A series of webinars delivered by local academics by HKIE-GD and HKGES
Webinar 1: 14th March 2022 (Mon), GMT+8 (HKT) 6:30pm

A General Simple Method for Calculating Consolidation Settlements of Layered Clayey Soils without/with PVDs under Any Staged Loading
在任意多級加載下有/無排水板的多層黏性土固結沉降計算通用簡化方法

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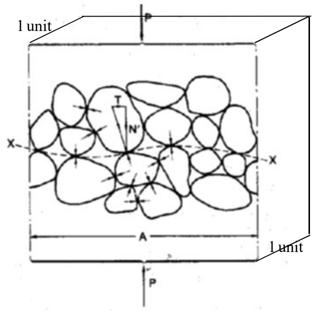
1. Introduction

What are "**consolidation**" and "**settlement**"?
We need to know "*saturated soil*" first.
Saturated soil is a mix of "incompressible" soil particles and their voids fully filled by "incompressible" water

We need to know "**Effective Stress Principle**" and equation:



$$\sigma = \frac{P}{A} \qquad P = \Sigma N' + uA$$

$$\sigma' = \frac{\Sigma N'}{A} \qquad \frac{P}{A} = \frac{\Sigma N'}{A} + u$$

Normal stress: $\sigma = \sigma' + u$

Shear stress: no change

Effective stresses control both **deformation** and **shear resistance** (or shear strength) since effective stresses reflect soil particle interaction. Why?

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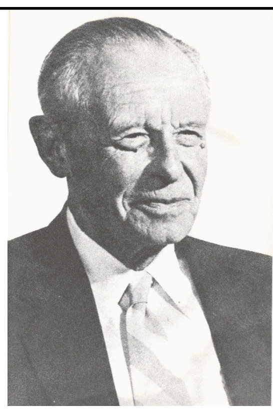
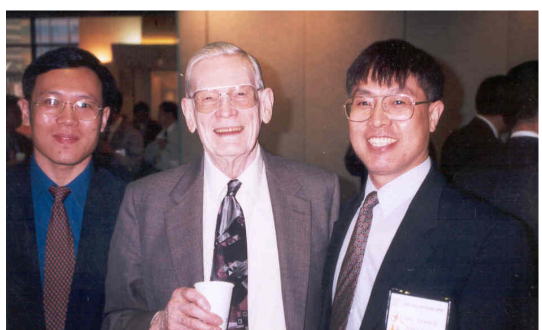


Terzaghi (1883-1963):
Father of ***Soil Mechanics***
Effective stress principle for saturated soils,
One-dimensional (1-D) ***consolidation theory*** and solution
…



Prof Dr Ralph Brazelton Peck (1912-2008): an eminent civil engineer specializing in soil mechanics, 33 years of teaching at University of Illinois

Prof Jian CHU
Nanyang Technological University, Singapore (NTU)

Prof Jian-Hua YIN
The Hong Kong Polytechnic University, Hong Kong

Photo taken at 16th Asian Regional Conference on Soil Mechanics and Geotechnical Engineering in Taipei, 1998

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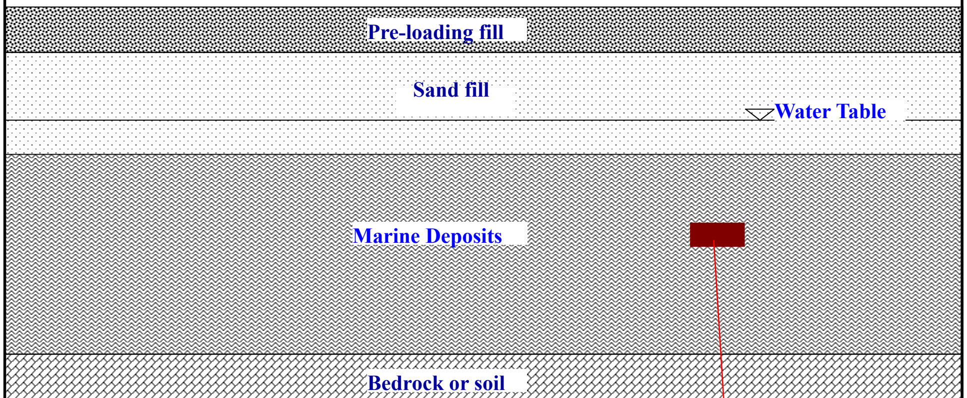
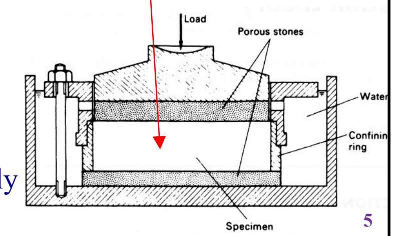
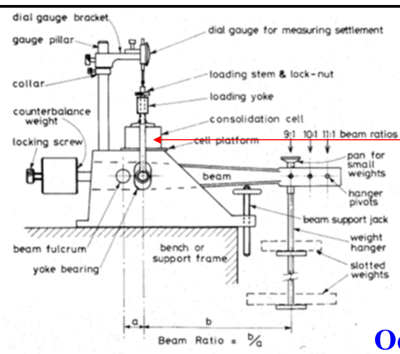
Oedometer test (1D straining or laterally confined consolidation test)



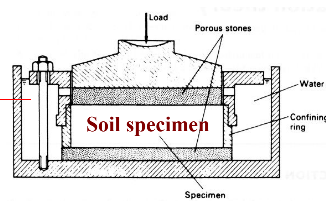
Confined or 1-D straining consolidation (or oedometer) condition:

- Soil layers are horizontal and uniform
- Loading is uniform (extensive UDL)
- Deformation & water flow are in vertical only





General arrangement of a typical oedometer press

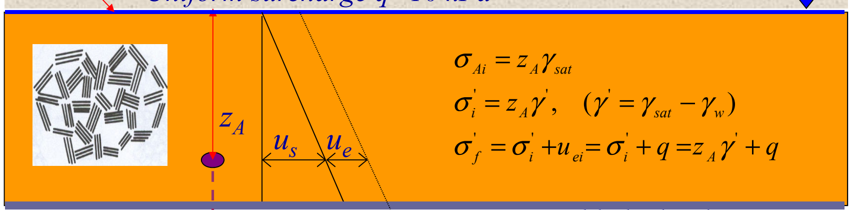


Oedometers in Soil Mechanics Laboratory

Impermeable at time=0+

Uniform surcharge q=10 kPa

Water table



$$\sigma_{Ai} = z_A \gamma_{sat}$$
$$\sigma_i^{'} = z_A \gamma^{'}, \quad (\gamma^{'} = \gamma_{sat} - \gamma_w)$$
$$\sigma_f^{'} = \sigma_i^{'} + u_{ei} = \sigma_i^{'} + q = z_A \gamma^{'} + q$$

Impermeable bedrock

Static porewater pressure:

$$u_s = z_A \gamma_w$$

Initial excess porewater pressure:

$$u_{ei} = q = 10kPa$$

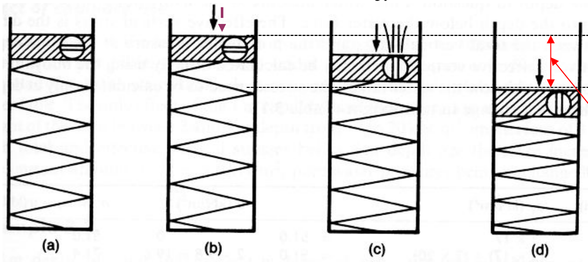


Figure 3.2 Consolidation analogy.

"**Consolidation**" is a coupled process of water coming out and compression of soil "**skeleton**", resulting in "**settlement**"

Due to increase of $\sigma_f^{'}$ *directly*

Neither σ, *nor u*

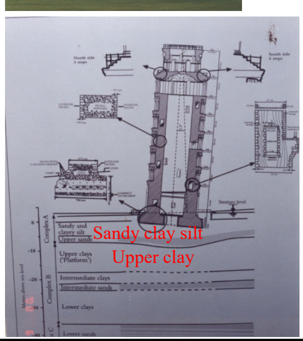
Settlement of soil ground – real cases

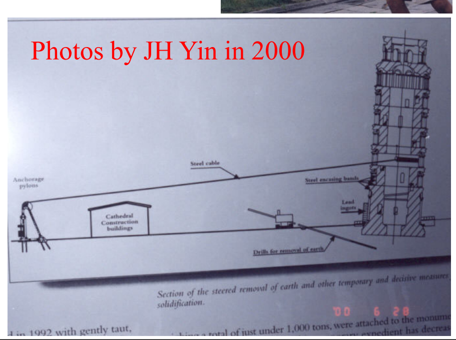
The Tower of Pisa

Construction began 1173 and settled approximately 3m into ground

1911-1981:

Inclined in N-S direction $2^{o}26^{'}$





Japan Kansai Airport Reclamation Issues

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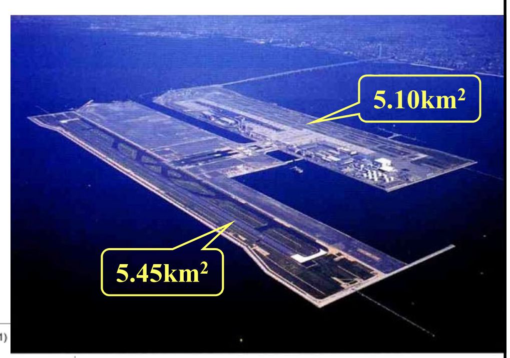
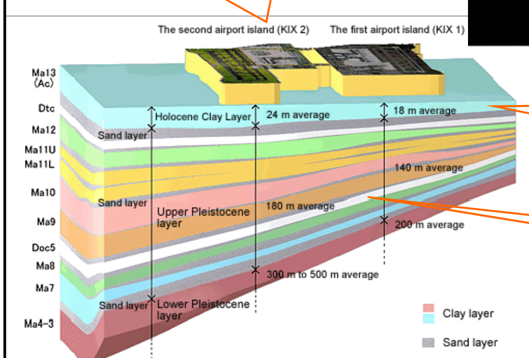
August 2007
Second Runway





Treated by Sand Compaction Piles

Untreated

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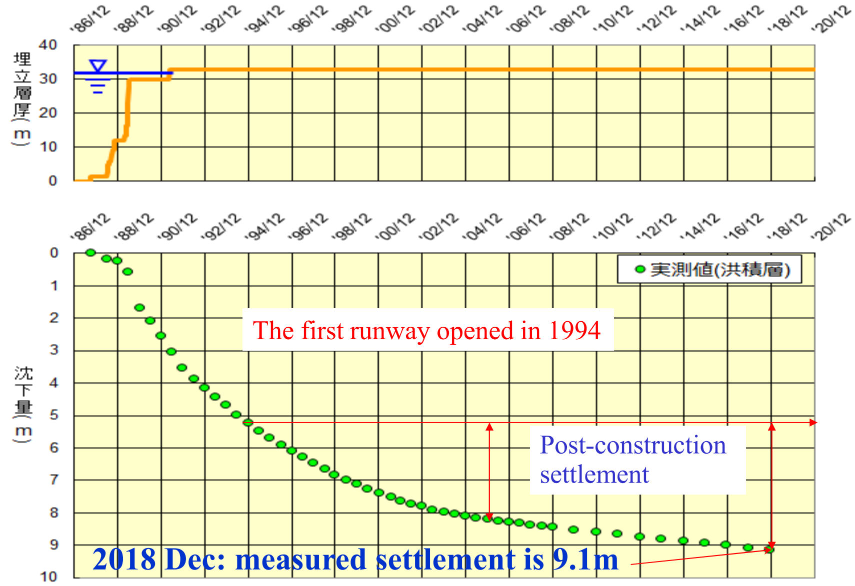
Kansai International Airport in Osaka, Japan
- First Runway Settlement (updated)



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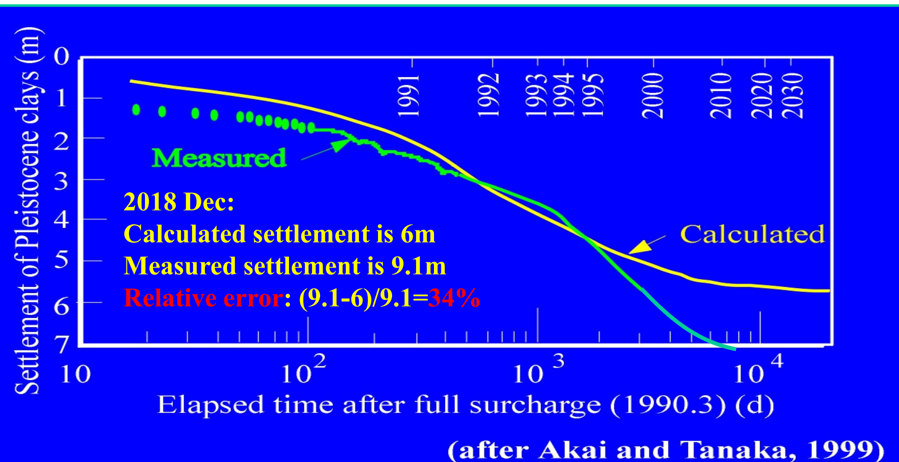
Is the excessive settlement a problem in Japan?



Measured settlement was larger than that calculated!

Hypothesis A method was used in such prediction (no creep/viscous compression in "primary" consolidation).

Creep/viscous compression in "primary" consolidation shall be included in settlement calculation.

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Japan Kansai Airport Reclamation Issues – Second Runway

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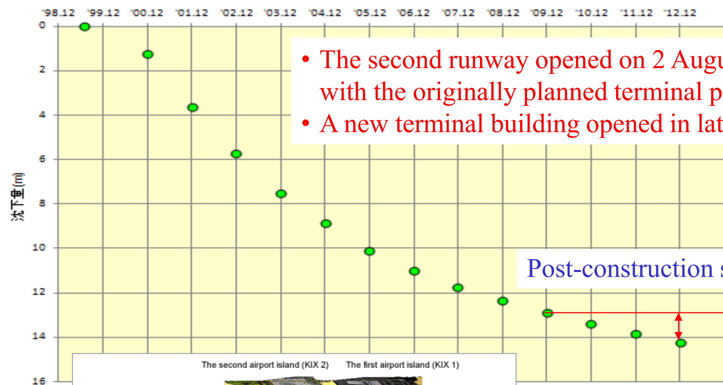
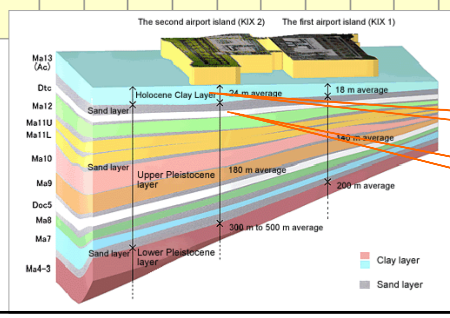
Second Runway Settlement (updated)



- The second runway opened on 2 August 2007, but with the originally planned terminal portion postponed
- A new terminal building opened in late 2012

Post-construction settlement



Treated sand compaction piles

No ground improvement

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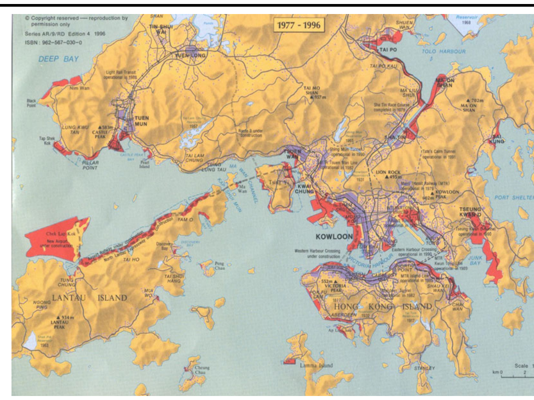
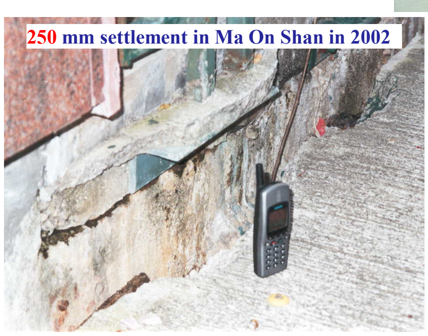
Location of major reclamation projects (1977~1996) 香港填海造地



Settlements due to

- Creep
- Dewatering (effective stress increased)
- Surface loading.



