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# STABILITY ANALYSIS OF BEHESHT-ABAD WATER CONVEYANCE TUNNEL INLET PORTAL USING EXPERIMENTAL, LIMIT EQUILIBRIUM AND NUMERICAL METHODS

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ABSTRACT

The Behesht-abad Water Conveyance Tunnel is one of the most important tunnels conveying water to central Iran plain having 60 km length and 6 m diameter. The tunnel portal intersects with important faults of the region which is nearby Ardal city. Therefore, the rock mass surrounding the tunnel portal faces instability problem. Initially, the joints characteristics of the rock mass surrounding the inlet portal were evaluated to find the dominant joint sets along with the characteristics required for stability analyses inputs. Also the deformation modulus and other engineering properties of the rock mass were assessed using the available drilled boreholes data. The extensive stability analyses were conducted using stereographic, empirical SMR, limit state equilibrium and 3-dimensional discontinuum numerical methods. Finally, the results of the analyses were compared together.

Keywords: Slope stability, Streography, Limit state equilibrium, 3-dimensional discontinuum numerical analysis.

## GENERAL PROJECT OVERVIEW AND GEOLOGY OF THE STUDY AREA AND EXPERIMENTAL INVESTIGATION

The project is aimed to transfer water from Behesht-abad river at intersection of Behesht-abad and Kuhrang rivers in Chahar-mahal province to Zayandeh-rud river in Isfahan province to provide the water for central Iran plain. The tunnel portal is located in Behesht-abad river left bank at Darkesh-varkesh valley. The topography of left bank along the river is very steep (more than 75º) but the topography of embankement nearby the portal is around 40º. The portal is also located in the hanging wall of the main tributary of very active Ardal fault. The fault has made a considerable displacement in calcareous lithological units of the study area. The engineering properties of rock mass and joint wall are calculated based on the laboratory tests on the samples taken from borehole cores and field survey and are listed in table 1.

Table 1. The engineering properties of rock mass and joint wall

| | | | |
|---|---|---|---|
| UCS (MPa) | 86.32 | Joint Wall Internal Friction Angle º | 41.2 |
| Young's Modulus (GPa) | 30.9 | Normal Stiffness (GPa/m) | 150 |
| Poisson's ratio | 0.2 | Shear Stiffness (GPa/m) | 75 |
| Joint Wall Cohesion (KPa) | 53.72 | | |

## STEREOGRAPHIC ANALYSIS

The trend characteristics of the joints (dip/dip direction) were measured using scanline method (Priest SD, Hudson JA.,1981) and then were analyzed using DIPS software (RocScience,2010a) to get the dominant joint sets. The Schmidt contour diagrams of joints' poles based on Fisher distribution function and equal area lower hemisphere projection were drawn by the software to distinguish main joint sets (Fig. 1). A less important joint concentration was also observed which may not be considered as a joint set. The joint sets characteristics including dip, dip direction, spacing joint wall roughness and strength are presented in table 2.

