RGNZ/MGPB

Rudarsko-geološko-naftni zbornik
(The Mining-Geology-Petroleum Engineering Bulletin)
UDC: 624.1:552.5:620.3
DOI: 10.17794/rgn.2025.2.9

Original scientific paper

Development of Cyclic Injection Schemes in Hydraulic Fracturing

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Abstract

Due to the increasing use of hydraulic fracturing in the exploitation of geothermal energy and the increase in the extraction of hydrocarbon resources, the depth and scale of this operation has expanded, which has led to the creation of special requirements and challenges. One of the most important challenges is the creation of earthquakes caused by the triggering of faults in the region. In order to solve this problem, various studies are being done. In the current study, based on the aforementioned points, three proposed methods of cyclic injection under the triaxial stress regime have been investigated and assessed to simulate the operation as accurately as possible. Stepwise injection (SI), stepwise cyclic injection (SCI) and stepwise progressive cyclic injection (SPCI) are three proposed methods that the results of the breakdown pressure, as well as the different parameters of acoustic emission events have been studied. The experiments were carried out by a laboratory true triaxial loading device. The results confirm the reduction of the breakdown pressure level in all three proposed methods. Stepwise injection has the highest reduction in fracture pressure compared to the test time. The results of the stepwise cyclic injection method show a decrease in the amount of energy released during the failure, so it can be considered in reducing the risk of earthquakes. Due to the combined effect of reducing the breakdown pressure level and creating a wider fracture network, the stepwise progressive cyclic injection method possibly has a better efficiency in the application of geothermal resource exploitation.

Keywords:

acoustic emission; cyclic hydraulic fracturing; fracture; injection scheme; true triaxial test

1. Introduction

In recent years, the use of hydraulic fracturing method has been greatly developed in various rock engineering applications. One of the special applications is the development of geothermal energy exploitation at a high depth (**Tomac and Sauter, 2018**). Geothermal energy is a renewable, clean energy source with a very high production capacity. It is expected that due to the many usable geological structures, the wide distribution of these structures and the high efficiency and exploitation coefficient, these resources will occupy an essential part of the future energy portfolio. However, these geological structures usually have low permeability and require the creation of cracks to develop the fracture network and thus improve the permeability of the rock. Therefore, by using large-scale hydraulic fracturing, it is possible to increase the permeability of geothermal reservoirs and exploit a wider range of rock structures (**Zimmermann et al., 2019**).

In conventional hydraulic fracturing methods, fluid is injected uniformly (an increase in pressure or injection rate) in the drilled borehole and this leads to fractures in the rock mass. Several challenges and problems, including: high breakdown pressure, the inability to create effective fracture networks, and induced earthquakes, especially at high operating depths and scales, have been reported in conventional hydraulic fracturing methods (**Zang and Stephansson, 2019**). The connection between conventional hydraulic fracturing and earthquakes has been explored and documented in numerous research studies (**Ellsworth, 2013; Fan and Parashar, 2019; Li et al., 2019**). Induced earthquakes with a magnitude up to 5.5 Richter have also been reported (**Kim et al., 2017; Lee et al., 2019**). For this reason, many countries have been forced to suspend hydraulic fracturing operations in geothermal projects (**McGarr, 2014**).

Also, due to the high depth rock structures for geothermal projects (usually more than 3000 meters), conventional hydraulic fracturing methods have difficulty in creating complex fracture networks. Therefore, increasing the permeability and while reducing the probability of earthquakes at the same time, is still a challenging issue. To compensate for the shortcomings of conventional hydraulic fracturing, hydraulic fracturing with cyclic fluid injection, which involves injecting fluid cyclically (and not uniformly) to create a network of frac-

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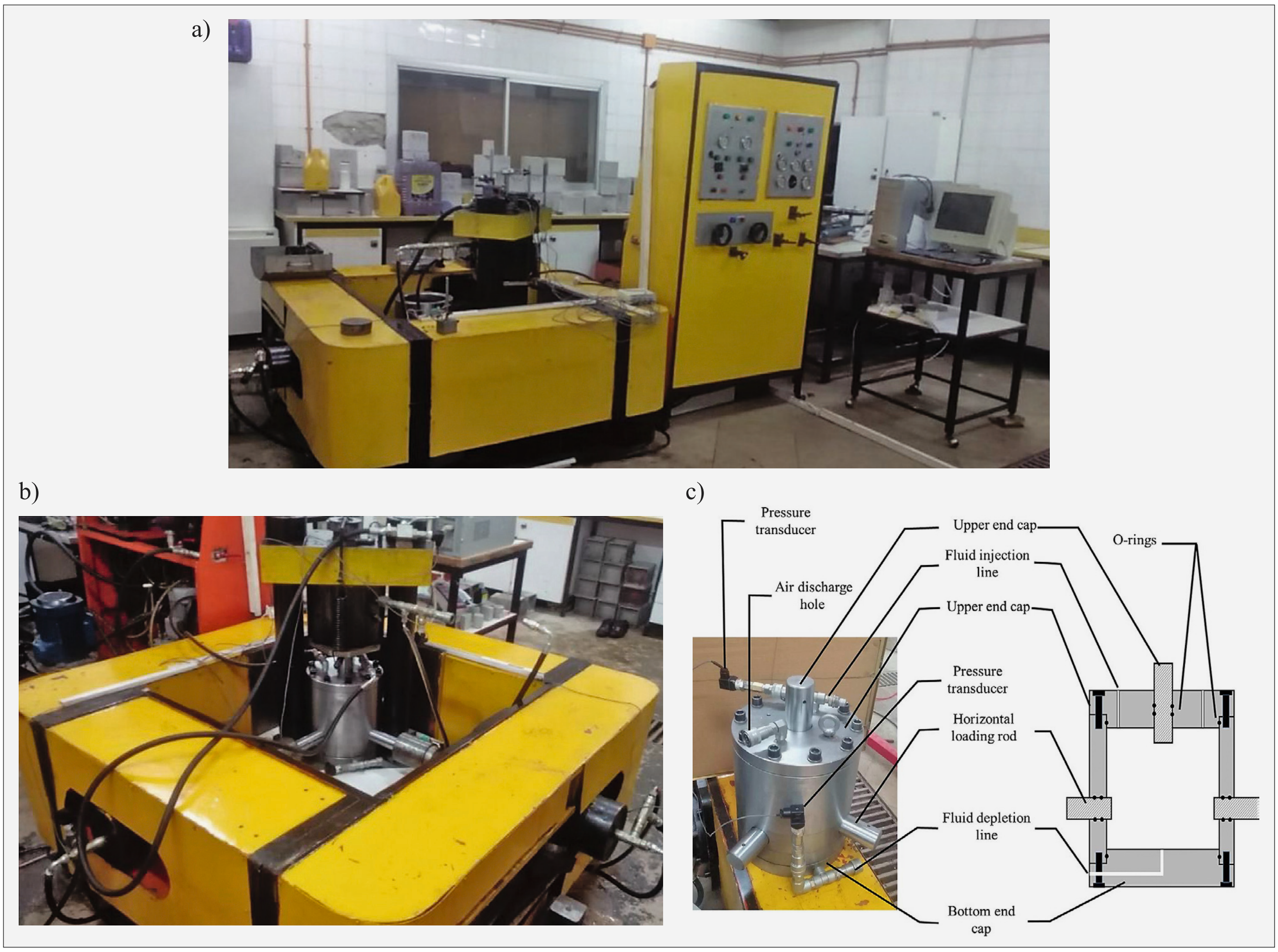

