



MODELING ELASTO-PLASTIC BEHAVIOR OF UNSATURATED SOIL USING A CONTROLLED SUCTION CUBICAL TEST CELL

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ABSTRACT

Computational constitutive drivers are implemented for the numerical simulations of suction-controlled conventional triaxial tests on unsaturated soils using two elasto-plastic critical state based formulations: Barcelona model and Oxford model. Simulations are obtained from both explicit and implicit integration techniques. The algorithms support numerical analyses in a deviatoric stress plane by using a mixed control constitutive driver in conjunction with a Generalized Cam-Clay model, within a constant-suction scheme. Results from a series of suction-controlled conventional triaxial tests on 10-cm side cubical specimens of compacted silty sand, using a controlled stress and suction cubical test cell, are used for validation of both models. Matric suction states in the specimens were induced and maintained constant during testing via axis-translation technique.

Keywords: unsaturated soil, matric suction, critical state, constitutive behavior

INTRODUCTION

This paper deals with two elasto-plastic critical state-based models to predict the constitutive stress-strain behavior of an unsaturated soil: the Barcelona model (Alonso et al., 1990) and the Oxford model (Wheeler and Sivakumar, 1995). The models are intended for use with soils of moderate- to low-plasticity. Even though the proposed models incorporate many of the essential features of unsaturated soil behavior, there is some room for enhancement and further elaboration. However, more experimental data are still needed to complete their validation, and additional experience should be gained through parametric investigation of the original formulations in their simplest form. The present work was motivated by these research needs.

In this work, the results from a series of stress/suction-controlled conventional triaxial tests conducted on several identically prepared, 10-cm side, cubical specimens of compacted silty sand are used to evaluate the ability of the models to quantitatively reproduce observed behavior of an unsaturated soil. The experimental program was accomplished using a cubical test cell suitable for testing soils under suction-controlled conditions via axis-translation technique (Hoyos, 1998;

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Hoyos and Macari, 2001). The present work concentrates only on soil response along isotropic and axisymmetric stress paths. Computational constitutive drivers were implemented to allow for the numerical simulations of constant-suction conventional triaxial tests using both explicit and implicit integration techniques. Algorithms support numerical analyses in a deviatoric stress plane using a mixed control constitutive driver (i.e., stress- and strain-controlled), in conjunction with a Generalized Cam-Clay model, within a constant-suction scheme.

EXPLICIT AND IMPLICIT INTEGRATIONS OF CONSTITUTIVE RELATIONS

Detailed description of Barcelona model's yield loci, flow rules, hardening laws, and elastic and plastic strain definitions is presented by Alonso et al. (1990). Detailed description of Oxford model's development and features is presented by Wheeler and Sivakumar (1995). Computational constitutive drivers were implemented for both formulations via the explicit integrations of constitutive relations. The computational implicit integration procedure developed herein is a BE return rule-based scheme for integrating the constitutive relations postulated by the Barcelona model (Macari et. al, 1997). The solution of the unsaturated soil problem can be devised as the projection of a trial stress state $(\boldsymbol{\sigma}, s)$ onto an updated yield surface ${}^{n+1}F$, as depicted in Fig. 1, where $\boldsymbol{\sigma}$ represents the total stress tensor, $s = (u_a - u_w)$ is matric suction, p_o is net yield stress, and s_o is maximum past suction.

