On the Effect of Grain Size on Rock Behavior under Cyclic Loading by Distinct Element Method

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(Received: April 2017, Accepted:May 2019)

Keywords

UDEC Software
Cyclic Period
Grain Size Impact on Rock Behavior
Fatigue Loading
Rock Stiffness
Distribution of Stresses in the Rock

Abstract

It is well-known that the mechanical behavior of rocks under cyclic loading is much different from static loading conditions. In most constructions, the load applied to structures is within dynamic ranges. That's why a great deal of attention has been paid to this field to identify the dynamic behavior of rocks in more detail. Nevertheless, the nature of dynamic failure in rocks has not yet been identified, particularly when it comes to cyclic loading The purpose of this study was to investigate the influence of grain size on the mechanical behavior of rocks under cyclic loading using numerical modeling by UDEC. A total of three grain-categories with a diameter of 1, 2, and 4 mm were modeled in the software. All models were of Brazilian type with 54 mm diameter. Behavioral parameters required for modeling were determined through laboratory studies and the software was adjusted accordingly. The stresses applied to the samples were in two forms of quasi-static and cyclic loading. The result of static loading is that the smaller the grain size, the model will have a higher elastic modulus. In other words, the elastic modulus of the grain size is inversely related to the grain dimensions. Analysis of data obtained from cyclic loading showed that the amount of strain in samples with smaller grain sizes was lower than the corresponding strain in samples with larger grain sizes during the same loading periods. In other words, the resistance of samples with smaller grain sizes to deformation under cyclic load was higher compared to those with larger grain sizes. Comparison of the stress vectors for these samples showed that with a decrease in grain size, stress distribution in the sample became more uniform and inclusive, and the stress concentration declined. Another important result was that the smaller the grain size, the more the axial stress applied to the sample inclined towards one. This indicated that with a decrease in grain dimensions, the sample behavior approached a plastic behavior.

1. INTRODUCTION

Grain size and dimensions are among the most important structural factors that can have a significant effect on rock mechanical parameters [1]. Since the mechanical behaviors of rocks are dramatically different under dynamic versus static loads, and as in most structures, force is applied to the structure in the form of dynamic loads, the issue of dynamic behaviors of rocks has received more attention. So far, the nature of rock fracture dynamics has remained vague specifically under cyclic loading conditions [2]. This study aimed to evaluate the effects of grain size on rock behavior under cyclical loads. For this purpose, the Universal Distinct Element Code (UDEC) software was used for numerical modeling. Some characteristics of UDEC are as follows.

UDEC is used for two-dimensional modeling based on the analysis of distinct elements and is capable of modeling discrete environments. For example, jointed rock masses can be modeled in this software and then be placed under dynamic and static loads with relative ease. In UDEC, blocks can be easily moved or rotated [3].

UDEC was first used in rock mechanics projects to investigate the stability of cracked and jointed rock walls. UDEC is a powerful software for the assessment of jointed spaces in the design of underground spaces. Some of the features that distinguished this software from other numerical modeling software are as follows [3]:

- ✓ Simulation of large displacements along separate surfaces;
- ✓ Design of rigid or deformable blocks;
- ✓ Utilization of different behavior models for the study of deformation behavior;
- ✓ Utilization of different behavior models for discrete environments;
- ✓ Ability to perform dynamic analysis;
- ✓ Ability to model extraction and filling in the underground spaces; and
- ✓ Ability to model fluid coupling in jointed environments.

UDEC has other capabilities in the field of heat and fluid coupling that can be used to model different conditions [4].

The above-mentioned features enable the software user to model different laboratory samples and analyze their behaviors. Some numerical studies carried out by UDEC are reviewed below.

An example of modeling that has been done with UDEC is modeling direct shear tests. In this study, samples with different roughness were modeled, and different amounts of horizontal and vertical displacement and stress were measured. The results were then compared with laboratory samples. The results of numerical modeling showed a very small deviation from laboratory results indicating that the UDEC had a good ability in modeling discontinuities [5].

Another example of modeling in the literature is the numerical modeling of desiccation cracks in the soil. In this modeling, a hybrid continuum-discrete element method was used and modeling was carried out via UDEC. To evaluate the results of the numerical method, laboratory samples were prepared and the results were compared with the numerical method. A good agreement was observed between the two sets of results [6]. The study used the Voronoi command to model the soil grains. This command in UDEC creates mosaic blocks in geometric models.

It is noteworthy that UDEC is capable of subsuming new conditions not present in its memory through its programming, and also can accommodate and adapt to new circumstances [7]. Cyclic loading is among the condition not available in the software memory and therefore need to be created and added to the software. A brief overview of cyclic loading is presented below.

