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DEVELOPMENT OF A NEW METHOD FOR UNDERGROUND STRUCTURE MODELING AND DESIGN

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Abstract: Underground urban railway systems have a great influence on transportation industry because it reduces traffic by providing an individual route and increasing efficiency of the network as well as reduction of pollution. One of the biggest challenges in underground urban railway design is providing safe and economical design of stations at the same time due to the limited budget and high number of stations. Hence, accurate analysis and design is very important. This paper introduces a new modelling method by which has been examined Tehran Metro projects. On the other hand, based on model results and economical requirements an optimized structure analysis has been performed.

For design optimization, two methods are described for underground railway station design. The first method considers risk assessment to select the best structural system and proper ways of soil stabilization through which reduces surface settlements up to allowable range. This procedure can be introduced as a modified NATM. By this method, a real design example including the comparison of the results with old construction method system (pile & rib) is compared. The second method presents a guideline to estimate the minimal rebar area required in sections which is crucial to maintain the serviceability of structures for 100 years and reduce the construction costs due to the scale and dimensions.

Key words: Crack Width, Cracking Factor, Settlement, Risk Assessment

1 INTRODUCTION

The underground railway transport is growing significantly recently all across the world and therefore, economic design and accurate analysis are very important challenges in designing of metro stations. Primarily because the soil behavior is complex and nonlinear analysis models of soil- structure interaction is unknown. This paper represents a method to model and design based on ACI, FHWA, FEMA and AASHTO codes and the main decisive factors in this regard are as follows:

1. There are various nonlinear behavior models for soil and this paper proposes the most effective case based on corrected result of soil mechanics tests.

2. The cracking factor is of a great importance in the analysis of the interaction of soil and structure. High values result in settlement reduction and the forces between soil and structure will increase.

3. The interaction of soil and structure leads to considerable thickness for each element in order to provide safety of all the buildings on the ground and the people who are underground.

4. Minimum flexural reinforcement is calculated according to the cracking strength. The maximum tension stress of high depth is low and the drying shrinkage causes reduction of cracking strength and therefore a suitable nonlinear analysis is needed to obtain the required strength but these models are built previously by ACI codes and this paper utilizes these results to complete the method.

5. The moment values are low except special zones like connections between walls and foundation; therefore, estimating the correct minimum bar area of sections are crucial to be considered because if the amount of bar exceeds, the project will become uneconomical and if the bar area is low, serviceability period will be reduced.

6. A simplified procedure to provide best model of soil-structure interaction in structural software programs according to the outcome of nonlinear analysis of soil and structure is outlined.

7. A trial and error method in order to optimize the design by risk assessment is proposed.

2 Literature Review:

The soil horizontal and vertical settlements cause rotation and displacement of building foundation. The detrimental effects of non-uniform settlement would be higher than uniform settlement. Damages to existing structures fall into three categories:

- Architectural damages that affect the visual appearance of structure
- Functional damages that may be disruptive to the operational
- Structural damages that affect the structural stability

Many researches are done about above subjects to determine quantitative criteria by Rankine (1988), Burland (1977), Meyerhof (1956), Polshin & Tokar (1957), Burland (1977) , Tafraouti, (2016) , Skempton & MacDonald(1956) . There are codes of practice conducted based on the researches done by the above researchers such as FHWA, EUROPCODE 7-Part 1.

The construction stages of underground structures and over burden affect surface settlement and building significantly; hence, many researches have been done in order to find empirical and semi-empirical relationships to calculate settlement by peck (1969), Leca(,2007).

As far as the safety of projects are concerned, as opposed to dealing with the aftermath of unfavorable incidents, identifying the potential hazards, estimating each hazard probability and preventative designing of structures would be a rational approach (Finno, et al J, RJ , 2005) . This goal can be reached by risk assessment. Mechanized tunnel in Porto, is a good example of the projects that preventative measures had been taken during the construction in 2003.