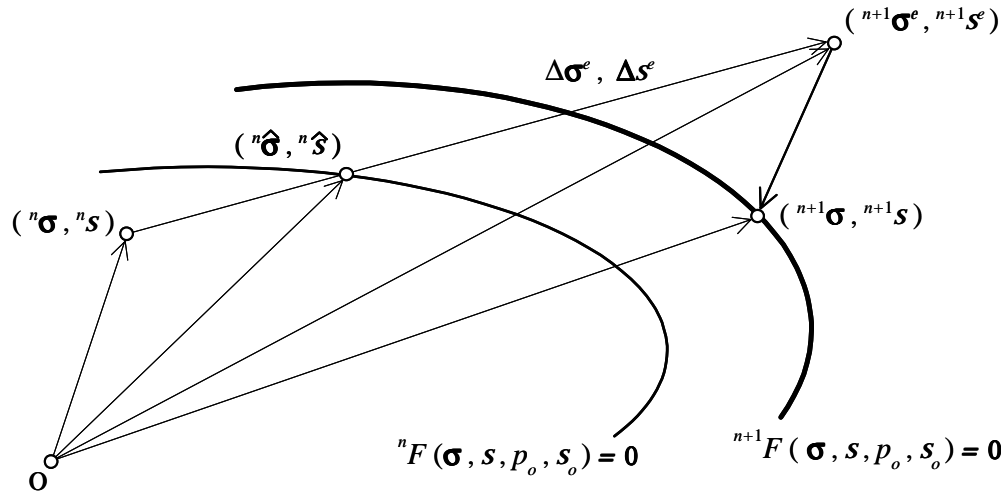


FIG. 1. Schematic of CPPM-based implicit integration problem.

SOIL RESPONSE UNDER ISOTROPIC LOADING

The soil is a low plasticity silty sand (SM) with natural moisture content $w_n = 25-33 \%$, average contents of sand, silt, and clay of 58.4 %, 36.8 %, and 4.8 %, plasticity index $PI = 4 \%$, average in-situ void ratio $e_o = 0.98$, and effective grain size $D_{10} = 0.02 \text{ mm}$. All 10-cm per side cubical specimens were prepared using in-place tamping compaction after full saturation of the 5-bar ceramic disk (Hoyos and Macari, 2001). A series of 8 constant-suction isotropic loading tests were conducted in the cubical device on 8 identically prepared specimens of compacted silty sand. In each case, a ramped consolidation (from $p = 50$ to 400 kPa) followed the equalization of the pore fluids (air and water) for the pre-established value of matric suction ($s = 50, 100, 200$ or 400 kPa), as depicted in Fig. 2.

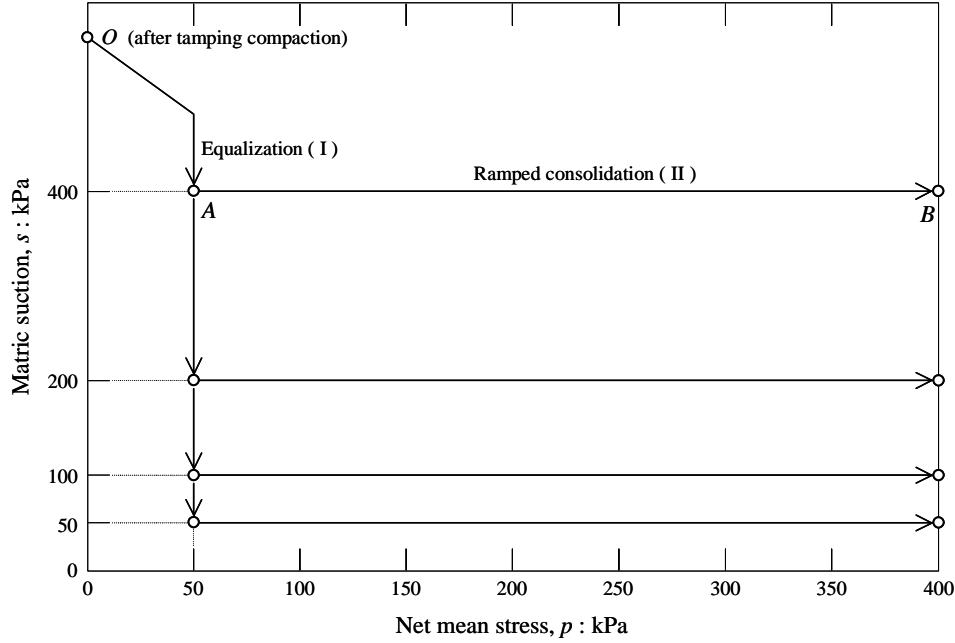


FIG. 2. Constant-suction isotropic loading tests.