Figure 1: a) Overview of experimental setup; b) The frame and jack for applying axial pressure; c) Pore pressure cell developed to apply injection load on samples (**Mortazavi and Atapour, 2018**).

tures, was developed (**Zang and Stephansson, 2019; Zhuang and Zang, 2021; Zimmermann et al., 2010**).

Zhuang et al. (2017) suggested a new methods of hydraulic fracturing with cyclic injection. Their experiments demonstrated that by applying 80% of the average pressure of uniform injection through cyclic injection, a wider fracture network can be created in the rock. **Patel et al. (2017)** assessed the option of utilizing cyclic injection to reduce rock breakdown pressure and enhance the impact around hydraulic fractures when subjected to true triaxial conditions. **Zhou et al. (2017)** used cement samples to assess the effect of stress, the number of cycles and injection pattern on the hydraulic fracture network. **Zhuang et al. (2019)** showed that cyclic hydraulic fracturing can reduce breakdown pressure by 20% and create more fractures in conditions of injection rates or pressure changes. **Goyal et al. (2021)** have reported a reduction of failure pressure in cyclic injection using dry and hot cylindrical rock samples. **Zhou et al. (2019)** conducted cyclic hydraulic fracture tests on rectangular concrete samples and the results showed that more fractures can be created between multiple branches by injection through a cyclic pump. **Jia et al. (2021)** have conducted laboratory tests along with numerical simulation models to study the mechanisms of failure, creating earthquakes and increasing permeability under cyclic fluid injection.

Zhuang et al. (2020) studied the effect of various injection patterns on seismic activity caused by hydraulic fracturing on granite rock. In the studies conducted and the proposed cyclic injection patterns, the different pressure limits and time operation of the pumps used in real operations have not been considered. **Diaz et al. (2020)** studied the development of fractures under cyclic injection pressure with different cycle periods by evaluating acoustic emission events, hydraulic energy during injection. In the study of **Diaz et al. (2020)**, the working limits of cyclic pump capacity and pressure holding time have been evaluated. The study of **Zhuang et al. (2020)** was analyzed by **Li et al. (2022)** and six schemes of cyclic fluid injection were presented. It is worth mentioning that, in these methods, the injection volume and pressure are controlled. **Liu et al. (2022)** studied the effect of cycle times and injection rates on the start and development of hydraulic fractures in granite under true triaxial conditions.

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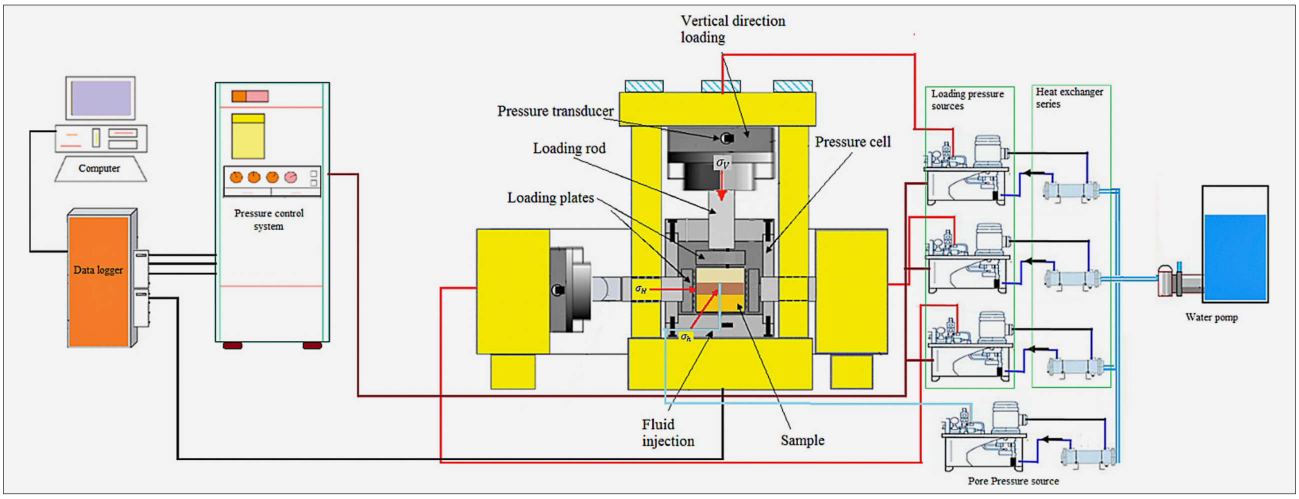

