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Optimum static and dynamic design of displacement chamber of headrace tunnel with bedding parallel shear zones in Siah Bishe Dam, Iran

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Abstract

The Siah Bishe pumped storage project is now under construction. The investigation results, the stability analysis and the support concept for the displacement chamber are discussed in this paper. The geometry of the transversal section and optimum maintenance system have been designed with respect to the unique geological and shear zone conditions encountered in Siah Bishe. The displacement chamber is arranged in sedimentary and volcanic rocks of Triasic and Jurasic ages. Length of the chamber is 50 m and the height is 10 m with relatively north–south trend. The results of geo-engineering surveys and statistical joint-graphics of stereograms reveal at least three discontinuity systems in the rock mass. The transversal section along the chamber was studied to analyze the stability of rock wedges inside the chamber. The frequency and width of bedding parallel shear zones determined the final support concept. Special attention was paid to the design of the transversal section so as to minimize the stress concentration in the critical regions of the wall, bottom of the chamber and corners. The results of analyses show that the chamber is stable in static and dynamic condition with 20 cm thickness of reinforced shotcrete, fully bonded rock bolt with 35 mm diameter, 3.5 m length and steel frame with 82 kg/m I section with 0.85 m spacing.

Keywords: Shear zones; Bedding; Displacement chamber; Investigation; Stability analysis; Support; Modeling

1. Introduction

Iran Water and Power Resources Development Company was entrusted in 1983 with the design of Siah Bishe pumped storage scheme. The waterways of the plant are now under construction (see Fig. 1). It is located in the northern part of the Alborz Mountain, at a distance of 80 km from the Caspian Sea (Moshanir Consultant Engineer, 2002).

The pumped storage plant is situated in layers of the Jurassic Shemshak, Triassic Elika and in the strata of Permian age called Dorud, Ruteh and Nessen formation. The Garmrudbar thrust fault separates the Jurassic Formation from the Triassic one.

The displacement chamber with the approximate dimensions of L: 50 m, W: 7 m, H: 10 m lies in the Shemshak and Elika formation. These formations consist of shaly, slightly sandy siltstone, sandstone and thin-layered limestone and intrusions of igneous rock such as spilitic basalt partially bedding parallel orientated.

The results of geo-engineering surveys and statistical joint-graphics of stereograms reveal at least three discontinuity systems in the rock mass. The transversal section along the chamber was studied to analyze the stability of

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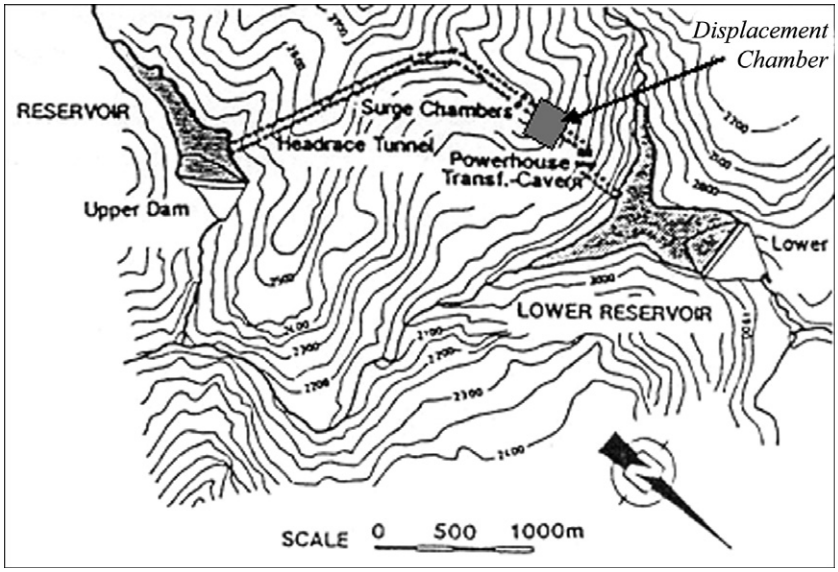

Fig. 1. Layout of Siah Bishe pumped storage project.

