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AN INVESTIGATION OF THE MICROSTRUCTURE OF FROZEN SOIL AT FATIGUE FAILURE UNDER DYNAMIC CYCLING LOAD WITH CONFINING PRESSURE

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Abstract

The micro-mechanism of frozen soil fatigue failure has been discovered based on the analysis of microstructure observations of frozen soil fatigue failure under dynamic cycling load with confining pressure using an electron scanning microscope. It includes aggregate particle fragmentation and alignment and the development of micro-cracks. With the variation of load cycling frequency, confining pressure, and vertical cycling load, the frozen soil has a gradual changing pattern of microstructures, and the frozen soil fatigue failure changes from fragile failure to plastic failure, and again to fragile failure.

Introduction

Frozen soil, as a multi-phase system, consists of aggregate particles, ice, water and air, and has its unique mechanical properties compared with unfrozen soil. Studies of these properties have broadened from static to dynamic. In turn the study of the dynamic properties including fatigue failure of frozen soil has expanded from simple analysis of the correlation between the mechanical strengths and influencing factors to discovery of mechanisms. Research tools such as electronic scanning microscope, electronic transmission microscope, and even computer tomography (CT) have been used to examine the mechanical properties of frozen soil by some researchers(Wu et al., 1995; Wu, 1996). Among these techniques, the electronic scanning microscope has been widely used in the study of microstructures in unfrozen soil (Chen, 1997), and the micromechanism analysis of static properties of frozen soil under different stress conditions (Ma et al., 1995; Zhu et al., 1995; Shen et al., 1996; Wang et al., 1996).

In this paper, fatigue failure tests of frozen silt clay soil samples taken from the Fenghuo mountains on the Qinghai-Tibet plateau were carried out with the condition of T=-2°C, low dynamic load cycling frequencies and low confining pressures. From analysis of the frozen soil microstructure observations, the test conditions, and the macro-features of frozen soil samples at fatigue failure, the mechanism for fatigue failure of frozen soil under dynamic cycling load with confining pressure was discovered. As far as the authors are aware, no similar research on the micromechanism of dynamic properties of frozen soil has been undertaken.

Preparation of samples

Frozen silty clay soil samples for the experiment were prepared as follows:

The soil was dried, ground and sieved. It was wetted, moulded, and saturated with distilled water in a vacuum for 2 hours, and frozen for 24 hours with its bulk density (γ) required to be 2.01g/cm^3, and its water content to be 21.1%. It was then cut into samples of 61.8 mm in diameter and 150 mm in height, and stored at the required temperature for 48 hours prior to the fatigue failure test.

Table 1. Results of frozen soil fatigue failure test under dynamic cycling load (T=-2°C)

Samples No.	Load cycling frequency f(Hz)	Confining pressure σ_3 (MPa)	Vertical load P_{min}, P_{max} (kN,kN)	Total load cycling time (min)	Total load cycles N	Min. strain rate $\Delta(s^{-1})$	Macro-feature of sample surface	Figures No.
FHS-192	1	1.0	0.1, 2	648.8	38933	$0.175*10^{-7}$	no obvious cracks and extrusion	2
FHS-193	5	1.5	0.1, 4	31.4	9343	$0.395*10^{-4}$	extrusion but no obvious cracks	3 & 4
FHS-194	5	2.0	0.1, 8	1.9	599	$0.422*10^{-3}$	obvious vertical cracks and slight extrusion	5 & 6

There are still some technical problems in making samples for direct observation of frozen soil microstructure at negative temperatures, so observations of frozen soil microstructure are made indirectly from the traces of frozen soil microstructures that are left and duplicated on dry films of chloroform colloid covering the cross-sections of the tested frozen soil samples, the so-called "replicating method".

Immediately after the test, the frozen soil samples are moved into the rooms at the same sub-zero temperatures as those of the samples before the test. The soil samples are split into pieces, and the 5% chloroform colloidal solution is poured slowly on the fresh cross-section. The samples covered with these films are then dropped into water to separate the films from the samples. After 2 days, the films are dried, and are cleaned with a soft brush in running water. They are then dried again and finally plated with gold powder.

