Geotechnical Workshop at Griffith University Gold Coast Campus,
29 Sept – 3 Oct 2008

Part III
Vacuum Preloading Techniques

3-1. Principles
3-2. Methods
3-3. Case Studies

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Need for vacuum preloading

- When there is a lack of granular fill, cohesive fill dredged from the seabed can be used for reclamation.
- In this case, fill surcharge preloading will not be practical as the soil to be consolidated is too soft to sustain the fill.
- In this case, vacuum preloading may be used.
- When the vacuum load is not sufficient, a combined fill and vacuum surcharge method can be used.

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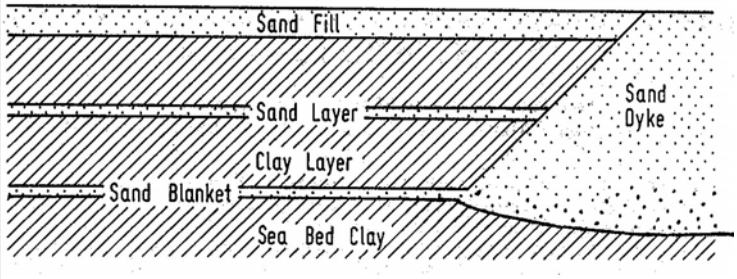

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the reclamation. The reclamation will be carried out using channel maintenance dredging materials consisting of river muds capped with sand, as has been the past practice. The seabed conditions, however, are significantly different in the seawall area because of the high water table, in-situ compressible clays over 30 metres deep and the increased thickness of up to 7 to 9 metres of river muds to be deposited into the reclamation.

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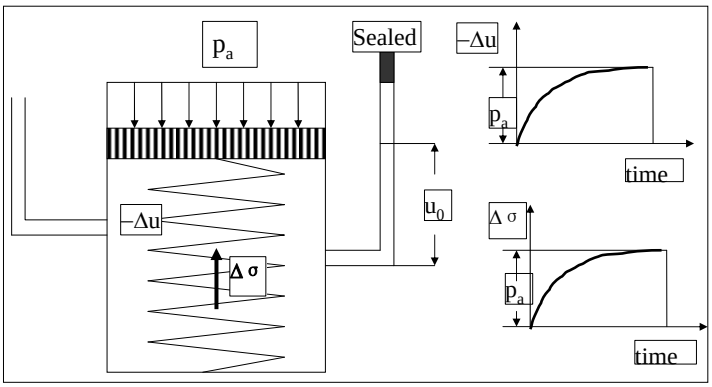
3.1 Principles

- The surcharge is applied using vacuum pressure.
- The limit of vacuum pressure is 98 kPa and the nominal value is about 80 kPa.



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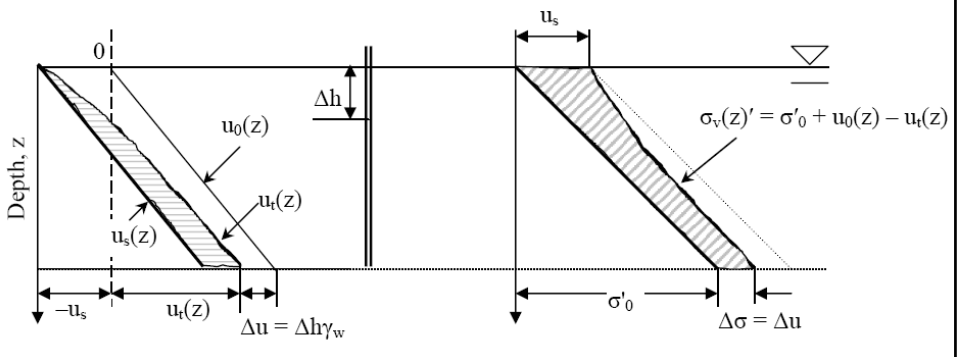
3.1 Principles (cont'd)



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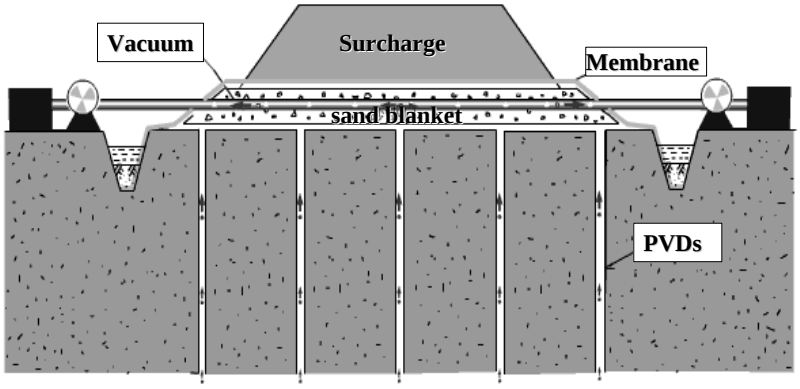
3.2 Combined vacuum and fill surcharge preloading method



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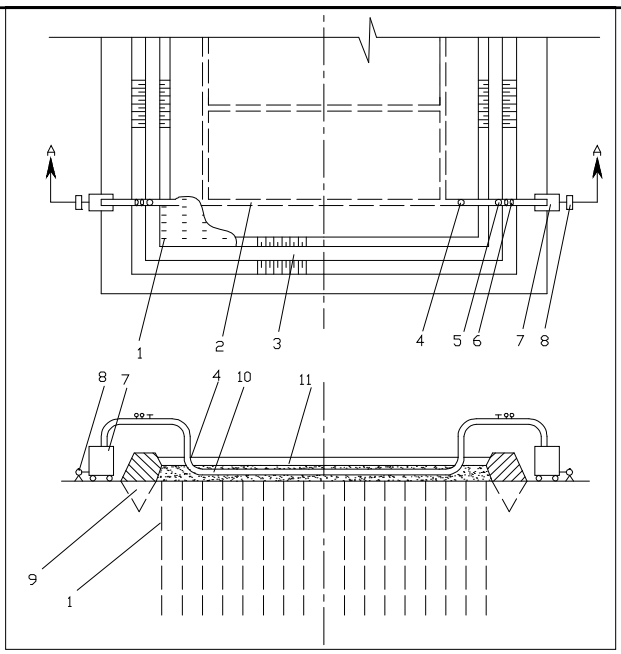

Schematic arrangement of vacuum preloading method

Schematic arrangement of vacuum preloading method:

1, drains;

2, filter piping;

3, revetment;

4, water outlet;

5, valve;

6, vacuum gauge;

7, jet pump;

8, centrifugal pump;

9, trench;

10, horizontal piping;

11, sealing membrane.

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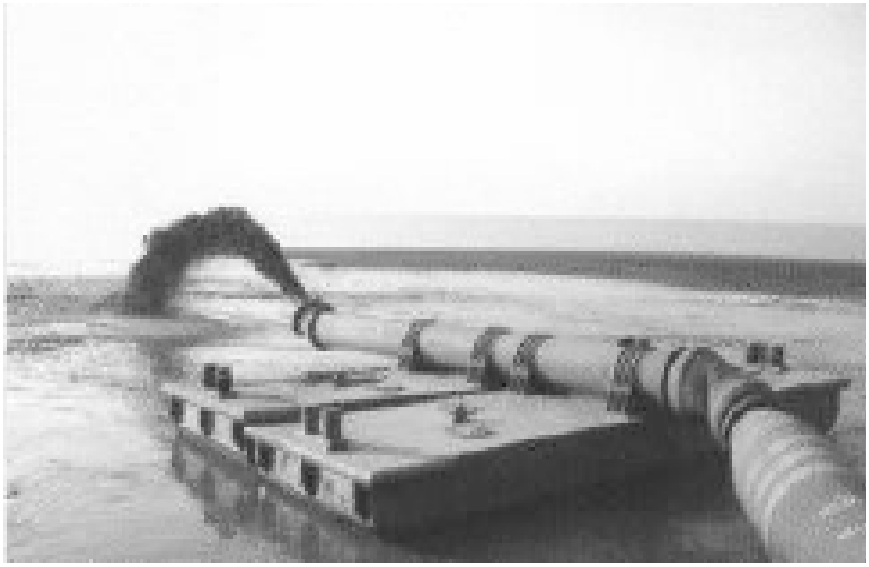

