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A Comparative Study Regarding Different Approaches for Tunneling Operation

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***Abstract*—Tunneling operation causes the redistribution of stresses around the soil; it becomes very difficult to determine the stress conditions around the soil or rock mass. Help of a constitutive model is often taken so as to determine the mechanical characteristics of soil surrounding the tunnel. Various approaches which are suggested by the investigators may be categorized as Analytical, empirical and semi-empirical one. Where analytical approaches rely on rigorous mathematical computation combined with numerical modeling, the other approaches take into the consideration of experimental findings conducted either to full plant scale or to a laboratory based reduced scale experimentation. The mostly used empirical approaches to investigate tunnel behavior followed by excavation are New Austrian Tunneling Method (NATM), Rock Mass Rating (RMR), Rock Mass Index (RMI) and Geological Strength Index (GSI). Studies advocates the use of a Semi-empirical approach for understanding the displacement and stress conditions within the rock mass.**

***Keywords*— Hoek-Brown yield criterion, horse shoe tunnels, in-situ stress ratio, jointed rock mass, single tunnel**

I. INTRODUCTION

Using subterranean space has recently evolved in the process of economies and population surge. Greater cost of building urban space drives up requirement for tunnels in large cities. As a result, the most cost-effective approach for constructing these structures should be chosen. A very popular and efficient underground construction methodis New Austrian Tunnelling Method (NATM).On situations NATM is assigned in a cross section, the face is split into temporary parts. The Side Wall Drift (SD), Central Diaphragm (CD), and Pile-Beam-Arch method are examples of this. Settlements due to sequences of excavation in non-cemented soil can deteriorate nearby structures. Consequently, it is essential to find out the most effective factors for managing tunnel-induced settlements and to alter the excavation stages. Many computational researches have been developed out on NATM in urban environments, with tunnels and small parts often being simulated. To know the effects of various patterns, many Finite Difference Method tests were conducted in NATM. The construction of a station is regarded as a major undertaking. Adjusting the pace of excavation, installing support, and partial-face excavation are all used to empirically monitor induced displacements. Driving a tunnel results in some stress release at the tunnelling face. The stresses in the lining are greatly affected by the time elapsed after the drive and the travel from the face when the lining is effectively contributing to the tunnel support opening (Duddeck 1988). As a result, deformation-stress fields can only be obtained via a 3-dimensional analysis (Duddeck 1991). A two-dimensional approach can be is viable where the ground is soft and the lining's support works very close to the face (as in shield driving) (Schulze and Duddeck 1964; Duddeck and Erdmann 1985).

II. REVIEW OF LITERATURE

Vital factor influencing mine and tunnel stability, according to Bieniawski (1984), is the contact between adjacent openings. Bray's (1987) definition of "the zone of control of an excavation" has proven to be extremely useful in this regard. When an underground opening is excavated, the in situ stress field is disrupted in a manner that the disruption is greatest near the opening and diminishes rapidly as one move away from it. The "zone of impact" refers to the area surrounding the opening where the disruption is important (Bray 1987). The opening geometry (i.e. size and shape) and in situ stresses determine the size of the zone of influence. This idea can be extended to the placement of two or more excavations in near proximity. The relation between the excavations is practically non-existent if none of the zones of influence overlap. In reality, excavations whose boundaries are located outside of each other's zones of influence may be planned without consideration for the involvement of others (Brady & Brown 1993). Bray (1987) derived and provided functional expressions for evaluating the width and height of the area of control for circular and elliptical openings using closed-form elastic solution for stresses. The mechanical interaction between two circular openings of the similar size in a hydrostatic stress field can be considered negligible if the pillar width remaining between them is larger than two tunnel diameters, owing to these expressions. Ghaboussi & Ranken (1977), who took help of finite element analyses to have a relationship between two parallel circular tunnels, reported similar results.

