

A conceptual model for lignosulfonate treated soils

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Abstract

This paper describes an anisotropic elastoplastic based constitutive model for describing the behaviour of lignosulfonate stabilized soils. The proposed model is an extension of the earlier model developed by Dafalias (1987). The theoretical formulations of the current model were based on the frame work of critical state concept. The novel feature of this model is the incorporation of a material constant β , which takes into account of the degree of cementation. It is demonstrated that the model can capture the behaviour of lignosulfonate treated soil.

1 INTRODUCTION

In recent years, chemical admixtures such as cement, lime, fly ash shows promising aspects in stabilising soft and unstable soil. These admixtures (stabilizing agents) generally alter the mineralogical structure of the clay and improves the inherent properties of the soil such as strength and stiffness. Vast numbers of studies were conducted to investigate the applicability of traditional stabilisers on problematic soils such as soft clay and erodible soils (e.g. Indraratna et al. 1991; Uddin et al. 1997; Balasubramaniam et al. 1998; Indraratna et al. 1995; Rajasesekaran et al. 1997, Chew et al. 2004).

However, problems such as sulphate attack on concrete and steel structures adjacent to gypsum treated soils, problems with vegetation and groundwater contamination of chemically treated soils due to high pH levels etc, have demanded researchers to find alternative stabilizers. Recently, lignosulfonate, a by product of wood industry shows a promising prospect as stabilizing agent especially for soft grounds. Preliminary investigation on lignosulfonate as stabilizing agent showed that, amount of lignosulfonate required to stabilize soft/unstable soils is much less compared to other traditional admixtures. Furthermore, it has also been observed that stress strain and volume change behaviour is distinctly different from those stabilized with traditional admixtures. During shearing lignosulfonate treated soils maintains a ductile characteristics. In the recent past, several constitutive models have been developed for soils treated with traditional admixtures (Gens and Nova, 1993; Liu et al. 1997; Kasama et al. 2000; Lee et al. 2004 & Namikawa & Mihira, 2007, amongst others). None of these models can be used to predict the behaviour of lignosulfonate treated soil as the shear behaviour of lignosulfonate treated soil is different from the soil stabilized with traditional admixtures. In view of the above, current study focuses on the development of

a conceptual model for lignosulfonate treated soils based on the behaviour observed from the preliminary triaxial laboratory investigation.

1.1 Review of Literature

Lignosulfonates were commonly used to stabilize cohesive to non-cohesive soils. These stabilizers are made from waste liquor by-products from wood processing industries such as paper mills (Karol, 2003). For stabilization purposes, solutions of lignosulfonate were used as raw liquor or used with other additives to achieve desire soil properties. In the recent past, investigations were carried out on cohesive soils with lignosulfonate as stabilisers on the strength improvement of cohesive soils (Puppala and Hanchanloet, 1999; Pengelly et al. 1997; Tingle and Santori, 2003). It has been reported that lignosulfonate with sulphuric acid as additive showed a profound increase in their shear strength and resilient modulus. Tingle and Santori (2003) investigated the effect of lignosulfonate on different clayey soils and found that lignosulfonate stabilizer significantly improved the strength of a low plasticity clayey soil. Again, a solution containing ammonium lignosulfonate and potassium chloride was injected into expansive soil and a significant reduction in the swell was observed (Pengelly et al. 1997). Recently, Indraratna et al. (2008) carried out erosion characteristics studies using Process Simulation Apparatus for Internal Crack Erosion (PSAICE) for lignosulfonate treated soils. It has been reported that significantly less lignosulfonate than cement was sufficient to achieve a given increase in the erosion resistance. An analytical model was developed for lignosulfonate treated soil to evaluate the reduction in erosion capturing its enhanced tensile behaviour (Indraratna et al. 2009). Microchemical analysis revealed that this improved performance can be attributed to a reduction of the double layer thickness by the neutralization of surface charges of the clay particles and the subsequent formation of a stable particle cluster (Vinod et al. 2010).

In addition to these investigation, a number of researchers performed experiments to investigate whether this particular type of chemical in low volume road construction would improve the strength of sub-grade and control dust emission (e.g. Chemstab 2003; Tingle and Santori 2003; Lohnes and Coree 2002).

