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Design Criteria of Subway Tunnels

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Abstract: This paper is dedicated to present criteria and rules for design of metro path including tunnel geometrical sections and choosing parameters, loads applied to tunnels, fundamentals of static and seismic analysis, and primaries of structural design, structural joints, and control criteria, behavior measuring and sensitive devices. Design criteria of shallow and semi-deep tunnels are presented in this paper.

Key words: Tunnel, Design, Subway, Seismic, Iran

INTRODUCTION

Since 1950s, urban developments in many cities have experienced continuous growth and expansion. Because of the large population and shortage of land resources, these cities have always had a strong demand for efficient, economic and environmental friendly urban civil infrastructure systems to accommodate the daily and routine travels of thousands and millions of commuters. The subway system is an obvious solution to meet the demand. To minimize the impact on the existing traffic during construction, tunnelling is usually adopted for the construction of the subway (Ding *et al.,* 2004).

1-1 Tunnel Design (Photayanuvat et Al., 2006):
The main steps of the design process were:

- Study and review of the general concept of existing preliminary design
- Overwork of the general concept of existing preliminary design as far as necessary
- Review of the geology along route.
- Selection of vertical alignment and considering various tunnel arrangements and different construction methods
- Definition of the typical tunnel cross section
- Planning for emergency shafts and ventilation
- Cost estimation and construction program.

In order to understand the issues involved the process of designing support for this type of tunnel it is necessary to examine some very basic concepts of how rock mass surrounding a tunnel, deforms and how the support systems act to control this deformation (Özsan *et al.,* 2001). The main parameters of weak rock related to tunnel designing was also studied by (Vahed *et al* 2009). Earthquake effects on underground structures falls into two groups: (1) ground shaking; and (2) ground failures such as liquefaction, fault displacement, and slope instabilities (Hashash *et al.,* 2001). The use of underground structures such as tunnel for subways, highways, material storage, sewage and water transport is increasing in developed countries. The safety of these facilities during operation in areas such as in Japan, Taiwan and Turkey with seismic activities in recent earthquakes has been questioned (Pakbaz *et al.,* 2005).

Geometrical Section of Subway Tunnels:
In order to select the drilling section in a determinant stress field, one aim must be trying to reach a

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uniform compressive stress distribution in the soil mass around the opening. This has been discussed extensively in technical references. The drilling sections which lead to uniform stress distribution around the tunnel are known as “Harmonic Holes”. In more accurate words, the drilling shape in which the compressive stress is the same along roof and walls will be within the optimum shape for the stress field. Thus, in terms of stress field, the drilling shape in which most uniform compressive pressure distribution happens, is oval or horseshoes whose axes directions is equal to principal stresses. The abovementioned concept is subjected to the following restrictions when is used in underground drilling:

- Designer of tunnel section geometry is rarely free enough to choose any shape of drilling since the drilling section dimensions have to be proper enough for the certain serviceability.
- In case the boundary stress is fairly little comparison to the soil mass strength, the concept of compressive stress homogenizing will be sensible to choose the optimum drilling shape, nonetheless, when the existing stress is so much that causes significant plastic areas in the soil mass around the opening, the assumption of elastic stress distribution might be too far from the reality. Under such circumstances, choosing the drilling shape based on Harmonic Holes concept may not lead to the best stability conditions. Thus, in such cases, the drilling shape must be selected in a way that the plastic area is limited to the soil mass strip around the opening being confined by the adjacent ground soil.
- In order to reduce the underground boring volume, the tunnel section designer has to choose a shape in which, as long as the ease of construction, the useless area inside the tunnel becomes minimum.
- In order to select the section geometrical shape, necessary measures must be taken to avoid any conflict with the adjacent civic facilities such as gas and water pipes and electrical and transmission networks.

Common geometrical sections for subway tunnels are presented in the following table 1 along with their properties:

Table 1: Common geometrical sections for subway tunnels along with their properties:

Section	Properties	Applicability
Circular	Simple geometrical shape, proper for homogenous stress field.	Mostly in mechanized boring used by drilling machine
Horseshoe	Gradual variation in curvature, dominance of axial forces over bending moments, good stability due to the curvature of floor and walls	Mostly in single-stage or multi-stage underground drilling
Arch Shape	Constructional simplicity in the lower part, arch behavior in the upper part, increase of bending forces in walls and floors	Two-stage underground drilling and cut and cover excavation
Tube	Constructional simplicity, High speed and low cost	Cut and cover excavation

Loads Applied to Tunnels:

Loads must be considered to determine the tunnel internal forces are presented in the following table 2.

Table 2: loads must be considered to determine the tunnel internal forces.

Loading Type	Description	Categorization	
Permanent	Tunnel structure dead load, Ground pressure (soil), Water pressure	Constant Loads	Main Loads
Variable	Vehicle Loads	Live Loads	
Accidental	Seismic Loads	Special Loads	

Tunnel Structure Dead Load:

That comprises the vertical load due to the tunnel weight which is distributed along the structure middle axis.