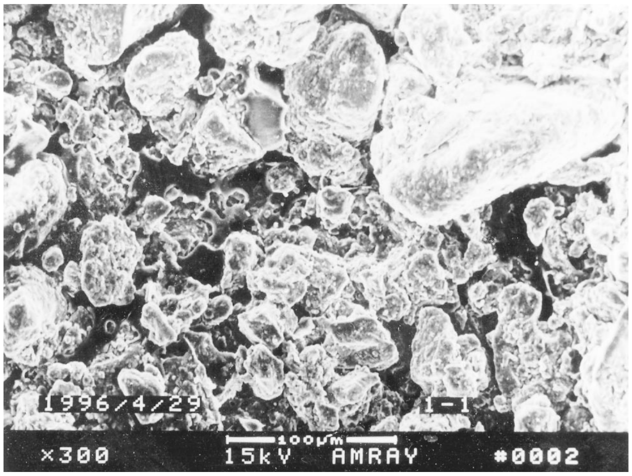

Figure 1. Microstructure of frozen soil sample FHS-191 before fatigue test: Aggregate particles are of uneven size and disordered; most voids are large and filled with ice; the structure is loose; no micro-cracks exist in soil. (x 300).

Results and analysis

The experimental conditions, results and the macro-features of frozen soil after the fatigue failure test are shown in Table 1.

From this table, it is clear that with an increase of confining pressure, especially the vertical load and load cycling frequency, the total cycles of vertical load to frozen soil fatigue failure decrease rapidly. In addition, the minimum strain rate increases, and the samples deform with vertical cracks. Changes in macroscopic features reflect the interior microstructure of frozen soil. Therefore, the microscopic mechanism of frozen soil fatigue failure under dynamic cycling load can be discovered by analysing the results of frozen soil microstructure under an electronic scanning microscope.

The microstructures of frozen soil samples under dynamic cycling load before and after the fatigue test are shown in the attached photos (Figures 1-6).

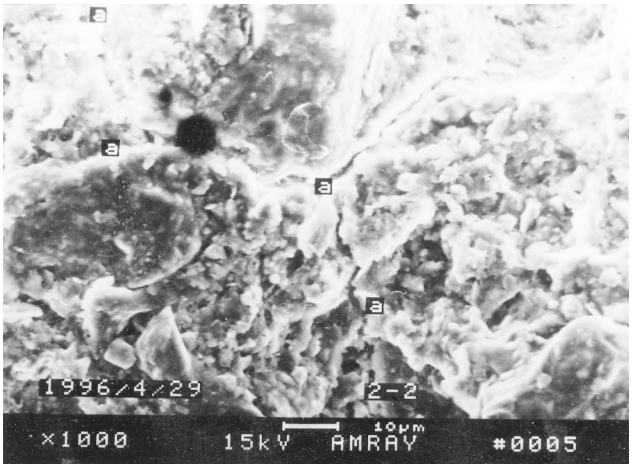

Figure 2. Microstructure of frozen soil sample FHS-192 at fatigue failure with test condition of
T=-2°C, σ_3=1.0 MPa, f=1 Hz, P_{min}=0.1 kN, P_{max}=2 kN:
Micro-cracks develop in an X shape along some aggregate particles, and cut through others; fragmentation of aggregate particles is not obvious. (x 1000).

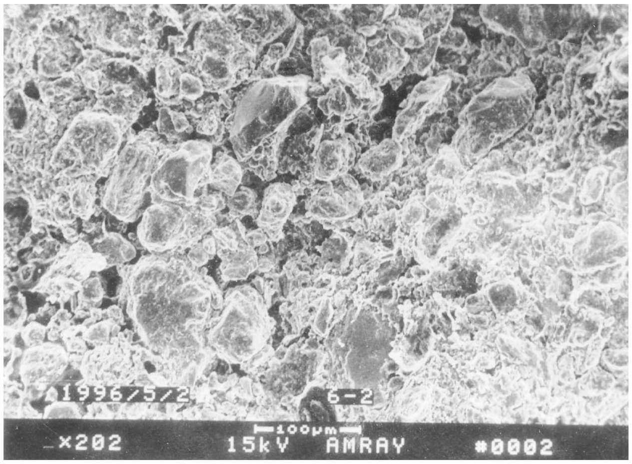

Figure 3. Microstructure of frozen soil sample FHS-193 at fatigue failure with test condition of
T=-2°C, σ_3*=1.5 MPa, f=5 Hz,* P_{min}*=0.1 kN,* P_{max}*=4 kN:*
Aggregate particles have slid along ice, and alignment of long axes is clear; fragmentation of particles is widespread. (x 200).

