



# Modelling of Monotonic and Cyclic Behaviors of Soil-Structure Interface Using Nonlinear Incremental Model<sup>a</sup>



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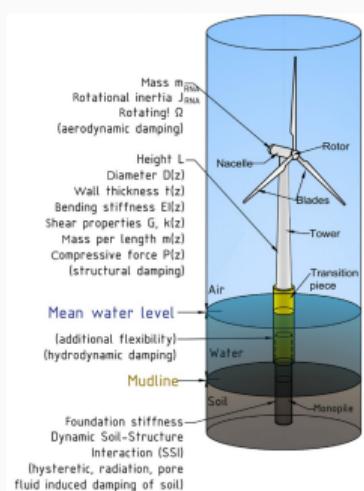
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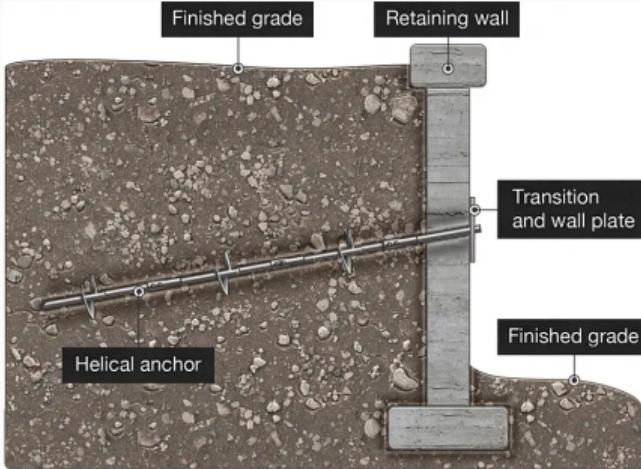
## Background

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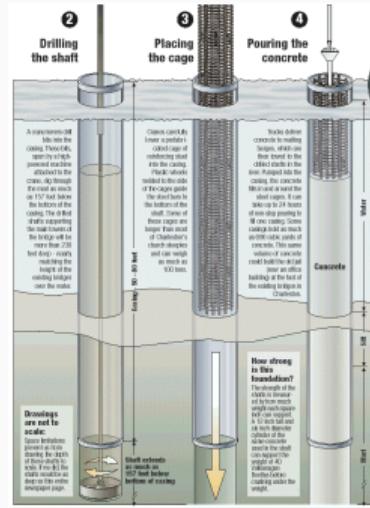
# Background



(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)
  - Polynormal Function (Desai et al., 1985; Desai & Nagaraj, 1988; Desai et al., 2005)
- **Elastoplastic Models:** Models based on elastoplasticity theories.
  - Elastic-Perfect-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

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# Basic Equation

- Basic equation:

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

- Coefficients:

$$G = \left. \frac{d\tau}{d\gamma} \right|_i \Rightarrow a = \frac{G}{b(\sigma_n + \sigma_a)} \quad (2)$$

$$\eta_u = \tan \phi_c \Rightarrow b = \tan \phi_c \Rightarrow b = \tan \phi_p \quad (3)$$

- Stress dilatancy:

