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Stability analysis and determination of rock pillar between two adjacent caverns in different regions of Asmari formation in Iran

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ABSTRACT

Large underground caverns are commonly used in variety of applications. In many cases, because of the geomechanical limitations of dimensions and requirement of high volume, several parallel caverns are used. Plastic zone integration requires a larger rock pillar distance of theses adjacent caverns while economic and access reasons require smaller distance. In Iran many underground projects are located in West and South West. Asmari formation covers a large part of these regions. The stability of underground spaces that are constructed or will be constructed in this formation has been investigated. A proper cross section based on plastic analysis and a stability criterion has been proposed for each region. Finally, in each case, allowable rock pillar between adjacent caverns with similar dimension was determined with two methods (numerical analysis and fire service law). Results show that *Fire Service Law* uses a very conservative safety factor and it was proposed to use a correction factor for allowable distance based on application of underground space.

1. Introduction

Underground spaces are common civil engineering projects that are built with different applications. One of these applications is hydrocarbons storage in caverns. Stability of these spaces, whether in short-term or long-term, is one of the most important parts of these projects, which needs technical and economical investigations. Many studies have been carried out concerning the stability analysis methods and stabilization of these underground spaces [1–5]. Dynamic stability analyses have been carried out using UDEC in jointed rock mass [6–8]. Cai et al. studied the acoustic emission on Canagava power plant cavern in Japan using a numerical method along with combination of FLAC and PFC [9]. Many researches focused on the use of heuristic methods for estimation and prediction of underground spaces [5,10–14]. Hong-gang used genetic algorithm, artificial intelligence, neural network and parallel computation and represented a synthetic, monolithic, intelligent and finite element method to optimize a set of large excavations [10]. Li et al. proposed a stability estimate criterion for multi-underground caverns according to modified equation of Fener and Fener [15]. Nengpan et al. investigated the stability of random blocks created from intersection of random joints or cracks in power plant cavern [16]. Stille and Palmstrom studied the effective parameters on behavior of environment surrounding the underground excavations [17]. Torres and Fairhurst studied the relation between Hoek–Brown criterion parameters and behavior of underground excavations, and presented an equation for elasto-plastic behavior as for Hoek–Brown criterion [18]. In this paper, stability of underground caverns that are constructed or will be constructed for Hydrocarbons storage in Iran is studied. Considering that many hydrocarbon projects are located in West and South West of Iran, geomechanical properties of three regions of these zones were considered. These regions are located in Busher, Ilam and Khuzestan province and in Asmari formation. Using two-dimensional numerical program, Phase2, FEM analyses are carried out. Also, the stability of caverns was investigated using an empirical criterion and plastic zone depth around caverns.

2. Geology of site

Asmari formation holds a great portion of underground engineering structures in the South West of Iran. Asmari formation is the youngest formation in these regions. This formation has 314 m thick and consists of lime stones and jointed shales with the inner black layers [19].

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3. Research methodology

In this study, a series of numerical analyses were performed to estimate rock load height for the design of a single cavern lining. Two-dimensional FEM program, Phase 2 has been used to model and analyze caverns [20]. The following simplifications and assumptions have been made:

- The surrounding rock mass is homogeneous and continuous, and the joint effect is considered using the equivalent deformation module, E using proposed model by Sitharam et al. [21].
- The initial in situ stress is uniformly distributed within the computational domain and the two principal stresses (minor and major principal stresses) act in horizontal and vertical directions, out-of-plane stress is intermediate principal stress.

The mechanical properties of rocks into which caverns have been excavated are presented in Table 1. m_b and s in Table 1 are dimensionless parameters of Hoek–Brown criterion. The desired parameters, when not present, were obtained using RocLab program. Caverns are excavated in 250 m depth. The vertical stresses are gravitational and the stress ratio (K) is considered equal to 1.5 [22–24]. It is assumed that the rock mass obeys Hoek–Brown criterion.

4. Cross section determination

Taking into account modified equation of Fener and Fener, Li et al. proposed a stability estimate criterion for multi-underground caverns using numerical or in situ control [15]. Nonetheless, a practical method for quick prediction of displacement and stability estimation of high walls of underground spaces has not been yet established. However, recently some attempts have been made towards prediction of cavern side wall displacements [25,26]. At present, there is no criterion for estimation of rock mass stability around the large underground constructions.

