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

A thesis in fulfilment of the requirement
for the award of the degree

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by

**Lam Dinh Nguyen**, BEng, BBus, MEng

School of Civil and Environmental Engineering
Faculty of Engineering and Information Technology

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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.

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*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 $\alpha$. 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 PUBLICATIONS

## Published Journal Papers

Nguyen, L.D., Fatahi, B. and Khabbaz, H. 2014. A constitutive model for cemented clays capturing cementation degradation, *International Journal of Plasticity*, 56: 1-18.

Nguyen, L. and Fatahi, B. 2016. Behaviour of clay treated with cement & fibre while capturing cementation degradation and fibre failure–C3F Model. *International Journal of Plasticity*, 81: 168-195.

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Nguyen, L., Fatahi, B. and Khabbaz, H. 2013. Predicting behaviour of cemented clay considering strength reduction due to high confining pressure. *GeoMontreal 2013*, Canadian Geotechnical Society, Montreal, Canada, pp. 1-6.

Nguyen, L., Fatahi, B. and Khabbaz, H. 2014. Modelling behaviour of cemented clay capturing cementation degradation. *Geotechnical Special Publication*, American Society of Civil Engineers (ASCE), pp. 168-177.

Nguyen, L., Fatahi, B. and Khabbaz, H. 2016. A novel model to simulate behaviour of cement treated clay under compression and shear. *GeoChina 2016, Geotechnical Special Publication*, American Society of Civil Engineers (ASCE)

Nguyen, L., Fatahi, B. and Khabbaz, H. 2016. Predicting the behaviour of fibre reinforced cement treated clay. *International Conference on Transportation Geotechnics 2016*, Guimarães, Portugal.

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## Abbreviations

| | |
|---|---|
| CSL | Critical State Line |
| CD | Consolidated-Drained triaxial test |
| CU | Consolidated-Undrained triaxail test |
| ELDPC | Enterprise Level Pressure/Volume Controllers |
| FRCS | Fibre Reinforced Cemented Soil |
| LVDT | Linear Variable Displacement Transfomer |
| 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

| | |
|---|---|
| $\alpha$ | non dimensional parameter |
| $\beta$ | Cementation degradation parameter due to mean effective stress |
| $\varepsilon_1$ | Axial strain |
| $\varepsilon_3$ | Radial strain |
| $\dot{\varepsilon}$ | Strain rate adopted for triaxial tests |
| $\varepsilon_f$ | Strain level at failure |
| $\varepsilon_{peak}$ | Strain level at peak stress |
| $\varepsilon_{res}$ | Strain level at residual stress |
| $\kappa$ | Swelling or recompression index |
| $\lambda$ | Compression index |
| $\eta$ | Stress ratio |
| $\eta^*$ | Modified stress ratio |
| $\nu$ | Poisson's ratio |

| | |
|---|---|
| $\omega$ | Cementation degradation parameter due to shear deformation |
| $\psi$ | Derivative of $p'_0$ with respect to $p'$ |
| $\sigma_1$ | Total axial stress |
| $\sigma'_1$ | Axial effective stress |
| $\sigma_3$ | Total radial stress |
| $\sigma'_3$ | Radial effective stress |
| $\sigma_\mathrm{f}^p$ | Plastic stress limit of the fibre |
| $\delta_\mathrm{sf}$ | Frictional component between fibre and soil matrix |
| $\xi$ | Correlation factor for the effect of cementation to the shear strength |

**Latin notations**

| | |
|---|---|
| $A$ | Derivative of $p'_\Omega$ with respect to $p'$ |
| $a_\mathrm{sf}$ | Adhesive component between fibre and soil matrix |
| $B$ | Derivative of $p'_\mathrm{f}$ 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 |
| $d_\mathrm{f}$ | Diameter of the fibre |
| $d_v$ | Total volumetric strain increment |
| ${d_v}^e$ | Elastic volumetric strain increment |
| ${d_v}^p$ | Plastic volumetric strain increment |
| $d_\varepsilon$ | Total plastic deviatoric strain increment |
| ${d_\varepsilon}^e$ | Elastic deviatoric strain increment |
| ${d_\varepsilon}^p$ | Plastic deviatoric strain increments |
| $dW_{in}$ | Internal plastic energy per unit volume |
| $d\lambda$ | Non-negative plastic multiplier |
| $\Delta s$ | Effect of soil fabric |
| $\Delta u$ | Excess pore water pressure |
| $\Delta u_{max}$ | 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 |
| $l_\mathrm{f}$ | 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 |
| $p'_\mathrm{f}$ | Describing the effect of fibre |
| $p''_\mathrm{f}$ | 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 |
| $p'{}_\Omega$ | $p'$(tension) when $q = 0$, describing the effect of cementation |
| $p''_\Omega$ | Cementation degradation due to plastic deviatoric strain |
| $p'_{\Omega,\mathrm{i}}$ | 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 |