



UNIVERSITY OF
TECHNOLOGY SYDNEY

Developing Constitutive Model to Simulate Behaviour of Cement Treated Clay Composite Capturing Effect of Cementation Degradation

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Lam Dinh Nguyen

Date:

DEDICATION

This thesis is deeply dedicated to the following people:

To my respective parents, Dinh Son Nguyen & Bach Hue T. Nguyen

For their sacrifices, endless love, hard work and inspiration

To my wonderful wife, Kim Ngan Huynh

For her constant love, supports and caring

To my lovely daughters, Amy & Helen Thien Nguyen

For bringing joy and hope

ABSTRACT

Stabilising soft clays with cement has become an effective ground modification method to improve the properties of the soft soils. However, laboratory experiments have shown that the cementation of clay gradually diminishes as the mean effective yield stress increases, due to the degradation of cementation bonds. Furthermore, the shear strength of cement treated clay is influenced by the shear degradation induced by the shear deformation, particularly at the post-peak state where a significant shear deformation and consequently breakage of cementation bonds occur. Moreover, a typical stress-strain relationship shows brittle failure behaviour of the soil treated with cement where the shear strength decreases rapidly after the peak strength state. Hence, in recent years, the inclusion of fibre into soil treated with cement has become increasingly popular to overcome the challenge of the unfavourable brittle behaviour of the cement treated soil. The soil treated with cement and fibre, referred to as the improved soil composite or the fibre reinforced cemented soil (FRCS) shows significant increase in ductility due to the bridging effects provided by the fibre during compression. However, when the accumulation of deviatoric straining becomes very large, the fibre failure due to pull-out or breakage occurs. Hence, an effective constitutive model is required to capture the effect of fibre and its failure mechanism on the behaviour of the fibre reinforced cement treated soil.

In this study, a constitutive model and its extended version were developed to simulate the behaviour of cement treated clay with or without fibre reinforcement, respectively. The proposed models include the formulation of the modified mean effective stress considering the effect of cement and fibre inclusion, together with the cementation degradation and fibre failure due to volumetric and shear deformation. A non-linear failure envelope was also formulated to merge with the Critical State Line (CSL) of the reconstituted soil mixture at high mean effective stresses in order to capture the cementation degradation and ruptured fibres. The special characteristics of the proposed models include a non-associated plastic potential function derived from a modified energy dissipation equation with the parameter α . When $\alpha = 0$ is adopted, the proposed models become associated with the yield surface being identical to the plastic potential surface. In addition, a general stress-strain relationship including the hardening and the softening processes to simulate the pre-and-post peak states of the treated clay

was also proposed. When the effects of cement and fibre are absent, together with $\alpha = 0$, the proposed models return to the Modified Cam Clay model.

Furthermore, a series of undrained and drained triaxial tests were conducted and the results were reported on the natural Ballina clay treated with different cement contents (i.e. 10%, 12% and 15%) and the artificial Kaolin clay treated with 5% cement under various loading conditions (confining pressures ranging from 50 kPa to 800 kPa) in order to study the effect of cementation and its degradation on the behaviour of the cement treated clay. The performance of the proposed model for the cement treated clay was evaluated by comparing the model predictions with the new experimental results in this study and existing case studies available in the literature. It has been evident that many researchers focus on the addition of fibre into sand, soft clay, and sand treated with cement, whereas the behaviour of soft clay treated with fibre and cement requires further investigations. Therefore, an extensive experimental program was carried out to determine how the fibre and cement contents affect the behaviour of cement treated clay with fibre reinforcement. Numerous triaxial tests were conducted and reported on the cement treated Ballina clay with 0.3% and 0.5% fibre contents while the results for the Kaolin clay treated with 5% cement and differing fibre contents (i.e. 0.1% and 0.5%) under various loading conditions were also included. In addition, the micro-structure of the Ballina clay with or without treatments were analysed using the SEM images for the pre-and-post shearing stages. The experimental results were used for the verification of the extended version of the proposed model for the improved soil composite.