Ground Pressure (Soil):

Considering the soil mass geomechanical properties along with the path and the embedment depth of tunnel, any method of direct loading or soil-structure interaction can be employed to calculate the soil pressure. In cut and cover parts, all the soil weight is applied to the structure in which lateral pressure will be calculated based on the tunnel walls displacements toward the side soil mass and with respect to the lateral reaction coefficient of the soil. In other parts, which are constructed in underground methods, loading for primary structure must be determined considering the succession and order of construction stages and by taking the soil-structure interaction into account.

Water Pressure:

In case the underground water table is high with respect to the tunnel floor, the hydrostatic water pressure distribution must be considered to see the effect of water load.

Vehicle Loads:

Vehicle loads must be considered along with the grade level according to Iranian Bridge Loading Code. Besides the mentioned load, tunnels must be designed for a uniform load of 2.4 Ton/m² on the street level separately. This uniform load includes impact coefficient.

Seismic Loads:

Considering the seismic danger in the project area, the retaining structure needs to be designed in a way that both primary cover and the final cover are able to bear static and seismic loads simultaneously with the proper safety factors. In order to determine the seismic loads, soil-structure interaction must be considered plus the stiffness proportions between the structure and soil.

Fundamentals of Static Analysis:

Static technique includes steps below:

- Geometrical model creation
- Identification of behavior model type, physical and mechanical parameters of model (soil has non-linier behavior model)
- Identification of static boundary condition
- Initial model equilibrium before excavation operation
- Static model analysis
- Excavation procedure
- Support installation
- Static equilibrium establishment
- Comparison of results with monitoring results

4-1 -Direct Loading Method:

In this method, the load will be calculated based on the soil depth on the tunnel using the finite element method. This load is independent of soil-structure proportional stiffness. In this method, restrain effects of the soil around the structure can be modelled by Winkler springs (compression only). In cut and cover parts, considering the whole soil weight on the tunnel crest can be a realistic method to determine the structure internal forces.

4-2- Soil-structure Interaction Method:

In this method, the effect of soil-structure proportional stiffness can be taken into account to determine the internal forces of the structure. In order to determine the erection loads of the structural components, it is necessary to consider the soil-structure proportional stiffness plus the order and succession of the construction. To achieve, Convergence Confinement Method (CCM) or Numerical Methods (NM) can be used, provided that the limitations, advantages and applicability of each is taken into account.

Fundamentals of Seismic Analysis:

Ground motion effects during the earthquake on the tunnel structure can be generally categorized to the following three classes:

- Longitudinal Bending
- Compression-Extension
- Warping (In-Plane deformation of the structure's section - Ovaling)

The mobilized strains in the structure due to longitudinal bending and compression extension are usually analyzable base on the model of Beam on Elastic Bed at which the equivalent linear or non-linear springs must be considered. However, it is easy to decrease the longitudinal strains by using structural joints along the tunnel. In order to calculate the structural internal forces due to the ground shear displacements which cause ovaling in the structure, Seismic Intensity Method or Soil-Structure Interaction Method by using time history or displacement methods such as Response Displacement Method can be employed. The effects of soil-structure proportional stiffness around the tunnel must be taken into account anyway. In calculation of maximum ground acceleration, it is essential to see the magnifying effects of alluvial layers on the bed rock.

Primaries of Structural Design:

It is worth mentioning that in underground tunnels which are drilled using NATM method, the retaining system to control the tunnel stability comprises two stages of primary covering and final covering. The load distribution assumption between these two parts is highly effective in the design procedure. Considering the special constructional conditions in this country plus the inaccuracies, it must be tried to make the primary covering that bear the erection loads alone as much as possible and avoid using the final covering capacity for that. Otherwise, it would be necessary to construct the final covering with a little distance from the primary covering to make sure that the primary covering is not supposed to bear the external loads singly for a long time. Thus, the primary covering will be designed for the erection loads and the final covering will be designed for the other loads as follows:

- Dynamic forces due to earthquake
- Loads due to strength loss of the primary covering after a long term
- Loads due to the probable saturation of the soil mass
- Live loads due to the on ground traffic
- Live load due to the train movement
- Dead load of platforms

Structural Joints:

The parts of the tunnel path in which structural dimensions, soil geomechanical conditions or external loads are subject to noticeable changes, or wherever it is necessary to reduce the stresses and displacements due to the earthquake, Structural joints must be foreseen. Using structural joints with 20 millimeters width is suggested at the following places:

- In connection of underground tunnel to the cut-and-cover constructed gallery
- In connection of tunnel and the station
- In connection of tunnel and the ventilator structure
- Every 30 meters along the tunnel length

In tunnels excavated by mechanical excavation technique, the joints that are equal to advance stroke (segment wide), are formed cross pointing two rings (usually 1.3 to 1.5 m). Generally, in semi mechanical excavated tunnels, structural joints are required at the excavation intervals of 30 m.

Connection of Two Tunnels Together with Different Sections:

Two tunnels that are excavated using different methods (mechanized and semi mechanized) are connected together in two ways. Connection of a Horseshoe Section Tunnel with a Circular Section Tunnel is presented in figure 1.