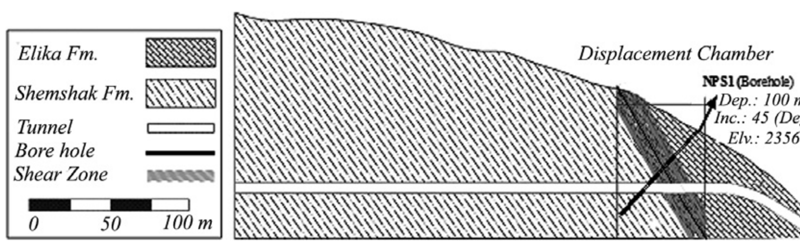

Fig. 2. Geological cross section along displacement chamber and Headrace Tunnel.

rock wedges inside the chamber. The frequency and width of bedding parallel shear zones determined the final support concept.

Using laboratory and in situ tests, rock mass classification and joint set statistical analysis the geomechanical parameters are obtained. The transversal section along the chamber was studied to analyze the stability of rock wedges inside the chamber. The frequency and width of bedding parallel shear zones determined the final support concept. In this paper, with repetitive modeling an optimum maintenance system consisting of reinforced shotcrete and steel frame suitable for dynamic conditions is achieved.

The whole formation is folded and forms the southern flank of an anticline. The folding process caused a shearing of incompetent layers such as thin layers of beds but also between siltstones with different content of fines like clay or fine sand.

2. Investigations

The area of the underground displacement chamber was investigated by the excavation of two test adits in total 320 m long, by underground drilling of 220 m, i.e. three boreholes were drilled in various directions and depths with different inclinations (Moshanir Consultant Engineer, 2002). Dilatometer tests as well as permeability tests have been performed in selected boreholes (Farab and Tablieh Geotechnical Company, 2003).

The displacement chamber with a length of about 50 m runs nearly normal to the strike of the layers of Shemshak and Elika formations (Fig. 2), mainly in thin and medium siltstone, sandstone, shaly layers and spilitic lava of Shemshak over the first 30 m, after that follows the limestone of Elika formation at the end of the displacement chamber. This exposed rock sequence has been geologically mapped (Fig. 3), the discontinuities as joints and bedding planes have been evaluated and according to these results a portal was fixed for a roof chamber considering all other aspects such as length of displacement chamber and overburden above the chamber roof.

3. Geology of the displacement chamber

3.1. Bedding

The roof of the displacement chamber exposed a rock sequence with a mean dip and dip direction of bedding planes of N105/50NE up to station (50 m), where a main thrust fault crossed the displacement chamber. The follow-

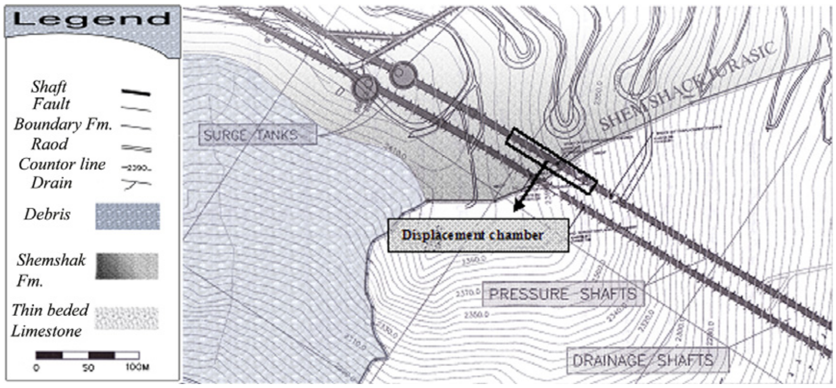

Fig. 3. Geology of displacement chamber.

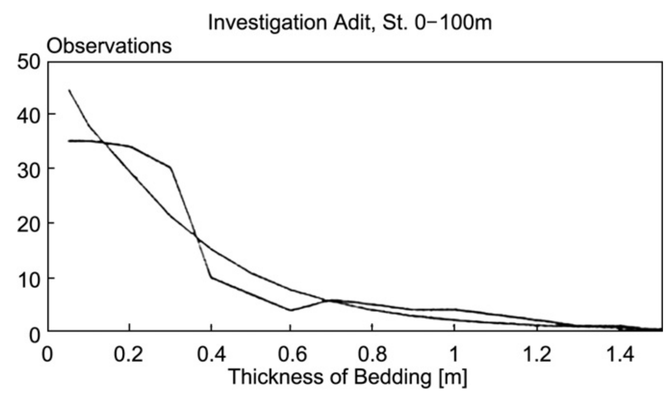

Fig. 4. Thickness of bedding.

ing rock sequence was striking normal to the direction of the displacement chamber.

