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Effects of transient axial stress or pore pressure disturbances on the permeability of Shikotsu welded tuff

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ABSTRACT: A persistent increase in the permeability of a rock mass caused by transient stress disturbances, when they exist, can explain the change in groundwater level as well as the petroleum production by seismic waves in the far-field. However, it has yet to be clarified whether the transient stress disturbances induce an increase or decrease in the rock permeability. To clarify the effects of transient stress disturbances on the rock permeability, permeability measurements were carried out on intact and triaxially fractured Shikotsu welded tuff, both before and after the occurrence of axial stress or pore pressure transient disturbances. Based on the experimental results, both types of stress disturbances showed an increasing effect on the permeability for fractured rocks. However, only the pore pressure disturbances showed an increasing effect for intact rocks. It can be estimated that rock masses consisting of glassy pyroclastic rock may exhibit an increase in the permeability through disturbances in the transient stress.

1. INTRODUCTION

Large earthquakes can cause persistent changes in the groundwater level in the near-field (within the fault length) (Wang and Chia, 2008; Orihara et al., 2014). Such groundwater changes are likely due to a persistent change in the permeability of the rock mass, which occur owing to the persistent strain change caused by the fault movement. Such a change may also occur in an intermediate-field (from one to multiple fault lengths) (Fujii et al., 2018a). However, it was shown that such persistent changes in the groundwater level may even occur in the far-field (many fault lengths), up to thousands of kilometers from the epicenter (Manga et al., 2012; Manga and Wang, 2015).

The persistent change in groundwater level in the far-field cannot be explained by the permeability change associated with the strain change owing to the fault movement, because the strain change in the far-field is transient. Manga et al. (2012) suggested that a persistent change in the groundwater level might rather be due to a persistent increase in rock mass permeability caused by transient stress disturbances from the seismic waves of an earthquake.

A persistent increase in the permeability of a rock mass caused by transient stress disturbances, if they occur, can

explain the increase in petroleum production caused by earthquakes or artificial vibrations (Pride et al., 2008; Roegiers, 2016) as well as that shown in enhanced oil recovery (Beresnev et al., 2005). Manga et al. (2012) also implied the possibility that seismic waves induce earthquakes in both the intermediate- and far-fields. Even the absence of $M \geq 8.4$ earthquakes during the period of 1966 to 2000, at which time the US and USSR frequently carried out underground nuclear explosion tests (Fujii et al., 2018b), might be explained by the induction of numerous small earthquakes. These were the result of the changes in rock mass permeability from transient stress disturbances caused by the seismic waves of the test explosions.

However, it has not been clarified whether the transient stress disturbances induce an increase or decrease in the rock permeability, as indicated in laboratory experiments. Tests on Berea sandstone demonstrated the increase in permeability of intact rock (Roberts, 2005) and fractured *in situ* rock under pore pressure disturbances (Elkhoury et al., 2011). Another experiment on three rock types, (limestone, basalt, and gabbro), working under axial stress disturbances induced an increase and decrease in permeability at high (130 – 250 °C) and low (20 °C) temperatures, respectively (Shmonov et al., 1999). Liu and Manga (2009) showed

that the fractured sandstone permeability decreased with the axial displacement.

Comparisons of the results from previous studies have been difficult to make, because the rock types differed from study to study, and the permeability was measured for only one rock condition (intact, fractured, or *in situ*), and for only one type of disturbances (pore pressure, axial displacement or axial stress) in each study.

In this research, however, the permeability of intact and triaxially fractured Shikotsu welded tuff were measured before and after the transient axial stress or pore pressure disturbances. Hence, the effects of transient stress disturbances on the rock permeability between the rock conditions and disturbance types could be clarified and compared between the rock conditions and disturbance types.

2. MATERIALS AND EXPERIMENTAL PROCEDURE

A block of Shikotsu welded tuff with a porosity of 32% (Table 1) was taken from Sapporo, Japan. The glassy rock sample, which originated from pyroclastic deposits from the eruption of the Shikotsu volcano 40,000 years ago, is predominantly composed of plagioclase, hypersthene, augite, hornblende, and transparent volcanic glass having a felt-like structure in the matrix. The mineral grain sizes are between 0.3–1.5 mm for plagioclase, approximately 0.5 mm for hypersthene, 0.3–0.7 mm for augite, and 0.5–1.0 mm for hornblende (Doi, 1963).