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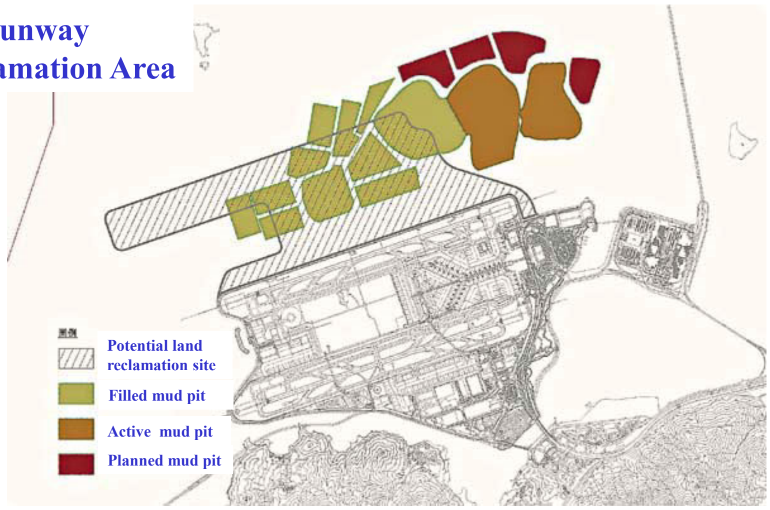
HK International Airport 3rd Runway Reclamation Methods

Settlement prediction?



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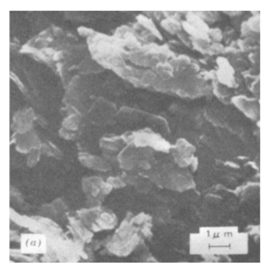
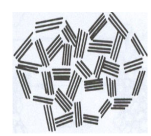
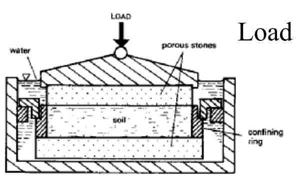
What is creep and why creep?

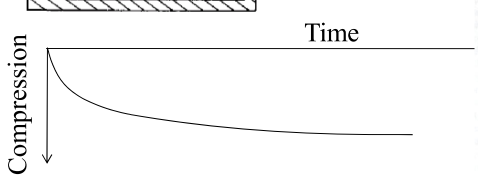
Creep: continuous deformation under a constant load/effective stress
Why: see micro-structures of soils







Load = constant



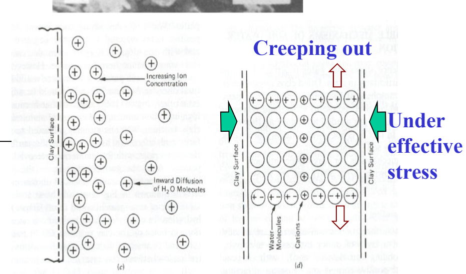


Figure 6.4 Possible mechanisms of water adsorption by clay surfaces. (a) Hydrogen bonding. (b) Ion hydration. (c) Attraction by osmosis. (d) Dipole attraction.

Creep is caused by
(i) viscous adsorbed water on clay particles,
(ii) viscous deformation of clay plates, and
(iii) viscous deformation of clay skeleton.
Adsorbed water is NOT free water and cannot flow freely under hydraulic gradient.

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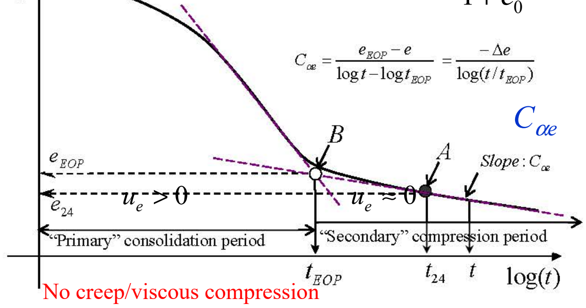
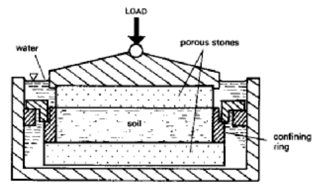
Compression due to creep (not use of "secondary" compression)

$$e = e_o + \Delta e; \quad \Delta\varepsilon = \frac{-\Delta e}{1+e_0}$$



No creep/viscous compression in "primary" consolidation?

Load = constant



$$C_{\alpha\varepsilon} = \frac{\Delta\varepsilon}{\Delta \log t} = \frac{1}{1+e_0}\frac{-\Delta e}{\Delta \log t} = \frac{C_{\alpha e}}{1+e_0}$$

$C_{\alpha e}$ *is so called "secondary" consolidation coefficient*

$$\varepsilon_{creep} = \frac{\Delta h}{h_o} = C_{\alpha\varepsilon} \log \frac{t}{t_{EOP,lab}}$$

$t_{EOP,lab}$ *: a few to tens of minutes, or*

t_{24hrs} *: 24 hours (1day)*

$t_{EOP,field}$ *: days to many years*

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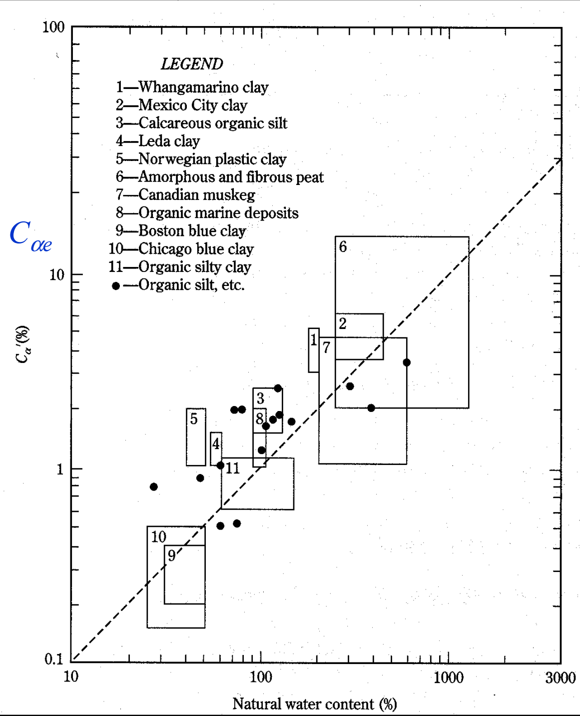

For Hong Kong Marine Clays:

$C_{\alpha e}$=0.3% to 4%

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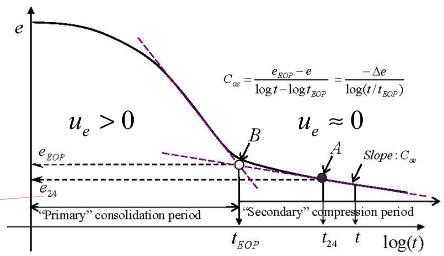
2. Hypothesis A and Hypothesis B Methods for Calculating Consolidation Settlements of Clayey Soils

Equation of Hypothesis A Method
(an old de-coupled method)：

No creep in "primary" consolidation?



$$S_{totalA} = S_{\text{"primary"}} + S_{\text{"secondary"}}$$

$$= \begin{cases} U_v S_f \quad + \quad 0 & for\ 0 \le t < t_{EOP,field} \\ U_v S_f + \frac{C_{\alpha e}}{1+e_o} \log\left(\frac{t}{t_{EOP,field}}\right) H & for\ \ t > t_{EOP,field} \end{cases}$$

$t_{EOP,field} = days\ to\ many\ years,\ depending\ on\ layer\ thickness,\ permeability\ ...$

How to define $t_{EOP,field}$ *at End Of Primary (EOP)? If* $u_e = 0, time = \infty$

We may calculate $t_{EOP,field}$ *at* $U_v = 98\%$ (*subjective*!)

Hypothesis A method：

- This method is incorrect since the creep/viscous settlement in the "primary" consolidation is not included.
- This method underestimates/低估 settlement.

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I refer to one journal paper and one ppt by Dr SA Degago (Norway)

[1] Degago SA , Grimstad G, Jostad HP, NORDAL S & Olsson M (2011). Use and misuse of the isotache concept with respect to creep hypotheses A and B. Geotechnique 61, No. 10, 897–908.

[2] Degago SA (2014). Primary Consolidation and Creep of Clays. A ppt from Norwegian Public Roads Administrations (SVV).

Two hypotheses on role of creep during primary consolidation

❖ Proposed by Ladd et al. (1977). "*Does creep act as a separate phenomenon while excess pore pressures dissipate during primary consolidation?*"

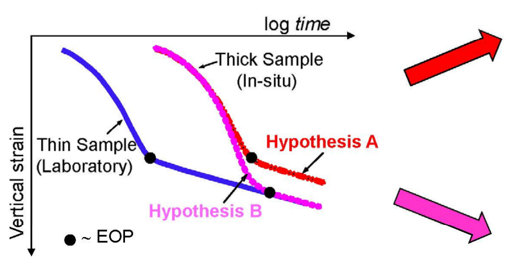
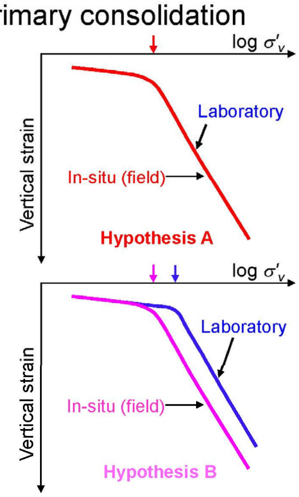


Fig. Hypothesis **A** and **B** (after Ladd *et al.*, 1977)



❖ Advocates of the two different creep hypotheses have *independently* presented voluminous laboratory and field data to substantiate their opinions.

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Equations of Hypothesis B Method (a fully coupled method including creep/viscous compression) ("rigorous/嚴格的" Hypothesis B method):

From continiuty condition:

$$\frac{k}{\gamma_w}\frac{\partial^2 u_e}{\partial z^2} = -\frac{\partial \varepsilon_z}{\partial t} \qquad (1)$$

This is from Terzaghi's 1D consolidation theory. He used a linear elastic model.

k = *permeability*; γ_w = *unit weight of water*;

u_e = *excess porewater pressure*; ε_z = *vertical strain*

The linear elastic model was replaced by a 1D EVP model.

$$\frac{\partial \varepsilon_z}{\partial t} = \frac{\kappa}{V}\frac{\dot{\sigma}'_z}{\sigma'_z} + \frac{\psi}{Vt_o}\exp\left[-(\varepsilon_z - \varepsilon_{zo}^{ep})\frac{V}{\psi}\right]\left(\frac{\sigma'_z}{\sigma'_{zo}}\right)^{\lambda/\psi} \qquad (2)$$

A constitutive model (effective stress-strain-rate relation) in (2) is needed.
Yin and Graham (1989, 1994) developed a one-dimensional Elastic Visco-Plastic (1D EVP) model in (2).

"Rigorous/嚴格的" Hypothesis B Method:

- No assumption between "primary" and "secondary" separation is needed.
- The creep/viscous compression during and after the "primary" consolidation is naturally included. This method is "rigorous" and shall give correct settlement.
- This is a theoretical proof of creep/viscous compression in "primary" period.
- Test data proof ? > see this later.

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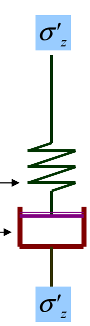
Yin and Graham's (1989, 1994) 1-D Elastic Visco-Plastic (1-D EVP) model:

$$\dot{\varepsilon}_z = \frac{\kappa}{V}\frac{\dot{\sigma}'_z}{\sigma'_z} + \frac{\psi}{Vt_o}\exp\left[-(\varepsilon_z - \varepsilon_{zo}^{ep})\frac{V}{\psi}\right]\left(\frac{\sigma'_z}{\sigma'_{zo}}\right)^{\lambda/\psi}$$

Non-linear elastic strain rate; non-linear visco-plastic strain rate

Linear elastic spring (non-linear for 1-D EVP model)

Linear visco dash-pot (non-linear for 1-D EVP model)



Maxwell's Rheoloical Model:

$$\dot{\varepsilon}_z = \frac{\dot{\sigma}'_z}{E} + \frac{\sigma'_z}{\eta}$$

Linear elastic strain rate; linear visco-plastic strain rate

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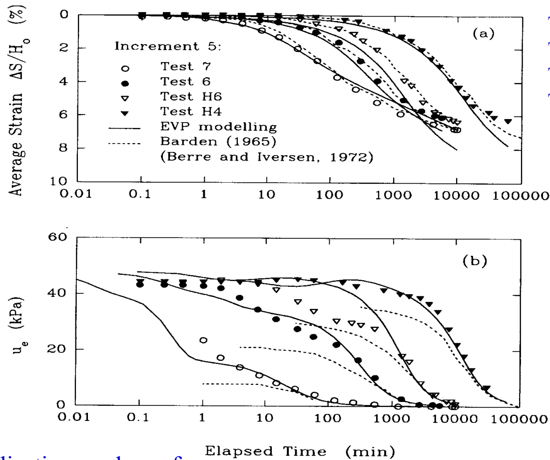
Proof 1: theoretical proof of creep/viscous compression in "primary" period.

See: Yin, J H. and Graham, J. (1996). Elastic visco-plastic modelling of one-dimensional consolidation. Geotechnique, 1996, 46(3): 515 - 527.



Test 7: H_o=18.8 mm
Test 6: H_o=75.7 mm
Test 6: H_o=150 mm
Test H4: H_o= 450 mm

Other applications and proofs:
Zhu, GF (1999, 2000a, 2000b, 2001a, 2001b, 2004) (HK of China)
Nash, DFT and Ryde SJ (2001) , Nash. DFT and Matthew Brown (2015) (UK)
Le, TM, **Fatahi, B**, Disfani, M, Khabbaz, H (2015) (Australia)
Hu, Ya-Yuan (2012); Hu, Ya-Yuan, Zhou, Wan-Huan, Cai, Yuan-Qiang (2014) (China)

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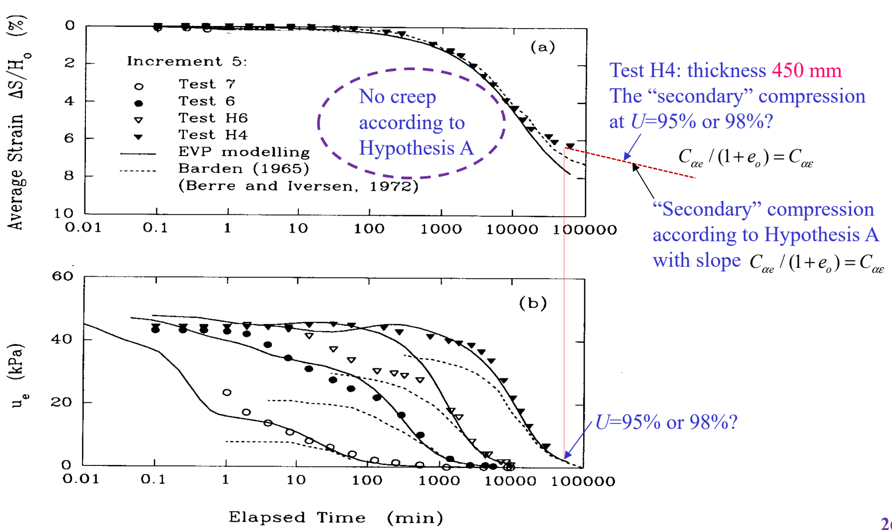
Proof 2: by test data

How do you prove creep (or viscous) compression existing in "primary" consolidation?