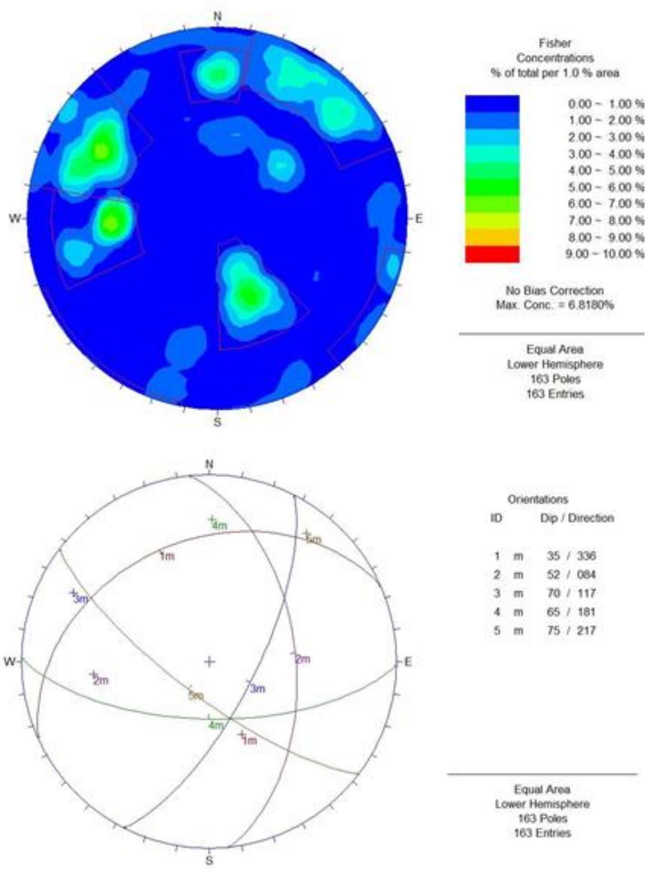


*Fig. 1. Contour diagrams of joints and their distinguished sets in the tunnel inlet portal*

Table 2. The joint sets characteristics in the tunnel inlet portal

| Joint set | Dip (°) | Dip direction (°) | Spacing (cm) | JRC | JCS (Mpa) |
|---|---|---|---|---|---|
| 1 | 35 | 336 | 10-20 | 13.38 | 93.17 |
| 2 | 52 | 84 | 20-60 | | |
| 3 | 70 | 117 | 20-60 | | |
| 4 | 65 | 181 | 10-20 | | |
| 5 | 75 | 217 | 20-60 | | |

The tunnel inlet portal includes 3 right, middle and left slopes (view towards the tunnel inlet). The results of stereographic analyses conducted by the software for the right slope are shown in figures 2,3 and 4. The stereographic analysis for middle and left slopes were done in the same way. The results of stereographic analysis all the 3 right, middle and left slopes at the portal are presented in Table 3.

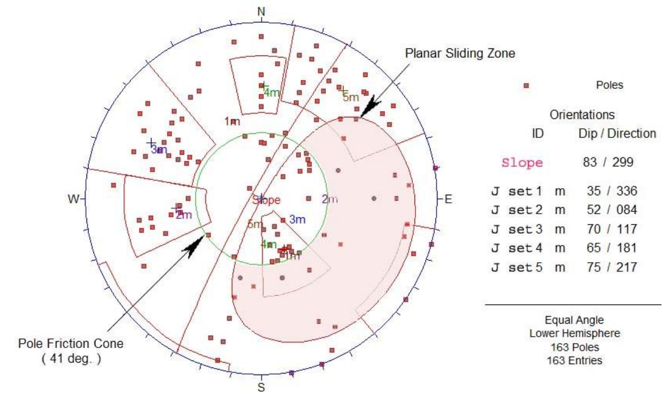


*Fig. 2 Joint sets and right slope situation and daylight envelope of plane failures*

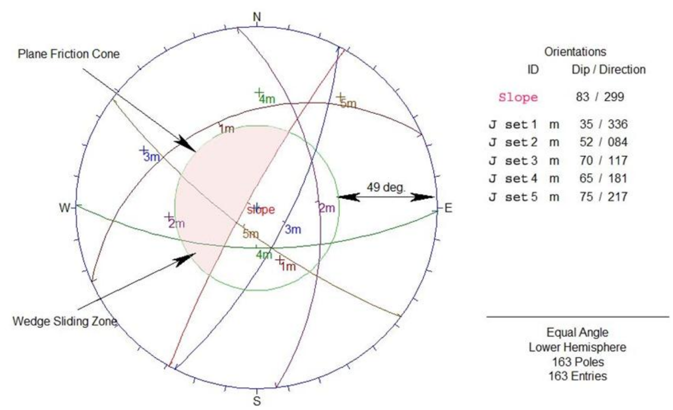


*Fig. 3. Joint sets and right slope situation and daylight envelope of wedge failures*

