RILS 土地及空間研究院 Research Institute for Land and Space

Research Institute for Land and Space (RILS) Public Lecture

3pm to 4pm on 19 Oct 2022, *via* Zoom, PolyU, Hong Kong, China

A Sustainable Approach for Marine Reclamations in Coastal Cities

by

Jian-Hua YIN/殷建華

(Chair Professor of Soil Mechanics)

(Email: cejhyin@polyu.edu.hk)

Research Institute for Land and Space (土地及空間研究院)

Department of Civil and Environmental Engineering (CEE)

The Hong Kong Polytechnic University (PolyU), Hong Kong, China

香港理工大學 土木及環境工程系

THE HONG KONG POLYTECHNIC UNIVERSITY 香港理工大學

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

Contents

1. Background and Motivation

1.1 Burning Social Issue in Hong Kong

- Short-supply of land for affordable housing is a burning social issue in Hong Kong.

1.2 Short-supply of Land and Marine Reclamations

- There is a severe problem of short-supply of land in Hong Kong for further development to meet long-term community needs.
- Marine reclamations provide the most feasible solution for a stable supply of land in Hong Kong for mid-term and long-term developments.
- Short-supply of land is also a problem in the Greater Bay Area, such as Macau and Shen Zhen, and other costal cities.

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"Lantau Tomorrow" reclamation in Hong Kong proposed in "The Chief Executive's 2018 Policy Address":

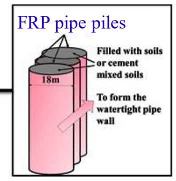
"Lantau Tomorrow": 1700 hectares of land for 700,000 to 1,100,000 people

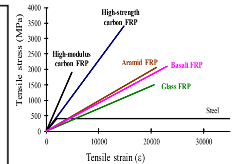
Macau Reclamation Plan (350 hectares):

Shen Zhen Qianhai Reclamation Plan (2800 hectares):

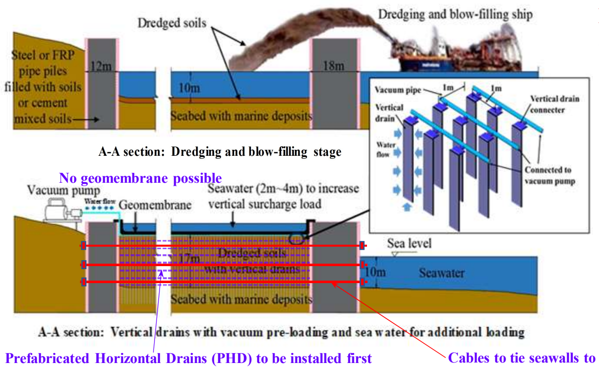
2. A New Approach for Marine Reclamations Using Dredged Marine Soils Improved by a Combined Improvement Method

Sketch of proposed "Lantau Tomorrow" reclamation project (1700 hectares)





Fibre Reinforced Polymer (FRP)



New approach for marine reclamations ("Lantau Tomorrow"):

- Using local **free** **marine deposits and wastes**
- Speeding up consolidation of soils using **Prefabricated Horizontal Drains (PHDs)** and Vertical Drains (VDs) with vacuum preloading
- Using Fibre Reinforced Polymer (FRP) pipe piles to build seawalls with cable ties.

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Figure 1: Tian Kun dredging and blow-filling ship

Example: **1700 hectares (17 km^2), average water depth of 15m, reclaimed to +6 mPD (2m settlement compensation)**

Sand volume =17×10^6 (m^2)×(15+6+2)(m)=3.91×10^8 (m^3)

Super-fast: **Local marine deposits will be dredged to blow-fill (*i.e.* pump and fill) a reclamation area**

Use 20 barges with load capacity of 4000 tons for imported sand:

Time required (24 hrs/day) is: 133.9 years

Use 20 dredge ships at a blow-filling speed of 4000 m^3/hour (assume only 40% of the mud is solid) using local HKMD:

Time required (24 hrs/day) is: 1.39 year

Large-area: **Reclaiming tens of square kilometers of land is easy**

Economical: **Local marine deposits are free**

Cost of imported sand: 3.91×10^8 (m^3)×155 ($/m^3) =$6.06×10^{10}=HK$60.6 billion dollars

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"Tian-Kun" dredging and blow-filling ship (17000 tons of displacement): dredging depth up to 35m; blow-filling speed at 6000 m^3/hour at a distance of 15 km away.