Land reclamation using dredged clay slurry

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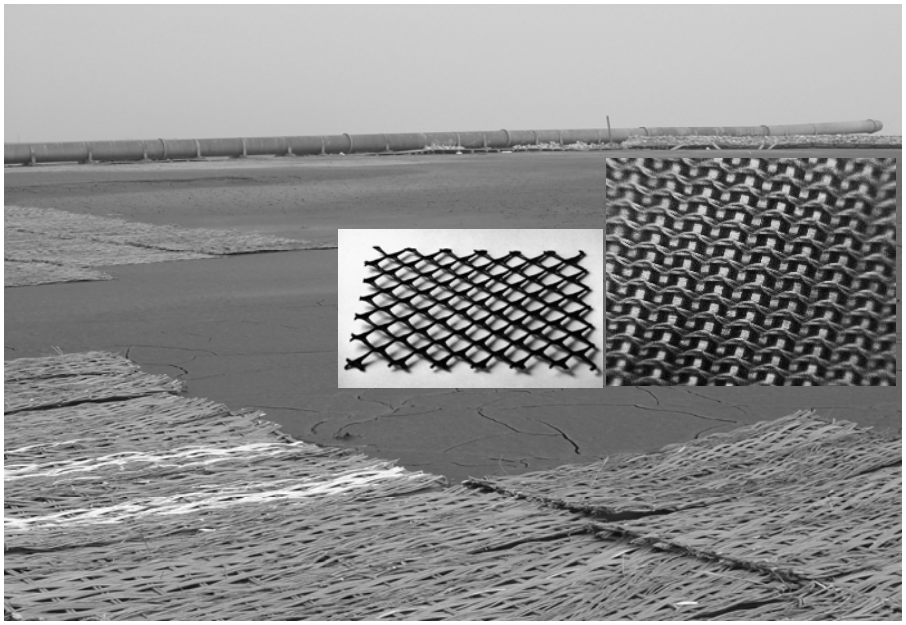

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Install a layer of sand blanket and vertical drains

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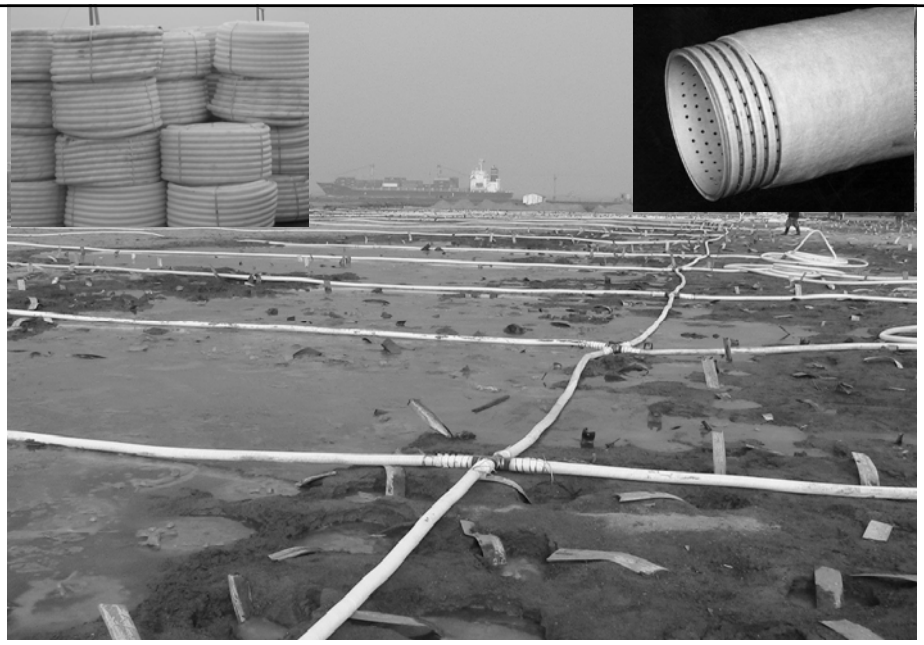

Place corrugated flexible pipes

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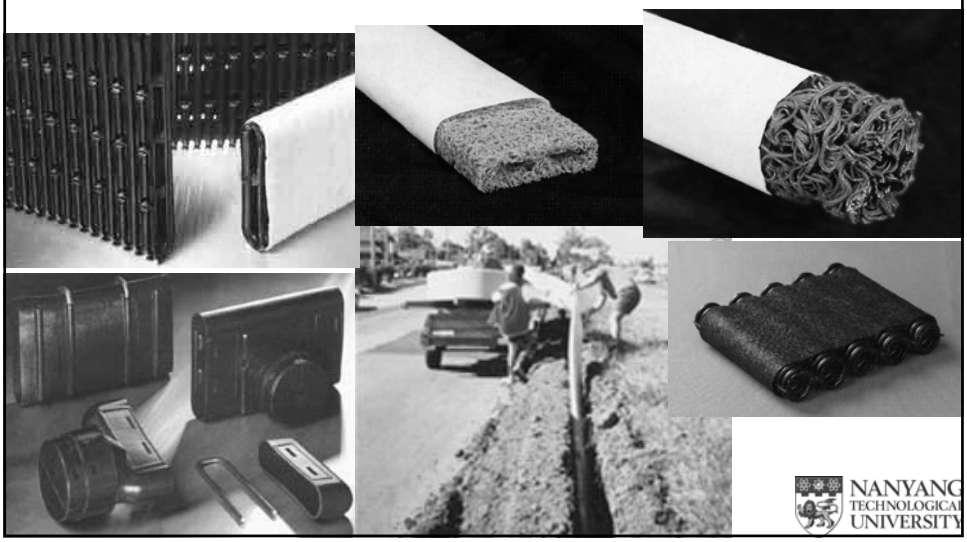
Horizontal drains



Installation of 2-3 layers of membrane

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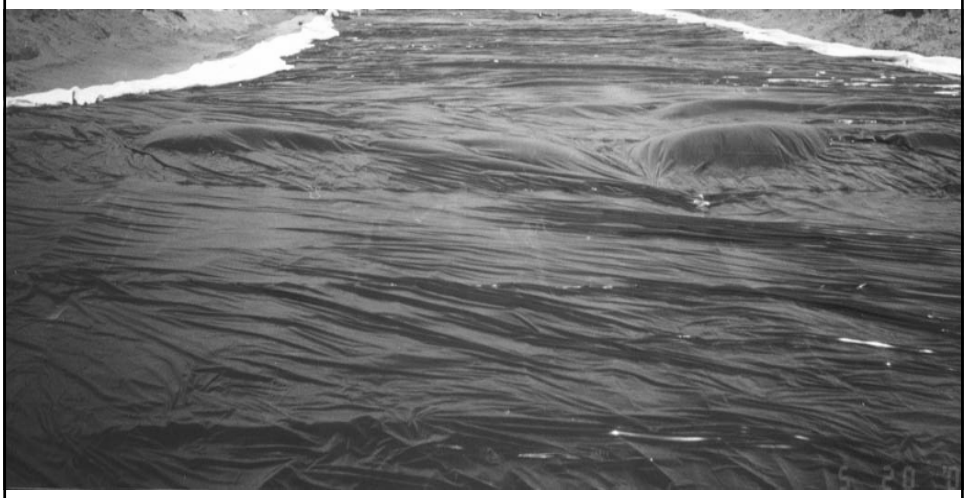

Seal with membranes

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Apply vacuum

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Apply vacuum and fill surcharge together