Berre, T. and Iversen, K. (1972). Oedometer tests with different specimen heights on a clay exhibiting large secondary compression. Geotechnique 22, No. 1, 53-70.



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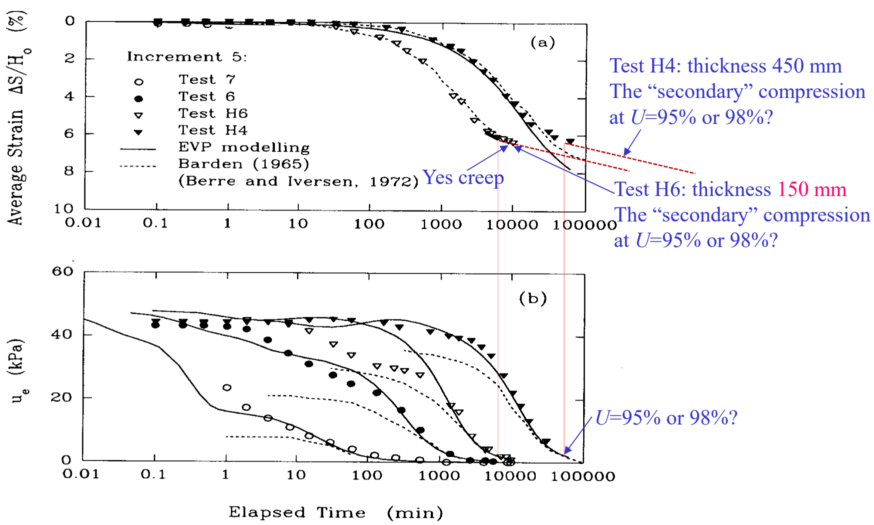

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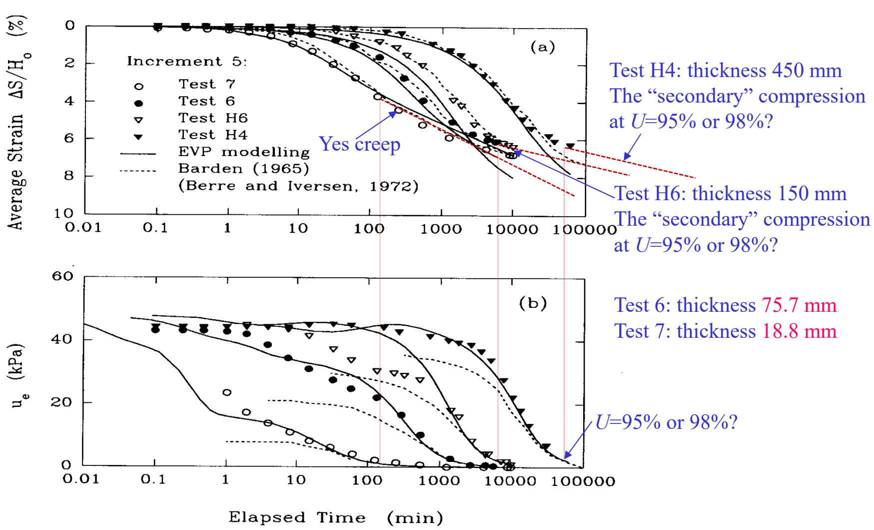

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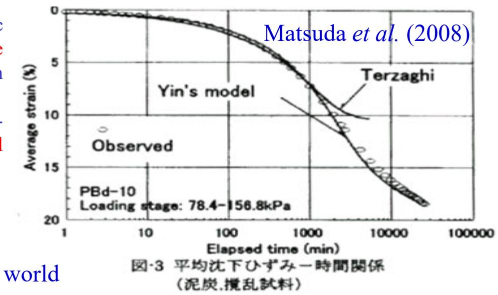
JH Yin and his co-workers have done a lot of works on the time-dependent (creep) stress-strain behavior and consolidation settlement analysis of soft soils since his PhD study in Canada in 1986:

Yin, JH and Graham, J, (1989). Viscous elastic plastic modelling of one-dimensional time dependent behaviour of clays. Canadian Geotech. J., .26, 199-209.

Yin, JH and Graham, J (1996). Elastic visco-plastic modelling of one-dimensional consolidation. Geotechnique, 46(3), 515-527.



A top journal (UK) in Geotechnics in the world

Zdravkovic, L. & Carter, J. (2008). *Géotechnique* **58**, No. 5, 405–412 [**doi:** 10.1680/geot.2008.58.5.405]

Contributions to *Géotechnique* 1948–2008:
Constitutive and numerical modelling

Over 60 years

L. ZDRAVKOVIC* and J. CARTER†

tests. However, it is the model of Yin & Graham (1996), which introduces the equivalent time concept, that makes a step forward in modelling creep. Although this paper showed model development for one-dimensional consolidation only

Yin and Graham's Elastic Visco-Plastic (non-linear) model (1989, 1994, 1996) was considered as a **milestone contribution** in modelling creep of soils.

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Zdravkovic, L. & Carter, J. (2008). Contributions to Geotechnique **1948–2008**: Constitutive and numerical modelling. **Geotechnique** 58, No. 5, 405–412.

"This paper reviews some of **the main milestones** in the evolution of geotechnical analysis in the past 60 years, commenting, where appropriate, on what problems still lie ahead."

"However, it is the model of Yin & Graham (1996), which introduces ***the equivalent time concept***, that makes a step forward in modelling creep. Although this paper showed model development for one-dimensional consolidation only (a complete model was published later, but not in Geotechnique), it assumed that the total strain consists of elastic and viscoplastic parts. ***The use of equivalent time allows the model to have stress–strain-equivalent time states independent of stress path*** (*i.e.* total strain rate is equal to creep strain rate). The model also introduces the limit time line, which helps to model soils that do not experience creep: that is, if the equivalent time is set to be very large (infinity), the creep rate will be equal to zero."

Zdravkovic, L.: Professor in Imperial College, UK

Carter, J P: Former Vice-President (R&D) of The University of Newcastle, Australia

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Proof 3: by test data and theoretical analysis
Creep (or viscous) compression existing in "primary" consolidation.

119 クリープが粘土の一次圧密領域における沈下に及ぼす影響

山口大学工学部 正会員 松田 博
山口大学大学院 学生会員○佐藤秀政
復建調査設計(株) 正会員 周藤宜二
山口大学大学院 学生会員 三原正之
山口大学大学院 学生会員 村上剛敏

Professor Matsuda and his co-workers (2008) used the 1D EVP model for consolidation analysis of soft soils exhibiting creep and compared calculated values with test data.

$$C_v \frac{\partial^2 u}{\partial z^2} = \frac{\partial u}{\partial t} - \frac{1}{m_v} g(u,\varepsilon_z)$$

This is from Terzaghi's 1D consolidation theory. He used a linear elastic model.

$$\frac{\partial \varepsilon_z}{\partial t} = -m_v \frac{\partial u}{\partial t} + g(u,\varepsilon_z)$$

The linear elastic model is replaced by 1D EVP model (Yin and Graham 1989, 1994).

$$g(u,\varepsilon_z) = \frac{\psi / V}{t_o}\left\{\exp\left(-\varepsilon_z \frac{V}{\psi}\right)\right\}\left(\frac{\sigma_z - u}{\sigma'_{zo}}\right)^{\lambda/\psi}$$

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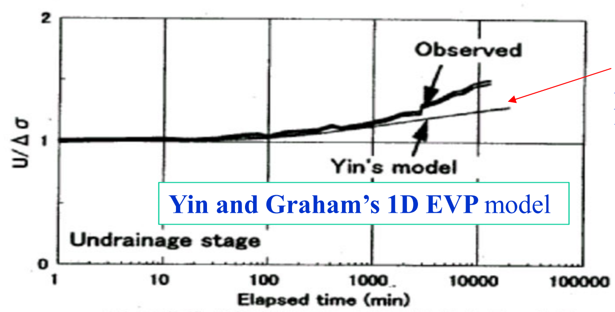

図-2 非排水載荷期間中の過剰間隙水圧の上昇
(泥炭,撹乱試料)

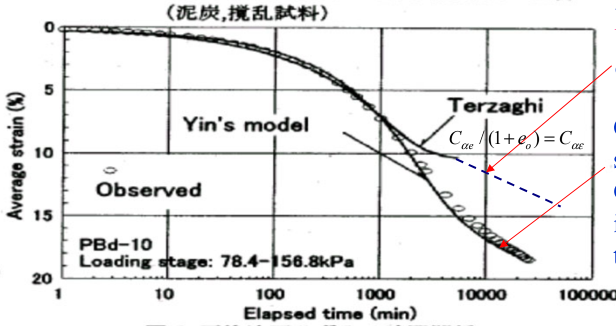

図-3 平均沈下ひずみ一時間関係
(泥炭,撹乱試料)

The excess porewater pressure u_e may be bigger than the initial value u_{ei}

Hypothesis A method underestimates consolidation settlements.

Computed consolidation settlement from **Yin and Graham 1D EVP's** model is in good agreement with test data.

32

Proof 4: by field measured data and theoretical analysis
Creep (or viscous) compression existing in "primary" consolidation.

Nash, D. F. T. & Ryde S. J. (2001). *Géotechnique* **51**, No. 3, 257 273

Modelling consolidation accelerated by vertical drains in soils subject to creep

D. F. T. NASH* and S. J. RYDE†

The settlement of embankments and reclamations over soft soils is frequently accelerated by the use of vertical drains. The magnitude of long-term settlement is sometimes reduced by the use of surcharge, although there is often uncertainty about how long the surcharge should be maintained to minimise creep movement. The design of vertical drains is generally based on closed-form solutions of Terzaghi's consolidation equation, and rarely takes into account non-linear stiffness and creep of the soil. In this paper a one-dimensional finite difference consolidation analysis is outlined showing how vertical and radial drainage of a multi-layer soil profile in the zone of influence of a vertical drain may be modelled. The analysis allows inclusion of a zone of peripheral smear around the drain and drain resistance, permeabilities may be varied with void ratio, and creep is modelled both during and after primary consolidation. The application of the model is illustrated with back-analysis of field data from construction of an embankment with temporary surcharge over estuarine alluvium.

Consolidation equation plus Yin and Graham's 1D EVP model

$$\frac{\partial}{\partial z}\left[\frac{k_z}{\gamma_w}\left(\frac{\partial u}{\partial z}+\gamma_w\right)\right]+\frac{1}{r}\frac{\partial}{\partial r}\left[\frac{k_r}{\gamma_w}r\frac{\partial u}{\partial r}\right] = m_v\left(\frac{\partial u}{\partial t}-\frac{\partial \sigma}{\partial t}\right)+\frac{\partial \varepsilon^{tp}}{\partial t} \quad (10)$$

where m_v is the coefficient of volume compressibility. The variation of total vertical stress elastic σ with time, and creep are taken into account by inclusion of additional terms on the right-hand side, which expresses the elastic and plastic components of strain rate. If the boundary pore pressures do not change, the equation may be expressed in terms of excess pore pressure $\bar{u}$, and the extra term involving γ_w is omitted. The soil may be modelled as linear elastic (using a constant m_v) or non-linear (by varying m_v with stress level), with or without creep. The EVP model outlined above is expressed in terms of engineering strain, and was implemented by Yin & Graham

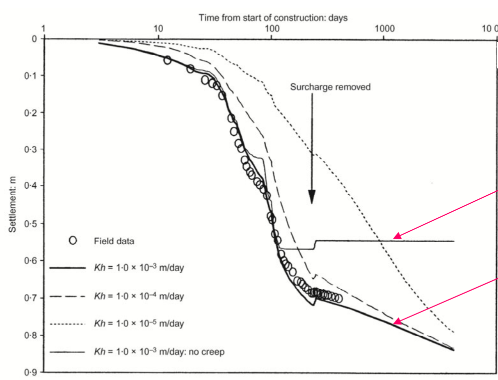

Fig. 13. Comparison between observed and predicted settlement and excess pore pressures at A403 overbridge embankment

Computed consolidation settlement without creep

Computed consolidation settlement with creep

The elastic visco-plastic constitutive model developed originally by Yin & Graham (1989, 1996) reproduces many features of soft clay behaviour commonly observed in the field and laboratory, and provides a helpful framework for the interpretation of data from high-quality oedometer tests and field instrumentation. It is axiomatic that the field and laboratory stress–strain paths predicted by the model are different on account of the longer drainage paths and slower strain rates in the field. The incorporation of this EVP model in the finite difference procedure BRISCON enables predictions to be made for full-scale problems. Parametric studies may be undertaken where there is uncertainty over soil properties such as permeability and creep parameters, and to examine the effects of varying the size and permeability of the smear zone and the effects of drain resistance.

由Yin and Graham （1989, 1996) 原創提出的彈粘塑性本構模型再現了在現場和試驗室通常觀察到的粘土行為的許多特徵，並提供了解釋高質量固結試驗數據和現場監測數據的有幫助的理論框架 。 ...

