Resistivity Response of Thermally Treated Granite During the Compression Test

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ABSTRACT: To determine the stress and damage state of rock mass is important for many geotechnical engineering. To study the feasibility of resistivity measurement in characterizing the damage and stress state, the resistivity measurement, uniaxial compression test, and incremental loading–unloading compression test were carried out on granite samples with different porosities (induced by different treatment temperatures). Results show that the resistivity is very sensitive to thermal damage and mechanical damage during compression. The evolution of resistivity can not only quantify thermal damage but also clearly indicate the critical stress (crack closure stress and crack damage stress) and damage stage during compression. In addition, the resistivity evolution was quite different in the pore closure stage, elastic deformation stage, and unstable cracking stage during the loading–unloading process, which is useful in field stress and damage state identification for field monitoring. The conductive mechanism variation during compression was discussed using the Archie equation considering crack volume strain evolution during the mechanical damage process. Overall, the resistivity measurement holds great potential in geotechnical engineering for field monitoring.

1. INTRODUCTION

For many geotechnical engineering studies, the rock mass is inevitably disturbed by excavation and construction. Therefore, the damage and stress state will be changed. Determining the damage and stress state is crucial for the safety of geotechnical engineering studies. Many physical responses such as displacement, acoustic emission, and resistivity change will occur during the construction of geotechnical engineering studies. The resistivity measurement, as an easy-to-use method, is wildly used in many geotechnical engineering studies.1−4 Choi et al.5 analyzed the relationship between the resistivity and the quality of the rock mass (Q) and proposed guidelines for rock mass classification using electrical resistivity. Li et al.6 systematically reviewed the resistivity measurement application in underground engineering, and they concluded that the resistivity measurement is promising for advanced detection of tunnel boring machine (TBM) excavation and 3D cross-hole resistivity measurement for water inrush early warning and water volume estimation. Walton et al.7 used resistivity measurements to delineate the excavation damage zone in the tunnel. Resistivity measurement was proved to be the most useful in delineating the highly damaged zone. Caselle et al.8 explored the relationship between electrical resistivity and saturation degree, which was used in the field date interpretation for ore body prospection. Qian et al.9 found that the resistivity measurement is able to characterize the grout seepage process, and resistivity measurement is a new way to monitor the grouting process and is helpful for the grouting design. Miškovic et al.10 carried out a laboratory study and performed forward modeling to study the feasibility and optimized survey design of direct current resistivity as a look-ahead geophysical imaging tool for TBM excavation. Overall, the field resistivity measurement/monitoring is wildly applied in water inrush and other disaster warning in underground engineering owing to its high sensitivity; however, research studies regarding rock damage quantification and stress state monitoring using resistivity measurement are quite rare.

Many laboratory experimental studies were carried out to study the mechanism of resistivity variation with changed stress. Glover et al.11 found that resistivity could track crack closure, dilatancy, crack linking, and failure under tri-axial compression. Also, the electrical data have also been used to derive an electrical-equivalent change in porosity. Hao et al.12 carried out resistivity tomography to study the cracking process under compression. Results showed that the image of resistivity can indicate the development of cracks. Chen and...
Lin\textsuperscript{13} studied the resistivity evolution under uniaxial compression on typical rocks, and they used resistivity as parameters to derive a stress–strain constitutive equation. Ji et al.\textsuperscript{14} investigated the relationship between the resistivity, elastic modulus, and strength of a rock using the cyclic loading and tri-axial compression test. Also, they proposed a meaningful method to characterize the change of mechanical properties for engineering disturbed rock mass using resistivity. Another physical indicator associated with crack development, acoustic emission, was studied simultaneously and compared with resistivity during compression.\textsuperscript{15–17} Results showed that resistivity was sensitive to stress change. Many research studies show that the resistivity of rock material is determined by the pore/crack state, which is not only closely related to the stress condition but also related to rock damage (experienced stress history).

To determine critical stress under a compression test is a crucial issue in understanding the rock damage process. During compression, the crack closure stress (\(\sigma_{cc}\)), crack initiation stress (\(\sigma_{ci}\)), and crack damage stress (\(\sigma_{cd}\)) were considered to be key parameters to describe the rock mass response for geotechnical engineering. The crack initiation stress (\(\sigma_{ci}\)) is closely related to spalling damage, and the crack damage stress (\(\sigma_{cd}\)) is regarded as a long-term strength of rock. Over the last few years, many methods have been developed to determine \(\sigma_{ci}\) and \(\sigma_{cd}\), such as crack volume strain,\textsuperscript{18} lateral strain response,\textsuperscript{19} and the moving point regression technique.\textsuperscript{20} Acoustic emission monitoring was proved to be an effective method in identifying critical stress due to its high sensitivity to the development of cracks.\textsuperscript{21} Since the resistivity is also a sensitive indicator for the pore/crack behavior, the resistivity measurement is a potential method in critical stress identification, which is worthy of in-depth analysis.

