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The Study of Reinforced Shotcrete Heterogeneity Effect on the Stability of Tunnels Excavated Using Austrian Tunneling Method

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Abstract- Based on the previous studies, heterogeneity models and the affecting factors on the heterogeneity of the shotcrete are studied in this paper. To investigate the effect of the heterogeneity degree on the stability of the tunnel, a shotcrete heterogeneous supporting layer (concrete and steel) with the thickness of 30cm with two heterogeneity plan (geomechanical properties) are considered. Then, the three-stage excavation method was modelled for 10 different elastic modulus using Plaxis 3D tunnel software in two longitudinal and transverse plans and the elastic modulus in transverse plan was increased by 200 KN/m^2 each time. In the next step, the Poisson's coefficient was set to 0.2, 0.25 and 0.3 in models. The obtained results show that, the effect of elastic modulus on the stability in the direction of two longitudinal and transverse axes, is a function of shotcrete Poisson's coefficient change in the direction of heterogeneity and this effect is of the same value in the roof, invert and the wall of the tunnel.

Keywords*- Horseshoe Tunnel, Shotcrete Heterogeneity, Tunnel Stability, Plaxis 3D Tunnel*

I. INTRODUCTION

Up until today, numerous studies have been carried out by the experts in the field of soil mechanic to present a design which be able to preserve the underground spaces and be safe as well as being economically reasonable. The results of this study emphasize on the application of the observational methods such as NATM in tunneling. The new Austrian tunneling method (NATM) was invented between 1957 and 1965 in Austria. The very first idea of this method, was the use the geological pressures embracing the soil and rock mass to reinforce and support the tunnel. The main purpose of the NATM is to create a semi rigid inner and outer arc using the supportive tools such as shotcrete, wedge, screw and others, immediately after the excavation. This adjusts the stress in the region around the tunnel, prevents destructive weakening and this is what that distinguishes the NATM from other conservative tunneling methods.

Generally speaking, concrete can be considered as a homogeneous mixture of aggregates, cement and water and is therefore commonly treated as an isotropic material. Anisotropy in shotcrete can be expected due to the spraying process and various uncertainties in material technology and curing conditions (Aldrian, 1991). Furthermore, imperfections of the tunnel shell can introduce certain anisotropy in the material behavior that can lead to unexpected loading conditions (Stelzer and Golser, 2002). For experiments regarding the strength development of shotcrete, it is very important to take into account the spraying direction for sample preparation. In standard tests on shotcrete cores the loading direction would be the same as the spraying direction, which is the opposite in a real tunnel structure. Within the tunnel lining the major compressive stresses would act perpendicular to the spraying direction. According to Thomas (2008), the quantification of this anisotropy for shotcrete in the literature seems to be difficult to establish. Huber (1991) and Fischnaller (1992) tested the early strength of shotcrete with two loading directions and came to the conclusion that the samples that where tested parallel to the spraying direction had a reduced strength of 20% compared to the samples tested perpendicular to the spraying direction. Steel fiber reinforced concrete exhibits pronounced anisotropy in its behavior for both compression and tension. However, anisotropy effects of shotcrete are usually ignored in a numerical analysis for the purpose of simplicity.

In this study, the stability of the tunnels, built using NATM method, are investigated considering this value.

II. CHOOSING THE SUITABLE BEHAVIOR MODEL AND DETERMINING ITS PARAMETERS

Different behavior models which are presented in the numerical modeling software can be used depending on the problem condition and the type of the model environment. The Mohr-Coulomb behavior model is a suitable model for the soil and rock mass among all the behavior models suggested in this software (Fig 1).

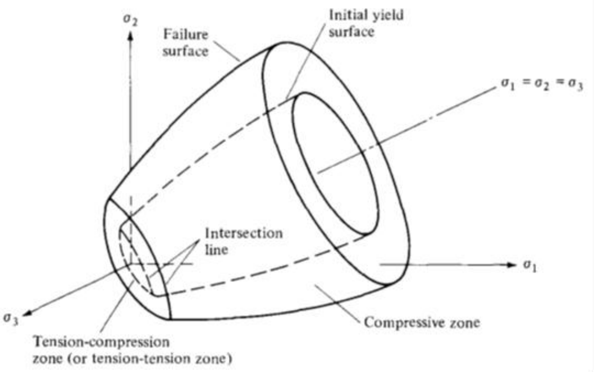

Figure 1. The Mohr-Coulomb yield and failure stress diagram

In order to model the supportive system and to apply the real conditions in this section of the tunnel, the interface layer system is needed to achieve the calculation conditions. Since there is jointed and cracked rock mass in this layer due to the different types of shotcrete performing, the layout system in the concrete part of the shotcrete is different in various directions of the tunnel. It is in a way that its anisotropy system is not equal in all parts of the tunnel. Therefore, different stiffnesses are formed in different directions of the rebound. In order to express this behavior in the software by imagining the anisotropy or heterogeneity plans, the material texture behavior model with different stiffness model in different plans such as jointed rocks are chosen.

