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“Research Note”

MODELING OF INITIAL INTENSE CONTRACTION IN SAND-STRUCTURE INTERFACES[*]

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Abstract– For many geotechnical engineering structures, the bearing capacity and load-deformation response depend on the stress-relative displacement behavior of interfaces in the contact area with surrounding soil. This issue may become of paramount importance considering that many of the existing interface constitutive models reveal remarkable limitations in the simulation of the intense contraction observed in the initial stage of shearing. In this research note, a proper state dependent constitutive equation is introduced to improve this deficiency. Direct comparisons against experimental data and some of the recent interface models are presented to show the improvements achieved.

Keywords– Soil-structure interface, state, dilatancy, plasticity theory, critical state

1. INTRODUCTION

Soil-structure interfaces are thin layers of soil adjacent to geostructures which transfer loads from structures to soil. In practical problems like piles, developed skin friction depends on the confining (normal) stress transferred from structures to surrounding soils [e.g., 1-3]. A majority of experimental studies on interface behavior has been conducted under fixed normal stress condition [e.g., 2-5]. However, in recent years, attention has been focused on the conditions which allow normal stress to change with normal and tangential displacements [e.g., 6-11]. These studies have definitely revealed that the normal stress component varies when a constraint is put on volume change. When volume change is not fully allowed, it is observed that the tendency toward contraction reduces the normal stress, while dilation results in normal stress recovery. In this path, Mortara et al. [11] has reported experimental evidence that the excessive tendency to contract may result in a liquefaction type drastic loss of interface shear strength when volume change is restricted. In the past, a number of elasto-plastic constitutive models have been developed for prediction of the mechanical behavior of interfaces [e.g., 12-17], but as it is discussed in section 4, (Fig. 5), they are generally incapable of properly simulating the intense contraction observed in the initial stages of shearing. This undesirable feature may lead to the unsafe design of geostructures. In this research note, the major causes of the mentioned massive contraction are described first, then, a modified state dependent stress-dilatancy law is introduced. It has been shown that the proposed modification is capable of predicting the intense contraction of interfaces compared to the experimental data.

2. MODIFIED STRESS DILATANCY CONSTITUTIVE LAW

There are a number of phenomena in the micro structural scale which must be addressed in the development of constitutive equations of sand-structure interfaces. Using Particle Image Velocimetry (PIV) technique, DeJong and Westgate [10] observed that thickness of the zone of intense shear in

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interfaces decreases with the increase of applied normal stress. This is because the required energy forcing particles to roll on each other (namely to generate dilation) increases for larger normal stresses. Moreover, at the initial stage of shearing, deformation within the interface zone is homogenous. As shear displacement proceeds, strong localization occurs and the steady state of shearing takes place within the interface zone (e.g., [6, 10, 15]). According to these experimental evidences, some researchers like Uesugi and Kishida [4], Ghionna and Mortara [9], and Yoshimi and Kishida [18] suggested that the plastic yielding of sand-structure interfaces is due to two independent mechanisms: initially homogeneous interface deforms mainly normal to the interface plane, but subsequently the tangential component of displacement overcomes as a consequence of the so-called strong localizations.

Stress-dilatancty functions of sand-structure interface models [e.g., 12-17] are generally inspired by the well-known Rowe's flow rule that is in the following form

$$d = A\left(M^{d} - \eta\right) \tag{1}$$

where A is assumed as a material constant, and $\eta = \tau/\sigma_n$ is the stress ratio in which τ and σ_n are respectively the tangential and normal stress components acting on the interface plane (*see* Fig. 1). M^d, dilatancy stress ratio, is the stress ratio at which contraction turns into dilation or *vice versa*. For $\eta < M^d$, $d > 0$ and thus the interface behavior becomes contractive. On the other hand, $d < 0$ and, as a consequence, interface dilates when $\eta > M^d$. The mathematical representation of M^d is introduced in the next section. It is observed that due to the lack of consideration on grains behavior within the zone of intense shear, the application of Eq. (1) does not result in satisfactory results. To improve this limitation, it is suggested here to calculate A by the following equation