Cylindrical specimens (30 mm diameter, 60 mm height) were drilled from a block of the Shikotsu welded tuff along the slowest (1.67 km/s) P-wave velocity direction. The velocities in the other two perpendicular directions were 1.82 and 2.11 km/s. The specimens were dried at 353K in an oven for approximately two days before being vacuum saturated in pure water. Each specimen was connected to a pair of stainless-steel end-pieces with a center hole to allow water to flow through the specimen. A coating of silicon sealant was applied to the lateral surface of each specimen to maintain the water flow within the specimens. Heat-shrink tubing was used to jacket the specimen with end-pieces to prevent direct contact of the confining fluid with the specimen. Each jacketed specimen was vacuum saturated again for 24 h and placed in an ultracompact triaxial cell (Alam et al., 2014). Transient disturbances of the axial stress or pore pressure were applied to the intact specimens, followed by the triaxially fractured specimens (Fig. 2).

Nearly rectangular axial stress disturbances were applied with pore pressures of 0.1 and 0.5 MPa and a confining pressure of 5 MPa (Fig. 2a). Axial stress disturbance amplitudes of zero or 8 MPa at 0.05 Hz for 200 s were

Table 1. Physical properties of rock samples shown as average value (number of specimens) $\pm$ standard deviation.

Shikotsu welded tuff		
Properties	Dry	Saturated
Porosity (%)	31.65 (18) $\pm$ 1.65	
Density (g/cm ³)	1.30 (18) $\pm$ 0.01	1.62 (18) $\pm$ 0.02
V_p (km/s)	2.14 (18) $\pm$ 0.07	1.92 (18) $\pm$ 0.14

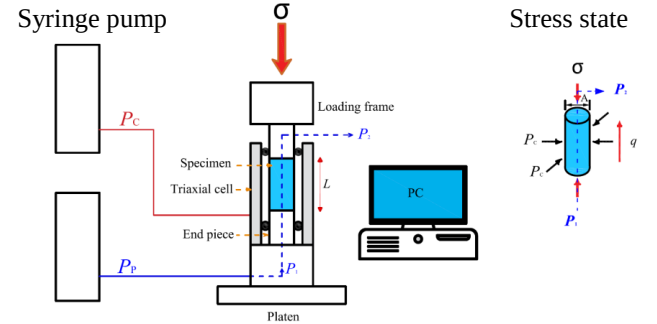
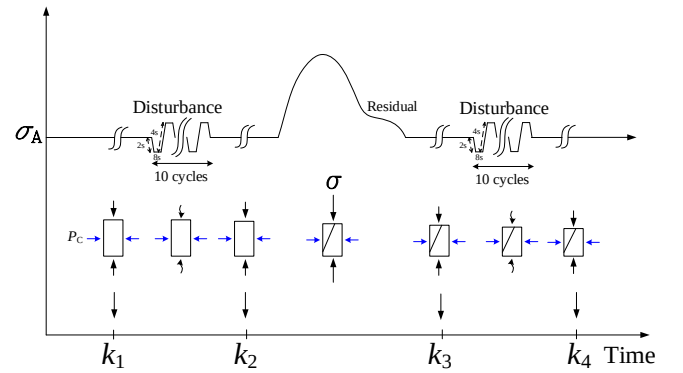
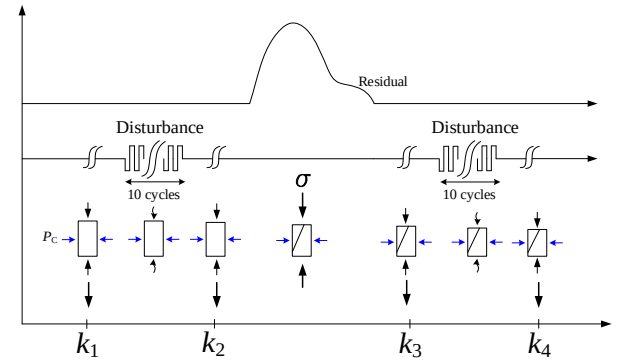


Fig. 1. Permeability measurement apparatus.



(a) Axial stress disturbances



(b) Pore pressure disturbances

Fig. 2. Experiment procedure.

applied (Table 2). The same pore pressures, confining pressure and disturbance frequency were used for the rectangular transient pore pressure disturbances (Fig. 2b). The applied disturbance amplitudes were between zero and 0.8 MPa.

The triaxial compression rate was set at 10^{-4} s^{-1} (0.36 mm/s), considering the high permeability. The axial

stress disturbances would not have caused pore pressure disturbances inside a specimen even for intact rock, because of their high permeability.