Overall, many research studies show that resistivity is sensitive to the variation of rock porosity and crack development and that the resistivity measurement or resistivity monitoring is a promising method in rock damage quantification, critical stress identification, and field stress/damage state monitoring. However, the resistivity response mechanism is complicated and the inherent mechanism is unclear, which is not only determined by the stress condition but also determined by stress history. In this study, granite samples with different porosities (due to different treatment temperatures) were used for the uniaxial compression test and incremental loading–unloading compression test and the resistivity was measured simultaneously to investigate the resistivity response to stress, stress history, and its application in critical stress identification.

2. EXPERIMENTAL WORK

2.1. Sample Preparation. To ensure the reliability of mechanical test results, all samples were cored from a 0.5 m \(\times\) 0.5 m \(\times\) 0.5 m cubic granite block from Jijicao, Beishan area, Gansu, China. The natural density of Beishan granite is about 2.61 g/cm\(^3\). Petrophysical analysis by X-ray diffraction shows that the main mineral components of Beishan granite are 34.09\% quartz, 60.59\% feldspar, and 5.32\% biotite.\textsuperscript{22} The average mineral grain size is about 5 mm. Cylindrical rock samples 50 mm in diameter and 100 mm in length were prepared according to the IRSM-suggested method. A tube-type high-temperature furnace GR.TF80/11 was used for thermal treatment. Granite samples were heated to 100, 300, 500, and 700 \(^\circ\)C, respectively, at 4 \(^\circ\)C/min and held for 60 min at the target temperature. Granite samples were then cooled slowly to room temperature in the furnace.

2.2. Experimental Work. A rock mechanics testing system (MTS 815.03) was used for the compression test. The axial stress was applied under the axial displacement control mode with the strain rate of 0.001 mm/s. Simultaneously resistivity was measured using an ANBO AT515 high-precision resistance tester. As shown in Figure 1, granite samples were first saturated with brine water (conductivity of brine water is 7600 \(\mu\)S/cm) using the vacuum saturation method, and then, the granite sample was sealed in the rubber sleeve (end faces were open for resistivity measurement) to maintain saturation during the compression test. The end faces of the sample were in direct contact with the high-strength steel plate. Additionally, electrodes were embedded in the steel plate. Insulating plates were placed outside the steel plates. During compression, the resistivity of the rock sample was measured by probing electrodes per second. Axial strain and lateral strain were monitored using axial and lateral strain gauge.

![Figure 1. Experimental setup.](https://doi.org/10.1021/acsomega.2c02143)
3. RESULTS

3.1. Physical Properties of Granite after Thermal Treatment. Table 1 and Figure 2 show porosity and resistivity of granite after being treated at various temperatures. For granite samples treated at a temperature lower than 500 °C, porosity increases slowly with the increasing temperature; however, porosity increases rapidly once the treatment temperature is higher than 500 °C. Resistivity values of granite after 100 and 200 °C treatments are approximately identical. For granite samples after 200 to 600 °C treatments, the resistivity decreases significantly with the increasing temperature and then decreases at a slower rate with temperature increase from 600 to 800 °C.

Many researchers have found that the resistivity of the rock material is closely related to rock porosity. Rock resistivity can be calculated using Archie’s equation, given below

\[ \rho = \frac{\rho_w}{\phi^{m}} \]

where \( \rho_w \) is the resistivity water filling in rock pores, \( S \) represents water saturation, \( n \) is the saturation exponent (around 2.0), \( \phi \) is the porosity, and \( m \) is the cementation factor.