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

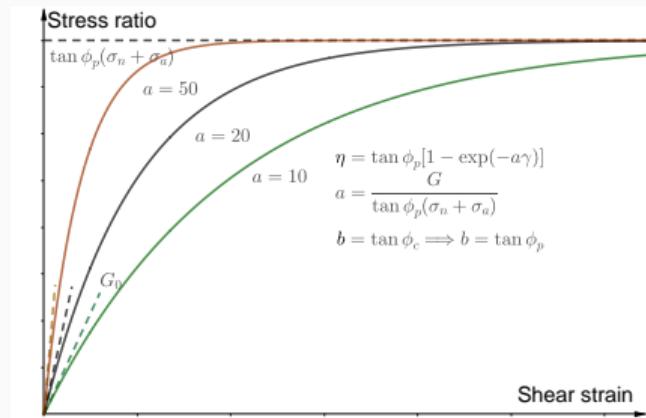


Figure 2: The asymptotic function

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

# Dealing with Different Boundary Conditions

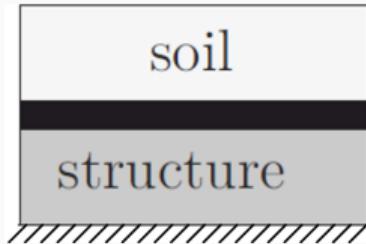


Figure 3: Constant Volume  
 $K = \infty$

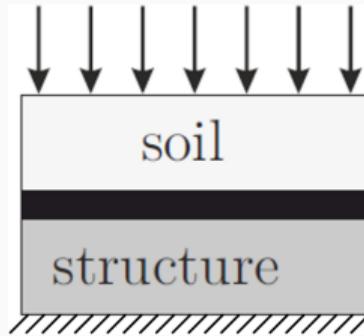


Figure 4: Constant Load  
 $K = 0$

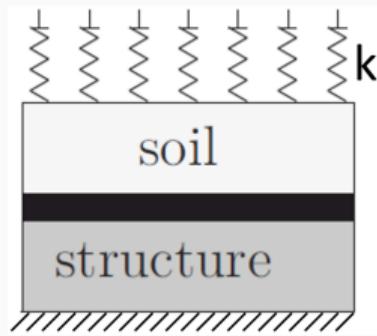


Figure 5: Constant Stiffness  
 $K = \text{const}$

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

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

# Dealing with Cyclic Loadings

Stress reversal effect on the stress displacement relationship

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

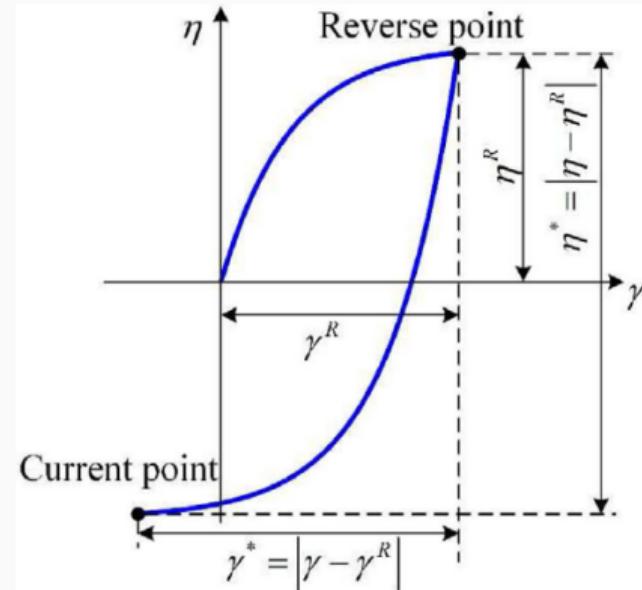


Figure 6: Principle of stress reversal in loading and unloading

