

NTUA-SAND

Theoretical background

The NTUA-SAND model (Andrianopoulos et al 2010a, b, 2011) is a bounding surface, critical state, plasticity model with a vanished elastic region, developed primarily for accurate simulation of the rate-independent dynamic response of non-cohesive soils under small, medium and large cyclic strain amplitudes. This is achieved using a single set of values for the model constants, irrespective of initial stress and density conditions, as well as loading direction. The model is equally efficient in simulating the monotonic response.

The NTUA-SAND model builds on the constitutive efforts of Manzari & Dafalias (1997) and Papadimitriou & Bouckovalas (2002) and to ensure numerical stability the UDM employs the modified-Euler integration scheme with automatic error control and sub-stepping (Sloan et al. 2001). Key constitutive ingredients of the NTUA-SAND model are:

- the inter-dependence of the critical state, the bounding and the dilatancy (open cone) surfaces (Fig. 1), that depict the deviatoric stress-ratios at critical state, peak strength and phase transformation, on the basis of the state parameter $\psi = e - e_{cs}$ (with e the void ratio, and e_{cs} the void ratio at critical state at the same mean effective stress p , as per Been & Jefferies 1985),
- a (Ramberg-Osgood type) non-linear hysteretic formulation for the “elastic” strain rate, that governs the response at small to medium cyclic shear strains (Fig. 2),
- a discontinuously relocatable stress projection center r^{ref} related to the “last” load reversal point, which is used for mapping the current stress point on model surfaces (see Fig. 1) and as a reference point for introducing non-linearity in the “elastic” strain rate, and finally
- an empirical index of the directional effect of sand fabric evolution during shearing, which scales the plastic modulus, and governs the rate of excess pore pressure build-up and permanent strain accumulation under large cyclic shear strains potentially leading to liquefaction and cyclic mobility (see Fig. 3)

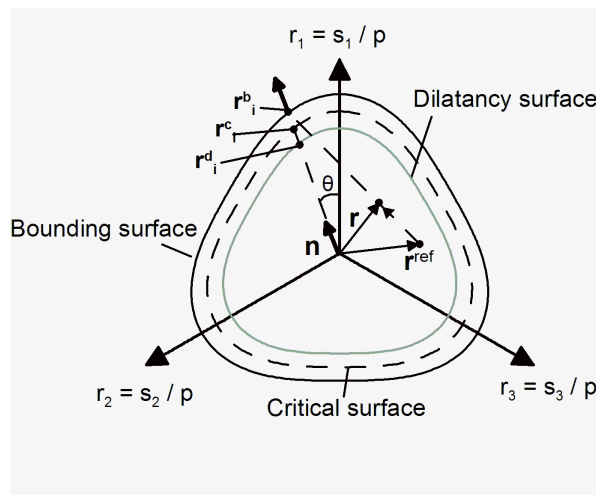


Figure 1: Model surfaces and adopted mapping rule in the π -plane of the deviatoric stress ratio space, based on a relocatable projection center r^{ref} (from Andrianopoulos et al 2010b)

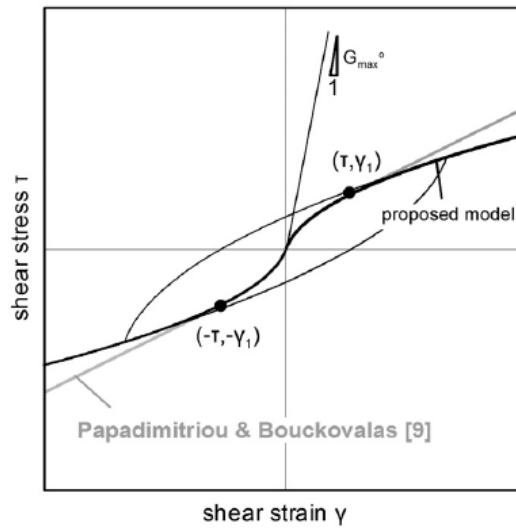


Figure 2: Exemplary deviatoric stress-strain loops according to the adopted Ramberg-Osgood formulation for the “elastic” strain rate (from Andrianopoulos et al 2010b).