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Install instruments for field monitoring

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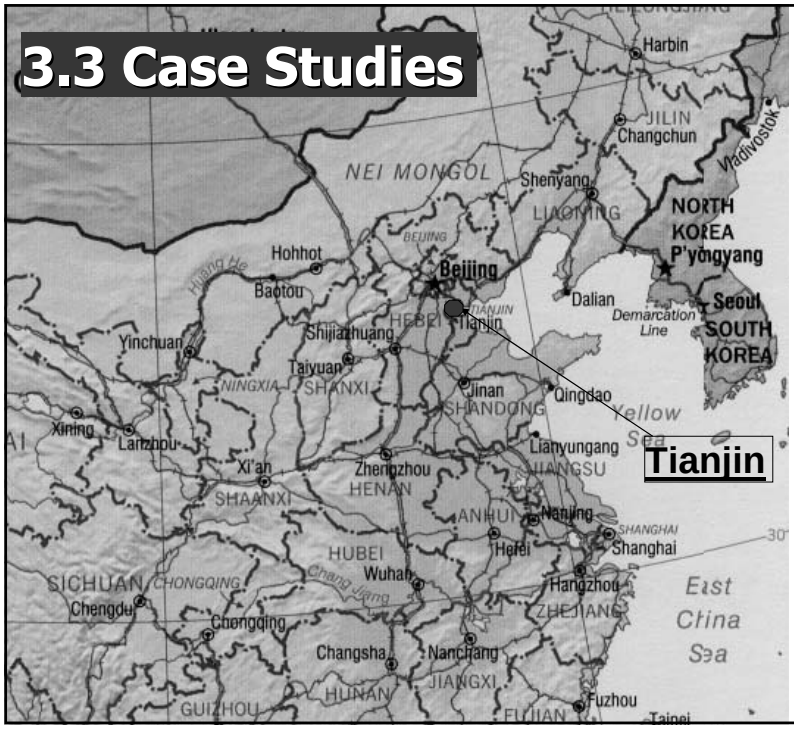
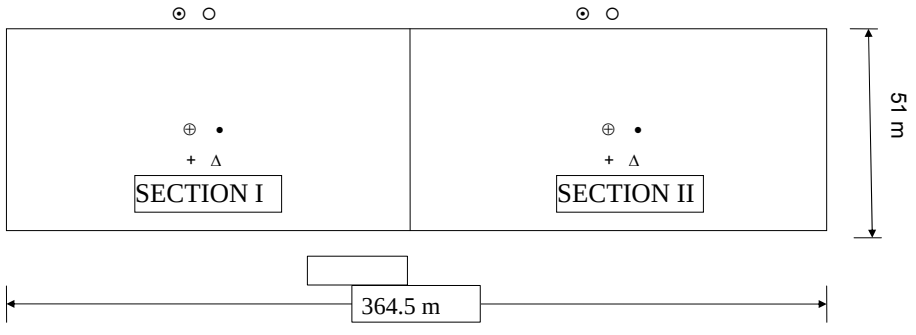
3.3 Case Studies



Case Study-1: a road on very soft clay



•	Borehole	⊕	Field Vane
○	Water stand pipe	⊙	Inclinometer
+	Multi-level settlement gauge	Δ	Pore-water pressure transducer

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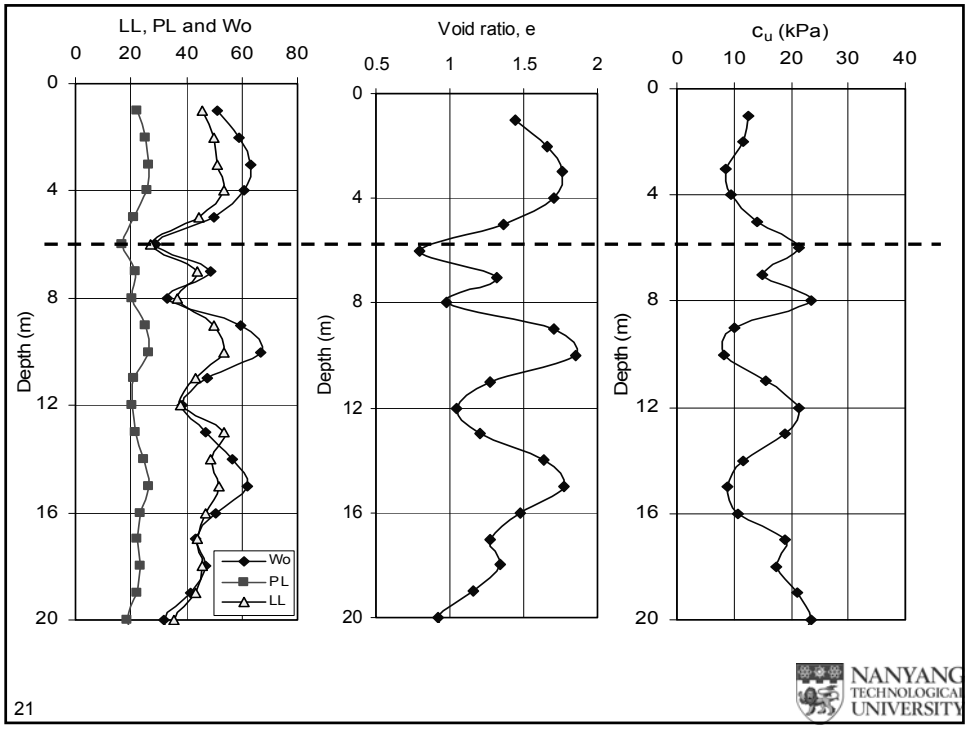

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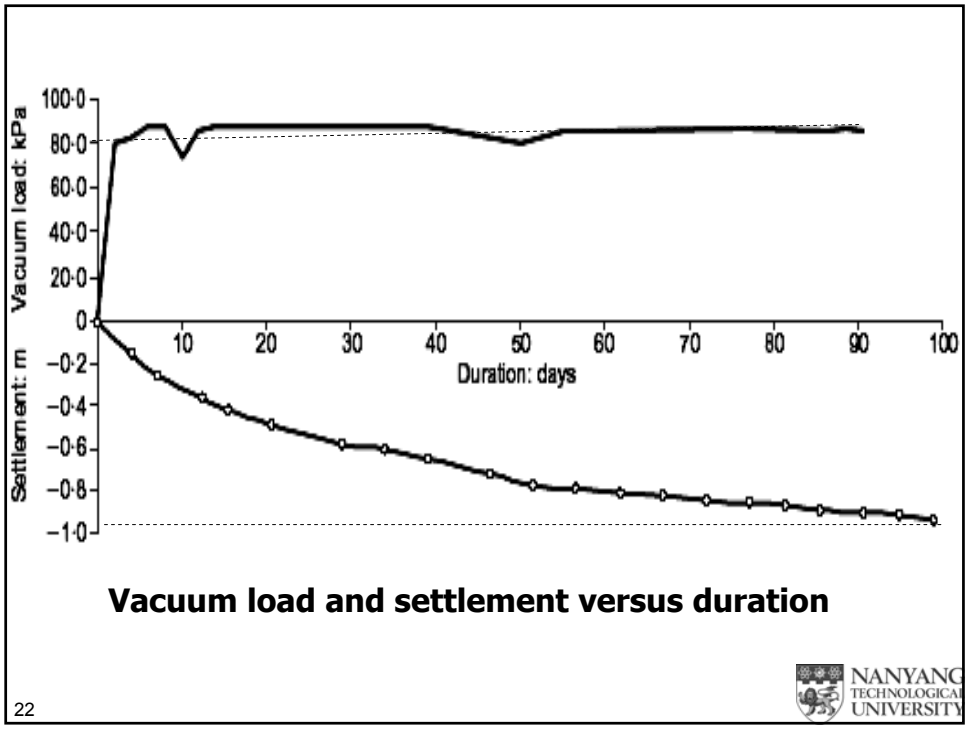