2 CONCEPTUAL MODEL FOR LIGNOSULFONATE STABILIZED SOIL

The formulation of the proposed model is presented in the triaxial space in terms of stress quantities $p = \frac{(\sigma_1 + 2\sigma_3)}{3}$ and $q = (\sigma_1 - \sigma_3)$ and strain quantities $\varepsilon_d = 2/3(\varepsilon_1 - \varepsilon_3)$; $\varepsilon_v = (\varepsilon_1 + 2\varepsilon_3)$. Where, suffix 1 and 3 represents the axial and radial direction of the triaxial specimen.

2.1 Elastic Behaviour

In the elastoplastic model total strain increments are decomposed into elastic and plastic strain increments

$$d\varepsilon_{ij} = d\varepsilon_{ij}^e + d\varepsilon_{ij}^p \quad (1)$$

Where $d\varepsilon_{ij}^e$ is the elastic strain increment and $d\varepsilon_{ij}^p$ is the plastic strain increment.

For simplicity, elastic strain increment in the proposed model is estimated based on the Hooke's law for isotropic soils. The elastic modulus is related to the swelling index κ from the assumption that soil behaves elastically during the isotropic loading.

In general for isotropic material,

$$d\varepsilon_{ij}^e = \frac{1+\nu}{E} d\sigma_{ij} - \frac{\nu}{E} d\sigma_{mm} \delta_{ij} \quad (2)$$

Where, $d\sigma_{mm} = d\sigma_{11} + d\sigma_{22} + d\sigma_{33}$

$\delta_{ij} = 1 (i=j)$, $0 (i \neq j)$ is Kronecker's delta, E is the elastic modulus and ν the Poisson's ratio.

From Equation (2),

$$d\varepsilon_v^e = d\varepsilon_{11}^e + d\varepsilon_{22}^e + d\varepsilon_{33}^e = \frac{3(1+2\nu)}{E} dp' \quad (3)$$

Assuming, $e - \ln p'$ curve to be linear

$$d\varepsilon_v^e = \frac{\kappa}{1+e_0} \frac{dp'}{p'} \quad (4)$$

Comparing equations (3) and (4) E can be estimated as $E = \frac{3(1-2\nu)(1+e_0)}{\kappa} p'$

Where e_0 is the initial values of the void ratio, κ is the slope of the $e - \ln p'$ space and p' is the mean effective stress.

2.2 Yield Curve

The yield curve proposed for lignosulfonate treated soil is an extension of Dafalias (1987), Davis and

Newson (1993) and Whittle and Kavvas (1994) model.

$$f = (q - \alpha p')^2 - (M^2 - \alpha^2)(p'_0 - p')p' = 0 \quad (5)$$

Where, M is the critical state value of the stress ratio, η ($\eta = q/p'$). p'_0 and α defines the size and orientation of yield curve. The value of α can be envisaged as the degree of plastic anisotropy. With $\alpha = 0$ the yield curve simplifies to original isotropic MCC model. The shape of the yield surface corresponding to the above equation for $\alpha = 0$ is shown in Figure 1. The influence of α on the yield curve is presented in Figure 2. The initial values of α can be computed from the methodology as described by Wheeler et al. (2003).

It is assumed here that the yield surface of lignosulfonate treated (cemented) soil in the $q - p'$ space is assumed to be enlarged to both q and p' space very similar to untreated clays (Fig. 1) which is identical to the conceptual framework of Gens and Nova (1993). This introduces two additional initial conditions p'_s and p'_t where p'_s represents the additional strength that could be applied to a cemented clay to account for the fact that higher mean stresses can be applied to the cemented soil without causing it to yield in isotropic compression and p'_t is the tensile strength produced by the interparticle cementation/bonding.

The modified yield function is of the form:

$$f = (q - \alpha p'^*)^2 - (M^2 - \alpha^2)(p'_0 - p'^*)p'^* = 0 \quad (6)$$

$$p'^* = p + p_t ; \beta = \frac{p'_t}{p'_s} ; \eta^* = \frac{q}{p'^*}$$

$$p'_0 = p'_0 + (1 + \beta)p'_s$$

where, β is the additional material constant which accounts for the degree of cementation/bonding, p'_0 is the hardening parameter and p'_s is assumed to be equal to $\frac{p'_0}{2}$ (Lee et al. 2004). Figure 3 shows the yield curves with incorporation of cementation. As expected, with the introduction of cementation, the yield curve expands to both q and p' axis.

