Review Articles

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An experimental study on the stress memory retrieval in rocks using deformation rate analysis method

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Abstract

Knowledge of the in situ stress state is an essential component in rock engineering, especially for underground spaces in civil, mining, petroleum geomechanics and geothermal energy projects. The most accurate methods of measuring the in situ stress of rock are direct and field measurement methods. However, since these methods are time-consuming and costly, indirect rock core-based methods have attracted specialists' attention for estimating of rock stress memory. Methods based on the rock stress memory, including acoustic emission (AE) and deformation rate analysis (DRA), are among the common methods used for this purpose. In this study has been applied the DRA method to investigate rock type and its characteristic behavior in stress retrieval at different stress levels. To this end, four types of rocks (i.e., granite, zeolite, sandstone, and gypsum) with different behaviors and characteristics were used. The results show that the stress memory retrieval values in the elastic behavior region had better recognizable and higher felicity ratio (FR) for all types of rocks studied. Based on the results obtained from DRA experiments on these rocks, it can be stated that there is no logical and clear relationship between the type of physical properties of rocks and preloading stress levels and the results of stress retrieval.

Keywords: *In-situ stress; Rock; DRA method; Stress memory; Strain .*

1. Introduction

A full knowledge of in situ stresses of rock masses is a critical requirement in mining, civil engineering, petroleum, and energy engineering (Cai et al. 2011). Stress state is a key component in designing an underground space when deciding on its proper location and stability analysis. Also, knowing this parameter is very important in petroleum engineering for understanding fluid flow, wellbore instability, hydraulic fracturing candidate-well selection and well integrity. Determination of the magnitude and direction of in-situ stresses in underground spaces, both in mining or civil engineering projects, is an essential requirement such that and its absence may lead to irreparable costs and damages (Ljunggren et al. 2003; Cai et al. 2011). The most appropriate and accurate methods for measuring the in-situ stress of rock masses are direct and in-situ methods. However, since these methods are very expensive and time-consuming, indirect rock core-based methods have attracted specialists' attention for estimating stress memory. Techniques based on the rock stress memory, including acoustic emission (AE) and deformation rate analysis (DRA), are among these methods.

The DRA method as an indirect and core based method, was first proposed for in situ stress estimation by Yamamoto et al. (1990). The deformation rate analysis (DRA) method is based on the deformation memory effect. In this method more than twice the cyclic uniaxial compressive load to pre-loaded cores is applied and measures the corresponding strain differences during loads. This method is related to the effect of previously applied stresses on the inelastic deformation of the rock sample under uniaxial cyclic loading. Yamamoto et al. (1990) showed that the rock previously experienced stress can be estimated from the slope changes of the stress- differential strain curve under cyclic successive uniaxial loading. The damage theory and the creation of new microcracks, somehow, explain this phenomenon. This phenomenon appears especially when the axial stress exceeds the previous peak stress because this is known as the beginning of irreversible microcracks. Fig 1. shows the fundamental concept of DRA and the strain differences between two curves with the same amount of axial loading stress. The basic formulation of the DRA method is expressed by the following differential strain function (Seto et al. 1998, 1999; Yamamoto et al. 1990, 2009; Villaescusa et al. 2002):

$$\Delta\varepsilon_{i,j}(\sigma) = \varepsilon_j(\sigma) - \varepsilon_i(\sigma); \qquad j > i \qquad (1)$$

Where ε_i is the axial strain in sample under i^{th} loading cycle, ε_j is the axial strain in samples under j^{th} loading cycle and σ is the applied stress corresponding to both strains.

The maximum previous stress can be detected by calculating the strain difference between the two reloading cycles. Therefore, an inflection point which is also called the Kaiser effect point, can be plotted using the strain difference in terms of differential stress-strain curves which indicates the previously applied maximum stress to the sample (Villaescusa et al. 2002). After unloading and reloading, the nucleation of new micro cracks in specimens does not begin until reaching the previous damage level, hence some new cracks will appear after exceeding that level (Lin et al.

