APPENDIX A CALIBRATION OF UCSDSAND3 MODEL

1.1 Sand Model (UCSDSAND3) Calibration

The Sand model is calibrated for sands having initial apparent relative densities of 33%, 57%, and 74% with corresponding SPT $(N_1)_{60}$ values of approximately 5, 15, and 25, respectively. Figure A.1 provides proposed calibrated input parameters for the above 3 relative densities. Table A.2 provides a brief description for each parameter and the adopted calibration procedure.

Figure A.1 shows the cyclic stress ratio (CSR) required to cause single-amplitude of 3% versus number of uniform loading cycles for the above 3 relative densities (for an initial K_0 value of 1.0), along with the result from Boulanger's PM4S model (Boulanger and Ziotopoulou 2015; Itasca 2011) for comparison.

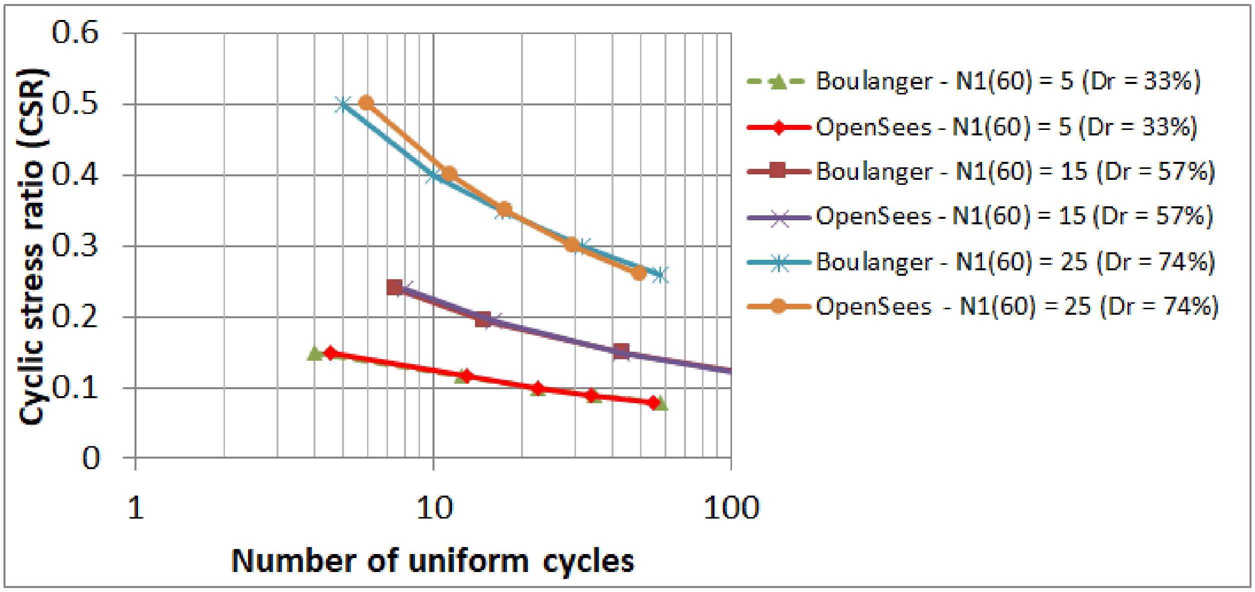

Figure A.1 Cyclic stress ratios versus number of equivalent uniform loading cycles in undrained DSS loading to cause single-amplitude shear strain of 3% for D_R = 33, 57, and 74% with vertical effective consolidation stresses of 1 atm for an initial K_0 value of 1.0