The rock sequence over the first 20 m consists of 33.5% of sandstone, 23% of siltstones with a varying content of fine sand, 22.4% of irregularly intercalated shale and 34.6% thin and medium limestone.

The sedimentary rocks are well stratified having an average thickness of 22 cm (see Fig. 4). The bedding planes form the prevailing discontinuities. Their properties are as follows:

Degree of separation: 100% related to the width of the structure.

Waviness: undulating to slightly irregular wavy.

Roughness: rough, slightly smooth in shaly parts only, no weathering or alteration on bedding planes was observed.

4. Shear planes

Bedding parallel shearing of strata is a common phenomenon over the whole sedimentary rock sequence (Hoek, 1999). The alternating beds of different rock mechanical properties led to shearing, e.g. thin layers of shale between sandstones. Sheared layers of less than 1 cm thickness contain often soft, slightly plastic silty clay. The layers with a thickness of more than 1 cm contain soft material in the area of the shear planes, but sheared rock fragments up to gravel size in the central part of the shear zone.

The spacing and thickness of the individual zones were measured in detail and evaluated for the determination of initial and permanent support measure. The average thickness revealed is $T = 1.8 \pm 1.1$ cm, the average spacing yields $D = 84 \pm 90$ cm (median value 40 cm, see Figs. 5 and 6).

The extension of these zones is unknown and may differ strongly. A conservative assumption is that the extension should not be taken less than 35% of the displacement chamber width.

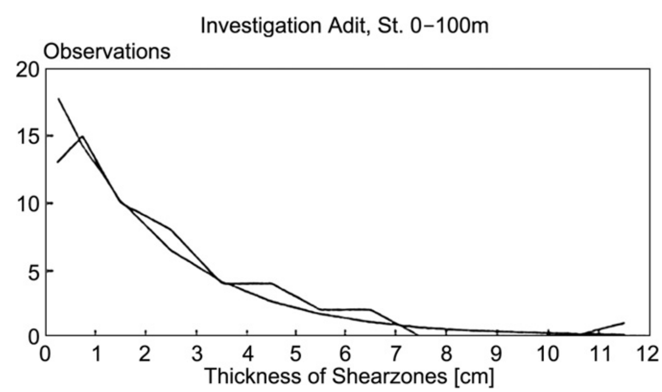

Fig. 5. Thickness of shear zones.

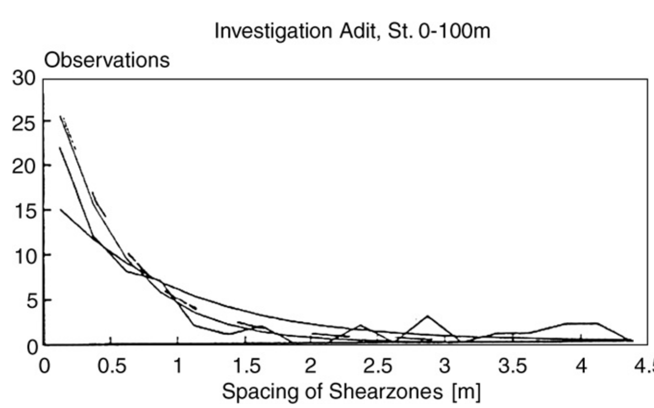

Fig. 6. Spacing of shear zones.

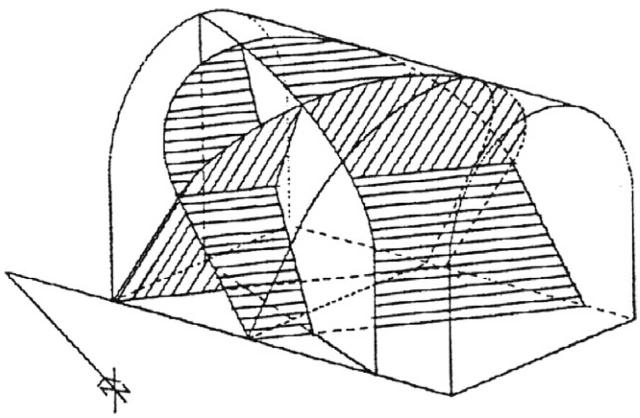

Fig. 7. Block diagram of displacement chamber and discontinuities.