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2006). This method is similar to the AE method because both use the inelastic properties of pressured rocks (Yamamoto et al. 1990; Seto et al. 1998, 1999; Villaescusa et al. 2002). Seto et al. (1999) used AE and DRA methods to estimate in-situ stress of sandstone and shale core samples prepared from underground coal mines. Next, they compared the results of these two methods with the results obtained from the hydraulic fracturing method and found that the estimated stresses by both methods were in good agreement with the values measured by the hydraulic fracturing. The vertical stresses obtained from these two methods were compatible with the overburden stress (Utagawa et al. 1997, Seto et al. 1999). In a similar study, Villaescusa et al. (2002) compared the results of the DRA method in in-situ stress estimation by conducting experiments on various specimens obtained from different geological environments with the over-coring method. Their results showed that in all cases, in-situ stress estimated by AE and DRA methods are similar to those obtained by the over-coring method.

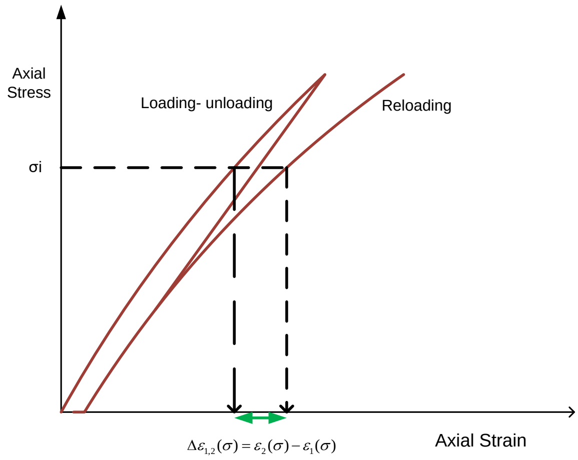

Fig 1. Fundamental concept differential strain used in the DRA

Line et al. (2004) performed experiments using AE and DRA methods and lateral strain to evaluate rock stress deformation (pre-stress) in sandstone samples. They showed that any lateral and axial strains could be used to evaluate rock stress. They also observed no significant relationship between the calculated stress errors and the lag time for sandstone (15 days).

Dight (2006) applied the DRA method to analyze an in-situ stress estimation based on testing core samples taken from exploratory drilling. He confirmed the accuracy of in situ stress and the Kaiser effect determined using this method and stated that this method is low-cost and gives acceptable and reproducible results. Wang et al. (2012) investigated the mechanism of the effect of deformation memory and the DRA in layered rocks at low stress levels. They concluded that the accuracy of the stress determination depends on a combination of rheological parameters of the material and the interface, and the loading rate. Therefore, loading rate was considered the only controllable parameter as its reduction leads to a decrease in reconstruction accuracy (Wang et al. 2002). Hsieh (2013) studied the influence of sample bending on stress reconstruction using the DRA method and stated that bending of specimens under uniaxial compression due to load frame defects or sample preparation can significantly affect stress reconstruction by DRA. They showed that the bending effect could cause a significant scatter in the pre-stress values retrieved from the stress-strain curves through the strain gauge position. Hsieh and Dight (2013) examined the favorable and unfavorable effects on stress retrieval using the DRA method. They proposed a method for testing DRA analysis and solutions to improve test conditions. According to these authors, the results of many studies conducted in such laboratory studies may be unfavorable due to ignoring such factors or questionable results. Attar et al. (2014) studied the capability of DRA in estimating the applied stress in different regions of the stress-strain curve of two rock types, brittle and ductile rock samples. In addition, they applied the DRA method and compared the results of this laboratory in-situ stress estimation technique with those obtained from the hydraulic fracturing method in a dam project. These researchers concluded that the DRA method is suitable for all types of intact rocks and can easily estimate stress values (with varying accuracy). They also showed good agreement between in-situ stress values obtained by the DRA method and the values obtained by the hydraulic fracturing method (Attar et al. 2014).

