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Detection of deformation anisotropy of tuff by a single triaxial test on a single specimen

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ABSTRACT

Rock anisotropy has conventionally been determined by numerous tests using many specimens sampled at several orientations, however, it is both costly and time consuming. The anisotropic deformation properties (transversely isotropic elasticity and its dominant orientation) of a tuffaceous rock sample obtained in Utsunomiya city, Japan, and characterized by a clear bedding plane, were determined by a newly proposed method, namely, a single triaxial test using a single specimen. Using this method, the dominant orientations of anisotropy are determined by the principal orientations of the strain during isotropic consolidation, and the elastic parameters can be determined by stresses and strains during triaxial compression. This method required the implementation of a triaxial testing apparatus with a newly designed cap including a slider mechanism and low-friction sheets. The six components of the symmetrical, small strain tensors of the tuff specimen were measured using nine strain gauges, while the 3D principal strains were evaluated during uniaxial and consolidated drained triaxial tests. To verify the proposed method, the anisotropic properties of four specimens sampled from a cubic block at different orientations, as characterized by the proposed method, were compared with those determined by multiple uniaxial tests using the specimens sampled for different orientations. The strain responses of the uniaxial tests demonstrated that the Young's modulus of the tuff in the bedding orientation is 1.5 times greater than that for the perpendicular orientation. The orientation of the principal strains deviate from the loading orientation due to the orientation of the bedding plane, and the orientations during isotropic consolidation were inclined in accordance with the dip orientation of the bedding plane. Similar values were evaluated for each anisotropic property determined by both a single triaxial test on each specimen and multiple uniaxial tests. The obtained values demonstrated that the Young's moduli for the bedding orientation are 1.5–2.7 times larger than that in the perpendicular orientation.

1. Introduction

Rocks usually exhibit anisotropic deformation characteristics due to their sedimentary structure and the orientations of their mineral particles.[1] For example, the Young's moduli of crystalline schist can vary by a factor of 3 due to the dip angle of the mineral array[2]; those of tuff and chalk can vary by a factor of 2 due to the inclination of the bedding plane.[3,4] Thus, to accurately evaluate the deformation behavior of rock structures such as those that occur as a result of stress being released when excavating a tunnel, it is essential to understand the anisotropic properties of the rocks. Since deformation anisotropy has conventionally been determined by numerous tests using many specimens sampled at several orientations, it is both costly and time consuming. In addition, the orientations of anisotropy cannot always be determined by such tests because the dominant orientation of anisotropy may not be included in the sampling orientations of multiple specimens. For these reasons, a method of determining the anisotropy with a smaller number of tests is needed for the rational examination of rock structures.

The incremental relationship between stress and strain is non-coaxial for anisotropic materials. For this reason, the stress-strain relationship of an anisotropic rock specimen in a triaxial test is non-axisymmetrical to the loading axes, as shown in Fig. 1.[5] Such deformation, which reflects the inherent anisotropy of the materials, is never

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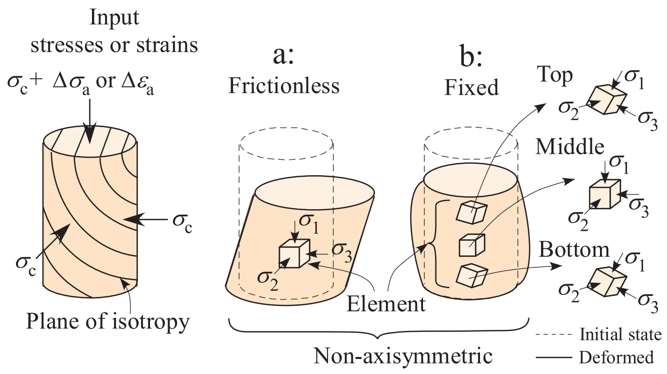

Fig. 1. Non-axisymmetrical deformation and stresses during triaxial compression due to boundary conditions at top and bottom of specimen.[5]

exhibited by isotropic materials. Thus, in our previous work,[5] we proposed a method for determining the anisotropic deformation properties and dominant orientations of anisotropy by utilizing such deformation in a single triaxial test and went on to confirm the validity of the method theoretically. In the aforementioned work,[5] we emphasized the importance of decreasing the friction at the top and bottom boundaries of the specimen because achieving a uniform distribution of stress and strain in the specimen, as shown in Fig. 1(a) is crucial to determining the elementary behavior of the specimen. Meanwhile, the deformation of the specimen becomes non-uniform due to the end friction, as shown in Fig. 1(b), thus preventing the inherent mechanical properties of the material from being analyzed easily.