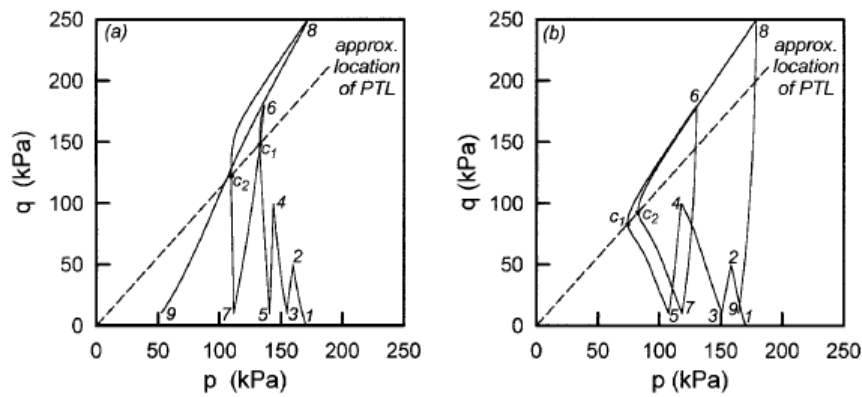


Figure 3: Exemplary undrained effective stress paths: a) accounting for sand fabric evolution during shearing, b) not accounting for sand fabric evolution (from Papadimitriou et al 2001).

The model requires the calibration of thirteen (13) dimensionless and positive constants for cyclic loading, and only eleven (11) for monotonic loading. Ten (10) out of the thirteen (13) model constants may be directly estimated on the basis of monotonic and cyclic element tests, while the remaining three (3) constants require trial-and-error simulations of element tests.

At element level, the performance of the model has been evaluated based on comparison with data from element laboratory tests on fine Nevada sand at relative densities of $D_r = 40$ & 60% and initial effective stresses between 40 and 160 kPa. In particular, data originated from tests on resonant column, direct simple shear and triaxial tests, offering a quantitative description of various aspects of non-cohesive soil response under cyclic loading, such as shear-modulus degradation and damping increase with cyclic shear strain, liquefaction resistance and cyclic mobility. Results from this evaluation are presented at Figs 4, 5 and 6.

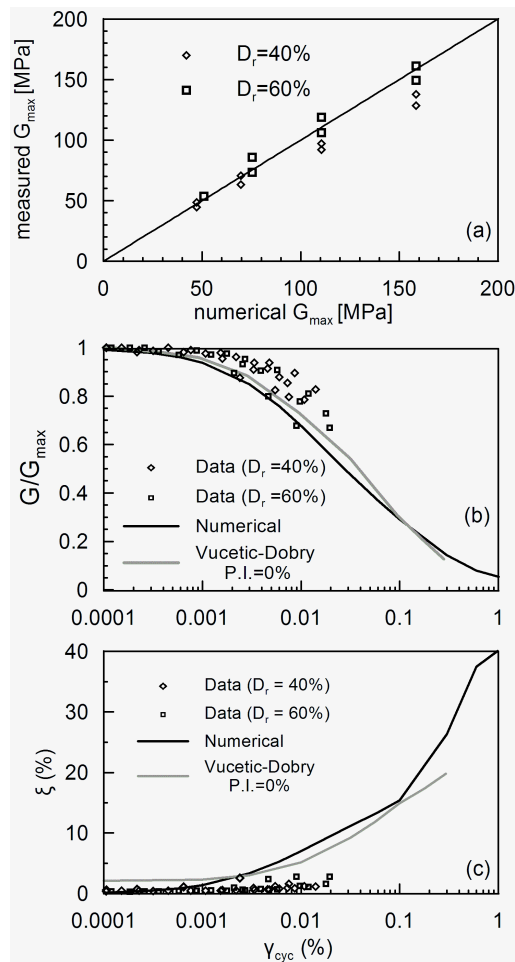


Figure 4: Summary comparison of simulations to data from resonant column tests on Nevada sand in terms of: a) the maximum shear modulus G_{max} , b) the secant shear modulus G/G_{max} degradation and c) the hysteretic damping ξ increase curves, with cyclic shear strain γ_{cyc} (from Andrianopoulos et al 2010b)