Wu et al. (2020) investigated accuracies of prestressed sandstone for geological CO2 storage under different prestressed, delay times and curing temperatures using the AE and DRA methods. Their experimental results validated the pre-stress evaluations using AE and DRA. The delay time and curing temperature were shown to have minor impacts on the measurement accuracy.

However, although both axial strain and lateral strain can be used in DRA, the stress memory fades as the delay time increases (Wu et al. 2020). Zhong et al. (2020) showed that as the number of cyclic loading times increases, the rock DME memory information precision significantly improves and then almost reaches accuracy; the angle at DRA inflection becomes sharper.

The DRA method has often been used to estimate rock stresses in mines and civil engineering projects, until recently it was studied and used by Fraser et al. (2021) in petroleum geomechanics. These researchers studied the application of the DRA in the determination of in-situ stress in unconventional gas shale formations on the cores taken from 1700 m to 1720 m depth of the Perth basin in Australia. It has been found that compliant shale samples may not be able to provide a good estimation of in-situ stresses, however, according to their opinion the DRA appears to be an effective method of in-situ stress determination for unconventional shale gas reservoirs (Fraser et al. 2021; Dehghan and Yazdi 2023). Shi et al. (2020) proposed a novel analytical model to characterize the bottom-hole pressure behavior of acid fracturing stimulated wells in the multilayered fractured carbonate reservoirs. In addition to the laboratory studies on this method, some numerical studies have been done on this method and the Kaiser effect, like the conducted researches by Hunt et al. (2003); Luchinkov (2004); Ren et al. (2012); Hsieh et al. (2013); Nikkhah (2017) and Tang et al. (2020).

Hunt et al. (2003) investigated the mechanism of the Kaiser effect and the interaction of microcracks. To this end, they used a numerical model to create an artificial rock core and simulate uniaxial loading experiments. According to their results, a numerical model could recreate the Kaiser Effect phenomenon and DRA, and a direct comparison can be made between numerical and laboratory observations. Luchinkov (2004) investigated the interaction of micro-cracks as the mechanism of the Kaiser effect or the effect of deformation memory. This researcher used the discrete element modeling (DEM) to show the micro-level damage occurring in the rock. Ren et al. (2012) numerically studied the directional dependency of AE and DRA methods on pre-loading and orthogonal loading directions. They identified no memory effect in the second loading in the orthogonal direction. However, the first loading in the orthogonal direction influences the cumulative crack number of the second loading and the differential strain at the inflection point. Nikkhah (2017) employed the three-dimensional particle flow code (PFC3D) based on the discrete-element method, and the influence of the confining stress on the Kaiser effect was examined. Tang et al. (2020) numerically evaluated the deformation memory effect of rocks in low-stress condition using particle-based the DEM and its feasibility was confirmed by comparing it with experimental results.

The main objective of the current research is to investigate the effects of the rock type and its characteristic behavior in retrieved stress using the DRA method at different stress levels. For that matter, four types of rocks including granite, zeolite, sandstone, and gypsum with different behaviors and characteristics were used. Then, retrieved stresses of pre-loaded stresses at different levels which have been selected with respect to their uniaxial compressive strength (UCS) in each rock type were investigated.

2. Experimental methodology

2.1. Testing apparatus

The loading device used in this test is a semi-automatic device manufactured by the Italian Controls company in 2016 (Fig 2). This device can automatically record stress and strain changes during loading and unloading in the rock samples.