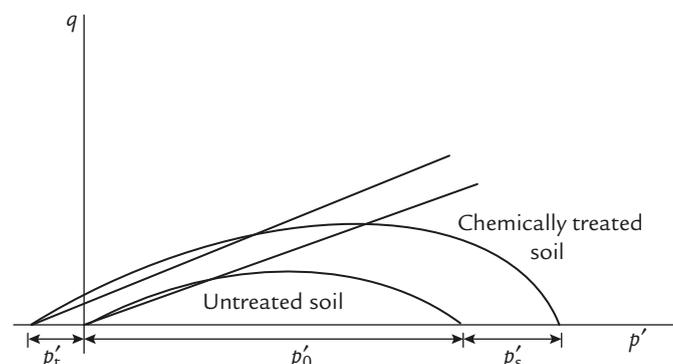


Figure 1 Yield curves for untreated and chemically treated soils.

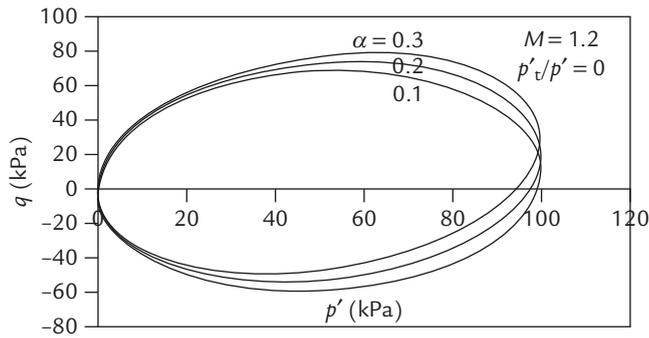


Figure 2 Yield curves for different initial values of α .

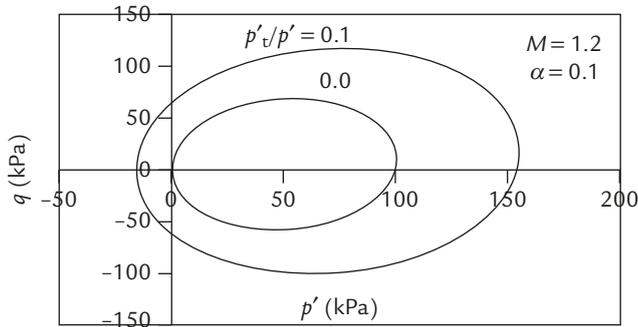


Figure 3 Yield curves with and without cementation.

2.3 Degree of Cementation From Shear Band Thickness

When a soil specimen is subjected to external loads, localized deformation regions in the form of shear bands will developed at failure. Shear bands is caused by the imperfection inherent in soil specimen, boundary conditions, non uniform loading conditions etc. (Hvorslev, 1960; Lade and Wang, 2001, to name a few). Recently, Oda et al. (2004) and Manikawa and Koseki (2006) reported that the addition of admixtures such as cement has a significant influence on the thickness of the shear band during shearing. The thickness of the shear band decreases with the increases in the amount of admixture. The difference in the shear band thickness may be due to the effect of the cementation, since cementation of the treated soil would restrict the movement of the particles along the shear boundary, resulting into narrower shear band than that without cementation. Therefore, shear band is considered to be one of the major factors which controls the overall observed mechanical response of specimen at or near to failure. In the present methodology, β , the material constant which accounts for the degree of cementation is determined from the shear band thickness observed for the treated and untreated soil samples during triaxial tests.

β is defined the as the ratio of the difference in shear band thickness (t_{sb}) of untreated samples, $t_{sb(untreated)}$ and treated samples $t_{sb(treated)}$ to the shear band thickness of treated sample, $t_{sb(treated)}$.

$$\beta = \frac{t_{sb(untreated)} - t_{sb(treated)}}{t_{sb(treated)}} \quad (7)$$

β is not defined for untreated soil and can be taken as zero. However, it is to be noted that there are difficulties in determining the thickness of shear band. Detailed laboratory experiments are in progress to determine the shear band thickness of lignosulfonate treated soil.