$$A = A_0\sqrt{\frac{p_{ref}}{\sigma_n}} + \left(A_1 - A_0\sqrt{\frac{p_{ref}}{\sigma_n}}\right)\left(\frac{\eta - \eta_{in}}{M^b - \eta_{in}}\right) \tag{2}$$

where A_0 and A_1 are interface parameters, and η_{in} is the stress ratio at the beginning of the recent plastic yielding. Usually, A_0 is larger than A_1. Hence, when a new loading starts, $\eta = \eta_{in} < M^d$. As a result, $A = A_0\sqrt{p_{ref}/\sigma_n}$ leads to relatively massive contraction at the initial stage of shearing. The term $\sqrt{p_{ref}/\sigma_n}$ is introduced to take account of the effect of normal stress on the thickness of the zone of intense shear. If shear loading proceeds, η gradually increases toward its asymptotic value i.e., M^b (definition of M^b is given in the next section). HenceS, the ratio $(\eta - \eta_{in})/(M^b - \eta_{in})$ gently approaches toward 1.0. Eventually, at critical state, $(\eta - \eta_{in})/(M^b - \eta_{in}) = 1$ and $A = A_1$. It can be observed that the double mechanism explanation for volume change behavior of interfaces [4, 9, 17] is adopted here and Eq. (2) guarantees the smooth transition from one mechanism to the other.

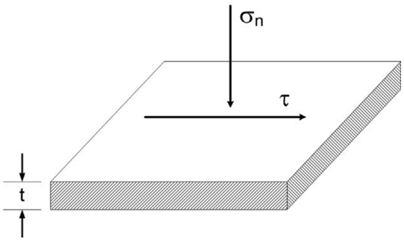

Fig. 1. Idealized representation of stresses acting on an interface

3. A SIMPLE SAND-STRUCTURE INTERFACE MODEL

According to the classical theory of elasto-plasticity, the following constitutive law holds between the rates of the stress and relative displacement vectors in the interfaces [e.g., 15-17]

$$\{\dot{\boldsymbol{\sigma}}\} = [\mathbf{D}]^{ep}\,\{\dot{\boldsymbol{\Delta}}\} = \frac{1}{t}\left([\mathbf{D}]^{e} - \frac{[\mathbf{D}]^{e}\{\mathbf{R}\}\{\mathbf{n}\}^{T}[\mathbf{D}]^{e}}{K_p + \{\mathbf{n}\}^{T}[\mathbf{D}]^{e}\{\mathbf{R}\}}\right)\{\dot{\boldsymbol{\Delta}}\} \tag{3}$$

where the stress and relative displacement vectors are defined by

$$\{\boldsymbol{\sigma}\} = \{\sigma_n \quad \tau\}^{T} \quad ; \quad \{\boldsymbol{\Delta}\} = \{v \quad u\}^{T} \tag{4}$$

σ_n and τ are normal and tangential components of the stress vector (*see* Fig. 1). The normal, v, and tangential, u, components of the relative displacement vector are introduced corresponding to those of the stress vector. {**n**} and {**R**} are vectors respectively defining yield and plastic strain rate directions. It is worthy to note that d, dilatancy function, was introduced in Eq. (1)

$$\{\mathbf{n}\} = \{n_n \quad n_\tau\}^{T} = \{-\eta \quad 1\}^{T} \quad ; \quad \{\mathbf{R}\} = \{R_n \quad R_\tau\}^{T} = \{d \quad 1\}^{T} \tag{5}$$

t ($\approx$5 times of mean grain size) in Eq. (3) is the interface thickness, $[\mathbf{D}]^{ep}$ is the elasto-plastic stiffness matrix, $[\mathbf{D}]^{e}$ is the elastic stiffness matrix, and K_p is the plastic hardening modulus

$$[\mathbf{D}]^{e} = \begin{bmatrix} K_n & 0 \\ 0 & K_t \end{bmatrix} = \begin{bmatrix} K_{n0}\left(\sigma_n / p_{ref}\right)^{0.5} & 0 \\ 0 & K_{t0}\left(\sigma_n / p_{ref}\right)^{0.5} \end{bmatrix} \tag{6}$$