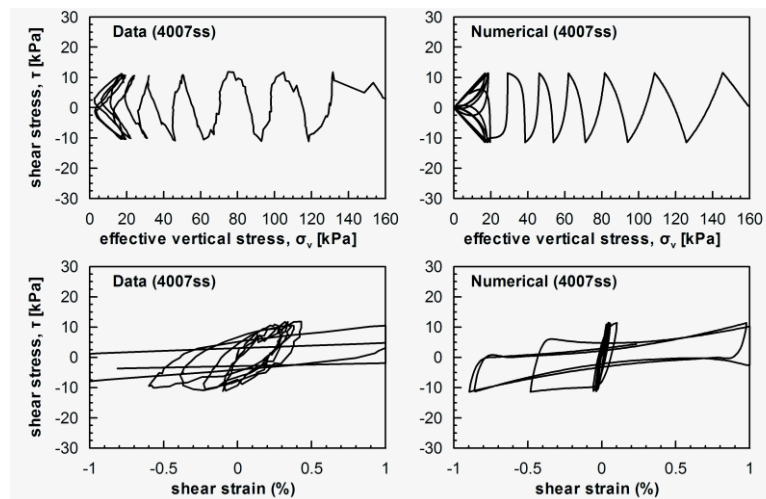


Figure 5: Comparison of simulation to data for a typical cyclic undrained simple shear test on Nevada sand with $D_r = 40\%$ (from Andrianopoulos et al 2010b)

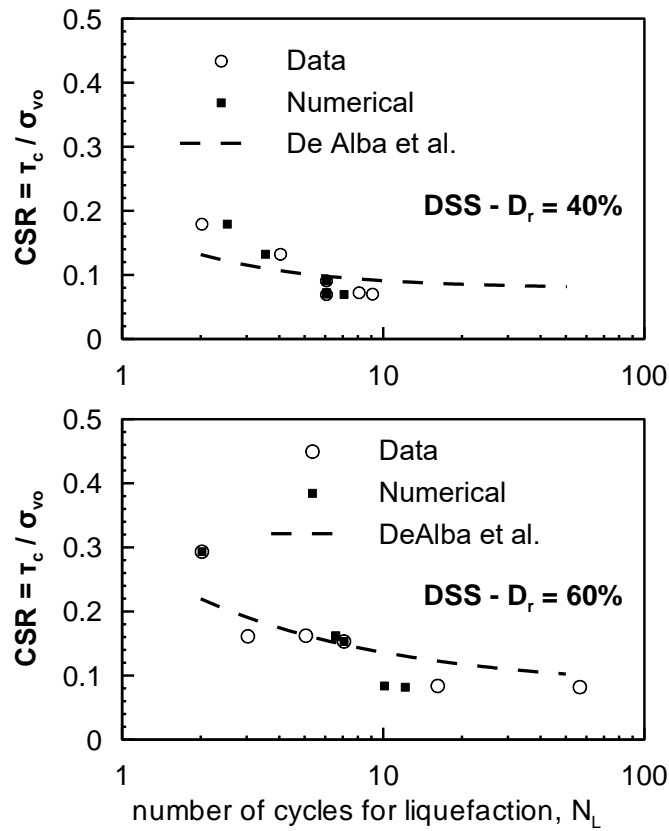


Figure 6: Summary comparison of liquefaction curves from simulations to data from cyclic undrained simple shear test on Nevada sand with $D_r = 40\%$ and 60% (from Andrianopoulos et al 2010b)

The performance of the NTUA-SAND model in relation to boundary value problems has been evaluated through the simulation of centrifuge experiments. For this purpose, Model tests No. 1, 2 and 12 of the well-known VELACS project were used, which reproduce the:

- the one-dimensional (1D) seismic response of a liquefiable soil layer under level ground conditions (Test No.1)
- the two-dimensional (2D) response of a mildly sloping liquefiable soil layer (Test No. 2)
- the response of shallow foundations on liquefiable soils (Test No. 12)

Results from this evaluation are presented in Figures 7 to 10.