3 Modeling process and verification

The required models for structural design are as follows:

- Nonlinear analysis of soil-structure interaction
- Linear analysis of concrete structure using AASHTO load combinations

Settlement of ground surface and the vertical and horizontal loads applying on tunnel are obtained by nonlinear analysis of soil-structure interaction. The hardening soil Model is the most comprehensive behavior model for soft and stiff soils. This model has not any fixed yield surface for principal stress space and this area can be expanded by increasing of plastic strain. Performance of shear and compression hardening is distinguished in this model. The modeling characters are calculated by Tri-axial test.

The cracking of a concrete structure is inevitable and therefore, ACI and FEMA codes provide reduction factor of inertia moment in bending moment directions and table 1 is based on the these codes.

Table 1: the bending moment reduction factor of concrete structure

Axial force	Reduction factor
$P_u < 0.1 f_c * A$	0.35
$P_u > 0.5 f_c * A$	0.7
others	0.5

* f_c represents concrete compression strength of 28 days in cylindrical sample and A represents gross concrete area.

This modeling is verified by comparing the results by soil data extracted from site in one station located in Tehran metro line 6 project. The soil specifications are given in table 2. Figure 1 and 2 demonstrate the geometry and comparison between modeling and measuring on the field.

Table 2: the soil specification at site

E (MPA)	C(KN/M^2)	ϕ
2000	40	30

The most important issue of soil mechanics is creeping because this behavior can change the value of soil-structure interaction and Bowls (1988) has clarified a reduction factor of 0.8; hence, all soil parameters are corrected by the given factor to design permanent structure.

The loads and displacements calculated between structure and soil are applied to structural software programs. Thus, moments and shear values of two models are identical.