Fig 2. Overview of the loading device

2.2. Rock specimens and test procedure

To accomplish the research objectives, four types of rock were selected in the current study. In this regard, blocks of sandstone, limestone, gypsum, zeolite, and granite were collected from areas close to the ground surface of the projects of Iran. Based on the low depth of overburden in the extracted area, it can be said that the rock has stored a very low level of stress in its memory. In fact, the proposed samples had little stress history due to their shallow depth. Before DRA testing, some laboratory tests had been done to determine the main physical and mechanical properties of the rock samples used in the study, according to the standards proposed by the International Society for Rock Mechanics (ISRM). Undercoring core specimens were prepared from each rock type block. These specimens had a diameter of about 32 mm, a height to diameter ratio of 2 to 2.5. for DRA tests. Also, an axial strain gauge was installed on the samples prepared for DRA testing. For example, Fig 3. illustrates samples of the core prepared from blocks of the sandstone for DRA testing and a sample under DRA testing. Before carrying out DRA tests, laboratory tests based on ASTM standards and the proposed International Society for Rock Mechanics (ISRM) methods were conducted with the aim to verify the main physical and mechanical parameters of rocks which are presented in Table 1. Table 1. shows the results of laboratory tests to determine some physical and mechanical properties of the studied rocks, including density, porosity, P-wave velocity, UCS, Poisson's ratio, and elasticity modulus. The value of each parameter was obtained based on three experiments on each rock type.

Fig 3. a) Prepared core samples from rock blocks of sandstone for DRA testing, b) sample under DRA testing

Table 1. Physical and mechanical properties of the studied rocks

Rock type / Features	Granite	Zeolite	Gypsum	Limestone	Sandstone
Density (ρ; g/cm^3)	2.62	1.77	2.22	2.68	2.66
Porosity (n; %)	1.3	18.6	7.1	1.3	1.2
Compressive wave velocity (V_p; m/s)	5303	2635	4879	6397	4991
Uniaxial compressive strength (UCS; MPa)	126	81	22	90	70
Poisson's ratio (υ)	0.1	0.26	0.30	0.1	0.24
Elasticity modulus (E; GPa)	65	32	6.2	27	50

Pre-loading stress levels for DRA tests on each rock type were determined based on the ratio of its UCS value, i.e in terms of percentage of UCS. The loading level is selected so that the DRA method can evaluate the stress estimation for different stress levels such as low, medium, and relatively high stress levels. The loading (and pre-loading) path and stress level for the different samples is presented in Table 2. In the pre-loading, each sample was loaded to induce stress memory at a specified stress level and under the pre-loading time. In the second step, samples were again loaded and unloaded for three to five times. The maximum stress level of the reloading was a little bit bigger than the pre-loading level. For each sample, three to five loading-unloading cycles with a same loading rate of 0.1 MPa/Sec in successive cycles were applied together with recording of axial strain data. Each sample was preloaded for at least 1 hour (Table 3) and then several loading-unloading cycles were applied immediately. Fig 4. exhibits the general loading path for DRA tests. There is no pause between reloading cycles; hence, for each cycle, the axial stress and strain was recorded. The maximum stress level of re-loading successive cycles was at least 1.5 times of preloading stress.

Table 2. Pre-loading of test rock samples

Rock type	Pre-loading stress level	Sample code	Number of loading cycles	Pre-loading time (Min)	Pre-loading stress, MPa	Re-loading stress, MPa
Gypsum	1	Gy_{5-4}	5	90	1.94	**5**
Gypsum	2	Gy_{5-15}	5	60	6.4	**11.8**
Gypsum	3	Gy_{2-22}	3	120	8.6	**14.8**
Gypsum	4	Gy_{2-32}	3	60	15.5	**23.4**
Zeolite	1	Z_{6-15}	4	60	7	**15.5**
Zeolite	2	Z_{7-26}	4	105	18.5	**32.1**
Zeolite	3	Z_{7-40}	5	60	21.8	**33.5**
Zeolite	4	Z_{6-53}	3	60	35.8	**49.5**
Sandstone	1	S_{4-5}	3	60	6.18	**17.3**
Sandstone	2	S_{2-23}	3	90	17.5	**28**
Sandstone	3	S_{2-34}	3	135	31.5	**42**
Sandstone	4	S_{2-45}	5	60	45.5	**68**
Granite	1	G_{7-20}	3	60	10.5	**26**
Granite	2	G_{2-40}	4	90	31.5	**49**
Granite	3	G_{7-60}	3	90	56.7	**75**
Granite	**4**	$\mathbf{G_{9-82}}$	**3**	**60**	**80.35**	**101.35**

