along with the effusion, steam explosions created dense volcanic clouds containing volcanic ashes which later on came down as rain covering the entire Valley. The volcanic ash decomposed into bentonite clay with approximately 20% of montmorillonite, (Zeevaert 1983). During this process, heavier particles such as volcanic glass were trapped in between fine particle layers forming thick glass layers. At the end of volcanic effusion era and up to present times, a fill largely containing coarse pyroclastic material and residual clays were eroded from surrounding hills and accumulated in the Valley. The result of the above described geological events is the multi-layered subsurface conditions of Mexico City.

The Mexico City's subsoil conditions in the downtown area can be delineated following the description presented by Rosenblueth and Ovando (1991) in one of their research project sites. In general, the subsurface material consists of an archeological deposit extending from the ground surface up to a depth of 6.0m (20ft) followed by 3.0m (10ft) of fine alluvial sediments. From 9.0m (30ft) to 33.0m (108ft) a silty clay deposit is located with an average water content of 300% and a soft to medium consistency. This layer contains numerous sand layers product of the volcanic activity and rains discussed above. A series of

cemented sand and silt deposits forms the next layer located between 33.0m (108ft) and 38.0m (125ft) with a water content varying from 10% to 20% and a compactness of dense to very dense. From 38.0m (125ft) to 48.0m (158ft) a lacustrine deposit containing green clayey silt, with an average water content of 200% and medium consistency is encountered. In the middle of this stratum, a well-defined 1.0m (3.30ft) thick white volcanic glass is located. For depths greater than 48.0m (158ft) different alluvial sediments are encountered which becomes coarser and denser with depth.
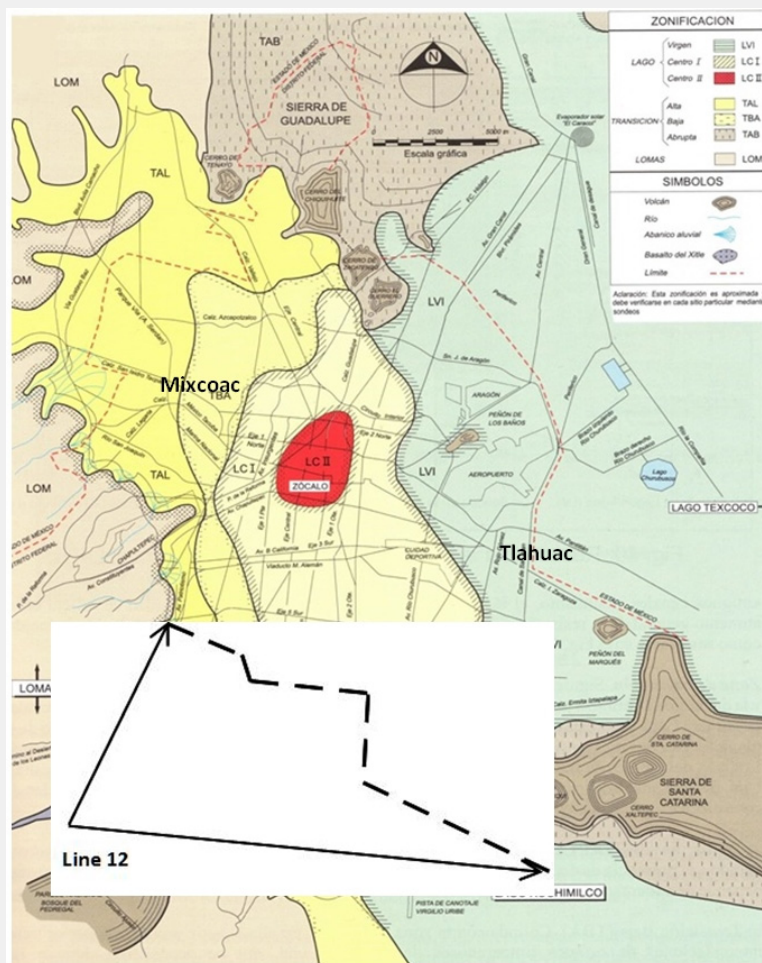
〈Figure 2〉 Mexico City Geotechnical Zones (Retrieved from Santoyo et al. 2004)