As shown in Figure 3, the resistivity of granite after being treated at different temperatures can be finely fitted using the Archie equation, and the cementation factor \( m \) is 1.38.

| sample number | treatment temperature (°C) | porosity (%) | resistivity (Ω·m) | sample number | treatment temperature (°C) | porosity (%) | resistivity (Ω·m) |
|---------------|----------------------------|-------------|------------------|---------------|----------------------------|-------------|------------------|
| 100-0         | 100                        | 0.87        | 649.00           | 500-1         | 500                        | 1.45        | 452.53           |
| 100-1         | 100                        | 1.05        | 726.33           | 500-2         | 500                        | 1.49        | 497.51           |
| 100-2         | 100                        | 1.13        | 597.00           | 500-3         | 500                        | 1.59        | 409.52           |
| 200-0         | 200                        | 1.06        | 706.44           | 600-0         | 600                        | 3.77        | 133.62           |
| 200-1         | 200                        | 1.18        | 732.21           | 600-1         | 600                        | 3.90        | 138.82           |
| 300-0         | 300                        | 1.09        | 643.28           | 600-2         | 600                        | 2.75        | 226.69           |
| 300-1         | 300                        | 1.02        | 637.52           | 600-3         | 600                        | 3.18        | 191.59           |
| 300-2         | 300                        | 1.28        | 650.12           | 700-0         | 700                        | 5.38        | 89.45            |
| 400-0         | 400                        | 1.20        | 522.44           | 700-1         | 700                        | 4.96        | 127.56           |
| 400-1         | 400                        | 1.25        | 685.45           | 700-2         | 700                        | 4.80        | 129.93           |
| 400-2         | 400                        | 1.23        | 596.17           | 700-3         | 700                        | 5.08        | 119.15           |
| 400-3         | 400                        | 1.42        | 523.91           | 700-4         | 700                        | 6.54        | 72.89            |
| 500-0         | 500                        | 1.72        | 419.32           | 800-0         | 800                        | 6.66        | 96.18            |

Figure 2. Porosity and resistivity of granite after being treated at different temperatures.

3.2. Evolution of Resistivity of Granite under Compression. 3.2.1. Under the Conventional Compression Test. Figure 4 shows stress–strain curves and resistivity curves of granite after treatments at various temperatures during the uniaxial compression process. Granite samples after being treated at different temperatures show a marked difference in the evolution of resistivity. For the granite sample after the 100 °C treatment, at the initial loading stage, the resistivity increases slightly with the increasing axial stress and the increase rate decreases, followed by a decrease in resistivity with the increasing applied axial stress, and at last, the resistivity increases sharply at the moment of rock failure stress. Compared to that of the granite sample after the 100 °C treatment, the evolution of resistivity of the granite sample after the 300 °C treatment is different at the initial loading stage, where the resistivity decreases slightly at initial loading. For granite samples after 500 and 700 °C treatments, at the initial loading stage, the resistivity decreases significantly with the increase of the applied stress, followed by a slow increase. Then, the resistivity decreases with the increasing applied stress, and at last, the resistivity increases rapidly at failure stress. Compared to granite samples after 100 and 300 °C treatments, the difference in the evolution of resistivity for granite samples after 500 and 700 °C treatments is that at the initial loading stage, the resistivity decreases significantly with the increase of the applied stress. Overall, the resistivity is sensitive to the applied stress during the compression process for granite subjected to treatments at different temperatures (with different porosities), and the difference in resistivity is

\[ R^2=0.89 \]
the reflection of the difference in the pore/crack of thermally damaged granite.

3.2.2. Under the Incremental Cyclic Loading—Unloading Compression Test. Actually, stress in rock mass always experiences a complicated loading—unloading process due to engineering disturbing, so it is important to study the physical response during the loading—unloading process. Granite samples after 300 and 500 °C treatments were used for the loading—unloading compression test. From the analysis above, the granite after the 300 °C treatment was slightly influenced by temperature, which represented a low-porosity rock material. In contrast, the granite after the 500 °C treatment was thermally damaged by the high temperature, which represented a high-porosity rock material.

Figure 5 shows the evolution of resistivity of granite with different porosities under the loading and unloading process. For the granite after the 300 °C treatment, the resistivity fluctuated in the range 417.9–685.2 Ω·m during loading—unloading compression. For the first loading—unloading cycle (C1), resistivity first decreased and then increased with the increasing applied axial stress during loading. Also, the resistivity remained almost constant during the unloading process. For C2 to C5, the resistivity also first decreased and then increased with the increasing axial stress. During the unloading process, the resistivity first decreased and then increased. For the last loading cycle to failure, the resistivity stabilized after decreasing with the increasing stress and rapidly increased around failure stress. In general, the evolution trends of resistivity were symmetrical for the loading and unloading process for C2 and C5, indicating that the changed resistivity due to the stress load can be recovered partially after unloading. However, this symmetry did not exist for the initial cycle (C1) and cycles at high stress (C6) for pore closure (irreversible deformation of some pores) and development of cracks, respectively. For the loading—unloading cycle under high stress, macro-cracks were initiated, so the conduction mechanism was changed and dominated by crack.

