PressureDependMultiYield03 (UCSDSAND3)

(The reference for **PressureDependMultiYield03** [**UCSDSAND3**] material: Khosravifar, A., Elgamal, A., Lu, J., and Li, J. [2018]. "A 3D model for earthquake-induced liquefaction triggering and post-liquefaction response." *Soil Dynamics and Earthquake Engineering*, 110, 43-52)

PressureDependMultiYield03 (**UCSDSAND3**) is modified from **PressureDependMultiYield02** material to comply with the established guidelines on the dependence of liquefaction triggering to the number of loading cycles, effective overburden stress (K_σ), and static shear stress (K_α). Element drivers for single element simulations under undrained cyclic, undrained monotonic, drained cyclic and drained monotonic loading can be downloaded from http://soilquake.net/opensees.

Table 1 provides the proposed calibrated input parameters for **PressureDependMultiYield03** (**UCSDSAND3**) for four different relative densities. Table 2 provides a brief description for each parameter and the adopted calibration procedure.

Table 1. Model Input Parameters

Model parameters	Loose Sand	Medium Dense Sand	Dense Sand	Very Dense Sand
$(N_1)_{60}$*	5	15	25	35
Relative density, D_R*	33%	57%	74%	87%
Cyclic resistance ratio, $\mathrm{CRR}_{\sigma'_v=1,M=7.5}$*	0.09	0.16	0.29	N.A.
Density, ρ	1.94 tonne/m^3	1.99 tonne/m^3	2.03 tonne/m^3	2.06 tonne/m^3
Reference mean effective pressure, p'_r	101 kPa	101 kPa	101 kPa	101 kPa
Small-strain shear modulus at reference pressure, $G_{max,r}$	46.9 MPa	73.7 MPa	94.6 MPa	111.9 MPa
Maximum shear strain at reference pressure, $\gamma_{max,r}$	0.1	0.1	0.1	0.1
Bulk modulus at reference pressure, B_r	125.1 MPa	196.8 MPa	252.6 MPa	298.3 MPa
Pressure dependence coefficient, d	0.5	0.5	0.5	0.5
DSS friction angle, φ_{DSS}*	30°	35°	40°	45°
Model friction angle, φ	25.4°	30.3°	35.8°	42.2°
Phase transformation angle, φ_{PT}	20.4°	25.3°	30.8°	37.2°
Contraction coefficient, c_a	0.03	0.012	0.005	0.001
Contraction coefficient, c_b	5.0	3.0	1.0	0.0
Contraction coefficient, c_c	0.2	0.4	0.6	0.8
Contraction coefficient, c_d	16.0	9.0	4.6	2.2
Contraction coefficient, c_e	2.0	0.0	-1.0	0.0
Dilation coefficient, d_a	0.15	0.3	0.45	0.6
Dilation coefficient, d_b	3.0	3.0	3.0	3.0
Dilation coefficient, d_c	-0.2	-0.3	-0.4	-0.5
S_0	1.73 kPa	1.73 kPa	1.73 kPa	1.73 kPa

*These are not input parameters to the constitutive model, but rather parameters computed during model calibration.