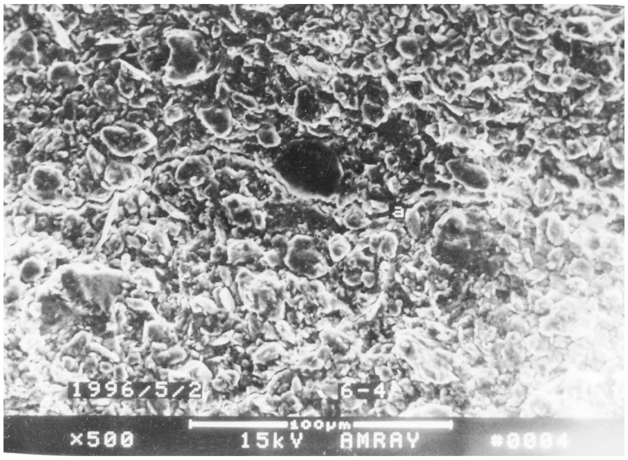

Figure 4. Microstructure of frozen soil sample FHS-193 at fatigue failure with test condition of
T=-2°C, σ_3*=1.5 MPa, f=5 Hz,* P_{min}*=0.1 kN,* P_{max}*=4 kN:*
Fragmentation of aggregate particles is obvious; micro-cracks develop along aggregate particles with narrow and short extension. (x 500).

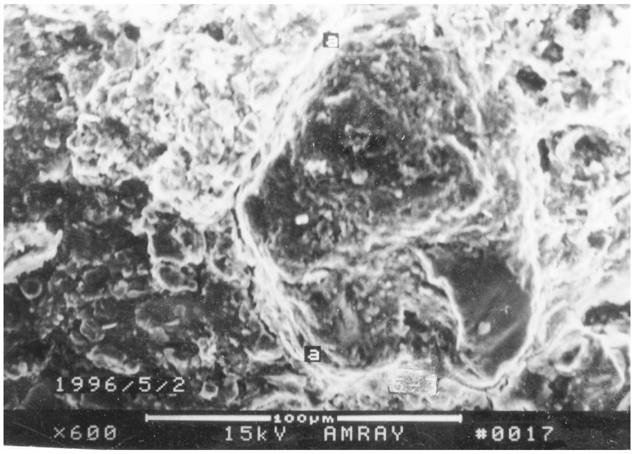

Figure 5. Microstructure of frozen soil sample FHS-194 at fatigue failure with test condition of
T=-2°C, σ_3*=2.0 MPa, f=5 Hz,* P_{min}*=0.1 kN,* P_{max}*=8 kN:*
Micro-cracks develop, partially cut through particles; some shear-torsion traces can be seen; fragmentation of particles around micro-cracks is very obvious. (x 600).

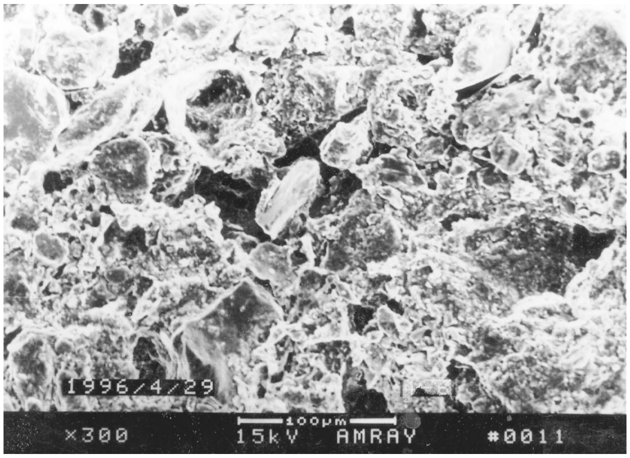

Figure 6. Microstructure of frozen soil sample FHS-194 at fatigue failure with test condition of
T=-2°C, σ_3*=2.0 MPa, f=5 Hz,* P_{min}*=0.1 kN,* P_{max}*=8 kN:*
Fragmentation of aggregate particles is severe, large aggregate particles are rare; some particles are partially aligned. (x 300).

Figure 1 shows the microstructure feature of frozen soil samples FHS-191 before the fatigue test. The frozen soil has following microstructure features: the aggregate particles are massive, different in size, disordered, and ice-linked; many of them have flat surfaces, and they are mostly in surface contact; some large voids are filled with ice. These features show that the microstructure of frozen soil under the sample-making conditions has the characteristics of uneven particle distribution with voids filled with ice and water.