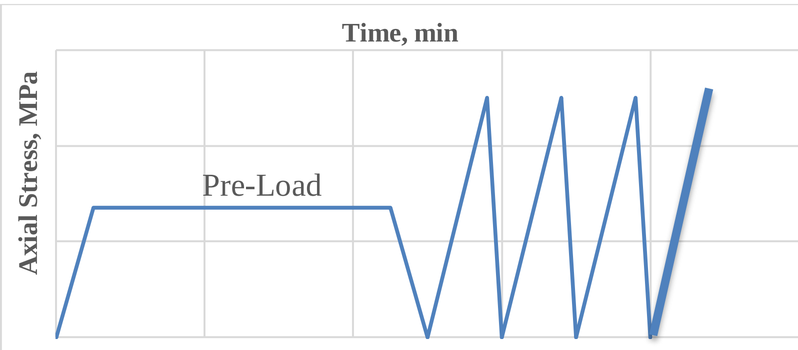

Fig 4. Uniaxial loading-unloading path for DRA tests

3. Results and data analysis

The axial stress and strain were recorded during each loading-unloading-reloading cycle and next the differential strain ($\Delta\varepsilon_{ij}(\sigma)$) between reloading cycles versus axial stress were plotted. From the plotted diagrams, the maximum inflection points, which represent the amount of previously experienced stress, were obtained. The MATLAB software was used to calculate and plot these diagrams. As an example some diagrams of the test results of the studied rocks were given in Fig 5. In this figure, the inflection point in curves is an evidence of redamaging onset in samples which is closer to the maximum experienced stress level. The strain rate was expected to be the same as before loading (previously induced stress to rock), if another micro crack was not created. As Fig. 5 shows, curves of differential strain versus stress for each sample were plotted between the two cycles. As seen in this figure, inflection points somewhat agree well with the preloading stress values applied to the samples. However, it should be noted that sometimes the inflection had low resolution and was difficult to identify. Table 3. presents the results of the DRA tests, including pre-loading stress level, the value of stress estimated from the test, and the calculated felicity ratio (FR). The FR is the ratio of S_{DRA}/S_P, where S_{DRA} is the estimated stress by DRA test, and S_P is the maximum pre-loading stress applied to the sample.

Table 3. Results of DRA test on core samples of each rock

Rock type	Sample name	Pre-loading stress level	Stress estimated from the DRA test (MPa)	felicity ratio (FR)
Granite	$G_{7\text{-}20}$	1	10.2	0.97
	$G_{2\text{-}40}$	2	26.5	0.84
	$G_{7\text{-}60}$	3	52.7	0.92
	$G_{9\text{-}82}$	4	-	-
Zeolite	$Z_{6\text{-}15}$	1	6.2	0.88
	$Z_{7\text{-}26}$	2	16.7	0.90
	$Z_{7\text{-}40}$	3	21.7	0.95
	$Z_{6\text{-}53}$	4	34	0.95
Sandstone	$S_{4\text{-}5}$	1	5.3	0.86
	$S_{2\text{-}23}$	2	16.2	0.93
	$S_{2\text{-}34}$	3	27.6	0.87
	$S_{2\text{-}45}$	4	40.9	0.90
Gypsum	$Gy_{5\text{-}4}$	1	-	-
	$Gy_{5\text{-}15}$	2	5.9	0.86
	$Gy_{2\text{-}22}$	3	7.5	0.87
	$Gy_{2\text{-}32}$	4	14.6	0.81

For a more complete analysis of the values obtained from the DRA test, the FR for different pre-loading stress levels and each rock type is presented in Table 4.

The following the results obtained from each type of rock are explained:

Granite: According to Table 5 and the stress-differential strain curves of the granite rocks, at loading level 1, the preloading stress estimated by the DRA method was retrieved with an error of about 3%. However, the retrieved stresses at levels 2 and 3 by DRA were obtained with an error of about 16% and 8%, respectively. The highest and lowest FRs were obtained in the granite rock at stress levels 1 and 2. These results show that the uniformity trend in the value of retrieval stress in this rock type cannot be evaluated, and the percentage of FR was more than 84% in all pre-stress levels. Therefore, it was possible to estimate stress retrieval in all pre-loading stress levels, although with some degrees of error.