Vacuum load and settlement versus duration

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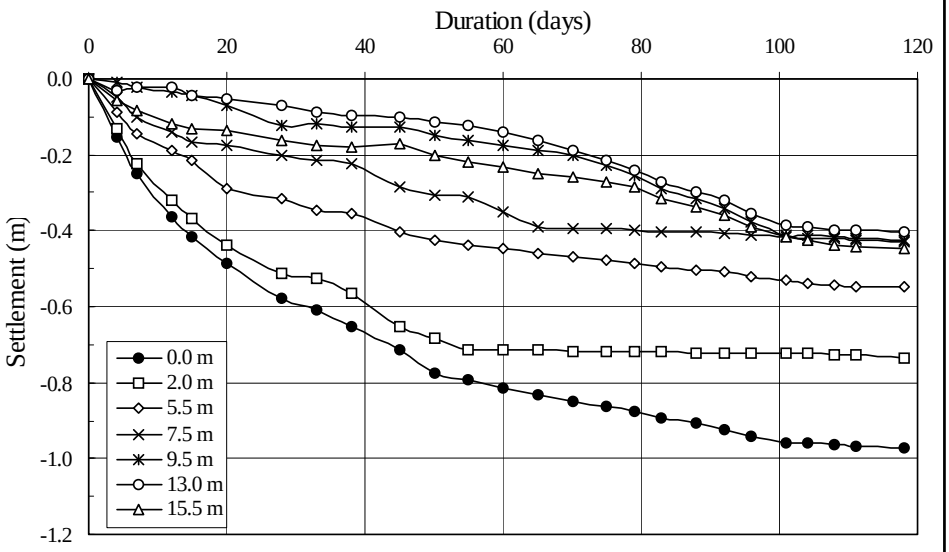

Settlement measured at Section I

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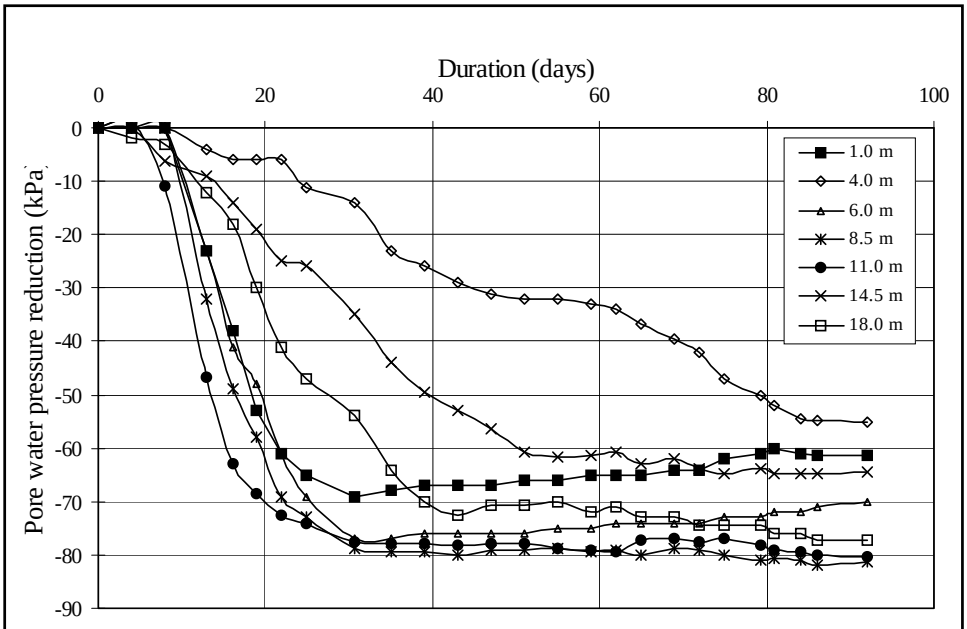

Pore water pressure reductions in Section 1

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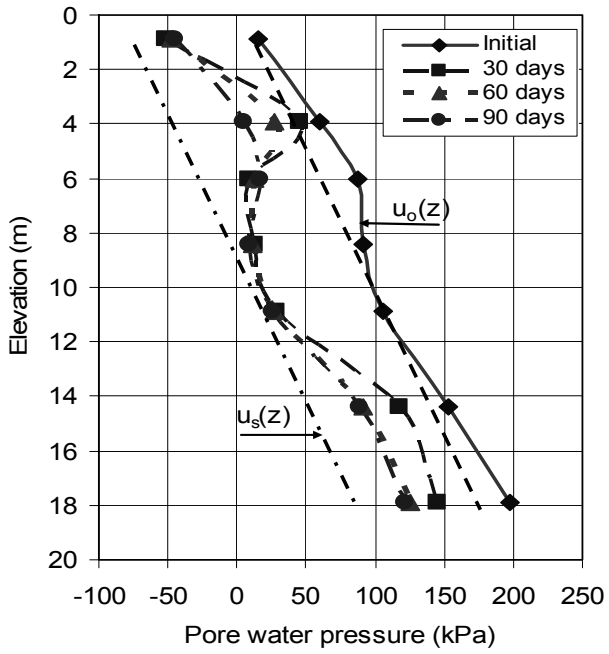

Pore water pressure variation versus depth profiles

Section I

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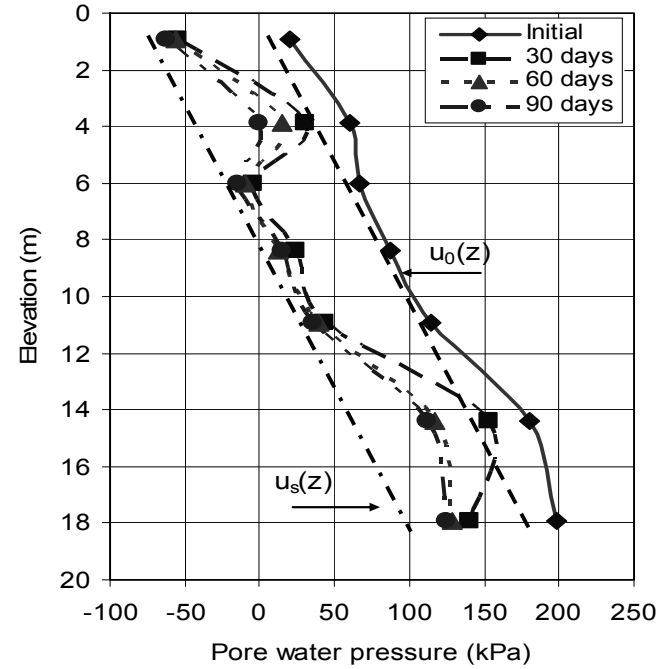