and

$$K_p = h_0 K_t \left(\frac{M^b}{\eta} - 1\right) \tag{7}$$

M^b [*see* Eqs. (2) and (7)] and M^d [*see* Eq. (1)] indicate the maximum permissible, and phase transformation stress ratios, respectively. According to Dafalias and Manzari [19] they are

$$M^b = M\exp(-n^b\psi) \quad ; \quad M^d = M\exp(n^d\psi) \tag{8}$$

where M is the slope of interface critical state line in the τ-σ_n plane. ψ (= e - e_c) is the state parameter of Been and Jefferies [20] measured in the e-σ_n plane in which e and e_c are the current and critical state void ratios respectively. In this study, the location of critical state line in the e-σ_n plane is calculated by

$$e_c = e_0 - \lambda\,\ln\left(\sigma_n / p_{ref}\right) \tag{9}$$

In the mathematical formulation presented, K_{n0}, K_{t0} , h_0, A (A_0 and A_1), M, n^b, n^d , e_0 and λ are model parameters, and p_{ref} is a reference pressure that is assumed equal to the atmospheric pressure (=101 kPa) here.

4. EVALUATION OF THE MODIFIED STRESS-DILATANCY LAW

The suggested stress-dilatancy law is implemented in a computer code written based on the presented interface model. The parameters used in simulations of experimental data reported by Evgin & Fakharian [6] and Mortara et al. [9] are given in Table 1.

For three constant normal stiffness tests conducted under different amounts of normal stress, the modified and the original interface models predictions are depicted versus the experimental data of Evgin & Fakharian [6] in Fig. 2. Comparisons of parts “a” with “d”, and “b” with “e” indicate the improvement achieved on simulation of intense contraction in the initial stage of shearing. However, in medium to large tangential displacements, predictions of the modified and the original approaches gradually tend together.

Predictions obtained from both approaches for three constant normal stress tests are demonstrated in Fig. 3. From comparison of part "b" with "d", improvement on simulation of initial intense contraction is evident.