"天鯤號" (排水量17000噸): 船長140米，寬27.8米，最大挖掘深度可達35米，能以每小時6000立方米的速度將海泥/沙以及海水混合物輸送到最遠15公里地方。

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A Combined Method for Improving Dredged HKMD Slurry and Existing HKMD

Key new ideas/points:

- **Seawalls (FRP/steel/concrete pipe pile, or steel sheet piles) to be built to surround a reclamation area,**
- **FRP/steel cables to tie the opposite seawalls to prevent seawall sliding,**
- **Prefabricated horizontal drains (PHDs) to be used to consolidate dredged HKMD slurry with/without vacuum without impermeable membrane (membraneless),**
- **Later, prefabricated vertical drains (PVDs) to be installed to consolidate *dredged HKMD* and existing HKMD under fill surcharge.**

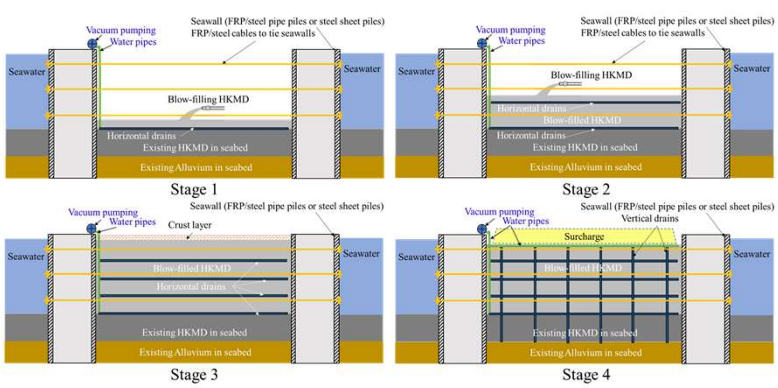

Figure 2: Illustration of a combined ground improvement method for HKMD slurry in stages

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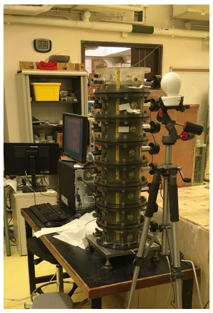
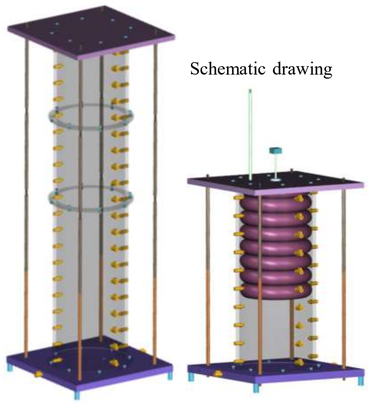
3. Two Types of Ongoing Physical Model Tests

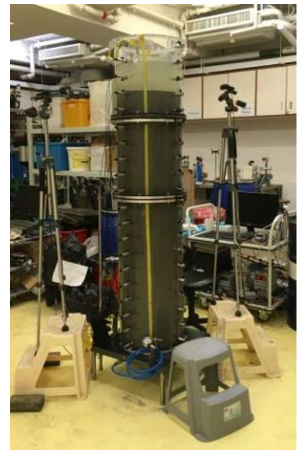
3.1 Cylindrical physical models and tests

Settling and self-weight & accelerated consolidation model
沉積固結聯合試驗儀 (patent under application)



Smaller 2D cylinder model:
0.8m×0.17m
(height × internal diameter)





Lager 2D cylinder model:
2m×0.4m
(height × internal diameter)
(can be up to 3m)

- **Sedimentation**
- **Self-weight consolidation**
- **Accelerated consolidation by horizonal + vertical drains with vacuum + surcharge**

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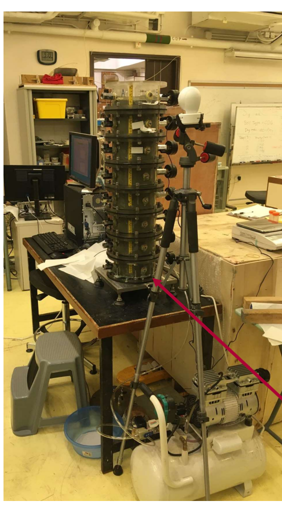
3.2 Cylindrical physical models and tests

2D cylindrical test on HKMD slurry with prefabricated horizontal drain (PHD) at bottom (Test 2) (using smaller model)



Connected to vacuum pump

With porous stone and geotextile as prefabricated horizontal drain (PHD) at the bottom

