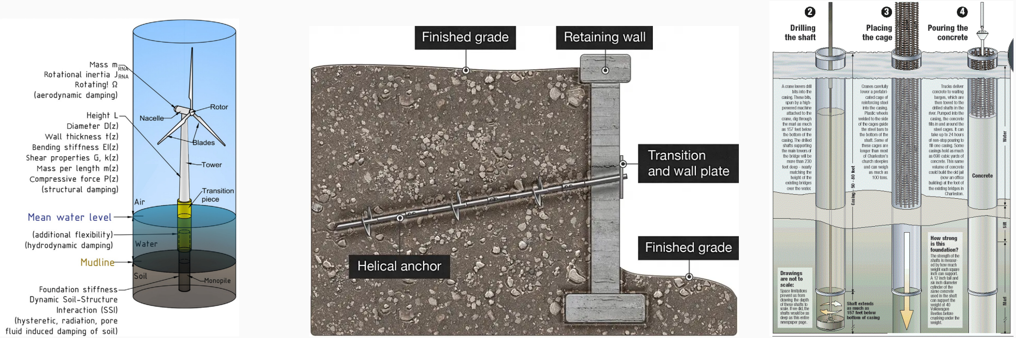
Outline

Background

Background



(a) Offshore Wind Power (Prakhya & Bhattacharya, 2021)

(b) Retaining Wall (LLC, 2022)

(c) Pile Foundation (Thursday, 2017)

Figure 1: Structures that are closely related to Soil-Structure Interaction (SSI)

Interface Models

- Nonlinear Elasticity Models: Use nonlinear functions to describe the SSI behaviors:
  - Hyperbolic Function (Clough & Duncan, 1971)
  - Polynormial Function (Desai et al., 1985; Desai & Nagaraj, 1988; Desai et al., 2005)
- Elastoplastic Models: Models based on elastoplasticity theories.
  - Elastic-Perfact-Plasticity Models (Brandt, 1985; Goodman et al., 1968)
  - Damage Plasticity Models (Hu & Pu, 2003, 2004; Navayogarajah et al., 1992; G. Zhang & Zhang, 2008)
  - Models based on Disturbed State Concept (Desai & Ma, 1992; Desai et al., 2005; Fakharian & Evgin, 2000)
  - Models based on Generalized Plasticity (Lashkari, 2010; H. Liu & Ling, 2008; H. B. Liu et al., 2006; J. M. Liu et al., 2014; Zhou & Lu, 2009)
  - Two-Surfaces Plasticity (Lashkari, 2012a, 2012b, 2013; Lashkari & Kadivar, 2016; Lashkari & Torkanlou, 2016; Mortara et al., 2002; Shahrour & Rezaie, 1997)
  - . . .

The Exponential Model

Basic Equation

- Basic equation:

$$\eta = \frac{\tau}{\sigma_n + \sigma_a} = b[1 - \exp(-a\gamma)] \qquad (1)$$

- Coefficients:

$$G = \left.\frac{\mathrm{d}\tau}{\mathrm{d}\gamma}\right|_{\mathrm{i}} \implies a = \frac{G}{b(\sigma_n + \sigma_a)} \qquad (2)$$

$$\eta_{\mathrm{u}} = \tan\phi_c \implies b_u = \tan\phi_c \implies b = \tan\phi_p \qquad (3)$$

- Stress dilatancy:

$$\begin{aligned} \mathrm{d}\sigma_n &= K_n(\mathrm{d}\varepsilon_n - \mathrm{d}\varepsilon_n^{in}) \\ &= K_n\left[\mathrm{d}\varepsilon_n - A_d(\tan\phi_{pt} - \eta)\right] \end{aligned} \qquad (4)$$

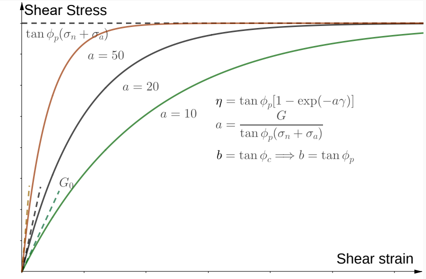


Figure 2: The asymptotic function

$$\mathrm{d}\tau = \frac{\partial\tau}{\partial\sigma_n}\mathrm{d}\sigma_n + \frac{\partial\tau}{\partial\gamma}\mathrm{d}\gamma = ? \qquad (5)$$

$$\Downarrow$$

Boundary Condition

Dealing with Diferent Boundary Conditions

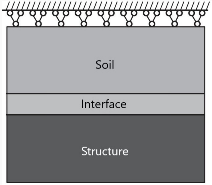


Figure 3: Constant Volume

$K = \infty$

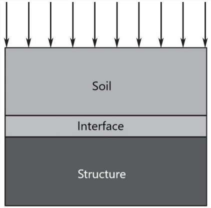


Figure 4: Constant Load

$K = 0$

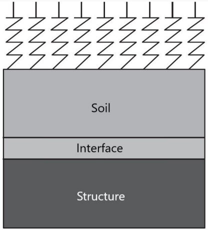


Figure 5: Constant Stiffness

$K = \text{const}$

The stress increment is (combine $\mathrm{d}\sigma_n = -K\mathrm{d}\varepsilon_n$) :

$$\begin{aligned} \mathrm{d}\sigma_n &= -\frac{K_n K}{K_n + K} A_d \left(\tan\phi_{pt} - \eta\right) \mathrm{d}\gamma \\ \mathrm{d}\tau &= \left\{ G\left(1 - \frac{\eta}{\tan\phi_p}\right) - \frac{K_n K}{K_n + K} A_d \left(\tan\phi_{pt} - \eta\right)\left[\eta - a\gamma\left(\tan\phi_p - \eta\right)\right] \right\} \mathrm{d}\gamma \end{aligned} \tag{6}$$