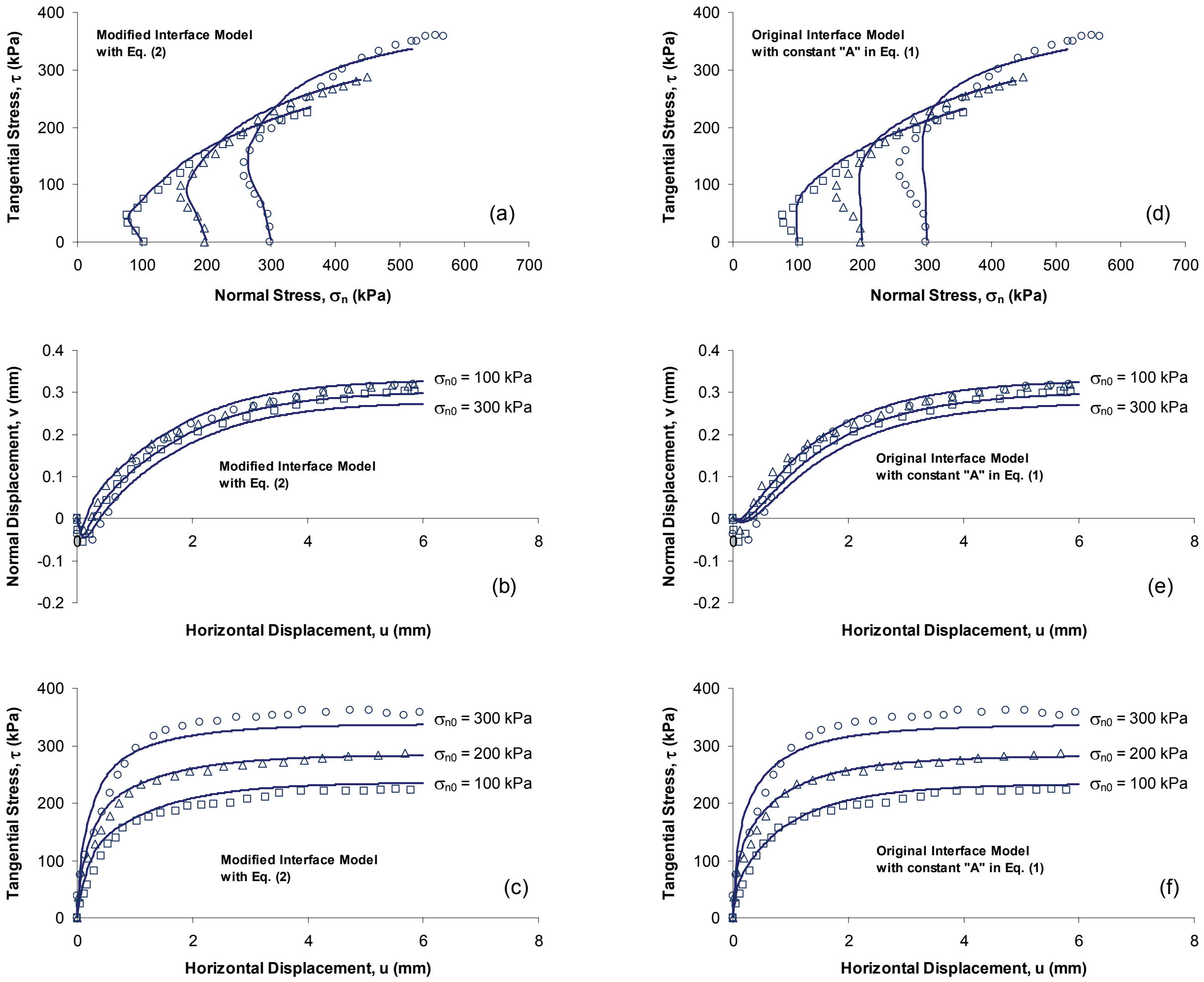

Fig. 2. Comparisons between the modified and the original interface models predictions against three constant normal stiffness tests with σ_{n0}=100, 200, and 300 kPa, K=800 MPa/m and e_0=0.696 (experimental data taken from Evgin and Fakharian [6])

Similar evaluations of the suggested stress-dilatancy law against constant normal stiffness data of Mortara et al. [9] are illustrated in Fig. 4. It can be observed that the predictive capability of the modified interface model is satisfactory.

To show the superiority of the suggested stress-dilatancy law, the modified model predictions for stress path and volume change behavior of Ottawa sand-steel interface tests with σ_{n0}=100 kPa, K=800 MPa/m and e_0=0.696 are compared with those of the other recent interface models (Fakharian and Evgin [13]; De Gennaro and Frank [14]; Liu et al. [15], and Lashkari [17]) in Fig. 5. In part “a” of the figure, the predicted stress paths are depicted. It can be observed that, except for the approach of this study and partly the model of De Gennaro and Frank [14], the other models are unable to simulate intense contraction at the initial stage of shearing. Part “b” of Fig. 5 illustrates the predicted tangential stress versus tangential displacement curves based on various approaches. It can be observed that the approach of this study still provides reasonable predictions, especially for critical state strength. In this regard, the prediction of De

Gennaro and Frank [14] is not satisfactory. This may be attributed to the shear stiffness fall due to the strong coupling between dilatancy and the plastic hardening modulus in [14] which does not exist in the approach of this study.