Zeolite: In zeolite, pre-loading values were applied at four stress levels according to Table 5, and the DRA test was performed. In this rock, for pre-loading stress level of 1 (8% of UCS), the appropriate FR of 0.88 was obtained, which has a 12% error compared to the DRA. This value was the lowest value of the FR of the retrieved stress among the different levels of pre-loading stress for this rock type. Meanwhile, for the pre-loading levels 2 to 4 (25, 45, and 65% of the compressive strength of the rock), the values retrieved by the mentioned method were obtained with errors of about 10, 5, and 5%, respectively. As shown in Table 4, the highest FR (i.e., the lowest error) was occurred for loadings in levels 3 and 4 of this rock.

Table 4. FR values obtained for different preloading levels in different rocks

Level / Rock type	Level 1	Level 2 and 3	Level 4
Granite	0.97	0.84 0.92 -	-
Zeolite	0.88	0.90 0.95 0.95	-
Sandstone	0.86	0.93 0.87 0.90	-
Gypsum	- 0.86	0.87	0.81

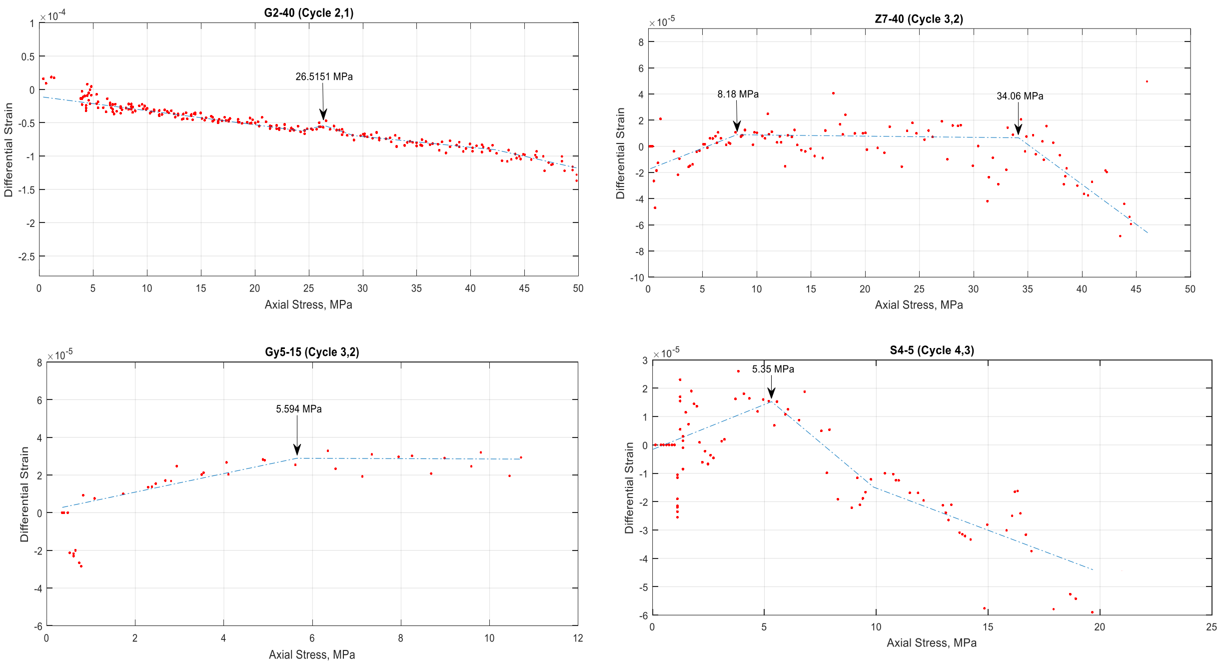

Fig 5. Variation of strain difference versus axial stress, (a) granite (b) zeolite (c) gypsum (d) sandstone

Sandstone: In sandstone, for pre-loading level 1, the retrieved stress was associated with an error of about 14%, which is the lowest value obtained from the DRA method for this rock. The retrieved values for the loading levels 2 and 3, both of which were in the elastic region of the rock, were obtained with an FR of 0.93 and 0.87, respectively. The estimated value for pre-loading at level 4 was also associated with an error of about 10%. Therefore, since the retrieved preloading stress would be not less than 0.87, it was possible to perform tests for stress memory retrieval at an acceptable error.