III. NUMERICAL MODELLING

The plaxis 3D tunnel is a software package utilizing finite element method which is particularly developed for analyzing the deformation and stability in tunnel projects. The graphical user interface allows to create complex finite element models and with the vast numbers of outputs from the software, one is able to extract a precise result from the calculation models.

It is expected that users reach to a fundamental insight into the mechanics of the soil which is mixed with modeling in the Windows environment.

The variables which are studied in this paper are as follows:

- Sum Msf parameter
- Poisson's coefficient in the direction of the plan A and B
- Elastic modulus of the shotcrete in different directions based on the spraying condition

IV. MODEL GEOMETRY

The model sections are created based on the points and lines which is done using the mouse pointer in the drawing region of the software. The geometry drawing tools are accessible from the toolbar. The geometric shapes of the subjects are inserted based on the horseshoe tunnel standard models drawing methods using lines and arcs. In the first stage, we should insert the geometry of the sample model into the software. To do this, the drawing tool is selected from the toolbar and the dimensions of the sample model are defined for the software (Fig 2 and Fig 3).

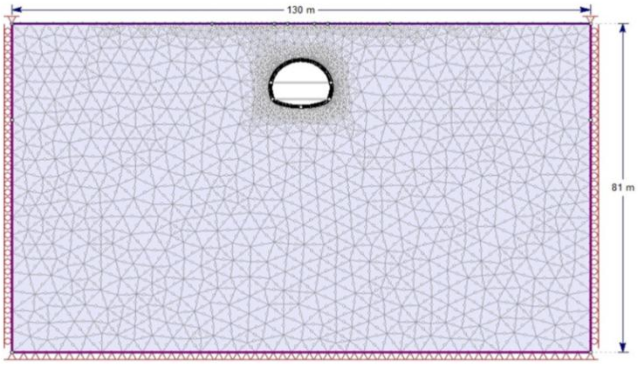

Figure 2. The modeling of horseshoe tunnel

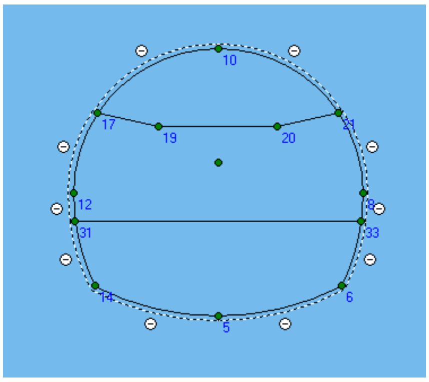

Figure 3. Cross section of the drawn tunnel geometry in the software environment with specified points numbers and the excavation stages (three-stage)

V. THE GEOMETRY STABILITY CONDITIONS OF THE TUNNEL

During the tunnel excavation, the process should be designed in a way that while the tunnel is being excavated, the pressure from the excavator system and the mechanical pressure do not cause the tunnel collapse. Consequently, for maintaining the stability of the excavation process, we use the governing equations for this type of excavation in sections where it is performed mechanically and by using excavation armed devices. The dimensions of the excavation frame are also chosen in a way that, for controlling the clamping stress due to the excavation frame, it could be minimized.

VI. GEOMECHANICAL PROPERTIES OF THE SOIL

After inserting the boundary conditions; materials, sections of the soil and other geometric properties of the soil are adjusted in the information input window. The options of the separation lines which are in the soil and interface information input window will be adjusted. For the subject of this study which is soft lands, the properties of the soil of the Amirkabir tunnel in Tehran is inserted as presented in table 1 according to the intended district geomechanical parameters table.