Figure 2: Schematic of the data collection system (**Moghaddam and Golshani, 2024**)

Li et al. (2024) compared the results of cyclic injection and conventional uniform injection by conducting laboratory tests under triaxial stress. The results of acoustic emission evaluation showed that the amount of shear events in cyclic injection is higher and the fracture network has larger dimensions. **Moghaddam and Golshani (2024)** also proposed a special type of cyclic injection pattern by conducting hydraulic fracture studies on layered cement samples. The results of this study show a 30% reduction in the pressure at the moment of failure and investigate the effect of layering on the growth and development of the fracture network.

Based on the results of the mentioned studies, various parameters are effective on the results of hydraulic fracturing with cyclic injection. Utilizing the correct injection pattern can effectively reduce fracture pressure, minimize earthquakes, and limit the extent of the fracture network. In this study, by taking the results of the studies into account, new schemes of cyclic injection have been proposed and the results have been compared with conventional hydraulic fracturing under true triaxial stress.

2. Experimental setup

In order to verify the results of injection schemes in hydraulic fracture tests, the tests were carried out by using a loading device, developed with the ability to apply high stresses under true triaxial conditions and fluid injection. The triaxial stress loading condition of this device is of rigid type, which provides the ability to apply high stress levels to simulate the real field conditions of the earth by using samples and different stress regimes (**Mortazavi and Atapour, 2018**). The device has the possibility of testing cubic samples with relatively large dimensions up to 300 mm. **Figure 1a** shows an overview of the true triaxial stress loading device and the pore pressure application device. The true triaxial loading set up used in this research consist of three main parts:

2.1. Loading section

The loading section consist of two frames, hydraulic lifts, pressure pumps, power transfer rods and sturdy loading plates (**Mortazavi and Atapour, 2018**). The frames have a hardness of 1200 MN/m, while the plates are made of strong alloys with 210 (GPa) elastic modulus (**Mortazavi and Atapour, 2018**). To avoid any minor contact between plates, their sizes are smaller than the designed sample, more details are shown in **Figure 1b**.

2.2. Pressure cell

The pressure cell is made of a steel alloy and has the possibility of applying pore pressure during true triaxial loading, which can withstand pressures up to 70 (MPa). The applied force is transferred through loading rod and the compression is accurately adjusted in each direction (**Moghaddam and Golshani, 2024**). Sensors placed around the cell, as depicted in **Figure 1c**, enable operation control and the recording of pressure changes. By using the designed pressure cell, this device enables various geo-mechanical investigations, including stress-strain behaviour investigation, permeability evaluation, hydraulic fracturing, and sand production in reservoir operations under high triaxial loading conditions up to 2500 (KN) and pore pressure. Pressures up to 700 bar have been recorded (**Mortazavi and Atapour, 2018**). Also, this system is equipped with high pressure energy control valves that can be used to perform creep tests.

2.3. Data collection

The data collection of this device is capable of collecting and saving information on parameters such as load, movement, compression, flow rate and temperature. This data acquisition includes measurement instruments, data collection tackles and programmable software that allows data collection at a speed of up to 500 data per second. As an outcome, the amount of injection pressure and the length of each cycle are precisely logged and described (**Moghaddam and Golshani, 2024**). **Figure 2** shows a schematic of the data collection system.

2.4. Samples preparation

In order to make pseudo-rock cubic samples, various mortar compositions consisting of water, cement, and ordinary plaster were investigated. The basis for choosing the mixing plan was the appropriate viscosity, and uniaxial compressive strength of the sample were chosen in such a way that the mortar does not become heterogeneous due to the presence of too much water, and that no air bubbles are trapped in it due to the high viscosity.

The final mixture was poured into standard cubic molds of 100 x 100 x 100 mm^3 and subjected to constant pressure for compression. The samples were left in the molds for 24 hours and then kept in water for 15 days. The samples made in the same conditions of temperature and humidity were kept at 20°C for 30 days to reach their final strength.

Table 1: Characteristics of the samples

Density (g/cm^3)	E (Gpa)	σ_c (MPa)	σ_t (MPa)	φ (Degree)
1.31	3.5	12.5±1	2.21	31

Cylindrical samples were prepared from the mixing design to determine the resistance parameters and were subjected to triaxial standard testing. The sample index parameters are given in **Table 1**. In the next step, a hole with a diameter of 10 mm is embedded in the centre of the sample to show the injection hole.

