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Creep failure of sands exhibiting various viscosity types and its simulation

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Abstract

The creep failure behaviour of three reconstituted sands exhibiting various viscous property types was evaluated by large-, medium- and small-scale drained triaxial, and medium-scale drained unconfined compression tests. The creep characteristics were evaluated by performing sustained loading during otherwise monotonic loading at a constant loading rate. Creep failure and Isotach viscous stress–strain behaviour were observed with well-graded Miho sand compacted heavily under the optimum water content condition. Creep failure of saturated and air-dried Toyoura sand exhibiting TESRA viscosity was observed at the nearly peak stress state. Degradation of the shear modulus of Toyoura sand during creep failure process was measured by the dynamic method. Creep failure did not occur with air-dried Albany silica sand exhibiting P&N viscosity. It was experimentally shown that the stability against creep failure was higher in order of P&N, TESRA and Isotach viscosities. The creep behaviour of various viscous property types was well simulated by the non-linear three-component model taking into account the effects of particle characteristics on the viscous property parameters.

Keywords: Creep failure; Viscous properties; Reconstituted sand; Dynamic measurement; Triaxial compression; Unconfined compression

1. Introduction

The evaluation of the residual deformation of ground and residual structural displacements for performance based design of civil engineering structures is often required. To this end, it is necessary to understand correctly the viscous properties of soils. Even though the long-term compression of sands and gravels is sometimes an important engineering issue (e.g., Di Benedetto et al., 2004; Jardine, et al., 2004; Day, 2005), there have been fewer studies on the viscous properties of unbound granular materials (GMs) than on clay (e.g., secondary consolidation). One of the reasons for this may be that unbound GMs tend to be considered practically nonviscous. However, according to some recent studies, unbound GMs exhibit significant creep deformation in drained triaxial compression (TC), plane strain compression (PSC), direct shear and torsional shear tests (e.g., Matsushita et al., 1999; Di Benedetto et al., 2002, 2004; Tatsuoka et al., 2002, 2008; Duttine et al., 2008, 2009; Enomoto et al., 2009) as well as in field full-scale cases (e.g., Oldecop and Alonso, 2007).

Creep is an important phenomenon from the engineering point of view since the failure of geomaterial occurs at a

Abbreviations: EDT, external displacement transducer; GMs, granular materials; LDTs, local deformation transducers; ML, monotonic loading; P&N, positive and negative; PSC, plane strain compression; SL, sustained loading; TC, triaxial compression; TESRA, temporary or transient effects of strain rate and strain acceleration; UC, unconfined compression

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certain stress level below its maximum strength. Creep behaviour leads to serious geotechnical problems such as residual settlement, landslides and failure. Therefore, the following studies on the creep failure behaviour of various types of geomaterials have been reported:

1) Creep failure behaviour of clay (e.g., Murayama and Shibata, 1958; Bishop, 1966; Campanella and Vaid, 1974): Campanella and Vaid (1974) revealed the effects of test methods on the behaviour by having conducted TC and PSC tests on undisturbed marine clay consolidated isotropically and unisotropically.
2) Creep failure of grouted sands in laboratory stress–strain tests: Their creep limit strengths were significantly smaller than the instantaneous unconfined compressive strengths (by a ratio of between about 10% and 50%). The creep limit strengths were dependent on the sand types, the properties of the grout, and the strain rate at which unconfined compression (UC) tests were performed (e.g., Koenzen, 1977; Borden et al., 1982; Littlejohn and Mollamahmutoglu, 1994; Delfosse-Ribay et al., 2006). On the other hand, limited studies have been published on pure sands. Murayama et al. (1984) conducted a series of drained TC tests on saturated pure Toyoura sand under constant mean effective principal stresses throughout shearing. It was reported that the primary creep was followed in some cases by tertiary creep, depending on the stress level.
3) Shibata et al. (2007) conducted a series of UC tests on tuffaceous rock under different temperatures from 24 °C to 95 °C. They showed that, with increasing temperature, the time until creep failure decreased while the minimum strain rate observed in the secondary creep increased.
4) Creep failure of sedimentary soft rock was studied by a series of drained TC tests (Aung et al., 2007). It was reported that the time until creep failure depended on the sustained stress level and that creep failure process started earlier when sustained loading (SL) was performed at a higher stress level.
5) Creep failure of gravelly soils: In some recent studies, creep failure was observed in a drained direct shear test on air-dried Chiba gravel (Duttine et al., 2010), and a drained TC test on moist compacted cement-mixed gravelly soil (Ezaoui et al., 2011). Ezaoui et al. (2011) showed that creep failure was one specific aspect of the whole viscous behaviour that could be simulated by the non-linear three-component model developed by Tatsuoka et al. (2008). This is a general and flexible elasto-viscoplastic model. In addition, Enomoto et al. (2015a) reported that creep failure of undisturbed gravelly soils occurred in drained TC tests and was simulated well in a consistent manner by the same model.

