International Journal of Engineering Science 133 (2018) 284–310

Contents lists available at ScienceDirect

International Journal of Engineering Science

journal homepage: www.elsevier.com/locate/ijengsci

Localised failure mechanism as the basis for constitutive modelling of geomaterials

Linh A. Le[a], Giang D Nguyen[a,*], Ha H. Bui[b], Abdul Hamid Sheikh[a], Andrei Kotousov[c]

[a] School of Civil, Environmental and Mining Engineering, The University of Adelaide, Adelaide, SA 5005, Australia
[b] Department of Civil Engineering, Monash University, Clayton, VIC 3800, Australia
[c] School of Mechanical Engineering, The University of Adelaide, Australia

ARTICLE INFO

Article history:
Received 20 August 2018
Revised 14 September 2018
Accepted 15 September 2018

Keywords:
Constitutive modelling
Geomaterials
Localised failure
Lode angle
Size effect
Localisation band
Cohesive-frictional

ABSTRACT

Localised failure of geomaterials in the form of cracks or shear bands always requires special attention in constitutive modelling of solids and structures. This is because the validity of classical constitutive models based on continuum mechanics is questionable once localised inelastic deformation has occurred. In such cases, due to the fact that the macro inelastic responses are mainly governed by the deformation and microstructural changes inside the localisation zone, internal variables, representing these microstructural changes, should be defined inside this zone. In this paper, the localised failure mechanism is identified and employed as an intrinsic characteristic upon which a constitutive model is based on at the first place, instead of being dealt with after developing the model using various regularisation techniques. As a result, inelastic responses of the model are correctly associated with the localisation bands, and not smeared out over the whole volume element as in classical continuum constitutive models. It is shown that this inbuilt localisation mechanism in a constitutive model can naturally capture important features of the material and possess intrinsic regularisation effects while minimising the use of additional phenomenological treatments, and also possessing intrinsic regularisation effects. The development of the proposed model is based on an additional kinematic enhancement to account for high gradient of deformation across the localisation band. This enrichment allows the introduction of an additional constitutive relationship for the localisation band, which is represented in the form of a cohesive-frictional model describing traction-displacement jump relationship across two sides of the localisation band. The model, formulated within a thermodynamically consistent approach, possesses constitutive responses of the bulk material and two localisation bands connected through internal equilibrium conditions. Its key characteristics are demonstrated and validated against experimental data from different types of geomaterials under different loading conditions at both material and structural levels.

* Corresponding author.
E-mail addresses: giang.nguyen@trinity.oxon.org, g.nguyen@adelaide.edu.au (G.D. Nguyen).

https://doi.org/10.1016/j.ijengsci.2018.09.004

Glossary

$\mathbf{a}_\mathrm{o}$	Elastic stiffness of material
$\mathbf{C}$	Kinematic constraint
D_k	Damage of crack k
E	Young's modulus
f_t	Tensile strength
f_c	Compressive strength
g	Potential function of cohesive-frictional crack
G_I	Mode I fracture energy
G_{II}	Mode II fracture energy
h_k	Thickness of crack k
H_k	Characteristic length of crack k
I_1	First invariant of stress tensor
J_2, J_3	Second and Third invariants of deviatoric stress tensor
K_n, K_s	Elastic normal and shear stiffness of crack
$\mathbf{K}_\mathrm{c}^\mathrm{sec}$	Secant stiffness of crack in local coordinate system
$\mathbf{K}_{\mathrm{c}k}^\mathrm{sec}$	Secant stiffness of crack k in local coordinate system
$\mathbf{K}_k^\mathrm{sec}$	Secant stiffness of crack k in global coordinate system
$\mathbf{K}_k^\mathrm{tan}$	Tangent stiffness of crack k in global coordinate system
m	Model parameters controlling shape of yield surface
n_i	Normal vectors of crack in index notation
$\mathbf{n}_k$	Normal vector of crack k in matrix form
p	Hydrostatic pressure
q	Deviatoric stress component
$\mathbf{r}_k$	Residual vector of crack k
$\mathbf{R}_k$	Transformation matrix from global to local coordinate system of crack k
$\mathbf{t}_k$	Traction of crack k in global coordinate system
$\mathbf{t}_k^\mathrm{tr}$	Trial traction of crack k in global coordinate system
$\dot{\mathbf{t}}_k^\mathrm{cor}$	Corrective traction of crack k in global coordinate system
$\mathbf{t}_\mathrm{c} = [\ t_n \quad t_{s1} \quad t_{s2}\ ]^T$	Traction of crack in local coordinate system
$\mathbf{t}_{\mathrm{c}k} = [\ t_{k,n} \quad t_{k,s1} \quad t_{k,s2}\ ]^T$	Traction of crack k in local coordinate system
u_p	Accumulated displacement parameter
$\mathbf{u}_k$	Total displacement jump of crack k in global coordinate system
$\mathbf{u}_\mathrm{c} = [\ u_n \quad u_{s1} \quad u_{s2}\ ]^T$	Total displacement jump of crack in local coordinate system
$\mathbf{u}_{\mathrm{c}k} = [\ u_{k,n} \quad u_{k,s1} \quad u_{k,s2}\ ]^T$	Total displacement jump of crack k in local coordinate system
$\mathbf{u}_\mathrm{c}^\mathrm{e}$	Elastic displacement jump of crack in local coordinate system
$\mathbf{u}_\mathrm{c}^\mathrm{p} = [\ u_n^p \quad u_{s1}^p \quad u_{s2}^p\ ]^T$	Plastic displacement jump of crack in local coordinate system
$\mathbf{u}_k^\mathrm{tr}$	Trial displacement jump of crack k in global coordinate system
$\mathbf{u}_k^\mathrm{p}$	Plastic displacement jump of crack k in global coordinate system
y	Yield-failure function crack
α_0, β	Parameters controlling damage evolution
γ	Parameter controlling the non-associativity
Γ_k	Area of crack k
δ_0	Displacement corresponding to peak stress in pure tension
$\boldsymbol{\varepsilon} = [\varepsilon_{11}\ \varepsilon_{22}\ \varepsilon_{33}\ \gamma_{12}\ \gamma_{23}\ \gamma_{31}]^T$	Overall strain of RVE
$\boldsymbol{\varepsilon}_\mathrm{o} = [\varepsilon_{\mathrm{o},11}\ \varepsilon_{\mathrm{o},22}\ \varepsilon_{\mathrm{o},33}\ \gamma_{\mathrm{o},12}\ \gamma_{\mathrm{o},23}\ \gamma_{\mathrm{o},31}]^T$	Strain of outer bulk material
η_k	Volume fraction of crack k
θ	Lode angle
$\dot{\lambda}$	Plastic multiplier
$\boldsymbol{\Lambda}$	Lagrangian multipliers
μ_0, μ	Model parameters controlling shape of yield surface
ν	Poisson's ratio
$\boldsymbol{\xi}_k$	Strain of crack k
$\boldsymbol{\sigma}_{ij}$	Stress of RVE in index notation form
$\sigma_i;\ i = 1,\ 2,\ 3$	Principal stress 1, 2 and 3
$\boldsymbol{\sigma}^\mathrm{tr}$	Trial stress of RVE
$\boldsymbol{\sigma}_\mathrm{o}$	Stress of outer bulk material
$\boldsymbol{\sigma} = [\sigma_{11}\ \sigma_{22}\ \sigma_{33}\ \sigma_{12}\ \sigma_{23}\ \sigma_{31}]^T$	Stress of RVE in matrix form
φ, κ	Failure plane orientation of crack
Φ	Dissipation potential of RVE