For weaker and highly fractured rocks both RMR and RQD an approach were found to be of limited use and seems to be inappropriate for classifying the rock. The relation between constants ‘m’ and ‘s’ of criterion suggested by Hoek-Brown and RMR values were not consistent and cannot be relied upon. Also for weaker rocks RQD value is zero, therefore a new system of classification for rocks was looked for, though this is still relevant for tunnel reinforcement and support design.

GSI approach relies on characterizing mechanical properties of rock mass, which can be used as input for developing a numerical program, to predict the rock mass behavior. It considers the rock mass as a continuum and when combined with visual detection can be used to prepare a model to estimate deformation and strength of rock mass. It is worth mentioning that GSI is only a tool indicative of rock mass properties and it alone cannot be used directly for designing of tunnels. As GSI approach assumes rock mass to be composed of several randomly positioned discontinuities and rock mass is considered an isotropic and homogeneous system it is no longer useful where rock mass is of anisotropic nature and there is presence of dominant weak plane or if there is gravitational driven instability. The GSI and Hoek–Brown treatments of the rock mass as an analogous continuum are valid where the rock mass is medium to strongly jointed and the rock mass is roughly isotropic. The notable features of Hoek–Brown criterion are; (a) Its shape (in the meridian plane) is non-linear, and it matches the findings obtained from experiments over a wide range of confining stresses;(b) It was created following an intensive audit of test data from a variety of intact rock types;(c) It provides a simple analytical method for estimating rock mass properties.

Soliman et al. 1993 performed study on two tubes of underground railways built closely. Both tubes were constructed in succession. The driving sequences affect the stresses in the linings and the ground, particularly in shallow tunnels with soft ground. As a result, a coherent stress-deformation analysis for the tunnels must consider the mutual effect of the successive tube driving. The results of a finite element technique to these problems for tunnels driven by shielding method as well as tunnels driven by excavation and shotcreting, were presented. These findings demonstrate that single-tunnel solutions can be used to develop double-tube solutions.

1. A three-dimensional analysis of two adjacent tunnels that are driven in the same direction, if stress release at the tunneling face is taken into consideration before the lining support, a three-dimensional approach is needed.
2. Assuming homogenous soil and identical excavation methods, the stress and deformation fields that move with the tunneling face through the ground converge on stationary patterns. As a result, a travelling measurement net may be used to perform a finite element analysis.
3. The final stress-deformation area can be obtained by adding the incremental values measured for each round of excavation at a fixed point in the ground or in the lining.

Yamaguchi et al. (1998) investigated in Kyoto City, Japan, where four subway tunnels were built that are aligned closely to each other. Prior to construction, problems associated with closely running tunnels were investigated at the planning and design phases. It resulted in the assemblage of a large amount of data, including transfer of load between tunnels and ground activity during the four tunnels' construction. Stresses acting on the lining together with displacements were tracked during the construction of four extremely near parallel tunnels, and the resulting data was examined in detail. This paper proclaims the outcomes of this investigation, which shed light on the ground's actions as a result of shield driving. on the basis of calculated ground behavior, a FEM-based model was evolved with the goal of knowing the connection between load reduction induced by tunnel driving and ground strain. As a result, an empirical parameter was introduced which gauges the amount of subsidence driven displacement and upheaval at each node of building.

Hu et al. (2003) investigated the construction of a deep excavation of a building foundations resting on saturated soil. Since it was situated in the close proximity of Shanghai Metro tunnels, this deep excavation was particularly interesting to investigate. When excavation was carried out, tunnels had to remain open. Problem encountered during the deep excavation's design and construction was the possibility of massive dislocation of the tunnels. The parameters and steps for regulating soil and tunnel deformation are discussed in great detail in this paper. Cast-in-place concrete diaphragm walls with bracing structural members, drainage consolidation by pumps, cement–soil mix pile systems, and rational excavation procedures were tried out. To estimate the increase in undrained shear strength in a soft clay layer due to pumping consolidation, a simplistic theoretical approach was suggested. In addition, traditional FE method is applied to reckon displacements of the soil owing to the excavation. The aforesaid values of the tunnels were could be managed within 5.0 mm and 9.0 mm, respectively, by employing the suggestions described.