- **Initial soil height: 0.80m.**
- **Initial water content: 215%.**

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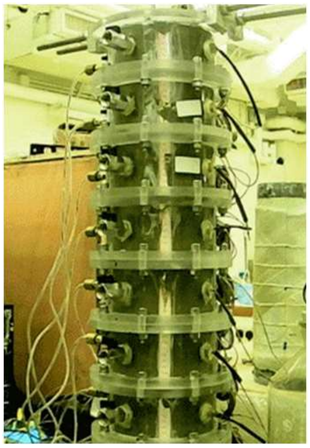
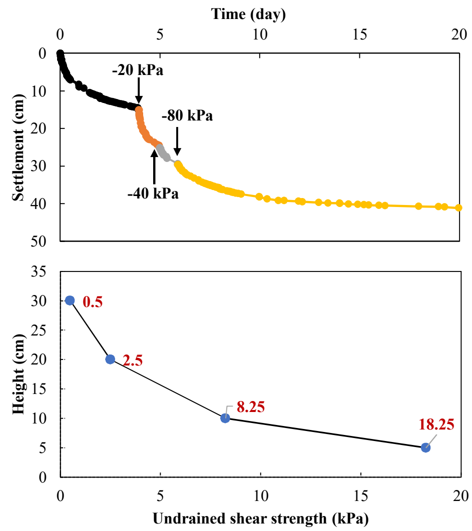
2D cylindrical test on HKMD slurry with PHD at bottom (Test 2) (using smaller model)



- **Staged vacuum: to avoid clogging.**
- **Soil height: from 0.80m to 0.34m.**

From Sep. 30th 2021 to Oct. 25th 2021



Finding: Settlement and shear strength of HKMD slurry were increased with time quickly due to PHD and vacuum loading.

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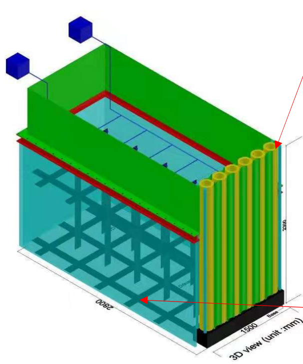
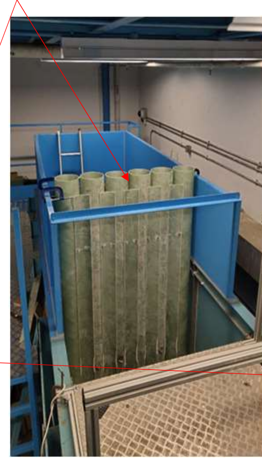
3.2 2D plane strain physical model test on HKMD slurry with PHD grid under vacuum preloading (on-going)

Fibre Reinforced Polymer (FRP) pipe piles:
2~4 times of steel strength





2.8m(long)×2.3m(high)×1.5m (wide) (internal dimension)

Bottom prefabricated horizontal drain (PHD) grid

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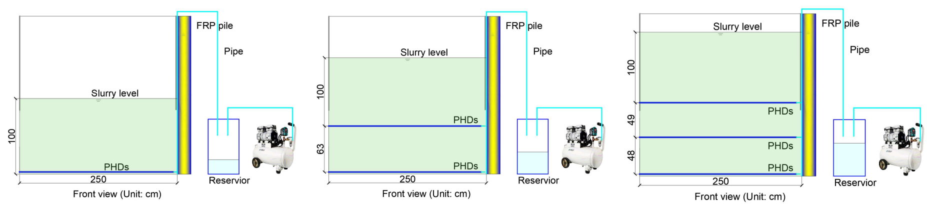
3.2 2D plane strain physical model test on HKMD slurry with PHD grid under vacuum preloading (on-going)

Required transducers are placed at selected locations first before each step of HKMD slurry pumping



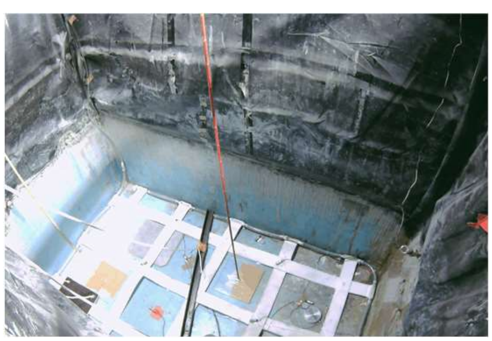
Step 1: Place PHD grid first at bottom, then pump in HKMD slurry, and apply vacuum pressure on PHD grid.

Step 2: After consolidation, place another PHD grid layer at the soil surface in Step 1, then pump in the second layer of slurry, then apply vacuum pressure on PHD grid.

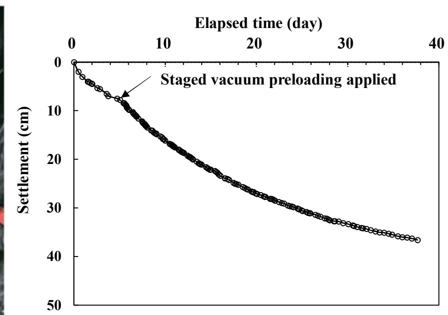
Step 3: After consolidation, place the third layer of PHD grid layer at the soil surface in Step 2, then pump in the third layer of slurry, then apply vacuum pressure on PHD grid.