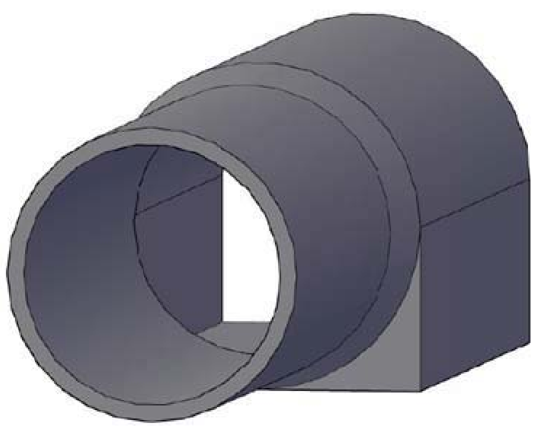

Fig. 1: Connection of a Horseshoe Section Tunnel with a Circular Section Tunnel

A. Intersection in Station:

In this case, two tunnels excavated by different techniques reach each other at the station position. The station plays the role of a connector. Generally, intersection of the tunnels is to be at the location of the station.

B. Intersection in Tunnel Alignment:

In this case, two tunnels excavated by different techniques are connected together along the tunnel route and a concrete structure is required to connect the tunnels together. The following Figure shows the connection of the two tunnels schematically.

Control Criteria:

Deformation in the soil mass is an inevitable consequence of the underground drilling, it is obvious that the underground area cannot be bored and then immediately protected by a very strong covering in a way that no deformation is occurred in the soil mass. During the drilling operation, due to the stress release, the soil mass around the opening deforms so that the soil system can reach the equilibrium. The occurred deformations in the soil mass manifests are as a bowl settlement on the ground surface. The surface settlements due to the drilling operation directly depend on soil geomechanical parameters, construction method, drilling steps and the stiffness of tunnel retaining structure. Surface structures with shallow foundations are affected by the surface settlements of drilling operation in a higher degree. For instance, older structures containing more masonry materials are more subjected to the danger of these settlements. In order to prevent any cracking and damage in surface buildings and civic facilities such as gas and water pipes, the absolute settlement must be limited to 20 millimeters. Besides, the differential settlement must be determined according to valid references depending on the building or facility type near the tunnel drilling right-of-way. Proper construction methods and plans must be considered to control the deformations.

Permanent lining must be performed in such a way that final internal tunnel surface has a ±4 cm variance in each measured points (from determined distance than to tunnel route axis). Amount of tunnel gradient line deviance than theoretical axis in each point, overall length should not exceed ±5 cm.

Behavior Measuring and Sensitive Devices:

Considering the heterogeneous nature of soil mass, it is not easily feasible to conduct enough experiments to determine soil mechanical properties along the whole tunnel length and predict the behavior of ground mass due to underground borings. Thus, soil-structure interaction analysis and tunnel structural design are based on the assumptions which can be far from the reality. One way to resolve this problem is soil structure behavior analysis during the tunnel construction which has the following goals:

- Safety control of drilling area during the tunnel construction
- Safety control of building and surface facilities inside the effective radius of the tunnel
- Assessment of the covering function under the external loads which may lead to design and construction modification if needed

In this project, since the tunnel passes under the city main streets near the urban buildings, it is suggested that convergence measuring of the boring area retaining structure in addition to the surface settlement measuring will be the least controls in the tunnel behavior measuring. The following actions must be taken to achieve that.

10-1-Convergence Measuring:

In order to determine the deformations of primary covering due to soil mass pressure, convergence or divergence at some certain points on the covering are being measured using the convergence measuring devices as the drilling operation proceeds. The required precision to do that is 0.1 to 0.2 millimetres. The measuring at the upper part is done by inserting two pins in one meter distance from arch downs and one pin on the crest. Afterwards, two more pins will be added in one meter distance from the floor to continue the measuring. Scheduling of convergence monitoring by convergence meter includes:

1. First monitoring is performed a maximum of 24 hours after setting convergence meter pines.
2. Twice a day with interval of at least 8 hours and after first monitoring until the distance of tunnel face to convergence meter station equal to one tunnel diameter (about 7 meter).
3. One time a day, when distance of construction tunnel face to convergence meter station equal to one to twice tunnel diameter (7 to 14 meter).
4. After instrument setting and while asymptotic of displacement- distance from construction tunnel face curve, interval is determined between 3 days to one month based on recommendation of contractor representative and confirm of residing supervision.

10-2-Surface Settlement:

In order to determine vertical deformations on the ground surface due to drilling operation and tunnel construction, a surface settlement measuring station must be placed almost every 100 meters along the main tunnel axis. Minimum required precision to read the levels by level cameras will be 0.2 millimetre. To read the surface levels, in every surface settlement measuring station, it is necessary to insert two local benchmarks in a distance of at least 100 meters from tunnel axis so that they will not be affected by surface settlements due to tunnel drilling.

Also, subsidence measuring instrument determine the vertical displacement of ground surface (subsidence), (at maximum depth of 0.4 m from ground surface). Ground subsidence measuring is performed by means of theodolite.

Monitoring scheduling of extensometer is explained below:

First monitoring is performed maximum of 24 hours after monitoring instrument. In time of reading, distance of station to tunnel face should be at least twice tunnel diameter. This reading is base reading.