Currently stability analysis and design for multi-underground spaces are based on dimensions of plastic zones in the surrounding rocks or values of displacement in the cavern walls, and then qualitative evaluation is given according to previous experiences.

Actually, plastic zone creation in numerical analysis cannot directly lead to understanding that the surrounding rocks are instable or failing. These analyses only show that the over-stress, relaxation or damaged zones have been created in the surrounding rock. Therefore, since elasto-plastic analysis is widely adopted by the researchers and engineers, how to use the computation results and give a certain evaluation method or criterion has become significantly important and a key issue to be solved. Depth of plastic zones around the cavern roof and ratio of elasto-plastic to elastic displacements has been used to evaluate stability (see Eq. (1)). In this method, the ratio of maximum elasto-plastic to elastic displacements in the cavern wall has been considered as the stability criterion. The method is based on the study investigated by Zhu [25]. The stability state of surrounding rock decreases quickly if the elasto-plastic to elastic displacements ratio become more than critical value [25].

$$\theta = \frac{U_{ep}}{U_e} \tag{1}$$

where U_{ep} and U_e are the elasto-plastic and elastic displacements of the key point, respectively.

Zhu et al. carried out several analyses and compared computation results at 6 different overburden depths. Using curve fitting they proposed Eq. (2) for the critical displacement ratio, θ_c (for $K \geqslant 1$):

$$\theta_c = 0.001403H - 0.01138E + 1.214375 \tag{2}$$

where H is the overburden depth, m; E the rock mass modulus, GPa. The correlation coefficient of Eq. (2) is 0.96 [25].

Elastic and elasto-plastic analyses have been carried out for all caverns cross sections at each region, using numerical method. Displacement parameters of all considered caverns and the ratio of these two displacements were computed. According to the importance of structures, the safety factor (FS) was determined to be 1.25 for powerhouses based on ESR (ESR = 0.8 and FS = 1/ESR, where ESR is excavation support ratio). Stability of the proposed spaces was evaluated based on Eq. (2).

As it can be seen in Table 2, according to the ratio of elasto-plastic to elastic displacements for different caverns' dimensions, some sections are stable ($\theta_{FS} < \theta_c$ where θ_{FS} = FS × θ). Plastic zone in roof was computed for all caverns by numerical method. Using computed plastic zone and results of Eq. (2), the most suitable cross section was selected. As a result, the sections of 33 m × 52 m, 60 m × 60 m and 18 m × 30 m were selected for Ilam, Khuzestan and Busher regions, respectively.

5. Allowable rock pillar between adjacent caverns

Many underground storage facilities use several parallel caverns with similar sizes to ensure enough storage capacity for high

Table 1
Geomechanical characteristics of rock mass in regions of cavern excavation.

Region (reference)	υ	ED (GPa)	UCS (MPa)	m_b	s	γ (MN/m^3)
Ilam [12]	0.25	12.00	48.3	2.700	0.0067	0.025
Khuzestan [13]	0.30	8.00	60.0	2.980	0.0120	0.025
Busher [12]	0.30	21.47	51.6	1.438	0.0117	0.027

Table 2
Results obtained for displacement by Phase2 software at different regions and dimensions.

Item	Ilam				Khuzestan				Bushehr			
Cavern dimension	18 × 30	22 × 43	33 × 52	60 × 60	18 × 30	22 × 43	33 × 52	60 × 60	18 × 30	22 × 43	33 × 52	60 × 60
Uep (mm)	20.350	29.140	36.280	46.440	29.150	41.840	51.720	60.820	11.280	16.220	19.060	25.300
U_e (mm)	19.540	28.150	34.640	39.060	28.800	41.320	51.150	59.410	10.730	15.390	20.070	22.130
θ	1.041	1.035	1.047	1.190	1.012	1.012	1.011	1.024	1.051	1.054	1.053	1.143
θ_{FS}	1.300	1.290	1.310	1.490	1.260	1.260	1.260	1.280	1.310	1.320	1.320	1.430
θc	1.430	1.430	1.430	1.430	1.450	1.450	1.450	1.450	1.320	1.320	1.320	1.320
Plastic radius (m)	1.200	1.700	2.600	4.200	1.000	1.300	1.900	2.300	1.800	2.900	3.750	5.700