27 CEE Scholars Ranked in "World's Top 2% Scientists" in 2021 Released by Stanford University (25 Nov 2021)

The full list in 2020 can be downloaded:

https://journals.plos.org/plosbiology/article?id=10.1371/journal.pbio.3000918

Authoir Name	Institute Name	Country	Number	firstyr	lastyr	Subject Field	Rank within field	Total authors w
Randolph, Mark F.	University of Western Australia	aus	497	1975	2020	Geological & Geomatics Engine	5	44176
Sloan, Scott William	University of Newcastle, Australia	aus	360	1980	2020	Geological & Geomatics Engine	18	44176
Rowe, R. Kerry	Queen's University, Kingston	can	419	1978	2019	Geological & Geomatics Engine	19	44176
Fredlund, Delwyn G.	Golder Associates Ltd.	can	282	1972	2020	Geological & Geomatics Engine	21	44176
Iverson, Richard M.	United States Geological Survey	usa	85	1954	2019	Geological & Geomatics Engine	24	44176
Cundall, Peter	Itasca Consulting Group, Inc.	usa	65	1975	2020	Geological & Geomatics Engine	26	44176
Houlsby, Guy T.	University of Oxford	gbr	220	1979	2020	Geological & Geomatics Engine	30	44176
Dafalias, Yannis F.	University of California, Davis	usa	180	1975	2020	Geological & Geomatics Engine	31	44176
Barton, Nick	Nick Barton and Associates	nor	190	1971	2020	Geological & Geomatics Engine	33	44176
Indraratna, Buddhima	University of Wollongong	aus	522	1987	2020	Geological & Geomatics Engine	40	44176
Seed, H. B.	University of California, Berkeley	usa	119	1970	2017	Geological & Geomatics Engine	46	44176
Bolton, M. D.	University of Cambridge	gbr	204	1978	2018	Geological & Geomatics Engine	47	44176
Poulos, Harry G.	The University of Sydney	aus	278	1967	2018	Geological & Geomatics Engine	51	44176
Zhao, J.	Monash University	aus	321	1991	2020	Geological & Geomatics Engine	52	44176
Borja, Ronaldo I.	Stanford University	usa	151	1985	2020	Geological & Geomatics Engine	58	44176
Hungr, Oldrich	The University of British Columbia	can	96	1978	2018	Geological & Geomatics Engine	63	44176
Ishihara, Kenji	Chuo University	jpn	175	1962	2018	Geological & Geomatics Engine	64	44176
Hoek, E.	Gas Engineering Consultant	can	68	1965	2019	Geological & Geomatics Engine	65	44176
Han, J.	University of Kansas, Lawrence	usa	557	1986	2020	Geological & Geomatics Engine	66	44176
Wood, David Muir	University of Dundee	gbr	152	1972	2019	Geological & Geomatics Engine	67	44176
Ng, C. W.W.	Hong Kong University of Science and	hkg	486	1991	2020	Geological & Geomatics Engine	73	44176
Yin, Jian Hua	Hong Kong Polytechnic University	hkg	321	1988	2020	Geological & Geomatics Engine	88	44176
Zhang, L. M.	Hong Kong University of Science and	hkg	627	1997	2020	Geological & Geomatics Engine	110	44176

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The full list in 2021 can be downloaded:
https://elsevier.digitalcommonsdata.com/datasets/btchxktzyw/3

authfull	inst_name	cntry	sm-subfield-1	rank sm-s	sm-subfiel
Randolph, Mark F.	The University of Western	aus	Geological & Geomatics Engineering	6	52,403
Sloan, Scott W.	The University of Newcast	aus	Geological & Geomatics Engineering	16	52,403
Lade, Poul V.	University of California, Lo	usa	Geological & Geomatics Engineering	17	52,403
Rowe, R. K.	Queen's University	can	Geological & Geomatics Engineering	19	52,403
Fredlund, Delwyn G.	University of Saskatchewa	can	Geological & Geomatics Engineering	20	52,403
Iverson, Richard M.	United States Geological S	usa	Geological & Geomatics Engineering	24	52,403
Cundall, Peter	Itasca Consulting Group, I	usa	Geological & Geomatics Engineering	28	52,403
Dafalias, Yannis F.	National Technical Univers	grc	Geological & Geomatics Engineering	31	52,403
Indraratna, Buddhima	University of Technology S	aus	Geological & Geomatics Engineering	32	52,403
Houlsby, G. T.	University of Oxford	gbr	Geological & Geomatics Engineering	34	52,403
Zhao, Jian	Monash University	aus	Geological & Geomatics Engineering	41	52,403
Barton, Nick	Nick Barton and Associate	nor	Geological & Geomatics Engineering	44	52,403
Bolton, M. D.	University of Cambridge	gbr	Geological & Geomatics Engineering	49	52,403
Ng, Charles Wang Wai	**Hong Kong University of S**	**hkg**	**Geological & Geomatics Engineering**	**55**	**52,403**
Borja, Ronaldo I.	Stanford University	usa	Geological & Geomatics Engineering	56	52,403
Hungr, Oldrich	The University of British C	can	Geological & Geomatics Engineering	61	52,403
Phoon, Kok Kwang	National University of Sing	sgp	Geological & Geomatics Engineering	63	52,403
Poulos, Harry	The University of Sydney	aus	Geological & Geomatics Engineering	65	52,403
Xie, Heping	Shenzhen University	chn	Geological & Geomatics Engineering	66	52,403
Hoek, E.	Gas Engineering Consultar	can	Geological & Geomatics Engineering	67	52,403
Wood, David Muir	University of Dundee	gbr	Geological & Geomatics Engineering	70	52,403
Ishihara, Kenji	Chuo University	jpn	Geological & Geomatics Engineering	72	52,403
Han, J.	The University of Texas at	usa	Geological & Geomatics Engineering	73	52,403
Huang, Run Qiu	Chengdu University of Tec	chn	Geological & Geomatics Engineering	76	52,403
He, Man Chao	China University of Mining	chn	Geological & Geomatics Engineering	82	52,403
Yin, Jian Hua	**Hong Kong Polytechnic Un**	**hkg**	**Geological & Geomatics Engineering**	**84**	**52,403**
Michalowski, Radoslaw L.	University of Michigan, An	usa	Geological & Geomatics Engineering	88	52,403
Zhang, L. M.	**Hong Kong University of S**	**hkg**	**Geological & Geomatics Engineering**	**90**	**52,403**

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Hypothesis A Method *vs* Hypothesis B Method

Can we draw a conclusion now?

I refer to one ppt by Dr SA Degago (Director of Norwegian Public Roads Administrations)

Degago SA (2014). Primary Consolidation and Creep of Clays. A ppt from Norwegian Public Roads Administrations (SVV).

本研究已表明已有足夠確定數據驗明假說B與粘性土的測得的行為一致。

- In response to the important question raised by Ladd *et al*. in 1977, this study has shown that there exist definitive data to demonstrate that hypothesis B agrees very well with the measured behaviour of cohesive soils.
- Several EOP laboratory tests considered in this study demonstrated the validity of hypothesis B. In fact, this study disclosed that all the empirical data that were previously used to support substantiate hypothesis A actually imply hypothesis B.

  在本研究中，幾組EOP(主固結完成時應力-應變關係)試驗室試驗數據證明假說B是對的。事實上，本研究發現之前所有支持假說A是對的試驗數據實質上是支持假說B是對。
- The experienced p'_c as well as EOP strain are rate dependent even for EOP loading conditions and this fact has been experimentally supported by several EOP tests and field observations.
- The isotache theory (hypothesis B (SSC)) can explain and convincingly capture important feature of various types of laboratory tests considered in this study.

  等速理論(假說B, 即SSC)（SSC 是Soft Soil Creep model in Plaxis）可以解釋和令人信服的模擬到（再現到）本研究中討論到的各種試驗的重要特徵。

37

YIN J-H. and GRAHAM J.(1989). Viscous elastic plastic modelling of one-dimensional time dependent behaviour of clays. Canadian Geotechnical Journal, 1989,26:,199 - 209.

YIN J H. and GRAHAM J. (1994). Equivalent times and elastic visco-plastic modelling of time-dependent stress-strain behaviour of clays. Canadian Geotechnical Journal, 1994,31: 42 - 52.

YIN J H. and GRAHAM J. (1996). Elastic visco-plastic modelling of one-dimensional consolidation. Geotechnique, 1996, 46(3): 515 - 527.

Zhu, G.F., Yin, J.H., and Graham, J. 2000. Consolidation modelling of soils under the test embankment at Chek Lap Kok International Airport in Hong Kong using a simplified finite element method", Canadian Geotechnical Journal, Vol.38, No.2, 349-363.

Yin, JH (2011). "From constitutive modeling to development of laboratory testing and optical fiber sensor monitoring technologies", Chinese J of Geotechnical Engineering, 33(1), 1~15. (14th "Huang Wen-Xi Lecture" in China in 2011).

Difficulties of using this "rigorous嚴格的" Hypothesis B Method:

(a) Numerical methods and programs (software) are needed.

(b) Knowledge and experience are needed.

Numerical methods and software:

(a) Finite difference method (Yin and Graham 1996).

(b) Finite element method and software (examples) below,

(i) Plaxis 2D and 3D for consolidation modelling and a soft soil creep model,

(ii) "Consol" developed by Zhu and Yin (2000).

Can we have a "simplified" Hypothesis B method by using spread-sheet calculation? Answer is **yes!**

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3. A New Simplified Hypothesis B Method for One-layer and Multi-layers of Clayey Soils (a new de-coupled method)

(a) For one layer (Yin and Feng 2017):

$$S_{totalB} = S_{"primary"} + S_{creep} =$$

$$= \begin{cases} U_v S_f + \alpha S_{creep,f} & for\ 1\ day \le t \le t_{EOP,field} \\ U_v S_f + [\alpha S_{creep,f} + (1-\alpha) S_{creep,d}] & for\ t \ge t_{EOP,field} \end{cases}$$

$$= U_v S_f + [\alpha S_{creep,f} + (1-\alpha) S_{creep,d}] \quad for\ t \ge 1\ day\ (but\ t \ge t_{EOP,field}\ for\ S_{creep,d})$$

where $0 \le \alpha \le 1$

$\alpha = 1$: *Old Yin's Simplified Hypothesis B Method* (Yin 2011)

$\alpha = 0$: *Hypothesis A Method*

$\alpha = 0.8$: *New Simplified Hypothesis B Method for* 1D *case*

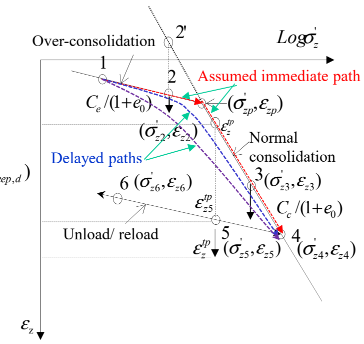
U_v *is average degree of consolidation*

S_f *is final settlement at end of "primary" consolidation*

(*see following slides how to calculate it*)

$S_{creep,f}$ *is the final creep settlement without excess porewater pressure* u_e *coupling* (*see following slides how to calculate it*)

$S_{creep,d}$ *is called "delayed creep settlemwent" similar to the "seondary" consolidaiton settlement starting at* $t_{EOP,field}$ (*Use* $U_v = 98\%$ *to find* $t_{EOP,field}$).



(Yin 2011: 14th "Huang Wen-Xi Lecture" in China for the old method)

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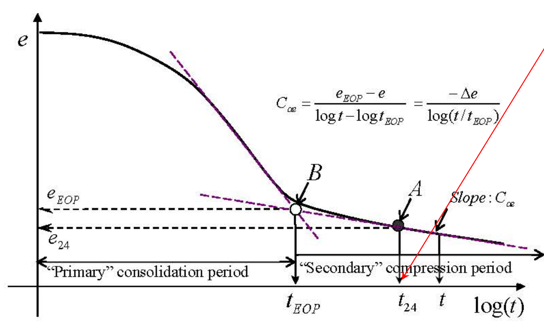
Table 1. Basic parameters used in the simple method

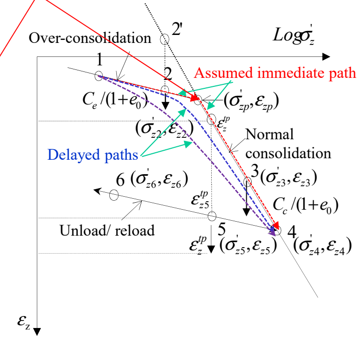
$C_e = C_r$	C_c	σ_{zp}'	$C_\alpha = C_{\alpha e}$	$t_o = 1$ day	e_0	k	$\alpha = 0.8$
(no unit)	(no unit)	(kPa)	(no unit)	(day)	(no unit)	(m/day)	

$$\varepsilon_{zp} = \varepsilon_{zi} + \frac{C_e}{1+e_o}\log\left(\frac{\sigma_{zp}'}{\sigma_{zi}'}\right); \quad m_v = \frac{\Delta\varepsilon_z}{\Delta\sigma_z'}; \quad c_v = \frac{k}{\gamma_w m_v}; \quad Use\ U_v = 98\%\ to\ find\ t_{EOP,field}$$

U can be obtained using existing charts and equations.

t_o=1 day since C_e, C_c, σ_{zp}' all from data with 1 day duration.





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How to calculate S_f:

$$S_{totalB} = \begin{cases} U_v S_f + \alpha S_{creep,f} & for\ 1\,day \le t \le t_{EOP,field} \\ U_v S_f + [\alpha S_{creep,f} + (1-\alpha) S_{creep,d}] & for\ t \ge t_{EOP,field} \end{cases}$$

Point 1 to Point 4:

$$S_f = \frac{C_e}{1+e_o} \log \frac{\sigma'_{zp}}{\sigma'_{z1}} H + \frac{C_c}{1+e_o} \log \frac{\sigma'_{z4}}{\sigma'_{zp}} H$$

Point 1 to Point 2:

$$S_f = \frac{C_e}{1+e_o} \log \frac{\sigma'_{z2}}{\sigma'_{z1}} H$$

Preconsolidation point $(\sigma'_{zp}, \varepsilon_{zp})$ *to Point 4:*

$$S_f = \frac{C_c}{1+e_o} \log \frac{\sigma'_{z4}}{\sigma'_{zp}} H$$

Point 4 to Point 6 (unloading):

$$S_f = \frac{C_e}{1+e_o} \log \frac{\sigma'_{z6}}{\sigma'_{z4}} H < 0$$

Point 6 to Point 5 (reloading): $S_f = \frac{C_e}{1+e_o} \log \frac{\sigma'_{z5}}{\sigma'_{z6}} H > 0$

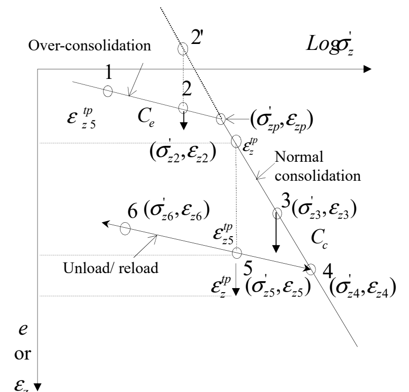

Figure 1. Relation and states of log(stress)-void ratio (or strain) from 1D straining

C_c and C_e can be determined from (a) compression with time 24 hours (t_{24}) of duration or (b) compression at the end of "primary" consolidation in lab ($t_{EOP,lab}$), which is about a few minutes.

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Creep of soils

$$S_{totalB} = \begin{cases} U_v S_f + \alpha S_{creep,f} & for\ 1\,day \le t \le t_{EOP,field} \\ U_v S_f + [\alpha S_{creep,f} + (1-\alpha) S_{creep,d}] & for\ t \ge t_{EOP,field} \end{cases}$$

How to calculate $S_{creep,f}$:

(a) Final point is at a normal consolidation (NC) state, for example Point 4 (see the right figure)

$$S_{creep,f} = \frac{C_{\alpha e}}{1+e_o} \log\left(\frac{t_o + t_e}{t_o}\right) H \qquad for\quad t_e \ge 0$$

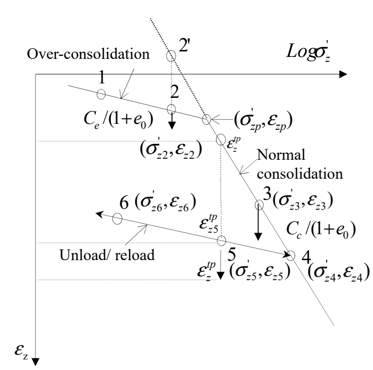
$$t_e = t - t_o$$

Note: $t_o = 1 day, if\ t = 1 day, t_e = 0$

The above equation is:

$$S_{creep,f} = \frac{C_{\alpha e}}{1+e_o} \log\left(\frac{t}{t_o}\right) H \qquad for\quad t \ge 1\,day$$

If $t = 1$day, $S_{creep,f} = 0$, back to Point 4.