Ng et al (2004) investigated the varied association and response among twin tunnels built in stiff clay using the modern Austrian tunneling method using a series of systematic, three-dimensional coupled finite element analyses. It was considered that twin tunnels are large sized and parallel. The tunnels were investigated for lag distance (L_T) and mechanism of load transfer, where (L_t) has its usual meaning. It is discovered that L_T has a greater impact on each tunnel's horizontal movement than on its vertical movement, and it has a major impact on the tunnels' horizontal diameter shortening. L_T is a linear function of pillar width. Maximum settlement is given as offset from the pillar's centerline, and the offset increases as the L_T value is increased. However, peak settlement is unaffected by L_T. It states that “The load is transferred from the right tunnel to the left tunnel as L_T increases, resulting in a rise in the left tunnel's bending moment but a decrease in the right tunnel's bending moment. The axial force at the left springline of the left tunnel increases correspondingly, while the axial force at the right springline of the right tunnel decreases. The distributions of pore-water pressures at both tunnels are significantly nonsymmetrical due to the twin tunnel interactions.

Gerçek Investigated about the interrelationship between parallel underground openings with traditional shapes. The study's parameters are based on problem configuration and the stress conditions in the field. Two-dimensional FE software with the ability to perform elastoplastic stress analysis is used for this. The correlation is studied in terms of size and relative location of openings. In a hydrostatic or anisotropic in situ stress zone, the openings are situated. The findings show that nearly all of the variables investigated have influenced the interaction of parallel openings in some way.

Byun et al. (2006) investigated the behavior of the near-surface ground in the tunnel-crossing zone, along with the behavior of the current tunnel located above the newly excavated tunnel. Several large-scale model experiments were conducted in 1/12 scale for the sample tunnel in operation, which has an upper tunnel with 8.4m cover over the crown and 7.2m diameter and a lower tunnel with 10.8m diameter. A large-scale test pit measuring 4.0m wide, 3.8m high, and 4.1m long was used to construct the test model. For middle density, sand raining was used to check the density of the ground. The current upper tunnel lining was 60cm in diameter with a 4mm steel thickness. The stress flow created by the longitudinal arching effect caused by the digging of the lower tunnel is disrupted by the upper tunnel, according to model tests and numerical analyses.

Investigation conducted on the geotechnical properties of the 9,325 m long twin tunnel metro route in the Greater Municipality of Ankara are discussed herein. The authors M. Karakus et al. (2007) analyzed and presented convergence measurements taken during tunnel construction. FE analysis was adopted to know mutual interaction of the twin metro tunnels. The measurements of field and the FE model predictions are compared. The tunnels were to be located at a shallow depth, mostly through Ankara Clay, which was found to be lightly over consolidated in oedometer tests. In the (FE) analysis, the Modified Cam Clay model, which was designed to reflect normally or lightly over consolidated soil action, was used. The Drucker–Prager behavior, in which the failure mechanism depends on the intermediate principal stress, was used to model the rendered ground over the Ankara Clay. The outcomes of the numerical analysis indicate that the values of displacements in vertical direction for the tunnel walls are in close agreement with observations, but horizontal displacements differ from real measurements. However, since the readings were made using these techniques, the observed convergence may be suspicious. Therefore, it is thought that a more precise method for the measurement of convergence in such ground may be a good choice. The construction of right tunnel took place after the left tunnel was completed, and not only the horizontal but also the displacements in vertical direction were observed to be 2–3 times greater for tunnel on right flank rather in the left tunnel. Perhaps reason behind this is the narrower pillar width developing in a wider plastic area around left tunnel.