The permeability of the intact rock before and after the transient stress disturbances in the pre-failure regime (k_1 and k_2 , respectively), and those of the fractured rock before and after the transient stress disturbances in the post-failure regime (k_3 and k_4), were evaluated by substituting the flow rate, which was calculated based on the changes of the water volume in the syringe pump for over 60 s (Fig. 2), into the following Darcy's equation.

$$k = \frac{q\mu}{A} \left(\frac{dp}{dx} \right)^{-1} \quad (1)$$

where k (m^2) is the permeability, q is the flow rate (m^3/s), μ is the fluid viscosity ($Pa \cdot s$), A is the cross-sectional area (m^2) of the specimen, and dp/dx is the pressure gradient (Pa/m). The viscosity of water (μ) is 9.57×10^{-4} ($Pa \cdot s$) at 295K, which is the air temperature of the testing room, which was kept constant with the aid of an air conditioner.

3. RESULTS

The Shikotsu welded tuff specimens failed in a ductile manner with slight-decrease in stress (Figs. 3a and 4a). The maximum stress was affected by neither the axial stress (Fig. 3b) nor the pore pressure disturbances (Fig. 4b) as shown by low correlation coefficients.

3.1. Axial stress disturbances

For the intact rocks, with the application of 0.5 MPa of pore pressure, the permeability increased under no axial

stress disturbances (Fig. 5a). When disturbances were applied (Fig. 5b), fluctuations in the permeability occurred (higher under the minimum axial stress, and lower under the maximum axial stress value). However, the increase in permeability was not affected by the amplitudes of the axial stress disturbance (Fig. 5c). Therefore, such an increase is due to the cleaning of the pore throats and the micro-pathways by the rapid water flow (Bai & Tien, 1997; Bergendahl & Grasso, 2000; Liu & Manga, 2009; Candela et al., 2014, 2015). The permeability showed a decrease through a failure, which is the same result presented by Alam et al. (2014) for the same rock type. This reduction in the permeability may be due to the crushing of the matrix, which consists of volcanic glass. The permeability further decreased in the post-failure rocks. This is due to the closure of the rupture planes and the clogging of the smallest apertures by fine particles over time. However, the reduction of k_4/k_3 (Fig. 5d) decreased as the axial stress disturbance amplitudes increased, which is due to the generation and unclogging of the microfracture paths (Elkhoury et al., 2006; Liu & Manga, 2009; Elkhoury et al., 2010; Manga et al., 2012).

Under a pore pressure of 0.1 MPa, the permeability decreased from k_1 to k_2 and k_3 (Figs. 6a and b). The reduced permeability from k_1 to k_2 (Fig. 6c) is almost constant with axial stress disturbance amplitudes for the intact rocks. This may suggest that the rock was slightly consolidated over time and that the water flow was not sufficiently rapid to clear out the pore throats. The permeability decreased for the fractured rocks at zero stress disturbances (k_3 to k_4 , Fig. 6d). However, the reduction decreased as the stress disturbances increased

Table 2. Experimental condition (P_C , confining pressure, P_p , pore pressure, $\Delta\sigma_A$, axial stress disturbance amplitude, ΔP_p , pore pressure disturbance amplitude, P_{p-min} , minimum pore pressure, P_{p-max} , maximum pore pressure).

Axial stress disturbances				Pore pressure disturbances									
Samples	$\Delta\sigma_A$ (MPa)	P_p (MPa)	P_C (MPa)	Samples	ΔP_p (MPa)	P_{p-min} (MPa)	P_{p-max} (MPa)	P_p (MPa)	P_C (MPa)				
AS-T1	0	0.5	5	Pp-T1	0	0.5	0.5	0.5	5				
AS-T2				Pp-T2									
AS-T3				Pp-T3									
AS-T4	8			Pp-T4	0.1	0.45	0.55						
AS-T5				Pp-T5									
AS-T6				Pp-T6									
AS-T7	0	0.1		Pp-T7	0.8	0.1	0.9						
AS-T8				Pp-T8									
AS-T9				Pp-T9									
AS-T10	8			Pp-T10	0	0.1	0.1	0.1					
AS-T11				Pp-T11									
				Pp-T12									
				Pp-T13	0.06	0.07	0.13						
				Pp-T14									
				Pp-T15									

(Fig. 6d), which was probably due to mechanisms similar to those of the 0.5 MPa case (Fig. 5d).