1.1. Cyclic loading

Cyclic loading is one of the mechanical loading types that are very important in designing engineering structures. Rock structures are subject to a wide range of loading rates in drilling operations, fire, military explosions, and in phenomena such as earthquakes, landslides, and passing vehicles. Past studies showed the fact that although the mechanical behaviors of rocks are different in different loading rates, rock failure happens in all loading rates though with different mechanisms. Therefore, the study of rock failure, mechanical behaviors, and cracking under various frequency and loading rates is very important [8]. According to research reports, more than 90% of mechanical failures are caused by fatigue [9]. Many studies have been done in the field of numerical modeling of fatigue, most of which have been on metals. Some cases of fatigue numerical modeling in rock and quasi-rock environments are reviewed below.

- ✓ Numerical and analytical study of fatigue in rocks: For this purpose, in a study, samples of sandstone were prepared and fatigue was tested by a three-point bending fatigue test so that the data obtained from numerical and analytical methods including the lifetime of fatigue and crack growth rates could be evaluated. It should be noted the study used nonlinear failure mechanics equations in the analytical method and finite element method in the numerical method. Comparison of the results showed that the analytical method provided good estimates in predicting fatigue life and crack growth rates. However, the best results and predictions were obtained by the finite element method based on J integral [10].
- ✓ Simulation of fatigue crack growth in heterogeneous materials by S-version Finite Element Method (S-FEM): This method is fully automated and is an extension of the finite element method that can properly model crack propagation in heterogeneous environments. In a heterogeneous material, stress at the crack tip has a mixed-mode condition, and the direction of crack propagation is affected by the degree of heterogeneity in the mixed-mode conditions. The stress intensity factor in the mixed-mode condition was estimated by virtual crack closure in the region. The main indicator for estimating the amount and direction of crack propagation was the virtual crack closure. First, the two-dimensional propagation direction of cracks was estimated by this method. Then the method was improved for the three-dimensional problems and showed a good ability to predict the propagation direction

of fatigue crack in a heterogeneous material [11].

2. NUMERICAL ANALYSIS

Like any other software, UDEC requires correct experimental input data to be able to model the environmental conditions well,. In this study, to investigate the effects of grain size on fatigue behavior, samples with standard Brazilian dimensions, i.e. a diameter of 54 mm, were modeled [12]. The texture of the samples contained grains of quartz together with the cement matrix. In this stud, direct shear tests and uniaxial compressive tests were conducted on laboratory specimens to determine the required parameters for numerical modeling.

2.1. Laboratory Studies

A simple direct shear machine was used for determining friction angle and cohesion, as well as the amount of shear stiffness and normal levels of contact between the silica particles and cement. Direct shear tests were performed under constant load, which was applied to the sample through the dead load. Since the shear machine had been designed for samples with maximum width and length of 30 cm, for the correct placement of cylindrical samples with a diameter of 54 mm in the machine, they were first placed in the mold and then embedded in the machine. The machine and mold are depicted in Figure 1.

Figure 1. Samples prepared for shear tests with the direct shear machine

To determine the normal stiffness of discontinuities, a uniaxial loading machine was used. Figure 2 shows the samples prepared and the uniaxial testing machine used.

Figure 2. Sample prepared to determine the normal stiffness, with the uniaxial testing machine

Parameters related to the contact surfaces between the cement and quartz grains were determined by two tests as presented in Table 1. Other required parameters related to quartz grains are presented in Table 2.

2.2. Numerical Modeling

As in other software programs, numerical modeling in UDEC includes several successive steps, each of which must be done properly so that the design can be continued in further steps. These steps are explained below.

2.2.1. Geometric Modeling

For geometric modeling, 3 groups of samples with a grain size of 1, 2, and 4 mm were modeled in UDEC. The width of the samples did not exceed 1.10 of the model width, which was itself 54 mm based on the Brazilian test standard. It should be noted that the Voronoi command was used to model the grains. This command can create blocks of random mosaic shapes in the geometric model of UDEC. Figure 3 shows the geometric models designed by UDEC.

2.2.2. Assignment of properties and applying boundary conditions

After geometric modeling in UDEC, the properties should be assigned to the grains created in the geometric model as well as to the existing joints. For this purpose, the values in

Table 1 were used for joints, and those in Table 2 for grains. It is noteworthy that in all three models, the amount of displacement at the bottom was zero, to apply appropriate boundary conditions.

Table 1. Parameters related to contact surfaces between the sand and quartz grains

Parameter	Cohesion (MPa)	Friction Angle (Degree)	Shear Stiffness (GPa)	Normal Stiffness (GPa)
Measure	0.8	28.83	3.5E9	2.9E10

Table 2. Mechanical properties of quartz grains

Parameter	Density (kg/m3)	Young's modulus (GPa)	Shear modulus (GPa)	Bulk modulus (GPa)	Friction Angle (Degree)	Cohesion (MPa)
Measure	2.7E3	88	39	37.7	48	70