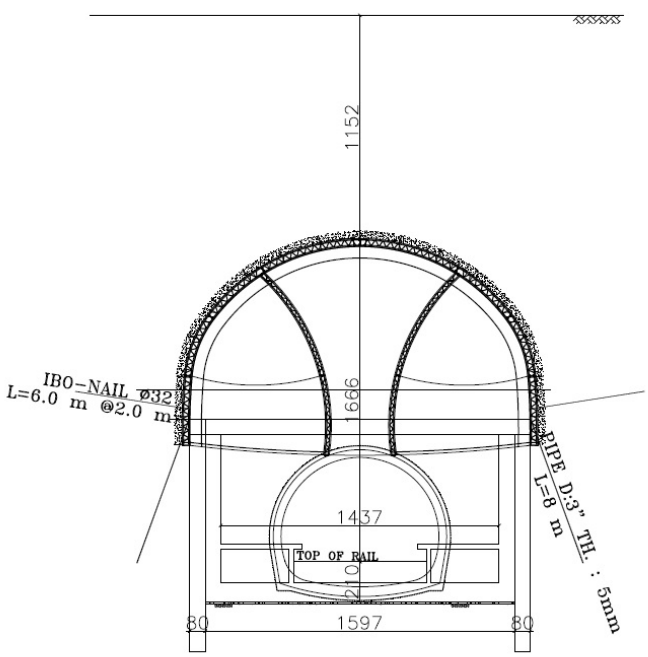


Figure 1: The station geometry

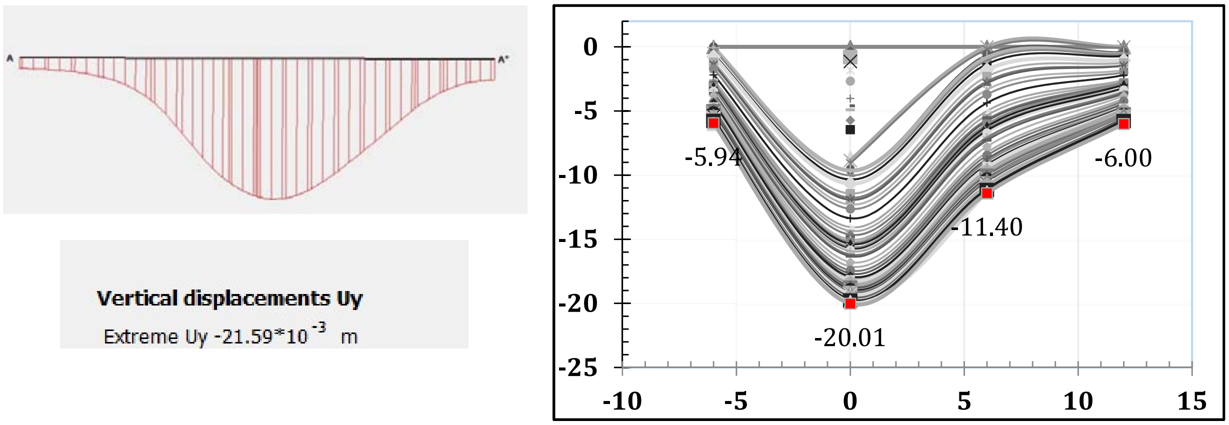


Figure 2: Result of measuring on the field (unit: mm) and 3d modeling

4 Determination of element thickness and construction method

The building settlement and safety of people, who are underground, would be the principle issues to determine the element thickness of underground structure. Differential and maximum settlement and tilt are the issues that have to be considered carefully and allowable values based on soil types have been provided in various codes and are given in table 3.

Table 3: The allowable settlement based on various codes

Max. settlement(mm)	Differential Settlement(mm)	Foundation type	Soil type
40-25	20-25	Mat foundation	sand
40-65	20-25	others	sand
65-100	4	Mat foundation	clay
65	40	others	clay

The rotation occurring between two foundations are also important. If this value is greater than 1/200 rad, the risk of damage begins to increase. An economic design of underground structure would be the outcome of changing elements' thicknesses and construction methods aiming to achieve the desirable level of risk in the modelling. This paper presents a simple method to analyse results of modeling on the basis of primary and advanced risk levels based on the codes and Burland (2002) respectively.

The existing buildings condition definitely cause reduction in allowable settlement stipulated in codes and this coefficient yields by vulnerability Index. As a result, the actual allowable settlement can be obtained. This part is called PRIMARY LEVEL because the trial and error becomes very easy in software packages by controlling actual allowable settlement. The factors affecting on Vulnerability Index are as follows.

- Structural information including building types (wooden, steel, reinforcement concrete), foundation types, underground story
- Importance Factor for type of operation according to IBC
- Interaction of tunnel and building, location and dimensions assigned by figure 3
- Architectural considerations such as historical buildings, glass facades etc.

- Actual conditions of existing buildings such as existing cracks width, cracks distribution and existing settlement.

Each country can have different scoring system and a sample is presented by Vittorio (et al,J.,2008). Maximum values of each factor proposed by Chiriotti are represented in table 4.

Table 4: maximum value of vulnerability Index components

item	Maximum value
Structural information	25
Operational building importance	10
Interaction of building and tunnel	25
Actual condition of existing building	20
Architectural considerations	20

The reduction coefficient of allowable settlement is given in table 5 based on the experiences of Porto Metro Project in 2003 Vittorio (et al,J.,2008) .

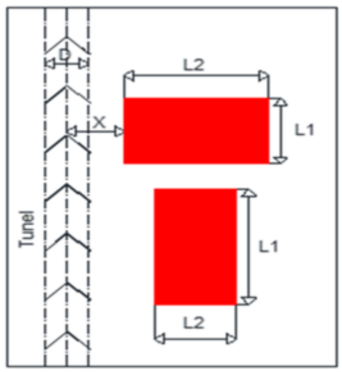


Figure 3: interaction tunnel and building

Table 5: the reduction factor of allowable settlement

80-100	60-80	40-60	20-40	0-20	Vulnerability Index
E	D	C	B	A	GROUP
2	1.75	1.5	1.25	1	Reduction factor

This method is helpful to choose excavation stages and underground structural system. For example, some designers prefer to select rigid system (Pile and rib) instead of NATM method because settlement of NATM method is higher. However, settlements calculated by NATM method can be altered by changing excavation stages and structural measures. The proposed method in this paper is simple by using finite element analysis. When trial and error is completed, according to the above process, the results are controlled by the advanced level method. The values of horizontal strain and maximum settlement of a building are calculated by finite element analysis and the damage intensity can be defined according to Burland(1997) criteria in figure 4b.

The proposed method has been applied for one of the largest stations in Shiraz metro line 2. The soil and geometry specifications are given in table 6 and 7. The scoring system is based on Vittorio (et al,J.,2008) .