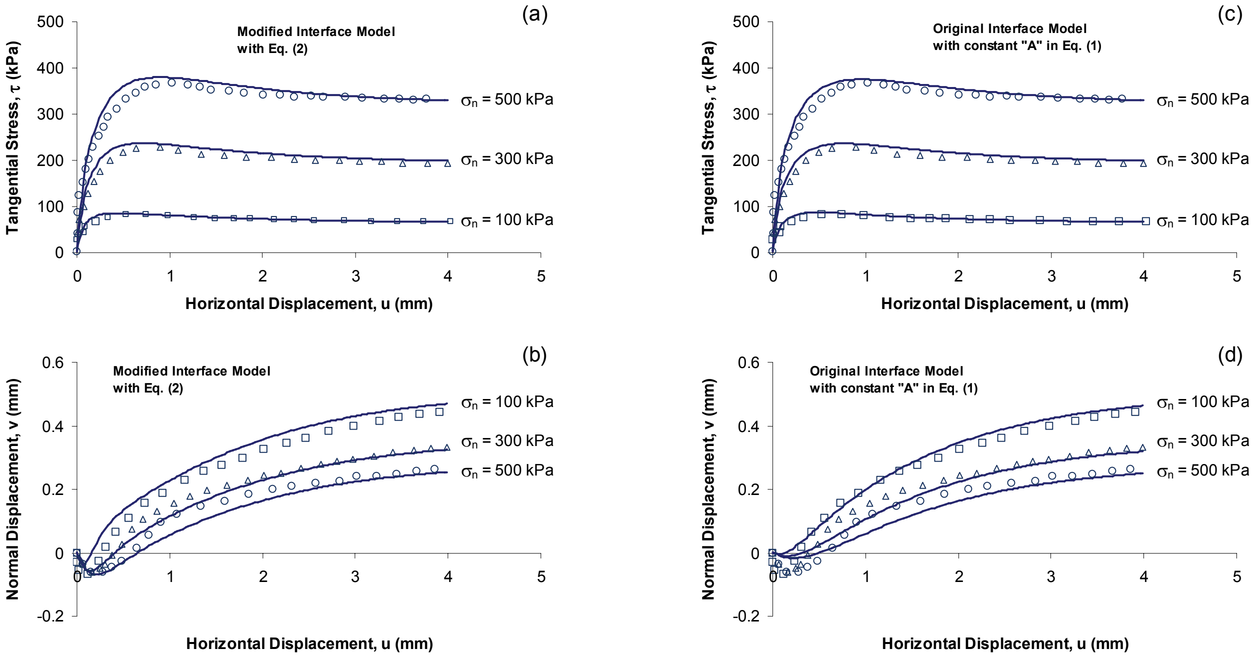

Fig. 3. Comparisons between the modified and the original interface models predictions against three constant normal stress tests with σ_{n0}=100, 300, and 500 kPa, and e_0=0.696 (experimental data taken from Evgin and Fakharian [6])

