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# Yielding of cement-mixed gravelly soil affected by viscous property, ageing and damage

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**Abstract**

The yielding of compacted moist cement-mixed gravelly (CMG) soil, subjected to arbitrary loading histories with two stress variables, is studied by means of non-standard drained triaxial compression tests. A non-linear three-component model is modified to describe the elasto-viscoplastic property affected by ageing and shear yielding-associated damage. The development of the inviscid yield locus (YL) is formulated based on the interactive double-yielding mechanism that comprises (i) the bounding mechanism controlled by "inviscid YL, YB" and (ii) the frictional mechanism controlled by "inviscid YL, YF". Each inviscid YL is determined as an inner envelope of a given set of YB and YF that have developed by ageing and shear yielding and have been affected by damage. As the inviscid YL approaches the peak strength line, the shape changes in association with a decrease in the effect of YB and an increase in the effect of YF. The size and shape of the respective YLs in total stresses (i.e., measured effective stresses) are different from those of the corresponding inviscid YLs due to the viscous effects. The total stress–strain relation for a given loading history is obtained by accounting for the viscous effects from the inviscid stress–strain relation, which is obtained from the basic inviscid stress–strain relation accounting for the effects of ageing and damage. It is shown that this model can properly simulate the development of YL for a wide variety of loading histories applied along various stress paths.


*Keywords:* Ageing; Cement-mixing; Gravelly soil; Triaxial compression; Viscous property; Yield locus; ICG: D6/D7

## 1. Introduction

As long as the stress state is kept below the current yield locus (YL) or yield surface for large-scale yielding, the tangent stiffness is substantially higher than that at the same stress level when large-scale yielding takes place. Unlike unbound geomaterials, the YL of cement-mixed soil expands not only with strain-hardening by yielding, but also with time by positive ageing (Tatsuoka et al., 2008b, 2008c). This feature is very important for the backfill used for important soil structures, such as bridge abutments, as it allows for very small deformation. This feature can be properly described only by a relevant elasto-viscoplastic (EVP) model incorporating ageing effects. For example, for loading histories (1), (2) and (3) in Fig. 1a, an elasto-plastic (EP) model predicts the same stress–strain relation seen in Fig. 1b. An elasto-viscoplastic (EVP) model predicts creep deformation *b*–*c*, which expands the YL from the one at stage *b* to the one at stage *d*, as seen in Fig. 1c.

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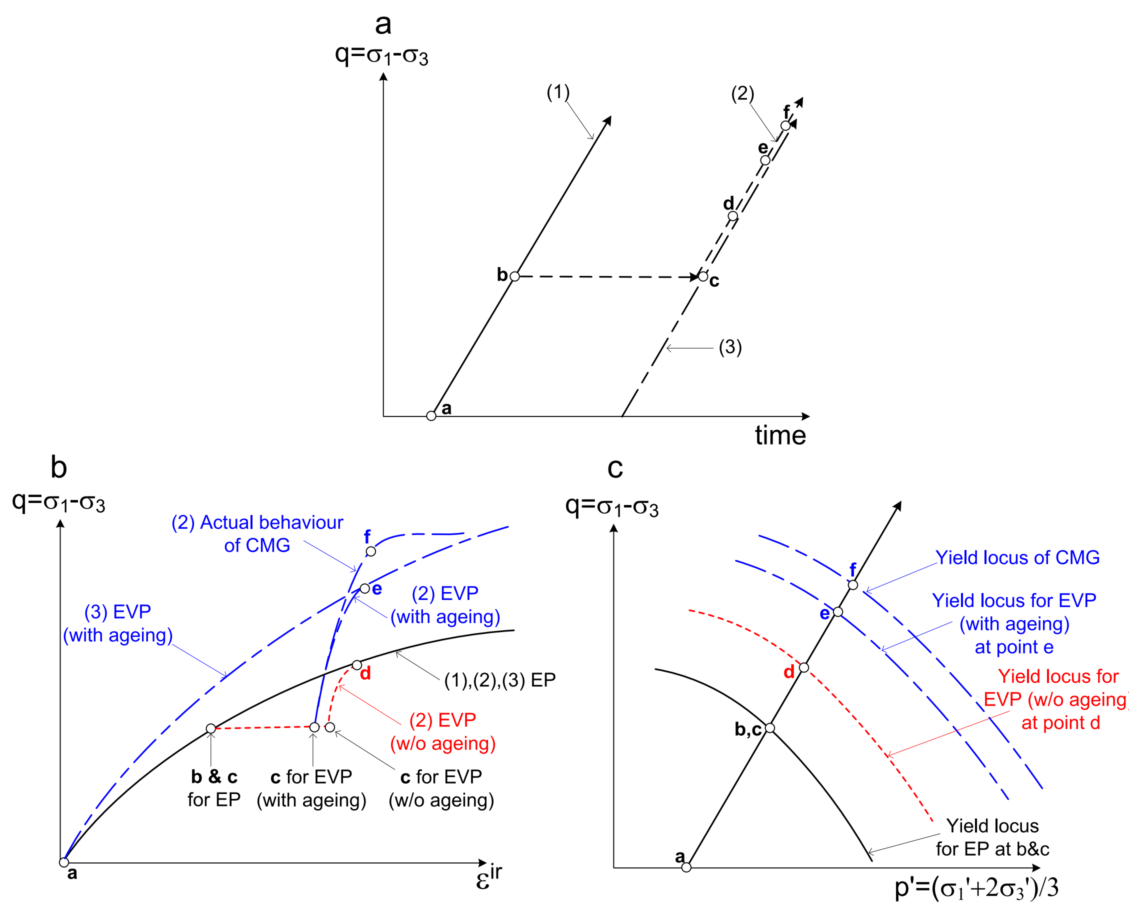