Table 2. Description of Calibration Parameters

Parameter	Description
$(N_1)_{60}$	Corrected SPT blow counts normalized for overburden stress of 1 atm.
D_R	Relative density correlated to SPT blow count using $D_R = \sqrt{\frac{(N_1)_{60}}{46}}$ from Idriss and Boulanger (2008)
$CRR_{\sigma'_v=1,M=7.5}$	The cyclic stress ratio to trigger liquefaction under vertical effective stress of 1 atm in 15 uniform loading cycles (equivalent number of uniform cycles for a magnitude 7.5 earthquake based on Seed and Idriss, 1982). Triggering of liquefaction is defined here as the moment at which the material reaches to a single-amplitude shear strain of 3%. Liquefaction triggering correlations by Idriss and Boulanger (2008) were used in this calibration study: $$CRR_{\sigma'_v=1,M=7.5} = \exp\left(\frac{(N_1)_{60}}{14.1} + \left(\frac{(N_1)_{60}}{126}\right)^2 - \left(\frac{(N_1)_{60}}{23.6}\right)^3 + \left(\frac{(N_1)_{60}}{25.4}\right)^4 - 2.8\right)$$
p'_r	Reference mean effective pressure at which small-strain shear modulus ($G_{max,r}$) and bulk modulus (B_r) are specified. It is taken as 101 kPa (1 atm) in this calibration.
$G_{max,r}$	Small-strain shear modulus at the reference mean effective pressure (p'_r) of 1 atm. $G_{max,r}$ was calculated from the shear wave velocity estimates by Andrus and Stokoe (2000) with slight modifications for very small blow counts by Ziotopoulou and Boulanger (2013): $V_{s,\sigma'_v=1} = 85[(N_1)_{60} + 2.5]^{0.25}$ where $V_{s,\sigma'_v=1}$ is the shear wave velocity at vertical effective stress of 1 atm. $G_{max,r}$ was adjusted by a factor of $\sqrt{3/2}$ to account for the change in confining pressure from $K_o = 0.5$ to 1.0 using d=0.5.
$\gamma_{max,r}$	The octahedral shear strain at failure at the reference mean effective pressure p'_r. This parameter is set to 0.1 (10%) in this calibration.
B_r	The bulk modulus at reference pressure (p'_r) is derived from the small-strain shear modulus; $B_r = (B/G)G_{max,r}$. The bulk modulus to shear modulus ratio is derived from: $(B/G) = \frac{2(1+\vartheta)}{3(1-2\vartheta)} = 2.6$ using Poisson's ratio of $\vartheta = 0.33$
d	The pressure dependency coefficient defines the dependency of the small-strain shear modulus and the shape of the modulus reduction curves to the effective confining stress.
φ_{DSS}	Friction angle obtained from direct simple shear (DSS) test.
φ	The input friction angle that defines the size of the outermost yield surface. In order to achieve a desired shear strength obtained from DSS tests, the input friction angle can be calculated from the following equation: $\varphi = \sin^{-1}\left[\frac{3\tan(\varphi_{DSS})}{2\sqrt{3}+\tan(\varphi_{DSS})}\right]$
φ_{PT}	The phase transformation angle is the angle over which the soil behavior changes from contractive to dilative (usually a few degrees smaller than the soil friction angle).
c_a	This parameter is the main input parameter controlling the contraction rate and subsequently the pore-water-pressure generation rate. This parameter was calibrated to trigger liquefaction in 15 loading cycles at a cyclic stress ratio equal to $CRR_{\sigma'_v=1,M=7.5}$.
c_b	This parameter accounts for fabric damage. In the absence of reliable laboratory data that quantifies fabric damage, this parameter was calibrated in combination with other contraction parameters to capture the triggering of liquefaction.
c_c	This parameter accounts for the overburden stress effect (i.e. K_σ effect).
c_d	A new parameter introduced in the updated model to increase (decrease) the rate of contraction for large (small) shear stress ratios. This feature can be disabled by setting $c_d = 0$.
c_e	A new parameters introduced in the updated model to control the dependency of contraction rate to static shear stress ratio and achieve desired $K\alpha$. This feature can be disabled by setting $c_e = 0$.
d_a	This parameter, combined with the difference between φ and φ_{PT}, are the primary parameters to control the dilation tendency after crossing the PT surface. d_a was calibrated to produce the desired post-liquefaction shear strain per cycle. This parameter was calibrated simultaneously with calibrating the model to liquefy at 15 cycles with a goal to produce approximately 1.5%, 1.0%, and 0.5% post-liquefaction shear strain per cycle for $(N_1)_{60}$ values of 5, 15, and 25 respectively.
d_b	This parameter accounts for fabric damage in the dilation equation. In the absence of reliable laboratory data that quantifies fabric damage, this parameter was calibrated in combination with other dilation parameters to result in the desired post-liquefaction accumulation of shear strain.
d_c	This parameter accounts for the effects of overburden stress on the dilation rate (i.e. K_σ effect).
NYS	Number of yield surfaces
S_0	Shear strength at zero mean effective pressure. For sands, a post-liquefaction strength of 2 kPa was assumed which results in octahedral shear strength equal to 1.73 kPa based on $\tau_{12,p'=0} = \frac{2\sqrt{3}}{3}S_0$