One time a day for the period that which distance of tunnel face is equal to twice diameter remained or passed to station (totally distance is about 28 m of tunnel construction).

After tunnel face passing through extensometer setting place equal to twice diameter and when asymptotic of displacement- distance from construction tunnel face curve, reading intervals scheduling is determined similar to convergence measuring reading.

10-3- Vibrations Control:

Vibrations due to constructional operations during the tunnel boring will be transmitted to the ground surface. These may cause anxiety in neighbor inhabitants as long as damaging historical and other buildings in case the amplitude of which is high. Thus, it is essential to control the vibrations amplitude on the ground surface so that the construction method can be modified in case the amplitude exceeds the maximum limit. The vibration problem can also exist during the service time (train pass), which in this case, proper plans (such as isolation of rail from structure using elastic materials) must be considered to prevent vibration transmission to the ground surface.

10-4-Pressure Cell:

In order to determine the load on the segment, the pressure cell was used. This tool is placed inside the segment and the applied stress is determined using displacement of tunnel walls and roof and also load applying on the pressure cell. Based on amount of loading and the tunnel stability situation, soil improvement is performed. This tool is located inside the segment by connection to reinforced mesh and Simultaneous to concreting in segment mould.

10-5-Strain Gage:

Usually the strain gage is used to strain measuring inside the concrete segments. Location of this tool is depended on the exerted stress condition on the segments and distribution of the axial and shearing forces and also bending moment on different parts of the structure. Based on the recorded strains in a ring and also the orientation of the strain gages, value and direction of the exerted strains are identifying by back analysis technique. And also the strain inside the segments are determined through results of strain gage, then by studying the segment situation and also the stress and loads condition on the segment, the soil improvement is carried out. In strain gage, the strain measurement is performed by vibrating fiber system and measurement of the results is carried out only through the electrical measurement.

Tunnel Stability Analysis Softwares:

In order to analyse the tunnel stability and determine the mechanical properties of rock mass and soil, there are various softwares with different technique which are described below.

11-1-Phases:

Phases is a two dimensional software which introduced by Toronto university of Canada and designed based on compound methods. This software models the rock masses behavior after failure and also studies the rock mass–support system reaction. In this software, Boundary element method is used but for analysis the in-situ stresses situation in far from the tunnel axis, finite element model has been used.

11-2-Phase 2:

In Phase 2 the finite element model is used and able to model the underground excavations. This software is complete version of Phases. Mohr-Columb, Dragger-Prager, Hock and Brown failure criterion are used in Phase 2. Stress, strain, vertical and horizontal displacement, and volumetric strains parameters are shown graphically after calculations.

11-3-Slide:

Slide is a two dimensional software which is used to assess the slope stability in rock and soil. This software is used easily and the complicated model analyses are carried out quickly and with high accuracy. External loading, underground water and support are model in different techniques. Slide software is employed for stability analysis the shaft, stations and TBM workshop.

11-4-FLAC:

Between softwares, FLAC is very complete and valid program and used to model the dam, tunnel, mine etc. Principle of FLAC is based on finite difference, which behavior of constructed structure on the soil, rock and other material when reach to yielding limit and then entering the plastic flow are carried out by means of this software. The various materials are defined by elements definition and mesh formations. Based on the stress-linier or non-linier strain roles which defined already, each element has reaction related to the exerted forces. In this technique the material reach to yielding limit then enters the plastic area. Consequently, the formed mesh with its defined material is deformed.

Other FLAC advantages are include: creation the interface elements to model the surfaces which the overlapping and separation are occurring in their orientation, modeling the plane strain and stress, axially symmetry, modeling the statuses in underground water condition, supports (e.g. tunnel walls concreting, rock bolt, pile, and …), material dynamic analysis, bearing the viscoelastic and viscoplastic statuses (creep), modeling the statuses which depending on material temperature and also possibility of statuses addition which defined by user in C++ media. FLAC program is used in Command driven and Graphically Codes format.

11-5-FLAC 3D:

FLAC 3D is a 3 Dimensional finite difference software which is provided due to FLAC 2D development. This is used to model behavior of the rock, soil and other material structures which have the plastic flow behavior when reaching to yielding limit. There are four different models in FLAC 3D:

1. Static analysis
2. Dynamic analysis
3. Temperature analysis
4. Material creep behavior modeling

FLAC 3D applications in geotechnical engineering are include:

1. Loading and deformation capacity (in slope stability and foundation design)
2. Study of failure and collapse potential (in the hard rock mines and tunnel)
3. Safety factor calculation (in slope stabilities, earthfilling and surface structures analysis)
4. Fault effect assessment (in mine design operation)
5. Support resistance on geological material
6. Pore pressure and water flowing study (in study of underground water flowing and soil stabilization and improvement)
7. Creep behavior of viscose material (in halite and potash mine design)
8. Dynamic loading of geological structures have sliding potential (in earthquake engineering and rock burst study)
9. Effects of the dynamic loading due to blasting and vibrations (in mining and tunnel advancement)
10. Structure instigation due to Earthquake (in dam design)
11. Deformation and mechanical instability resulted from induced temperature loads (in underground radioactive waste reservoirs assessment)
12. Very deformable material analysis (in massive flowing the material in mine failure)

11-6-UDEC:

UDEC is a two dimensional software which is used for discontinue media and is principle of distinct element method. In this method, joints are observed as contact planes inside the distinct blocks. The numerics parameters correspond to dynamic behavior are defined by scheduling algorithm. The calculation process is composing of force-motion law applying and Newton's second law.