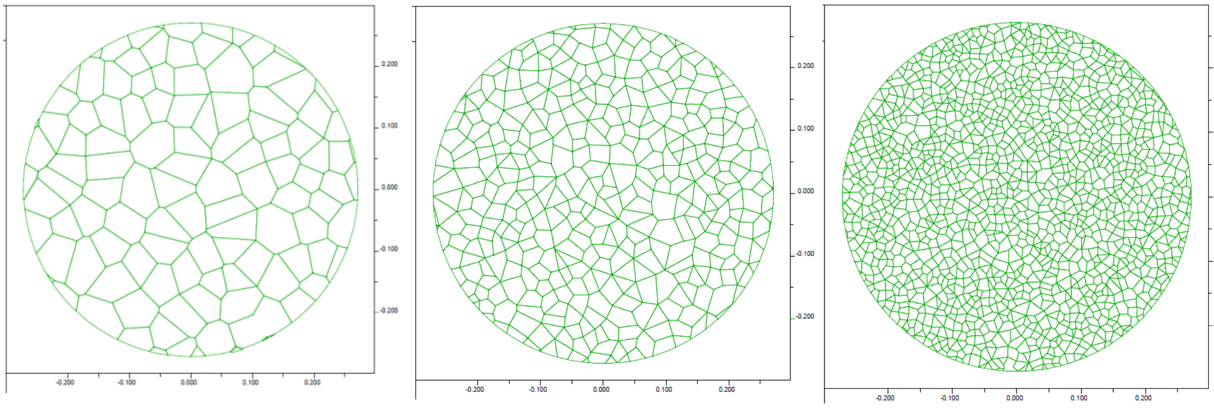


Figure 3. Geometric modeling of Brazilian samples with dimensions of 1, 2, and 4 mm in UDEC.

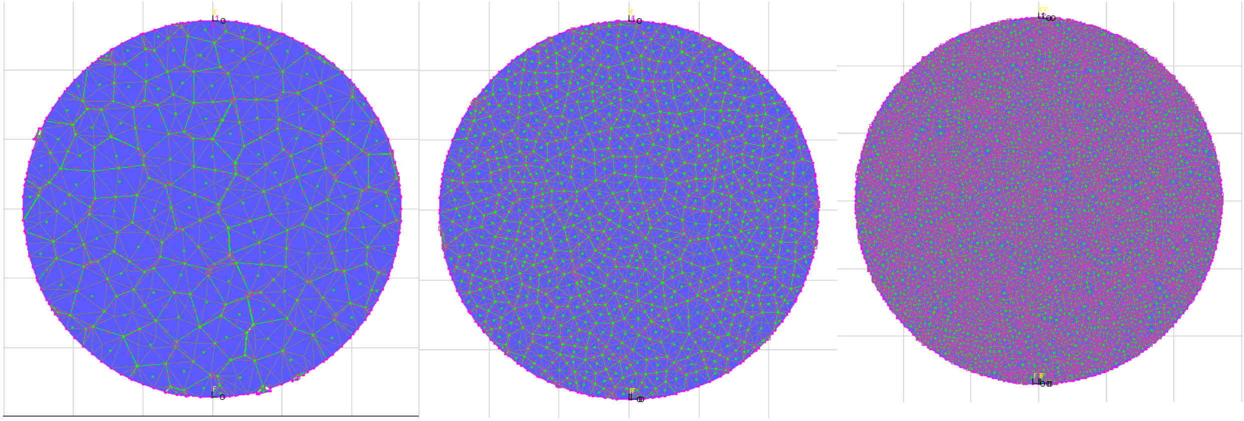


Figure 3. Assignment of properties to the geometric model in UDEC

2.2.3 Loading

To study the behavior of models with varying grain sizes, the geometric models were put under quasi-static and cyclic load types. These two types of load are explained below.

2.2.3.1. Quasi-static load

In this type of load, geometric models were put under loads with constant strain rate and the stress-strain curve for each was prepared as shown in Figure 4.

As shown in Figure 4, the elastic modulus, as well as poisson ratio, increased with a reduction in grain size, so that the grain size of 1 mm had the maximum elastic modulus and Poisson value and the grain size of 4 mm had the lowest elastic modulus and Poisson's ratio (Table-3).

Elastic modulus is a parameter by which the stiffness of the material is shown. Its value results from the bond among the material's atoms and does not change much without a change like the material [13]. Since the reduction in the grain size increases the surface among grains, it can be expected that the bond among the atoms and the elastic modulus increase by reducing the grain size.

A sensitivity analysis on grain size was performed to evaluate sensitivity of grain size on two Young modulus and Poisson's ratio. As a result, the Poisson's ratio is more sensitive than the young modulus. In other words with alteration of the grain size, Poisson's ratio will change more than the young modulus as shown in figure 5.