3.2 2D plane strain physical model test on HKMD slurry with PHD grid under vacuum preloading (on-going)

Step 1: Place PHD grid first at bottom, then pump in HKMD slurry, and apply vacuum pressure on PHD grid.



The period for Step 1: From Nov. 4th 2021 to Dec. 13th 2021



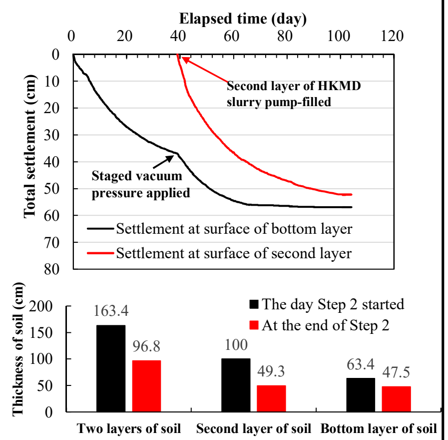
The increase of settlement with time under staged vacuum preloading

- **The height of the bottom layer of HKMD soil was decreased from 1m to 0.634m.**
- **Average water content was decreased from 181% to 101%.**

3.2 2D plane strain physical model test on HKMD slurry with PHD grid under vacuum preloading (on-going)

Step 2: After consolidation, place another PHD grid layer at the soil surface in Step 1, then pump in the second layer of slurry, then apply vacuum pressure on PHD grid.

The period for Step 2: from Dec. 14th 2021 to Feb. 20th 2022



Test result summary:

- **Average water content of two layers of soil was decreased from 155% to 76%.**
- **Average water content of the second layer of soil was decreased from 220% to 89%.**

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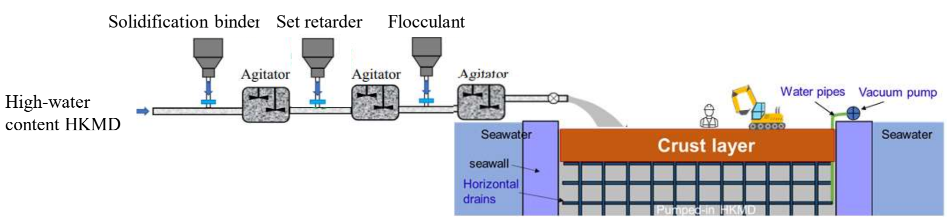
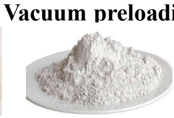
4. Use of Wastes as Mixing/Filling Materials for Marine Reclamations



Crust layer formation

- **High-water content HKMD**
- **Solidification binder (Industrial wastes):**
  - Alkali-activated Incinerated Sewage Sludge Ash (ISSA) 焚化污水污泥灰
  - Alkali-activated Ground Granulated Blast-furnace Slag (GGBS) 粒化高爐礦渣粉(a by-product of iron and steel-making)
- **PHDs + Vacuum preloading**

ISSA GGBS

Industrial wastes

Lime

Alkali activator

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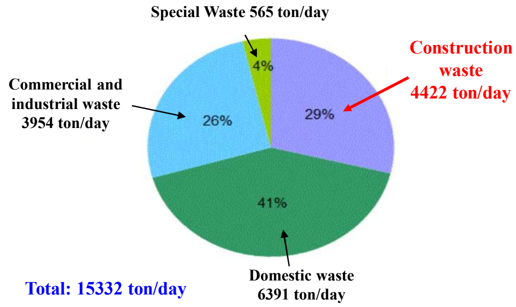
Inert wastes can be utilized as fills directly:

Large volume of construction waste

Environmentally-Friendly

The landfills in Hong Kong will be saturated within 2 years

Types of solid waste disposed of at landfills in 2016



Total: 15332 ton/day

The total volume of construction waste in 2016 was equal to 502 standard swimming pools.

Utilization of mining waste

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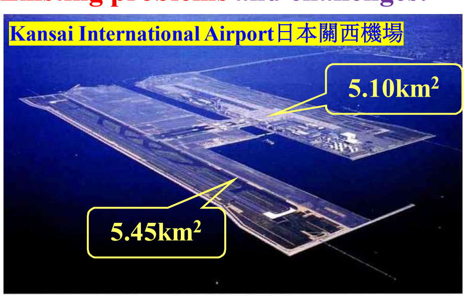
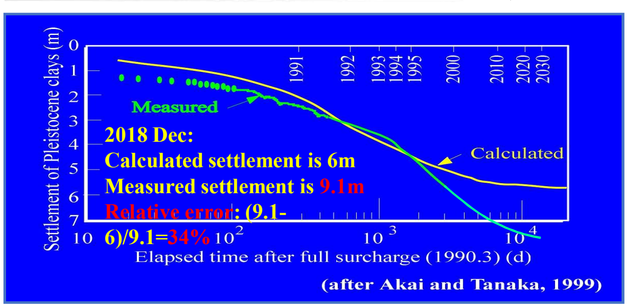
5. A General Simple Method for Settlement Prediction

Existing problems and challenges:



(9.4.2018, flooded after a super typhoon)



- Measured settlement is much larger than that calculated.
- The *calculation method* is a problem?