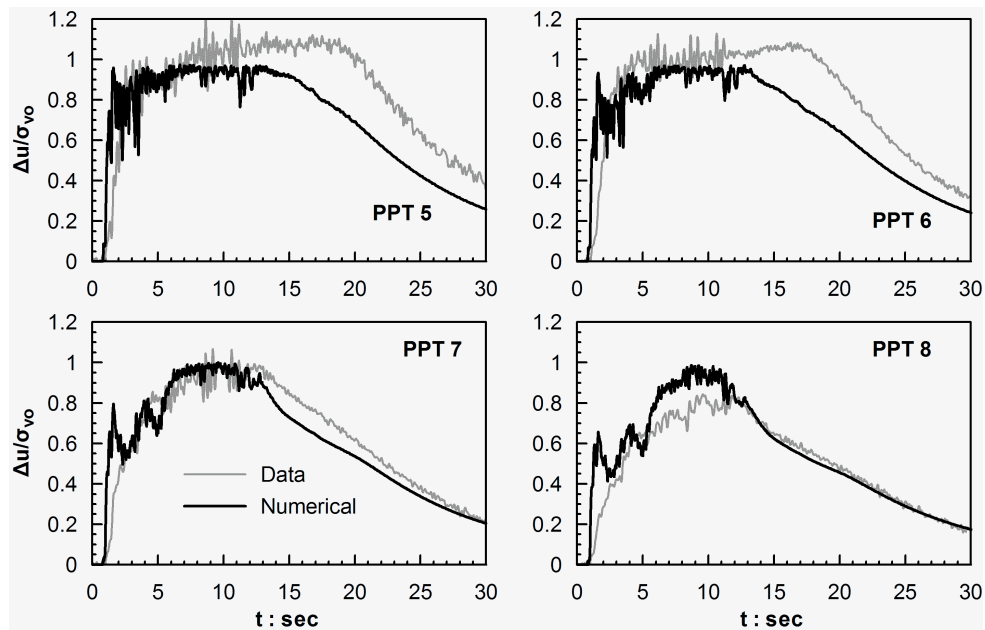


Figure 7: Comparison of data to simulations for the time history of the excess pore pressure ratio $\Delta u/\sigma_{vo}$ developed at various depths along the axis of the model of the VELACS centrifuge Model No 1 test (from Andrianopoulos et al 2010b)

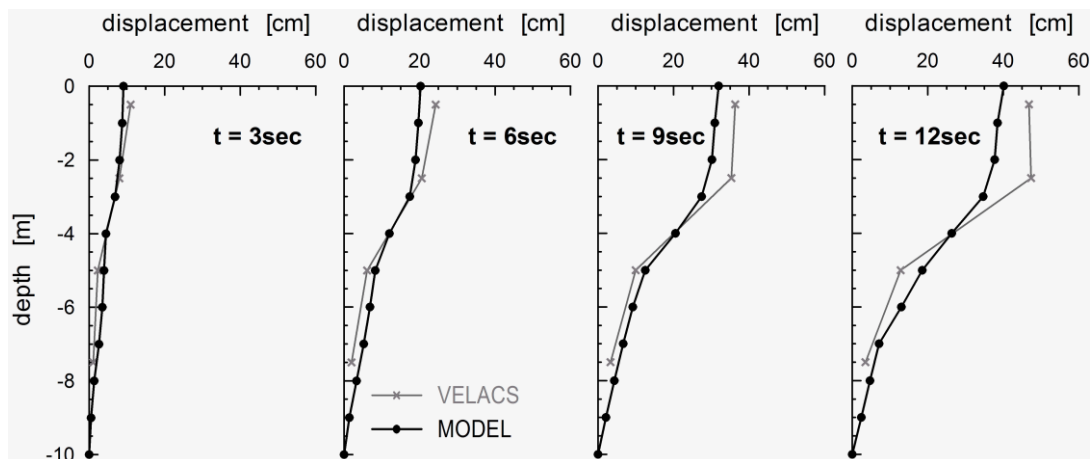


Figure 8: Comparison of data to simulations for the (relative to the base) lateral displacement profile of the soil layer at various times of the shaking for the VELACS Model No 2 (from Andrianopoulos et al 2010a)