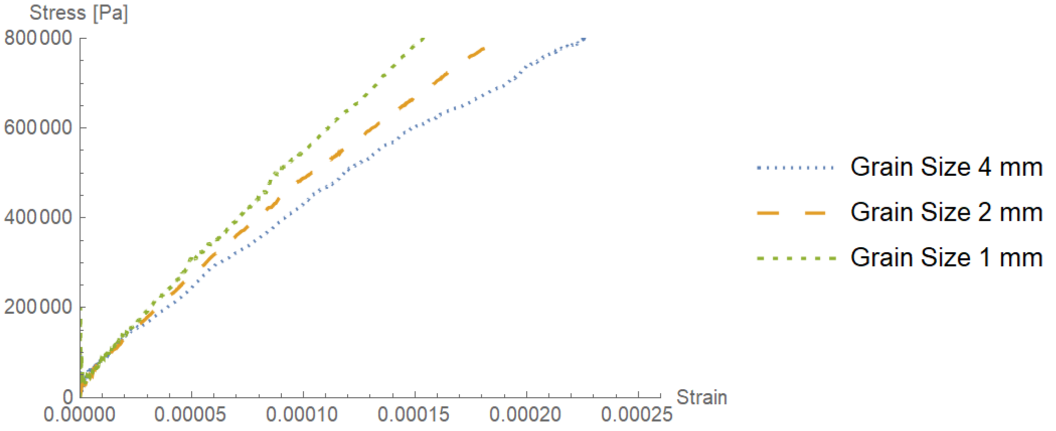


Figure 4. Stress-strain curves for 3 types of granularity

Table 3. Elastic modulus and Poisson's ratio obtained for three levels of granularity

Grain Size	4 mm	2 mm	1 mm
Poisson ratio	.0295	.042	.055
Young modulus (GPa)	2	3	4

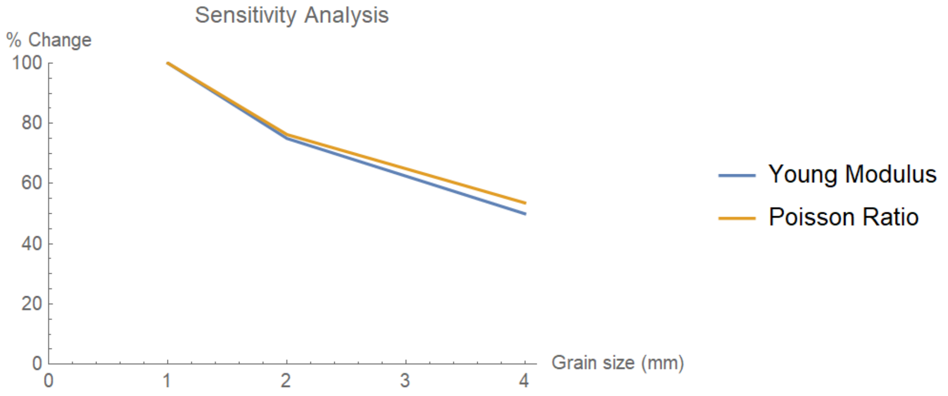


Figure 5. Sensitivity analysis diagram for young modulus and Poisson's ratio base on grain size change

2.2.3.2. Cyclic loading

Loading in fatigue tests varies based on the amplitude and wavelength of loading and can be divided into different types as follows [14].

1. Fully reversed cycle: In this type of loading, the sample is placed under equal compressive and tensile load, so that the mean stress is zero and the value of the maximum and the minimum stress is equal regardless of their sign.

2. Variable amplitude cycle: In this type of loading, the sample is only placed under compressive loads and the stress value is at least equal to zero and the mean stress equals half of the maximum stress.

3. Variable wave cycle: In this type of loading, samples are usually placed under compressive loads and the mean stress value is always positive.

4. Haphazard loading: In this type, the samples are placed under haphazard loads so that neither load range nor load wavelength is specified.

In this study, the variable wave cycle loading with compressive loads was used, the stress-cycle graph of which is shown in Figure 6.

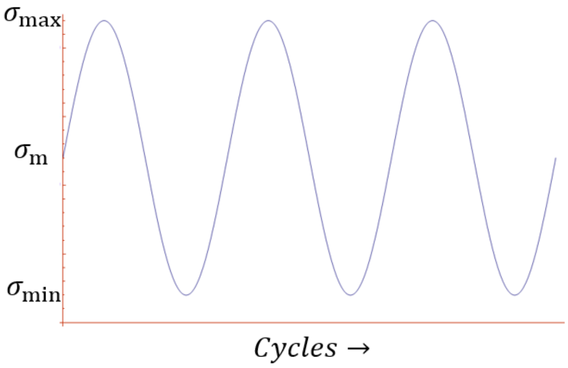


Figure 6. Stress-cycle curve for variable wave cycle loading with compressive loads

The loads were applied to the models with the same range and strain rate. It should be noted that the number of cycles for each strain rate was between 1 to 10 cycles and a total of 4 strain rates were considered for each grain size. Figure 6 shows the load cycles applied to the models with grain dimensions of 4 mm.

As Figure 7, curves show, all loads were applied with a constant strain rate. In general, 120 stress-strain curves were obtained for all of the models as presented in Figure 6 after analysis.