Table 6: soil specification at site

Level (m)	γ (ton/m^3)	E (kg/cm^2)	E50 (kg/cm^2)	C (KN/M^2)	ϕ	SOIL TYPE
0-12	2	225	195	7	29	CL

12-30	2.1	350	265	15	27	CL

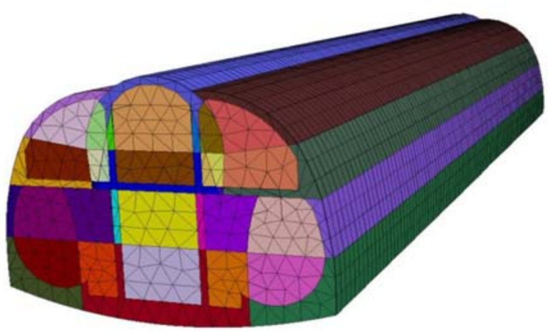
Table 7: tunnel geometry

LENGTH(m)	WIDE(m)	Top of rail	story
147	26.1	19.5	2

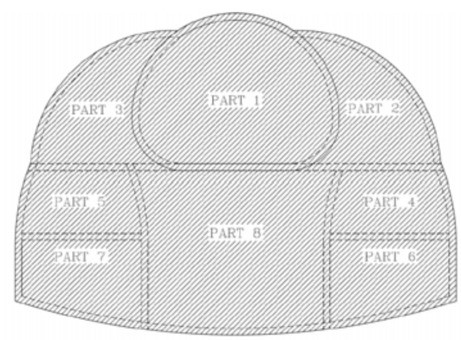
Construction of two columns after stage one and the slab of ticket hall level after stage three are the structural measures done based on design considerations. The settlement curve and damage intensity are presented in figure 4b and indicates that the proposed method is an appropriate way. Table 8 presents an economical comparison of rigid system and the proposed method and it can be clearly seen that the proposed method would be more economical and the damage intensity is slight for the majority of buildings. In other words, the risk is low.

Table 8: construction cost of underground station by this method

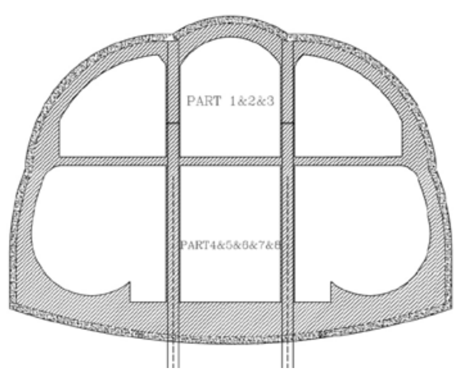
Rigid system ($)	NATM method ($)
3,450,000	1,680,000