Pore water pressure variation versus depth profiles

Section II

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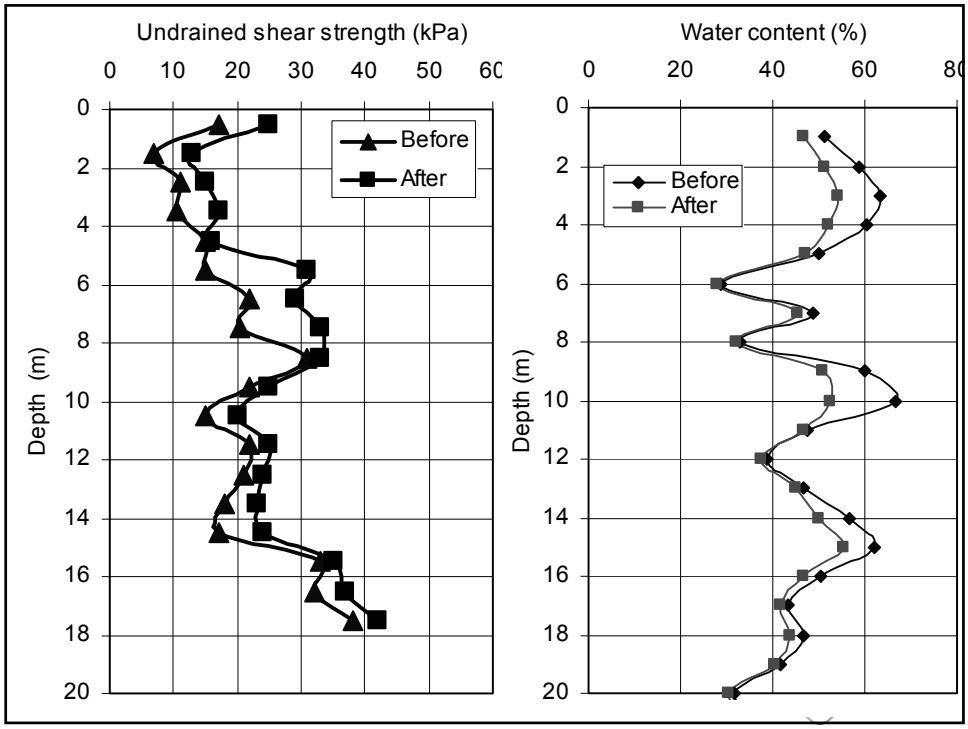
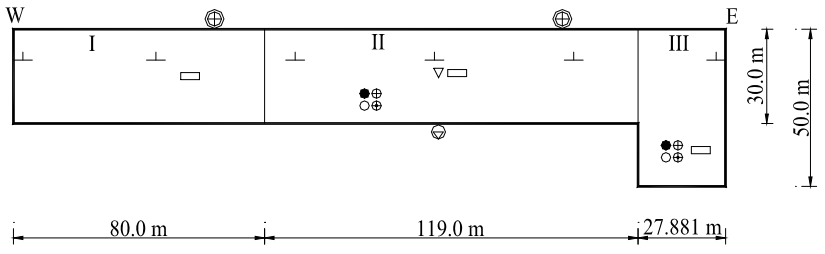


Case Study-2: A Storage Yard using Combined Vacuum and Fill Preloading



Settlement gauge
PWP transducer
Multi-level gauge
Borehole
Field vane
Inclinometer
Piezometer

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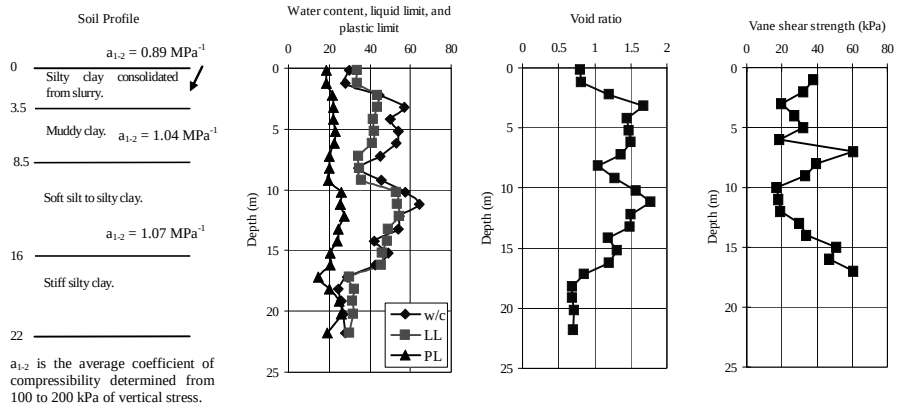
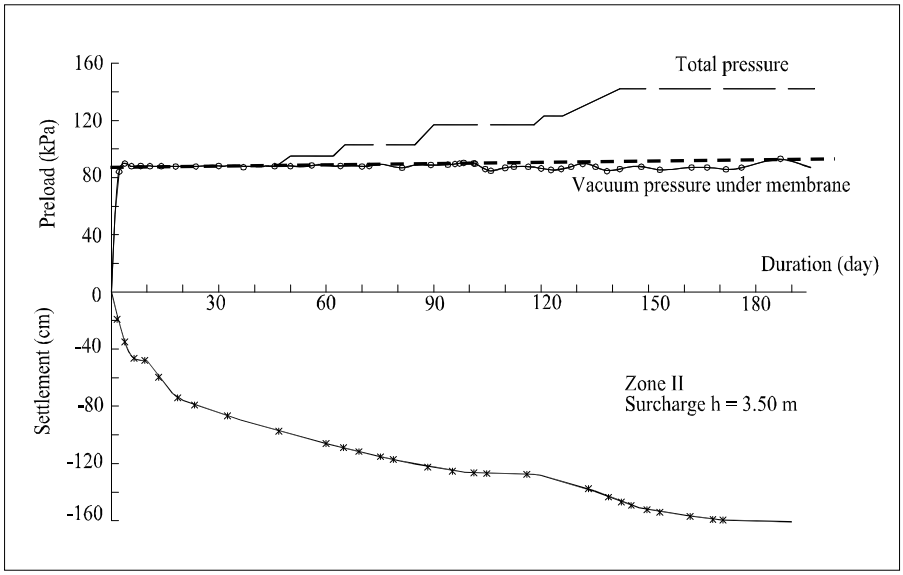
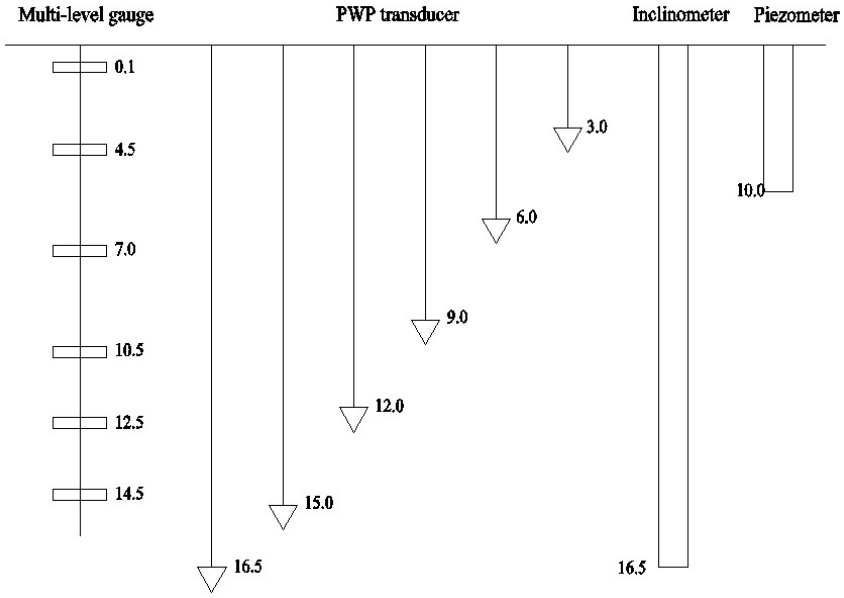
Soil Profile and Soil Properties