The used laws in this software are Newton's laws of motion, conservation of energy laws and momentum law. In this software, the behavioral models of Blocks are including:

- Bare model
- Elastic-plastic model
- Drager-Prager model
- Mohr-Columb plastic model
- Omnipresent joint model
- Softness / stiffness strain model
- Double yielding model

This two dimensional software is used to calculate the perimeter stress of underground opening and the underground surroundings rock behavior after excavation and also before and after supports installation.

11-7-3DEC:

3DEC is 3Dimensional software based on distinct element method and generally uses to discontinue media model. 3DEC principles are similar to UDEC software. 3DEC can be able to model and analysis the discontinue medias, for example jointed rock mass under dynamic and static loading.

A discontinue media is a composition of distinct blocks which the discontinues are as boundary condition between blocks. Therefore in 3DEC, analysis the large displacement in along of discontinues and the blocks rotation is possible. In blocks behavior study the blocks can be considerate as the stiffness or deformable material. Further, the deformable blocks are divided to the meshes which exist in finite difference element and in each element according to stress-strain law; they have a linier or non-linier behavior. The relative displacement of discontinues is controlled through force-displacement liner or non-liner relations.

3DEC have the several behaviors modeling for intact rock and discontinues, so the behavior model of structural discontinues and geological layers can be bring close together with their actual behavior. 3DEC operation is similar to Lagrange method, therefore is appropriated technique for large displacement and deformation of the block systems.

11-8-PLAXIS:

PLAXIS is a finite element computer programming which mainly is used to stress-deformation analysis; stability and leakage analysis in geotechnical projects include the soil and rock. In geotechnical applications the advanced behavioral models in order to model the non-linier behavior and time depended soils are required. Furthermore, since the soil is a multiphase's environment, the particular techniques for considering the hydrostatic and no hydrostatic pore pressures are required. On the other hand and soil modeling is important and there are many geotechnical engineering projects in structures modeling and structures-soil reaction. PLAXIS software has programs which can be considerate to the different aspects the complicated geotechnical structures and also is supported the different and advanced models for soil behavior and other media modeling. Other capabilities of PLAXIS, is the initial stresses assessment (without deformation), considering the stable pore pressures (based on hydrostatic pressure distribution under water table or fluid net and infiltration analysis) and also the excess pore pressures, step construction (modeling the structure and soil removal process) and determination of the safety factor. With regard to PLAXIS advantages and effecting causes on flexible walls behavior, this software due to include the beam elements and interface and also differential soil behavior models for numeric analysis the flexible walls and sandy soil reaction is used.

11-9-ANSYS:

ANSYS Computer programming which is based on the finite element theory is one of the high capability engineering softwares in numerical problems solution. In this program through graphical definition of problem, complicated modeling and also element creation in shapes are performed easily.

Various capabilities of ANSYS which considerate in this paper include of:

- Possibility of graphically and modeled information import
- Use of different elements with several capability
- Use of different solution techniques
- Graphically results presentation in each time of analysis
- Possibility of time historic results presentation

Due to ANSIS advantages which are presented above, this software is suitable software in different engineering branches. Beside, in ANSYS software some disadvantages are observed. The most significant disadvantage is in dynamic analysis which is does not include the semi extreme elements and elements with energy attractable which act as an irreversible boundary.

Other softwares such as Swedge, RocSupport, Roc Plane, Roclab, RocData, Dips, and Unwedge are used to determine the geological parameters and tunnel stable analysis.

Determination of the Area Seismic Characteristics and Methods for the Tunnels Seismic Analysis and Design:

Generally, before exact analysis and calculation the ground motion parameters in considerate tunnel site, in order to introduce the area seismic condition, the magnitude of earthquake is assessed. Then with regards to area situation view of earthquake magnitude, the required accuracy and extending to area analysis are specified and the area seismic parameters affecting the seismic design are determined. Generally, there are two techniques to analysis the earthquake hazard:

- Determine seismic hazard analysis (DSHA)
- Probable seismic hazard analysis (PSHA)

A. Determine Seismic Hazard Analysis:

In this method, in considerate areas the earthquake occurrence with particular magnitude is estimated and then the earthquake hazard is specified determinedly.

B. Probable Seismic Hazard Analysis:

In determination of seismic hazard analysis method, possible main earthquake occurrence, occurrence place, expected vibration grade during specified periods are not appropriately specified. Therefore based on developments in probable analysis, the probable analysis of earthquake risk should be useful. In this method based upon the previous earthquake statistics and use of a mathematical model, the earthquake occurrence with specified magnitude will be considerate in future.

