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Patterns, fabric, anisotropy, and soil elasto-plasticity

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Abstract

This paper proposes a new method in the theory of soil plasticity – an advance on Hill [The Mathematical Theory of Plasticity, Clarendon Press, Oxford]. The method assumes that soil fabric consists of inter-locking, inter-twining, inter-laced, juxtaposed, and superposed elementary units called "patterns". A mechanics of patterns is developed. As well as elastic and plastic components, a third strain-increment component is deduced which helps explain non-associated flow. The proposed method leads to explanations of critical states, anisotropy, sensitivity, the Bauschinger effect, and swept-out memory. All these appear in the method as near-inescapable features of plastic solids. Results are illustrated in detail for plane strain biaxial processes.

Keywords: *Anisotropy*; Bauschinger effect; Compatibility; Constitutive model; *Critical states*; Dilatancy; Dissipation; Elasticity; Energy; *Fabric*; Failure; Finite deformations; *Flow rule*; Fundamental assumptions; Hardening; Hvorslev surface; Internal variables; Liquefaction; Plastic potential; Plasticity theory; Proportional straining; Sensitivity; Softening; *Soils*; Steady states; Strain increments; Swept-out memory; *Thermodynamics*; Thermomechanics; Work; Yield

1. Introduction

The concept of soil fabric and its relation to anisotropy has been discussed by Oda (1972, 1985), Matsuoka and Geka (1983), Hashiguchi (1985), Cambou (1990),

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Subhash et al. (1991), Kuganenthira et al. (1996), Bai and Smart (1997), Cottechia and Chandler (1997); Zlatovijc and Ishihara (1997), Masad and Muhunthan (2000), Dudoignon et al. (2001), Wan and Guo (2001), Chaudhary et al. (2002), and others.

This paper proposes a new method of describing the anisotropic, elasto-plastic behaviour of soils, based on Dean's (2003) proposal that fabric is built from "patterns". Anisotropy is an association between constitutive response and physical direction or orientation so that, for example, an undisturbed sample of clay taken from the ground will behave differently in a triaxial cell depending on its orientation in the apparatus (Saada and Bianchini, 1977; Molenkamp, 1998). Anisotropy for geotechnical and geological materials occurs in:

- clay (e.g., Wood, 1973; Saada and Bianchini, 1977; Al-Tabbaa, 1984; Molenkamp, 1998);
- silt (e.g., Zdravković, 2000, 2001),
- sand (e.g., Casagrande and Carillo, 1944; Arthur and Menzies, 1972; Arthur et al., 1977; Elgamel et al., 2003);
- gravel (e.g., Jiang et al., 1997; Tanaka, 2001);
- sandstone (Benson et al., 2003), claystone (Chiarella et al., 2003), limestone (Cornet et al., 2002), and rock-like materials generally (Litewka and Debinski, 2003);
- numerical models of granular assemblies (Shodja and Nezami, 2002).

Anisotropy seems so common that one suspects plasticity in solids may be impossible without it. A brief review of recent publications shows that anisotropy is recognized in:

- metals and metal forming (Barlat et al., 2003a,b; Brünig, 2003; Corradi and Vena, 2003; Lopes et al., 2003; Maudlin et al., 2003; Wu, 2003a,b; Wu et al., 2003; Bron and Besson, 2004; Green et al., 2004; Roos et al., 2004; Stroughton and Yoon, 2004; Tugcu et al., 2004; Yoon et al., 2004);
- crystalline, polycrystalline, and fibrous materials (Bohlke et al., 2003; Castro and Ostoja-Starzewskib, 2003; Darrieulat and Montheillet, 2003; Dumont et al., 2003; Kobayashi et al., 2003; Langlois and Berveiller, 2003; Li et al., 2003; Carrere et al., 2004; Glazoff et al., 2004; Habraken and Duchêne, 2004; Han et al., 2004; Hashiguchi and Proasov, 2004; Kalidindi et al., 2004; Kowalczyk and Gambin, 2004; Raabe and Roters, 2004);
- metallic foams (Doyoyo and Wierzbicki, 2003);
- viscoplastic and rate-dependent materials generally (Haupt and Kersten, 2003; Häusler et al., 2004; Voyiadjis et al., 2004).

The existence of anisotropy across such a wide range of material types suggests that there may be a role for a concept that generalizes, and perhaps finds a common factor in, some of the many existing ideas. For soils, anisotropy and finite strains need careful consideration in relation to familiar concepts (Mroz, 1967; Hashiguchi, 1992; Gutierrez and Ishihara, 2000; Cleja-igoiu, 2003; Bruhns et al., 2003; Collins and Muhunthan, 2003; Tsakmakis, 2004). Noll's (1958) Axiom of Local Action formalizes the notion that constitutive behaviour occurs "at a point in a continuum". In fact, soil consists of grains and voids and pore fluids. Lambe and Whitman (1979, p. 99) state that "when we talk about stresses at a point ... we often must envision a rather large point". Other approaches include Desai (2001). Because