TABLE I. TECHNICAL PROPERTIES OF THE CLAY SOIL LAYER ACCORDING TO THE CLAY SOIL MASS GEOMECHANICAL PROPERTIES OF THE AMIRKABIR TUNNEL IN TEHRAN

Initial element loading	Field stress & body force
Unit weight	19 kN/m3
Elastic type	isotropic
Young's modulus	72000 kPa
Poisson's ratio	0.35
Failure criterion	Mohr-Coulomb
Tensile strength	0 kPa
Peak friction angle	33 degrees
Peak cohesion	35 kPa
Material type	Plastic
Dilation Angle	0 degrees
Residual Friction Angle	33 degrees
Residual Cohesion	35 kPa
Piezo to use	None
Ru value	0

VII. SAFETY ANALYSIS

Although the stability during the tunneling process is important, but considering the operation safety and not the final stability is vital. The stability against the failure is defined by the safety factor. In structure engineering, the safety factor (safety coefficient) is usually defined as the ratio of the failure load to the performing load. However, this definition is not always useful and the following definition of the safety factor can be used as a suitable substitute;

$$\text{safety factor} = \frac{S_{\text{available}}}{S_{\text{needed for equilibrium}}} \qquad (1)$$

Where S denotes the shear strength. The amount of available strength is used for the calculation of the minimum needed strength and for the safety factor in the equilibrium condition which is also used in the soil mechanics. By introducing the standard condition of the Coulomb, the safety factor includes;

$$\text{safety factor} = \frac{c+\sigma_n \tan\varphi}{c_r+\sigma_n \tan\varphi_r} \qquad (2)$$

Where c and ϕ are the input strength parameters and σ_n is the real normal stress. c_r and ϕ_r are the reduced strength parameters and their magnitudes are high up to a point to just maintain the equilibrium. The principle described above, is the basis of the Phi-c reduction method which is used by the Plaxis software to calculate the total safety factor. In this expression, the cohesion and the friction angle tangent will reduce by the same value.

$$\frac{c}{c_r} = \frac{\tan\varphi}{\tan\varphi_r} = \Sigma\text{Msf} \qquad (3)$$

The reduction of the strength parameter is controlled by the ΣMsf coefficient. These parameters are raised step by step for the failure to occur. The safety factor is defined at the failure point after the value of the ΣMsf. Presenting it at the point of failure and lower or higher than a constant value can be obtained by passing some successful calculation steps.

VIII. MODELS TYPES

In order to optimize the excavation process some more configurations are needed considering the base tunnel’s dimensions, including changes in the elastic modulus (EA) in two longitudinal and transverse axes, changes in the Poisson’s ratio in two longitudinal and transverse axes and also changes in the internal friction angle in the inner performed lining (φ) which are affective on the shear strength of the performed lining. On this basis, the heterogeneity modulus can be defined for models as $\sigma_g = G_{ppt}/G_{pp0}$ and the stability coefficient which is equivalent to ΣM_{sf} in the software output can be obtained. The stability values and final stresses are categorized as the models presented in tables 2 to 4.

TABLE II. GEOMECHANICAL PROPERTIES IN PLANS 1 AND 2 OF THE STEEL REINFORCED SHOTCRETE SUPPORTING SYSTEM (FIRST CASE)

Model Characteristics	Longitudinal elastic modulus	Shotcrete thickness oriented elastic modulus	Transverse Poisson’s coefficient	Longitudinal Poisson’s coefficient	Shear Modulus	Specific weight	Internal friction angle	Cohesion angle	Cohesion
Unit	E1(kn/m^2)	E2(kn/m^2)	υ_1(nu)	υ_2(nu)	G(kn/m^2)	γ(kn/m^3)	φ(phi °)	Ψ(psi ◦)	C(kn/m^2)
PA1	8.00E+06	6.00E+05	0.2	0.2	7000	25	22	0	5000
PA2	8.00E+06	6.20E+05	0.2	0.2	7000	25	22	0	5000
PA3	8.00E+06	6.40E+05	0.2	0.2	7000	25	22	0	5000
PA4	8.00E+06	6.60E+05	0.2	0.2	7000	25	22	0	5000
PA5	8.00E+06	6.80E+05	0.2	0.2	7000	25	22	0	5000
PA6	8.00E+06	7.00E+05	0.2	0.2	7000	25	22	0	5000
PA7	8.00E+06	7.20E+05	0.2	0.2	7000	25	22	0	5000
PA8	8.00E+06	7.40E+05	0.2	0.2	7000	25	22	0	5000
PA9	8.00E+06	7.60E+05	0.2	0.2	7000	25	22	0	5000
PA10	8.00E+06	7.80E+05	0.2	0.2	7000	25	22	0	5000

