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Effect of coupled triaxial stress-perforation on fracture mechanism and acoustic wave velocity of limestone

Peyman Norouzi[a,*], Alireza Baghbanan[a], Hamid Hashemolhosseini[b]

[a] *Department of Mining Engineering, Isfahan University of Technology, P.O. Box 84156 - 83111, Isfahan, Iran*
[b] *Department of Civil Engineering, Isfahan University of Technology, P.O. Box 84156 - 83111, Isfahan, Iran*

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ABSTRACT

Perforation with shaped charges establishes the hydraulic communication between cased wellbore and reservoir. Higher DoP[1] is one of the most important goals of perforation. Performance of a perforation is greatly influenced by confining pressure, which was mostly anisotropic, around the target. Therefore, it is necessary to consider the triaxial confining pressure on the target to achieve the actual results. In this study, a new triaxial perforation machine designed and constructed to investigate the effect of anisotropic in-situ stress on the DoP and failure pattern of limestone targets. The number of tests was optimized by Taguchi's method and ANOVA[2] was used to determine the cross effect of the different combination of applied in-situ stresses on DoP. The ultrasonic *P*-wave velocity was measured before and after perforation under different conditions of anisotropic loading. The results show that the Measured DoP is more controlled by the off plane stresses (stresses normal to shooting axis) than the stress in the direction of penetration. The created fractures by perforation are more oriented along the maximum horizontal stress, which is less propagated around a hole with increasing the maximum to the minimum off plane stress ratio. The measured p-wave velocity showed that V_P increases along the perforation hole from the beginning of the hole toward the block boundaries. It was found the loading conditions control the V_P values along the shooting axis. In anisotropic loading mode, the velocity of *P*-waves in direction of the maximum stress was greater than minimum horizontal stress. In the isotropic loading condition, V_P values were same along the direction perpendicular to the firing axis.

1. Introduction

Perforation as a most important well completion operation extensively used to create the flow path between reservoir formation and cased wellbore (Casero et al., 2017; Papamichos et al., 1993; Renpu, 2011). Generally, the principal objectives of perforation are to achieve a high DoP[1], more effective flow path, and puncture the reservoir rock without unwanted damage (Harris, 1966; Van Gijtenbeek and Pongratz, 2004; Sarmadivaleh et al., 2010; Deisman et al., 2013; Allison et al., 2015). The factors associated with DoP of shaped charges and perforation performances have been examined experimentally and theoretically. According to the literature, target's intrinsic properties and operational parameters control the DoP.

Target's properties—such as rock strength, in-situ stress, bulk density, formation porosity, lithology, bulk modulus, acoustic wave velocity, grain size and distribution, pore pressure, rock saturation and type of fluid—affect DoP (Thompson, 1962; Venghiattis, 1963; Klotz et al., 1974; Hong, 1975; Saucier and Lands, 1978; Locke, 1981; Aseltine, 1985; Behrmann and Halleck, 1988a; Halleck et al., 1988; Halleck and Behrmann, 1990; Halleck et al., 1991; Behrmann et al., 1992; Ott and Bell, 1994; Bird and Blok, 1996; Smith et al., 1997; Brooks et al., 1998; Karacan and Halleck, 2003; Halleck et al., 2004; Gladkikh et al., 2009; Nabipour et al., 2010; Sarmadivaleh et al., 2010; Elshenawy and Li, 2013). Operational properties—such as charge and gun position, casing thickness, the quality of the cement sheath around casing, wellbore pressure, and jet quality,—also control DoP (King et al., 1986; Behrmann and Halleck, 1988b; Halleck, 1994).

Most researchers conducted tests on core samples to estimate DoP and perforator performance. However, they have not considered the effect of confining stresses (Thompson, 1962; Weeks, 1974; Behrmann and Halleck, 1988a). For instance, Thompson (1962) performed a series of experiments with the unstressed rocks of variable strength and found a semi-logarithmic inverse regression between DoP and rock strength. Further studies revealed that DoP decreases as confining stresses increases (Halleck and Behrmann, 1990; Grove et al., 2008). Saucier and Lands (1978) studied the effect of confining stresses on DoP of the

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* Corresponding author.
E-mail address: p.norouzi@mi.iut.ac.ir (P. Norouzi).

[1] Depth of Penetration (DoP).

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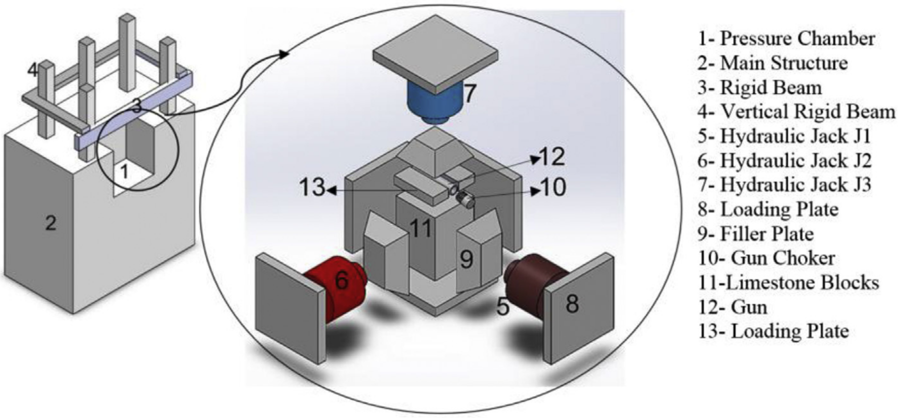

Fig. 1. Schematic view of true triaxial comperssive perforation machine.

limestone and sandstone core samples. They found that DoP in all rocks decreased with different trends with increasing an overburden stress. Ott and Bell (1994) linked surface and downhole DoP.