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Creep of soils

$$S_{totalB} = \begin{cases} U_v S_f + \alpha S_{creep,f} & for\ 1\,day \le t \le t_{EOP,field} \\ U_v S_f + [\alpha S_{creep,f} + (1-\alpha) S_{creep,d}] & for\ t \ge t_{EOP,field}\end{cases}$$

How to calculate $S_{creep,f}$:

(b) Final point is at an over-consolidation state, for example Point 2 (see the right figure)

$$S_{creep,f} = \frac{C_{\alpha e}}{1+e_o}\log(\frac{t_o+t_e}{t_o+t_{e2}})H \quad for\ \ t_e \ge t_{e2}$$

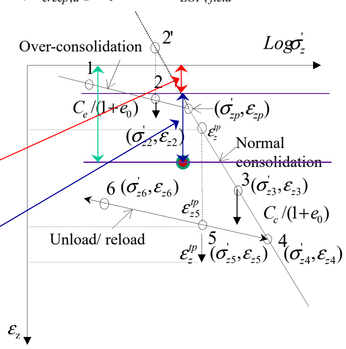
According to the "equivalent time" (Yin and Graham 1989, 1994):

$$\varepsilon_z = \varepsilon_{zp} + \frac{C_c}{V}\log\frac{\sigma'_z}{\sigma'_{zp}} + \frac{C_{\alpha e}}{V}\log\frac{t_o+t_e}{t_o}$$

From the above: $$\log\frac{t_o+t_e}{t_o} = (\varepsilon_z-\varepsilon_{zp})\frac{V}{C_{\alpha e}} - \frac{C_c}{C_{\alpha e}}\log\frac{\sigma'_z}{\sigma'_{zp}}$$

$$\therefore \frac{t_o+t_e}{t_o} = 10^{\left[(\varepsilon_z-\varepsilon_{zp})\frac{V}{C_{\alpha e}} + \log(\frac{\sigma'_z}{\sigma'_{zp}})^{-\frac{C_c}{C_{\alpha e}}}\right]} = 10^{\left[(\varepsilon_z-\varepsilon_{zp})\frac{V}{C_{\alpha e}}\right]}\times(\frac{\sigma'_z}{\sigma'_{zp}})^{-\frac{C_c}{C_{\alpha e}}}$$

$$\therefore t_e = t_o\times 10^{(\varepsilon_z-\varepsilon_{zp})\frac{V}{C_{\alpha e}}}(\frac{\sigma'_z}{\sigma'_{zp}})^{-\frac{C_c}{C_{\alpha e}}} - t_o$$



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Creep of soils

$$S_{totalB} = \begin{cases} U_v S_f + \alpha S_{creep,f} & for\ 1\,day \le t \le t_{EOP,field} \\ U_v S_f + [\alpha S_{creep,f} + (1-\alpha) S_{creep,d}] & for\ t \ge t_{EOP,field}\end{cases}$$

How to calculate $S_{creep,f}$:

(b) Final point is at an over-consolidation (OC) state, for example Point 2 (see the right figure)

$$t_{e2} = t_o\times 10^{\left[(\varepsilon_{z2}-\varepsilon_{zp})\frac{V}{C_{\alpha e}}\right]}(\frac{\sigma'_{z2}}{\sigma'_{zp}})^{-\frac{C_c}{C_{\alpha e}}} - t_o$$

t_e in (1b):

$$t_e = t_{e2} + t - t_o = t_o\times 10^{\left[(\varepsilon_{z2}-\varepsilon_{zp})\frac{V}{C_{\alpha e}}\right]}(\frac{\sigma'_{z2}}{\sigma'_{zp}})^{-\frac{C_c}{C_{\alpha e}}} + t - 2t_o$$

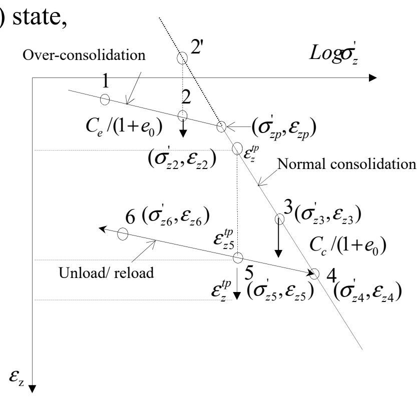
$$\because S_{creep,f} = \frac{C_{\alpha e}}{1+e_o}\log(\frac{t_o+t_e}{t_o+t_{e2}})H$$

$$S_{creep,f} = \frac{C_{\alpha e}}{1+e_o}\log(\frac{t+t_{e2}}{t_o+t_{e2}})H \quad for\ \ t \ge t_o = 1day$$

If no porewater pressure coupling:

$$S_{creep,f} = \frac{C_{\alpha e}}{1+e_o}\log(\frac{t+t_{e2}}{t_o+t_{e2}})H = 0 \quad (if\ t = 1\text{day})$$

This is why: $t_e = t_{e2} + t - t_o$



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Creep of soils

$$S_{totalB} = \begin{cases} U_v S_f + \alpha S_{creep,f} & for\ \ 1\,day \le t \le t_{EOP,field} \\ U_v S_f + [\alpha S_{creep,f} + (1-\alpha) S_{creep,d}] & for\ t \ge t_{EOP,field} \end{cases}$$

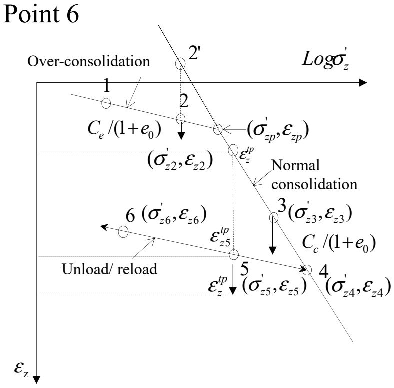
How to calculate $S_{creep,f}$:

(c) For any point in over-consolidation (OC) state, including un/reloading state, for example, Point 5 (unloaded from Point 4) and Point 6

$$S_{creep,f} = \frac{C_{\alpha e}}{1+e_o}\log\left(\frac{t_o + t_e}{t_o + t_{eOC}}\right)H \quad for \quad t_e \ge t_{eOC}$$

$$t_{eOC} = t_o \times 10^{\left[(\varepsilon_{zOC}-\varepsilon_{zp})\frac{V}{C_{\alpha e}}\right]} \left(\frac{\sigma'_{zOC}}{\sigma'_{zp}}\right)^{-\frac{C_c}{C_{\alpha e}}} - t_o$$

$$t_e = t_{eOC} + t - t_o = t_o \times 10^{\left[(\varepsilon_{zOC}-\varepsilon_{zp})\frac{V}{C_{\alpha e}}\right]} \left(\frac{\sigma'_{zOC}}{\sigma'_{zp}}\right)^{-\frac{C_c}{C_{\alpha e}}} + t - 2t_o$$



$$S_{creep,f} = \frac{C_{\alpha e}}{1+e_o}\log\left(\frac{t + t_{eOC}}{t_o + t_{eOC}}\right)H \quad for \quad t \ge t_o = 1day$$

$$t_{eOC} = t_{e5}, t_{e6}, or\ t_{e2} \qquad \varepsilon_{zOC} = \varepsilon_{z5}, \varepsilon_{z6}, or\ \varepsilon_{z2} \qquad \sigma'_{zOC} = \sigma'_{z5}, \sigma'_{z6}, or\ \sigma'_{z2}$$

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Creep of soils

$$S_{totalB} = \begin{cases} U_v S_f + \alpha S_{creep,f} & for\ \ 1\,day \le t \le t_{EOP,field} \\ U_v S_f + [\alpha S_{creep,f} + (1-\alpha) S_{creep,d}] & for\ t \ge t_{EOP,field} \end{cases}$$

How to calculate $S_{creep,d}$:

$S_{creep,d}$ is called "delayed creep settlemwent" similar to the "seondary" compression settlement starting at $t_{EOP,field}$ (Use U_v = 98% to find $t_{EOP,field}$).

$S_{creep,d}$ is called "delayed creep settlement". "Delayed" means that $S_{creep,d}$ will occur at time $t_{EOP,field}$ at U_v=98%. $S_{creep,d}$ is related to $S_{creep,f}$ in all above cases, but calculated as below (delayed by time of $t_{EOP,field}$).

How to calculate $S_{creep,d}$ for any point in normal consolidation (NC) state?

For NC state, e.g. from Point 1 to Point 4 : $S_{creep,f} = \frac{C_{\alpha e}}{1+e_o}\log\left(\frac{t_o + t_e}{t_o}\right)H \quad t_e \ge 0$

$$S_{creep,d} = \frac{C_{\alpha e}}{1+e_o}\log\left(\frac{t_o + t_e}{t_o + t_{e,EOP,field}}\right)H \quad for \quad t_e \ge t_{e,EOP,field} \qquad (1)$$

$\because t_e = t - t_o; \quad \therefore t_{e,EOP,field} = t_{EOP,field} - t_o$ (*t is the time from starting loading*)

Replace : $t_e = t - t_o$ *and* $t_{e,EOP,field} = t_{EOP,field} - t_o$ *into Eq(1)*

We have :

$$S_{creep,d} = \frac{C_{\alpha e}}{1+e_o}\log\left(\frac{t}{t_{EOP,field}}\right)H \quad for \quad t \ge t_{EOP,field} \qquad (2)$$

Eq(2) is the same as the secondary consolidation equation.

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Creep of soils

A new simplified Hypothesis B method for one layer

How to calculate $S_{creep,d}$ for any point in over-consolidation (OC) state?

$$For\ any\ OC\ state, e.g.\ Point\ 2, 5, or\ 6: S_{creep,f} = \frac{C_{\alpha e}}{1+e_o}\log(\frac{t+t_{eOC}}{t_o+t_{eOC}})H \quad for\ \ t \ge t_o$$

Since we include the creep settlement after time $t_{EOP,field}$, therefore, we have:

$$S_{creep,d} = \frac{C_{\alpha e}}{1+e_0}\log(\frac{t+t_{eOC}}{t_o+t_{eOC}})H - \frac{C_{\alpha e}}{1+e_0}\log(\frac{t_{EOP,field}+t_{eOC}}{t_o+t_{eOC}})H$$

$$S_{creep,d} = \frac{C_{\alpha e}}{1+e_0}\log(\frac{t+t_{eOC}}{t_{EOP,field}+t_{eOC}})H \quad for\ \ t \ge t_{EOP,field} \qquad (3)$$

$$t_{eOC} = t_{e5}, t_{e6}, or\ t_{e2}$$

$$\varepsilon_{zOC} = \varepsilon_{z5}, \varepsilon_{z6}, or\ \varepsilon_{z2}$$

$$\sigma'_{zOC} = \sigma'_{z5}, \sigma'_{z6}, or\ \sigma'_{z2}$$

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Equation of Hypothesis A Method (an old de-coupled method):

$$S_{totalA} = S_{"primary"} + S_{"secondary"} = \begin{cases} U_v S_f \quad + \quad 0 & for \quad 0 \le t \le t_{EOP,field} \\ U_v S_f + \frac{C_{\alpha e}}{1+e_o}\log(\frac{t}{t_{EOP,field}})H & for \quad t \ge t_{EOP,field} \end{cases}$$

$C_e = C_r$	C_c	σ'_{zp}	$C_\alpha = C_{\alpha e}$	e_0	c_v
(no unit)	(no unit)	(kPa)	(no unit)	(no unit)	(m^2/year)

Use U_v = 98% to find $t_{EOP,field}$

$C_\alpha \sim OCR$ or σ'_{zp}? or creep tests at different OCR

$OCR = \sigma'_{zp} / \sigma'_{zi}$

Equation of Simplified Hypothesis B Method (a new de-coupled method):

$$S_{totalB} = S_{"primary"} + S_{creep} = \begin{cases} U_v S_f + \alpha S_{creep,f} & for\ \ 1\ day \le t \le t_{EOP,field} \\ U_v S_f + [\alpha S_{creep,f} + (1-\alpha) S_{creep,d}] & for\ t \ge t_{EOP,field} \end{cases}$$

If $\alpha = 0$; back to Hypothesis A method

In normal consolidation (NC) state:

$$S_{creep,f} = \frac{C_{\alpha e}}{1+e_o}\log(\frac{t}{t_o})H \quad for\ \ t \ge 1\ day; \quad S_{creep,d} = \frac{C_{\alpha e}}{1+e_o}\log(\frac{t}{t_{EOP,field}})H \quad for\ \ t \ge t_{EOP,field}$$

In over-consolidation (OC) state: *If $OCR = 1;\ t_{eOC} = 0$*

$$S_{creep,f} = \frac{C_{\alpha e}}{1+e_o}\log(\frac{t+t_{eOC}}{t_o+t_{eOC}})H \quad for\ \ t \ge 1 day; \ S_{creep,d} = \frac{C_{\alpha e}}{1+e_0}\log(\frac{t+t_{eOC}}{t_{EOP,field}+t_{eOC}})H \quad for\ \ t \ge t_{EOP,field}$$

$$t_{eOC} = t_o \times 10^{\left[(\varepsilon_{zOC}-\varepsilon_{zp})\frac{V}{C_{\alpha e}}\right]}(\frac{\sigma'_{zOC}}{\sigma'_{zp}})^{-\frac{C_c}{C_{\alpha e}}} - t_o$$

One value of C_α from a NC state is used for all OCR cases ($OCR = \sigma'_{zp} / \sigma'_{zi}$)

$C_e = C_r$	C_c	σ'_{zp}	$C_\alpha = C_{\alpha e}$	t_o = 1 day	e_0	k	α = 0.8
(no unit)	(no unit)	(kPa)	(no unit)	(day)	(no unit)	(m/day)	

$$\varepsilon_{zp} = \varepsilon_{zi} + \frac{C_e}{1+e_o}\log(\frac{\sigma'_{zp}}{\sigma'_{zi}}); \quad m_v = \frac{\Delta\varepsilon_z}{\Delta\sigma'_z}; \quad c_v = \frac{k}{\gamma_w m_v}; \quad Use\ U_v = 98\%\ to\ find\ t_{EOP,field}$$

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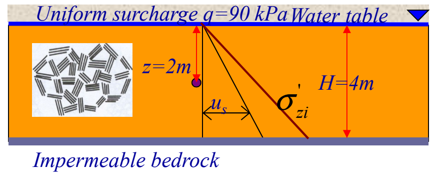
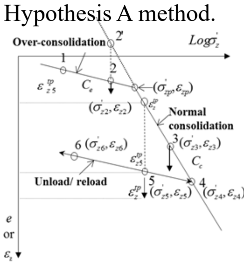
Example 1:



H of a clay layer is 4m with top free drainage and bottom impermeable in 1D straining. Other parameters are in the following table. The initial vertical stress is 30 kPa constant for this layer and the initial strain is zero.

Calculate final settlements at two different loading cases (see below) at loading duration of 5 years and 50 years using both the simplified Hypothesis B method and Hypothesis A method.