Stress reversal effect on the stress displacement relationship

$$\begin{cases} \left|\eta - \eta^R\right| = \tan\left(\phi_p\right)^* \left(1 - e^{-a\left|\gamma - \gamma^R\right|}\right) \\ \mathrm{d}\varepsilon_n^{in} = A_d \left(\tan\left(\phi_{pt}\right)^* - \left|\eta - \eta^R\right|\right) \left|d\gamma\right| \\ \tan\left(\phi_p\right)^* = \left|\tan\left(\phi_p\right) n - \eta^R\right| \\ \tan\left(\phi_{pt}\right)^* = \left|\tan\left(\phi_{pt}\right) n - \eta^R\right| \end{cases} \tag{7}$$

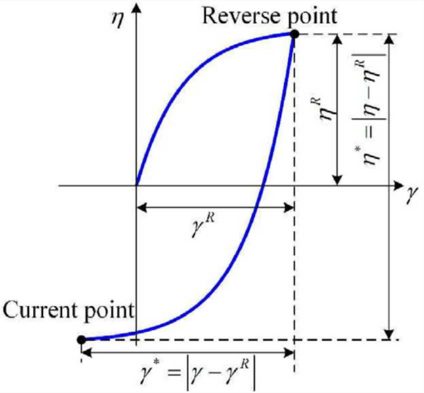


Figure 6: Principle of stress reversal in loading and unloading

Enhancements

- Nonlinear Elasticity

$$G = G_0 \frac{(2.97 - e)^2}{1 + e} \left(\frac{\sigma_n + \sigma_a}{P_{at}} \right)^{0.6} \tag{8}$$

- Critical State

$$e_c = e_{ref} \exp \left[-\lambda \left(\frac{\sigma_n}{P_{at}} \right)^{\xi} \right] \tag{9}$$

$$\tan \phi_p = \left(\frac{e_c}{e} \right)^{n_p} \tan \phi_c \tag{10}$$

$$\tan \phi_{pt} = \left(\frac{e}{e_c} \right)^{n_d} \tan \phi_c \tag{11}$$

- Breakage Effect

$$e_{ref} = e_{refu} + (e_{ref0} - e_{refu}) \exp \left(-\rho B_r^* \right) \tag{12}$$