# Enhancements

- Nonlinear Elasticity

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

- Critical State

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

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

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

- Breakage Effect

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

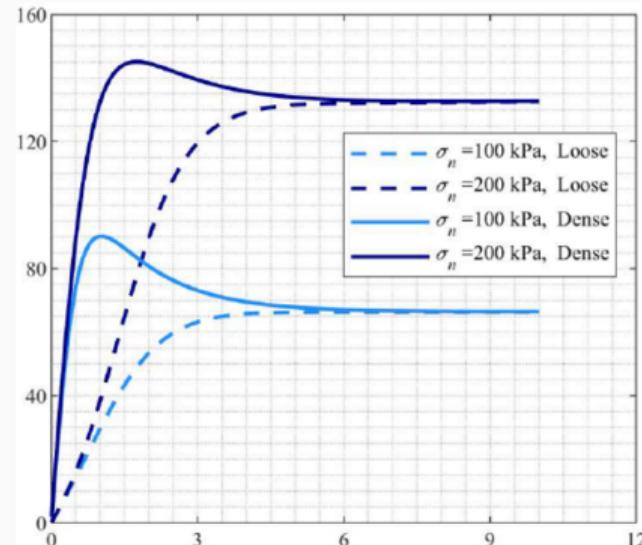


Figure 7: Typical shear stress

## Results and Discussions

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# Model Behaviors

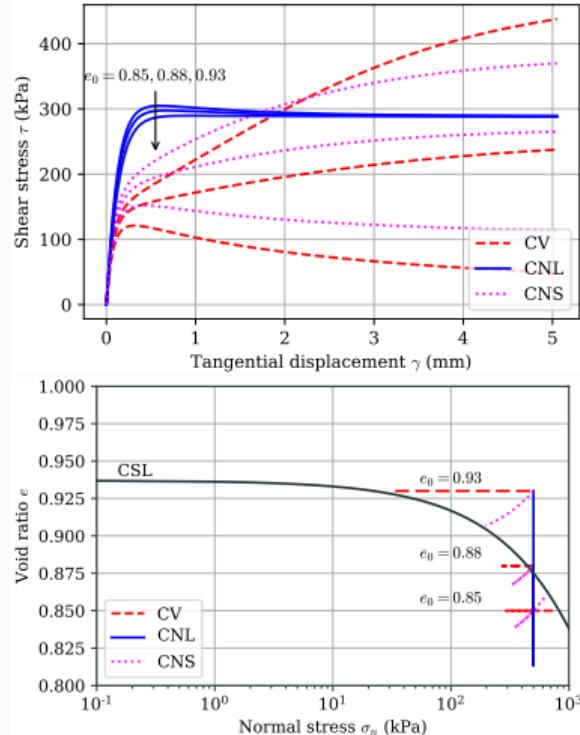
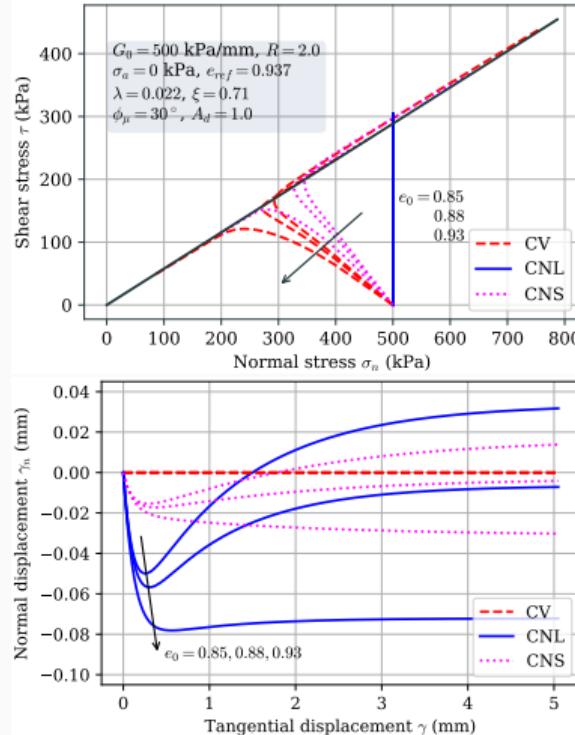


Figure 8: Typical simulation results

# Experiments under Monotonic Loadings

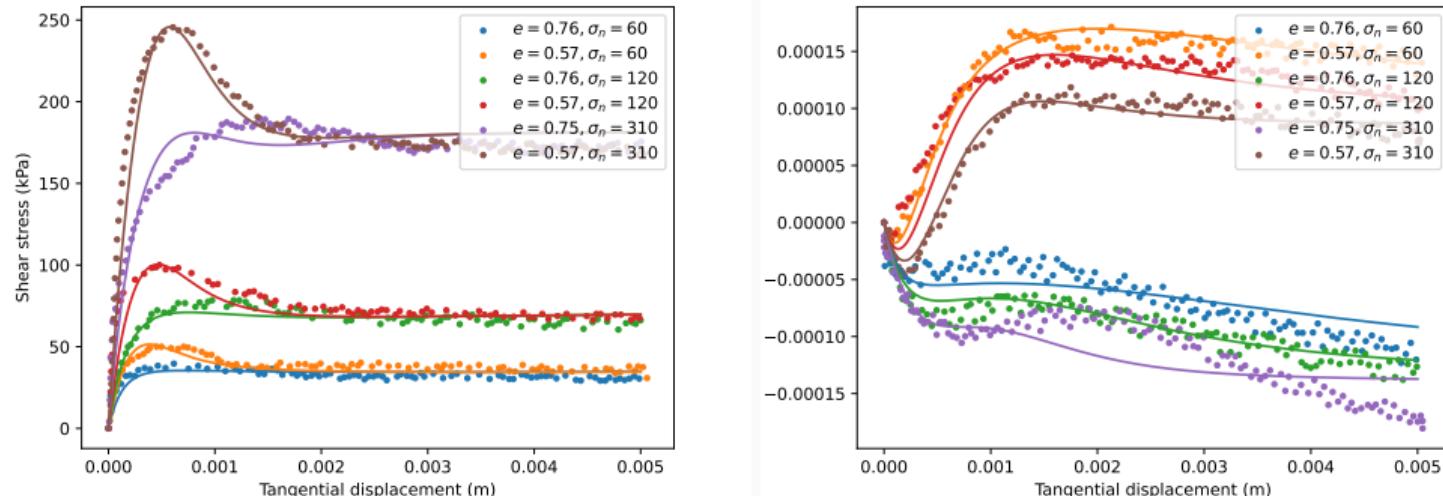
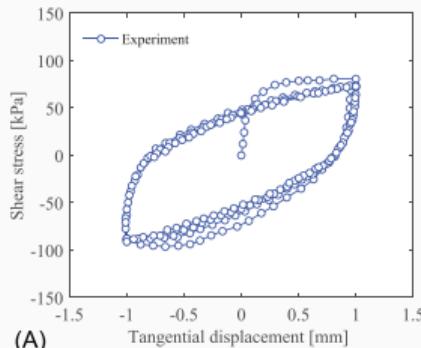
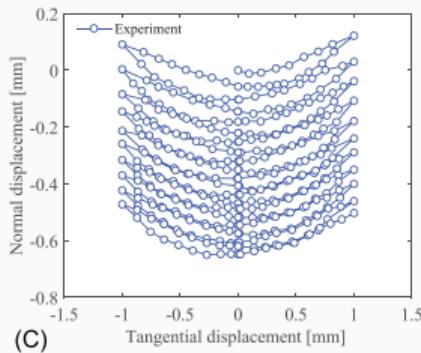