$C_e = C_r$ (no unit)	C_c (no unit)	σ'_{zp} (kPa)	$C_\alpha = C_{\alpha e}$ (no unit)	$t_o = 1$ day (day)	e_0 (no unit)	k (m/day)	α=0.8
0.07	0.8	60	0.018	1	1	5x10^{-5}	0.8



Solution:

$$\varepsilon_{zp} = \varepsilon_{zi} + \frac{C_e}{1+e_o}\log(\frac{\sigma'_{zp}}{\sigma'_{zi}}) = 0 + \frac{0.07}{1+1}\log(\frac{60}{30}) = 0.01054$$

Case 1 – The vertical stress is suddenly increased to 120 kPa (increased by 90 kPa)

$$Point\ 1\ to\ Point\ 4: \Delta\varepsilon_z = \frac{C_e}{1+e_o}log\frac{\sigma'_{zp}}{\sigma'_{z1}} + \frac{C_c}{1+e_o}log\frac{\sigma'_{z4}}{\sigma'_{zp}} = \frac{0.07}{1+1}log\frac{60}{30} + \frac{0.8}{1+1}log\frac{120}{30} = 0.1309$$

$$m_v = \frac{\Delta\varepsilon_z}{\Delta\sigma'_z} = \frac{0.1309}{120-30} = 1.455\times10^{-3}\ 1/kPa; \quad c_v = \frac{5\times10^{-5}}{9.81\times1.455\times10^{-3}} = 3.503\times10^{-4}\ m^2/day = 1.279\ m^2/year.$$

$$S_f = \Delta\varepsilon_z H = 0.1309\times4 = 0.524m$$

$$For\ U = 98\%; \quad T_v = -0.933\log(1-0.98) = 0.085 = 1.500$$

$$t_{EOP,field} = \frac{T_v d^2}{c_v} = \frac{1.500\times4^2}{1.279} = 18.77 \quad years$$

$$T_v = \frac{c_v t}{d^2}$$

$$for\ U_v < 0.6;\ T_v = \frac{\pi}{4}U_v^2;\ U_v = \sqrt{\frac{4T_v}{\pi}}$$

$$For\ U > 0.6; \quad T_v = -0.933\log(1-U_v);\ U_v = 1-10^{-\frac{T_v+0.085}{0.933}}$$

$t = 5\ years$

$$T_v = \frac{c_v t}{d^2} = \frac{1.279\times5}{4^2} = 0.400\ years;$$

$$U_v = 1-10^{-\frac{0.400+0.085}{0.933}} = 0.698$$

$In\ normal\ consolidation\ (NC)\ state:$

$$S_{creep,f} = \frac{C_{\alpha e}}{1+e_o}\log(\frac{t}{t_o})H = \frac{0.018}{1+1}\log(\frac{5\times365}{1})\times4 = 0.117m$$

$$S_{creep,d} = \frac{C_{\alpha e}}{1+e_o}\log(\frac{t}{t_{EOP,field}})H = 0$$

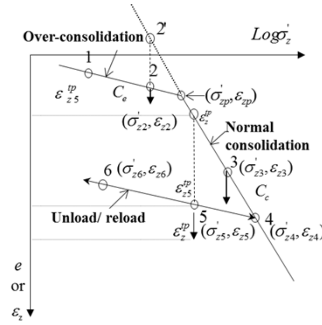
$t = 50\ years$

$$T_v = \frac{4.092\times50}{4^2} = 3.996\ years;$$

$$U_v = 1$$

$$= \frac{0.018}{1+1}\log(\frac{50\times365}{1})\times4 = 0.153m$$

$$= \frac{0.018}{1+1}\log(\frac{50}{18.77})\times4 = 0.0153m$$



$$B\ method: \quad S_{totalB} = \begin{cases} U_v S_f + \alpha S_{creep,f} & for\ 1\ day \le t \le t_{EOP,field} \\ U_v S_f + [\alpha S_{creep,f} + (1-\alpha)S_{creep,d}] & for\ t \ge t_{EOP,field} \end{cases}$$

$$= 0.698\times0.524 + 0.8\times0.117 = 0.459m$$

$$= 1\times0.524 + [0.8\times0.1534 + 0.2\times0.0153] = 0.650m$$

$$A\ method: \quad S_{totalA} = \begin{cases} U_v S_f + 0 & for\ 0 \le t \le t_{EOP,field} \\ U_v S_f + \frac{C_{\alpha e}}{1+e_o}\log(\frac{t}{t_{EOP,field}})H & for\ t \ge t_{EOP,field} \end{cases}$$

$$= U_v S_f = 0.698\times0.524 = 0.365m$$

$$= U_v S_f + \frac{C_{\alpha e}}{1+e_o}\log(\frac{t}{t_{EOP,field}})H = 1\times0.524 + \frac{0.018}{1+1}\log(\frac{50}{18.77})\times4 = 0.539m$$

Case 2 – The vertical stress is suddenly increased to 50 kPa (increased by 20 kPa only)

$$Point\ 1\ to\ Point\ 2: \Delta\varepsilon_z = \frac{C_e}{1+e_o} log \frac{\sigma'_{zp}}{\sigma'_{z1}} = \frac{0.07}{1+1} log \frac{50}{30} = 0.0078$$

$$m_v = \frac{\Delta\varepsilon_z}{\Delta\sigma'_z} = \frac{0.0078}{50-30} = 3.882\times10^{-4}\ 1/kPa;$$

$$c_v = \frac{5\times10^{-5}}{9.81\times3.882\times10^{-4}} = 1.313\times10^{-2} m^2/day = 115.0\ m^2/year$$

$$S_f = \Delta\varepsilon_z H = 0.0078\times4 = 0.031m$$

$$For\ U = 98\%;\quad T_v = -0.933\log(1-0.98) = 0.085 = 1.500$$

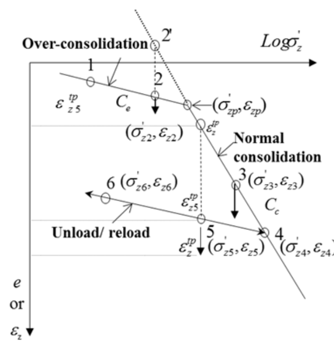
$$t_{EOP,field} = \frac{T_v d^2}{c_v} = \frac{1.500\times4^2}{115.0} = 0.209\quad years$$

$$\varepsilon_z = \varepsilon_{zi} + \Delta\varepsilon_z = 0 + 0.0078 = 0.0078$$

$$\sigma'_{zp} = 60kPa;\ \varepsilon_{zp} = 0.0105$$

$$t_{eOC} = t_o \times 10^{\left[(\varepsilon_{zOC}-\varepsilon_{zp})\frac{V}{C_{\alpha e}}\right]} \left(\frac{\sigma'_{zOC}}{\sigma'_{zp}}\right)^{-\frac{C_c}{C_{\alpha e}}} - t_o =$$

$$= 1\times10^{\left[(0.0078-0.0105)\frac{2}{0.018}\right]} \left(\frac{50}{60}\right)^{-\frac{0.8}{0.018}} - 1 = 1625.45 day = 4.45 years$$



$$C_\alpha = a * \exp(bOCR)$$

Table 3 The values of coefficient in exponential equation under different surcharge preloading

Preloading pressure (kpa)	a	b
400	0.0011	− 0.125
800	0.0014	− 0.071
1600	0.0007	− 0.028

Wang, et al. (2021). Secondary compression behavior of over-consolidated soft clay after surcharge preloading. Acta Geotechnica, https://doi.org/10.1007/s11440-021-01276-9

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$$T_v = \frac{c_v t}{d^2}$$

$$for\ U_v < 0.6;\ T_v = \frac{\pi}{4}U_v^2;\ U_v = \sqrt{\frac{4T_v}{\pi}}$$

$$For\ U > 0.6;\quad T_v = -0.933\log(1-U_v);\ U_v = 1-10^{-\frac{T_v+0.085}{0.933}}$$

t = 5 years

$$T_v = \frac{c_v t}{d^2} = \frac{115.0\times5}{4^2} = 35.939\ years;$$

$$U_v = 1-10^{-\frac{35.939+0.085}{0.933}} = 1$$

In normal consolidation (NC) state:

$$S_{creep,f} = \frac{C_{\alpha e}}{1+e_o}\log\left(\frac{t+t_{e2}}{t_o+t_{e2}}\right)H =$$

$$= \frac{0.018}{1+1}\log\left[\frac{(5+4.45)\times365}{1+4.45\times365}\right]\times4 = 0.0118m$$

$$S_{creep,d} = \frac{C_{\alpha e}}{1+e_o}\log\left(\frac{t+t_{e2}}{t_{EOP,field}+t_{e2}}\right)H = 0.0111$$

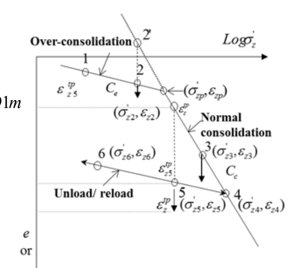
t = 50 years

$$T_v = \frac{115.0\times50}{4^2} = 359.39\ years;$$

$$U_v = 1$$

$$= \frac{0.018}{1+1}\log\left[\frac{(50+4.45)\times365}{1+4.45\times365}\right]\times4 = 0.0391m$$

$$= \frac{0.018}{1+1}\log\left(\frac{50}{0.209+4.45}\right)\times4 = 0.0384m$$



$$B\ method:\quad S_{totalB} = \begin{cases} U_v S_f + \alpha S_{creep,f} & for\ 1\ day \le t \le t_{EOP,field} \\ U_v S_f + [\alpha S_{creep,f} + (1-\alpha)S_{creep,d}] & for\ t \ge t_{EOP,field} \end{cases}$$

$$= 1\times0.031 + [0.8\times0.0118 + 0.2\times0.01105] = 0.0427m$$

$$= 1\times0.031 + [0.8\times0.0391 + 0.2\times0.0384] = 0.0701m$$

$$A\ method:\quad S_{totalA} = \begin{cases} U_v S_f + 0 & for\ 0 \le t \le t_{EOP,field} \\ U_v S_f + \frac{C_{\alpha e}}{1+e_o}\log\left(\frac{t}{t_{EOP,field}}\right)H & for\ t \ge t_{EOP,field} \end{cases}$$

$$= U_v S_f + \frac{C_{\alpha e}}{1+e_o}\log\left(\frac{t}{t_{EOP,field}}\right)H =$$

$$= 1\times0.031 + \frac{0.018}{1+1}\log\left(\frac{5}{0.2087}\right)\times4 = 0.0807m$$

$$= 1\times0.031 + \frac{0.018}{1+1}\log\left(\frac{50}{0.2087}\right)\times4 = 0.117m$$

Note:

- The C_α from NC state cannot be used for calculating "secondary" commission in OC state.
- C_α from OC state is needed.

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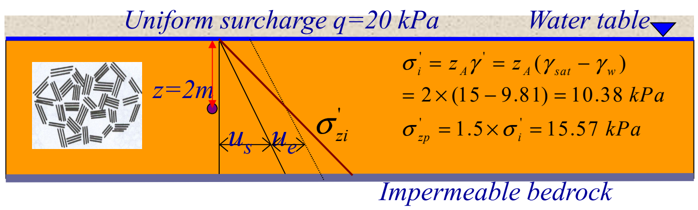
Example 2:

The thickness of one layer of Hong Kong Marine Clay in seabed under seawater table is 4m with bottom impermeable and top free drainage in 1D straining. The over-consolidation ratio (OCR) is 1 and 1.5 in two cases. A uniform pressure due to sand fill is applied suddenly to cause an increase of vertical stress 20 kPa. The saturated unit weight of the clay is 15 kN/m^3. Other parameters are given in the table below. Calculate the average strain, m_v, C_v and final settlement S_f by dividing the layer into 1, 2, 4, and 8 sub-layers and discuss the differences. Use both the simplified Hypothesis B method and Hypothesis A method to calculate the cures of S *vs* log(time) for 100 years.

$C_e = C_r = \kappa / \ln(10)$ (no unit)	$C_c = \lambda / \ln(10)$ (no unit)	σ'_{zp} (kPa)	$C_\alpha = C_{\alpha e} = \psi / \ln(10)$ (no unit)	t_o (day)	e_0 (no unit)	k (m/day)
0.0913	1.4624	$= OCR \times \sigma'_{zi}$	0.0639=6.39%	1	2.65	1.90×10^{-4}



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Example 2:

OCR=1

Layer=4m, sub-layer=4m, OCR=1

	Mid sub-layer depth	σ'_{zi} (kPa)	σ'_{zi} +20 kPa (kPa)	σ'_{zp} (kPa) (OCR=1)	ε_{zp}	ε_z after 20kPa	m_v (1/kPa)	$c_v=k/(m_v \times r_w)$ (m^2/day)
	2	10.38	30.38	10.38	0	0.187	0.0093	2.074E-03
					0	0.187		
					Total strain	**0.187**		
					Settlement:	0.747	(m)	

Layer=4m, sub-layer=2m, OCR=1

	Mid sub-layer depth	σ'_{zi} (kPa)	σ'_{zi} +20 kPa (kPa)	σ'_{zp} (kPa) (OCR=1)	ε_{zp}	ε_z after 20kPa	m_v (1/kPa)	$c_v=k/(m_v \times r_w)$ (m^2/day)
	1	5.19	25.19	5.19	0	0.275	0.0105	1.851E-03
	3	15.57	35.57	15.57	0	0.144		
					0	0.209		
					Total strain	**0.209**		
					Settlement:	0.837	(m)	

Layer=4m, sub-layer=1m, OCR=1

	Mid sub-layer depth	σ'_{zi} (kPa)	σ'_{zi} +20 kPa (kPa)	σ'_{zp} (kPa) (OCR=1)	ε_{zp}	ε_z after 20kPa	m_v (1/kPa)	$c_v=k/(m_v \times r_w)$ (m^2/day)
	0.5	2.60	22.60	2.60	0	0.377	0.0111	1.743E-03
	1.5	7.79	27.79	7.79	0	0.221		
	2.5	12.98	32.98	12.98	0	0.162		
	3.5	18.17	38.17	18.17	0	0.129		
					0	0.222		
					Total strain	**0.222**		
					Settlement:	0.889	(m)	

Layer=4m, sub-layer=0.5m, OCR=1

	Mid sub-layer depth	σ'_{zi} (kPa)	σ'_{zi} +20 kPa (kPa)	σ'_{zp} (kPa) (OCR=1)	ε_{zp}	ε_z after 20kPa	m_v (1/kPa)	$c_v=k/(m_v \times r_w)$ (m^2/day)
	0.25	1.30	21.30	1.30	0	0.487	0.0115	1.684E-03
	0.75	3.89	23.89	3.89	0	0.316		
	1.25	6.49	26.49	6.49	0	0.245		
	1.75	9.08	29.08	9.08	0	0.202		
	2.25	11.68	31.68	11.68	0	0.174		
	2.75	14.27	34.27	14.27	0	0.152		
	3.25	16.87	36.87	16.87	0	0.136		
	3.5	18.165	38.165	18.165	0	0.129		
					0	0.230		
					Total strain	**0.230**		
					Settlement:	0.921	(m)	

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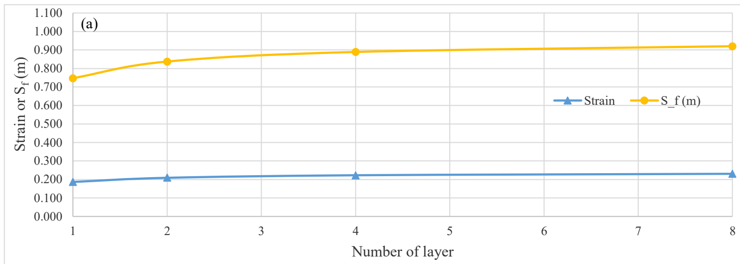
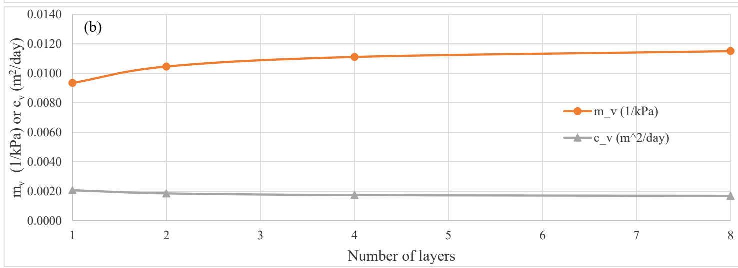
Example 2:

OCR=1

Number layers	Strain	m_v (1/kPa)	c_v (m^2/day)	S_f Settlement (m)
1	0.187	0.0093	2.074E-03	0.747
2	0.209	0.0105	1.851E-03	0.837
4	0.222	0.0111	1.743E-03	0.889
8	0.230	0.0115	1.684E-03	0.921





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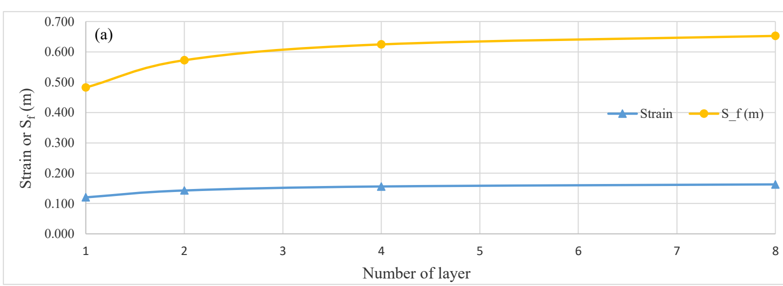
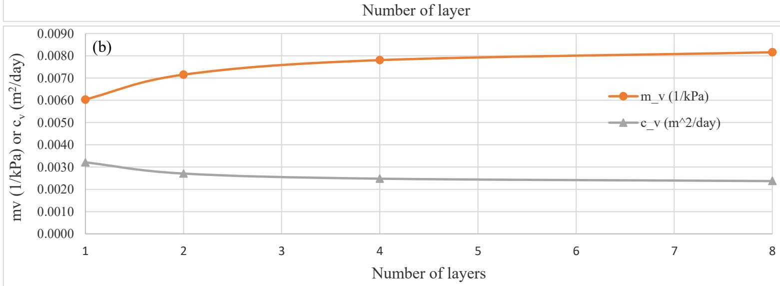
Example 2:

OCR=1.5

Number layers	Strain	m_v (1/kPa)	c_v (m^2/day)	S_f Settlement (m)
1	0.121	0.0060	3.210E-03	0.483
2	0.143	0.0072	2.707E-03	0.573
4	0.156	0.0078	2.481E-03	0.625
8	0.163	0.0082	2.374E-03	0.653





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Example 2: OCR=1

	Layer=4m, sub-layer=0.5m, OCR=1										
								β=	0	0.3	1
	Time (yea)	Time (day)	$T_v=c_v t/d^2$ (1 way drain)	U_v	$U_v{*}S_f$ (m)	$S_{creep,f}$ (m)	S_creep,d (m)	A Method: $S_{totalA}=U_v{*}S_f$ + $S_{secondary}$	B Method 1: $S_{totalB}=$ $U_v{*}S_f+S_{creep}$	B Method 2: $S_{totalB}=$ $U_v{*}S_f+S_{creep}$	B Method 3: $S_{totalB}=$ $U_v{*}S_f+S_{creep}$
		1	0.000	0.012	0.011	0.000	0.000	0.011	0.011	0.011	0.011
		2	0.000	0.016	0.015	0.000	0.000	0.015	0.015	0.015	0.015
		3	0.000	0.020	0.018	0.033	0.000	0.018	0.045	0.027	0.019
		4	0.000	0.023	0.021	0.042	0.000	0.021	0.055	0.032	0.022
		8	0.001	0.033	0.030	0.063	0.000	0.030	0.081	0.048	0.032
		16	0.002	0.046	0.043	0.084	0.000	0.043	0.110	0.069	0.046
		32	0.003	0.065	0.060	0.105	0.000	0.060	0.145	0.097	0.066
		64	0.007	0.093	0.085	0.126	0.000	0.085	0.186	0.135	0.095
		128	0.013	0.131	0.121	0.148	0.000	0.121	0.239	0.185	0.136
		256	0.027	0.185	0.171	0.169	0.000	0.171	0.305	0.252	0.195
		512	0.054	0.262	0.241	0.190	0.000	0.241	0.393	0.343	0.281
		1024	0.108	0.370	0.341	0.211	0.000	0.341	0.510	0.466	0.403
		1000	0.105	0.366	0.337	0.210	0.000	0.337	0.505	0.461	0.398
		2000	0.210	0.518	0.477	0.231	0.000	0.477	0.661	0.628	0.572
		4000	0.421	0.713	0.656	0.252	0.000	0.656	0.858	0.839	0.800
		7000	0.737	0.868	0.799	0.269	0.000	0.799	1.015	1.006	0.986
		11300	1.189	0.957	0.881	0.284	0.000	0.881	1.108	1.105	1.098
$t_{EOP,field}$=	38.597	14088	1.483	0.979	0.901	0.290	0.000	0.901	1.134	1.132	1.129
	45	16425	1.729	0.989	0.910	0.295	0.005	0.915	1.147	1.146	1.144
	50	18250	1.921	0.993	0.914	0.298	0.008	0.922	1.154	1.154	1.153
	80	29200	3.073	1.000	0.920	0.313	0.022	0.942	1.175	1.175	1.175
	100	36500	3.841	1.000	0.921	0.319	0.029	0.949	1.182	1.182	1.182

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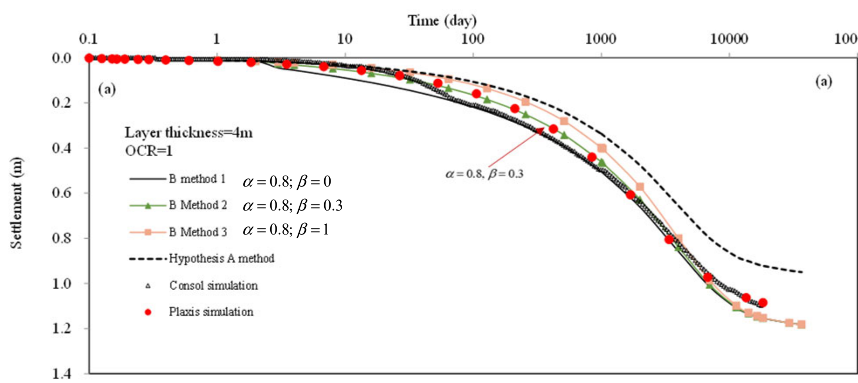
Example 2: OCR=1

Verification 1: Compared to "rigorous" Plaxis and Consol Simulations:



$$S_{totalB}=\begin{cases} U_v S_f+\alpha S_{creep,f} & for\ \ 1\,day \le t \le t_{EOP,field} \\ U_v S_f+[\alpha U_v^{\beta} S_{creep,f}+(1-\alpha U_v^{\beta})S_{creep,d}] & for\ \ t \ge t_{EOP,field} \end{cases}$$

- The results from the new simplified Hypothesis B method are closer to curves from Plaxis and Consol.
- Hypothesis A method underestimates the settlement a lot.

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Example 2: OCR=1.5

	Layer=4m, sub-layer=0.5m, OCR=1.5										
								β=	0	0.3	1
	Time (yea)	Time (day)	$T_v=c_v t/d^2$ (1 way drain)	U_v	U_v*S_f (m)	$S_{creep,f}$ (m)	S_creep,d (m)	A Method: $S_{totalA}=U_v$*S_f + $S_{secondary}$	B Method 1: $S_{totalB}=U_v$*S_f+S_{creep}	B Method 2: $S_{totalB}=U_v$*S_f+S_{creep}	B Method 3: $S_{totalB}=U_v$*S_f+S_{creep}
		1	0.0001	0.0137	0.0090	0.0000	0.0000	0.0090	0.0090	0.0090	0.0090
		2	0.0003	0.0194	0.0127	0.0211	0.0000	0.0127	0.0295	0.0179	0.0130
		3	0.0004	0.0238	0.0155	0.0334	0.0000	0.0155	0.0423	0.0242	0.0162
		4	0.0006	0.0275	0.0179	0.0421	0.0000	0.0179	0.0517	0.0294	0.0189
		8	0.0012	0.0389	0.0254	0.0632	0.0000	0.0254	0.0760	0.0445	0.0273
		16	0.0024	0.0550	0.0359	0.0843	0.0000	0.0359	0.1033	0.0641	0.0396
		32	0.0047	0.0778	0.0508	0.1054	0.0000	0.0508	0.1351	0.0899	0.0573
		64	0.0095	0.1100	0.0718	0.1264	0.0000	0.0718	0.1729	0.1240	0.0829
		128	0.0190	0.1555	0.1015	0.1475	0.0000	0.1015	0.2195	0.1690	0.1199
		256	0.0380	0.2199	0.1436	0.1686	0.0000	0.1436	0.2784	0.2292	0.1732
		512	0.0760	0.3110	0.2031	0.1896	0.0000	0.2031	0.3548	0.3099	0.2503
		1024	0.1519	0.4398	0.2872	0.2107	0.0000	0.2872	0.4558	0.4189	0.3613
		800	0.1187	0.3888	0.2538	0.2032		0.2538	0.4164	0.3763	0.3170
		2048	0.3039	0.6170	0.4029	0.2318	0.0000	0.4029	0.5883	0.5633	0.5173
		2500	0.3710	0.6754	0.4410	0.2379	0.0000	0.4410	0.6313	0.6101	0.5695
		5000	0.7419	0.8701	0.5681	0.2589	0.0000	0.5681	0.7752	0.7667	0.7483
$t_{EOP,field}$=	27.699	10110	1.5001	0.9800	0.6399	0.2803	0.0000	0.6399	0.8641	0.8628	0.8596
		14000	2.0774	0.9952	0.6498	0.2902	0.0099	0.6597	0.8839	0.8836	0.8828
	50	18250	2.7080	0.9990	0.6522	0.2983	0.0180	0.6702	0.8945	0.8944	0.8942
	80	29200	4.3328	1.0000	0.6529	0.3126	0.0322	0.6851	0.9094	0.9094	0.9094
	100	36500	5.4160	1.0000	0.6529	0.3194	0.0390	0.6919	0.9162	0.9162	0.9162

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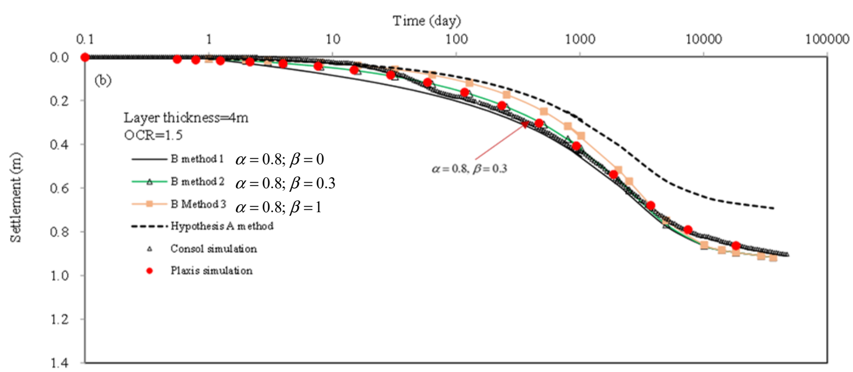
Example 2: OCR=1.5

Verification 1: Compared to "rigorous" Plaxis and Consol Simulations:



$$S_{totalB}=\begin{cases} U_v S_f+\alpha S_{creep,f} & for\ \ 1\,day\le t\le t_{EOP,field} \\ U_v S_f+[\alpha U_v^{\beta} S_{creep,f}+(1-\alpha U_v^{\beta})S_{creep,d}\,] & for\ \ t\ge t_{EOP,field} \end{cases}$$

- The results from the new simplified Hypothesis B method are closer to curves from Plaxis and Consol
- Hypothesis A method underestimates the settlement a lot.

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(b) For multiple (two) layers (Feng and Yin 2017):

$$S_{totalB} = \sum_{i=1}^{n} S_{"primary"i} + \sum_{i=1}^{n} S_{creepi} = \begin{cases} U\sum_{i=1}^{n} S_{fi} + \sum_{i=1}^{n} \alpha S_{creep,fi} & \text{for } 1day \le t \le t_{EOP,field} \\ U\sum_{i=1}^{n} S_{fi} + \sum_{i=1}^{n} [\alpha S_{creep,fi} + (1-\alpha) S_{creep,di}] & \text{for } t \ge t_{EOP,field} \end{cases}$$

$$= U\sum_{i=1}^{n} S_{fi} + \sum_{i=1}^{n} [\alpha S_{creep,fi} + (1-\alpha) S_{creep,di}] \quad \text{for } t \ge 1day \ (\text{but } t \ge t_{EOP,field} \text{ for } S_{creep,di})$$

$\sum_{i=1}^{n} S_{"primary"i}$: the "primary consolidation settlements of n soil layers,

U : the average degree of consolidation of n soil layers,

$\sum_{i=1}^{n} S_{fi}$: the total final settlements of n soil layers,

$\sum_{i=1}^{n} S_{creepi}$: the total creep settlements of n soil layers,

$\sum_{i=1}^{n} S_{creep,fi}$: the total *final* creep settlements of n soil layers,

$\sum_{i=1}^{n} S_{creep,di}$: the total "delayed creep" settlements of n soil layers.

Yin, JH and Feng. WQ (2017). A New Simplified Method and Its Verification for Calculation of Consolidation Settlement of a Clayey Soil with Creep. Canadian Geotechnical Journal, Can. Geotech. J. 54 (3), 333–347.
Feng, WQ and JH Yin (2017). A New Simplified Hypothesis B Method for Calculating Consolidation Settlements of Double Soil Layers Exhibiting Creep. International J for Numerical and Analytical Methods in Geomechanics, 41, 899–917.

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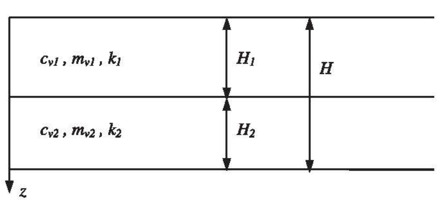
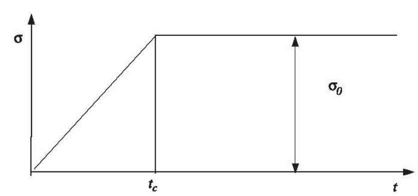
U_v (or U_a) for two layers and multiple layers

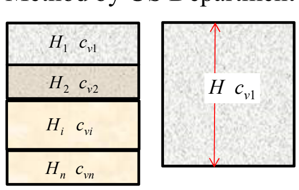
(i) Zhu and Yin (1999, 2005) solution (equations and charts) for two layers:

$$U(T,T_c) = \begin{cases} \frac{T_c}{T} - \sum_{n=1}^{\infty} \frac{c_n}{\lambda_n^4 T_c}[1-\exp(-\lambda_n^2 T)] & T \le T_c \\ 1 - \sum_{n=1}^{\infty} \frac{c_n}{\lambda_n^4 T_c}[1-\exp(-\lambda_n^2 T_c)] \times \exp[-\lambda_n^2 (T - T_c)] & T > T_c \end{cases}$$





(ii) Method by US Department of the Navy (1982) for multiple layers:



$$H_2^{'} = H_2\sqrt{c_{v1}/c_{v2}}, \ldots H_i^{'} = H_i\sqrt{c_{v1}/c_{vi}}, \ldots H_n^{'} = H_n\sqrt{c_{v1}/c_{vn}}$$

$$H = H_1 + \sum_{2}^{n} H_i^{'}, T_v = c_{v1}t/H^2 \ (\text{if one way drainge})$$

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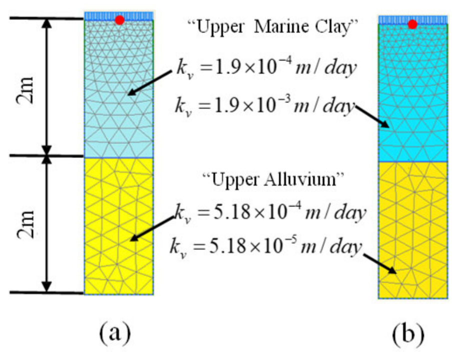
Verification 2: Compared to fully coupled modelling results

An "Upper Marine Clay" of 2m is overlaying an "Upper Alluvium" layer of 2m (total thickness 4m). OCR is assumed to be 1.5. A uniform pressure due to sand fill is applied suddenly to cause an increase of vertical stress 20 kPa. Other parameters can be found in Feng and Yin (2017)

Calculate curves of settlement *vs* log(time) using Hypothesis A method, the new simplified Hypothesis B method, and Plaxis for Case I (2m+2m) and Case I (2m+2m) (impermeable bottom).