2.4 Flow Rule

Associated and non associated flow rules applied to soils were topic of discussion for the last few decades. However, Graham and Houlsby (1983); Korhonen and Lojander (1987) and Wheeler et al. (2003) suggests that associated flow rule is a reasonable approximation for natural clays when combined with inclined yield surface. Associated flow rule postulates that irrespective of the stress increment vector which takes the sample beyond yield, the corresponding plastic strain increment vector should be normal to the yield surface.

For simplicity, associated flow is assumed and it can be shown from Eq. (A5) that:

$$\frac{d\varepsilon_d^p}{d\varepsilon_v^p} = \frac{2(\eta^* - \alpha)}{(M^2 - \eta^{*2})} \quad (8)$$

2.5 Hardening Rule

The hardening rule describes the dependence of the size of the yield locus on the plastic strain. In the present model the change of size of the yield curve is solely to plastic volumetric strain very similar to MCC.

Differentiating and rearranging Eq. (A3) leads to:

$$\frac{\partial p_0^{*'}}{\partial \varepsilon_v^p} = \frac{(1+e)p_0^{*'}}{(\lambda - \kappa)} \quad (9)$$

In general the modified yield function takes the form:

$$f = (p^{*'}, q, p_0^{*'}) = 0$$

Based on the critical state frame work hardening modulus is represented as:

$$H = -\frac{(1+e)p_0^{*'}}{(\lambda^* - \kappa^*)} \left(\frac{\partial f}{\partial p_0^{*'}} \right) \left(\frac{\partial f}{\partial p^{*'}} \right) \quad (10)$$

The plastic volumetric and deviator strains can be expressed as:

$$d\varepsilon_v^p = \frac{1}{H} \left[\left(\frac{\partial f}{\partial p^{*'}} \right)^2 dp^{*'} + \left(\frac{\partial f}{\partial p^{*'}} \right) \left(\frac{\partial f}{\partial q} \right) dq \right] \quad (11)$$

$$d\varepsilon_d^p = \frac{1}{H} \left[\left(\frac{\partial f}{\partial p^{*'}} \right) \left(\frac{\partial f}{\partial q} \right) dp^{*'} + \left(\frac{\partial f}{\partial q} \right)^2 dq \right] \quad (12)$$

The expressions for $\left(\frac{\partial f}{\partial p^{*'}} \right) \left(\frac{\partial f}{\partial q} \right)$ and $\left(\frac{\partial f}{\partial p_0^{*'}} \right)$ is presented in Appendix B.

3 MODEL ASSESSMENTS

It is imperative to assess the prediction of the new model under different initial conditions and model parameters before using it to envisage the behaviour of the real stress strain behaviour of chemically treated soil. Preliminary drained triaxial laboratory experiments show that the soil sample treated with lignosulfonate exhibit a ductile behaviour when compared untreated sample.

3.1 Influence of β

Figures 4 & 5 show the effect of β on the drained stress strain behaviour of soils. The initial conditions and model parameters used are: $M=1.2$, $\lambda=0.3$, $\kappa=0.06$, $\alpha=0.0$, $e_0=0.6$, $p_0=100\text{kPa}$. The critical state constants are similar to those reported by Wood (2004). The deviator stress increases with the increase in the value of β (Fig. 4), and the corresponding increase in the volumetric strain for different values of β is depicted in Figure 5. This clearly shows that the parameter, β is capable of predicting the stress strain and volumetric strain behaviour exhibited by lignosulfonate treated soils. More specifically, the model is capable of capturing the ductile behaviour generally exhibited by lignosulfonate stabilized soils.

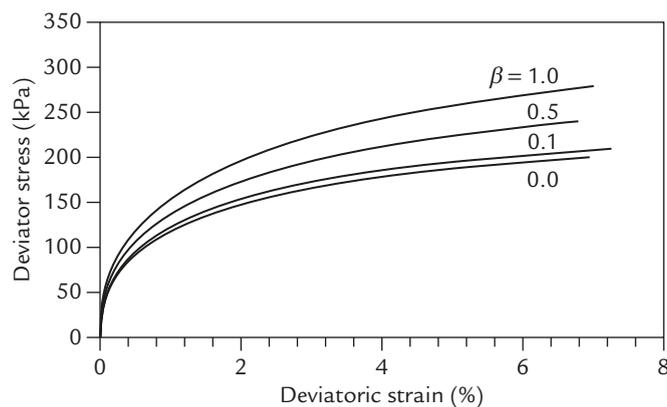


Figure 4 Variation of deviator stress with deviatoric strain for different values of β .

