Strain-softening behaviour of sand in true triaxial testing

Nagoya Institute of Technology De'an Sun, Hajime Matsuoka, Masatake Hibino
BeiHang University Yangping Yao

True triaxial apparatus with three pairs of rigid loading plates is capable of applying uniform deformation to the specimen and preventing development of the shear band even at post-failure. Hence it is suitable for studying strain-softening behavior of sands as a real material property. Using such type of apparatus, true triaxial tests have been performed on cubical specimens of Toyoura sand to study the mechanical behaviour of sand in the ranges of pre-failure, failure and post-failure under three different principal stresses. Especially the strain-softening response under three different principal stresses is investigated.

Experimental procedure

The used triaxial apparatus in this study is a rigid-boundary type. The original development of the apparatus was presented by Matsuoka et al. (1985) for multiaxial testing of sand, and updated and modernized for further testing on cemented sand (Matsuoka and Sun 1995) and on unsaturated soil (Matsuoka et al. 2002). Some improvements on the apparatus were conducted to determine the stress-strain relationship in the full shear process including post-failure. The maximum principal stress σ_1 is provided not only by an air cylinder but also by a displacement-controlled propeller geared with an electric motor, so the loading in the σ_1–direction was applied with stress or strain control. Three pairs of the stainless steel loading plates were provided with high vacuum grease-lubricated surface to avoid development of significant friction between the loading plates and the specimen. All experiments in this study were conducted on Toyoura sand. The initial void ratio e_0 of most tested specimens were controlled at about 0.68. True triaxial tests were performed on cubical specimens with 10cm×10cm×10cm.

Experimental Results

Figure 1 shows the stress-strain-volume change curves with different θ-value (about θ, see Fig.3) under p=98kPa and e_0=0.68. It can be seen that considerable amounts of softening and strength reduction occurred after peak failure, and in all cases a slow strength reduction rate was observed after peak failure under three different principal stresses. As θ increases for 0° to 33°, the stress-strain behaviour becomes increasingly stiff and the strain at peak failure decreases. The peak strength obtained at θ=8°, 16°, 23° and 33° are considerably higher than those at θ=0°. Positive or negative amount of the intermediate principal strain ε_2 depends on the θ-value, as shown in Fig.2. When θ=0°, 8° and 16°, ε_2 is negative, i.e. the length in the σ_2-direction increases monotonously as shearing progresses in both hardening and softening ranges. When θ=23°, ε_2 is negative in the initial shear stage while ε_2 becomes positive in the range of high stress ratio and softening. When θ=33°, ε_2 is positive, i.e., the length decreases monotonously during shear process including hardening and softening. It can be seen from Fig.2 that the tendencies of relation between the major principal strain ε_1 and the intermediate principal strain ε_2 in hardening and softening ranges are the same.

Figure 3 shows the comparison of the failure points from the true triaxial tests on Toyoura sand with initial void ratio of about 0.68 and the SMP failure curves at the peak and residual strengths in the π-plane. The curves were predicted by the SMP failure criterion ($I_1 I_2 / I_3 = 8\tan^2\phi + 9$: I_1, I_2 and I_3 =first, second and third stress invariants, and ϕ =internal friction angle) using the values of ϕ at the peak and residual strengths, which were determined from the results of triaxial compression test (θ=0°). Mark ○ shows the measured stress states at peak strength in the π-plane and the solid curve is the predicted result by the SMP failure criterion using ϕ_p=40.5°. It can be seen that the SMP failure criterion predicts well the measured peak strength. Mark △ shows the measured stress states at the residual strength in the π-plane and the dotted curve is the predicted result by the SMP failure criterion using ϕ_r=33.2° . The strain at the residual or critical state is very large, because the measured strain of 25~30% still does not reach the residual or critical state, as shown in Fig.1, at which the strength reduction and the volume dilation cease. In this paper, the state where the shear strain ($\varepsilon_d = \sqrt{2((\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2)/3}$) reaches 30% is provisionally assumed to be the residual or critical state. ϕ_r=33.2° is based on result of triaxial compression test (θ =0°) at ε_d=30.0%. It can be seen from Fig. 3 that the SMP failure criterion using the residual triaxial strength predicts well the measured residual strengths under three different principal stresses. Therefore, the SMP failure criterion is applicable to predictions for not only peak strength but also the residual strength of sand.

The measured data of θ =0° shown in Fig.1 were arranged as Fig.4 based on the stress-dilatancy relation. It can be seen from Fig.4 that the stress-dilatancy relation are the same during the shear process including hardening and softening ranges. This experimental results is beneficial to construct the constitutive model for granular materials with softening, i.e. the same plastic potential function can be used before and after the peak strength.

References 1)Matsuoka H., Koyama H., and Yamazaki H. 1985, Soils and Foundations, **25**(1):27-42. 2)Matsuoka H and Nakai T. 1974, Proc. JSCE, No.**232**:59-70. 3)Matsuoka H. and Sun D. A. 1995, Soils and Foundations, **35**(4): 63-72. 4)Matsuoka H., Sun D. A., Kogane A., Fukuzawa N., and Ichihara W. 2002, Canadian Geotechnical Journal, **39**(3):608-619.