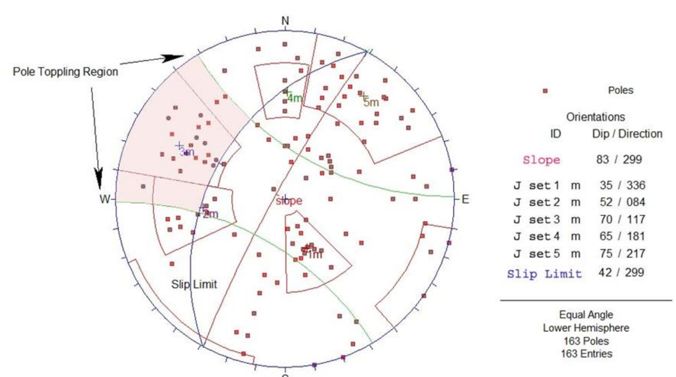


*Fig. 4. Joint sets and right slope situation and daylight envelope of toppling failures*

Table 3. The stereographic analyses results for the tunnel inlet portal slopes

| Slope | Planar failure | Wedge failure | Falling failure |
|---|---|---|---|
| Right | 1 joint from joint set no. 5 ; 2 joint from joint set no. 1 ; and 11 isolated joints | None of joint sets show wedge failure | Joint set no. 3 and 2 isolated joints |
| Middle | Joint sets no. 4 , 5 and few isolated joints | None of joint sets show wedge failure | Joint set no. 2 and 2 isolated joints |
| Left | Joint sets no. 4 , 5 and few isolated joints | $I_{43}$ , $I_{53}$ , $I_{45}$ | 7 isolated joints |
| $I_{ij}$ : Intersection of i and j joint sets nos. | | | |

## STABILITY ANALYSIS USING EMPIRICAL SMR METHOD

The rating for the rock mass surrounding the tunnel inlet portal is calculated according to Bieniawski's RMR classification (Table 4 ). The Slope Mass Rating (SMR) (Romana, 1985 & Romana, 1993) is also determined for all the 3 right, middle and left slopes at the portal. The results are listed in Table 5.

Table 4. Rating for the rock mass surrounding the tunnel inlet portal according to Bieniawski's RMR classification

| **Parameter** | **Value** | **Rating** |
|---|---|---|
| UCS (MPa) | 82.36 | 7 |
| RQD (%) | <25 | 3 |
| Spacing (mm) | 60-200 | 8 |
| Condition of discontinuities | Rough and slightly weathered Seperation<1mm | 25 |
| Ground water in joints | Dry | 15 |
| **$RMR_{Basic}$** | | **58** |

Table 5. The Slope Mass Rating (SMR) classification results for the tunnel inlet portal slopes

| Slope | Failure Type | Controlling Joint or Intersectioin | SMR | Rock mass class |
|---|---|---|---|---|
| Right | W | $I_{15}$ | 64.4 | II |
| | W | $I_{14}$ | 66.6 | II |
| | T | $J_3$ | 64.2 | II |
| Middle | P | $J_4$ | 59.0 | III |
| | P | $J_5$ | 60.5 | II |
| | T | $J_2$ | 64.2 | II |
| Left | W | $I_{14}$ | 66.6 | II |
| | W | $I_{35}$ | 59.0 | III |
| | W | $I_{25}$ | 60.3 | II |
| | P | $J_5$ | 25.5 | IV |
| | P | $J_4$ | 44.0 | III |

## STABILITY ANALYSES USING LIMIT STATE EQUILIBRIUM METHOD

The limit state equilibrium stability analyses were conducted based on the results of the stereographic analyses using ROCPLANE (RocScience, 2010b) and SWEDGE (RocScience, 2010c) softwares for the planar and wedge modes of failure.The analysis input data for SWEDGE and ROCPLANE are listed in tables 6 and 7. The calculated factors of safety are presented in Table 8.