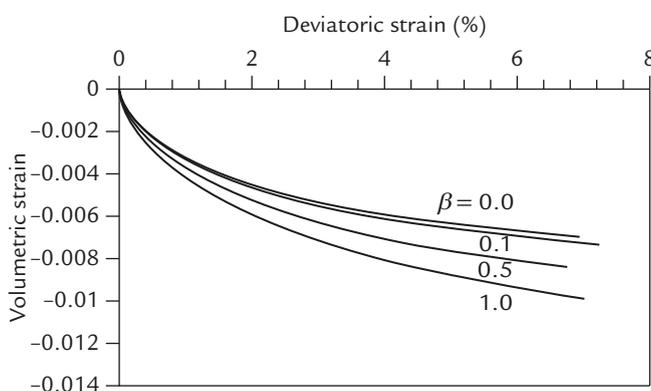


Figure 5 Variation of volumetric strain with deviatoric strain for different values of β .

4 CONCLUSIONS

A conceptual model has been proposed for lignosulfonate treated soils. The proposed model is an extension of the anisotropic models developed by Dafalias (1987). The yield surface extend to both left and right to account for the tensile strength and yield stress during isotropic compression. During the development of the model efforts are made to retain simplicity, while attempting to accurately describe the characteristics of the lignosulfonate treated soil. The salient feature of the model is the incorporation on the material constant β which takes into account of the degree of cementation. The value of β is measured from the shear band thickness of the sample during triaxial shear test at a particular axial strain value. The model requires only a set of parameters ($M, \lambda, \kappa, \alpha, \beta, e_0$) to fully define the chemically treated soil.

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APPENDIX A

From Figure A1 the following relation can be obtained.

$$\epsilon_\nu^e = \frac{\kappa}{1 + e_0} \ln \left(\frac{p_x'^*}{p_0'^*} \right) \tag{A1}$$

$$\epsilon_\nu = \frac{\lambda}{1 + e_0} \ln \left(\frac{p_x'^*}{p_0'^*} \right) \tag{A2}$$

$$\epsilon_\nu^p = (\epsilon_\nu - \epsilon_\nu^e) = \frac{\lambda - \kappa}{1 + e_0} \ln \left(\frac{p_x'^*}{p_0'^*} \right) \tag{A3}$$

Modified expression for rate of plastic work is given by:

$$p'^* (d\epsilon_\nu^p) + q(d\epsilon_d^p) = p'^* \left[(d\epsilon_\nu^p)^2 + (Md\epsilon_d^p)^2 + 2\alpha(d\epsilon_\nu^p)(d\epsilon_d^p) \right]^{\frac{1}{2}} \tag{A4}$$

Rearranging Eq.(A4) leads to:

$$\left(\frac{d\epsilon_d^p}{d\epsilon_\nu^p} \right) = \frac{2p'^* (q - \alpha p'^*)}{(M^2 p'^{*2} - q^2)} \tag{A5}$$

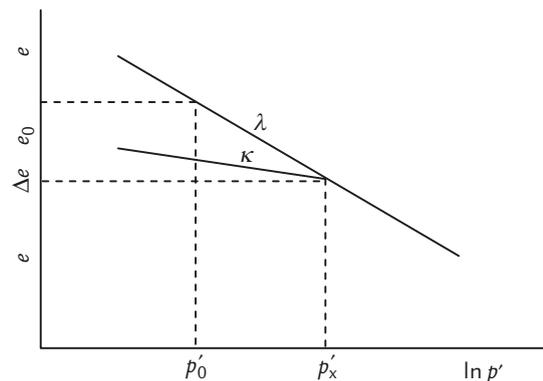


Figure A1 void ratio with mean p .

APPENDIX B

$$\frac{\partial f}{\partial p'^*} = -2\alpha(q - \alpha p'^*) - (M^2 - \alpha^2)(p_0'^* - 2p'^*) \tag{B1}$$

$$\frac{\partial f}{\partial q} = 2(q - \alpha p'^*) \tag{B2}$$

$$\frac{\partial f}{\partial p_0'^*} = -(M^2 - \alpha^2)p'^* \tag{B3}$$