Despite these investigations, however, creep failure behaviour of unbound (i.e., pure) sands is not well understood. In particular, different viscous property types of sands may exhibit different creep characteristics. It is important, not only for practical application but also for fundamental research, to clarify their creep behaviour. In view of the above, in the present study, the creep characteristics of three types of unbound sands exhibiting various viscous property types were evaluated by a series of large-, medium- and small-scale drained TC tests and a series of medium-scale drained UC tests. The simulation of test results by the non-linear three-component model was also conducted under a consistent framework employed in the previous studies.

In laboratory stress–strain tests such as TC, PSC and UC, the creep failure process can be represented by three distinct stages as shown in the above-mentioned previous studies and the later session of this paper; the primary creep stage of decreasing strain rate, the secondary creep stage of constant strain rate and the tertiary creep stage of accelerating strain rate. Among those previous studies, for example, Shibata et al. (2007) defined the condition of creep failure in their experiments as the moment when the total axial strain during shearing followed by SL reached 2%. However, this definition is arbitrary, and depends on the tested materials and the testing methods among other factors. On the other hand, according to Campanella and Vaid (1974), it is reasonable to consider that the moment representing creep failure must be the terminal point in the tertiary creep stage on the time histories of strain and its rate. The definition of creep failure by Campanella and Vaid (1974) is also employed in the present study although it may depend on the apparatuses used (e.g., the capacities of the axial loading devices and the data acquisition components) due to a rather rapid compression of specimens.

Meanwhile, the small strain stiffness of geomaterials is also important in order to predict the instantaneous and long-term residual deformation of the ground/backfill and structural displacements, and is one of the important parameters that reflect the soil particle structure. By measuring the long-term changes in the small strain properties of the ground, backfills or slopes associated with their deformation, it may also be possible to predict geotechnical disasters such as landslides and failure. In view of the above, as a fundamental research, Enomoto et al. (2015a) investigated the changes in the shear moduli of undisturbed gravelly soils during the creep failure process by means of the laboratory wave-propagation tests. They reported that the soil particle structure was damaged noticeably after primary creep possibly due to the accumulation of irreversible strain. However, the changes in the small strain properties caused by creep failure are not well known. In the present study, to evaluate those changes in Toyoura sand during SL with and without creep failure, dynamic measurements were also conducted in the drained TC tests mentioned above.

2. Brief reviews of previous studies

2.1. Various viscous property types

According to the non-linear three-component model (Fig. 1), the stress (i.e., the measured effective stress), σ, is obtained by adding the viscous component, σ^v, to the inviscid (or rate-independent) component, σ^f, at the same ε^{ir} value. The total strain rate, $\dot{\varepsilon}$, is obtained by adding the irreversible (or inelastic or visco-plastic) component, $\dot{\varepsilon}^{ir}$, to the hypo-elastic component, $\dot{\varepsilon}^e$. A