An Engineering-Data Driven Digital Twin
- DigitaLand@Tuas

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Contents of Presentation

- General Definition of Digital Twin
- Uniqueness of Tuas Next Generation Port
- Digitaland@Tuas – An Enginering-Data Driven Digital Twin Model
- Closing Remarks

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What is Digital Twin

- **Vision of Digital Twins:**
  - Wouldn't it be extraordinary to simulate plans or build what-if scenarios for the products, facilities, and processes you wished to change before you actually put real-world resources behind real-world implementation?

- **What is a Digital Twin:**
  - A digital replica of a living or non-living physical entity in the physical world. Data gathered to bridge the physical and the virtual world, allowing the virtual entity to exist simultaneously with the physical entity.

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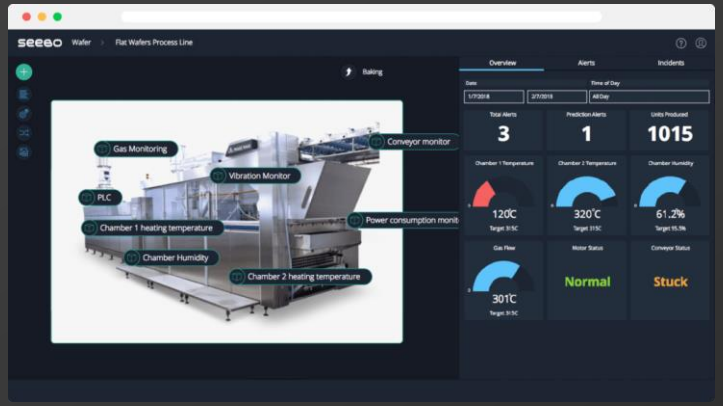
What is Digital Twin



Monitoring Health of Production Line

Urban Planning of Cities

Training Simulators

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Uniqueness of Tuas Next Generation Port

- **Stiffer Ground Settlement Requirements than Before:**

S/N	Land Usage	Design Loading	Settlement Criteria (includes both primary consolidation and creep)
1	Industrial use	30kPa	Residual Settlement under 30kPa ≤ **100mm**
2	Military Training Ground	20 kPa	Residual settlement under 20 kPa < **800mm**
3	Port Terminal	**180 kPa** (Container Stacking Yard) 30kPa (Road)	<u>Container Stacking Yard</u> Differential settlement under 180kPa not steeper than 1:500 over a span of 20m. <u>Roads & Thoroughfares, Part of Wharf Apron</u> a) Residual settlement under 30kPa during design service life of 60 years ≤ **40mm** b) Differential settlement under 30kPa not steeper than 1:400.

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Uniqueness of Tuas Next Generation Port

- **Stiffer Ground Settlement Requirements Than Before:**
  - Use of precision electronics for automation in port operations + track guided vehicles (criteria of max 4cm settlement in 60 years)
  - Heavy and repetitive AGV wheel loads :- rutting failures
  - Surface irregularities : - excessive vibrations to AGV's on-board electronics.
  - Depressed ground surface :- ponding of water in terminal areas

Embedded transponders

Rutting of Port Pavements

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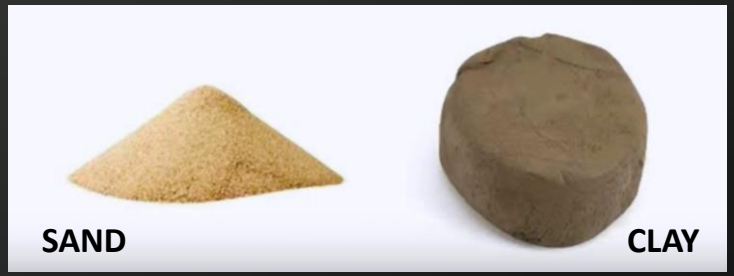
Uniqueness of Tuas Next Generation Port

- **Usage Requirements More Challenging Than Before:**
  - From Deferred to Immediate Land Use:
    - **Marina Bay** ~ Reclaimed with **sand** (no creep concern)
      - Even so, the land was left to settle for decades [**Deferred** Land Use]
    - **Next Generation Tuas Port** ~ Reclaimed with soft dredged and excavated materials (settlement concern)
      - Requires land to be available upon reclamation [**Immediate** Land Use]
      - Not feasible to drive piles throughout entire ~5.5mil sqm site (too costly)



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Engineering-Based Digital Twin Model

- **Purpose of Digital Twin for Long Settlement:**
  - To anticipate maintenance planning
    - When should the surface of the port be serviced?
    - How extensive would the servicing be?
    - Where are the potential locations at the port which requires more attention?