Generally, in each project the first design phase is collection the experimental results which obtained from same completed projects. With employment and analysis the obtained results, the effecting parameters in preliminary design are appropriately specified. Means that for vibration design the underground structures, at first with collection and analysis the experimental research results, primary assessment the project should be performed, and then if required based on project importance, the future design phases are carried out (mathematical analysis and numerical modeling). The experimental methods for tunnel seismic design are based on the several researcher's studies and investigations such as Rosen, Dowdinge, Sharma, Jude, Awn, school, and … which in these investigations the damages on tunnel due to seismic waves emission and the fault motion damages will be studied and presented. Mathematical analysis is composing two techniques which include: consideration of the ground-support system reaction and inconsideration of the ground-support system reaction, which will be described in following.

12-1-Tunnel Seismic Design without Consideration of the Ground-Support System Reaction:

This performed theory is named free field analysis which is assumed that there are not any supports in the tunnel and the seismic waves are released in an infinite media and cause the stresses and strains in tunnel perimeter.

The Created Strains Calculation through Closed form Mathematical Methods:

If a wave impact to the tunnel axis is φ angle, then a part of this wave is created the tensile stress and strain in the tunnel axis orientation and another part is caused by the bending deformation in tunnel axis. If tunnel is considerate as a beam and simple mathematical relations are extended under affecting a force, the calculation of created strain in tunnel is possible.

B. Spherical Deformation of Circular Section Tunnels:

Under affecting the vertical direction of dynamic loads, the sections of circular tunnels are deforming to egg shape. The tunnel deformation problems are studied in two ways, firstly if there are not tunnel and excavation operation and in an elastic media, only one virtual tunnel is considerate. In below Figure under affecting the dynamic wave, in virtual tunnel section is deformed which this deformation is only depended on produced strain and seismic load which are calculated by below formula:

$$\frac{\Delta d}{d} = \pm \frac{\gamma_{max}}{2} \quad (1)$$

Which, $\gamma_{\max}$ is the maximum shear strain of the material in virtual excavation perimeter. The elastic media and virtual circular section tunnel are presented in figure 2.

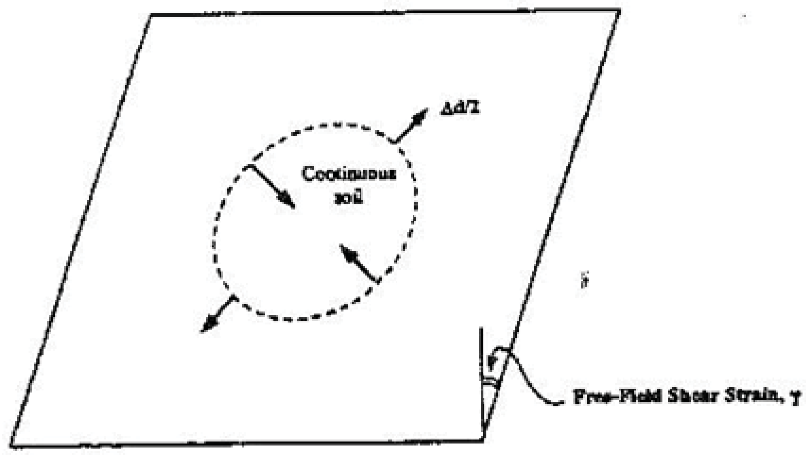

Fig. 2: The elastic media and virtual circular section tunnel.

In an actual tunnel excavation, the section deformation in addition to shear strain is depended on the material poison ratio in tunnel perimeter and the formula to calculation the tunnel section deformation to egg shaped is presented as below:

$$\frac{\Delta d}{d} = \pm 2\gamma_{\max}\left(1-\upsilon_m\right) \quad (2)$$

C. Tilting the Rectangular Section Tunnels:

When a rectangular underground structure is affected under seismic loading, the unique deformation is formed which called tilting the rectangular section tunnels (below figure). In order to acquire the tiling rectangular tunnels in free field loading condition (without considering the ground and structure reaction), the shear strain can be used. Tilting the rectangular section structures in free field condition is represented in figure 3.

Maximum Tilting the Rectangular Tunnels = Maximum Formed Shear Strain * Height of Rectangular Section Tunnel:

12-2-Tunnel Seismic Design with Consideration of the Ground-Support System Reaction:

It is clear that in actual condition, there is reaction between structure and ground which in first previous method, this problem is not considered. Consequently, the obtained results in seismic design of the tunnels without consideration of the surrounding ground - support system reaction was stuffy. In this stage, the structure and perimeter environment reaction are imported to in calculations and results are close to actual results.

12-3-Numerical Methods to Tunnels Seismic Design:

In primary design stage, the experimental methods which are based on same projects and previous completed constructions are appropriated and in high important projects exclusive employing of this method are not suitable. Also in accurate designs of the mathematical closed form due to consideration of the sampling assumptions, this technique was not used practically for design of the complex structures and conditions. However, the application of mathematical techniques to control; the computer models can be useful.

