Creep and Stress Relaxation Envelopes of Granular Materials in Direct shear

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Abstract. The behaviours of creep and stress relaxation (SR) during otherwise monotonic loading (ML) drained direct shear (DS) at a fixed shear displacement rate of air-dried specimens of three types of clean sand and a gravel having different particle shapes were evaluated and compared. As the particles become rounder, the grading becomes more uniform, the specimen becomes looser and the shear displacement becomes larger, the viscous property type deviates more from Isotach type. For the same duration of time, a SR envelope comprising multiple stress-shear displacement states reached by SR is always located considerably below the creep envelope reached by creep process. The difference becomes larger as the viscous property becomes less Isotach.

Keywords. creep, direct shear, granular material, stress relaxation

1. Introduction

A number of case histories demonstrated paramount importance of better understanding of the viscous properties of geomaterial for realistic prediction of ground deformation and structural displacements. The Isotach model (Suklje, 1957, 1969) can describe rather properly the rate-dependent stress-strain behaviour of many types of geomaterial comprising particles well bound or interlocked: e.g., undisturbed and reconstituted plastic clays; sedimentary soft rocks and cement-mixed soils (e.g., Hayano et al., 2001; Leroueil, 2006; Sorensen et al., 2007; Kongsukprasert & Tatsuoka, 2005; Ezaoui et al., 2010, 2011; Kongkitkul et al., 2007). Correspondingly, many elasto-viscoplastic constitutive models assuming the Isotach property have been proposed for geomaterials.

However, recent studies have revealed that the Isotach viscous property is only a specific type among others (Di Benedetto et al., 2002; Tatsuoka et al., 2002, 2008; Tatsuoka, 2011; Kongkitkul et al., 2008; Enomoto et al., 2009; Duttine et al., 2008, 2009; Duttine & Tatsuoka, 2009). The following four viscous property types have been identified with geomaterials in drained shear: Isotach, Combined, TESRA (Temporary Effects of Strain Rate and strain Acceleration) and P&N (Positive and Negative).

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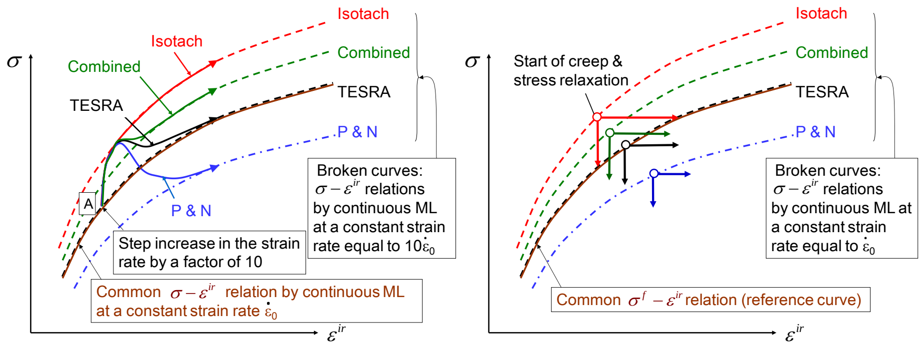
Isotach or combined type is observed with well-graded angular granular materials (GMs), TESRA type with poorly graded angular GMs and P&M with poorly graded round GMs. Upon a step increase in the shear strain rate (e.g., from $\dot{\varepsilon}_0$ to $10\dot{\varepsilon}_0$ at point A in Fig. 1a) during otherwise monotonic loading (ML) at a constant strain rate, the Isotach type material exhibits a persistent stress increase. Under loading conditions along a fixed stress path, a unique stress is defined for given instantaneous irreversible strain, ε^{ir}, and its rate, $\dot{\varepsilon}^{ir}$. The stress-strain relation by infinitely slow loading (i.e., $\dot{\varepsilon}^{ir} = 0$), which does not include any viscous effects, is called the reference relation (Fig. 1b). In Fig. 1b, a common reference relation is assumed for the four viscous property types. During creep at a given fixed stress and also during stress relaxation (SR) at a given fixed strain, after an infinitive long period, the stress-strain state reaches the reference relation with Isotach type.