5. Joint pattern

The exposed strata along the displacement chamber walls and roof are moderately jointed, i.e. a spacing of 0.3–1.0 m according to the classification of Deer (1989). The observed joint pattern is confined to the individual beds of sedimentary rocks and the igneous intercalations.

According to the stereographic projection of measured joints, two major joint sets could be established: Longitudinal joints running parallel to the strike of the beds and transversal joints.

The longitudinal joints have a mean orientation of N98E/58E. This joint set shows however a wide range of scatters of ±40 in regard to the strike. The joint sets J2 should be considered as diagonally orientated joints to the longitudinal joint set J1.

The distribution of these joints is irregular over the length of the chamber. From station 8 to 35 m the spacing is in the range of 1.5–4.6 m and from 35 to 50 m it is 9.2 m. This different arrangement cannot be attributed to a prevailing arrangement of strata.

The transversal joints are less distinctly developed in comparison to the longitudinal joints. Their mean orientation is N172E/90. The spatial distribution from 10 to 26 m is 2.1 m, from 26 to 50 m, 12 m.

According to the exposure of all discontinuities of the rock mass, their spatial distribution (Fig. 7), their degree of separation and their rock mechanical properties, a direction of the chamber axis of N357 was determined which is most suitable regarding the major in situ stress direction and the direction of the general slope (see Fig. 8).

Fig. 4 shows the number of observations against the thickness of bedding in m. Broken line obtained from actual data and curve is a nonlinear regression. The relation is as follows:

$$y = e^{-3.33x} \tag{1}$$

where y is the number of observations and x is the thickness of bedding in m.

Fig. 5 shows the number of observations against the thickness of shear zone in cm. Broken line obtained from actual data and curve is a nonlinear regression. The relation is as follows:

$$y = e^{-0.45x} \tag{2}$$

where y is the number of observations and x is the thickness of shear zone in cm.

Fig. 6 shows the number of observations against shear zone spacing in m. Broken line obtained from actual data and curve is a nonlinear regression. The relations are as follows:

$$y = e^{-(x/\text{Median})} \tag{3}$$

$$y = e^{-(x/\text{Average})} \tag{4}$$

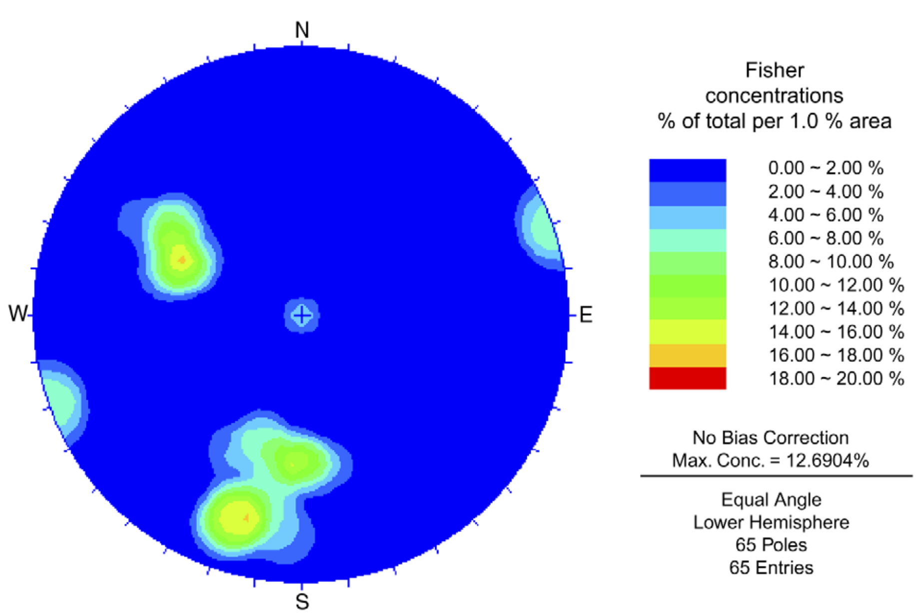

Fig. 8. Joint representations.

where y is the number of observations and x is the shear zone spacing in m.