Loading History and Ground Settlement



Instrumentation plan

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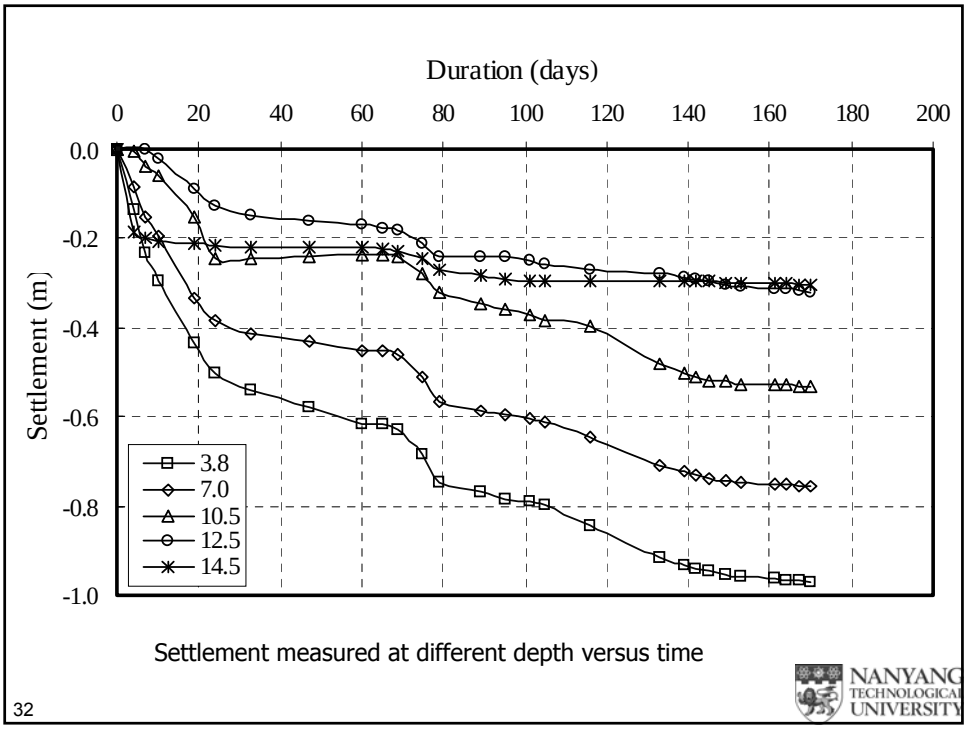

Settlement measured at different depth versus time

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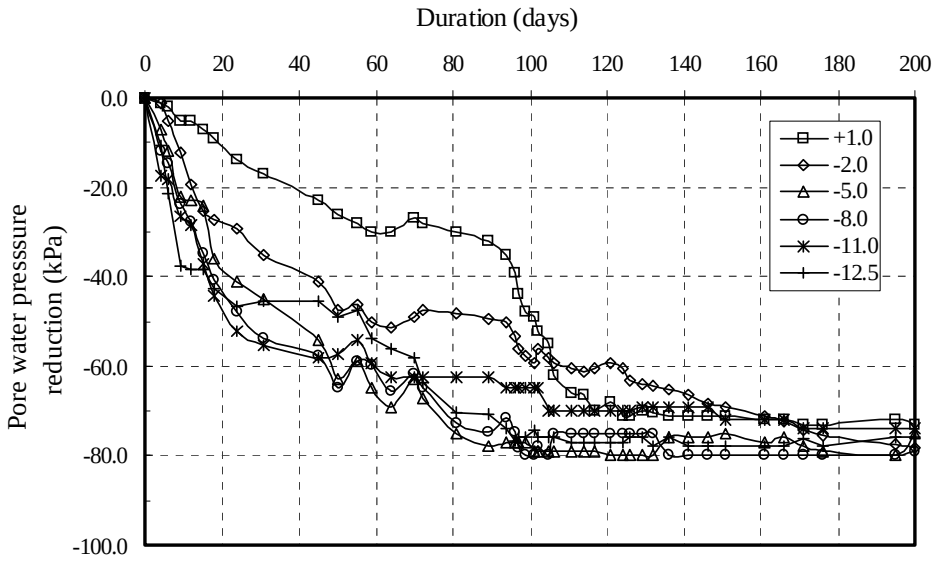

Pore pressure reduction at different depths versus time

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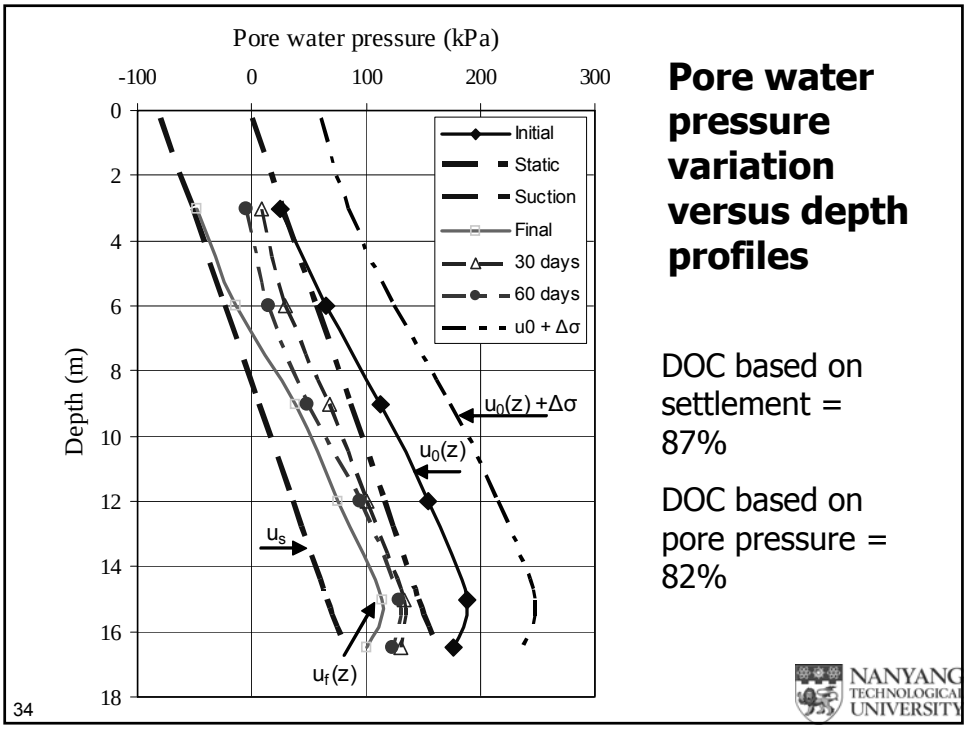

Pore water pressure variation versus depth profiles

DOC based on settlement = 87%

DOC based on pore pressure = 82%

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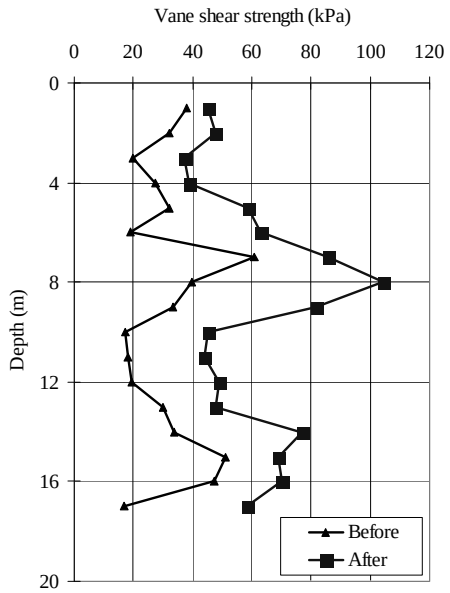

Field vane shear profiles

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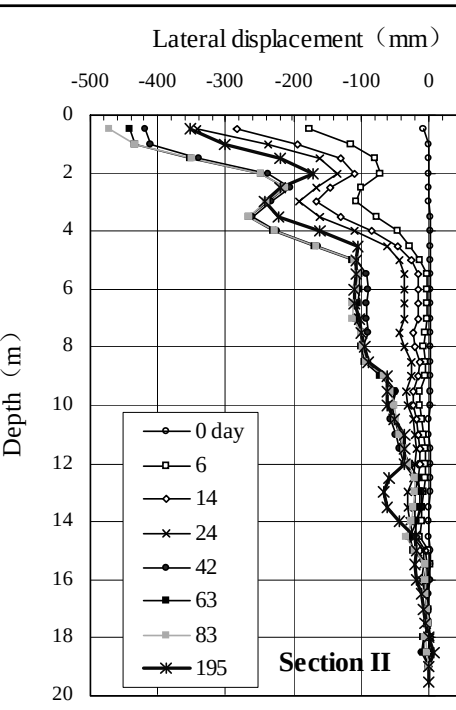