With the other viscous property types (Combined, TESRA and P&N), the increase in the stress upon a step increase in the strain rate is 'temporary' (or 'transient'), which decays towards different residual values during subsequent straining. In Fig. 1a, a common stress-strain relation by continuous ML at the same strain rate ($= \dot{\varepsilon}_0$) is assumed for the four viscous property types. Then, the current stress state is determined not only by given instantaneous strain and its rate but also by strain history. The test results indicated that, with Combined, TESRA and P&N types, during creep and SR stages, the stress-strain state ultimately passes the reference relation as illustrated in Fig. 1b (Kongkitkul et al., 2008; Duttine et al., 2008; 2009; Duttine & Tatsuoka, 2009; Enomoto et al., 2009).



a) b)

Figure 1. Four different viscous property types of geomaterial in shear: different behaviors: a) upon a step increase in the strain rate from a common curve at the same strain rate; and b) during creep and stress relaxation during otherwise monotonic loading at a certain strain rate for a common reference curve.

Di Benedetto et al. (2002) and Tatsuoka et al. (2002, 2008) showed that the three-component model is relevant to simulate a wide variety of rate-dependent stress-strain behaviour caused by these viscous property types observed in triaxial and plane strain compression tests of GMs and this model can simulate both creep and SR behaviours. Fig. 2 shows this model modified to the DS test condition. Despite the above, systematic tests performing both creep and SR tests on geomaterials exhibiting different viscous property types are very limited (e.g., Lade et al., 2010; Lade & Karimpour, 2010). When using a displacement-control apparatus developed to perform ML tests at fixed strain rates, SR tests by simply fixing the displacement are much easier to perform than creep tests. Besides, the time needed reach the same stress-strain state relative to the ML stress-strain relation is much shorter in a SR test than in a creep test. For these reasons, it is very convenient if the long-term creep behaviour (and other rate-dependent phenomena) can be predicted from SR tests performed for a much shorter duration.

In the present study, to understand the processes of creep and stress relaxation (SR) and their relationship, effects of the viscous property type on the amount and rate of creep deformation and SR were evaluated by performing a series of drained direct shear tests on four types of granular materials (GMs). In the companion paper (Tatsuoka et al., 2015), it is examined whether the three-component model can simulate these test results in the consistent manner.

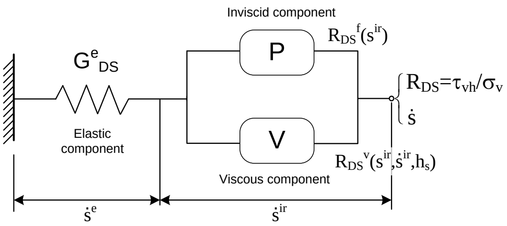
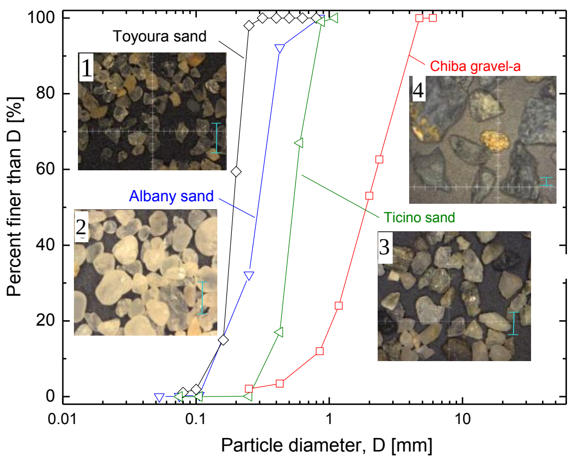


Figure 2. Non-linear three-component model adapted for the DS test conditions (Duttine & Tatsuoka, 2009).