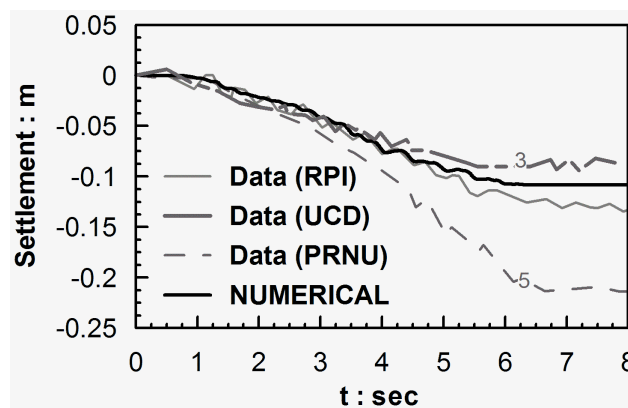


Figure 9: Comparison of data to simulations for the time history of the structural settlement of the VELACS centrifuge Model No 12 test

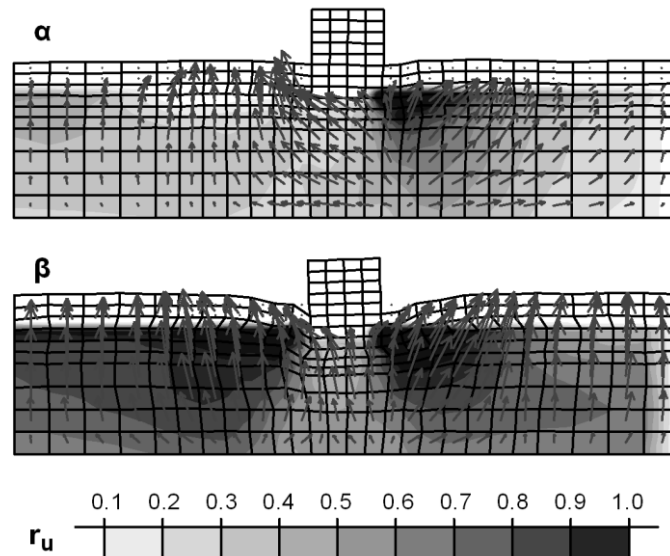


Figure 10. Excess pore pressure ratio contours and flow vectors from analyses of the VELACS centrifuge Model No 12 test for (a) $t=2\text{sec}$ & (b) $t=5\text{sec}$.

Example input file

This section presents the input file for FLAC v7.0 (Table 1) and FLAC3D (Table 2) as well the parameters used (Table 3) for the simulation of a undrained cyclic shear test. The FLAC simulation is carried out using a single zone of unit dimensions (1m x 1m). The gridpoints are fixed and the shear strain is applied as horizontal displacement at the upper gridpoints. A servo function is used in order to perform cyclic testing under constant stress amplitude ($\tau_{\text{cyc}} = 16\text{kPa}$). The parameters used refer to Nevada sand of VELACS project of approximately 40% relative density. Initial stress field corresponds to vertical effective stress equal to 80kPa and horizontal effective stress equal to 36 kPa (i.e. lateral earth pressure coefficient at rest equal to $k_0 = 0.45$). Further information can be found in Andrianopoulos et al. (2010a, b, 2011).

Table 1: Input file for undrained cyclic shear test (FLAC)

INPUT FILE - FLAC
<pre> ;-- Start New Analysis -- new ;-- Configuration for CPPUDM -- config cppudm ;model load modelntuasand003.dll ;-- Grid Creation -- grid 1 1 gen 0,0 0,1 1,1 1,0 ;-- Assign Model -- model ntua_sand ; Density - prop dens=1.537 ; Void Ratio - prop m_void=0.737 ; Elastic Modulus - prop m_b=600.0 m_poiss=0.33 ; Ramberg Osgood - prop m_g1=0.00025 m_a1=0.6 ; State Parameter - prop void_cr=0.809 lamda=0.022 ; Model Surfaces - prop mc_comp=1.25 m_c=0.72 </pre>

```

prop kb_comp=1.45 kd_comp=0.3
;- Plastic Moduli -
prop ao=0.8 ho=15000.
;- Fabric -
prop no=40000.
;- Substepping -
prop dt_min=1e-3 stol=1e-3

```

```

;-- Initial Conditions --
fix x y
ini syy -80.
ini sxx -36.
ini szz -36.
ini sxy 0.