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Hypothesis A and Hypothesis B methods for calculating consolidation-creep settlements of one clayey soil layer:

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

No creep in "primary" consolidation?

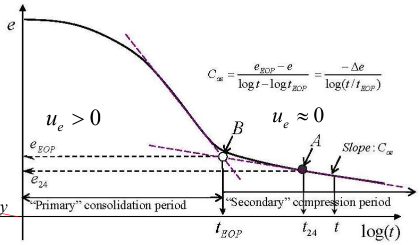
$$S_{totalA} = S_{\text{"primary"}} + S_{\text{"secondary"}}$$

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

$t_{EOP,field}$ = 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!)



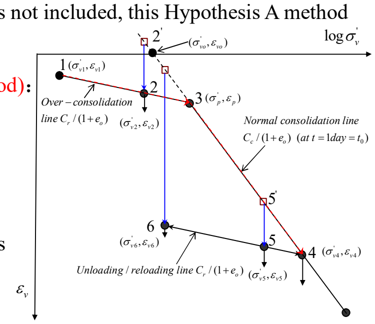
Since creep/viscous settlement in "primary" consolidation is not included, this Hypothesis A method underestimates/低估 settlement.

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

$$S = S_{primary} + S_{creep} =$$

$$= \begin{cases} US_{pf} + \alpha U^{\beta} S_{creep,f} & for\ \ t_0 \le t \le t_{EOP,field} \\ US_{pf} + [\alpha U^{\beta} S_{creep,f} + (1-\alpha U^{\beta}) S_{creep,d}] & for\ \ t \ge t_{EOP,field} \end{cases}$$

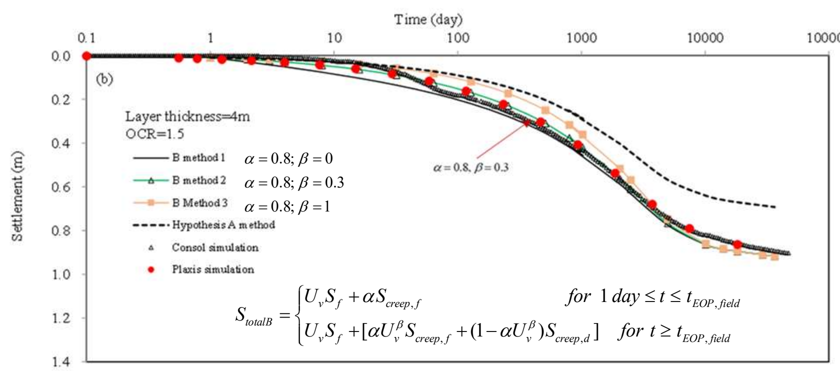
Since creep/viscous settlement in "primary" consolidation is included, this Hypothesis B method estimates settlement more accurate.



Relationship of strain and log(effective stress) with different consolidation states (after Yin et al. 2022)

Example 2: OCR=1.5

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



C_r	C_c	σ'_p (kPa)	C_α	$t_o = 1$ day	e_0	$\alpha = 0.8$	$\beta = 0.3$	k (m/day)

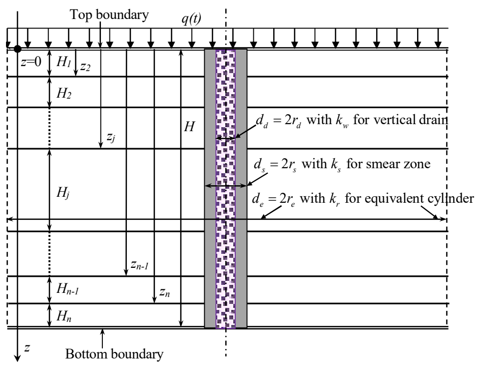
- The results from the new simplified Hypothesis B method are closer to curves from "rigorous" Plaxis and Consol simulations (**Hypothesis B method = fully coupled method**).
- Hypothesis A method underestimates the settlement a lot.