6. Rock mechanical parameters

The different rock types to be expected during excavation of the chamber have been tested in the laboratory using NX-size cores from the various drillings and also in situ by the performance of dilatometer tests and large flat jack tests.

The average results are listed in Table 1.

The shear strength parameters for the discontinuities were established as are given in Table 2. The existence of shear planes of considerable extent strongly influences the anisotropy of the rock mass deformability characteristics (Goodman, 1976, 1989). Assuming an average width of 2–0.5 cm and an average spacing of 0.40–0.50 m the contribution to the rock mass volume is 4–5%. Consequently, the deformation modulus perpendicular to bedding is roughly 50% of the value parallel to bedding.

The lateral load factor without the consideration of tectonic stresses will be at least 100% higher perpendicular to bedding than parallel to bedding.

7. Stability analysis

To investigate the sensitivity of displacement chamber stability and support to the scatter of geotechnical conditions the following variations were made in finite element analyses:

Lateral safety factor is between 0.67 and 0.73, most probable is a factor of 1.0.

Different bedding parallel shear plane strength according to the thickness smaller or larger than 1 cm.

The displacement chamber is located on a shear zone. The upper layer of the shear zone is Elika formation and the lower layer is Shemshak formation. Critical section of the displacement chamber occurs when all of the overburden is located on the shear zone. Therefore this section has been simulated by well-known finite element software that is named Phase^2. The height of the overburden in the section is 82 m. There are three joints and one fault, in this section.

Dip and dip direction of the fault, joints, bedding and displacement chamber are as follows:

Fault: N110/55NE

Table 2
Discontinuity shear strength parameters

	Siltstone		All other rock types	
	Friction angle (deg.)	Cohesion (MPa)	Friction angle (deg.)	Cohesion (MPa)
Bedding planes and shear planes	25[a] 20[b]	0[a] 0.05[b]	25[a] 20[b]	0[a] 0.05[b]
Longit. joints	27.5	0.05	30	0.10
Transv. joints	27.5	0.05	30	0.10

[a] Thickness > 1 cm.
[b] Thickness < 1 cm.

Joints: J_1: N98E/58E, J_2: N172E/90
Bedding: N105/50NE
Displacement chamber: N357/0

Appearance dip in the section plane is calculated as follows:

$$\mathrm{tg}\upsilon' = \cos\gamma \cdot \mathrm{tg}\,\upsilon \tag{5}$$

where υ' is the appearance dip, γ is the horizontal angle between the actual plane – a plane that is normal to the strike of the layer – and section plane and υ is the actual dip.

Therefore, appearance dip and dip direction are as follows:

Fault: $\gamma = 113°$, $\upsilon = 55°$, $\upsilon' = 29°$
Joints: J_1: $\gamma = 101°$, $\upsilon = 58°$, $\upsilon' = 24°$
J_2: $\gamma = 172°$, $\upsilon = 90°$, $\upsilon' = 90°$
Bedding: $\gamma = 65°$, $\upsilon = 50°$, $\upsilon' = 24°$

Geological strength index (GSI) in the shear zone and Shemshak formation is 15, 38, respectively. Shear modulus and normal and shear stiffness are as follows (Goodman, 1976):

$$G = \frac{E}{2(1+\upsilon)} \tag{6}$$

$$K_N = \frac{E_m \cdot E_r}{s(E_r - E_m)} \tag{7}$$

$$K_S = \frac{G_m \cdot G_r}{s(G_r - G_m)} \tag{8}$$

where K_N, K_S are normal and shear stiffness in MPa/m; E_m, G_m are Young's modulus and shear modulus in rock mass in MPa; E_r, G_r are Young's modulus and shear modulus of intact rock in MPa; S is joint spacing in m and υ is Poisson's ratio. C is cohesion in MPa, ϕ is internal friction angle. The elastic moduli of the rock mass for the shear zone