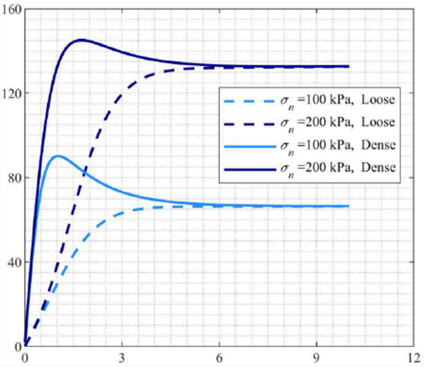


Figure 7: Typical shear stress

Results and Discussions

Model Behaviors

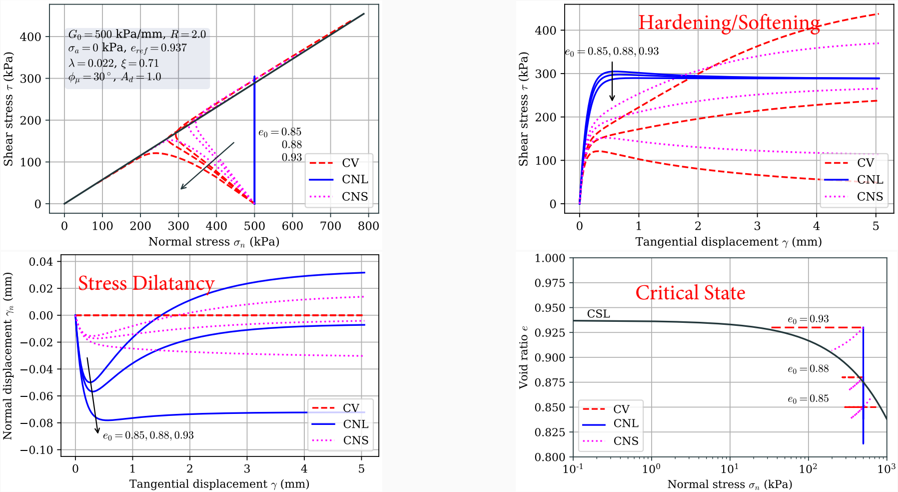


Figure 8: Typical simulation results

Experiments under Monotonic Loadings

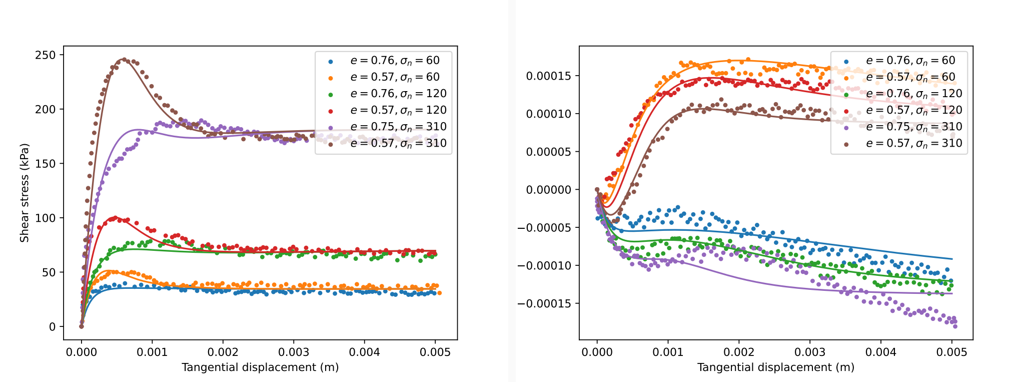


Figure 9: Comparison between simulations and experiments under monotonic loadings

Experiments under Cyclic Loadings

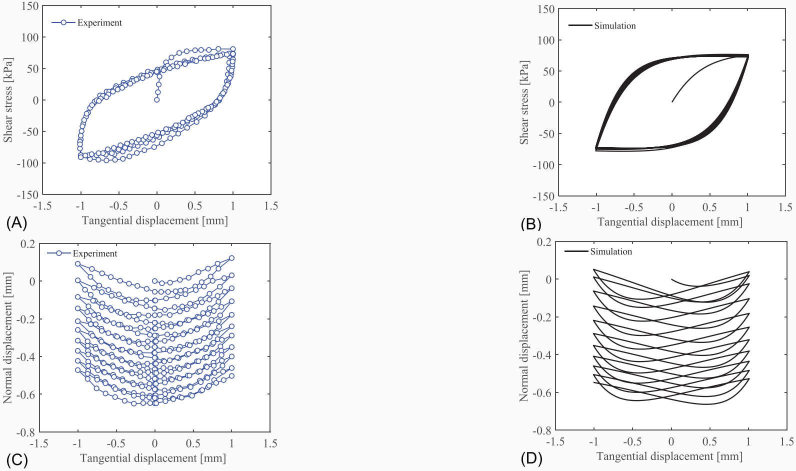


Figure 10: Comparison between simulations and experiments under cyclic loadings

The breakage index

$$B_r^* = \frac{W^n}{b + W^n}$$
$$W = \int \tau \mathrm{d}\gamma + \langle \sigma_n \mathrm{d}u_n \rangle \tag{13}$$

The grain size distribution (C. Zhang et al., 2013)

$$F_d = B_r F_u + (1 - B_r^*) F_0$$
$$F_u = \left(\frac{d^{\,3-\alpha} - d_m^{\,3-\alpha}}{d_M^{\,3-\alpha} - d_m^{\,3-\alpha}} \right) \tag{14}$$

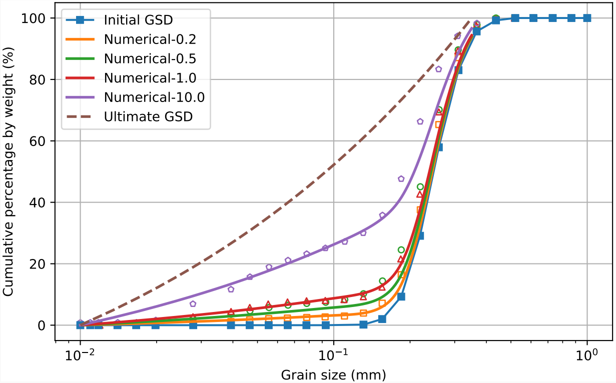


Figure 11: Calibration result of the breakage effect

Conclusions

Conclusions

- A simple nonlinear incremental constitutive model based on an **exponential function** was developed to capture the characteristics of the soil-structure interface.
- The **nonlinear shear modulus**, the **critical state** concept and the **grain breakage** concept were introduced gradually to enhance the model.
- The model is capable of simulating the complex behavior of granular soil-structure interfaces such as **stress hardening and softening**, **stress dilatancy**, and **grain particle breakage**.
- The variation of grain size distribution induced by grain breakage during shearing could be estimated.

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Questions?

Modelling of Monotonic and Cyclic Behaviors of Soil-Structure Interface Using Nonlinear Incremental Model [1]

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[1] Yang, J., & Yin, Z.-Y. (2021). Soil-structure interface modeling with the nonlinear incremental approach. International Journal for Numerical and Analytical Methods in Geomechanics, 45(10), 1381–1404. https://doi.org/10.1002/nag.3206.