TABLE III. GEOMECHANICAL PROPERTIES IN PLANS 1 AND 2 OF THE STEEL REINFORCED SHOTCRETE SUPPORTING SYSTEM (SECOND CASE)

Model Characteristics	Longitudinal elastic modulus	Shotcrete thickness oriented elastic modulus	Transverse Poisson's coefficient	Longitudinal Poisson's coefficient	Shear Modulus	Specific weight	Internal friction angle	Cohesion angle	Cohesion
Unit	E1(kn/m^2)	E2(kn/m^2)	υ_1(nu)	υ_2(nu)	G(kn/m^2)	γ(kn/m^3)	φ(phi °)	Ψ(psi ∘)	C(kn/m^2)
PA11	8.00E+06	6.00E+05	0.2	0.25	7000	25	22	0	5000
PA12	8.00E+06	6.20E+05	0.2	0.25	7000	25	22	0	5000
PA13	8.00E+06	6.40E+05	0.2	0.25	7000	25	22	0	5000
PA14	8.00E+06	6.60E+05	0.2	0.25	7000	25	22	0	5000
PA15	8.00E+06	6.80E+05	0.2	0.25	7000	25	22	0	5000
PA16	8.00E+06	7.00E+05	0.2	0.25	7000	25	22	0	5000
PA17	8.00E+06	7.20E+05	0.2	0.25	7000	25	22	0	5000
PA18	8.00E+06	7.40E+05	0.2	0.25	7000	25	22	0	5000
PA19	8.00E+06	7.60E+05	0.2	0.25	7000	25	22	0	5000
PA20	8.00E+06	7.80E+05	0.2	0.25	7000	25	22	0	5000

TABLE IV. GEOMECHANICAL PROPERTIES IN PLANS 1 AND 2 OF THE STEEL REINFORCED SHOTCRETE SUPPORTING SYSTEM (THIRD CASE)

Model Characteristics	Longitudinal elastic modulus	Shotcrete thickness oriented elastic modulus	Transverse Poisson's coefficient	Longitudinal Poisson's coefficient	Shear Modulus	Specific weight	Internal friction angle	Cohesion angle	Cohesion
Unit	E1(kn/m^2)	E2(kn/m^2)	υ_1(nu)	υ_2(nu)	G(kn/m^2)	γ(kn/m^3)	φ(phi °)	Ψ(psi ∘)	C(kn/m^2)
PA21	8.00E+06	6.00E+05	0.2	0.3	7000	25	22	0	5000
PA22	8.00E+06	6.20E+05	0.2	0.3	7000	25	22	0	5000
PA23	8.00E+06	6.40E+05	0.2	0.3	7000	25	22	0	5000
PA24	8.00E+06	6.60E+05	0.2	0.3	7000	25	22	0	5000
PA25	8.00E+06	6.80E+05	0.2	0.3	7000	25	22	0	5000
PA26	8.00E+06	7.00E+05	0.2	0.3	7000	25	22	0	5000
PA27	8.00E+06	7.20E+05	0.2	0.3	7000	25	22	0	5000
PA28	8.00E+06	7.40E+05	0.2	0.3	7000	25	22	0	5000
PA29	8.00E+06	7.60E+05	0.2	0.3	7000	25	22	0	5000
PA30	8.00E+06	7.80E+05	0.2	0.3	7000	25	22	0	5000

As it can be seen in all the 30 models ranging from PA1 to PA30 presented in the above tables, the ratio of the longitudinal elastic modulus to transverse elastic modulus has changed in 10 cases and in each table the ratio of the longitudinal Poisson's coefficient to transverse Poisson's coefficient has changed in 3 cases. In the following tables only the internal coefficient angle will change in 2 cases.

IX. THE DEFINITION OF THE BASIC CALCULATION POINTS FOR THE OBSERVATION OF THE EFFECT OF THE HETEROGENEITY IN TUNNEL'S WALL

After performing the modeling based on the above tables, software outputs in the output frame of the software, the intended points for observing the intensity of the heterogeneity effect based on the mentioned parameters in invert, wall and the roof sections are determined (Figs. 4 to 7).