Lateral displacement

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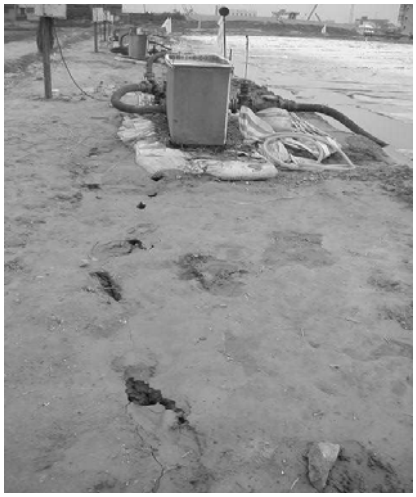
Effect of lateral displacement



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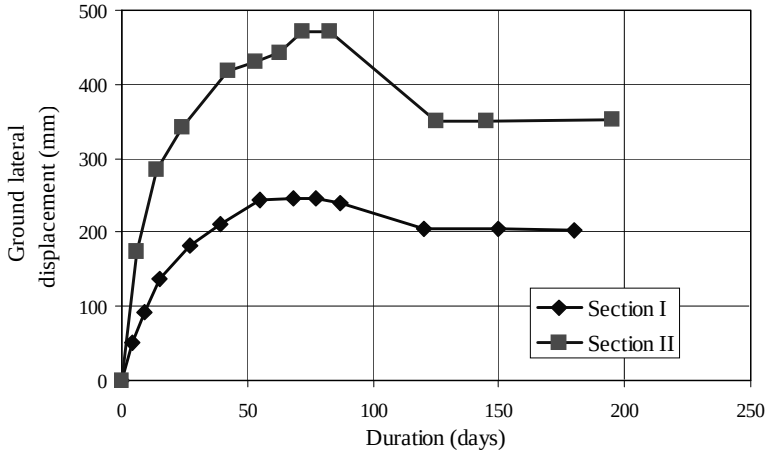
Combined loading can reduce lateral displacement



Ground lateral displacement versus time curves

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Remarks on Combined Vacuum and Fill Surcharge Preloading

- The case study shows that under a vacuum pressure of 80 kPa plus a 40 kPa of surcharge, >80% degree of consolidation was achieved within 4 months. The rate of settlement at all depths reduced to residual levels after about 100 days. The maximum ground settlement was >1m. The field vane shear strength increased two to three times.
- Field instrumentation is essential in evaluating the performance of soil improvement.

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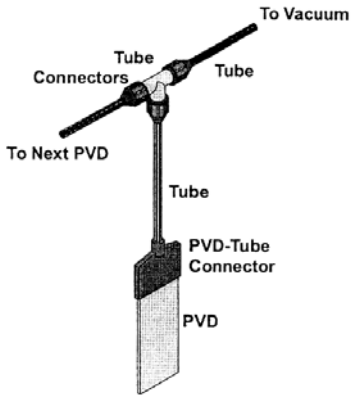
Other New Techniques

- When the top layer is not purely clayey soil, a cut-off wall is required to seal the area to be vacuum loaded. Alternatively, PVD with plastic sleeve or a direct connection of PVD to vacuum tube can be used.



PVD and tubing for vacuum preloading (after Seah, 2006)

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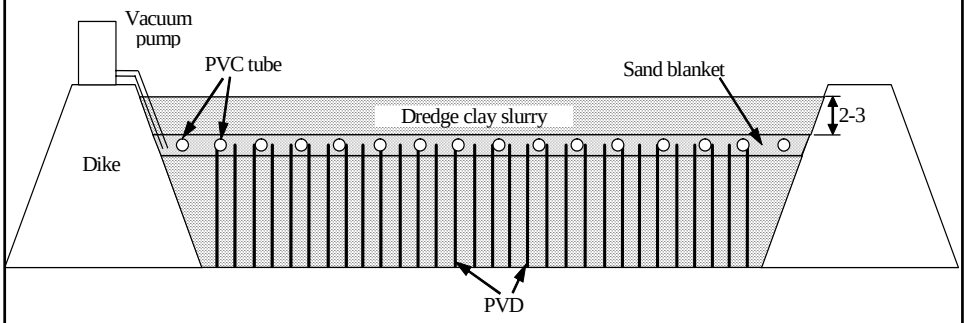
Membrane-less vacuum preloading method



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Back Analysis and Degree of Consolidation Estimation using Field Measurement

Based on settlements

Based on Pore pressure measurements

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Design Specifications

- (Average) Degree of Consolidation (DOC or U_{avg}) is often used as one of the contract specifications. However, different DOC values can be obtained depending on the methods adopted in estimating DOC. This often leads to dispute between consultant and contractor.

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Methods for Calculating DOC

- Normally based *settlement* monitored:

  $$DOC = S(t)/S_{ult}$$

  Different methods for estimating S_{ult} has been adopted (Asoaka, Hyperbolic, and Zeng et al.).

- Based on *pore water pressure* (PWP) monitored.

  Can be done easily using the following method.

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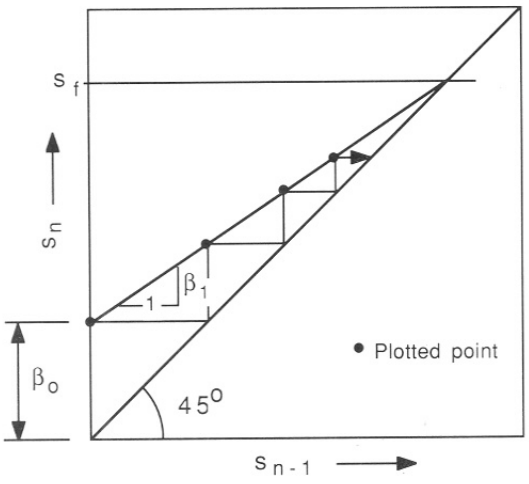
Asaoka's method

The procedure requires settlement readings to be taken at constant time intervals Δt, or equivalent values interpolated from a time-settlement curve. Settlement reading s_n is plotted versus the preceding settlement s_{n-1}. A line drawn through the points plotted, extrapolated, and intersected with the 45⁰ line. This intersection point represents the final settlement s_f.



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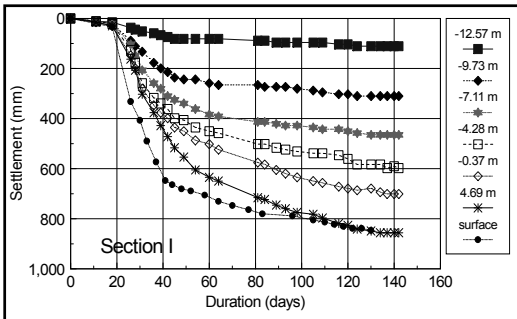
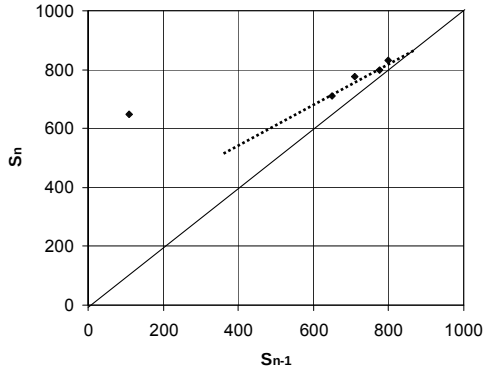
Example





t (days)	s(n-1)	s(n)
20	110	650
40	650	710
60	710	775
80	775	800
100	800	830
120	830	

Asaoka's method (cont'd)

The method is based on the fact that 1D consolidation settlement at times 0, Δt, 2Δt, 3Δt, etc. can be expressed mathematically in the general form:

$$s_n = \beta_0 + \sum_{i=1}^{i=w} \beta_n s_{n-i}$$

For w = 1, a first-order approximation is obtained:

$$s_n = \beta_0 + \beta_1 s_{n-1}$$

Then β_1 is the slope of the line in the Asaoka plot.