Table 1
Test results

Type of rocks	UCS (MPa)		TS (MPa)		Ed (GPa)	
	Average	Range of value	Average	Range of value	Average	Range of value
Red shale	50	43.2–67.1	7.5	5.2–9.7	7.5	6.4–8.7
Sandy siltstone	60	51.3–74.8	7.5	6.7–11.2	8.0	7.1–9.5
Quartzite and sandstone	100	95.6–113.9	15	14.5–21.3	15.0	13.2–17.4
Igneous rocks	100	93.2–108.4	15	13.6–19.8	15.0	13.8–18.3

Where UCS is uniaxial compressive strength, TS is tensile strength, Ed is modulus of elasticity.

Table 3
Geomechanical properties of rock mass

Parameters	E_r	E_m	G_r	G_m	K_n	K_s	S	C	ϕ
Shear zone	2300	942.94	884.6	362.7	639.25	245.87	2.5	0.168	33.08°
Shemshak formation	8000	3882.2	3200	1552.9	1639.6	655.84	4.6	0.425	45.73°

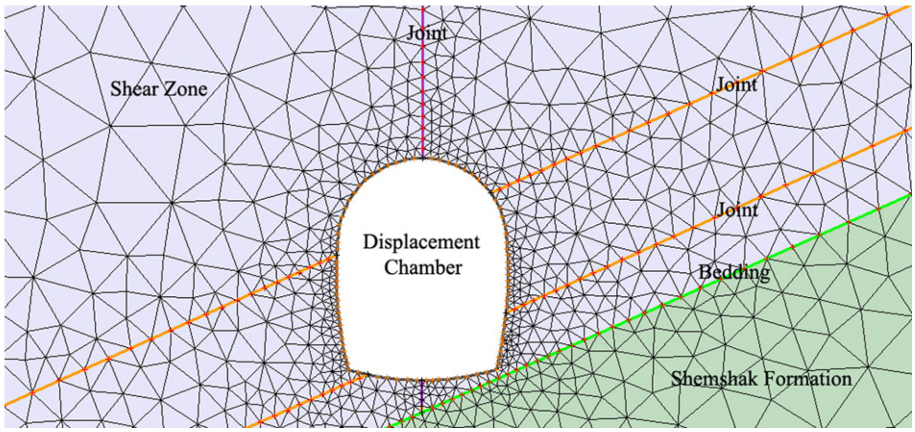

Fig. 9. Mesh modeling of displacement chamber without support.

and Shemshak formation are obtained from the in situ measurements, Table 3.

Dilation angle for rock mass is calculated by Sh. Arshadnejad formula (Arshadnejad et al., 2006):

$$\begin{cases} \delta = -0.28\phi\left[\frac{\text{GSI}}{100}\right]^2 + 0.85\phi\left[\frac{\text{GSI}}{100}\right] - 0.23\phi \\ 30\langle \text{GSI} \langle 75 \\ \delta = 0^\circ, \quad \text{GSI} \leqslant 30 \end{cases} \tag{9}$$

where GSI is Geological strength index and ϕ is internal friction angle in rock mass and δ is dilation angle of rock mass. Then δ for shear zone is 0° and for Shemshak formation is 2.57°.

Using finite element method (Phase^2), the stability of chamber was investigated. Elements types are three-noded triangle and there are 3103 elements and 1837 nodes. Failure criterion is Mohr–Coulomb for rock mass. Mohr–Coulomb slip criteria are considered for joints and beddings, because the rock mass is crushed and it likes to compacted soil material.

Fig. 9 shows the displacement chamber without support in mesh modeling.

The results (Figs. 10 and 11) show that the chamber is stable in static condition. Table 4 shows the support systems including shotcrete thickness, rock bolt dimension and steel frame.