Table A.1. Model Input Parameters for UCSDSAND3 Model

Model parameters		Loose	Medium Dense	Dense
$(N_1)_{60}$		5	15	25
Relative density, D_R*		33%	57%	74%
Density, ρ (ton/m3)		1.94	1.99	2.03
Reference mean effective pressure, p'_r (kPa)		101	101	101
Shear wave velocity at vertical effective stress of 1 atm, $V_{s,\sigma'v=1}$* (m/s)		141	174	195
In-plane shear modulus at vertical effective stress of 1 atm, $G_{max,\ \sigma'v=1}$* (MPa)		38.3	60.2	77.2
Octahedral shear modulus at reference pressure of 1 atm, $G_{max,r,oct}$ (MPa)		46.9	73.7	94.6
Maximum shear strain at reference pressure, $\gamma_{max,r}$		0.1	0.1	0.1
Bulk modulus at reference pressure, B_r (MPa)		125.1	196.8	252.6
Pressure dependent coefficient, d		0.5	0.5	0.5
In-plane DSS friction angle, φ_{DSS}*		30°	35°	40°
Model friction angle, φ		25.4°	30.3°	35.8°
Cohesion, c (kPa)		1.73	1.73	1.73
Phase transformation angle, φ_{PT}		20.4°	25.3°	30.8°
Cyclic Resistance Ratio, $CRR_{\sigma'_v=1,M=7.5}$		0.09	0.16	0.29
Contraction coefficient, c_1		0.1	0.035	0.015
Contraction coefficient, c_2		5.0	3.0	1.0
Contraction coefficient, c_3		0.05	0.2	0.45
Dilation coefficient, d_1		0.1	0.15	0.2
Dilation coefficient, d_2		3.0	3.0	3.0
Dilation coefficient, d_3		0.05	0.2	0.45
Liq_1		1.0	1.0	1.0
Liq_2		0.0	0.0	0.0
Additional contraction parameters (K_0 = 1)	b1	0.9	0.5	0.22
	b2	30	30	30
	b3	0.0	0.0	0.0
	b4	0.001	0.001	0.001

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

Table A.2. Description of Calibration Parameters for the UCSDSAND3 Model

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)
e	Void ratio can be derived from: $e = e_{max} - D_R(e_{max} - e_{min})$. e_{min} and e_{max} were assumed as 0.5 and 0.89 respectively as typical values for Nevada sand.
ρ	Saturated density derived from: $\rho = \rho_w \frac{(G_s+S.e)}{1+S.e}$, where S is saturation ratio. G_s was selected as 2.65.
p'_r	Referenced mean effective stress, at which other model input parameters are calibrated, selected as 101 kPa (1 atm).
$V_{s,\sigma'_v=1}$ (m/s)	Shear velocity at vertical effective stress of 1 atm derived from the equation by Andrus and Stoke (2000) with slight modifications for very small blow counts by Ziotopoulou and Boulanger (2013): $V_{s,\sigma'_v=1} = 85[(N_1)_{60} + 2.5]^{0.25}$. It is important to note that if other values are used, the contraction and dilation parameters have to be re-calibrated to result in desired CRR.
$G_{max,\sigma'_v=1}$	In-plane low-strain shear modulus at vertical effective stress (σ'_v) of 1 atm derived from: $G_{max,\sigma'_v=1} = \rho.(V_{s,\sigma'_v=1})^2$
$G_{max,1}$	In-plane low-strain shear modulus at mean effective pressure (p’) of 1 atm. $G_{max,1} = (\sqrt{3/2})G_{max,\sigma'_v=1}$
$G_{max,r,oct}$	Octahedral low-strain shear modulus at reference pressure (p'_r) of 1 atm is a function of stress and strain components. For the range of stresses and strains in this calibration study and for the stress conditions in a DSS test, $G_{max,r,oct} = G_{max,1}$ was used.
$\gamma_{max,r}$	Maximum octahedral shear strain at the reference mean effective pressure p'_r. It was picked as 0.1 (10%).
K_o	Lateral pressure ratio at rest was assumed to be 0.5 after initial consolidation. After the material undergoes plastic deformations in shear cycles, K_o quickly approaches 1.
ϑ	Poison’s ratio is derived from: $\vartheta = \frac{K_o}{1+K_o} = 0.33$
(B/G)	The bulk modulus to shear modulus ratio is derived from: $(B/G) = \frac{2(1+\vartheta)}{3(1-2\vartheta)} = 2.6$
B_r	The bulk modulus at reference pressure (p'_r) is derived from the octahedral shear modulus: $B_r = (B/G).G_{max,r,oct}$