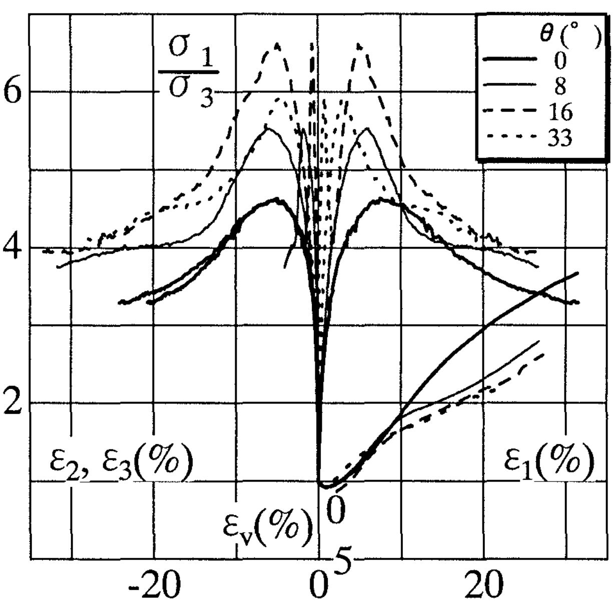

Fig.1 Stress- strain relation in true triaxial tests under p=98kPa

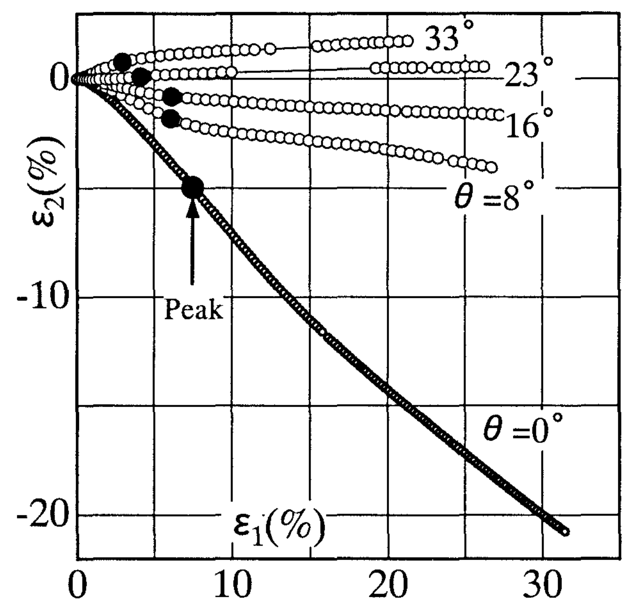

Fig.2 Relation between ε_1 and ε_2 in true triaxial tests under p=98kPa

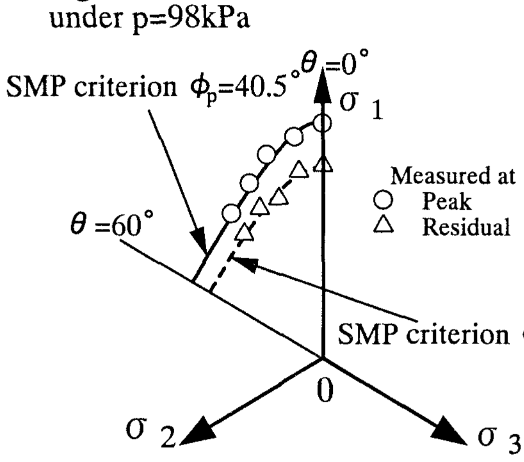

Fig. 3 Measured peak and residual strengths and predition by SMP criterion in π-plane

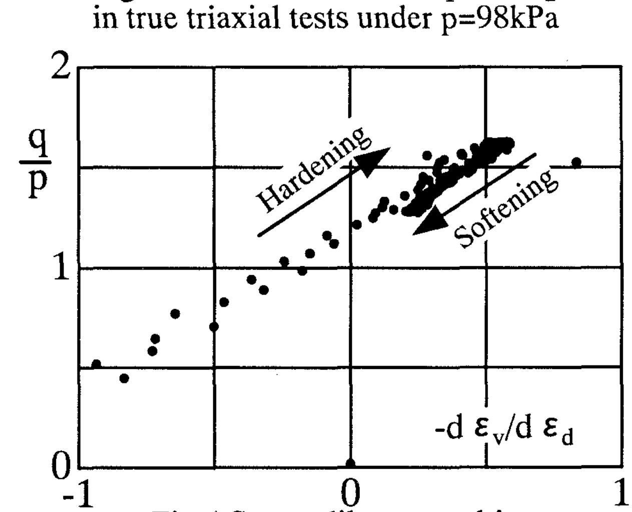

Fig.4 Stress-dilatancy reltion