Chapman et al. (2007) in their paper discussed ground movement due to tunneling operation in soft soil. A Lot of research work for single tunnel driving is already done and to predict the ground movement Gaussian curve method has proved to be an effective tool. However, for multiple tunneling especially sbs tunneling operation very little understanding is developed yet. An experimental setup is prepared on a scale of 1 in 50 and (1g) to study the ground response under multiple and sbs tunneling. The soil taken for this is Kaoline clay and findings show that for a single tunnel Gaussian curve method gives satisfactory results when compared with field results as reported in literature. However, for multiple tunneling is not giving satisfactory results and fits very badly. Therefore this same approach is modified and though it is very difficult to simulate field conditions in the lab due to not being able to simulate in situ stress conditions and effect of small size scaled model, still results obtained so are fair enough to the real results.

Cai et al. (2006) investigated about the residual strength of rock mass and reported that since its advent in the year 1995, GSI system has gained tremendous popularity in evaluating the strength of rock mass and the elements that command the deformation of rock mass. The GSI method focuses on describing two variables: rock fabric and state of block surface. The GSI framework provides instructions for estimating the peak strength variables of jointed rock masses. There seem to be no guidelines provided by the GSI or any other tool for assessment of residual strength with satisfactory reliability. The GSI scheme has been augmented to measure the residual firmness of a rock. The two main deciding features in the GSI—the Vr^b and J^r_c where notations have their usual meaning—are suggested to be used to change the peak GSI to the residuary GSI_r value. The predicted residual strengths, deduced using the residual GSI_r value after making due reduction, are found to comply well with field test or results obtained through back-analysis

Chehade et al. (2008) probed into the building of twin tunnels or new tunnels adjacent to existing tunnels. The Lining is greatly affected by soil disturbance and internal forces and procedure adopted for the same. Attempts were made to examine the issue, with a focus on optimizing both the relative location and the construction method. In order to find the impact of forces and settlement of soil resulting from tunnel construction, a parametric analysis was performed. The numerical model is presented first, followed by analyses for three patterns of the twin-tunnels: aligned-horizontally, vertically, and inclined. It demonstrates how the building method influences subsidence of soil and internal stresses. Higher values of settlement and bending moment are observed due to the earlier construction of upper tunnel. Vertically aligned tunnels caused the most soil subsidence, while horizontally aligned tunnels caused the least.

Using 2D FEM, the response of a tunnel in working condition to overlying excavation was investigated by Zhengand Shao (2010). Three standard tunnel excavation positions were considered: the central line under the excavation bottom, directly under the base of the diaphragm wall, and outside of the diaphragm. The variation in tunnel response as a function of tunnel position was investigated. During the excavation process, the locus of stress of the soil surrounding the tunnel was compared. The results of numerical analysis show that due to overlying excavation, the tunnels underneath at various locations under the excavation can undergo convergence and divergence. Furthermore, the tunnel under the diaphragm wall's foundation would be distorted. The deformation is primarily caused by uneven ground contact pressure variations on tunnel linings. The tunnel's vertical and horizontal displacements decrease as the tunnel's submerged depth under the excavation structure increases.

Deb et al. (2010) in their findings revealed that strength and deformation characteristics of rock mass varies largely with joint condition and spacing of joints, and engineering properties of rock mass has relatively lesser influence on these characteristics. In most of the approaches an interface element is sandwiched between two adjacent rock matrix elements to perform mathematical analysis of discontinuities such as joints, faults, shear planes, and others. However, because of the inherent numerical difficulties in rock mechanics problems with multiple discontinuities, the applicability of interface elements is reduced, resulting in pseudo solutions. Recent advances in the extended finite element method (XFEM), which incorporates a strong discontinuity within a standard element, allow for the analysis of distinct discontinuities in rock masses with minimal numerical challenge. This philosophy is based on the idea of partition of unity and can be extended to rock joints of cohesive nature. In their paper described the mathematical models for implementing strong discontinuities in three and six nodded triangular components, as well as numerical examples of the use of XFEM in one and two-dimensional problems with single and multiple discontinuities.