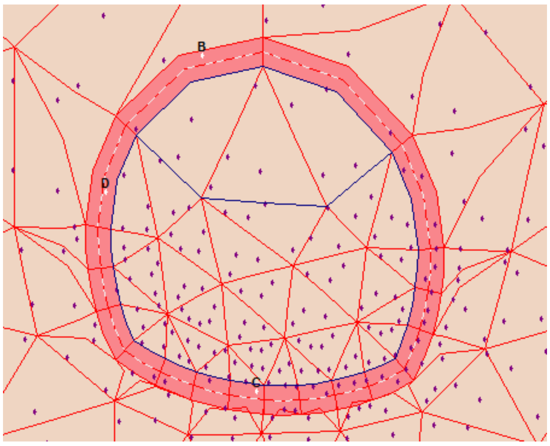

Figure 4. The determination of the basic points for observation of the anisotropic effect on them according to anisotropy plans different positioning style in the section

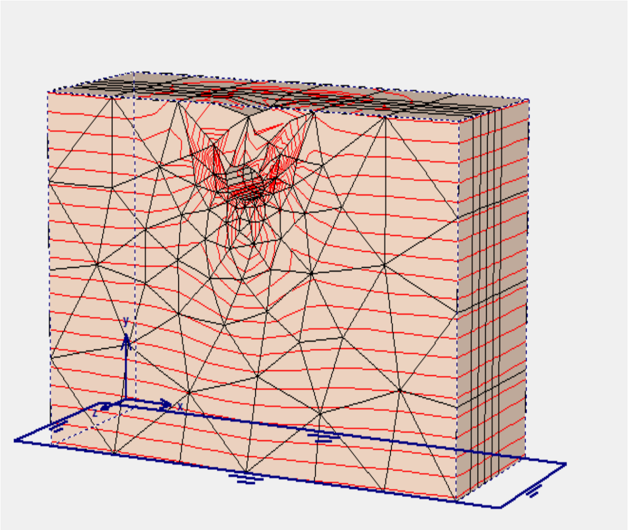

Figure 5. Stress deviation linear diagram for PA1 model

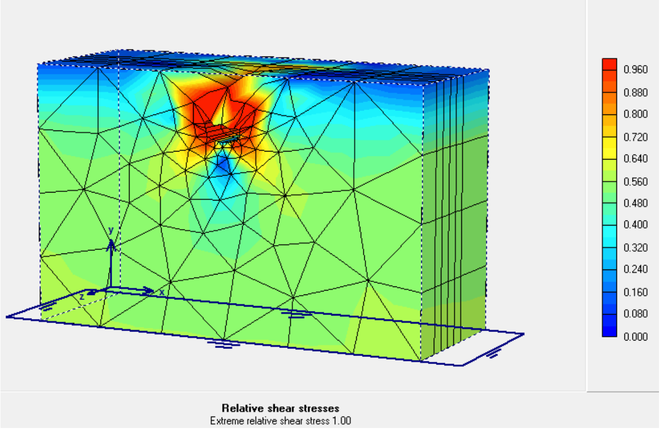

Figure 6. The relative shear stresses magnitude in the PA1 model

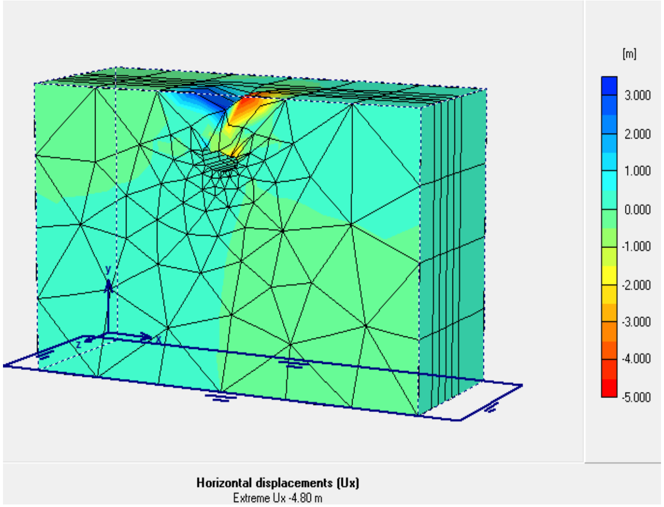

Figure 7. Horizontal displacements diagram

X. THE RESULTS OF THE PA1 TO PA30 MODELS ANALYSES USING THE THREE-STAGE EXCAVATION METHOD

PA1 to PA30 models were modeled using the three-stage excavation method to study the effect of the NATM excavation method on the anisotropy factors in equivalent analyses and the results are as Figs. 8 to 10.