Figure 9: Comparison between simulations and experiments under monotonic loadings

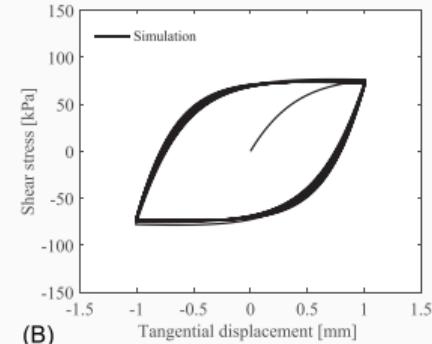
# Experiments under Cyclic Loadings



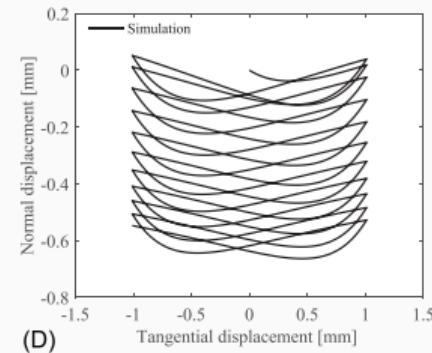
(A)



(C)



(B)



(D)

Figure 10: Comparison between simulations and experiments under cyclic loadings

# The breakage effect

The breakage index

$$B_r^* = \frac{W^n}{b + W^n} \quad (13)$$
$$W = \int \tau d\gamma + \langle \sigma_n du_n \rangle$$

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

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

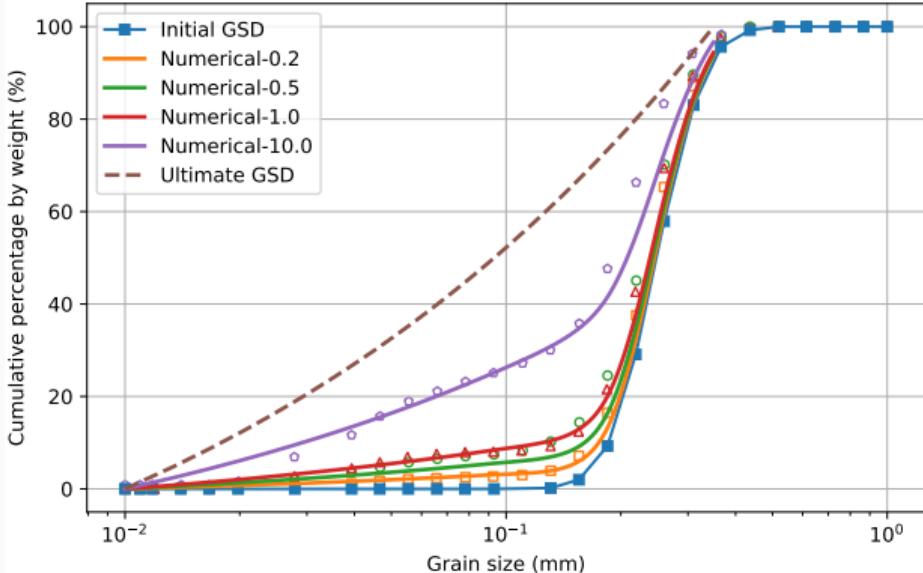


Figure 11: Calibration result of the breakage effect

## Conclusions

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# 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<sup>-1</sup>

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