Figure 2 shows the microstructure of frozen soil sample FHS-192 after fatigue failure with the test condition: T=-2°C, σ_3=1.0 MPa, f=1 Hz, P_{min}=0.1 kN, P_{max}=2 kN. Two groups of micro-cracks have developed in an X shape with an angle of $45°\pm\Phi/2$ to the largest stress, which is actually the largest dynamic shear stress in frozen soil. The micro-cracks have generally developed and extend along the boundaries of frozen soil particles, few soil particles are cut by them, and there are no particles being obviously fragmented. All of these features are caused by the small vertical cycling load, small confining pressure and slow load cycles. This loading condition results in a long acting and cycling time of vertical load on frozen soil sample (648.8 minutes) and more load cycles (38933). The small strain rate of the soil sample in the test means that there was only a small deformation in frozen soil. Most of the deformation occurs in voids, but some large uneven deformation develops into micro-cracks cutting through some particles. Neither fragmentation, nor features indicating that particles slide along ice planes in a certain direction occurs. This demonstrates that the type of fatigue failure is fragile failure without fragmentation of aggregate particles.

Figures 3 and 4 show the micro-structure of frozen soil sample FHS-193 after fatigue failure with the test conditions: T=-2°C, σ_3=1.5 MPa, f=5 Hz, P_{min}=0.1 kN, P_{max}=4 kN. Compared to the microstructure of sample FHS-192, it can be seen that with the increase of confining pressure from 1.0 MPa to 1.5 MPa, load cycling frequency from 1 Hz to 5 Hz, maximum vertical cycling load from 2 kN to 4 kN, the load cycling time has shortened greatly from 648.8 minutes to 31.4 minutes. The load cycles have also decreased sharply from 38933 to 9343, and the strain rate has increased significantly from $0.175 \bullet 10^{-7}$/s to $0.395 \bullet 10^{-4}$/s. At fatigue failure, the sample has the following microstructure characteristics: some aggregate particles have slid along ice, and have a preferred long-axis orientation; some fragmentation of particles has taken place, even in-between the particles; aggregates have become very rare; some narrow and short discontinuous micro-cracks have developed along the boundaries of particles, and cut through others. These features are a reflection of larger vertical cycling load with longer cycling time, more load cycles and larger confining pressure. The fatigue failure of frozen soil belongs to a type of plastic failure with aggregate particles being obviously fragmented.

Figures 5 and 6 show the microstructure of frozen soil sample FHS-194 after fatigue failure with the test condition: T=-2°C, $\sigma3$=2.0 MPa, f=5 Hz, P_{min}=0.1 kN, P_{max}=8 kN. The further increase of confining pressure, together with increased vertical cycling load and cycling frequency, have shortened the vertical load cycling time to only 1.9 minutes, and decreased the total load cycles to 599. The strain rate increased to $0.422 \bullet 10^{-3}$/s. The microstructure characteristics are as follows: some aggregate particles still exist in frozen soil, and some of them have been partially fragmented; there is a tendency for fragmented particles to align with one another; micro-cracks have developed along the boundaries of aggregate particles, and some of these are wide and long, the cracks cut through some aggregate particles, torsion appears in some sections of these micro-cracks, and there is fragmentation around and in the cracks. These features demonstrate that despite the higher load level than on samples FHS-192 and FHS-193, the aggregate particles do not have enough time to slide along ice and align only partially. This is because the load cycling time is short, and the load cycles are few. This loading condition also makes the fragmentation of aggregate particles rare; the fast strain rate of frozen soil causes micro-cracks to develop and is commonly accompanied by some torsion. The fatigue failure of frozen soil is a type of fragile failure with rare fragmentation of aggregate particles and limited alignment.

Conclusions

Compared with the disordered microstructure of frozen soil before the fatigue tests, the microstructure of frozen soil under dynamic cycling loads with different loading conditions, evolves with different degrees of aggregate particles fragmentation and sliding, and alignment along ice, and micro-cracks developing along boundaries of particles, and cutting through particles.

Microstructure characteristics of frozen soil at fatigue failure reflect several factors, including the confining pressure, the vertical load level and load cycling frequency. Increases in these factors result in gradual changes of microstructure at fatigue failure, and the fatigue failure types of frozen soil vary correspondingly from fragile failure to plastic failure, and again to fragile failure.

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