Based on the geological events, the urban area of Mexico Valley is traditionally divided in three main geotechnical zones (Marsal and Mazari 1975): Foothills (Zone I), Transition (Zone II) and Lake (Zone III), Figure 2. In the foothills, very compact but heterogeneous volcanic soils and lava are found. These materials contrast with the highly compressible soft soils of the Lake Zone. Generally, in between these Zones, a Transition Zone is found where clayey layers of lacustrine origin alternate with sandy alluvial deposits, Figure 2.

Typical soil profile including soil characteristics were presented by Marsal and Mazari (1975), Figure 3. A representative borehole (Pc-28) corresponds to the Lake Zone has been considered to illustrate the Mexico City's subsurface profile and the water content variation, Figure 3. Three clayey layers are to be distinguished, denominated upper (Formaci n Arcillosa Superior, FAS), lower (Formaci n Arcillosa Inferior, FAI) and deep deposits (Dep sitos Profundos, DP). The FAS are separated from the FAI by a hard layer (Capa Dura, CD), comprising a 3-m (10-ft) thick sandy clayey stratum.
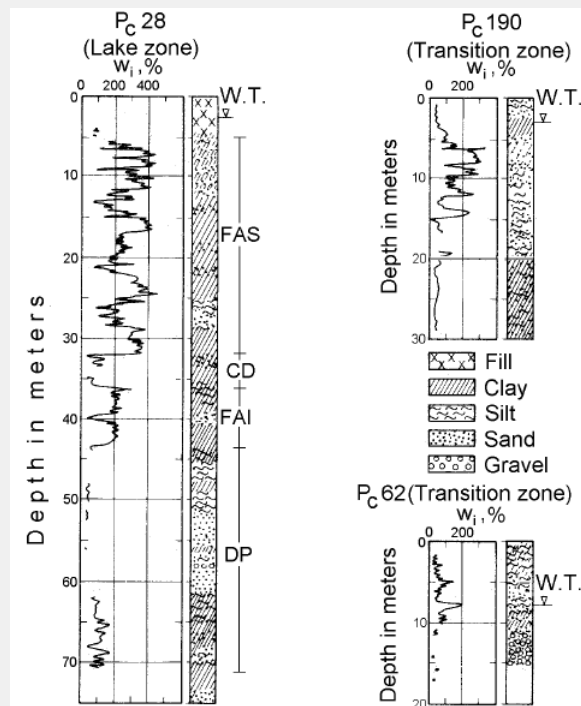
〈Figure 3〉 Typical Soil Profile in Mexico City Downtown (Marsal and Mazari, 1975)

4. Tunnel Mixcoac Design

For purposes of this paper and to illustrate the simplified design method, the tunnel corresponding to Mixcoac Station has been selected. Mixcoac station is located in the vicinity Zone I and II which is referred to as the Transition Zone, Figure 2. A common soil profile for this part of Mexico consists of lacustrine clayey layers alternated with sandy alluvial deposits. At the location of the tunnel section highly cemented granular deposits with unit weight of 1.7ton/m^3 (106pcf), internal angle of friction of 25° to 28°, a cohesion of 8 to 10ton/m^2 (11 to 14psi), and a Young's modulus of 420 to 1000kg/cm^2 (6 to 14ksi) were encountered, Figure 4.
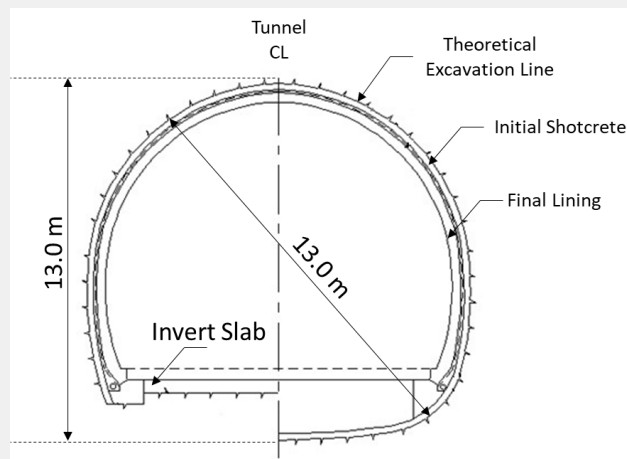