Maximum support pressure (bearing capacity) for the steel frame determined by Hoek formula (Hoek, 1999):

$$P_{i\max} = 17.6\frac{D^{-1.29}}{S} \tag{10}$$

where $P_{i\max}$ is maximum support pressure in MPa, D is excavation diameter in m and S is frame spacing in m. Width of the chamber is 7 m and height of the chambers

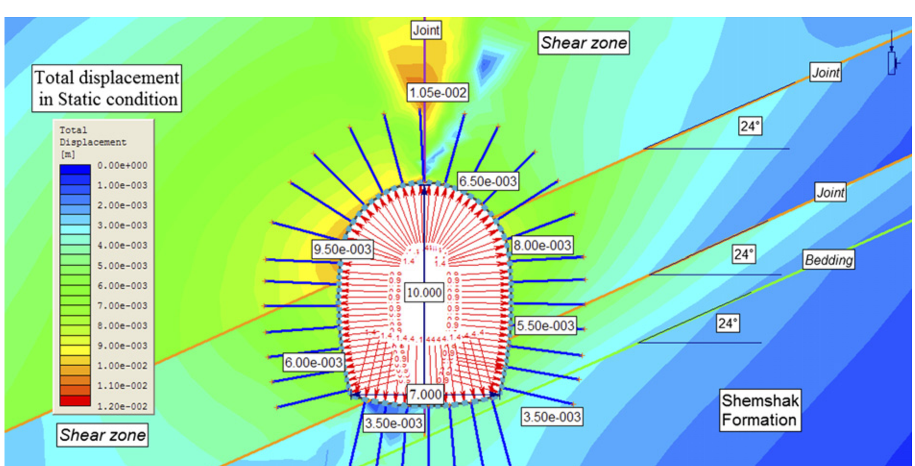

Fig. 10. Displacement (m) around chamber under static condition.

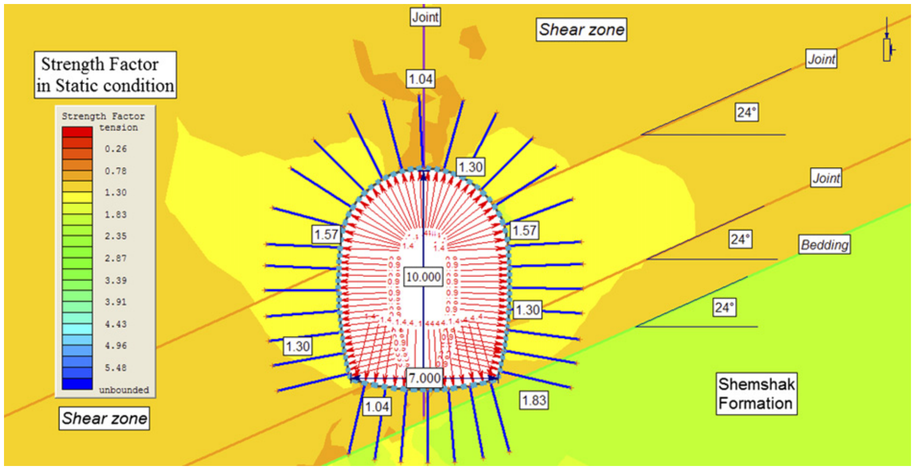

Fig. 11. Safety factor around chamber in static condition.

Table 4
Support system of the chamber in static condition

Reinforced shotcrete (thickness)	Rock bolt (fully bonded)	Steel frame
Roof and walls: 20 cm Floor: 20 cm	Spacing: 1 × 1 m Length: 3.5 m Diameter: 35 mm fy: 343 MPa	Profile: 82 kg/m I section fy: 343 MPa

fy: Yield stress.

Table 5
Support pressure in static condition

$P_{i\max}$ (MPa)		
Roof and floor	Walls	*S* (m)
1.43	0.903	1.0

is 10 m. If spacing of the steel frame be 1 m, support pressure will be obtained as given in Table 5. Table 5 shows the values of support pressure in static condition for numerical modeling.

Table 6
Support pressure in dynamic condition

$P_{i\max}$ (MPa)			
Roof and floor	Walls	S (m)	*a*
1.682	1.062	0.85	0.35 g

In dynamic condition related acceleration is 0.35 g. Then for suitable condition, the steel frame spacing must be decreased from one meter to 0.85 m. Table 6 shows the $P_{i\max}$ in dynamic condition for numerical modeling. The results given in Tables 5 and 6 are obtained using Eq. (10).