The rock mass possessing clear systematic discontinuity sets, passing through sandstone siltstone rock strata is investigated by a comparative numerical model located in a highway in Turkey by Satici and Bahtiyar (2014). When investigating by FEM Modeling for the stability of tunnel, the repercussions of incongruities of rock mass is often not taken into account. In order to make up for this shortcoming while modeling FE models, geotechnical properties of rock mass are reduced proportionately. This research targets to demonstrate how systemic and recurrent discontinuity sets affect FE numerical modeling when there are discontinuities. On this basis, two separate conditions were modeled in order to compare and contrast stability conditions. For modeling, the FE numerical analysis programme ‘‘Phase2 8.0" was used. When FEM software is used for discontinuum media, the appearance of discontinuities displays a major impact on tunnel stability and model performance. Consequently, using FE computational models without taking discontinuities into account would almost certainly result in incorrect tunnel stability assessments

Fu et al. (2014) suggested that deformity of ground by tunneling operation is influenced by the interactivity of twin-parallel tunnels, which could put adjacent structures in jeopardy. On the basis of complex variable theory, this paper presents an empirical approach for problems involving determining deformations and stresses around deforming twin-parallel tunnels in an elastic half plane. The boundary condition for each of the two tunnels, for example, regarded as a uniform radial deformation. To gain a thorough understanding of the impact of the interdependency between twin-parallel tunnels using the proposed theoretical method, careful consideration was given to the influence of tunnel depth and separation of tunnels on the surface movement. It is discovered that as the above alluded factors increase, the efficacy of twin tunnel interaction on surface movement decreases. The presented analytical solution demonstrates that, similar to most current numerical findings, the method of superposition can be beneficial in knowing ground deformation of twin-parallel tunnels with a certain substantial depth and spacing; however, the interaction efficacy between the two tunnels must be considered for accurate ground movement prediction.

Investigative study was conducted by Aversa et al. (2015) where one nook of an old church constructed in the 16th century is under passed by railway tunnel in the city of Napoli's underground network. The tunnel, diameter of which is 8.15 metres, extends underneath the church foundations.EPB tunnel boring machine was employed to do the excavation. The church was meticulously monitored during construction to ensure its pertinence. The presence of the church was considered cautiously in the design stage, with settlement predictions based on a conservative range of expected volume loss during tunnel construction. At midsized strain levels, 3D finite element tests of stiffness strain dependence were conducted. The paper explains the method of monitoring and compares the observed displacements in the greenfield parts of the public gardens in front of the church to those estimated by 3D FEA. The effect of the structure's stiffness and the underground line's relative location in relation to the church's plan portion is also addressed

III. OBSERVATIONS

Attempts are made to develop a flexible strength theory that is applicable to analyze the elasto-plastic properties of underground tunnel rock. The generalized nonlinear unified strength theory in association with elasto-plastic mechanics are used to derive analytic solutions of the radius and stress of tunnel plastic zone and the periphery displacement of tunnel under uniform ground stress field in order to know the effects of intermediate principal stress and rock properties on the breakage of rock mass. The finding has a revelation that the intermediate principal stress coefficient ‘b’ has quite an impact on the plastic range, stress magnitude, and rock pressure in the zone of concern. Huang et al. (2016)

A two staged method of analysis considering elastic and plastic response is proposed and introduced into software called “Analysis of Structural Response to Excavation” (ASRE) by Franza et al. (2019). The basic aim was to know the effect of tunneling on nearby soil and structures if any and their mutual interaction. A variety of parameters can be incorporated like different loading conditions, ground motions in horizontal and vertical directions. It also provides a window for slippage and gap formation if there is any. By this program one may opt for isolated and continuous footings. Attempt is made to access the interaction of structure and soil by incorporating appropriate conditions of soil and structure apart from clarifying the behavioral difference between equivalent simple beams and framed structures.

IV. CONCLUSIONS

The works reported in case of finite element analysis of interaction of deep underground openings are very few. Generally, the effect of different yield criteria for deep interacting tunnels has not been reported. The effect of variation of insitu stress ratio with different pillar width between non circular tunnels has not been reported. The effect of joint condition in rock masses for interaction between deep tunnels has not been studied so far. Characteristics of support system for interaction between deep underground openings in jointed rock masses has not been reported. A necessity for detailed analysis of such situation is very obvious.

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