Figure 4. Evolution of resistivity under compression. (a) after the 100 °C treatment, (b) after the 300 °C treatment, (c) after the 500 °C treatment, and (d) after the 700 °C treatment.

Figure 5. Resistivity of granite under incremental cyclic loading—unloading compression: (a) granite sample after the 300 °C treatment and (b) granite sample after the 500 °C treatment.
For the granite after the 500 °C treatment, the resistivity fluctuated in the range 256.8–466.8 Ω·m during loading–unloading compression, which was lower than that of the granite after the 300 °C treatment. For loading cycle C1, the resistivity first decreased and then increased slowly with the increasing applied axial stress during loading. Also, the resistivity first decreased and then increased with the increasing applied axial stress. For C2 to C4, the resistivity first increased and then decreased with the increasing axial stress. During unloading, the resistivity kept decreasing then increasing. For the last loading to failure cycle, the resistivity first decreased and then rapidly increased around the failure stress. Thermally induced cracks abounded in the granite samples after the 500 °C treatment, so the conduction mechanism was changed, which led to a remarkably different resistivity evolution under the loading process.

Overall, the resistivity evolution responses were quite different in the pore closure stage, elastic deformation stage, and unstable cracking stage during the loading–unloading process, which is useful in damage/stress state identification using resistivity monitoring. The resistivity is a good indicator...
in the determination of crack closure stress and crack damage stress of the rock.

4. DISCUSSION

4.1. Critical Stress Identification Using Resistivity Measurement. From the analysis above, the resistivity of the granite material is very sensitive to stress and the development of pore/cracks in the rock, so resistivity could be a good indicator in identifying the stress or damage state of granite. As shown in Figure 6, average axial stiffness was used for crack damage stress identification using Eberhardt’s moving point regression method. The evolution of resistivity and the average axial stiffness with the applied stress were consistent. The average axial stiffness reflects the deformation resistance to the applied stress, which also reflects the structure (rock matrix with pores/cracks) bearing the stress load. In essence, the resistivity and the deformation property are both indicators of pore/crack behavior under stress loading.

The resistivity and average axial stiffness of granite after being treated at different temperatures all decreased remarkably around crack damage stress. The crack damage stress of granite can be clearly identified by the evolution of resistivity (Table 2). For granite samples treated at temperatures higher than 500 and 700 °C, during the initial loading stage, the resistivity decreased with the increasing axial stress, followed by an increasing trend. The evolution of resistivity at the initial loading stage was induced by crack/pore closure. The stress corresponding to the turning point could be regarded as crack closure stress. However, the resistivity decreases in the range of crack closure to crack damage stress. Also, no obvious indicator in resistivity can be found to determine crack initiation stress.

The resistivity is sensitive to crack/pore closure at the initial compaction stage. Meanwhile, it is sensitive to the development of macro-cracks at crack damage stress, so resistivity is good indicator for the determination of crack closure stress and crack damage stress of rock.

4.2. Mechanism of the Resistivity Evolution under Compression. Figure 7 shows the mechanism of resistivity evolution under the compression process. For water-saturated granite at the initial state, pores and cracks in granite are all filled with brine water. Evolution of resistivity can be divided into the following stages during compression.

(1) At the compaction stage, pores are closed with increasing stress. The resistivity should have increased for the sample with high porosity, but it decreases actually for granite with high porosity. This could be attributed to the increase of effective pore (connected pores) volume due to the pore shape change under compression. Meanwhile, drained water from compacted pores will enlarge the dominant conductive pathway for electric conduction. For granite with low porosity, the resistivity decrease phenomenon is missed due to which the pore/crack closure is slight in the compaction stage. In this stage, some pore deformation is irreversible, which is demonstrated by an irreversible resistivity change after unloading.

(2) With the increasing stress in the elastic deformation stage, most of the pores are closed. The conductive pathway is narrowed with increasing stress at the elastic stage, so the resistivity increases at this stage for all granite samples with high and low porosities. In this stage, the deformation of the granite sample is almost reversible, and the resistivity is also reversible after unloading.

(3) As the stress increases to crack damage stress, the resistivity reaches its maximum. The volume of pores and especially cracks increases once the applied stress exceeds crack damage stress, which provides enough volume for the convergence of conductive water to form a dominant conductive pathway. Thus, the resistivity starts to decrease once the applied stress exceeds crack damage stress. The maximum of resistivity and the followed decreasing trend during loading is meaningful for in situ geotechnical engineering monitoring, which is the potential precursor for geotechnical engineering failure.