- **Key Difference in Role of Maintenance in Tuas Port vs Conventional Applications:**
  - Long term process: Creep settlement (approx. 0.1 to 0.8mm/year assuming 20m thick fill) may be visible only after 5 years or even few decades later.
    - No benefit/incentive to adopt costly instrumentation and real-time data management systems to monitor ground settlement.

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Engineering-Based Digital Twin Model

- **NUS's Smart Predictive Digital Twin of Tuas Port:**
  - Since real-time instrumentation sensors is excessively costly and time consuming for slow process ground deformation, **state-of-art engineering development** would be adopted to **model long term settlement**.
  - Shifting from a more active sensing role where external data takes precedent of modelling in conventional digital twin, to a passive role is suggested here where **modelling is developed based on engineering fundamentals and external data merely used for validation**.
  - Numerical simulation of settlement to **compare with field instrumentation records** and fine-tune ground properties to **improve forecasting over time using AI**.
  - Adoption of **machine learning techniques** to derive the most appropriate engineering properties of these heterogeneous soil for modelling.

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Engineering-Based Digital Twin Model

Running the surrogate model in DigitaLand@Tuas to give more accurate predicted settlement

Potential digital survey of ground surface settlements

Development of a Surrogate Model from Machine Learning algorithms

Finite Element Modelling and Analysis of Settlement

AI-managed database of heterogeneous reclamation fill materials at Tuas Port

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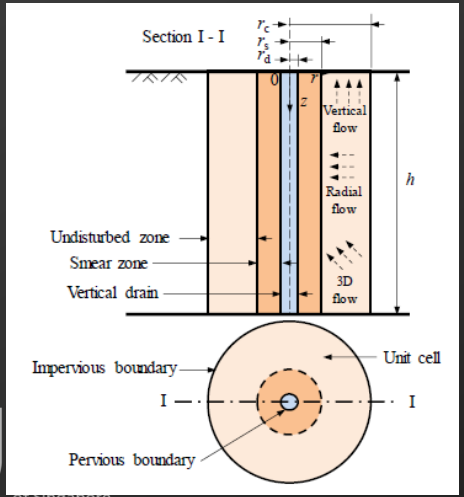
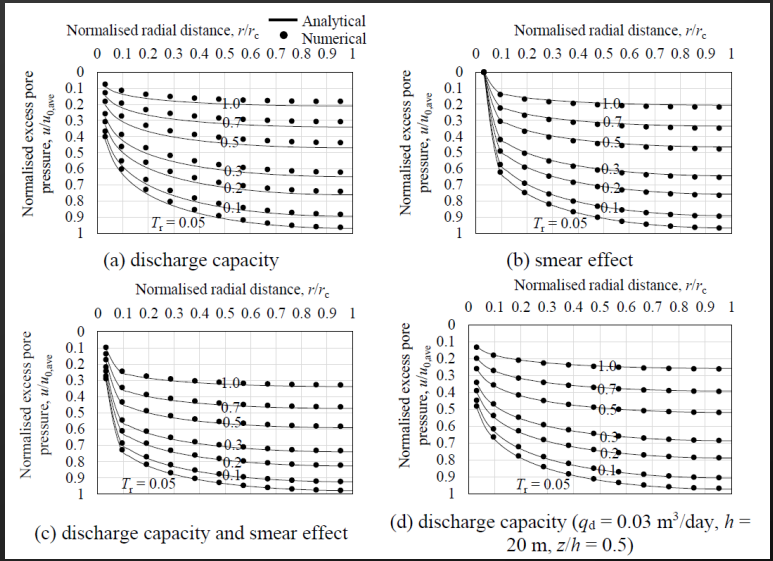
Engineering-Based Digital Twin Model

- **State-of-art unit cell model capable of encompassing 3D radial discharge as well as smear disturbance was developed.**
  - Validated with classic analytical solutions and field measurements from extensometer readings.
  - Finally, a 3D numerical modelling of the boreholes located at the proof load test site was carried out and estimates of the ground settlement including creep settlement up to the design lifespan of 60 years were obtained.