A General Simple Method (Simplified Hypothesis B Method) and Verification

(a) Equation:

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

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

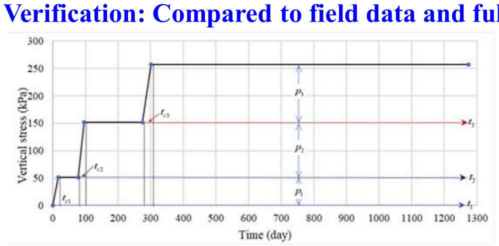


A soil profile of *n*-layers with vertical drain subjected to uniform surcharge *q(t)* with time

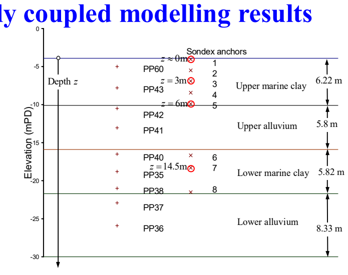
This method is a **new "de-coupled" (新的解耦)** method for

- layered soils exhibiting creep 多層流變粘性土,
- zero or small initial effective stress considered 考慮初始有效應力為零或小,
- without or with vertical drains 有(無)排水板,
- under any staged loading including un/re-loading 任何多級加載，包卸載再加載,
- spread-sheet calculation with good accuracy 電子表格(Excel)计算，高精度。

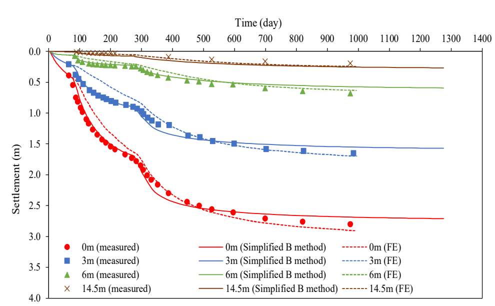
Verification: Compared to field data and fully coupled modelling results



Staged ramp-loading

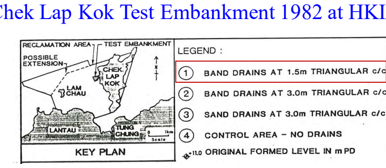


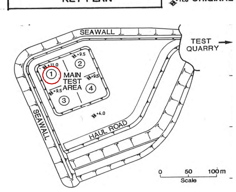
Soil profile and settlement monitoring points: only top two layers are considered



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

Chek Lap Kok Test Embankment 1982 at HKIA Site

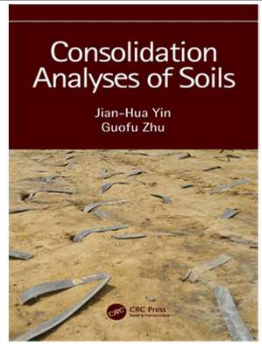




More details on the simple method on one/double layers, and this general simple method, see:

(i) A new book by Yin and Zhu (2020)

https://www.routledge.com/9780367555320

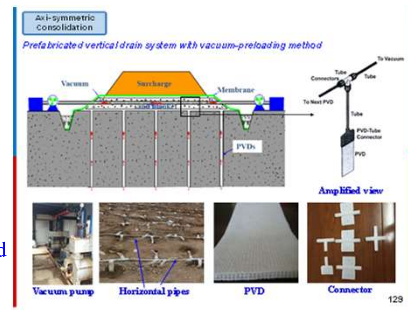


(ii) Papers:

Yin, J.-H., Feng, W.-Q. (2017). A new simplified method and its verification for calculation of consolidation settlement of a clayey soil with creep. Canadian Geotechnical Journal, 2017, 54(3), pp. 333–347

Feng, W.-Q., Yin, J.-H. (2017). A new simplified Hypothesis B method for calculating consolidation settlements of double soil layers exhibiting creep. International Journal for Numerical and Analytical Methods in Geomechanics, 2017, 41(6), pp. 899–917

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, 2022, 17(8), pp. 3647–3674.



6. A Prototype Field Trial of Using HKMD for Reclamation

- A prototype field trial was successfully conducted at the Tung Chung New Town Extension project site with the concerted efforts of CEDD, PolyU and the site team.
- This to further demonstrate the practicality and benefits of PolyU's method and technology in utilizing HKMD for marine reclamations.
- Within the trial pit of 12 m (length) by 8 m (width) by 3.5 m (depth), the marine deposits gained significant strengths during the 7-month test period, and would be capable of supporting subsequent typical constructions.