It should be noted that the rock mass is crushed and the minimum thickness of 20 cm for the shotcrete is necessary. For this thickness, the excavation will give rise to stable dynamic condition. Rock bolting with grouting helps the continuity of rock mass. Steel frame serves as a passive support with high bearing capacity and long life. According to the results of simulations the chamber in both static and dynamic conditions is stable. This is evident from Figs. 10–13 as there is no yield element around the chamber in rock

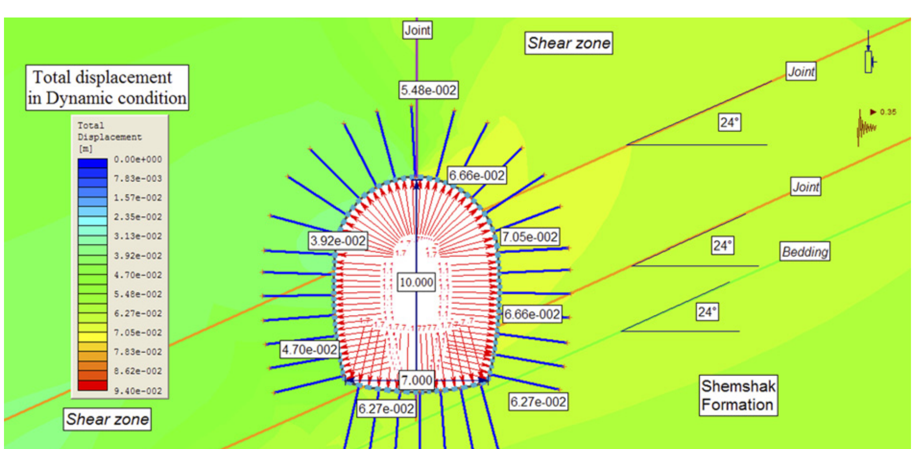

Fig. 12. Displacement (m) around chamber under dynamic condition.

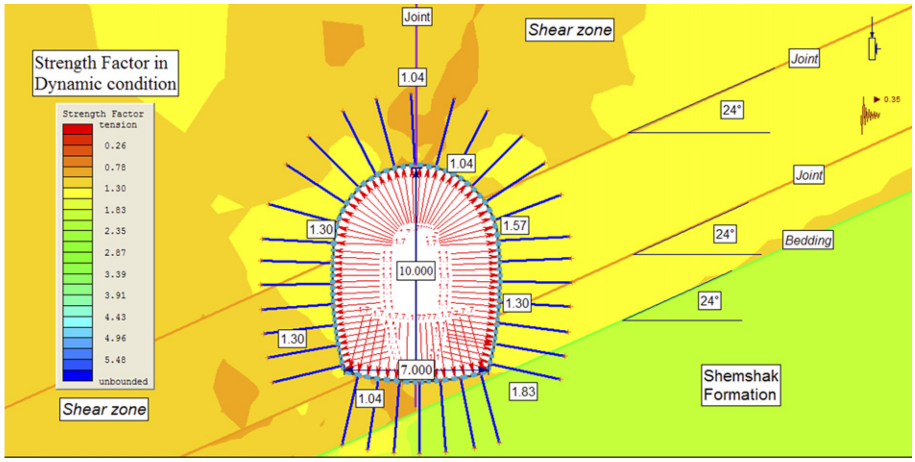

Fig. 13. Safety factor around chamber under dynamic condition.

mass. This implies that the combination of the supports consisting of shotcrete, rock blot, and steel frame is optimum.

8. Conclusions

Details of the investigation, rock mass parameters determination, stability analysis and support systems design for the Siah Bishe displacement chamber are discussed in this paper.

The chamber is situated in sedimentary and volcanic rocks. The folding and thrust faulting of the rock sequence caused shearing of weak sedimentary layers. These observed shear planes defined the amount of systematic chamber support consisting of shotcrete, fully bonded rock bolts and steel frame. Simulations by computer show that the chamber is stable in static and dynamic conditions with 20 cm thickness of reinforced shotcrete, fully bonded rock bolt with 35 mm diameter, 3.5 m length and steel frame with 82 kg/m I section with 0.85 m spacing.

The chamber axis is oriented in such a way to minimize the unfavorable effects of bedding parallel shear planes, longitudinal joints, major in situ stress and nearby valley slope.

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