Asaoka's method (cont'd)

$$\beta_1 = \frac{s_f - s_i}{s_f - s_{i-1}} = \frac{s_f\left(1-\frac{s_i}{s_f}\right)}{s_f\left(1-\frac{s_{i-1}}{s_f}\right)} = \frac{1-U(t_i)}{1-U(t_{i-1})}$$

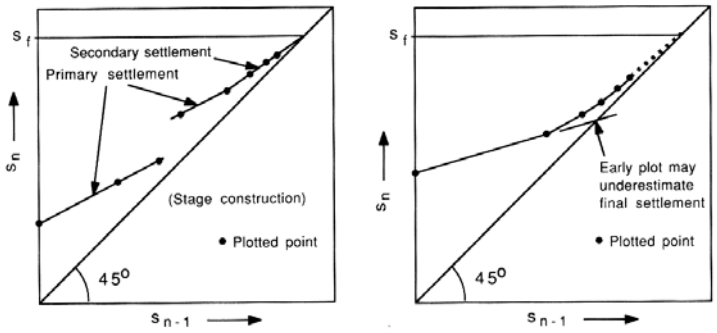
$$1-U = (1-U_h)(1-U_v) = e^{-\frac{8T_h}{F(n)}} \frac{8}{\pi^2} e^{-\frac{\pi^2}{4}T_v} = \frac{8}{\pi^2} e^{-\left(\frac{8}{F(n)}\frac{c_h}{d_e^2}+\frac{\pi^2}{4}\frac{c_v}{H_d^2}\right)t} = \frac{8}{\pi^2} e^{-\Lambda t}$$

$$\beta_1 = \frac{\frac{8}{\pi^2} e^{-\Lambda t_i}}{\frac{8}{\pi^2} e^{-\Lambda t_{i-1}}} = e^{-(\ldots)(t_i - t_{i-1})} = e^{-\Lambda \Delta t}$$

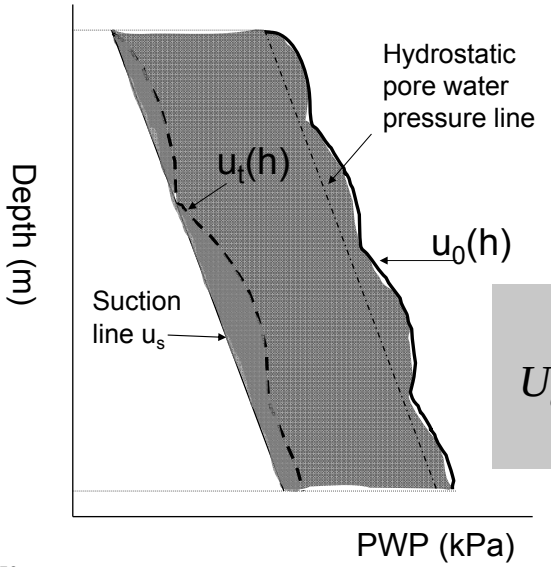
$$-\frac{\ln \beta_1}{\Delta t} = \Lambda = \frac{8c_h}{d_e^2 F(n)} + \frac{\pi^2}{4}\frac{c_v}{\mathrm{H}_d^2}$$

Asaoka's method (cont'd)

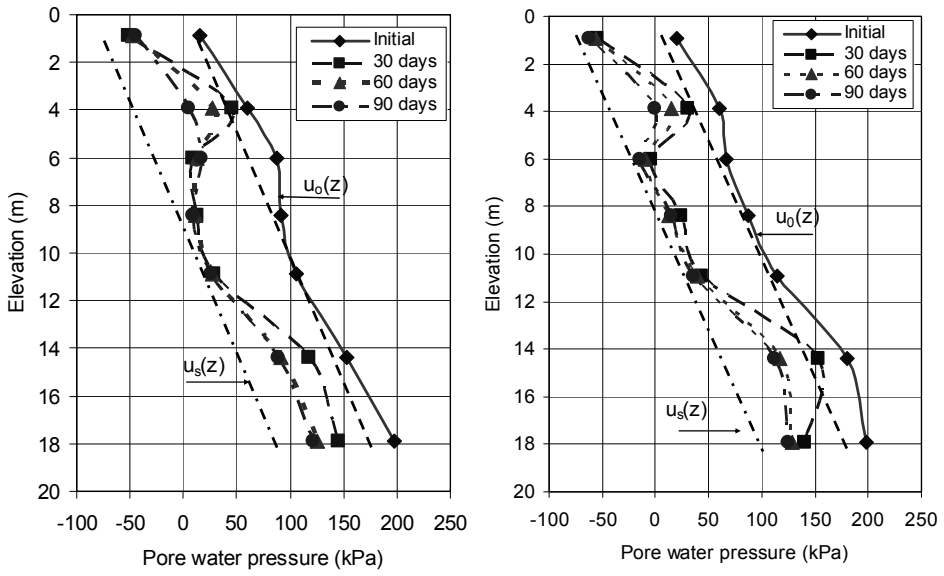
Note: The results of Asaoka's method is affected by the time interval used (the larger the Δt, the smaller the S_f) and the secondary settlement. Early plot (with DOC<70%) may not be reliable.



Calculation of DOC using PWP



$$U_{avg} = 1 - \frac{\int [u_t(h) - u_s] dh}{\int [u_0(h) - u_s] dh}$$



PWP Distribution Profiles in a vacuum preloading project

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DOC Calculated using PWP and Settlement

Degree of consolidation (DOC)	Based on settlement data				Based on pore water pressure data			
	30	60	90	End	30	60	90	End
Section I	54%	77%	86%	90%	54%	69%	73%	-
Section II	49%	66%	83%	90%	54%	66%	75%	-

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Why DOC_PWP is smaller than DOC_Settlement?

- It is related to how PWP and settlement are measured. When limited instruments are used, instruments will be placed to measure the largest settlement and PWP.
- When DOC is more than 85%, the differences tend to be small.

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Disadvantages of Each Method

- ***DOC_Settlement***: uncertainties in the S_{ult} predicted. No unique S_{ult} value even when the same method is used.

- ***DOC_PWP***: the spatial PWP profile can hardly be obtained. The PWP measurement is affected by the position of the transducers to the drain.

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Recommendations

- As both settlements and PWPs are measured, DOC should be calculated using both settlement and PWP data.
- Even if DOC is to be evaluated using settlement, PWP distribution profiles provide a way to visualize how PWP and effective stress are changing with time.

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List of references

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- **Bo, M. W., Chu, J., Choa, V. (2005). "Changi East Reclamation and Soil Improvement Project." Chapter 9, In *Ground Improvement – Case Histories,* Eds. B. Indraratna and J. Chu, Elsevier, 247-276.**
- **Chu, J., Bo, M. W. and Choa, V. (2006). "Improvement of ultra-soft soil using prefabricated vertical drains." *Geotextiles and Geomembranes, Vol. 24, 339-348*.**
- **Chu, J., Yan, S. W., and Yang, H. (2000). "Soil improvement by vacuum preloading method for an oil storage station". *Geotechnique*, Vol. 50, No. 6, 625-632.**
- **Chu, J. and Yan, S. W. (2005). "Application of the vacuum preloading method in land reclamation and soil improvement projects." Chapter 3, In *Ground Improvement – Case Histories,* Eds. B. Indraratna and J. Chu, Elsevier, 91-118.**
- **Chu, J. and Yan, S. Y. (2005). "Estimation of degree of consolidation for vacuum preloading projects." *Int. Journal of Geomechanics*, *ASCE*, Vol. 5, No, 2, 158-165.**
- **Yan, S. W. and Chu, J. (2005). "Soil improvement for a storage yard using the combined vacuum and fill preloading method" *Canadian Geotechnical Journal*, Vol. 42, No. 4, 2094-1104.**

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