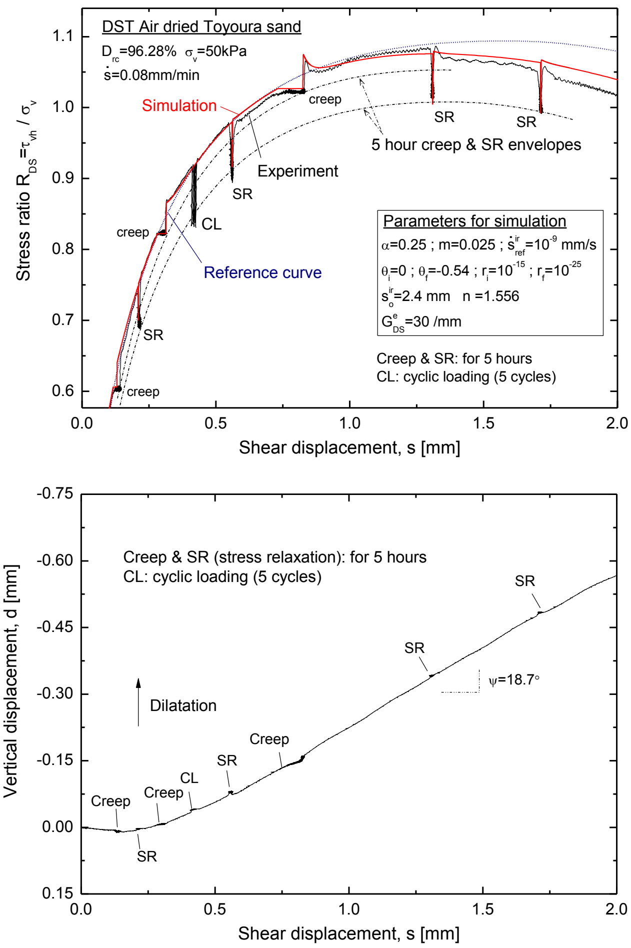
Material	G_s	D_{50} (mm)	U_c	e_{min} (1)	e_{max} (1)	A*(2)
Chiba gravel-a	2.74	1.93	3.05	0.602(*)	0.907(*)	1967
Toyoura sand	2.648	0.180	1.625	0.592	0.978	896
Ticino sand	2.680	0.527	1.521	0.590	0.960	449
Albany sand	2.671	0.300	2.200	0.505	0.804	209

(1) Determined following JIS A 1224:2009 (the Japanese Geotechnical Society).
(2) Total degree of angularity (Lees, 1964). (*) ± 0.016 (scatter due to relatively large particle size).

Figure 3. Granular materials used in this study.

2. Apparatus and test materials

A fully automated precise direct shear (DS) apparatus (Duttine et al., 2008, 2009) was used. The shear displacement history was controlled to an accuracy of less than 1 μm to perform in a single test: i) arbitrary smooth switching between displacement and load control phases and among sustained loading (i.e., creep), stress relaxation and constant displacement rate loading; and ii) stepwise or gradual changes in the displacement rate by a factor of up to 100. The specimens (12 cm x 12 cm x 12 cm) were produced using the granular materials described in Fig. 3. They are three poorly-graded natural sands: a sub-angular to angular sand (Toyoura sand, Japan) and a round sand (Albany sand, Australia), both quartz-rich sands; and a sub-round/sub-angular sand (Ticino sand, Italy), comprising quartz (28 % by volume), feldspar (30 %) and mica (5 %) (Bellotti et al., 1996); and an angular gravelly soil (Chiba gravel-a, Japan), comprising crushed angular sandstone particles from a quarry in Japan. The specimens were divided into several sub-layers (typically 7 or 8) and each sub-layer was tamped with a square steel



a)

b)

Figure 4. a) Stress ratio - shear displacement relation and its simulation; and b) volume change – shear displacement relation, dense Toyoura sand.