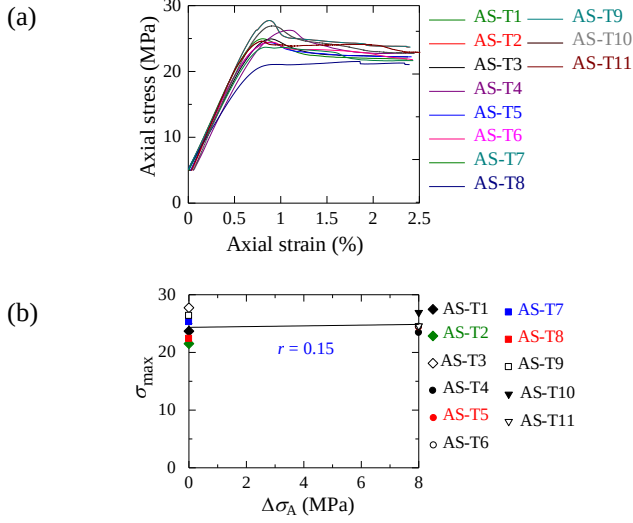


Fig. 3. (a) Stress–strain curves and (b) maximum stress (σ_{max}) vs. amplitude of the axial stress disturbances ($\Delta\sigma_A$).

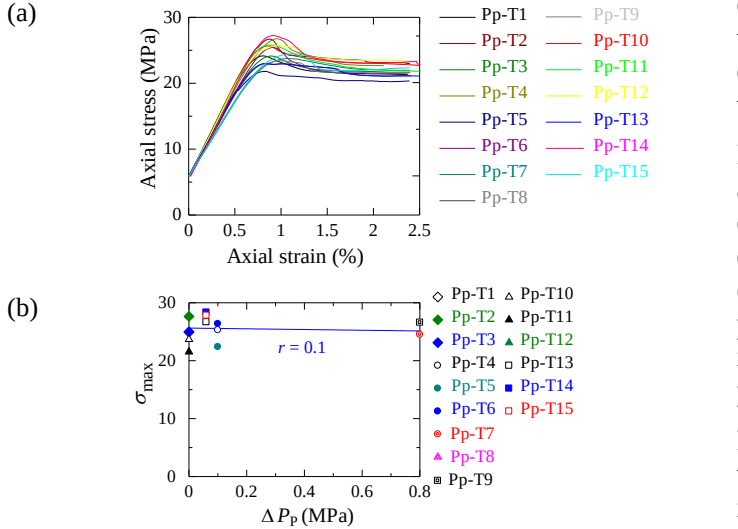


Fig. 4. (a) Stress–strain curves and (b) maximum stress (σ_{max}) vs. amplitude of the pore pressure disturbance (ΔP_p).

3.2. Pore pressure disturbances

The pore pressure disturbances applied under 0.5 MPa of pore pressure (Fig. 7) exhibited results similar to those of the axial stress disturbances, except that the permeability decreased and increased at the minimum and maximum pore pressures, respectively (Figs. 7b and c). Further, the increased permeability also increased also in the pre-failure regime (k_1 to k_2 , Fig. 7d).

The results under a 0.1 MPa pore pressure (Fig. 8) were also similar to those of the axial stress disturbances. However, the effects of the disturbances were not clear because the amplitude of the pore pressure disturbances at a pore pressure of 0.1 MPa was only 0.06 MPa. Fundamentally, these results demonstrate the good repeatability of the tests, except for a reduction of the

permeability from a rock failure, which varied from specimen to specimen.

The value of k_2/k_1 with zero disturbances was found to be less than that under a pore pressure of 0.1 MPa and greater than that under a pore pressure of 0.5 MPa (Fig. 9a). This is the same result found for the axial stress disturbances and indicate that, for the intact rocks, a higher pore pressure promotes a more rapid flow that clears out the trapped particles in the pore throats (Brodsky et al., 2003; Roberts, 2005). Fractured rocks experience a greater reduction in the permeability with a lower pore pressure (Fig. 9b), which may suggest that more particles are accumulated owing to the slower water flow.

4. DISCUSSION

The experimental results are summarized in Table 3.

In the post-failure regime, the permeability showed a decrease without stress disturbances and the stress disturbances themselves showed the effect of increasing the permeability except for the case of the pore pressure disturbances at 0.1 MPa, P_p , in which the amplitude of the pore pressure disturbances were extremely small.

In the pre-failure regime, the permeability showed either an increase or decrease without the stress disturbances depending on the pore pressure level. The axial stress disturbances induced no permeability changes. The effect of the pore pressure disturbances under a pore pressure of 0.1 MPa is again not clear. However, the increase amount of permeability increased with pore pressure disturbances under a pore pressure of 0.5 MPa.

From the above experimental results, it can be estimated that the stress disturbances basically have the effect of increasing permeability, and the effect is stronger in the post-failure than in the pre-failure regime. This occurs because the unclogging effect is more effective for a triaxially crushed volcanic glass matrix than for an intact matrix. It can also be estimated that the effect from the pore pressure is stronger than from the axial stress disturbances because the pore pressure isotropically enlarges the water flow path, thereby removing particles, and the axial stress disturbances act only in the axial direction.