(4) At the stage when the stress approaches the failure stress and at the post-failure stage, macro-cracks penetrate, and the rock breaks into pieces. Macro-cracks abound in the rock. The void volume is too large to be filled with pore

| samples | treatment temperature (°C) | crack closure stress (MPa) | crack damage stress (MPa) |
|---------|-----------------------------|---------------------------|--------------------------|
| T100    | 100                         | —                         | 84                       |
| T300    | 300                         | —                         | 79                       |
| T500    | 500                         | 8                         | 85                       |
| T700    | 700                         | 1.5                       | 25.6                     |

“Note: “—” means that the corresponding critical stress is not suitable using the method.

Figure 7. Mechanism of the evolution of resistivity under compression.

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water in the rock, and the dominant conductive pathway is destroyed, so resistivity increases significantly from the peak stress to residual stress.

As analyzed above, the resistivity during compression is determined by the variation of pores and cracks. Herein, the resistivity is analyzed using the volume of pores and cracks during compression. Crack volume strain is determined using

\[ \varepsilon_v^c = \varepsilon_v - \frac{1 - 2\nu}{E} (\sigma_l - \sigma_i) \]  

(2)

where \( \varepsilon_v = \varepsilon_1 + 2\varepsilon_3 \) is the volume strain, \( E \) is Young's modulus, and \( \nu \) is the Poisson ratio. Crack volume strain determined using eq 2 is shown in Figure 8.

For the rock during mechanical compression, the volume of pores and cracks is given as

\[ \phi = \varepsilon_v^c + \phi_i \]  

(3)

Saturation is the ratio of the volume of water to the volume of pores and cracks in the rock, given as

\[ S = \frac{V_w}{\phi V_r} = \frac{V_w}{(\varepsilon_v^c + \phi_i) V_r} \]  

(4)

where \( V_w \) is the volume of water, \( V_r \) is the volume of the rock and \( \phi_i \) is the initial porosity before compression.

Substituting eq 3 and eq 4 into eq 2, the Archie equation for rock under compression can be expressed as

\[ \rho = \rho_0 (\varepsilon_v^c + \phi_i)^{m-\alpha} V_r^{\alpha-\alpha} V_w^{\alpha} \]  

(5)

According to eq 5, the calculated resistivity is shown in Figure 9, and the measured resistivity is also shown for comparison. In general, the calculated resistivity can roughly capture the characteristics of measured resistivity, such as resistivity decreasing at the initial loading stage and increasing significantly at failure stress. However, the calculated resistivity is unable to capture the evolution of resistivity as first decreasing and then increasing before crack damage stress. This contributed to the difference in the conduction mechanism between the rock pore and rock crack. The Archie equation is good for resistivity porous medium characterization but not suitable for the resistivity of the fractured medium with an anisotropic structure caused by mechanical loading (deformed pores and induced cracks). Meanwhile, the result demonstrates that the resistivity measurement method is more sensitive for stress than for crack volume strain. Overall, pores and cracks are variable during compression, and the Archie equation is unable to analyze the process.

Results show that resistivity is very sensitive to stress and show the variation of pores and cracks (damage state) in the rock. This has good application potential in many engineering, such as in rock slope stability monitoring and excavation damage quantification. However, as outlined in the analysis above, more attention needs to be paid to carefully analyze the loading-unloading process, the variation in water saturation, and the anisotropy and homogeneity of pore/cracks in the rock mass. Only after careful consideration of these influencing factors can reasonable results be derived.

5. CONCLUSIONS

Resistivity of granite samples with different porosities during the entire compression process after being treated at different temperatures was measured. The following conclusions can be drawn.

(1) Resistivity can be used for thermal damage quantification. The resistivity decreases with increasing porosity of granite after treatments at different temperatures.

(2) For granite samples with different porosities, resistivity is very sensitive to stress under compression, which is characterized as decreasing at the initial loading stage, followed by increasing at the elastic stage, then decreasing from crack damage stress, and finally increasing significantly at failure stress.

(3) Resistivity has good capability for critical stress identification. The resistivity evolution response was quite different in the pore closure stage, elastic deformation stage, and unstable cracking stage during the loading-unloading process, which is useful in damage/stress state identification in field monitoring using resistivity measurement.

(4) The conduction mechanism of the rock changed with pore shape deformation and the development of cracks during compression. Under stress lower than crack damage stress, the change of the pore shape and porosity dominates conduction, while the development of cracks dominates under higher stress.

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Figure 8. Crack volume strain.

Figure 9. Comparison of calculated resistivity with measured resistivity.
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Notes
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