2.5. Test conditions

The cubic specimens were positioned within the triaxial cell following the preliminary preparation procedures to evaluate the hydraulic fracture. The injection borehole was meticulously sealed, after which the sample was exposed to three principal stresses applied in various directions. In order to make the applied stress conditions uniform, the study method of **Moghaddam and Golshani (2024)** was used. The three main applied stresses were determined to be 0.4 of the sample's compressive strength in the vertical direction, 0.2 of the sample's compressive strength for the maximum horizontal stress, and 0.1 of the sample's compressive strength for the minimum horizontal stress. Therefore, it is expected that the fracture will occur along the minimum horizontal stress, which has the smallest tensile strength among the three stress levels. In order to avoid applying unbalanced stresses in the sample, at first, a minimum amount of force was applied in each direction, and then the maximum force of horizontal stresses was gradually increased. After reaching the predetermined maximum value of the horizontal stresses, finally the vertical stress gradually increased to reach the determined value, so the main stress levels determined in three directions were

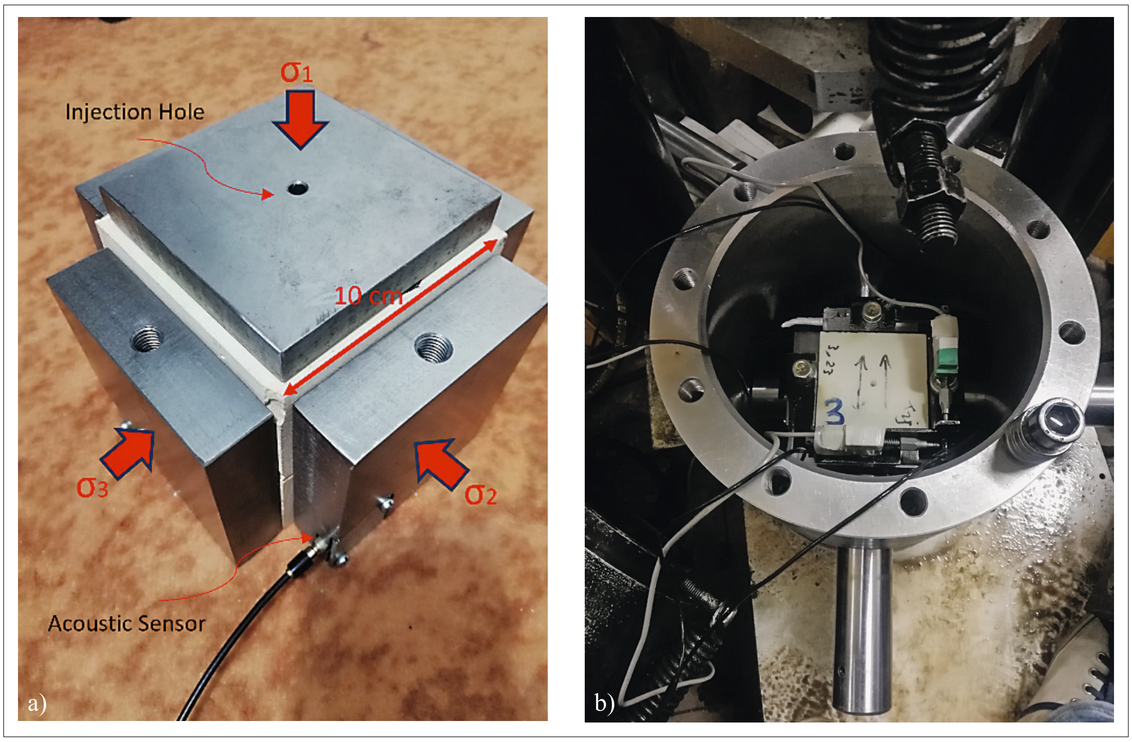

Figure 3: a) Test condition, acoustic sensor location and injection hole on samples; b) Samples placed in the testing machine.