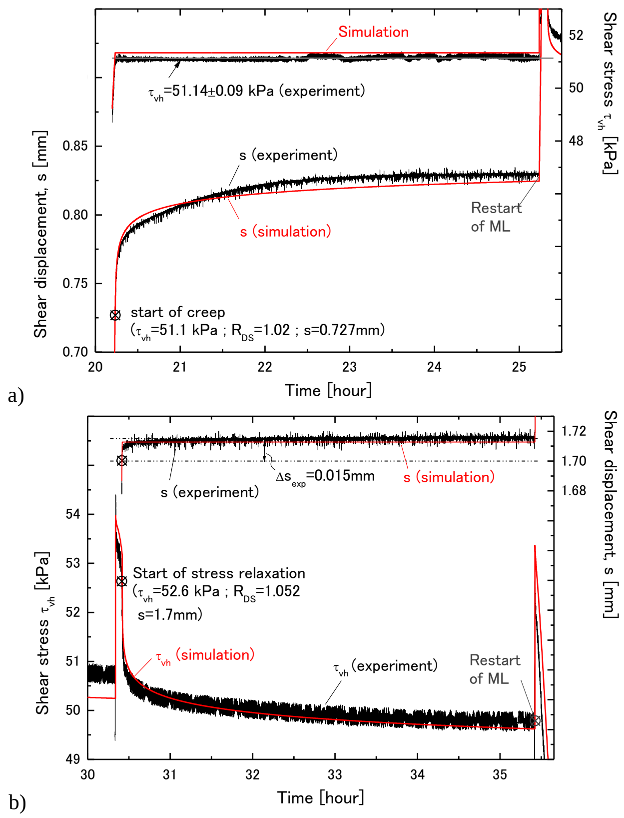


Figure 5. Typical time histories of shear displacement and shear stress during: a) sustained loading; and b) stress relaxation and their simulations, dense Toyoura sand (Fig. 4).

rod very carefully so that the prescribed dry density was precisely achieved. The initial opening between the top and bottom shear boxes (before consolidation) was set equal to $10 \cdot D_{50}$ for dense specimens and $20 \cdot D_{50}$ for loose specimens of the respective materials, except Chiba gravel-a, with which the opening was set equal to 10 mm. The drained DS tests were performed at a constant normal pressure σ_v= 50 kPa.

3. Test results

Fig. 4a presents the relationship between the ratio of R_{DS}= "average shear stress τ_{vh}" to "average vertical stress σ_v" and the shear displacement (s) of dense air-dried Toyoura sand. The simulations shown in this and other similar figures are explained in the companion paper (Tatsuoka et al., 2015). At different shear stress levels during otherwise ML shearing, the specimen was subjected alternatively to a series of 5-hour sustained loading for creep and 5-hour stress relaxation (SR). A set of five small unload/reload cycles was also applied to evaluate the elastic properties at different stress states. Significantly rate-dependent stress-strain behaviours may be seen. Fig. 4b shows the relationship between the vertical displacement, d (i.e., the volume change, positive in compression) and s. The d - s relation exhibits a small deviation during SR