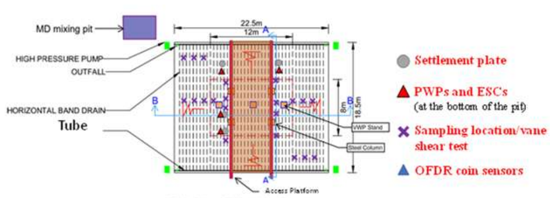
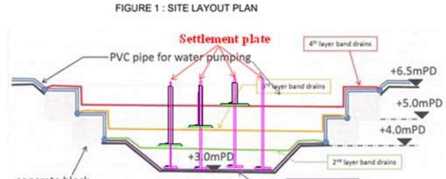


FIGURE 1 : SITE LAYOUT PLAN



A-A cross-section (schematic drawing)

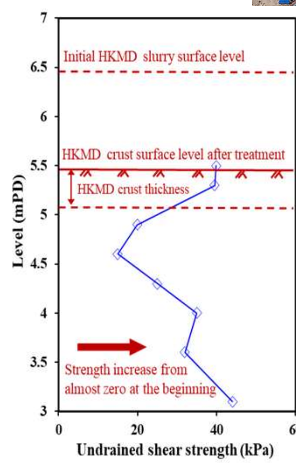
Hong Kong marine deposits (HKMD) slurry was fast consolidated by horizontal drains and vacuum loading.

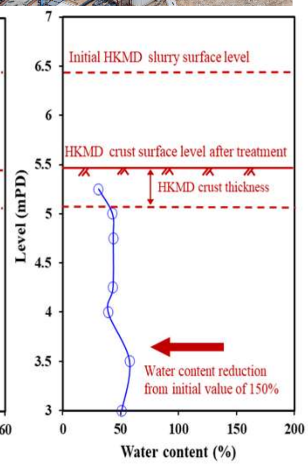
After treatment (26/07/2022)


Filling HKMD slurry to initial surface level


Forming a crust surface layer


Cross-section profiles along depth after treatment

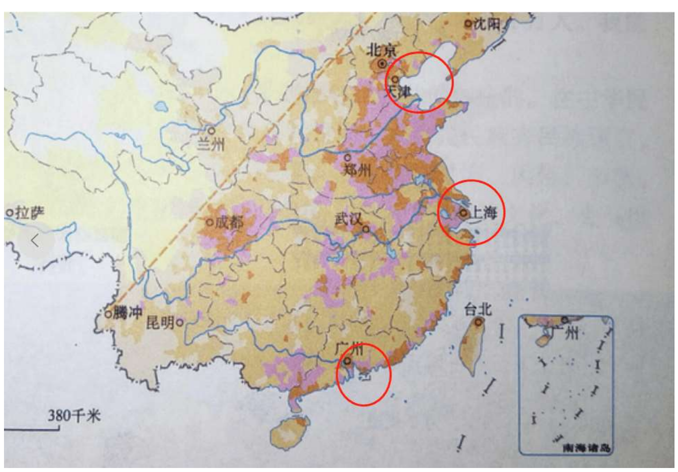




7. Use of Dredged Local Marine Deposits for Reclamations in Other Coastal Cities

我國最適合填海造陸的三大地區，從南到北分佈，都位於江河入海口：

環渤海周圍的海域深度都只有十幾米，對於填海造陸來說工程量也不是很大，像天津的濱海新區的大部分土地都是通過填海而來，這對於經濟發展來說是十分的有利的。



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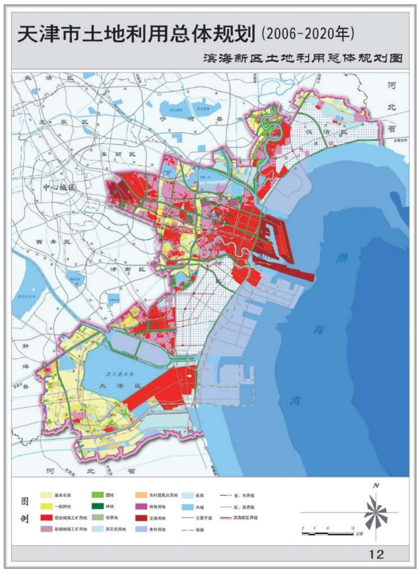
(a) Tian Jin (天津)

- 天津的濱海新區：總面積2270平方公里
- 截至2010年，天津濱海新區共圍墾灘塗108平方公里。 2010-2022：填海面積？



- **Use local dredged marine soils for reclamation:**
  本地海洋土吹填造地
- **Vertical drains and vacuum/surcharge preloading are used to fast consolidate the marine soils**
  用垂直排水板和真空/堆載來加快軟土固結。

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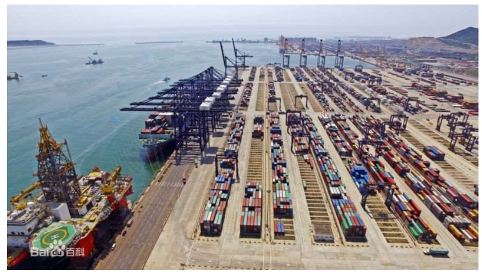
濱海新區臨港經濟區分區規劃(2010-2020年)：