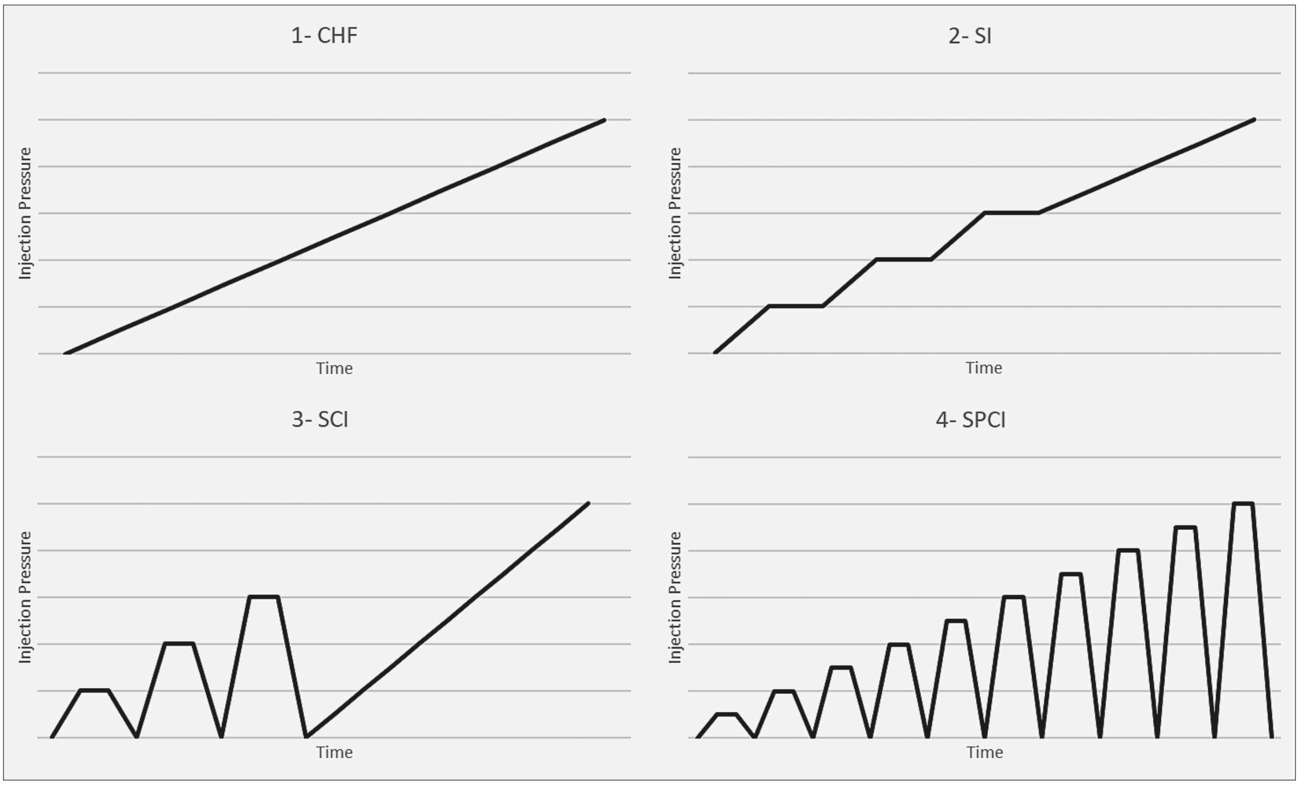

Figure 4: Schematic of the proposed injection schemes; 1) Conventional injection (CHF); 2) Stepwise injection (SI); 3) Stepwise cyclic injection (SCI); 4) Stepwise progressive cyclic injection (SPCI).

completed. After this methodical procedure, the samples were prepared for fluid injection into the borehole. **Figure 3** shows the samples prepared for testing and placed in the testing machine.

The tests were conducted with the aim of investigating the effect of factors related to the definite features of cyclic loading, which included the effect of various parameters, including the length of each loading cycle and the form of injection loading. To accomplish this goal, a total of 9 samples were carefully designed and evaluated. During the hydraulic fracture test, the injection rate was considered constant at 15 (ml/min). The viscosity of the fluid was 4 (mPas).

Acoustic events were also recorded during the experiment by four sensors installed directly on the samples. The sensors were placed in a way to provide maximum coverage on the sides of the sample. By using special gels, the contact between the sensors and the surface of the stone was increased to prevent the interference of waves. Acoustic signals were collected using the complete system and after the investigations, the threshold limit of 42 (dB) was determined. Acoustic analyses were also performed by the software of the device.

2.6. Injection schemes

The three injection schemes used in this study are shown in **Figure 4**. In order to compare the results, hydraulic fracturing under conventional (continuous) injection conditions has also been performed in each proposed method. According to the study of **Zhuang et al. (2020)** and **N. Li et al. (2022)**, changing the injection pressure is more effective in reducing the fracture pressure than changing the injection rate. Therefore, three suggested patterns are recommended based on the change of pressure. Also, based on the experiments, it was shown that injection with a stepwise increase in pressure can be effective in reducing the number of seismic events (**N. Li et al., 2022**). Also, the results of the experiments showed that after a number of steps of stepwise increase in pressure, failure results will not change much. Also, frequent changes of pressure in each step of increase (pressure pulse oscillation), only lead to the branching of the fracture network and did not play a role in the development of the main crack (**Zhuang et al., 2020**). Therefore, the three-stage injection method of pressure increase was investigated. This pattern was named stepwise injection (SI). The second injection pattern is recommended in order to compare the results of stepwise increase in pressure and a corresponding three-stage cycle. This pattern was named stepwise cyclic injection (SCI). The three-stage pressure level is due to the creation of pre-stress conditions, and the levels of 20, 40 and 60% of the breakdown pressure obtained from the failure of the control sample are considered.

The combination of stepwise and cyclic injection pressure increases by applying the pressure level retention time, which was shown to have a beneficial effect on

Table 2: The results of tests and evaluations of acoustic diffusion

Test Number	Sample Type	Injection Type	Time of test (second)	Max of Pressure (bar)	Max of Energy (eu)	Max of Amp [dB]	Cumulative Hits	Cumulative Counts	Max of Counts
1	TI	CHF	55	148.2	506738875	81.45	5704	242690	194807
2	TI	SI	115	133	535552539	97.26	16920	318070	195303
3	TI	SI	107	120.5	700012517	89.12	14979	366204	173670
4	T2	CHF	61	150.8	490019200	84.82	5231	214734	239222
5	T2	SCI	190	126.96	361642080	79.21	20362	394684	185376
6	T2	SCI	164	123.7	432568922	80.9	23287	379906	213570
7	T3	CHF	62	157	471524864	79.64	6185	262147	190971
8	T3	SPCI	306	124.16	701426240	91.45	41765	489247	198015
9	T3	SPCI	312	111.23	621911200	84.69	39512	510693	158572