Considering that the effects of the transient stress disturbances of rock masses differ from those of intact rocks but are not significantly different from those of fractured rocks, and considering that similar effects are likely to occur for similar rock types, the permeability of rock masses consisting of glassy pyroclastic rocks may increase through the transient stress disturbances.

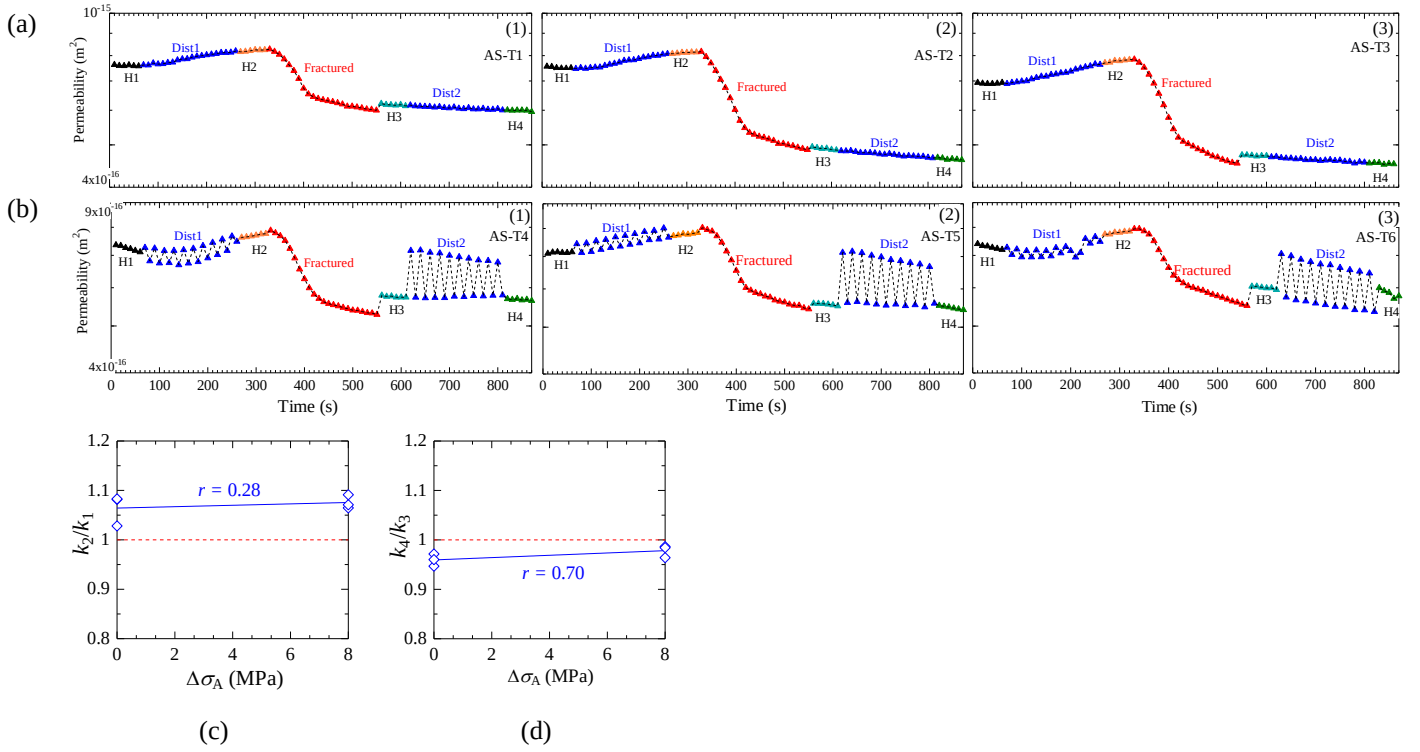


Fig. 5. Permeability changes (a) with no disturbances, and (b) with $\Delta\sigma_A = 8$ MPa, and the average permeability ratio for the (c) intact or (d) fractured rocks ($P_P = 0.5$ MPa) owing to transient axial stress disturbances and triaxial compression. H1, H2, H3 and H4: the permeability variation during a state of constant hydrostatic stress; Dist1 and Dist2: first and second disturbances, k_1 , k_2 , k_3 and k_4 : the average permeability under each state of constant hydrostatic stress, respectively.