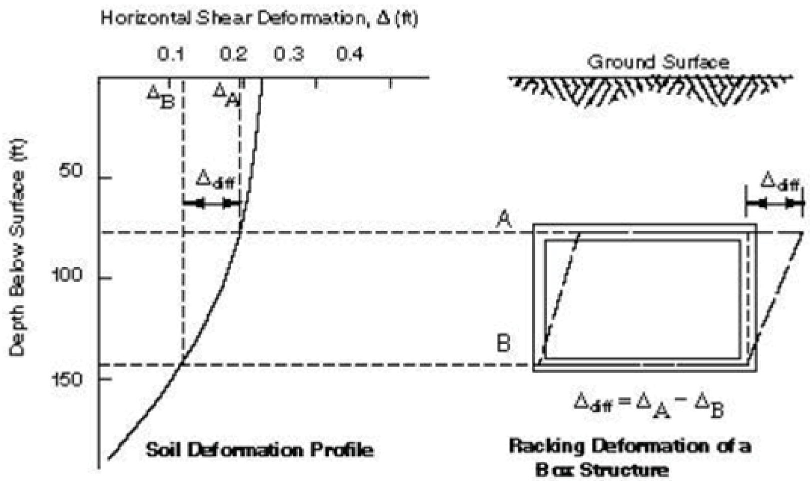

Fig. 3: Tilting the rectangular section structures in free field condition

Direct solution method is one of the existing numerical methods. In this method the soil and structure reaction are performing through the finite elements method. In many problems solution with different geometry, this method is used. Through this technique, the structure and the main part of the structure surrounding soil (e.g. tunnel) are modeled and all of the system is analyzed. One of the method advantages is the consideration of the soil and rock heterogeneity. Furthermore, in direct solution method, non-linier behavior would be considered for the soil. One of the method disadvantages is the degree of freedom which produced in problem solution and hence, leads to time consume the computer calculations.

Dynamic Solution Method for Iran Metros:

In Tehran metro, the mathematical technique of free field analysis has been used and then shear strain and tunnel maximum tilting were calculated by means of above relations. In southern lot of Isfahan metro, seismic analysis is performed by direct solution method and consideration of of the time history of records which result from probable seismic hazard analysis (PSHA).

Instruction of Tunnels Seismic Design:

As for the tunnel design, regarding the seismic loading two things must be taken into consideration; the first step is the tunnel stability under seismic loads due to wave emissions which must be calculated and upon this stage, the tunnel dimensions and required supports obtained. Secondly , the earthquake related subjects and special characterized features which affect the tunnel stability such as the fault motion when earthquake is occurred and local instability which increase the earthquake occurrence chance.First step in the tunnels seismic design and calculation of the force which the tunnel is directly undergone seismic loading, is the determination of the dynamic properties and geomechanic parameters required to seismic design, which are specified by existing standards experiments. After determination of the soil mass dynamic properties, the quantity of seismic load which are experimented in tunnel life time should be specifyed. It means, the seismic degree of area, the active faults and their distance to the tunnel must be determined. After specification the area seismic parameters, based on existing relations these parameters should be correlated to determine dynamic properties then the strength of tunnel surrounding soil or lining must be determined under seismic loading.

Mentioned issues in tunnel design phases are for loading due seismic wave emissions. Beside, the tunnel damages due to the earthquake occurrence are consisted of damages due to faults motions which intercept the tunnel axis and also the intensity of local instability such as unstable wedges falling. Hence, addition to tunnel design for loading due seismic waves emission, the tunnels must be designed for faulting zones and special damages. Therefore, the maximum faults displacement is taken into account for determinate earthquakes and also in order to hazards mitigation the appropriated measures should be taken into consideration. In below Figure general process of the tunnels seismic design is presented. By driving the flowchart, from start to end, the tunnel designs are performing for seismic loads.

14-1- Determination of the Required Dynamic Properties and Geomechanic Parameters:

A first phase in design beginning is acquiring the sufficient and complete information about dynamic and geomechanic properties of project area. Hence, it must be clear that, firstly, which of the dynamic and geomechanic parameters of tunnel construction area and secondary which condition of area in-situ stresses and joints situation should be considered. In the structure numerical modeling, use of the area in-situ stress condition is very important.

Determination of the dynamic properties is perfectly necessary for seismic analysis. In other hand, whit applying a seismic load on substance, as a rule, the substance dynamic compressive strength should be used unless (use of static compressive strength) the performed analysis will be stuffy, because, usually the substance static strength is less than the dynamic strength. Therefore in order to perform seismic analysis, the dynamic properties must be used. General process of tunnel seismic design is presented in figure 4.