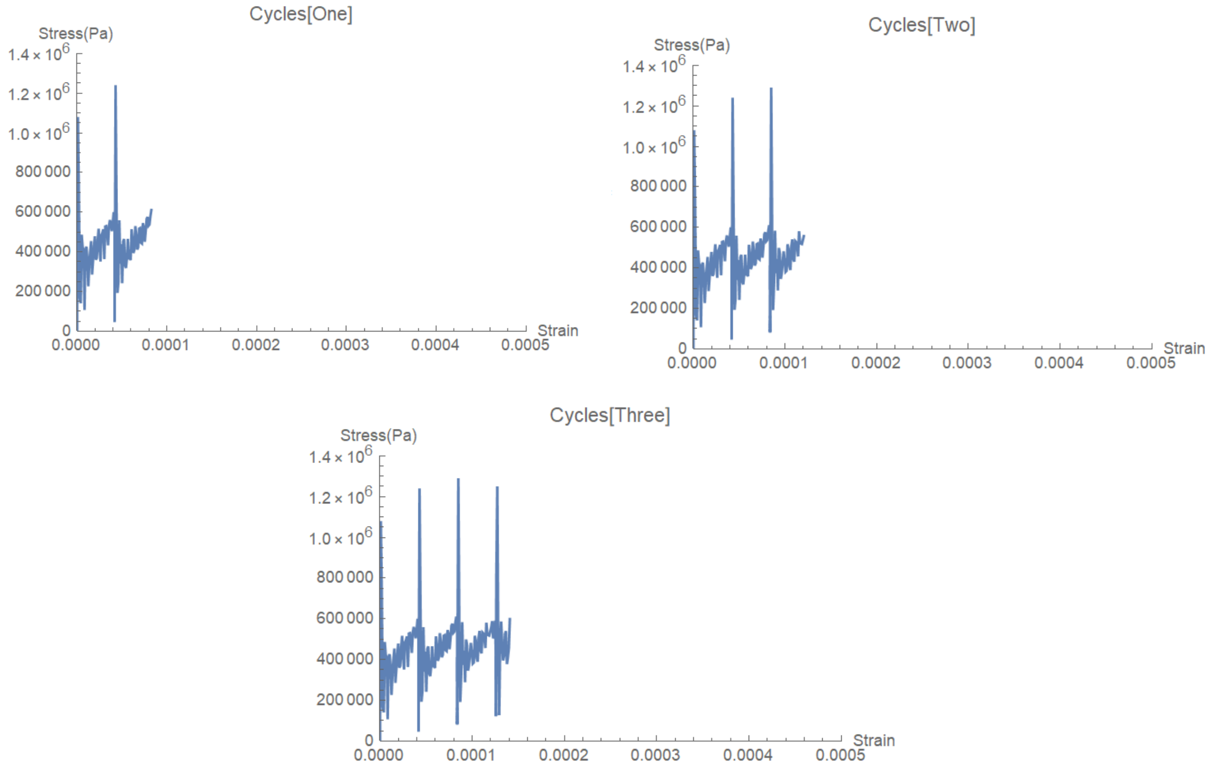
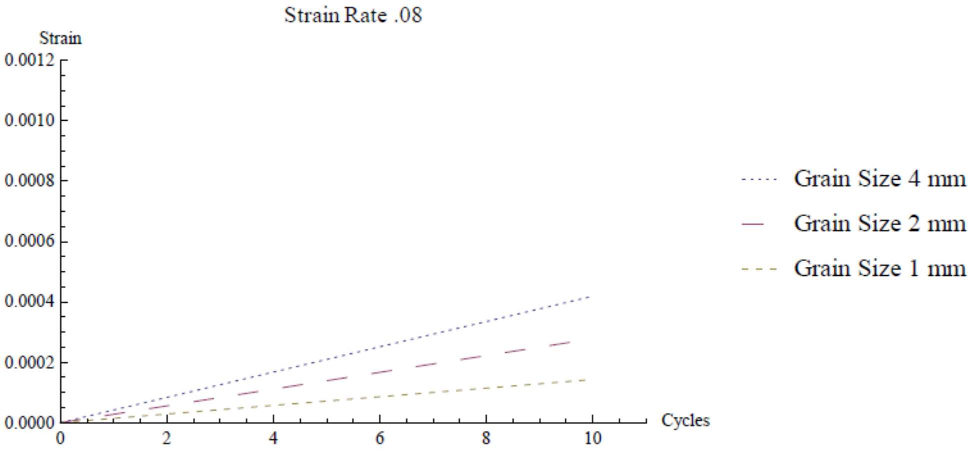