Fig. 9 shows the specific volume versus net mean stress response of compacted silty sand during ramped consolidation stage (Stage II). Yield stress values of $p_o(100) = 56$ kPa, $p_o(200) = 72$ kPa, and $p_o(400) = 78$ kPa can be devised. In the tests conducted at $s = 50$ kPa, no yield point can readily be identified, suggesting that the entire ramped consolidation took place under virgin conditions. Variation of soil stiffness parameter $\lambda(s)$ is consistent with Barcelona model, which postulates a monotonic decrease in $\lambda(s)$ with increasing suction. Best-fit values of $\lambda(50) = 0.117$, $\lambda(100) = 0.075$, and $\lambda(200) = 0.051$ can be obtained. Using $p = p_{at}$ (100 kPa) as reference pressure in Fig. 3 (Oxford model), best-fit values of $N(50) = 2.098$, $N(100) = 2.152$, and $N(200) = 2.161$ were found. Barcelona model's predictions show good agreement with experimental response.

SOIL RESPONSE UNDER AXISYMMETRIC SHEARING

Constant-suction axisymmetric shearing consists of three steps: equalization (Stage I), ramped consolidation (Stage II), and axisymmetric shearing (Stage III), as shown in Fig. 4. Tables 1 and 2 summarize best-fit values of Barcelona and Oxford models parameters obtained from tests in Figs. 2 and 4. Parameters in Tables 2 and 3 are used for models validation in $p-q-s-v$ space. Figs. 5-7 show experimental and predicted $q-v-\varepsilon_q$ response of compacted silty sand from constant-suction TC tests with constant $p = 50$ kPa. Predictions from Barcelona model are calculated via both explicit and CPPM-based implicit integrations. Predictions from Oxford model are calculated via explicit integration. In terms of $q-\varepsilon_q$ response, it appears that numerical predictions from explicit integration diverge slightly from those obtained from implicit integration, but eventually both methods converge at critical state. Both schemes are able to adequately capture the $q-\varepsilon_q$ response of compacted silty sand. Differences between Barcelona and Oxford models predictions may be attributed to differences in the stress increase intervals and flow rules adopted in each case. In terms of $v-\varepsilon_q$ response, implicit integration appears to predict higher volume changes than explicit integration. This may be attributed to differences in the non-associativity adopted in each case. In general, both models show good agreement with observed behavior. Similar agreement was observed for CTC/TC tests at initial $p = 100, 200,$ and 400 kPa.