根據《規劃》，臨港經濟區規劃成陸面積200平方公里，用海面積230平方公里。

(b) Da Lian (大連连)



Dalian soft marine soils:
- VDs + vacuum preloading of dredged soft marine soils
- Reference: 《大連大窯灣三期軟基處理》中交水運規劃設計院有限公司, 2011年2月20日。

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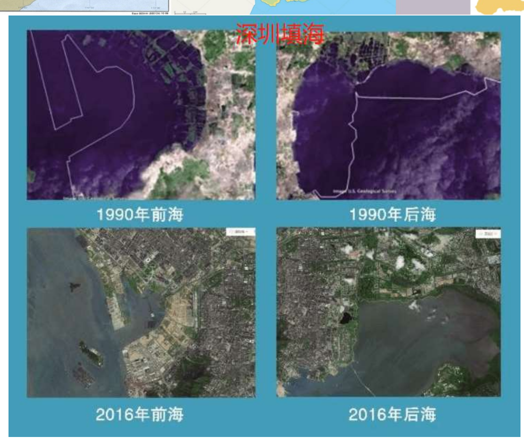
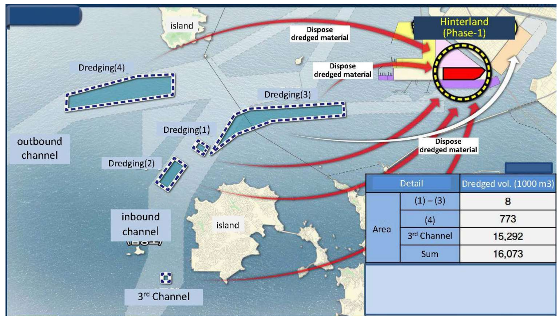
(c) Macau (澳门)

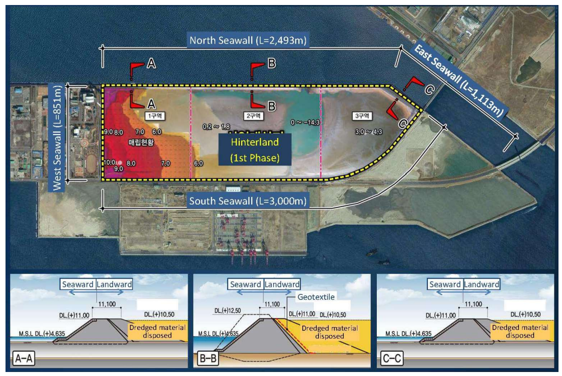
(d) Shen Zhen (深圳)



(e) Incheon New Port Hinterland Development Plan (Phase 1) in Korea 南韓仁川新港腹地開發計劃



Local dredged marine deposits were used as fill for reclamation



- **Local dredged marine deposits have been used as fill for many reclamation projects in other costal cities.**
- **Why Hong Kong Marine Deposits cannot be dredged and used for reclamations in order to provide lands for residential buildings and related infrastructures with both time and cost savings?**
- **Effects on marine environment are the main concern?**
- **Then, why 19 years ago, marine sands in Hong Kong waters could be dredged and used for reclamations?**

See: https://www.cedd.gov.hk/eng/public-services-forms/fill-management/marine/marine-fill/index.html

- From 1990 to the end of 2003, about 270 millions m^3 of marine sand had been extracted from the seabed in Hong Kong waters and used as marine fill for Hong Kong reclamation projects (HK International Airport, HK Convention & Exhibition Centre at Wan Chai, and the Theme Park at Penny's Bay).
- Before 1990, even more marine sands in HK waters were dredged and used for Hong Kong reclamation projects (Tseung Kwan O, Ma On Shan, Terminals in Tsing Yi, …).

8. Conclusions and Remarks

(a) Using local dredged marine soils and wastes for marine reclamations in Hong Kong will save time and money a lot.

(b) The new method combining horizontal and vertical drains with vacuum and/or surcharge preloading is very effective for consolidating HKMD slurry quickly.

(c) Data from physical model tests have proved that the new improvement method can increase HKMD slurry strength effectively and quickly.

(d) Alkali-activated industrial wastes, like ISSA and/or GGBS, have a great potential for forming the **crust layer** quickly on the top of the HKMD slurry.

(e) The simplified Hypothesis B method introduced here is simple and accurate for predicting settlements of soft soils.

(f) A prototype field trial has demonstrated that dredged HKMD slurry can be used for reclamation and our new method is suitable for improving HKMD slurry.

(g) Project cases have shown that dredged local marine deposits have been used successful for reclamations in many other coastal cities.

Why local marine deposits cannot be dredged and used for reclamations in Hong Kong?

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