Figure 7. Stress-strain curve applied to the sample with dimensions of 4 mm



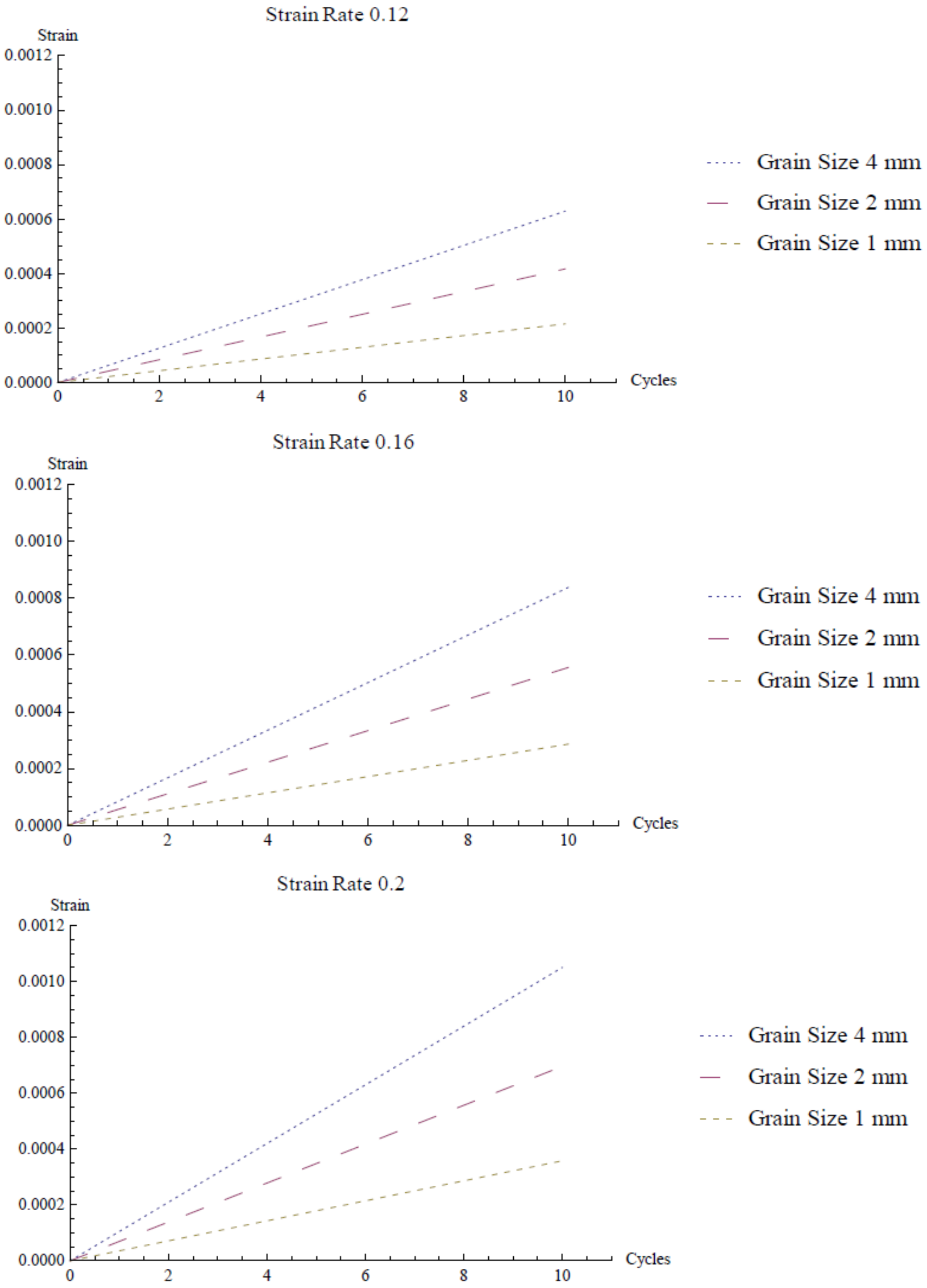


Figure 8: Strain curve based on the number of load cycles applied to the models, based on different strain rates

As is clear from Figure 8, since the rate of strain applied to the models is fixed for each curve, but the strains created in the models are different, the maximum strain belongs to the sample with dimensions of 4 mm and the minimum strain belongs to the sample with dimensions of 1 mm. Therefore, it can be concluded that grain dimension has a direct relationship with the strain created in the sample under cyclic load. In other words, the larger the grain size, the higher the strain created in the sample will be. Another important conclusion based on the results of modeling is that the amount of stress applied to the samples vary for different strain rates. Table 4 shows different amounts of stress for different strain rates.

According to the curves in Figure 5 and Table 4, it can be concluded that as grain size becomes smaller, applying loads with constant strain rate, reduces the deformation created in the sample, while the amount of stress imposed on the sample increases. In other words, reducing the grain size increases the sample stiffness. Figure 6 clarifies this conclusion.