Fig. 1. Different responses under TC stress conditions predicted by different models and actual behavior of CMG.

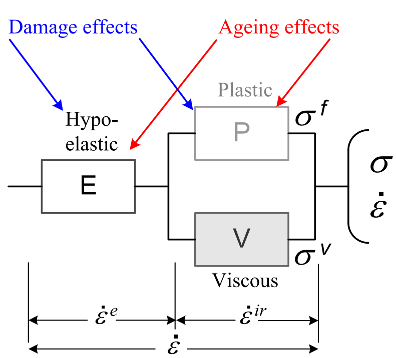


Fig. 2. Non-linear three-component model with effects of ageing and damage (Tatsuoka et al., 2008b).

Upon the restart of monotonic loading (ML), the stiffness is very high until point *d* (on the current YL). The yield point (YP) changes to point *e*, also due to ageing, during sustained loading (SL), as seen in Fig. 1b and c. Di Benedetto et al. (2002) and Tatsuoka et al. (2002, 2008a) showed that the non-linear three-component model, shown in Fig. 2, can simulate these EVP behaviors. The behavior of cement-mixed gravelly (CMG) soil is even more complicated, as illustrated in Fig. 1b and c, due to the effects of the positive interaction between ageing and yielding taking place during SL *b*–*c* and the yielding-associated damage to inter-particle bonding during subsequent ML.

To predict yielding for general stress paths, the changes in shape, size and location of YL during a given loading history should be known. Tatsuoka et al. (2008c) obtained a set of YL for CMG aged at different triaxial compression (TC) stress states. Ezaoui et al. (2010) proposed the interactive double-yielding (IDY) mechanism. Therefore, the objective of the present study is to examine whether the evolution of YL, observed along a wide variety of TC stress paths, can be appropriately simulated based on the IDY mechanism, that develops due to the yielding-associated strain hardening and ageing, and their interaction during shrinking due to damage.

## 2. EVP framework incorporating ageing effect

### 2.1. Non-linear three-component model (Isotach)

According to the model (Fig. 2), total stress $\sigma$ (i.e., measured effective stresses) comprises inviscid stress $\sigma^f$, activated in plastic body *P*, and viscous stress $\sigma^v$, activated in viscous body *V* (Eq. (1)). Strain rate $\dot{\varepsilon}$ comprises elastic part $\dot{\varepsilon}^e$ and visco-plastic (irreversible) part $\dot{\varepsilon}^{ir}$ (Eq. (2)).

$$\sigma = \sigma^f + \sigma^v \tag{1}$$

$$\dot{\varepsilon} = \dot{\varepsilon}^e + \dot{\varepsilon}^{ir} \tag{2}$$