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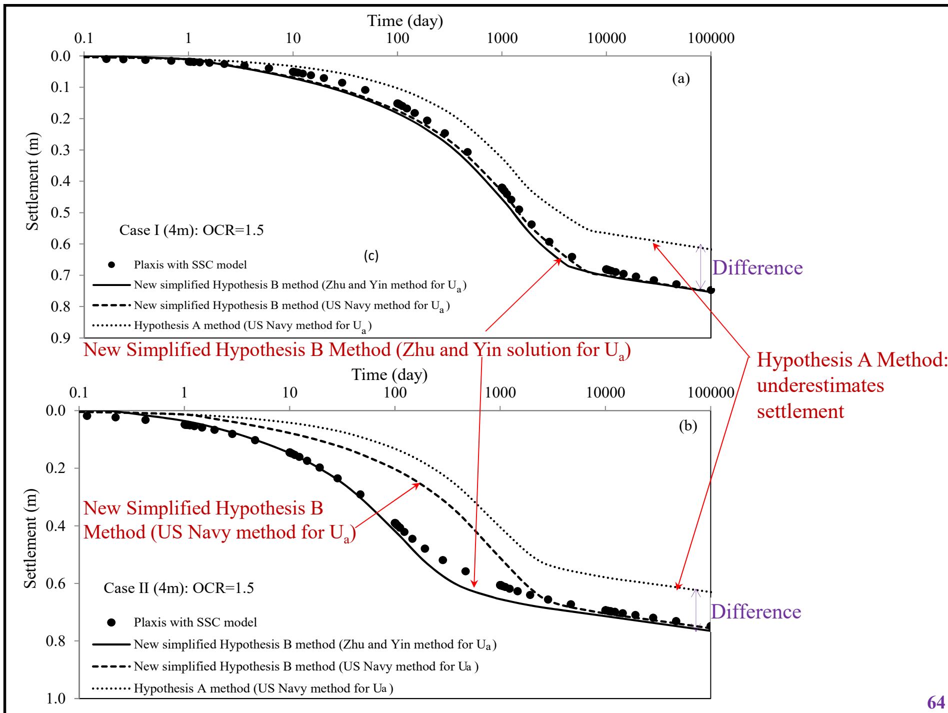

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$$S_{totalB}=\begin{cases}U_vS_f+\alpha S_{creep,f} & for\ 1\,day\le t\le t_{EOP,field}\\ U_vS_f+[\alpha U_v^{\beta}S_{creep,f}+(1-\alpha U_v^{\beta})S_{creep,d}] & for\ t\ge t_{EOP,field}\end{cases}$$

(a) Solution (equations and charts) for one layer:

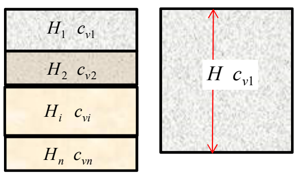
$$T_v=\frac{c_vt}{d^2}:\quad for\ U_v<0.6;\ T_v=\frac{\pi}{4}U_v^2;\ U_v=\sqrt{\frac{4T_v}{\pi}}$$

$$For\ U>0.6;\quad T_v=-0.933\log(1-U_v);\ U_v=1-10^{-\frac{T_v+0.085}{0.933}}$$

(b) Zhu and Yin (1999, 2005) solution (equations and charts) for two layers:

$$U=U_a(T,T_c)=\begin{cases}\frac{T_c}{T}-\sum_{n=1}^{\infty}\frac{c_n}{\lambda_n^4T_c}[1-\exp(-\lambda_n^2T)] & T\le T_c\\ 1-\sum_{n=1}^{\infty}\frac{c_n}{\lambda_n^4T_c}[1-\exp(-\lambda_n^2T_c)]\times\exp[-\lambda_n^2(T-T_c)] & T>T_c\end{cases}$$

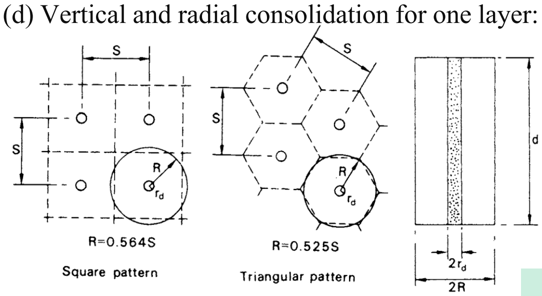
(c) Method by US Department of the Navy (1982) for multiple layers:



$$H_2^{'}=H_2\sqrt{c_{v1}/c_{v2}},\dots H_i^{'}=H_i\sqrt{c_{v1}/c_{vi}},\dots H_n^{'}=H_n\sqrt{c_{v1}/c_{vn}}$$

$$H=H_1+\sum_{2}^{n}H_i^{'},\ T_v=c_{v1}t/H^2\ (if\ one\ way\ drainge)$$

(d) Vertical and radial consolidation for one layer:



$$\frac{\partial u_e}{\partial t}=c_h\left(\frac{\partial^2u_e}{\partial r^2}+\frac{1}{r}\frac{\partial^2u_e}{\partial r^2}\right)+c_v\frac{\partial^2u_e}{\partial z^2}$$

$$U_v=f(T_v);\quad T_v=\frac{c_vt}{d^2};$$

$$U_r=f(T_r);\quad T_r=\frac{c_ht}{4R^2}$$

$$U=1-(1-U_v)(1-U_r)$$

(e) Consolidation of multiple layers with/without vertical drains:

Solution by Walker and Indraratna (2009) and Walker *et al.* (2009) using a spectral method.

$$\frac{m_v}{\overline{m}_v}\frac{\partial\bar{u}}{\partial t}=-\left[dT_r\frac{\eta}{\overline{\eta}}\bar{u}-dT_v\left(\frac{\partial}{\partial Z}\left(\frac{k_v}{\overline{k}_v}\right)\frac{\partial\bar{u}}{\partial Z}+\frac{k_v}{\overline{k}_v}\frac{\partial^2\bar{u}}{\partial Z^2}\right)\right]+\frac{m_v}{\overline{m}_v}\frac{\partial\bar{\sigma}}{\partial t}+dT_r\frac{\eta}{\overline{\eta}}w$$

Walker R and Indraratna B (2009). Consolidation analysis of a stratified soil with vertical and horizontal drainage using the spectral method. *Géotechnique* 2009a;59: pp. 439–449. https://doi.org/10.1680/geot.2007.00019.

Walker R, Indraratna B, Sivakugan N (2009). Vertical and Radial Consolidation Analysis of Multilayered Soil Using the Spectral Method. *J Geotech Geoenvironmental Eng* 2009b;135: pp. 657–663. https://doi.org/10.1061/(asce)gt.1943-5606.0000075.

An Excel file for the above solution is available.

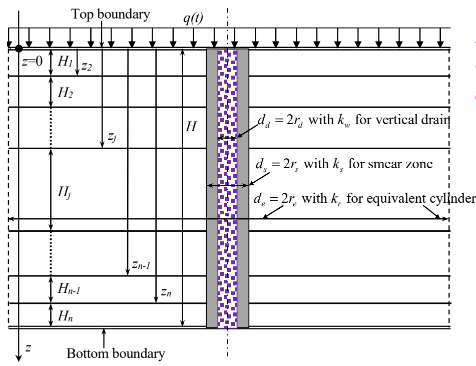
5. A General Simple Method and Verification

(a) Equation:

$$S_{totalB} = S_{primary} + S_{creep} = \sum_{j=1}^{j=n} U_j S_{fj} + \sum_{j=1}^{j=n} S_{creepj} = \begin{cases} \sum_{j=1}^{j=n} U_j S_{fj} + \sum_{j=1}^{j=n} \alpha U_j^{\beta} S_{creep,fj} & for\ 1day \le t \le t_{EOP,field} \\ \sum_{j=1}^{j=n} U_j S_{fj} + \sum_{j=1}^{j=n} [\alpha U_j^{\beta} S_{creep,fj} + (1-\alpha U_j^{\beta}) S_{creep,dj}] & for\ t \ge t_{EOP,field} \end{cases}$$

$$= \sum_{j=1}^{j=n} U_j S_{fj} + \sum_{j=1}^{j=n} [\alpha U_j^{\beta} S_{creep,fj} + (1-\alpha U_j^{\beta}) S_{creep,dj}] \quad for \quad t \ge 1day\ (but\ t \ge t_{EOP,field}\ for\ S_{creep,dj})$$

(b) This method is a new "de-coupled" method for (i) layered soils exhibiting creep, (ii) zero or small initial effective stress considered, (iii) without or with vertical drains, (iv) under any staged loading including un/re-loading, and (v) spread-sheet calculation with good accuracy.



A soil profile of *n*-layers with vertical drain subjected to uniform surcharge *q(t)* with time

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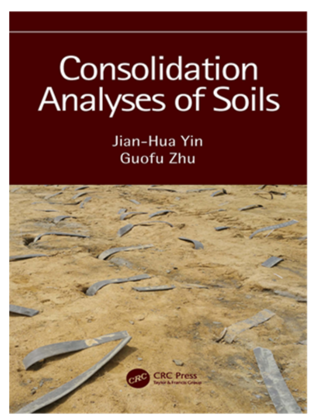
5. A General Simple Method and Verification

More details on this general simple method, see:

(i) A new book by Yin and Zhu

https://www.routledge.com/Consolidation-Analyses-of-Soils/Yin-Zhu/p/book/9780367555320



(ii) Yin, JH, Chen, ZJ, and Feng, WQ (2022).
A General Simple Method for Calculating Consolidation Settlements of Layered Clayey Soils with Vertical Drains under Staged Loadings. **Acta Geotechnica.**

This method is a **new "de-coupled" (新的解耦)** method for
(i) layered soils exhibiting creep/多層流變粘性土,
(ii) zero or small initial effective stress considered/ 考慮初始有效應力為零或小,
(iii) without or with vertical drains/ 有(無)排水板,
(iv) under any staged loading including un/re-loading / 任何多級加載, 包卸載再加載,
(v) spread-sheet calculation with good accuracy /電子表格(Excel)计算, 高精度。

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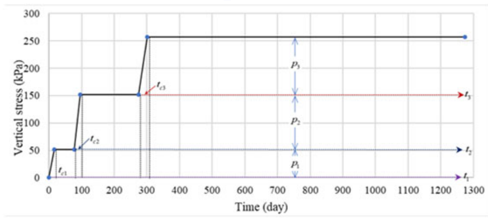
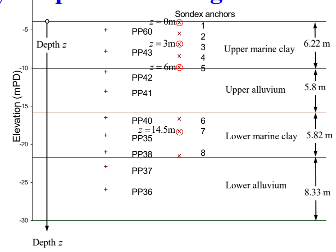
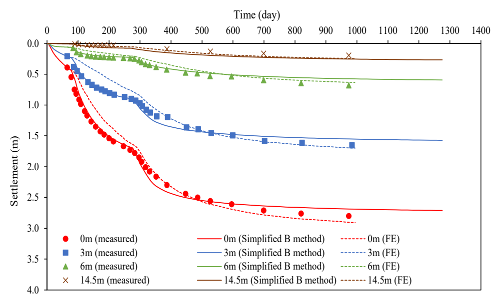
Verification 3: Compared to field data and fully coupled modelling results



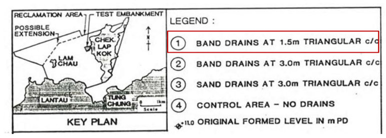
Staged ramp-loading

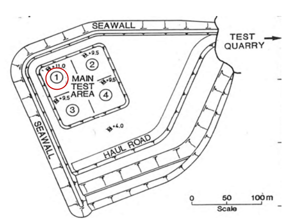


Soil profile and settlement monitoring points: only top two layers are considered



Comparison of settlements at depths of z=0m, 3m, 6m, and 14.5m from the general simple method, finite element modelling (Plaxis), and measurement





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6. Conclusions and Remarks

(a) Hypothesis A method (an old de-coupled method) is wrong and underestimates consolidation settlements of clayey soils.

(b) Hypothesis B method (a fully coupled method) is correct, but difficult to use (numerical methods, constitutive models, and right software needed).

(c) The new simplified Hypothesis B method (a new de-coupled method) is easy to use (spread-sheet calculation) and has good accuracy (relative error 0.2% ~ 6%).

(d) The new general simple method has been verified for different cases without/with vertical drains in layered soils under any staged loading including unloading and reloading.

(e) The settlements from the general simple method are in good agreement with those from fully coupled method and field measurement.

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DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING
土木及環境工程學系

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Attachments

(1) 4 papers by Prof Yin and co-authors:

[1] Yin, JH and Feng. WQ (2017). A New Simplified Method and Its Verification for Calculation of Consolidation Settlement of a Clayey Soil with Creep. Canadian Geotechnical Journal, Can. Geotech. J. 54 (3), 333–347.

[2] Feng, WQ and JH Yin (2017). A New Simplified Hypothesis B Method for Calculating Consolidation Settlements of Double Soil Layers Exhibiting Creep. International J for Numerical and Analytical Methods in Geomechanics, 41, 899–917.

[3] Yin, JH, Chen, ZJ, and Feng, WQ (2022). A General Simple Method for Calculating Consolidation Settlements of Layered Clayey Soils with Vertical Drains under Staged Loadings. Acta Geotechnica.

[4] Yin, J H. and Graham, J. (1996). Elastic visco-plastic modelling of one-dimensional consolidation. Geotechnique, 1996, 46(3): 515 - 527.

(2) 2 papers and 1 ppt from Degago and Nash:

[1] Degago, S. A. et al. (2011). Use and misuse of the isotache concept with respect to creep hypotheses A and B. Geotechnique 61, No. 10, 897–908 [http://dx.doi.org/ 10.1680/geot.9.P.112]

[2] Degago SA (2014). Primary Consolidation and Creep of Clays. A ppt from Norwegian Public Roads Administrations (SVV).

[3] Nash, D.F.T., and Ryde, S.J. 2001. Modelling consolidation accelerated by vertical drains in soils subject to creep. Geotechnique, 51(3): 257–273. doi:10.1680/geot.2001.51.3.257.

(3) One Excel file for Examples 1 and 2.

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