Table 4: Different amounts of stress in the samples for different strain rates

Strain rate	Produced tension, 4 mm (MPa)	Produced tension, 2 mm (MPa)	Produced tension, 1mm (MPa)
0.08	1.31	2.2	2.77
0.12	1.94	3.02	3.73
0.16	2.5	4.1	5.28
0.2	3.2	4.7	6.6

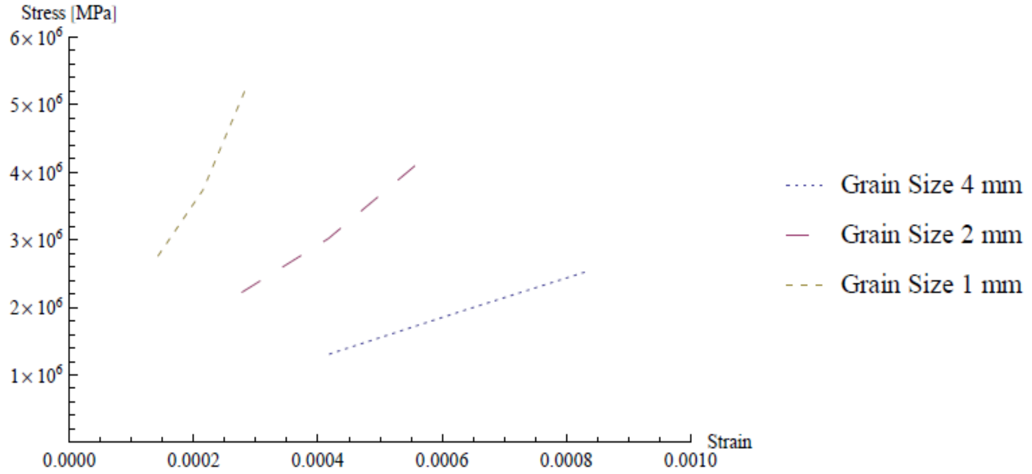
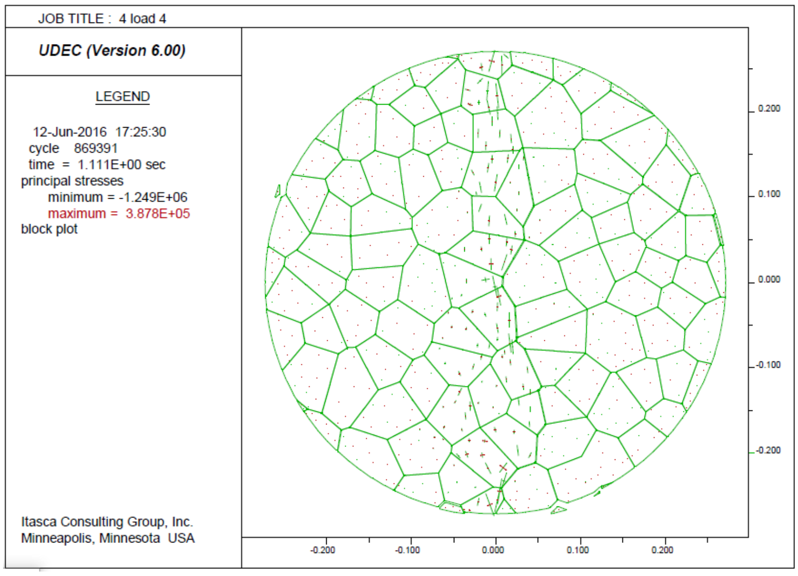


Figure 8: Stress-strain curve based on 10 cycles of load applied to the models based on different strain rates

As shown in curves of Figure 8, with a reduction in the grain size, the slope of the stress-strain curve increases, and this increase remains constant and does not decrease with the application of more loading cycles to the sample.

If the value of constant critical strain is considered as a measure of failure in the sample, based on Figure 8, it can be concluded that samples with smaller grain size had higher resistance against cyclic load, because more loading cycles were needed so that the sample could reach the critical strain.

Another important parameter that was investigated in this study was the stress distribution in the sample. Figure 9 shows the loading stress distribution in the samples after 10 loading cycles.