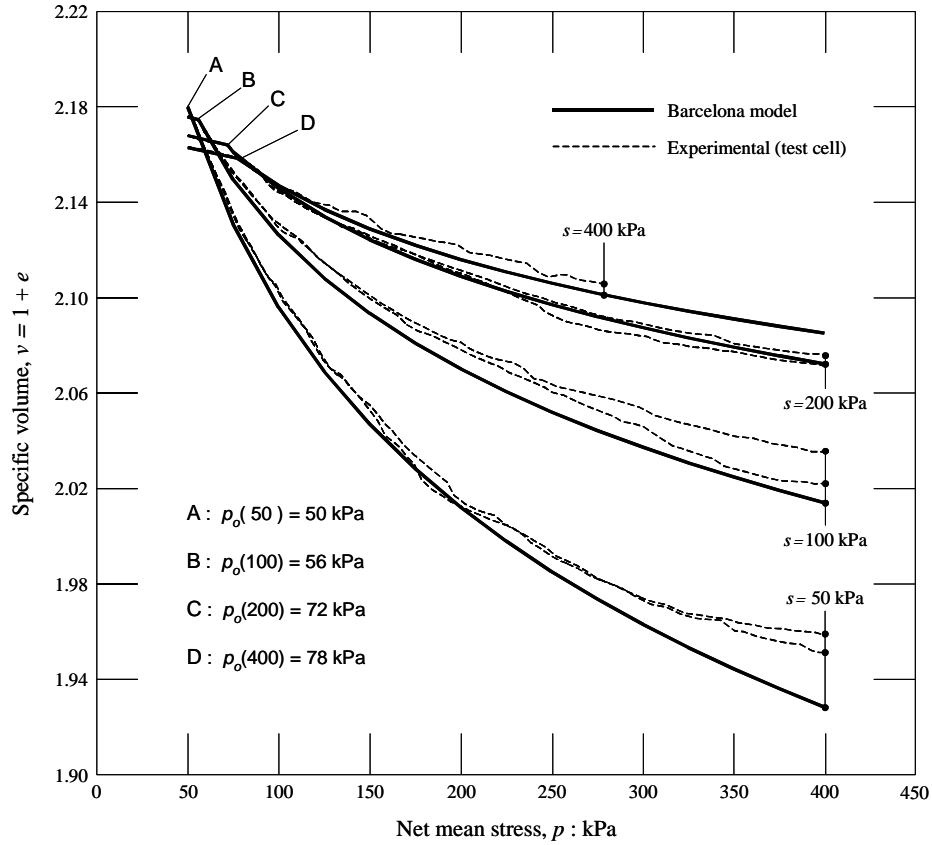


FIG. 3. Soil response under constant-suction isotropic loading.

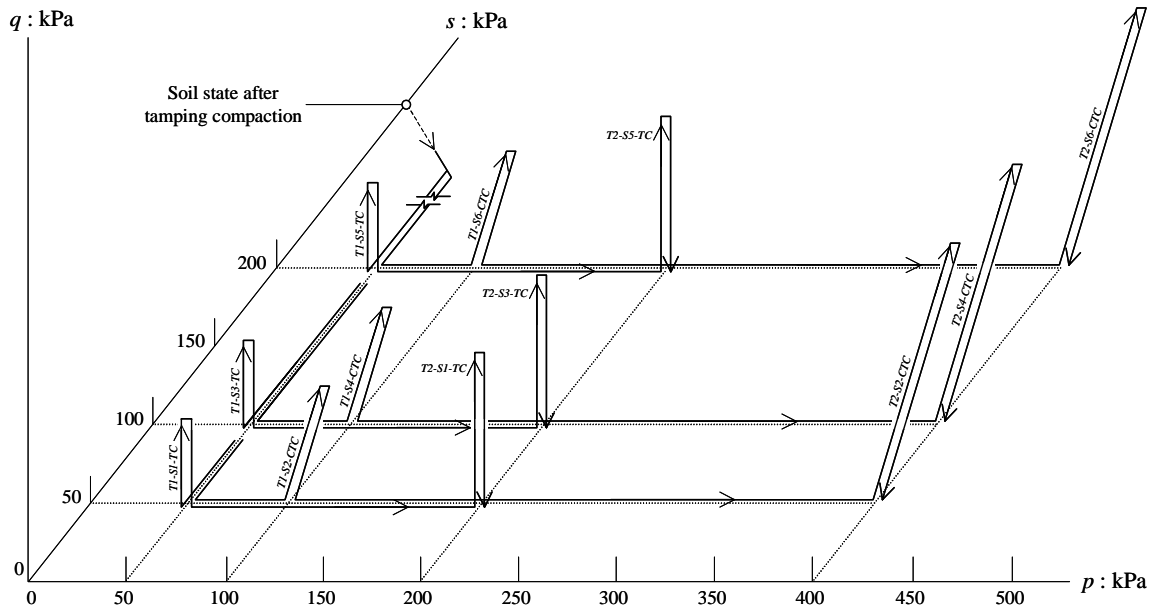


FIG. 4. Constant-suction axisymmetric shearing tests.