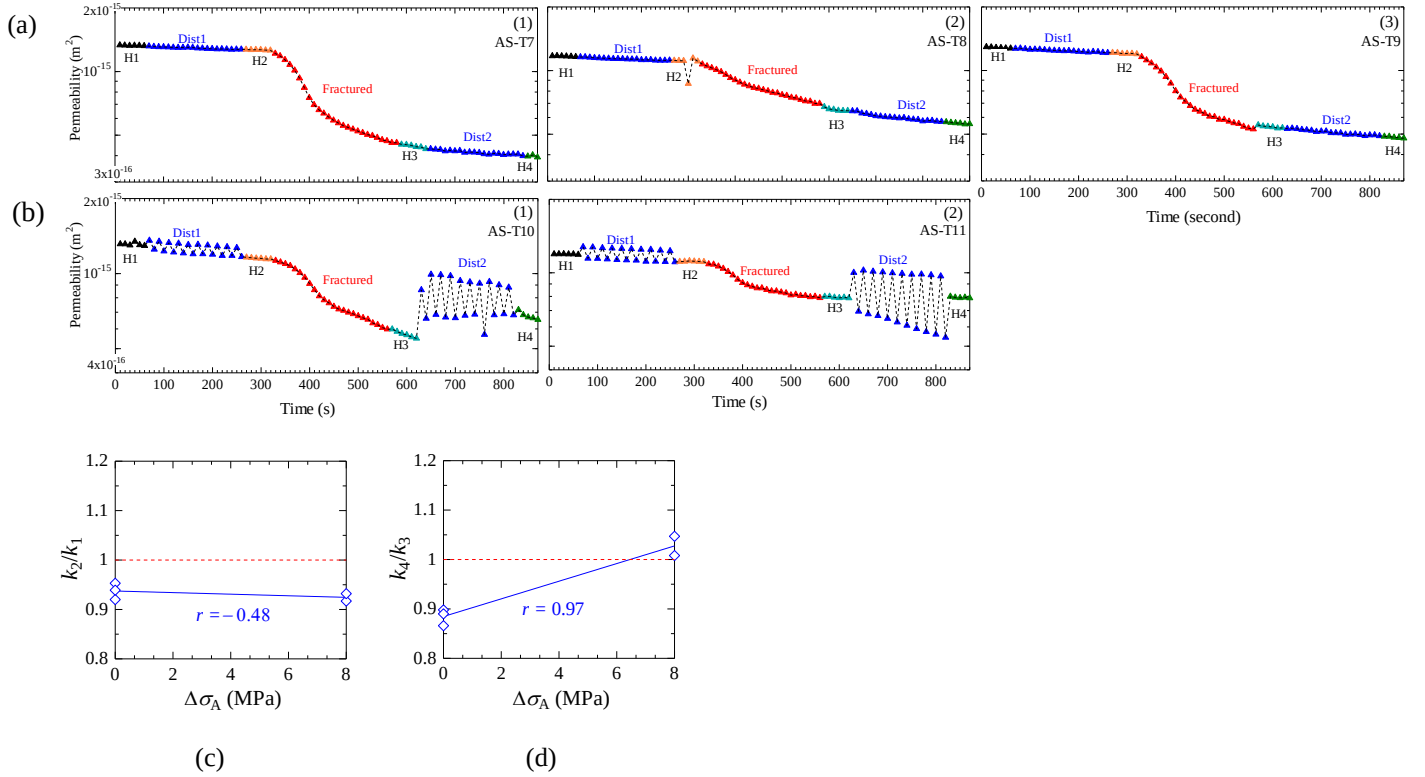


Fig. 6. Permeability changes (a) with no disturbances, and (b) with $\Delta\sigma_A = 8$ MPa, and the average permeability ratio for the (c) intact or (d) fractured rocks ($P_P = 0.1$ MPa) owing to transient axial stress disturbances and triaxial compression.

