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Experimental mapping of elastoplastic surfaces for sand using undrained perturbations

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Abstract

Elastoplastic models are commonly used in modern geotechnical practice to numerically predict displacements, stresses, and pore pressures in large construction projects. These elastoplastic models use presumed functional forms for yield and plastic potential functions that are rarely obtained from experimental measurements. This research describes a simple experimental technique that can be used to obtain the slopes of the plastic potential and yield functions during shear based on the deformation theory of plasticity. The method imposes small perturbations in the direction of the stress increment by closing the drainage valve, thereby abruptly switching from drained to undrained loading conditions during plastic loading. Elastoplastic moduli are obtained immediately before and after the perturbations from the measured deviatoric stress, mean effective stress, deviatoric strains, and volumetric strains for the stress paths immediately before and immediately after closing the drain valve. During drained shear, samples were sheared while the mean effective stress was maintained constant. Combining tests performed at several confining stresses, the proposed method was able to map conventional isotropic yield and plastic potential surfaces and predict their evolution for a wide range of stresses. The proposed technique can also be used for kinematic yield surfaces and to develop new and more accurate elastoplastic constitutive models.

Keywords: Soil plasticity; Yield surface; Plastic potential; Plastic flow; Constitutive modeling; Non-associated flow; Elastoplastic behavior

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1. Introduction

Using numerical simulations to predict permanent deformations caused by surcharges, excavations, and other similar geotechnical loading mechanisms requires constitutive models that successfully estimate the anticipated level of irrecoverable strains. The use of numerical modeling for the design of large geotechnical projects has become widespread in recent years, especially for large infrastructure projects such as dams, tunnels, and highway embankments, as well as for deep excavations next to existing buildings. The considerable importance of the modeling in the analysis and the design of geo-structures was acknowledged in 2010, when it was named one of the focus areas at the Geo-Institute's national conferences (ASCE, 2010).

Constitutive models commonly implemented in finite element computer programs, such as PLAXIS (2015), or finite difference programs, such as FLAC (Itasca, 2011), are generally elastoplastic in nature and use single or dual isotropic yield surfaces. As illustrated in Fig. 1, commonly used models exhibit significant differences in the treatment of yield surfaces and plastic potential surfaces. The simplest models consist of a Mohr-Coulomb or Drucker-

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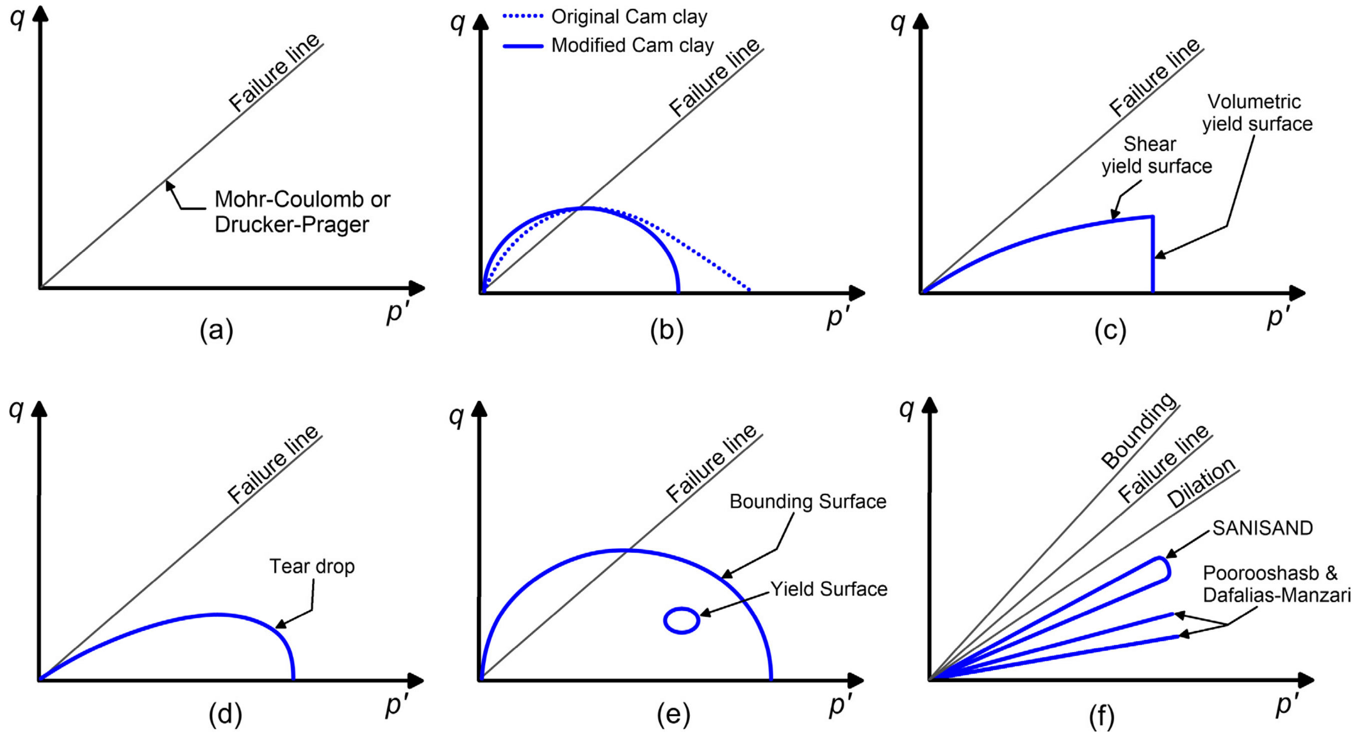