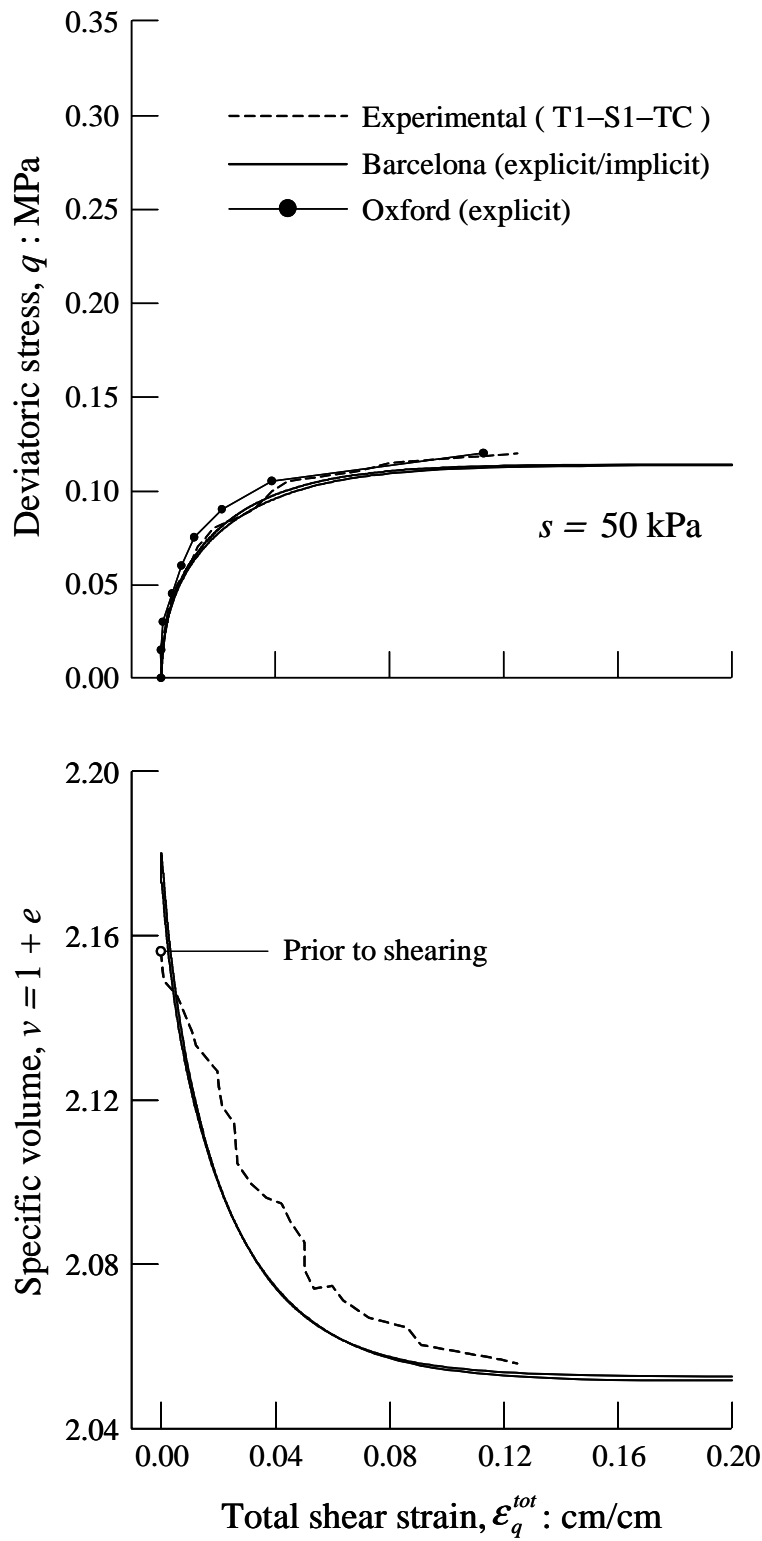


FIG. 5. Experimental/predicted q - v - ϵ_q response from TC test for $p = 50$ kPa and $s = 50$ kPa.