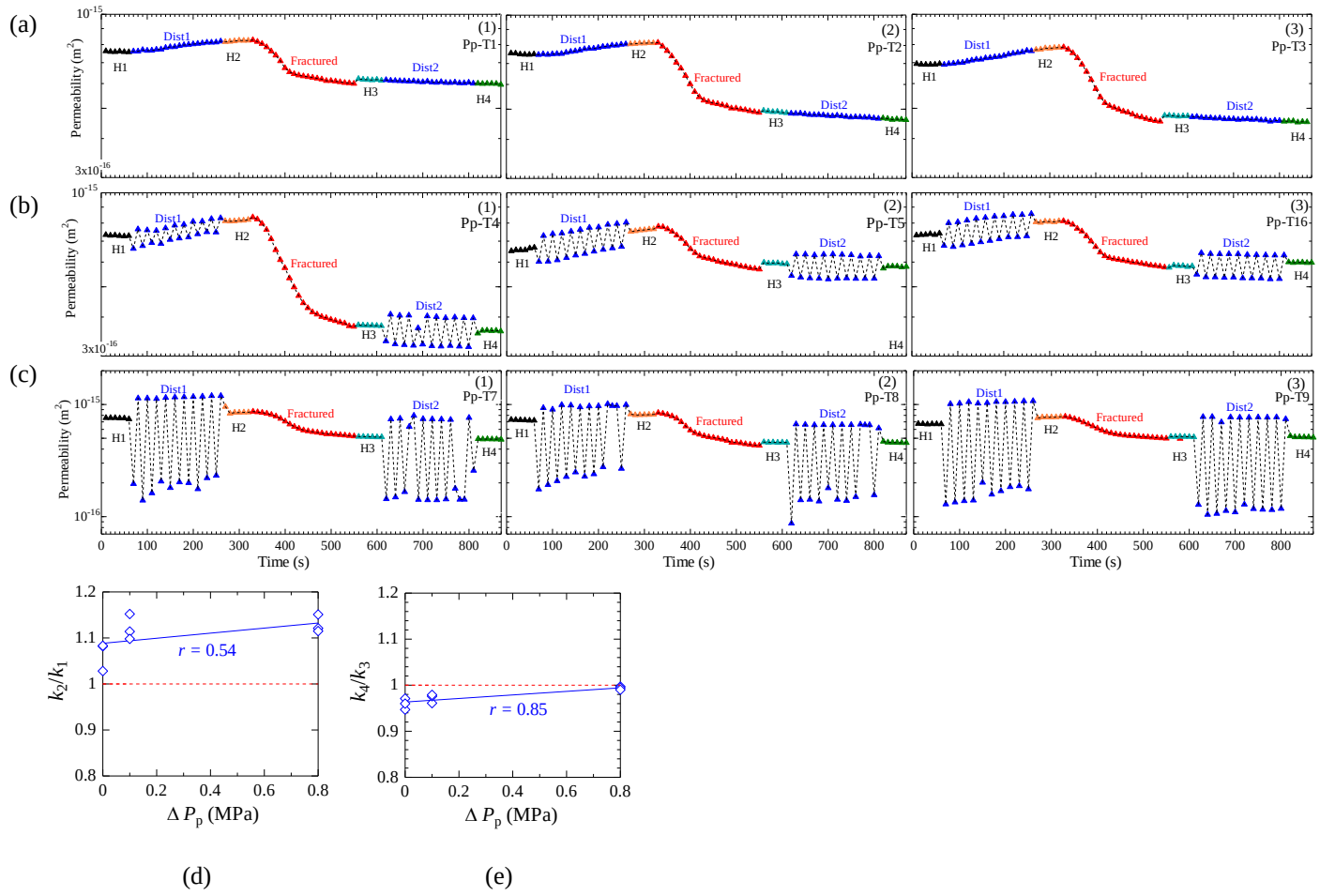


Fig. 7. Permeability changes (a) with no disturbances, (b) with $\Delta P_p = 0.1$ MPa, and (c) with $\Delta P_p = 0.8$ MPa, and the average permeability ratio for the (d) intact or (e) fractured rocks ($P_p = 0.5$ MPa) owing to transient pore pressure disturbances and triaxial compression.