```

```

;-- Histories --
his xd i=1 j=2
his sxy i=1 j=1
his sxx i=1 j=1
his syy i=1 j=1
his szz i=1 j=1

```

```

;-- Cyclic Loading --
ini xv 1e-6 j=2

```

```

def servo
  while_stepping
  if sxy(1,1)>16. then
    loop i (1,2)
      xvel(i,2)=-xvel(i,2)
    end_loop
  endif
  if sxy(1,1)<-16. then
    loop i (1,2)
      xvel(i,2)=xvel(i,2)
    end_loop
  endif
end

```

```

;-- Solution --
step 75000

```

```

;-- Output Results --
set hisfile his_sxy-vs-syy.dat
his write 2 vs -4
set hisfile his_sxy-vs-gamma.dat
his write 2 vs 1
set hisfile his_syy-vs-gamma.dat
his write 4 vs 1

```

Table 2: Input file for undrained cyclic shear test (FLAC3D)

INPUT FILE – FLAC3D

```

;-- Start New Analysis --
new

```

```

;-- Configuration for CPPUDM --
config cppudm
model load modelIntuasand002.dll

```

```

;-- For the 64 bit version use modelIntuasand002_64.dll
;-- For FLAC3D v5.0 32 & 64 bit use modelIntuasand005.dll and modelIntuasand005_64.dll respectively

```

```

;-- Grid Creation --
gen zone brick size 1,1,1 p0 0,0,0 p1 1,0,0 p2 0,1,0 p3 0,0,1
range name x0 x -0.1 0.1
range name x1 x 0.9 1.1
range name y0 y -0.1 0.1

```

```

range name y1 y 0.9 1.1
range name z0 z -0.1 0.1
range name z1 z 0.9 1.1

;-- Assign Model --
model ntua_sand
;-- Density -
prop dens=1.961
;-- Void Ratio -
prop m_void=0.737
;-- Elastic Modulus -
prop m_b=600.0 m_pois=0.33
;-- Ramberg Osgood -
prop m_g1=0.00025 m_a1=0.6
;-- State Parameter -
prop void_cr=0.809 lamda=0.022
;-- Model Surfaces -
prop mc_comp=1.25 m_c=0.72
prop kb_comp=1.45 kd_comp=0.3
;-- Plastic Moduli -
prop ao=0.8 ho=15000.
;-- Fabric -
prop no=40000.
;-- Substepping -
prop dt_min=1e-3 stol=1e-3

;-- Initial Conditions --
fix x y z
ini syy -80.
ini sxx -36.
ini szz -36.
ini sxy 0.
ini sxz 0.
ini syz 0.

;-- Histories --
his gp xd 0,1,0
his zone sxy 0.5 0.5 0.5
his zone sxx 0.5 0.5 0.5
his zone syy 0.5 0.5 0.5
his zone szz 0.5 0.5 0.5
his zone sxz 0.5 0.5 0.5
his zone syz 0.5 0.5 0.5

;-- Cyclic Loading --
ini xv 1e-6 range y1

def servo
  while_stepping
    p_z=z_near(0.5,0.5,0.5)
    if z_sxy(p_z)>16. then
      command
        ini xv -1e-6 range y1
      endcommand
    endif
    if z_sxy(p_z)<-16. then
      command
        ini xv 1e-6 range y1
      endcommand
    endif
  end
end

;-- Solution --
step 75000

;-- Output Results --
his write 2 vs -4 file his_sxy-vs-syy.dat
his write 2 vs 1 file his_sxy-vs-gamma.dat
his write 4 vs 1 file his_syy-vs-gamma.dat

```

Table 3: Model parameters for Nevada sand (according to Andrianopoulos et al. 2010a,b)

Model Parameters		
Name	Description	Value
void_cr	Model parameter $(e_{cs})_a$ – Critical state line location at $p' = 98.1 \text{ kPa}$ ($= \Gamma_{cs} - \lambda \ln 98.1$)	0.809
lamda	Model parameter λ – Slope of Critical state line	0.022
mc_comp	Model parameter M_c^c – Critical state strength in triaxial compression	1.25
kb_comp	Model parameter k_c^b – Effect of ψ on peak deviatoric stress in triaxial compression	1.45
kd_comp	Model parameter k_c^d – Effect of ψ on dilatancy deviatoric stress in triaxial compression	0.3
m_c	Model parameter c – Ratio of deviatoric stress ratios at critical state in triaxial extension (TE) over triaxial compression (TX)	0.72
m_b	Model parameter B – Elastic shear modulus constant	600
m_a1	Model parameter α_1 – Non-linearity of 'elastic' shear modulus	0.6
m_g1	Model parameter γ_1 – Reference cyclic shear strain for non-linearity of 'elastic' shear modulus	0.00025
m_poiss	Model parameter ν – Elastic Poisson's ratio	0.33
ao	Model parameter A_o – Dilatancy constant	0.8
ho	Model parameter h_o – Plastic modulus constant	15000
no	Model parameter N_o – Fabric evolution constant	40000
m_void	Void ratio e	0.65-0.75
stol	Substepping parameter STOL – Tolerance value	0.001
dt_min	Substepping parameter ΔT_{\min} – Minimum step size	0.001