Gypsum: In this rock, the pre-loading stress could not be estimated for the level 1 pre-loading stress. For levels 2 and 3 pre-loading, retrieval stress occurred with an error of about 14 and 13%, respectively. While, at level 3, the retrieved stress was higher than the previous case, and the DRA produces the maximum retrieval stress. However, at level 4, the value of pre-loaded stress was obtained with an error of about 19%. This value was the lowest value retrieved by the DRA method for gypsum and the lowest value among all samples of studied rocks and all levels of pre-loading stress.

In general, based on the results obtained, zeolite had the lowest density and P-wave velocity, the highest porosity, but the best stress retrieval at preloading stress levels, which can be attributed to the brittleness behavior of the rock and elastic region of pre-stress. The results show that this rock had the best results among the studied rocks.

The reason is its integrated structure, uniform texture, and brittle behavior of this rock. As a result, the damage caused by preloading (inelastic strains) was well stored in the memory of the rock, leading to better stress retrieval. Gypsum, which had the lowest UCS and elasticity modulus among the studied rocks, had the weakest results in preloading stress retrieval. This result may be due to the ductile behavior of this rock type. In this respect, the inelastic strains, which are the basis of the DRA method, are not well measurable and retrievable. The best preloading stress retrieval using the DRA method is obtained for granite and zeolite, in the order of their appearance. These rocks have different geomechanical properties, including density, porosity, compressive strength, modulus of elasticity, and velocity of the p-wave, while their brittle behavior was their similarity. Despite different recognizable curvature points in the studied rocks and based on the obtained FR, it can be claimed that retrieval stress in rock samples with different behaviors and properties is possible by the DRA method. However, better results are obtained in rocks with brittle behavior.

4. Conclusion

As explained earlier, in the present study, the DRA method was used to investigate stress memory retrieval for four types of rocks with different characteristic behavior and at several levels of pre-loading stress under uniaxial compression tests. Based on the above discussion, the following conclusion can be made:

- Based on the results obtained from DRA tests on the studied rocks, it can be inferred that there is no logical and clear relationship between the type of physical properties of rocks, pre-loading stress levels, and the results of stress retrieval. However, the recognizable and clear inflection point in granite, sandstone, and zeolite rocks was better than gypsum, which had a more deformable behavior than other studied rocks. In addition, the F.R of these rocks was higher and close to 1.
- According to the obtained FR values, stress retrieval is possible using the DRA method in the samples of tested rocks with different characteristic behavior and properties. The test results show that the Kaiser effect was observed in all defined pre-loading levels for all types of the studied rocks. In each test, the stress value estimated by the DRA method was slightly different at a point of inflection where the value of stress at that point was close to the value of stress at pre-loading level. However, stress levels in the elastic region had more satisfactory results and felicity ratio was closer to the unit.
- According to the stress-strain diagram for granite, the point of inflection was less recognizable than zeolite and sandstone. In general, the values of previous stress retrieval in the elastic region were better for all types of the studied rocks.
- It is noted that there is uncertainty in almost all experimental data and geotechnical measurement parameters, and the measurement of strain and its difference in successive cycles is also similar. In order for uncertainties in this method to lead to more reliable data, it is recommended that the DRA test be performed according to the same loading as well as a larger number of tests and more than three times successive cycles.
- Based on the obtained results, it can be stated that the DRA method can be suitable for estimating the previous stresses of different rock types (hard or brittle rocks and soft or ductile rocks) while better results are obtained for brittle rocks.

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