A Strain Hardening/Softening Elasto-Plastic Constitutive Model for Plastic Concrete Materials

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1-Introduction

Plastic concrete, a kind of concrete with higher ductility and less penetration and strength in comparison with conventional concrete, is used as one of the effective methods to control hydraulic structure leakage built on alluvial deformable foundations. Due to the behavioral difference between plastic concrete and conventional concrete, most of the constitutive models proposed for conventional concrete have very limited ability to simulate deformable behavior of plastic concrete materials and in most cases they use the simple Mohr-Coulomb model for this material. Therefore, determining a constitutive model which can simulate plastic concrete volumetric strain-axial strain and stress-strain behavior seems essential. In this study, using a series of drained triaxial test results, plastic concrete material behavior is modeled with an elasto-plastic model that includes hardening strain and softening strain behavioral characteristics of this type of material. FLAC^{2D} has been used for simulation purposes. In this regard, by accurate investigation of available experimental data and with the help of the Vermeer and De Borst hardening-softening strain model, some equations are presented to predict the hardening and softening behavior of plastic concrete. This constitutive model consists of Mohr-Coulomb yield surface and includes mobilized Experimental functions for Mohr - Coulomb main parameters (ψ, c, φ), which can simulate the hardening strain and softening strain behavioral characteristics. With proposing special functions for friction, cohesion and dilatation mobilized, we have modified yield and potential surface in order to have enough reprehensive ability to simulate stress-strain and volumetric strain-axial strain behavior of plastic concrete in drained triaxial test loading conditions. Simulation results have shown that the modified constitutive model has excellent performance in simulating plastic concrete material behavior.

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2- Modified Version of the Vermeer and De Borst hardening / softening strain model to plastic concrete:

An accurate constitutive model for plastic concrete should be able to consider maximum shear strength, hardening/softening behavior, and stiffness change dependent on confining pressure.

Elastic modulus dependence to confining pressure is represented by the Janbu equation:

$$E_i = K.P_a\left(\frac{\sigma_3}{P_a}\right)^n \tag{1}$$

where P_a is the atmospheric pressure, K is the modulus number, and n is the exponent constant that determines the rate of variation of E with σ_3.

In order to simulate the hardening and softening behavior of materials, we used the mobilized friction angle φ^* and the mobilized cohesion c^*, both of which are dependent on plastic strain ε^p. Therefore, yield function may be defined by the following equation:

$$f = \tau^* - \sigma^* \sin\varphi^* - c^* \tag{2}$$

where τ^* is the mobilized shear strength.

In pursuance of increasing the accuracy of distinguishing between plastic and elastic behavior in plastic concrete materials and to simulate material frictional hardening, the Vermeer and de Borst equation is modified to eq. 3:

$$\begin{cases} sin\varphi^* = sin\varphi_0 + 2\dfrac{\sqrt{(\varepsilon^p\varepsilon^f)}}{\varepsilon^p + \varepsilon^f} \\ \quad (sin\varphi_p - sin\varphi_0) & for \quad \varepsilon^p < \varepsilon^f \\ sin\varphi^* = sin\varphi_p & for \quad \varepsilon^p > \varepsilon^f \end{cases} \tag{3}$$

where, ε^f is plastic strain at peak friction angle φ_p and φ_0 is the initial friction angle.

Eq. 4 is suggested for the purpose of simulating the strain softening behavior of plastic concrete material in this study:

$$c^* = c\exp\left[-\left(\frac{\varepsilon^p}{\varepsilon^c}\right)^{\frac{3}{2}}\right] \tag{4}$$

where ε^c is a constant similar to ε^f in dehardening eq. 3 for the mobilised friction angle φ^*.

