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Characterizing the deformation behavior of Tertiary sandstones

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Abstract

Tertiary sandstones possess deformational behavior different from hard rocks, especially the relatively larger amount of volumetric dilation during shearing. Such excess dilation contributes to the increase of crown settlement during tunnel excavation and accounts for several cases of tunnel squeezing within Tertiary sandstones. Therefore, the deformation behavior of Tertiary sandstones sampled from more than 13 formations was studied. To distinguish the volumetric deformation induced by hydrostatic stress or by shear stress as well as to decompose the elastic and the plastic components of strains, special experimental techniques, including pure shear tests and cycles of loading–unloading were applied.

The experimental results reveal that the deformation of Tertiary sandstone exhibits the following characteristics: (1) significant amount of shear dilation, especially elastic shear dilation; (2) non-linear elastic and plastic deformation; (3) plastic deformation occurs prior to the failure state. Furthermore, features of plastic deformation were inferred from experimental results and, as a result, the geometry of plastic potential surface and the hardening rule were accordingly determined. A constitutive model, involving nonlinear elastic/plastic deformation and volumetric deformation induced by shear stress, is proposed. This proposed model simulates the deformational behavior for the shear-dilation-typed rocks reasonably well. Furthermore, tests on the versatility of the proposed model, including varying hydrostatic stress and stress paths, indicate that the proposed model is capable of predicting deformational behavior for various conditions.

Keywords: Sandstone; Constitutive model; Deformation; Shear dilation

1. Introduction

Tertiary sandstones have a digenetic age of no more than 70 million years and such relatively short rock forming period is insufficient to classify them as hard rocks. For instance, the typical strength of Tertiary sandstones in Taiwan ranges from 10 to 80 MPa [1].

While tunneling through the Tertiary strata, several unsuccessful cases were reported [2]. Difficulties, including severe squeezing and raveling, were encountered during construction of these tunnels. For instance, a crown settlement of 180 cm of a 12.4 m wide highway tunnel passing through a faulted zone of Tertiary formations was reported. A crown settlement ranging from 14 to 30 cm occurred in several sections of the tunnels under construction, in which Tertiary sandstone (Mushan Formation) was encountered. The crown settlement in other sandstones' strata is often within several centimeters. Therefore, the deformational characteristics of Tertiary sandstones should be involved while the deformation of a constructing tunnel is analyzed.

When compared to hard rock, it was found that the deformational behavior of Tertiary sandstones is characterized by large amount of nonlinear deformation, shear dilation and plastic deformation prior to the failure state [3–5]. Jeng et al. [6] compared the mechanical properties of sandstone, the uniaxial compressive strength (UCS) and the reduction of strength due to wetting ($R = \mathrm{UCS_{dry}}/\mathrm{UCS_{wet}}$) with the petrographic features of the 13 sandstones listed in Table 1,

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Nomenclature

α_1	hardening rule parameter for Cap model
α_f	slope of F_1
α_d	state variable of proposed model
b_1	elastic constant of proposed model
b_2	elastic constant of proposed model
b_3	elastic constant of proposed model
β_1	hardening rule parameter for proposed model
β_2	hardening rule parameter for proposed model
β_3	hardening rule parameter for proposed model
β_4	hardening rule parameter for proposed model
CTC	conventional triaxial compression test
ε_{ij}	second strain tensor
$\varepsilon^e_{v,p}$	elastic volume strain induced by hydrostatic stress
$\varepsilon^e_{v,s}$	elastic volume strain induced by shear stress
e_{ij}	second deviatoric strain tensor
ε_v	volume strain
$d\varepsilon^p$	increment of plastic strain, $d\varepsilon^p = \sqrt{d\varepsilon^p_{ij}\, d\varepsilon^p_{ij}}$
$F(I_1, J_2)$	yield surface
$G(I_1, J_2)$	plastic potential surface
G	shear modulus
G_0	initial shear modulus
γ	shear strain, $\gamma = 2\sqrt{J_2'} = \sqrt{2 \cdot e_{ij}e_{ji}}$
γ^e	elastic shear strain
γ^p	plastic shear strain
γ^t	total shear strain
γ_d	square of slope of failure envelope F
η_1	hardening rule parameter for cap model
J_2	second deviatoric stress invariant, $J_2 = \frac{1}{2}s_{ij}s_{ji}$
J_2'	second deviatoric strain invariant, $J_2' = \frac{1}{2}e_{ij}e_{ji}$
K	bulk modulus
k_f	interception of F_1
λ	positive scalar factor of proportionality
m	parameter for plastic potential surface
Ω	strain energy density function
p	hydrostatic stress $p = \frac{1}{3}I_1 = \frac{1}{3}\sigma_{kk}$ (MPa)
PS	pure shear test
R	strength reduction ratio = UCS_{wet}/UCS_{dry}
RTE	reduced triaxial extension test
R_c	axis ratio defined by Cap model
s_{ij}	second deviatoric stress tensor
σ_{ij}	second stress tensor
T	interception of failure envelope with I_1 axis
UCS	uniaxial compressive strength (MPa)

Superscripts

e	elastic deformation
p	plastic deformation
t	total deformation

Table 1
Sandstones of this research

Formation	Classification (Pettijohn et al., 1987)	Geological age	Sedimentary facies	Remark
WGS1	Lithic graywacke	Oligocene	Marine–terrestrial mixed facies	
WGS2	Lithic graywacke	Oligocene	Marine–terrestrial mixed facies	Apparent preferred orientation
MS1	Lithic graywacke	Miocene	Littoral facies	
MS2	Lithic graywacke	Miocene	Littoral facies	
MS3	Lithic graywacke	Miocene	Littoral facies	Apparent preferred orientation
TL1	Lithic graywacke	Miocene	Marine facies	
TL2	Lithic graywacke	Miocene	Marine facies	
ST	Lithic graywacke	Miocene	Littoral facies	
NK	Lithic graywacke	Miocene	Marine facies	
TK	Lithic graywacke	Miocene	Littoral facies	Apparent preferred orientation
SFG1	Quartzwacke	Miocene	Littoral facies	
SFG2	Lithic graywacke	Miocene	Littoral facies	Apparent preferred orientation, rich mica content
CL	Lithic graywacke	Pliocene	Littoral facies	Rich calcite content

and found that these Tertiary sandstones can be classified in terms of Grain area ratio (GAR) and porosity (n), as illustrated in Fig. 1. Two groups of sandstones, termed as *Type A* and *Type B* (with $R>0.5$ and $R\leqslant 0.5$, respectively), have been identified. Comparing to *Type A*, *Type B* sandstone is characterized by greater degree of deformation (or being "softer") and by having a more significant reduction not only in strength but also in stiffness, as shown in Fig. 2. This characteristic highlights that *Type B* can be the problematic rock type, which is prone to tunnel squeezing.

This paper explores the deformational behavior of Tertiary sandstones in details. In addition to the above-mentioned research results, the work focuses on the following aspects:

1. To characterize the deformational behavior of Tertiary sandstones, including elastic and plastic