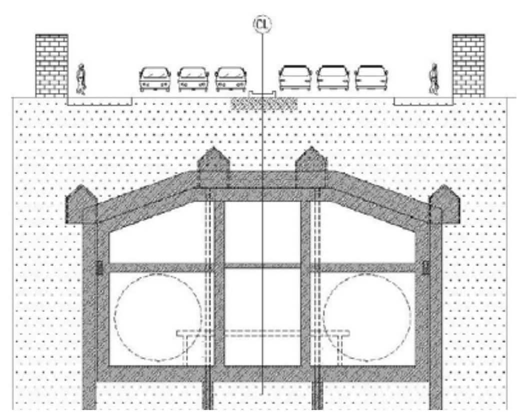
a)3D modeling



b) excavation stages

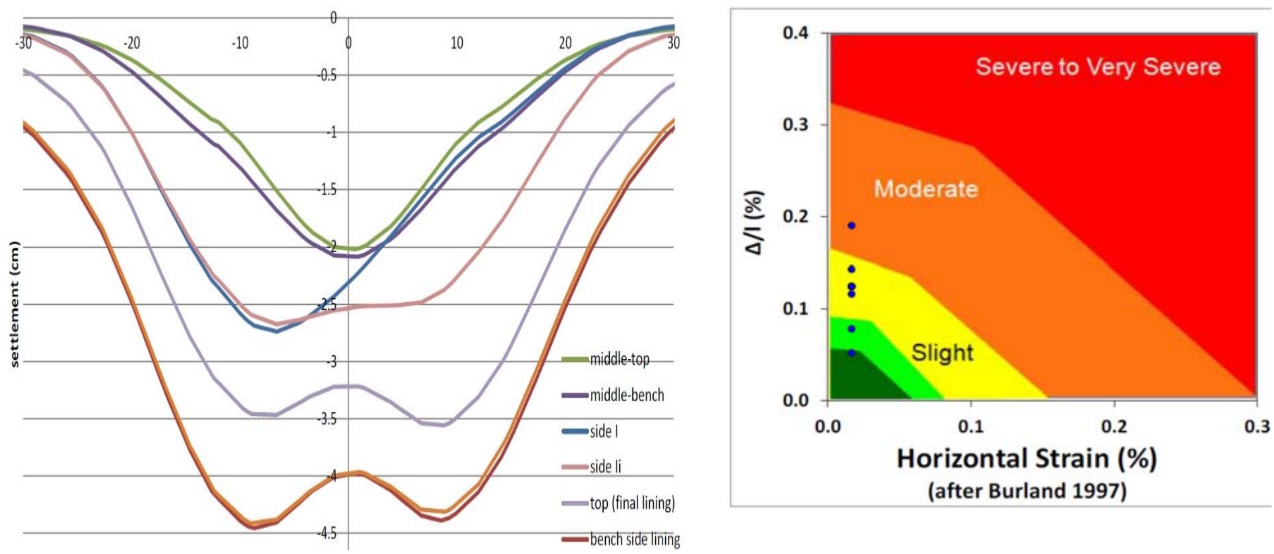


c) final NATM



d) final of rigid system

Figure 3: modeling and excavation stages



a)settlement of each excavation stages

b) damage intensity

Figure 4: settlement consideration result in line 2 of Shiraz metro

5 Determination of minimum reinforcement

The moment values are low except special zone like connections between walls and foundation. The figure 5 clearly shows this:

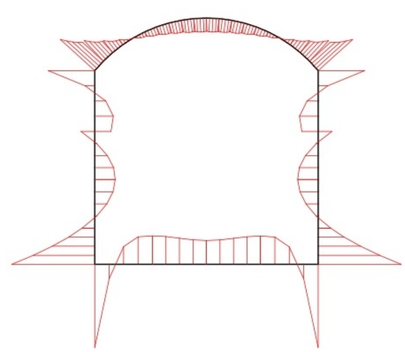
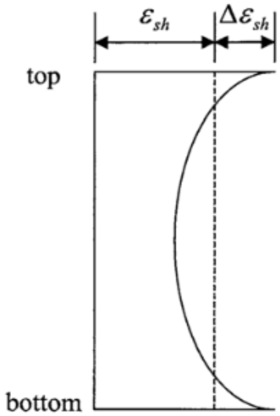


Figure 5: moment diagram in a sample

The temperature and shrinkage bars are used according to all codes and the influences on the shrinkage rebar area are as follows:

- Section height
- Effective area of section
- Cracking factors of elements
- Factors of controlling crack width excluding reinforcement increase
- Rebar percentage
- Interaction of shrinkage and bending

When section height increases, the ultimate shrinkage value will decrease and the section stress distribution and height effect are similar to figure 6 and 7 according to ACI-109,207,224.



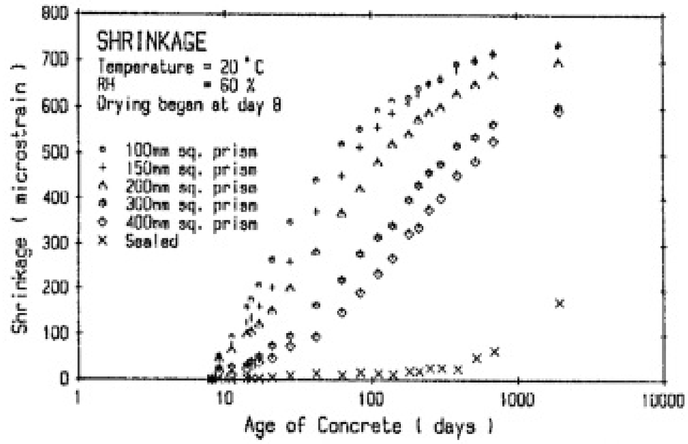


Figure 6: distribution stress in section   Figure 7: interaction of height and ultimate shrinkage

The effective area of concrete section should be used to determine the minimum reinforcement for shrinkage and temperature effect and the effective thickness is 40 centimeters according to ACI-224,207,109. The strictest provision of controlling crack width is ACI-350 used to design concrete water tanks and this criterion is the highest value so it is considered as maximum value.