d	The pressure dependency coefficient defines the dependence of maximum octahedral shear modulus and bulk modulus with mean effective pressure : $\mathrm{G_{max,oct}} = \mathrm{G_{max,r,oct}} \left(\frac{\mathrm{p'}}{\mathrm{p'_r}}\right)^{\mathrm{d}}$ and $\mathrm{B} = \mathrm{B_r} \left(\frac{\mathrm{p'}}{\mathrm{p'_r}}\right)^{\mathrm{d}}$
φ_{DSS}	In-plane friction angle in a direct simple shear (DSS) test.
φ	The friction angle used by the model as an input parameter can be obtained from the in-plane friction angle in DSS test using Equation 7.
φ_{PT}	The phase transformation angle was adjusted in accordance with the dilation parameters ($\mathrm{d_1}$, $\mathrm{d_2}$ and $\mathrm{d_3}$) to produce desired dilation tendency. In this calibration the phase transformation angle was adjusted to be 5 degrees lower than φ .
$\mathrm{CRR}_{\sigma'_v=1,\mathrm{M}=7.5}$	The cyclic stress ratio to trigger liquefaction under vertical effective stress of 1 atm and zero initial static shear stress in 15 cycles (equivalent number of uniform cycles for a magnitude 7.5 earthquake based on Seed and Idriss, 1982). Liquefaction triggering is defined here as single-amplitude in-plane shear strain of 3% in undrained cyclic DSS test. Liquefaction triggering correlations by Idriss and Boulanger (2008) were used in this calibration study: $\mathrm{CRR}_{\sigma'_v=1,\mathrm{M}=7.5} = \exp\left(\frac{(N_1)_{60}}{14.1} + \left(\frac{(N_1)_{60}}{126}\right)^2 - \left(\frac{(N_1)_{60}}{23.6}\right)^3 + \left(\frac{(N_1)_{60}}{25.4}\right)^4 - 2.8\right)$
$\mathrm{c_1}$	This parameter is the main input parameter controlling the contraction rate and pore water pressure generation rate (Equation 13). This parameter was calibrated to trigger liquefaction in 15 cycles under cyclic stress ratio equal to $\mathrm{CRR}_{\sigma'_v=1,\mathrm{M}=7.5}$. The model was calibrated to take 9 to 13 contractive cycles to reduce the effective vertical stress ratio from 1 to about 0.2 (approximate stress ratio where PT surface is crossed and butterfly-shape loops start to form) for dense to loose sands, respectively. The contractive cycles are followed by 6 to 2 contractive/dilative cycles with approximately 0.5% to 1.5% shear strain accumulation per cycle to achieve the target single-amplitude shear strain τ_{12} of 3%. The shear strains that develop during the initial contractive cycles before crossing the PT surface are negligible compared to the strains that develop afterwards during the contractive/dilative cycles.
$\mathrm{c_2}$	This parameter accounts for fabric damage. It also controls how close the model can get to zero vertical effective stress ratio after the initiation of

	butterfly-shape loops, e.g. the effective vertical stress ratios can get very close to zero for loose sand.
c_3	This parameter accounts for the overburden stress effect (k_σ effect).
d_1	This parameter, combined with the difference between φ and φ_{PT} controls the dilation tendency after crossing PT surface. First, $\varphi - \varphi_{PT}$ was set to a value described earlier. Then, d_1 was adjusted to produce desired accumulated shear strain per cycle after crossing PT surface. This parameter was adjusted in this calibration to produce about 0.5%, 1.0% and 1.5% shear strain accumulation per cycle in undrained cyclic DSS test at shear stress ratio of $CSR_{\sigma'_v=1,M=7.5}$ for dense, medium dense and loose sands, respectively.
d_2	This parameter accounts for fabric damage.
d_3	This parameter accounts for the effect of overburden stress (k_σ effect) on the dilation rate. In this calibration study, this parameter was set equal to c_3 with an opposite sign following Equation 14.
liq_1 and liq_2	Parameters liq_1 and liq_2 control the liquefaction-induced perfectly plastic shear strain (γ_y). This feature activates at effective confining pressure values less than liq_1. This plastic shear strain is limited to liq_2 and is defined as: $\gamma_y = liq_2 \cos^3 \frac{\pi p'}{2 liq_1}$. This feature is disabled in the current calibration study by assigning $liq_2 = 0$.
NYS	Number of yield surfaces
cohesion	Shear strength at zero mean effective pressure. For cohesive materials the following conversions can be used: $\tau_{oct,p'=0} = \frac{\sqrt{8}}{3}\text{cohesion}$, $\tau_{12,p'=0} = \frac{2\sqrt{3}}{3}\text{cohesion}$, and $q_{p'=0} = 2\text{cohesion}$
Additional contraction parameters b1, b2, b3 and b4	$P'' = -B\left(1 - \text{sign}(\dot{\eta})\frac{\eta}{\eta_{PT}}\right)^2 (c_1 + \varepsilon_c c_2)\left(\frac{p'}{p_{atm}}\right)^{c_3}$ where $B = b_1(b_2(\eta - b_3)^2 + b_4)$

REFERENCE

Boulanger, R.W., and Ziotopoulou, K. (2015). PM4SAND (Version 3): a sand plasticity model for earthquake engineering applications, Report No. UCD/CGM-15/01, Univ. of California, Davis

Itasca Consulting Group, Inc. (2011). FLAC — Fast Lagrangian Analysis of Continua, Ver. 7.0. Minneapolis: Itasca.