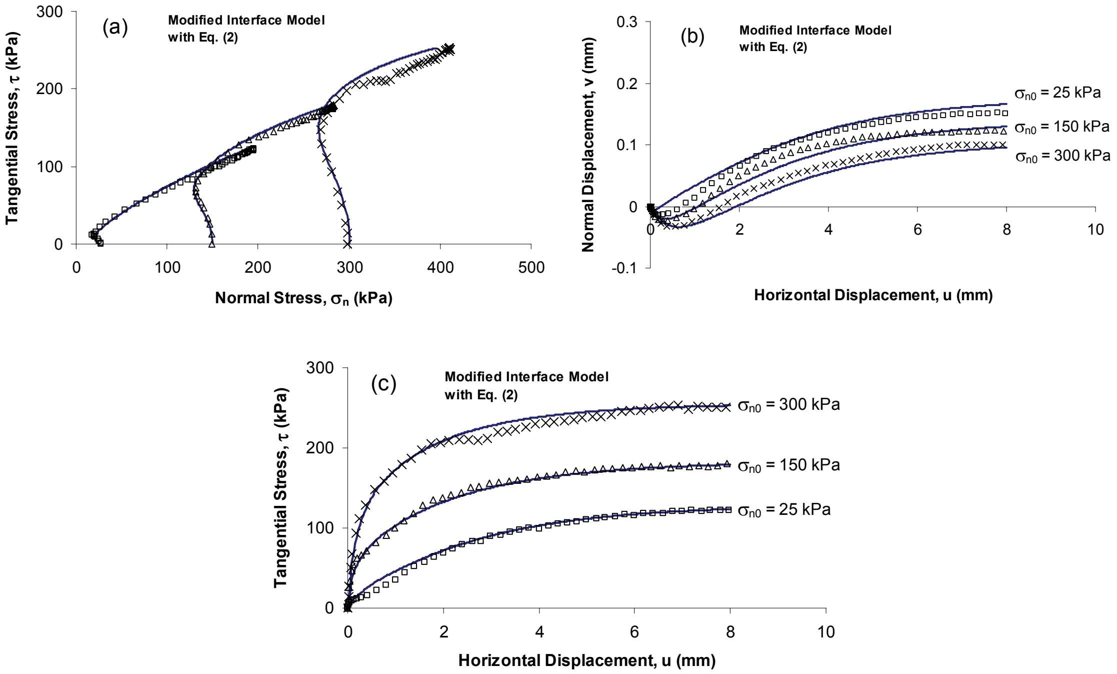

Fig. 4. Comparisons between the modified interface model predictions against three constant normal stiffness tests with σ_{n0}=25, 150, and 300 kPa, K=1.0 GPa/m and e_0=0.654 (experimental data taken from Mortara et al. [9])

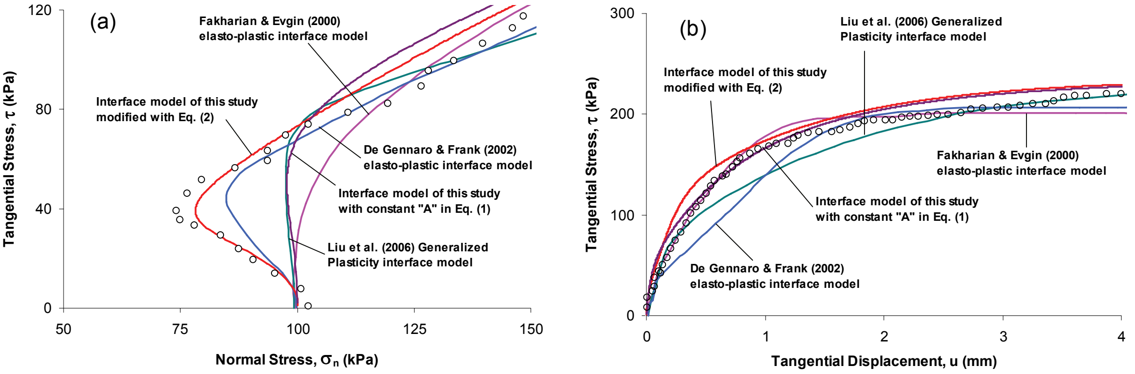

Fig. 5. Comparisons between the modified interface model predictions with some of the existing interface constitutive models on simulation of a constant normal stiffness tests with σ_{n0}=100, K=800 MPa/m and e_0=0.696 (experimental data taken from Evgin and Fakharian [6])

Table 1. Values of the model parameters used in simulations

Interface type	Elasticity		Critical state line			State		Dilatancy		Hardening
	K_{t0} (MPa)	K_{n0} (MPa)	M	e_0	λ	n^b	n^d	A_0	A_1	h_0
Ottawa sand-steel [6]	5.0	5.85	0.638	1.010	0.090	1.15	0.73	11.0	0.85	0.35
Gioia Tauro sand-steel [9]	1.57	1.85	0.630	0.787	0.0557	1.40	1.20	2.3	0.60	0.20

5. CONCLUSION

Soil-structure interfaces have a great influence on the bearing capacity and load-deformation response of geotechnical structures. Recent studies have indicated the importance of imposed constraints on the variation of normal stress during interface shearing. It is observed that many of the existing sand-structure interface models are incapable of simulating the intense contraction reported in the initial stage of shearing. In other words, the existing constitutive models predict stiffer responses which are unrealistic, and may lead to the unsafe design of geostructures. In this technical note, the sources of the mentioned contraction were discussed. Then, the interfaces stress-dilatancy law was modified in order to consider some particular aspects of the sand-structure interfaces behavior from the micro scale view. Comparisons against experimental data and some of the existing constitutive models were presented to demonstrate the improvements achieved.

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