Table 6. SWEDGW analysis input data

| Swedge input data | Joint set 3 | Joint set 4 | Joint set 5 | Slope | Upper face |
|---|---|---|---|---|---|
| Dip (°) | 70 | 65 | 75 | 83 | 45 |
| Dip direction (°) | 117 | 181 | 217 | 209 | 254 |
| Cohesion (t/m$^2$) | 3-7 | 3-7 | 3-7 | — | — |
| Friction angle (°) | 30-50 | 30-50 | 30-50 | — | — |
| Slope height (m) | — | — | — | 20 | — |
| Unit weight (t/m$^3$) | — | — | — | 2.68 | — |

Table 7. ROCPLANE analysis input data

| Roc Plane input data | | Right Slope | Middle Slope | | Left Slope | |
|---|---|---|---|---|---|---|
| | | J 45/300 | Joint set 4 | Joint set 5 | Joint set 4 | Joint set 5 |
| Slope | Angle (°) | 83 | 83 | 83 | 83 | 83 |
| | Height (m) | 20 | 20 | 20 | 20 | 20 |
| | $G_s$ | 2.68 | 2.68 | 2.68 | 2.68 | 2.68 |
| Failure Plane | Angle (°) | 45 | 65 | 75 | 65 | 75 |
| | Wavines s | 20 | 20 | 20 | 20 | 20 |
| Upper face | Angle (°) | 38 | 45 | 45 | 25 | 25 |
| Strength | Φ (°) | 30-50 | 30-50 | 30-50 | 30-50 | 30-50 |
| | C (t/m$^2$) | 3-7 | 3-7 | 3-7 | 3-7 | 3-7 |

Table 8. Calculated factors of safety for limit state equilibrium stability analyses using ROCPLANE and SWEDGE softwares for the tunnel portal slopes

| Slope | Failure Type | Controlling Joint or Intersectioin | Factor of Safety |
|---|---|---|---|
| Left | Wedge | $I_{35}$ 65/342 | 2.4 |
| | | $I_{34}$ 65/342 | 2.36 |
| | | $I_{45}$ 65/342 | 0.46 |
| | Planar | $J_5$ 75/217 | 7.68 |
| | | $J_4$ 65/181 | 15.12 |
| Middle | Planar | $J_5$ 75/217 | 7.68 |
| | | $J_4$ 65/181 | 15.12 |
| Right | Planar | J 45/300 | 5.8 |

## THREE-DIMENSIONAL DISCONTINUUM NUMERICAL ANALYSES

Stability analyses were conducted using three-dimensional discontinuum numerical method by 3DEC software (Itasca,2010). 3 more critical joint sets were chosen for the numerical analyses out of the 5 joint sets distinguished by the results of the stereographic analyses. The input values of the numerical analyses are taken from the geometrical, mechanical and strength properties of the joint sets presented in Tables 1 and 2.

Displacement vector and magnitudes at cross section of the portal middle, left and right slopes are illustrated in figures 7,8 and 9, and maximum displacement of portal slopes are presented in table 9.

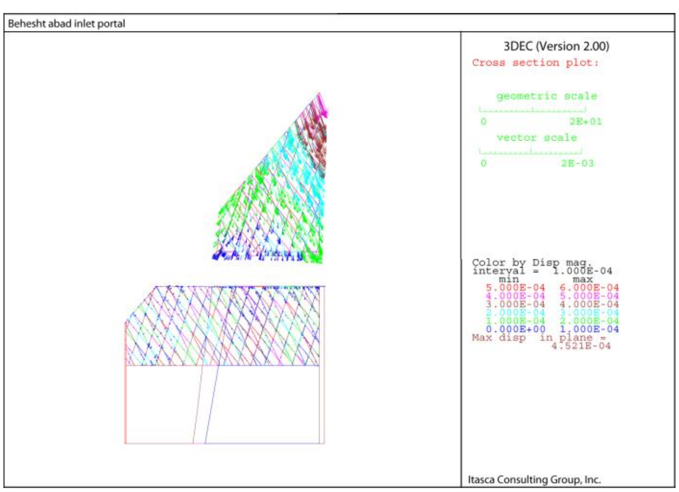


*Fig. 5. Displacement vector and magnitudes at cross section of the portal middle slope*