Fig. 1. Examples of yield surfaces, $f = 0$, used for geotechnical applications: (a) Mohr-Coulomb and Drucker-Prager, (b) original and modified Cam-clay (Roscoe and Schofield, 1963 and Roscoe and Burland, 1968), (c) Vermeer's double hardening model (Vermeer, 1978), (d) Teardrop-shaped surface (Lade and Kim, 1988), (e) Cam-clay bubble model (Al-Tabbaa and Wood, 1989), and (f) Drucker-Prager type of kinematic hardening surfaces (Poorooshasb and Pietruszczak, 1985 and Dafalias and Manzari, 2004) and SANISAND (Taiebat and Dafalias, 2008).

Prager type of yield surface, with the plastic flow direction controlled by a constant dilation angle (Fig. 1a). These models disregard many fundamental features of soil behavior, including plastic volumetric flow under isotropic loading conditions (i.e., do not generate irrecoverable strains in isotropic consolidation), small-strain yielding, and critical state soil mechanics. Roscoe and Schofield (1963) introduced the original Cam-clay model (Fig. 1b), which utilizes a logarithmic function to define the yield surface in the q–p' stress invariant space, and an associated flow rule (i.e., the plastic potential surface and yield surface coincide). This model conforms to critical state soil mechanics, meaning that the failure condition is associated with the zero volumetric strain rate as the plastic shear strains continue to accumulate, and it is capable of capturing the consolidation behavior although its yield surface generates deviatoric strains under isotropic consolidation conditions. The modified Cam-clay model (Roscoe and Burland, 1968) uses an elliptic yield surface to eliminate deviatoric strains under isotropic loading conditions. Since the formulation of these yield surfaces is isotropic, their elastic region is quite large. To improve predictions for different stress increment directions, Vermeer (1978) developed a double hardening model for sand consisting of a nonlinear surface for deviatoric yielding (non-associated) and a separate vertical surface (associated) for volumetric yielding (Fig. 1c). The formulation in Vermeer's model is also isotropic, and thus, more appropriate for monotonic loading conditions. Lade and Kim (1988) developed a teardrop-shaped model (Fig. 1d) that eliminated the sharp corner in Vermeer's double hardening model and some of the associated return mapping difficulties at the cost of slightly less accurate predictions.

Yield surfaces that exhibit isotropic hardening, such as those in Fig. 1b–d, result in a large elastic region after significant yielding, rending the models inappropriate for reverse or cyclic loading conditions. To more accurately model cyclic behavior, Mróz et al. (1979) proposed a modeling technique based on kinematic hardening, that translates and rotates during loading, generally within the context of a larger bounding surface that exhibits isotropic and/or kinematic hardening (Fig. 1e). Examples include the Cam-clay bubble model developed by Al-Tabbaa and Wood (1989) for clays (Fig. 1e) in which a small "bubble" yield surface moves inside of an isotropic bounding surface. Both the yield and bounding surfaces have the shape of the modified Cam-clay model. A similar approach for sands includes the Dafalias and Manzari (2004) model, that utilizes a small Drucker-Prager type of yield surface, along with a Drucker-Prager type of bounding surface, critical state line, and dilatancy surface (Fig. 1f). The model lacks a volumetric cap, and therefore, exhibits only elastic volumetric strains upon loading at a constant stress ratio. Taiebat and Dafalias (2008) developed a SANISAND model that uses a rounded yield surface in conjunction with a Drucker-Prager type of bounding surface that permits

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