In the present study, we performed a series of laboratory tests on tuff to check the validity of the method for determining the stiffness anisotropy, applying a single triaxial test to a single specimen.[5] A new cap with a sliding mechanism and low-friction sheets was developed and implemented to decrease the end friction in the triaxial testing apparatus. Three uniaxial tests and four consolidated-drained triaxial compression tests were conducted on tuff specimens taken from the same cubic block but at different orientations, and the strain responses were evaluated to understand the basic deformation properties of the tuff. Each test result produced by the triaxial test was then applied to the proposed method to determine the set of anisotropic parameters, such as the anisotropic stiffness and the orientations of anisotropy. The method was verified by comparing the four sets of parameters, obtained using the four tuff specimens sampled from the same block, with each other. The validity of the proposed method was further discussed by comparing the anisotropic stiffness, obtained using the ordinary method involving a set of uniaxial tests on three specimens sampled from the same block, with the bedding, the vertical, and 30° inclined orientations.

2. Method for determining anisotropic deformation properties and its verification

2.1. Testing apparatus including cap with sliding mechanism

Decreasing the friction at the top and bottom boundaries of a specimen in a uniaxial or triaxial test is important to the observation of the elementary response of anisotropic specimens. The two-dimensional finite element method (FEM) was applied to a transversely isotropic elastic body, as assumed in the case of an elementary test, was conducted as part of a previous study,[6] and the results indicated that the stiffness was not evaluated accurately due to the friction at the ends of the specimens. Hence, a cap with a sliding mechanism, which allows the free displacement of the top boundary of the specimen relative to the radial direction, as shown in Fig. 2(a, b), was developed. Furthermore, two Teflon sheets (coefficient of static friction ≒ 0.04)[7] with lubricant between them were installed at the top and bottom boundaries of the specimen. The cap consisted of upper and lower platens, between which ring-shaped ball bearings were installed, as shown in Fig. 2(a, b). Fig. 2(c, d) shows the testing apparatus incorporating this cap, which was used for both the uniaxial and triaxial tests in this study.

2.2. Specimens

Cylindrical specimens (diameter d = 50 mm and height h = 100 mm) were cored from a 30-cm cubic block of Tage tuff which is rhyolitic welded tuff of the Neogene/Miocene period. The tuff was sampled from a depth of 100 m in Utsunomiya, Japan. It features fewer black or dark brown spots (soft gravels) that contain montmorillonite and zeolite.[3] Although Oya tuff is a well-known rock found in the same region, it contains more soft gravel than the Tage tuff. The mechanical and physical properties of the Tage and Oya tuff have been extensively investigated as shown in Table 1.[8–15] In the table, the Young's modulus E was determined by a uniaxial compression test and consolidated drained (CD) triaxial test. The confining pressure dependence of the Young's modulus for the tuff is smaller at a lower stress levels ($\lesssim$ 7 MPa).[8,14] Tage tuff is stiffer than Oya tuff, and the porosity of Tage tuff is lower than that of Oya tuff. The physical properties, ρ_t, ρ_s, and n, were carefully examined as shown in Table 1, and were found to have little influence on the deformation behaviors due to anisotropy. In the present study, therefore, the wet density was investigated to confirm the variations between the specimens. As the block has apparent bedding planes that can be visually observed, as shown in Fig. 3(a), seven cylindrical specimens were taken, but at different orientations, as shown in Fig. 3(b). All the specimens were fully saturated by being immerse in water for 48 h before loading in accordance with the Japanese Geotechnical Standard (Japanese Geotechnical Society)[16] because the mechanical properties of the rock change significantly with their water content, as shown in Table 1. The variation in the wet densities, ρ_t, of the specimens proved to be very small at ρ_t = 1.72–1.79 g/cm^3. The specimens appear to have intermediate physical properties between Tage and Oya tuff, notably in terms of their density, as shown in Table 1. Both ends of the specimens were shaped with parallelisms of less than 0.05 mm.[17]

2.3. Uniaxial tests

To evaluate the basic mechanical properties of tuff, such as its stiffness in the bedding, perpendicular, and inclined orientations, uniaxial compression tests were conducted on three specimens for which the bedding planes were inclined from the axial loading direction by 0°, 90°, and 30°, respectively, as listed in Table 2. The test results were applied to Amadei's theoretical method,[18] which is a conventional method that uses three uniaxial test results to determine the parameters of transversely isotropic elasticity. The parameters obtained using the proposed method were compared with those obtained with the conventional method. In the tests, the specimen was covered by a rubber sleeve to prevent the lateral surface from drying out.

2.4. Triaxial tests

Consolidated-drained triaxial compression tests with the newly developed cap and low- friction sheets were conducted on four samples for which the bedding plane was inclined at 15°, 30°, 45°, and − 45°, respectively, as listed in Table 3. Four sets of parameters and the orientation of the stiffness anisotropy were obtained using the proposed method. Assuming an undrained condition, the deformation properties were regarded as being significantly changed by locally concentrated pore pressure. Thus, the drained condition during axial compression was adopted for the present study. First, the specimens were isotropically consolidated with a mean effective stress σ'_c = 1.0 MPa (cell pressure σ_c = 1.2 MPa, back pressure u_b = 0.2 MPa), for which the