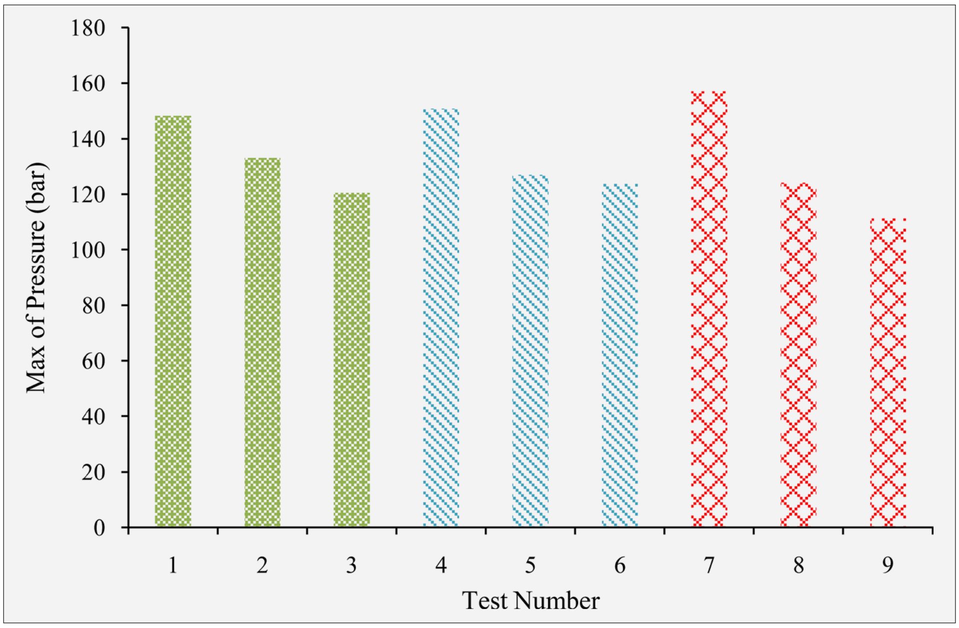

Figure 5: Injection pressure results in the proposed methods
(SI Schemes: green color with dot-hatch pattern, SCI Schemes:
blue color with cross-hatch pattern, and SPCI Schemes is red color with brick-hatch pattern).

the fracture surface in the study of **Diaz et al. (2020)** been investigated. **Figure 6** shows the schematic of the increase ratio and the approximate pattern of each method. The duration of the pressure level of 60 seconds is regarded as consistent across all the proposed schemes.

3. Experimental results

The conditions and results of the experiments are summarized in **Table 2**. For the same injection scheme, the injection parameters such as the rate, amplitude of pressure changes, and injection frequency are assumed to be constant. Due to the small size of the sample and the outflow of the injected liquid from around the sample after failure, the effect of the total injected volume was not investigated in this study, although it has been determined that it is an important factor in causing induced earthquakes in geothermal projects (**McGarr, 2014**).

In order to make a proper comparison between the results, important parameters such as the breakdown pressure, and the results of acoustic evaluations, including: the amount of energy released at the time of failure, the amplitude of events at the time of failure, the count number at the time of failure and the total hits and counts of acoustic events have been evaluated throughout the test. The use of acoustic results can help improve the analysis of the mechanism and development of failure. **Figure 5** shows the breakdown pressure changes due to injection for different proposed schemes.

To evaluate the stepwise injection schemes, the control sample was broken after approximately 55 seconds of injection at a constant rate. The maximum amplitude

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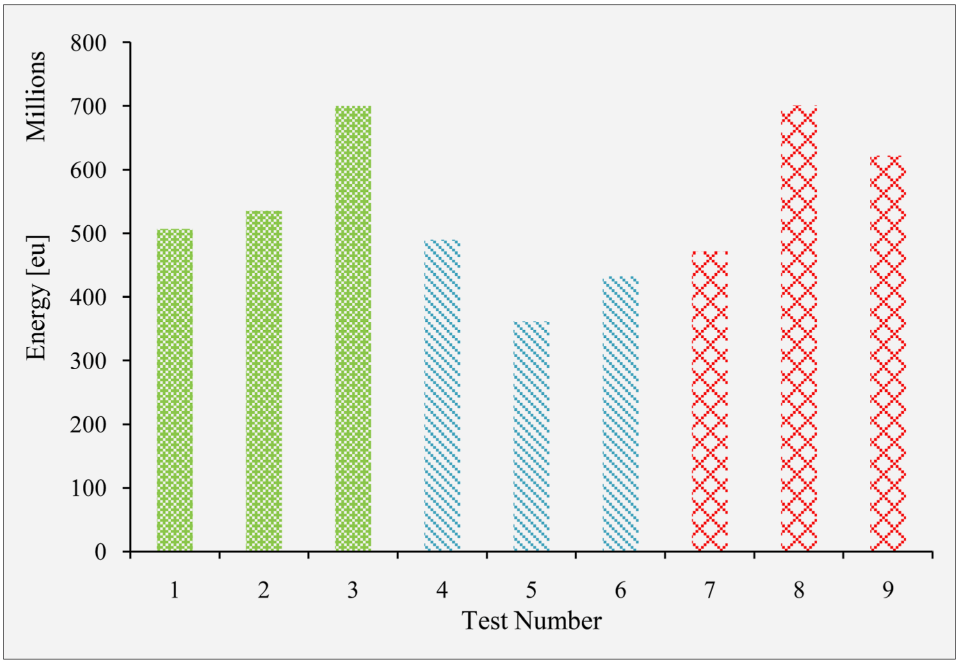

Figure 6: The results of the energy released in the proposed methods (SI Schemes: green color with dot-hatch pattern, SCI Schemes: blue color with cross-hatch pattern, and SPCI Schemes is red color with brick-hatch pattern).

of acoustic events equal to 81 dB occurred at the time of failure. The next two tests were performed with the proposed schemes of stepwise injection. The injection pressure decreased by an average of 15% from the peak value of 148.2 bar in the control sample. The average test time in the first proposed scheme was doubled, and as shown in **Figure 6**, the average amount of energy released in this SI schemes is 22% more than the control sample with the conventional injection pattern.

For stepwise cyclic injection, the injection pressure is increased in three stages and each stage is equal to 20% of the failure pressure in the control sample number 2, until it reaches 60% of the control sample's failure pressure after 3 steps. In the SCI Scheme, the test time increases by 2.9 times, but the average pressure at the moment of failure shows a decrease of about 17%. Meanwhile, according to **Figure 7a**, a 19% reduction in the amount of energy released during failure has occurred.