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JOB TITLE :  4 load 4
UDEC (Version 6.00)
LEGEND
 12-Jun-2016  17:25:30
 cycle   869391
 time  =  1.111E+00 sec
principal stresses
     minimum = -1.249E+06
     maximum =  3.878E+05
block plot
Itasca Consulting Group, Inc.
Minneapolis, Minnesota  USA
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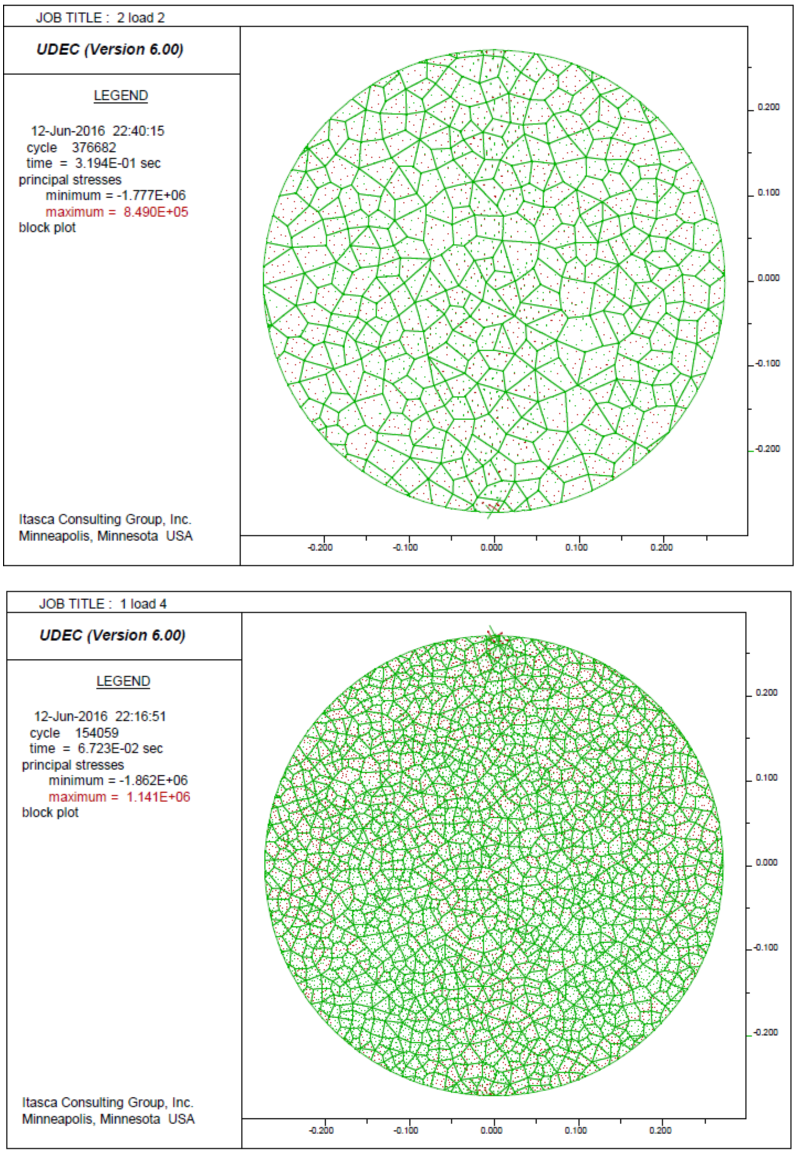

Figure 9: Stress distribution for grain sizes of 1, 2, and 4 mm.

Two important points can be concluded from Figure 7 as follows:

First, as is clear from Figure 7, the stress distribution is more uniform across the surface of the sample with finer grain size. It can be argued that the finer the grain size, the more homogeneous the sample and the lower the structural flaws in the sample. These lead to more uniform stress distribution in the surface of the sample with a grain size of 1 mm than in the sample with a grain size of 4 mm.

Second, if the amount of stress applied to the samples is examined and the maximum lateral stress-induced to the sample is calculated, the results show that the smaller the grain size, the lower the difference between the maximum and minimum stress values. Table 5 shows this well. In addition, it can be concluded that with the increase in inclination of the stress to 1, the sample behavior approaches plastic behavior. In other words, with a reduction in grain size, the sample brittleness is reduced. The grain size is directly related to the brittleness of the material.

Table 5: The proportion of minimum stress to maximum stress for different grain dimensions.

Grain size (mm)	Minimum stress/Maximum stress
4	0.3
2	0.48
1	0.61

3. CONCLUSIONS

This study investigated the effect of grain size on the behavior of rocks under quasi-static and cyclic loads. To this end, three categories of grains with dimensions of 1, 2, and 4 mm were selected and loads with a carious number of cycles were applied to the sample. Analysis of the data showed important results as follows.

Elastic modulus and Poisson’s ratio increase by reducing the grain size, so that the grain size of 1 mm had the maximum elastic modulus value and the grain size of 4 mm had the lowest elastic modulus value. Elastic modulus is a parameter whose value is a function of the amount of the bonds between the material’s atoms. Thus, since the reduction of grain dimensions increases the surface contact among the grains, it can be expected that reducing the grain size increases the bond between the material’s atoms and in turn, increases the elastic modulus. Therefore, it can be concluded that the grain size was inversely related to the elastic modulus.

The result of the sensitivity analysis for the young modulus and Poisson's ratio shows that Poisson’s ratio is more sensitive than the young modulus. In other words with alteration of the grain size, Poisson’s ratio will have more change than the young modulus.

In cyclic loading, the maximum deformation was caused in samples with dimensions of 4 mm, and the minimum deformation was caused in samples with dimensions of 1 mm for the same number of loading cycles. Therefore, it can be concluded that in cyclic loading, the resistance of samples with finer grains was higher than that of samples with the larger grain.

Stress distribution was more uniform across the surface of samples with a finer grain size because with a reduction in grain size, the sample became more homogeneous and its structural flaws reduced. As a result, stress distribution across the surface of the sample with grains of 1mm dimensions was more uniform and had a lower stress concentration than did the sample with grains of 4 mm dimensions.

With a reduction in grain size, the sample behavior inclined towards plastic behavior. In other words, the grain size was directly related to the brittleness of the material.

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