In order to model the volumetric behavior of plastic concrete, Rowe dilatation theory is applied. According to both Rowe limiting assumptions and numerical modeling of available plastic concrete experimental results, eq. 5 that is a modified form of Rowe function is presented:

$$\sin\psi^{*} = \begin{cases} \sin(F.\theta) & F.\theta \le \psi_p \\ \sin\psi_p & F.\theta > \psi_p \end{cases} \qquad (5)$$

where

$$\theta = \sin^{-1}\left(\frac{\sin\varphi^{*} - \sin\varphi_{cv}}{1 - \sin\varphi^{*}\sin\varphi_{cv}}\right) \qquad (□)$$

$$\sin\varphi_{cv} = \frac{\sin\varphi_p - \sin\psi_p}{1 - \sin\varphi_p \sin\psi_p} \qquad (□)$$

where ψ^{*} is the mobilized dilatation angle and F is a constant value which shows the mobilized dilatation angle increase rate (□□F□1). φ^{*} and ψ_p are the mobilized dilation angle and peak dilation angle, respectively. φ_{cv} is the critical state friction angle or friction angle of constant volume.

3- Simulation and Results

In this study, two groups of data are used for modeling. First, drained consolidated triaxial experimental results of plastic concrete of Soumbar dam are used as an example of low strength and soft plastic concrete and second plastic concrete of Three Gorges pro□ect cofferdams is used as an instance for high strength and relatively hard plastic concrete. Simulation has been done on an element and all the aforementioned functions and dependencies are applied on the plastic concrete constitutive model using FIS□. In each step of the analysis, plastic shear strain is calculated and are updated based on the defined functions for every variable all parameters. By changing the parameters and conducting trial and error, the results obtained from the modified model are in good agreements with the experimental data. These parameters are determined as a function of confining pressure. The results of the simulation in different confining pressure are given in Figure 1.

4- Conclusion

The main purpose of this research study is to present a perspective to simulate plastic concrete material with a hardening/softening strain constitutive model in the deviated stress- axial strain and volumetric strain-axial strain conditions. According to simulation results of experimental data, stress-strain curves resulted from numerical analysis for both soft plastic and hard one is in compliance with experimental outputs considering the modifications made in the hardening/softening plastic concrete. Furthermore, volumetric strain-axial strain curves resulted from modified potential function for soft plastic concrete, in low confining pressure for hard plastic, are fit to the data although in high confining pressures for hard plastic concrete before maximum value, volumetric strain values of numerical model have some deviations from the experimental data.

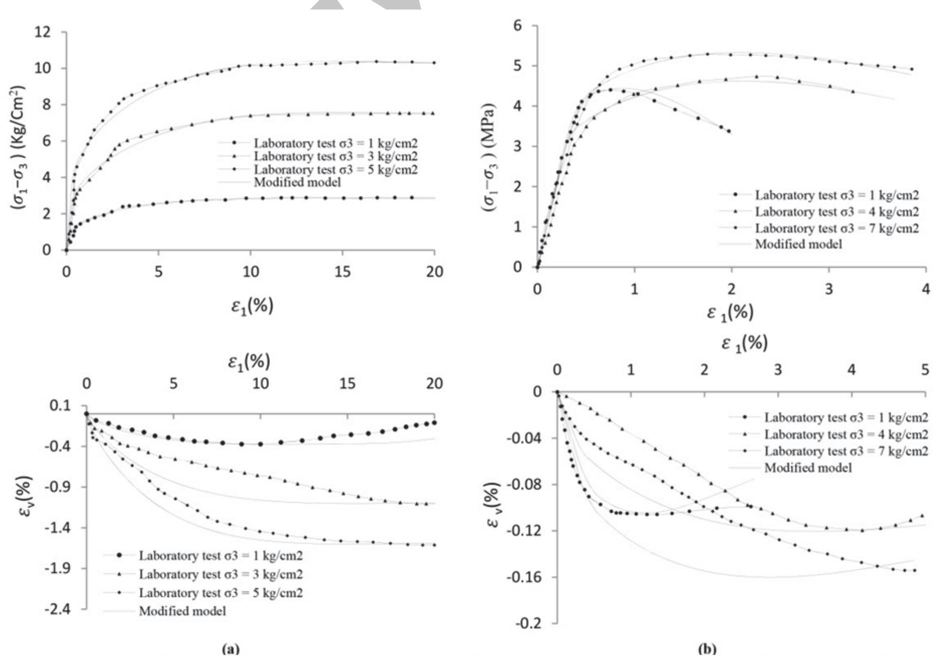

Fig. 1. The results of the Simulation Stress-Strain and Volumetric Strain-Axial strain behavior of plastic concrete (a) Soumbar dam, (b) Three Gorges project cofferdams