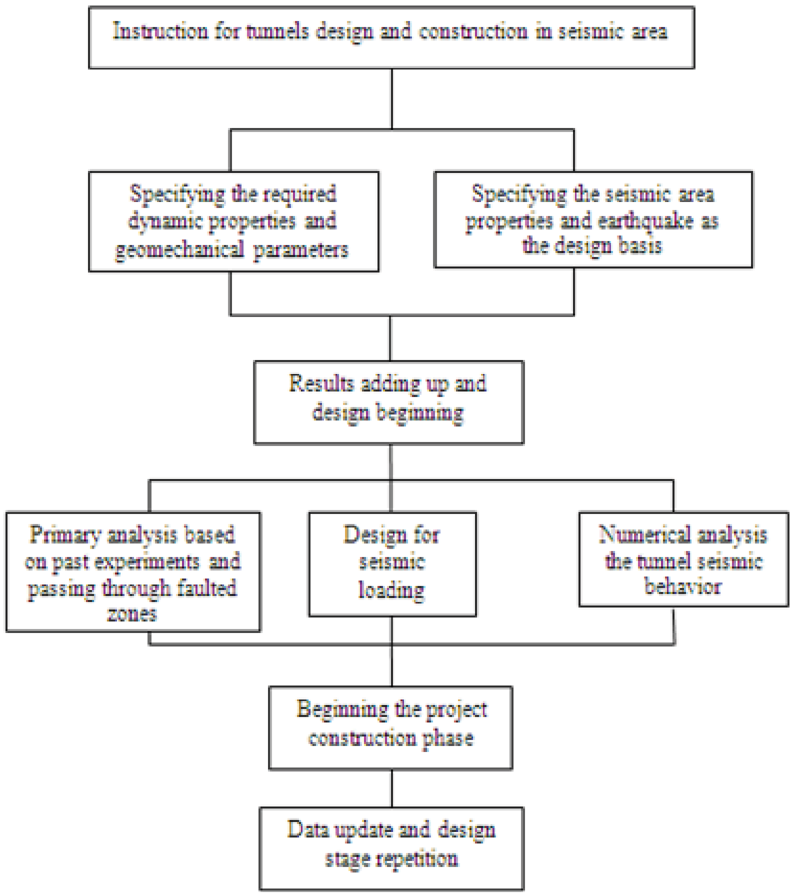

Fig. 4: General process of the tunnel seismic design

14-1-1-Determination of the Required Dynamic Properties:

Material dynamic properties are specified by two methods in the field and laboratory investigations. The field investigation methods are expensive but have the appropriate adoption with rock mass properties. Beside, the experimental methods are various and for under tested specimen, more information can be specified.

14-1-2-Determination of the Required Geomechanic Properties:

Further more on the dynamic properties, due to establishing the seismic analysis stability on initial static designs, determination of the geomechanic parameters are necessary especial in computer modeling. In computer modeling the dynamic loading, at first, model should be equalized under static loads. Also determination of the area in-situ stresses is the fundamental issue in modeling and in mathematical analysis.

14-2-Determination of the Area Seismic and Earthquake Characterizes as the Design Basis:

The major difference between structures design for static and dynamic loads is that in static analysis, the amount of applied load is specified unlike the dynamic analysis. Which means, in seismic design, the earthquake that will occur is specified exactly and scaled as well as characterizes are uncertainly so based on these and with consideration of the structure dynamic properties design operation is performing. Therefore in order to fulfill the consequences of this defect, the foreseeing earthquake occurring is unavoidable.

14-3-Determination of the Area Seismic and Earthquake Characterizes Methods as a Design Basis:

The determination of methods of the area seismic characterizes and prediction of a earthquake that will occur in the future and in an area are named earthquake risk analysis and are performed in two techniques. These methods consist of determining seismic hazard analysis and probable seismic hazard analysis.

14-4-Primary Analysis Based on Past Experiments and Passing Through Faulting Zones:

Beside determination of the area dynamic properties and seismic situation, in order to tunnels seismic design the first step is study of tunnels behavior that is subjected to seismic loads before. Also studying of produced hazards effect in tunnels stability due faults motion and implementation of practical mitigation measures are completing parts of this discussion.

14-5-tunnel Design for Seismic Loading with Use of Mathematical Methods:

Uses of mathematical methods for tunnels design are sequent step in seismic design. After determination of the area dynamic and geomechanic properties and also primary assessment based on past experiments, at present more practical step of design is started by using expressed mathematical formulas. In this case various formulas were expressed but generally two type of seismic design using mathematical methods which are more practical than other techniques. First method is based on maximum acceleration and particle velocity of considered load and other method is based upon wave emission in elastic media, that firstly method has more practical formulas.

14-6-Numerical Analysis the Tunnel Seismic Behavior:

Different types of design methods are complementary together and each of them is based on its nature that has the special advantages and disadvantages. A numerical analysis method that is developed with software and hardware extension are most appropriated methods for solution of complicated problems, Therefore it is the most appropriate tunnel seismic design methods although complicated.

First step of numerical modeling is the type of appropriated numerical method determination; hence firstly geometry modeling should be performed. Also about model dynamic analysis of, at first performing the static analysis of model is required, it means initially the model must be equalized against static loads then seismic load must be applied.

Conclusion:

This article is dedicated to present criteria and rules for metro path design including tunnels geometrical section and the parameters to choose, loads applied to tunnels, essentials of static and seismic analysis, and primaries of structural design, structural joints, and control criteria, behavior measuring and sensitive devices. Design criteria of shallow and semi-deep tunnels which are constructed using cut and cover method, are just as those of stations while design criteria of deep and semi-deep tunnels. The following codes and references must be used for loading and design of tunnel and stations structural components and also other subway components.

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