Critical and absolute minimum reinforcement areas are calculated based on various codes. The minimum reinforcement is required for early cracks (CIRIA,2007) and is called Critical Minimum Reinforcement and the figure below shows the rebar area for different thicknesses and codes of practice and the material specifications are given in table 11.

The yellow bars represent the critical minimum reinforcement. Hence, the bars that have values less than those of yellow, haven less safety factors. Due to this fact, ACI-318 does not consider the effective thickness, which leads to uneconomical designs.

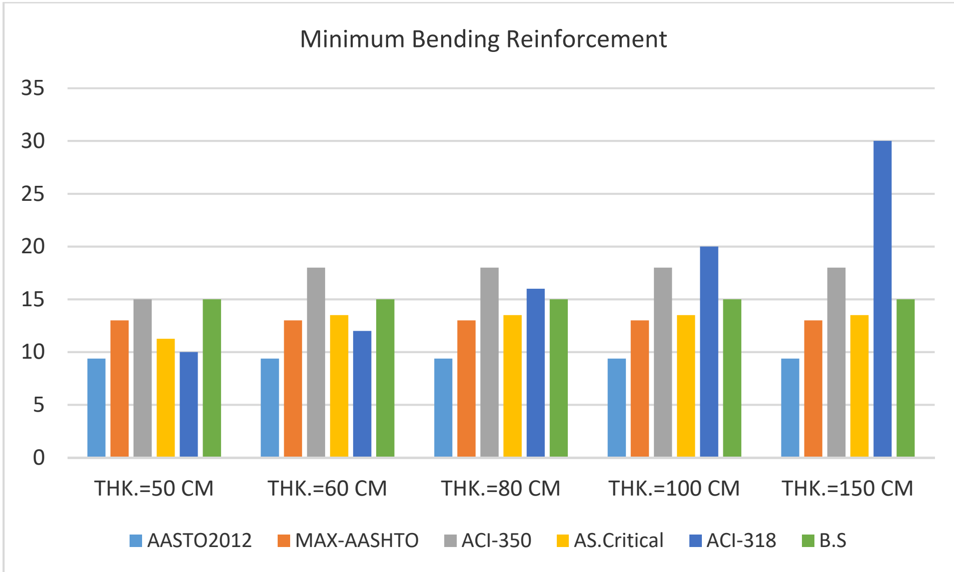


Figure 8: minimum reinforcement according to various codes

The table 9 and 10 are given rebar percentage of Critical and Absolute Minimum Reinforcement and the effective thickness is 60 centimeters according to ACI-350.

Table 9: critical rebar percentage for each concrete compression strength

50	45	40	35	30	f_c (mpa)
0.81	0.76	0.70	0.63	0.57	S300
0.61	0.57	0.53	0.48	0.43	S400

Table 10: rebar percentage for absolute minimum reinforcement

S400	S300	STEEL
0.6	0.8	bar Percent value

Table 11: material specification of figure 2

f_y (mpa)	f_c (mpa)
400	25

6 Conclusion:

1. Using modified NATM based on risk assessment and new software packages, can reduce the construction costs up to 50% in comparison of traditional methods.
2. Required minimum rebar for final design is calculated based on various codes and two maximum and minimum limits is determined. If the minimum rebar is in this interval, the design can be accepted.
3. ACI-318 criteria are appropriate for normal buildings but for design of underground structures, it cannot provide optimized design.
4. The minimum rebar area calculated using AASHTO 2012 is less than the critical minimum rebar reinforcement and should not be apply in design of underground structures.

5. A computer program is recommended that integrates the software packages applied to model and design (based on the proposed methods), and visualisation.

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