The laboratory results indicated that the combined effects of cementation and fibre reinforcement increase the shear strength and ductility of the treated soft clay. Under triaxial conditions the peak shear strength of soft clay treated with cement and fibre increases dramatically due to the formation of cementation bonds and the bridging effect provided by the fibres, and the brittleness caused by the cementation bonds breaking also improves significantly due to the inclusion of fibre. However, when shearing at a high mean effective yield stress, the cementation bonds break and the fibre ruptures due to the plastic deviatoric strain which caused major cracks to appear within the sample. By capturing the main features of the cement treated clay with or without fibre reinforcement, the proposed model provides reliable predictions that agree well with the experimental results.

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LIST OF SYMBOLS

Abbreviations

CSL	Critical State Line
CD	Consolidated-Drained triaxial test
CU	Consolidated-Undrained triaxial test
ELDPC	Enterprise Level Pressure/Volume Controllers
FRCS	Fibre Reinforced Cemented Soil
LVDT	Linear Variable Displacement Transducer
MCC	Modified Cam Clay
MSCC	Modified Structured Cam Clay
PWPT	Pore Water Pressure Transducer
SEM	Scanning Electron Microscopy
SCC	Structured Cam Clay
UCS	Unconfined Compression Strength

Greek notations

α	non dimensional parameter
β	Cementation degradation parameter due to mean effective stress
ε_1	Axial strain
ε_3	Radial strain
$\dot{\varepsilon}$	Strain rate adopted for triaxial tests
ε_f	Strain level at failure
ε_{peak}	Strain level at peak stress
ε_{res}	Strain level at residual stress
κ	Swelling or recompression index
λ	Compression index
η	Stress ratio
η^*	Modified stress ratio
ν	Poisson's ratio

ω	Cementation degradation parameter due to shear deformation
ψ	Derivative of p'_0 with respect to p'
σ_1	Total axial stress
σ'_1	Axial effective stress
σ_3	Total radial stress
σ'_3	Radial effective stress
σ_f^p	Plastic stress limit of the fibre
δ_{sf}	Frictional component between fibre and soil matrix
ξ	Correlation factor for the effect of cementation to the shear strength

Latin notations

A	Derivative of p'_Ω with respect to p'
a_{sf}	Adhesive component between fibre and soil matrix
B	Derivative of p'_f with respect to q
b	Cementation degradation parameter due to shear deformation
C_c	Shear strength contributed by cementation when $p' = 0$
C_f	Shear strength contributed by fibre
d_f	Diameter of the fibre
d_v	Total volumetric strain increment
d_v^e	Elastic volumetric strain increment
d_v^p	Plastic volumetric strain increment
d_ε	Total plastic deviatoric strain increment
d_ε^e	Elastic deviatoric strain increment
d_ε^p	Plastic deviatoric strain increments
dW_{in}	Internal plastic energy per unit volume
$d\lambda$	Non-negative plastic multiplier
Δs	Effect of soil fabric
Δu	Excess pore water pressure
Δu_{max}	Maximum excess pore water pressure
e	Void ratio of the soil
f	Yield function

G'	Shear modulus
g	Plastic potential function
I_B	Brittleness index
l_f	Length of the fibre
M	Slope of failure envelope of reconstituted soil composite
m	Fibre degradation parameter due to shear deformation
n	Fibre degradation parameter
p	Total mean stress
p'	Mean effective stress
p'_f	Describing the effect of fibre
p''_f	Fibre degradation due to plastic deviatoric strain
p'^*	Modified mean effective stress
p^*_{crit}	Critical mean effective stress
p'^*_0	Modified mean effective stress on the yield surface when $q = 0$
p'_0	Hardening parameter – mean effective stress on the yield surface when $q = 0$
$p'_{0,i}$	Initial mean effective yield stress
p'_Ω	p' (tension) when $q = 0$, describing the effect of cementation
p''_Ω	Cementation degradation due to plastic deviatoric strain
$p'_{\Omega,i}$	Describing the beneficial effect of cementation
q	Deviatoric stress
q_c	Critical deviatoric stress
q_{peak}	Peak shear strength
q_{res}	Residual shear strength
t_f	Time to failure
u	Pore water pressure
u_{max}	Maximum pore water pressure