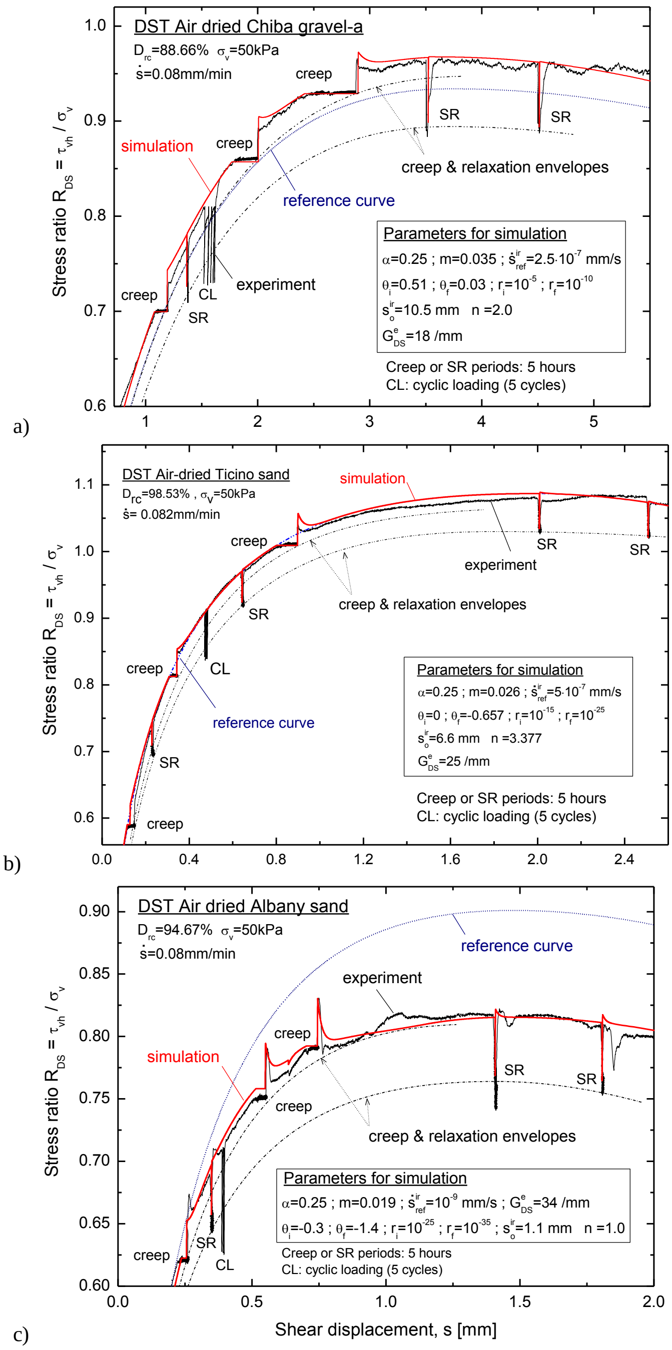


Figure 6. Stress ratio - shear displacement relations and their simulations from DS tests on dense specimens of: a) Chiba gravel-a; b) Ticino sand; and c) Albany sand.

stages from the relation during ML at a constant displacement rate. This trend is due essentially to elastic rebound associated with a decrease in the shear stress and its recovery during reloading. On the other hand, the volume change during creep stages is due essentially to volumetric creep, which is a different phenomenon from creep shear deformation-induced volume changes. Duttine et al. (2008) showed that the shear deformation-induced volume change characteristics (contractancy/dilatancy, i.e., the flow characteristics) are essentially rate-independent, while the volumetric creep becomes more significant as the specimen becomes looser. Typical time histories of s and τ_{vh} during creep and SR are shown in Figs. 5a & b. The shear stress was kept nearly constant during creep (Fig. 5a). During SR, an inevitable very small elastic rebound of the loading frame Δs of around 15μm took place immediately after the start of SR stage (Fig. 5b). This instantaneous small displacement increment was taken into account in the simulations. After a period of 5 hours, the rates of creep and stress relaxation have become very small (although they have not become perfectly null).

In this paper, only the test results of dense specimens are presented. **Figs. 6a, b** and **c** show the similar test results of dense specimens of Chiba gravel-a, Ticino sand and Albany sand. The same remarks as Toyoura sand are relevant to these test results, other than effects of different viscous property types, as described below. In the companion paper, based on the results from other test series in which the displacement rate was step-wise changed and their analysis by the model (Fig. 2), it is shown that, for the pre-peak behaviors, the viscous property of Toyoura and Ticino sands is Isotach, that of Chiba-gravel-a is Combined, and that of Albany sand is P &N. Referring to Fig. 1b, these different viscous property types can be identified by comparing each R_{DS} - s relation at a constant displacement rate with the respective reference curves inferred by the simulation presented in Figs. 4 and 6.

In Figs. 4a and 6, the 5-hour creep and stress relaxation (SR) envelopes experimentally obtained by connecting multiple end states (R_{DS}, s) of creep and SR processes are depicted. With all these granular materials, for the same period (i.e., five hours), the SR envelope is systematically located significantly lower than the creep envelope, regardless of viscous property type. The difference between these creep and SR envelopes with Albany sand P&N is noticeably larger than with Chiba gravel-a (Combined) and TESEA (Toyoura and Ticino sands). This corresponds to the fact that the effects of viscous property type on the creep deformation are larger than those on the stress drop during SR. In the companion paper, these trends are explained by detailed numerical analysis based on the three-component model.

4. Conclusions

From the test results, the following conclusions can be derived:

1) The unbound natural sands and gravel tested having largely different particle shapes and exhibiting different viscous property types showed significant creep and stress relaxation (SR) during otherwise monotonic loading (ML) of drained direct shear at a constant displacement rate.
2) With these granular materials, the creep and SR envelopes representing the shear stress-shear displacement states reached after a series of creep and SR for five hours from different stress states along the same ML shear stress-shear displacement curve are very different from each other. Consistently, the SR envelope is located largely below the creep envelope relative to the ML curve.
3) The difference between the creep and SR envelopes for five hours increases as the viscous property type becomes less Isotach, corresponding to the fact that the

effects of viscous property type on the creep deformation are larger than those on the stress drop during SR.

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