References

Model formulation:

- Andrianopoulos K. I., Papadimitriou A. G., Bouckovalas G. D. (2010), "Explicit integration of bounding surface model for the analysis of earthquake soil liquefaction", International Journal for Numerical and Analytical Methods in Geomechanics, 34 (15): 1586-1614
- Andrianopoulos K. I., Papadimitriou A. G., Bouckovalas G. D. (2010), "Bounding surface plasticity model for the seismic liquefaction analysis of geotechnical structures", Soil Dynamics and Earthquake Engineering, 30(10): 895-911
- Andrianopoulos K. I., Papadimitriou A. G., Bouckovalas G. D. (2011), "Applications of the NTUA-SAND model for the seismic liquefaction analysis of geotechnical structures", 2nd International FLAC/DEM Symposium, paper no. 77 (in press)
- Been K., Jefferies M. G. (1985), "A state parameter for sands", Geotechnique, 35 (2): 99-112
- Papadimitriou A. G., Bouckovalas G. D., Dafalias Y. F. (2001), "Plasticity model for sand under small and large cyclic strains", Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 127(11): 973-983
- Papadimitriou A. G., Bouckovalas G. D. (2002), "Plasticity model for sand under small and large cyclic strains: a multiaxial formulation", Soil Dynamics and Earthquake Engineering, 22: 191-204
- Manzari M. T., Dafalias Y. F. (1997), "A critical state two-surface plasticity model for sands", Geotechnique, 47(2): 255-272
- Sloan S. W., Abbo A. J., Sheng D. (2001), "Refined explicit integration of elastoplastic models with automatic error control", Engineering Computations, 18(1/2): 121-154

Model application:

- Bouckovalas G., Tsiapas Y., Theocharis A., Chaloulos Y. (2017), "Ground response at liquefied sites: seismic isolation or amplification?", Soil Dynamics and Earthquake Engineering (in press)
- Andrianopoulos K., Agapoulaki G., Papadimitriou A. (2016), "Simulation of seismic response of passively stabilised sand", Geotechnical Research 3 (2), 40-53

- Chaloulos Y., Bouckovalas G., Karamitros D. (2013), "*Pile response in submerged lateral spreads: common pitfalls of numerical and physical modeling techniques*", Soil Dynamics and Earthquake Engineering 55, 275-287
- Karamitros D., Bouckovalas G., Chaloulos Y. (2013), "*Insight into the seismic liquefaction performance of shallow foundations*", Journal of Geotechnical and Geoenvironmental Engineering 139 (4), 599-607
- Bouckovalas G., Papadimitriou A., Niarchos D., Tsiapas Y. (2011), "*Sand fabric evolution effects on drain design for liquefaction mitigation*", Soil Dynamics and Earthquake Engineering, 31(10): 1426-1439
- Valsamis A., Bouckovalas G., Papadimitriou A. (2010), "*Parametric investigation of lateral spreading of gently sloping ground*", Soil Dynamics and Earthquake Engineering, 30: 490-508

Contact address

Institute Name	National Technical University of Athens
	Dr. Konstantinos Andrianopoulos, Dr Achilleas Papadimitriou, Prof. George Bouckovalas, Dr. Yannis Chaloulos, Dr. Dimitrios Karamitros,
Address	School of Civil Engineering, Geotechnical Department Heron Polytechniou 9, 15780 Zografou
Country	Greece
Phone	+30 210 772 3780
Fax	+30 210 772 3428
Email	kandrian@tee.gr , apapad@civil.ntua.gr , gbouck@central.ntua.gr , ioannischaloulos@gmail.com , dimkaram@gmail.com