In the stepwise progressive cyclic injection scheme, the injection pressure in each step is increased by 10% of the failure pressure obtained from the control sample number 3. The injection pressure is kept constant for 60 seconds and after that, the next cycle is applied with an increase in the maximum pressure. The increase in cycles is continued until the sample breaks. The results of the tests conducted with an SPCI scheme show a 5-fold increase in the test time until the failure of the sample, an average decrease of 26% in the pressure at the moment of failure according to **Figure 5**, and a 40% increase in the energy released at the moment of failure according to **Figure 6**.

4. Analysis and discussion

Figure 7 shows the results of four important acoustic emission evaluation indices obtained from hydraulic fracturing tests. In **Figure 7a**, the maximum amplitude of acoustic events at the time of failure is shown, in **Figure 7b**, the total number of hits of acoustic events in the entire test time, in **Figure 7c**, the total number of counts of acoustic events received in the entire test time, and in **Figure 7d**, the number of received acoustic counts at the time of failure are presented.

Due to the high impact of microcracks and sample heterogeneity on the results of breakdown pressure and the number of acoustic events (**Zhuang et al., 2020**), an attempt has been made to make and use homogeneous samples. This importance can be seen in the acceptability of the percentage difference of the results of the breakdown pressure in the control samples.

In the SI scheme, due to the increase in released energy and the subsequent 14% increase in the maximum range of events at the time of failure compared to the control sample, this indicates an increase in the number of crack development branches. The 5% decrease in the number of counts received at the time of failure shows the growth of the development of major and large-scale cracks. In all the tests, due to the increase in the test time, the number of cumulative hits and counts has increased a lot. The decrease in the breakdown pressure is probably due to the application of constant pressure retention time in each step and also the development of the fracture zone at the tip of the main crack.

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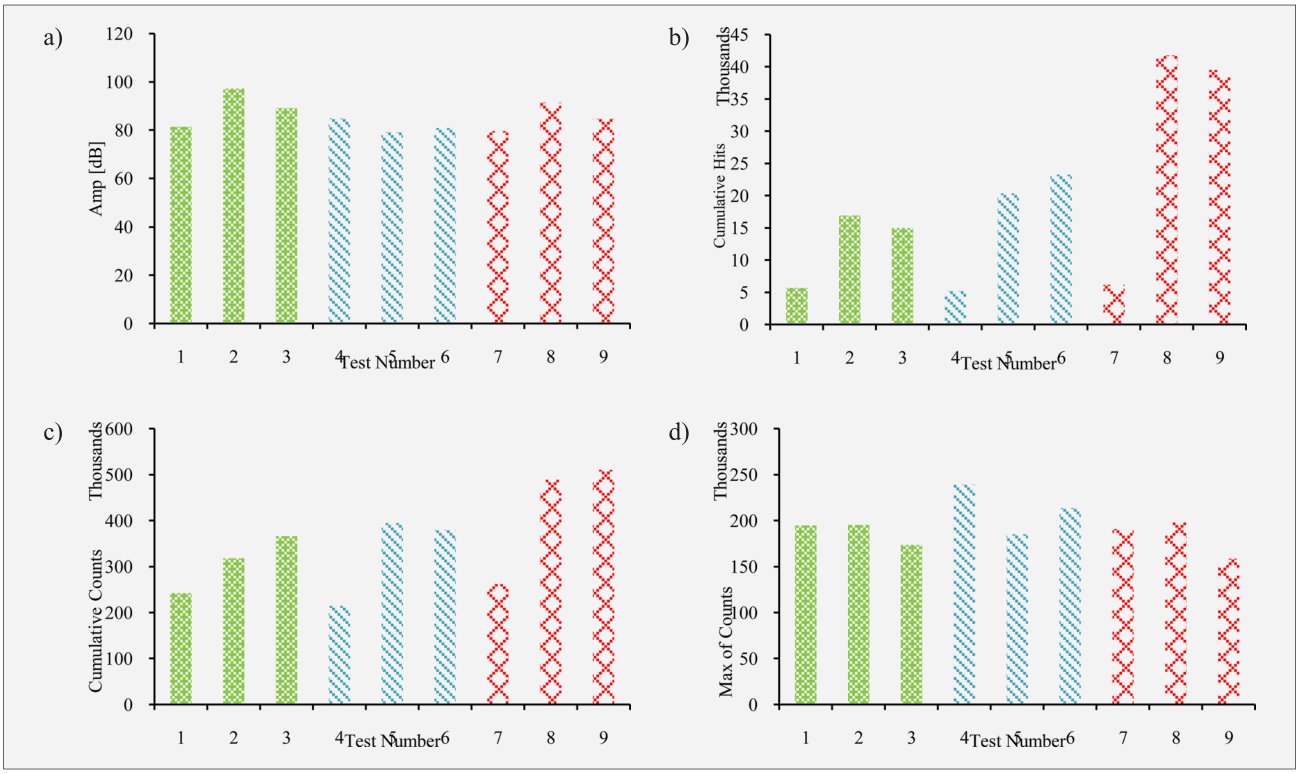

Figure 7: The results of the phonetic parameters taken in the experiments in the proposed injection methods (SI Schemes: green color with dot-hatch pattern, SCI Schemes: blue color with cross-hatch pattern, and SPCI Schemes is red color with brick-hatch pattern).

In the second proposed scheme, the range of acoustic events received at the time of failure has decreased by 5% and the number of counts received at the same time has decreased by 18.5% compared to the control sample. In these conditions, the main crack developed more intensively and fewer branches have been observed. However, due to the cyclic nature of the injection and the decrease in the pressure level during the entire test time, the number of counts and cumulative hit increased several times.