Pucknell and Behrmann (1991) investigated the failure mechanism of perforation holes in stressed sandstone cores. They reported the perforation hole was formed by pushing the surrounding rock outwards. The in situ stresses try to collapse the perforation hole that could cause the fracturing. They showed the different type of fractures, including circular, radial and curved fractures were created around the perforated hole under conventional triaxial loading. In reality, in-situ stress fields in reservoirs are not uniform. In situ stresses play an important role in failure pattern and fracture orientation around the wellbores (Karatela et al., 2016). The ratio of effective stresses can change the plastic zone around expansion cavities (Xu et al., 2015). The in-situ stress distributions control hydraulic fracture orientation and height, reduction of sanding risk using oriented perforation, failure of perforation and fracture initiation (; Warpinski, 1983; Yew et al., 1993; Papanastasiou and Zervos, 1998; Romero et al., 2000). Therefore, the created fractures by perforation under different confinement stress regimes may also violate the elastic wave velocities. The real effect of anisotropic in-situ stresses on DoP, fracture propagation and failure pattern of targets cannot investigate using perforation under the conventional triaxial loading condition. Halleck et al. (1988) studied and reported the effect of stress patterns on DoP. They used a simple pulse transmission to establish a correlation between increasing acoustic velocity and decreasing DoP. However, they did not consider the effect of different stress ratios and geometrical parameters of charge on DoP and failure pattern of targets. Elastic waves is a good remote sensing tool for determining the fracture density because they were frequently measured in well logging procedure and easily measured in the laboratory in pressurized rock samples (Halleck et al., 1988; Blake et al., 2013). A number of studies have attempted to examine the effect of confining pressure on the P- and S-wave velocity of rocks (Huang and Song, 1991; Mashinskii, 2005; Přikryl et al., 2005; Reuschlé et al., 2006; Nasseri et al., 2009; Nara et al., 2011). On the other hand, the rock fracture density can be determined using elastic waves (Leucci and De Giorgi, 2006; Sayers and Kachanov, 1995; Sjøgren et al., 1979; Blake et al., 2013).

Fractures in a rock mass influence the travel times of waves that have propagated through them. The existence of fractures makes the material properties of rock mass anisotropic. The P-wave velocity control by fractures parameters such as size, density, aperture, type of infilling material and the fractional area of the fracture walls in contact (Boadu and Long, 1996; Leucci and De Giorgi, 2006).

The first objective of this research is to investigate the effect of coupled anisotropic stress-perforation on DoP and the failure pattern of limestone targets. The second one is to study the effect of perforation fractures on the P-wave velocity around the perforation hole. The third one is to provide an effective perforation strategy on the anisotropic field stresses.

In this case, a true triaxial compressive perforation apparatus was designed and made to perforate blocky scale Asmari limestone that is a reservoir rock in the south oil field of Iran. A set of laboratory tests were conducted based on Taguchi's Orthogonal Scheme. Taguchi's test design can extremely reduce the number of tests, using the orthogonal concept (Taguchi, 1990; Jeyapaul et al., 2005; Ross, 1996; Sadeghi et al., 2012; Turgut et al., 2012; Wang and Huang, 2007; Yizong et al., 2017). The blocky scale limestones were perforated under conventional and true triaxial loading conditions with the same shaped charges. The effect of stresses along and perpendicular to shooting axis on the DoP, failure patterns, and elastic wave velocity were investigated. Finally, a perforation strategy was proposed based on DoP and P-wave velocity results for perforating operation in an anisotropic field stress.

2. Materials and methods

In this study, first a blocky scale true triaxial compressive apparatus was designed and constructed. Then the perforation tests were conducted on stressed blocky limestones. Finally, the failure patterns of targets and the variation of P-wave velocities were studied under different loading conditions.

2.1. True triaxial compressive test machine

A novel polyaxial compressive perforation apparatus was designed and constructed to perform perforation tests on large-scale samples under different loading conditions (see Fig. 1). The main structure of the pressure chamber was built with reinforced concrete. Three different hydraulic jacks with a nominal capacity of $3.55e+5$ kg were used to apply horizontal stresses up to 29.6 MPa (perpendicular to perforation axis) and vertical stress up to 22 MPa (parallel to perforation axis). All compressive jacks were calibrated with 95% accuracy. These jacks were placed in an orthogonal arrangement along the coordinate axes x, y and z to apply the desired forces on the cubic samples (see Fig. 2). In this device, jack numbers 1 and 2 (J_1 and J_2) provide horizontal forces along axes x, y and jack number 3 (J_3) was used to apply the vertical force along axis z. J_1 and J_2 were fixed inside the chamber while J_3 could able to move in and out of the chamber as necessary. The lower parts of horizontal jacks were fixed to the walls of the pressure chamber by two thick loading plates (as shown in Fig. 2). Another loading plate was used to fix the lower part of vertical jack to a moving horizontal rigid bar.

In each test setup, a cubic sample was placed at the intersection point of three jacks at one corner of the pressure chamber and then it was subjected to the desired true triaxial forces. Three manual hydraulic pumps equipped with separate manometers provided the