〈Figure 4〉 Dimensions of Mixocac Tunnel portal

The tunnel portal was a horseshoe section with a cross diameter, D, of 13.0m (43ft) and height, A, of 13.0m (43ft). The failure mechanism considered for the simplified design approach and the stability of the excavation front consisted of a static analysis to determine the equilibrium at the front of the excavation based on three main failure zones, Figure 5.

(a)

1. Triangular prism of failure in front of excavation
2. Rectangular prism of failure on top of the front of excavation
3. Rectangular prism above the Tunnel crown
   D: Tunnel width
   A: Tunnel Height
   H: Depth to the Tunnel Crown
   L: A tan (45−φ/2)
   a: Supported Section
   b: Unsupported Section
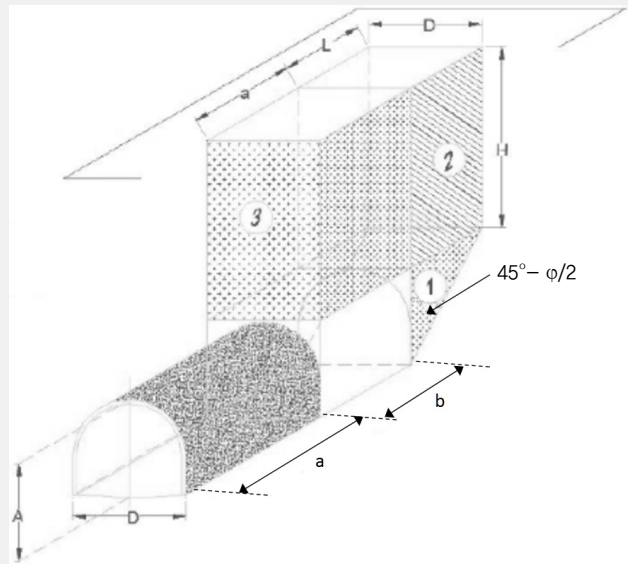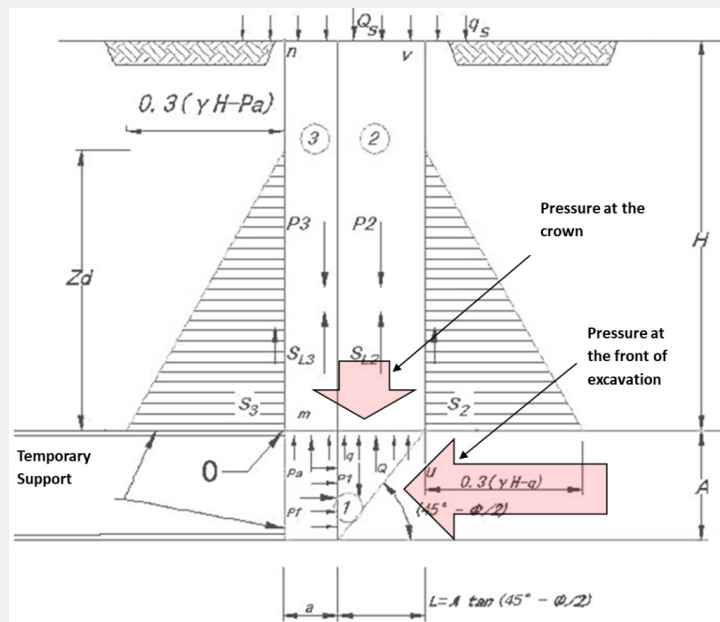
(b)

〈Figure 5〉 Failure Mechanism for the Simplified Method (a) three zones and (b) Force Equilibrium

For the preliminary design of the tunnel section, the initial excavation was designed based on the soil information determined from the design stratigraphy. From the design stratigraphy, soil strength parameters were selected to be used in the preliminary crown deformation calculations, Figure 6.