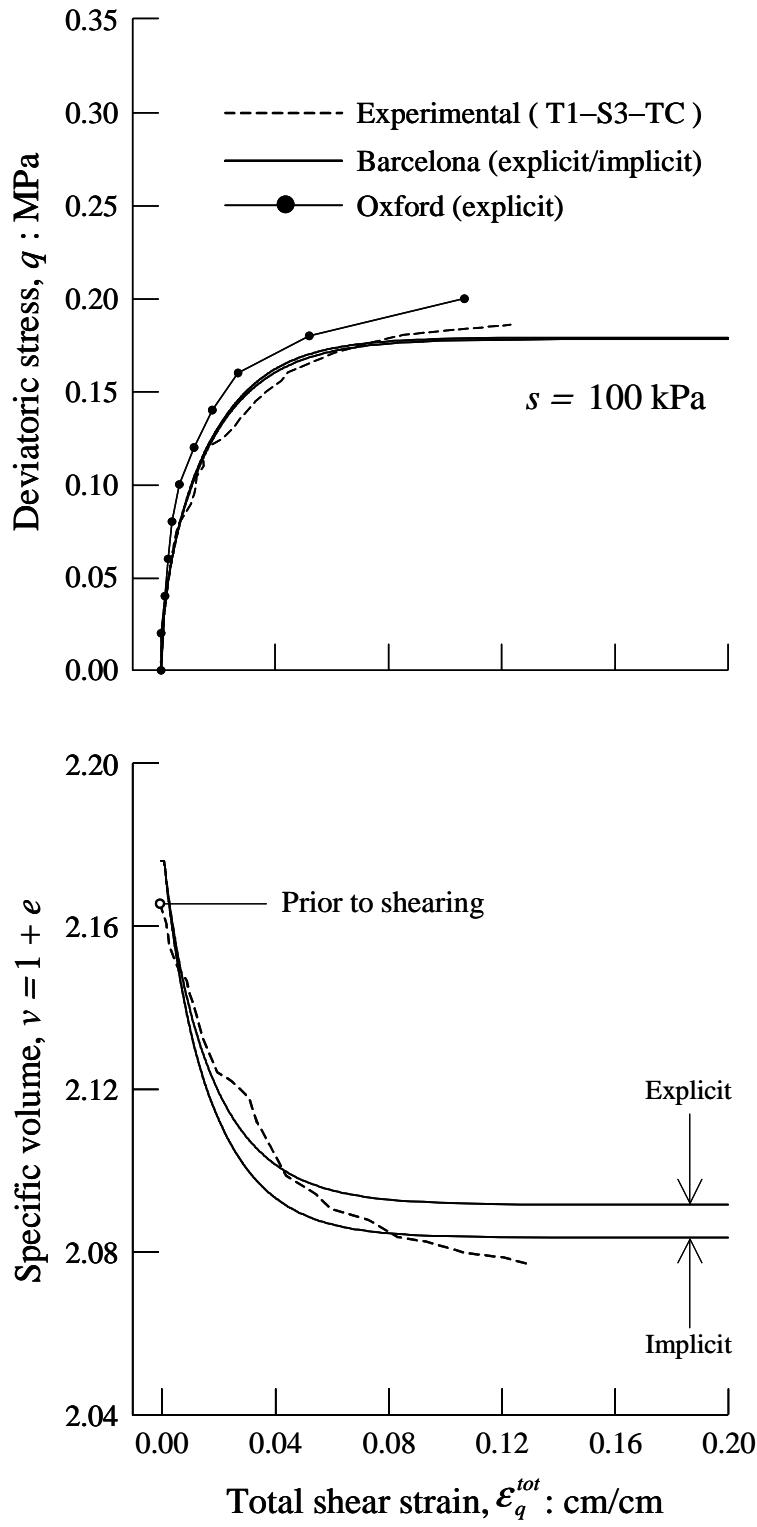


FIG. 6. Experimental/predicted q - v - ϵ_q response from TC test for $p = 50$ kPa and $s = 100$ kPa.