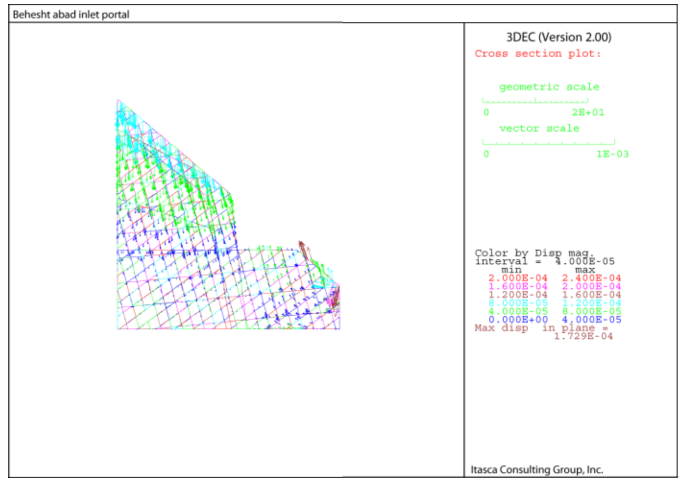


*Fig. 6. Displacement vector and magnitudes at cross section of the portal left slope*

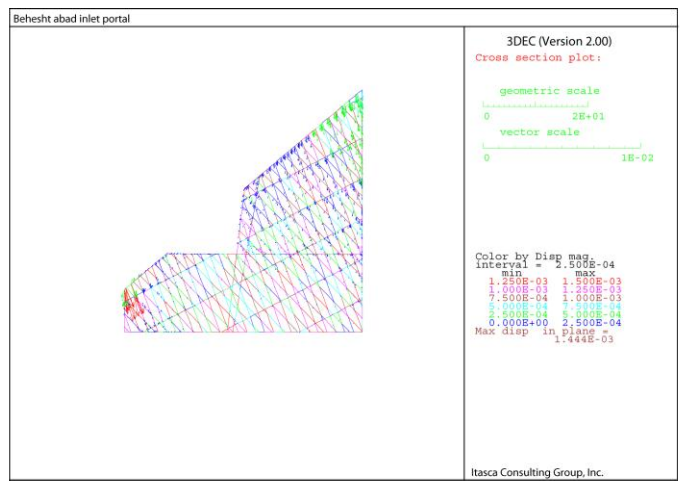


*Fig. 7. Displacement vector and magnitudes at cross section of the portal right slope*

Table 9. Maximum displacement of various portal slopes

| Right | Left | Middle |
|---|---|---|
| 1.44E+00 | 1.73E-01 | 4.52E-01 |

## SUMMARY AND CONCLUSION

Based on the stereographic analyses, the planar and wedge failure are more probable at the middle and right portal slopes and less probable at left slope.

Based on the empirical SMR classification as presented in Table 5, the middle and right portal slopes are classified as II ,i.e., stable. Unsystematic support is recommended to prevent local small failures. The left portal slope is also rated as class IV ,i.e., unstable. To prevent large planar and wedge failures, a systematic support including systematic reinforced shotcrete and heel wall or concrete.

Based on the limit state equilibrium stability analyses using ROCPLANE and SWEDGE softwares, the wedge mode of failure is probable at the intersection of joint sets no. 4 and 5 in left portal slope.

Based on the three-dimensional discontinuum numerical analyses results conducted by 3DEC software, maximum displacement for the middle, left and right portal slopes are found as 0.45, 0.17 and 1.44 mm. Therefore, the rock mass surrounding the tunnel inlet portal seems to be stable according to the numerical analyses.

Comparing the stability analyses results using various methods, the stereographic and 3-dimensional discontinuum numerical analysis are the most and least conservative (two extremes) methods, respectively. The empirical SMR and limit state equilibrium methods present more or less same results rated as in between the two extremes. Relatively, the empirical SMR method is more conservative than the limit state equilibrium method.

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