The layout of the proposed tunnel excavation is matched with the design stratigraphy, Figure 6, to observe changes in soil layers and properly select the design approach. It is noted that for the crown deformation calculations, the failure zones 2 and 3 comprise a weaker soil compared to those existing in the from of the excavation (i.e. triangular Zone 1).
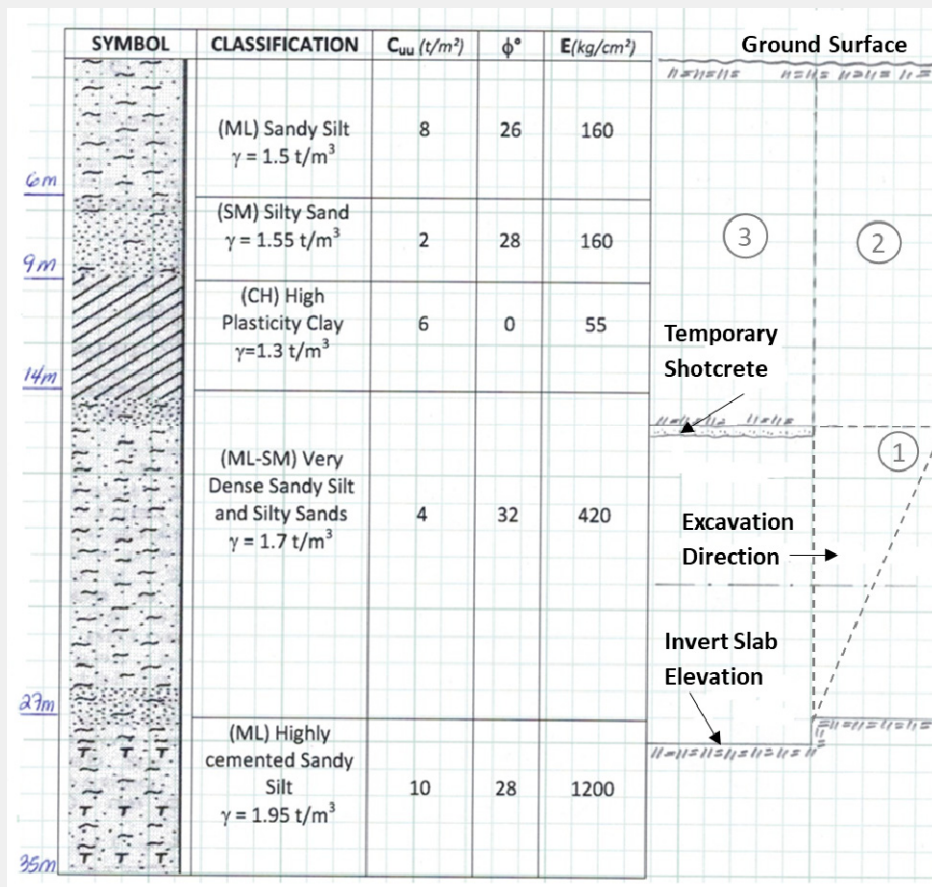
⟨Figure 6⟩ Design Stratigraphy and soil parameters for calculations

The analysis shown in this manuscript was used as a quick check prior to generating precise and thorough calculations using finite element models. Therefore, for simplicity, soil strength weighted average parameters were used to determine the undrained cohesion and the internal angel of friction resulting in 5.07ton/m^2 (1ksf) and 21.5°, respectively.