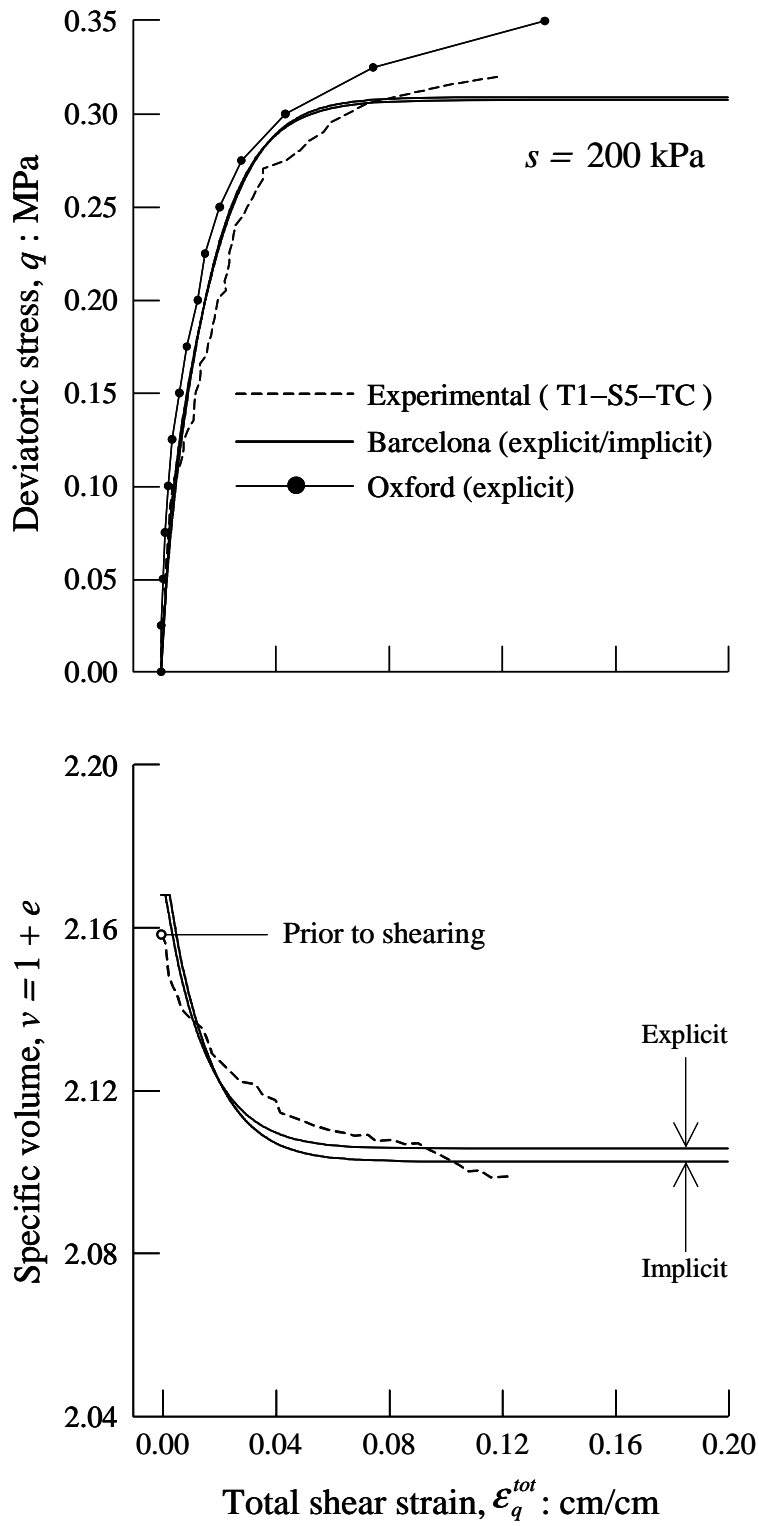


FIG. 7. Experimental/predicted q - v - ϵ_q response from TC test for $p = 50$ kPa and $s = 200$ kPa.

TABLE 1. Barcelona model parameters

Parameter	Best-fit Value	Units
$\lambda(0)$	0.220	–
κ	0.011	–
β	17.89	MPa ⁻¹
r	0.210	–
p^c	0.036	MPa
G	8.800	MPa
M	0.982	–
k	1.324	–
$p_o(0)$	0.041	MPa
s_o	(Undetermined)	MPa

TABLE 2. Oxford model parameters

s : kPa	$\lambda(s)$	$N(s)$	$M(s)$	$\mu(s)$: kPa	$\psi(s)$	$\Gamma(s)$
50	0.117	2.098	0.987	68.64	0.097	1.991
100	0.075	2.152	0.978	140.23	0.056	2.049
200	0.051	2.161	0.976	292.97	0.034	2.082

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