In the stepwise progressive cyclic injection schemes, due to the 40% increase in the energy released at the moment of failure, the 9% increase in the range of events and the 7% decrease in the number of counts at this time, the growth of the main crack branched from the microcracks created during the injection cycle. The fracture network created in this injection method is much larger and has more branches. Similar findings show that the hydraulic fractures created by cyclic injection methods were relatively shorter in length compared to the conventional injection method, despite covering a wider area in the fracture network (**Zhuang et al., 2019; Zimmermann et al., 2019**). Also, past studies show that the longer duration of the test leads to the creation of a larger and wider fracture radius and network (**Wu et al., 2016**).

Evaluating and comparing the fracture results observed in different injection schemes can be important and effective in fracture mechanism analysis. First, the fracture length affects the hydraulic performance. Specimens subjected to SPCI schemes consistently exhibited relatively larger fracture lengths than specimens subjected to different injection schemes. In particular, the breaks of the SCI samples that have the lowest amplitudes of acoustic events are obviously shorter compared to other injection schemes.

Second, in injecting with an SCI scheme, there is a tendency to create failure paths with the least resistance. Stepwise cyclic injection and stepwise progressive cyclic injection schemes have produced better results regarding the failure network. This point is due to the creation of more microcracks in each injection cycle and a wider fracture area at the tips of these cracks. The results of a previous study have shown that cyclic injection causes more intergranular fractures compared to conventional injection (**Zhuang et al., 2019**). As a result, in the conducted experiments, due to the homogeneity of the samples, the energy of each injection cycle is used to produce a larger fracture area at the tips of the microcracks, and as a result, the efficiency of the injection pattern increases.

5. Conclusion

Laboratory hydraulic fracture tests were performed on homogeneous samples made using 3 different injection schemes. The failure results were evaluated by measuring the pressure at the time of failure, the energy released at the time of failure, the amplitude of events at the time of failure, and the number of total acoustic events and the time of failure. The research findings are summarized as follows:

- Regardless of the injection design and considering the homogeneity of the samples, the results of the fractures created based on the tensile fracture mechanism are in accordance with the applied stress regime and in true triaxial stress conditions.
- Injection in a stepwise injection (SI) has the greatest reduction in pressure at the time of failure compared to the time of the test. The fracture created has a smaller fracture network, which can be used in applications such as stress measurement due to the reduction of the pressure required to cause fractures.
- Stepwise cyclic injection (SCI) has the highest reduction of released energy among the schemes, which can be used in seismic risk areas due to the reduction of breakdown pressure.
- Stepwise progressive cyclic injection (SPCI) has shown the greatest reduction in breakdown pressure at the time of failure. Due to the creation of microcracks during injection cycles, a wider fracture network has been created, which can be used in various applications, including geothermal and increased extraction of hydrocarbon resources.

Further evaluation of the impact of these proposed methods, particularly regarding the influence of these injection techniques on the formation of fracture networks, interaction with discontinuities, and failure mechanisms, should be conducted and studied under various conditions.

Acknowledgement

The authors would like to express their appreciation to Tarbiat Modares University and Amirkabir University of Technology for their collaboration in accompanying the tests.

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SAŽETAK

Razvoj shema cikličkoga utiskivanja u hidrauličkome frakturiranju

Zbog sve veće primjene hidrauličkoga frakturiranja u eksploataciji geotermalne energije i porasta eksploatacije ugljikovodika proširili su se dubina i razmjeri ovoga postupka, što je dovelo do stvaranja posebnih zahtjeva i izazova. Jedan od najvećih izazova jesu potresi uzrokovani pokretanjem rasjeda u regiji. Kako bi se riješio ovaj problem, provode se brojna istraživanja. U ovome su radu, temeljem ranije navedenog, istraživane i procijenjene tri metode cikličkoga utiskivanja u režimu troosnoga naprezanja kako bi se operacije što točnije simulirale. Tri predložene metode kojima su proučavani rezultati tlaka frakturiranja kao i različiti parametri pojave akustične emisije jesu postupno utiskivanje (engl. *stepwise injection*, SI), postupno cikličko utiskivanje (engl. *stepwise cyclic injection*, SCI) i postupno progresivno cikličko utiskivanje (engl. *stepwise progressive cyclic injection*, SPCI). Eksperimenti su provedeni laboratorijskim uređajem za stvarno troosno opterećenje (engl. *true triaxial test*). Rezultati potvrđuju smanjenje tlaka frakturiranja u slučaju svih triju predloženih metoda. Metoda postupnoga utiskivanja (SI) pokazala je najveće smanjenje tlaka frakturiranja u odnosu na vrijeme testiranja. Rezultati metode postupnoga cikličkog utiskivanja (SCI) pokazuju smanjenje količine energije otpuštene tijekom nastanaka frakture, pa se ona može razmatrati za smanjenje rizika od nastanka potresa. Zbog kombiniranoga učinka smanjenja tlaka frakturiranja i stvaranja šire mreže pukotina metoda postupnoga progresivnog cikličkog utiskivanja (SPCI) ima bolju učinkovitost u primjeni u eksploataciji geotermalnih izvora.

Ključne riječi:
akustična emisija, cikličko hidrauličko frakturiranje, shema utiskivanja, testiranje troosnoga opterećenja

Author’s contribution

Mohammad Hossein Arabnejad (PhD Candidate of Rock Mechanics): initialised the idea, provided the initial manuscript, and analysed experiment results. **Morteza Ahmadi** (Professor) supervised the experiments, and edited the manuscript.