Two types of deformations were determined with their corresponding pressure. The first deformation is for the tunnel crown without the temporary shotcrete to predict possible deformations prior to the shotcrete process. The second deformation is determined for the front of the excavation with its corresponding pressure. The calculation process consisted of the determination of the effective vertical stress at the depth of the tunnel crown. The tunnel crown is located at a depth of 16m (53ft) below the ground surface and the centerline of the tunnel is located at a depth of 22.5m (74ft) below ground surface. Therefore, the effective vertical stress at the crown elevation and the tunnel centerline was determined to be 23.55ton/m^2 (34psi) and 34.60ton/m^2 (49psi), respectively. After determining the effective vertical stresses, stresses acting at the crown, P_a, and the excavation front, P_{af}, are then obtained using the following expressions:

$$P_a = \gamma H_0 (1 - \sin\phi) - cCos\phi \tag{1}$$

$$P_{af} = \frac{\gamma H - \dfrac{2cH}{D}}{1 + \dfrac{H}{2D}\tan\phi} \tag{2}$$

Where γ is the soil unit weight, ϕ is the internal angle of friction, c is the cohesion, H_0 is the distance from the surface to the tunnel crown, H is the distance from the ground surface to the horizontal centerline of the excavation front, and D is the tunnel section diameter.

Corresponding displacements can be determined for the tunnel crown, δ_a, and the excavation front, δ_{af}, using the following expressions:

$$\delta_a = (\gamma H_0 - P_a)\frac{(1+\nu)D}{2E} \tag{3}$$

$$\delta_{af} = \frac{D}{2}\left(1 - \sqrt{\frac{1}{1+\alpha}}\right) \tag{4}$$

$$\alpha = \frac{2(1+\nu)}{E}(\gamma H_0 + cCot\phi)\sin\phi\left[(1-\sin\phi)\frac{\delta H_0 + cCot\phi}{P_{af} + cCot\phi}\right]^{\beta} \tag{4a}$$

$$\beta = \frac{1-\sin\phi}{\sin\phi} \tag{4b}$$

Where ν is the Poisson's ratio; and all other parameters have been previously defined. With equations 1 to 4 the corresponding deformations for the crown and the excavation front were determined to be 3.5cm (1.4in) and 6cm (2.4in), respectively. These values were further verified using finite element analysis including various defined soil constitutive models. The main advantage of a simplified method is to obtain index results prior to the development of rigorous models. These values can be used for preliminary assessments and selection of monitoring and instrumentation for the final construction project. It is important to note that many of the soil parameters selection requires in-depth engineering knowledge regarding the local subsurface conditions. However, it is still a reliable approach to obtain preliminary data.

5. Summary

This case study presented a simplified failure mechanism approach used as a preliminary deformation prediction for the Mexico City's metro system expansion. Because of the Mexico City's difficult subsoils, Line 12 project was considered one of the most challenging projects in Mexico.

Mexico City's subsurface conditions can be described as a multilayered stratigraphy changing from soft high plastic clays to dense to very dense cemented sands. The Line 12 trajectory crossed all three main geotechnical Zones in Mexico City. Starting from to west of the City, Line 12 was projected to pass through very dense cemented sands corresponding to the Foothills zone changing to the Transition zone and finalizing in the Lake zone. Due to the change in the subsurface conditions, different constructions methods were implemented including the use of TBM (Tunnel Boring Machine), the NATM (New Austrian Tunneling Method), and cut-and-cover using braced Diaphragm walls for the underground section of the project.

Preliminary crown and excavation front deformations were determined using a simplified failure mechanism prior to performing finite element modeling and analysis. Results showed corresponding deformations for the crown and the excavation front to be 3.5cm (1.4in) and 6cm (2.4in), respectively. Considering the complexity of Mexico City's difficult subsoil formation, construction method selection becomes a challenge to overcome.

The use of a preliminary results in order to have a notion of possible deformations prior to advanced modeling and analysis could be beneficial and helpful to select possible construction procedures.

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[This article is composed entirely based on the authors' opinion and does not have any relation to do with the Korean tunnelling and underground space association's official stance.]