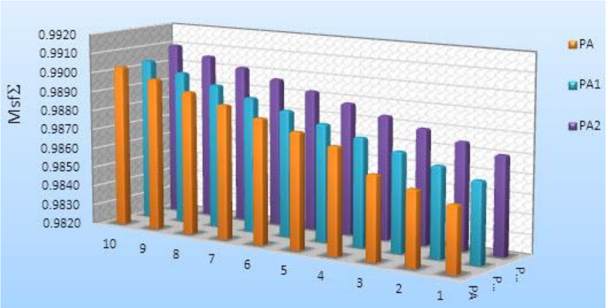

Figure 8. The diagram of the sumMsf versus PA1 to PA30 models outputs in upper point of the tunnel (point A)

As it can be seen, for the upper point in the tunnel in one group of models ranging from 1 to 10, the safety factor was increasing as the elastic modulus in plan 2 changed. There was the same trend for the models PA11 to PA20 as the Poisson's coefficient changed but the slope is decreased. There was again the same trend in models PA21 to PA30 for the last case of Poisson's coefficient change and the safety factor has increased by the increase of the elastic modulus.

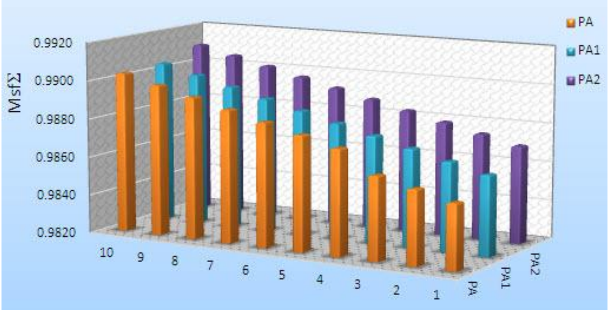

Figure 9. The diagram of the sumMsf versus PA1 to PA30 models outputs in lower point of the tunnel (point B)

As it can be seen, for the lower point in the tunnel in one group of models ranging from 1 to 10, the safety factor was increasing as the elastic modulus in plan 2 changed. There was the same trend as the Poisson's coefficient in models PA11 to PA20 changed to 0.05 except that the slope of the growth was decreased. There was again the same trend in models PA21 to PA30 for the last case of Poisson's coefficient change and the safety factor has increased by the increase of the elastic modulus.

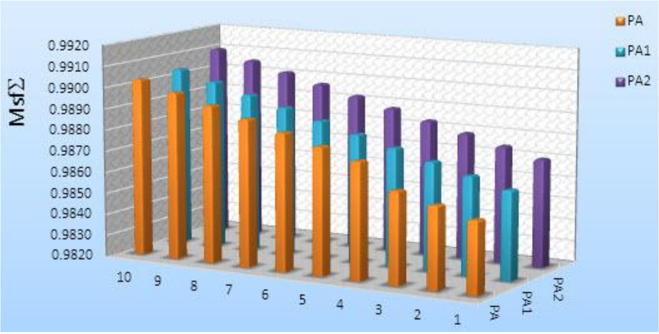

Figure 10. The diagram of the sumMsf versus PA1 to PA30 models outputs in wall point of the tunnel (point C)

As it can be seen, for the wall point in the tunnel in one group of models ranging from 1 to 10, the safety factor was increasing as the elastic modulus in plan 2 changed. There was the same trend as the Poisson's coefficient in models PA11 to PA20 changed to 0.05 expect that the slope of the growth was decreased. There was again the same trend in models PA21 to PA30 for the last case of Poisson's coefficient change and the safety factor has increased by the increase of the elastic modulus.

XI. THE MAIN RESULTS OBTAINED FROM THE 3D DIAGRAMS FOR THE PA GROUP MODELS IN THE CASE OF THREE-STAGE EXCAVATION METHOD

The following results are obtained from the initial interpretation of the diagrams:

As it can be seen in PA group three diagrams, the safety factor has increased as elastic modulus in transverse plan changed.

The safety factor has increased with lower slope with change of the Poisson's coefficient in models PA11 to PA20.

There was the same trend in models PA21 to PA30 as the Poisson's coefficient changed and the safety factor has increased with the increase of the elastic modulus.

The responses of all three points were the same for the stability coefficient.

XII. CONCLUSION

After analyzing the obtained results, it was found out that the changes in the values of the heterogeneity factors parameters in the shotcrete lining are effective on the stability of tunnels excavated using the NATM method. And the effect of the Poisson's coefficient parameter changes in transverse and longitudinal plans in an excavation method is more than other parameters. The change of the elastic modulus along the second axis is influenced appreciably by the Poisson's coefficient in excavation safety factor and in special ranges of the other two parameters, it shows a different behavior.

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