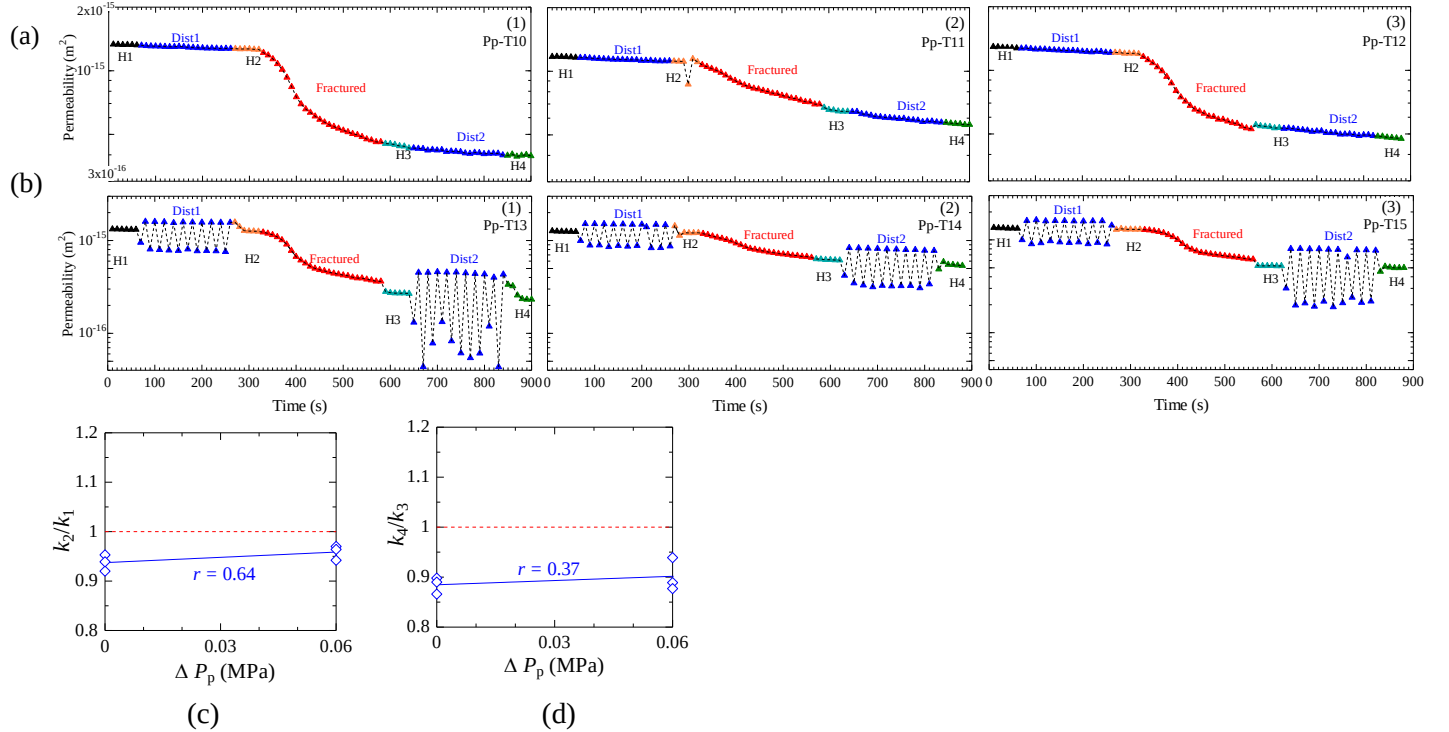


Fig. 8. Permeability changes (a) with no disturbances, and (b) with $\Delta P_p = 0.06$ MPa and the average permeability ratio for the (c) intact or (d) fractured rocks ($P_p = 0.1$ MPa) owing to transient pore pressure disturbances and triaxial compression.

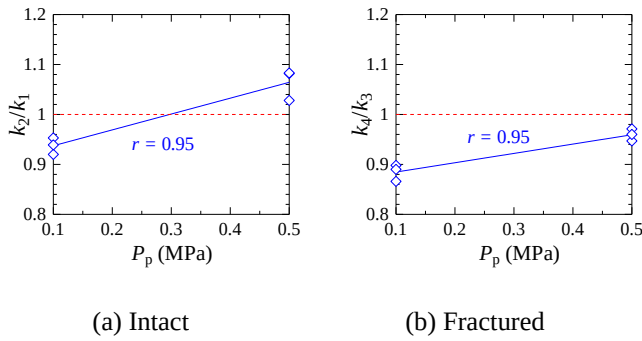


Fig. 9. Effects of pore pressure on the permeability ratio without stress disturbances.

Table 3. Summary of the changes in permeability for Shikotsu welded tuff.

Disturbances	Intact	Fractured
Axial stress		
Pore pressure		

5. CONCLUDING REMARKS

To clarify the effects of transient stress disturbances on rock permeability, permeability measurements were carried out on intact and triaxially fractured Shikotsu welded tuff before and after axial stress or pore pressure transient disturbances. According to the experimental results, both types of stress disturbances show an increasing effect on the permeability of fractured rocks. Only the pore pressure disturbances showed an increasing effect for the intact rocks. It can be estimated that rock masses consisting of a glassy pyroclastic rock may exhibit an increase in permeability through transient stress disturbances.

Permeability changes owing to transient stress disturbances have already been used as a seismic wave enhance oil recovery technique in which an increase in permeability from the movement of the entrapped fluid in the reservoir (Pride et al., 2008) is expected. An increase in the permeability may encourage its future utilization to enhance the natural gas recovery, prevent large earthquakes by inducing a large number of small earthquakes (Manga et al., 2012; Wang & Manga, 2009;

Fujii et al., 2018b), and reroute underground water flows for various purposes.

Further experiments on different rock types under various conditions, as well as investigations into the mechanisms of the permeability changes will assist the clarification of the effects of the transient stress disturbances. The persistency of the permeability changes, among other factors, should also be investigated in the future.

6. ACKNOWLEDGMENT

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