Geometry of a unit cell



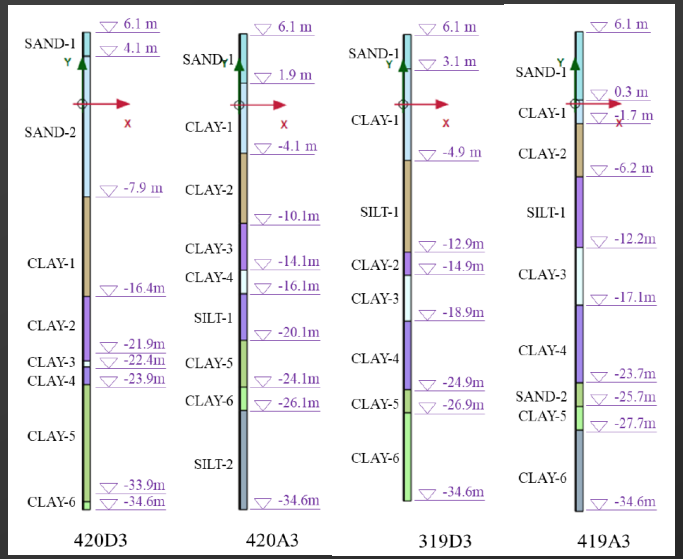


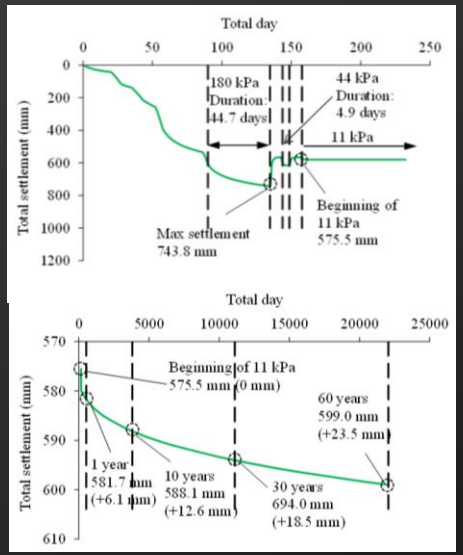
Validation of model with analytical solutions

- **Discharge capacity**
- **Smear effect**

Engineering-Based Digital Twin Model

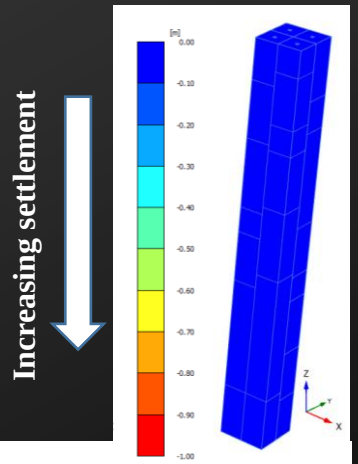
- State-of-art unit cell model capable of encompassing 3D radial discharge as well as smear disturbance was developed.

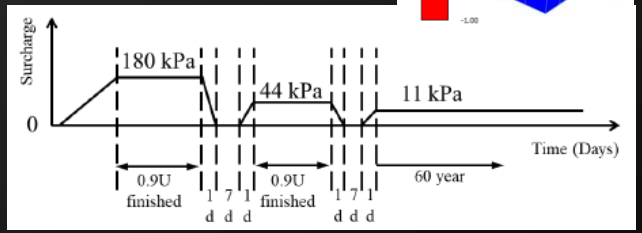




Settlement during ground improvement: 575.5mm

Settlement after 60 years of creep: 23.5mm





Ground condition, loading regime and ground settlement over 60 years

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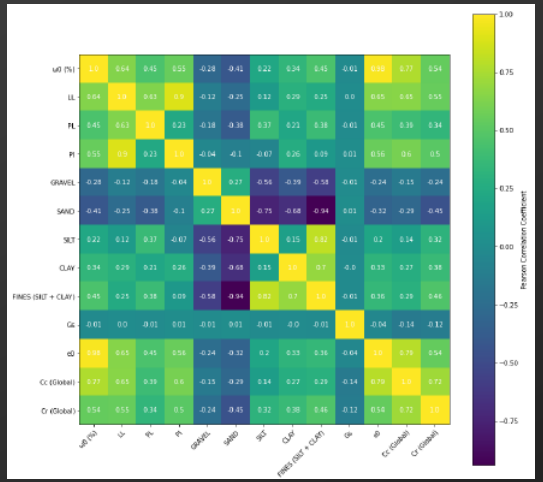
Engineering-Based Digital Twin Model

- **Library of a wide range of soil properties was compiled and correlation studies carried out using state-of-art machine learning techniques.**
  - Wealth of data from 9 berths of site investigation reports and 77 publications collated.
  - Imputation of gaps of soil parameters achieved with machine learning as input for large-scale numerical modelling of the reclaimed land that was incorporated into the digital twin model.



Correlation matrix of soil parameters

Machine learning adopted in Cc prediction

Features	XGBoost		Random Forest		SVM		ANN	
	Min features	Min CVMSE features	Min features	Min CVMSE features	Min features	Min CVMSE features	Min features	Min CVMSE features
LL		√	√	√	√	√	√	√
PL	√	√	√	√		√	√	√
PI		√		√				√
SAND		√			√	√	√	√
SILT				√				√
CLAY	√	√		√	√	√		√
FINES		√		√		√		
Gs	√	√		√		√		√
e0	√	√	√	√	√	√	√	√
w0	√	√	√	√	√	√	√	√

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Engineering-Based Digital Twin Model

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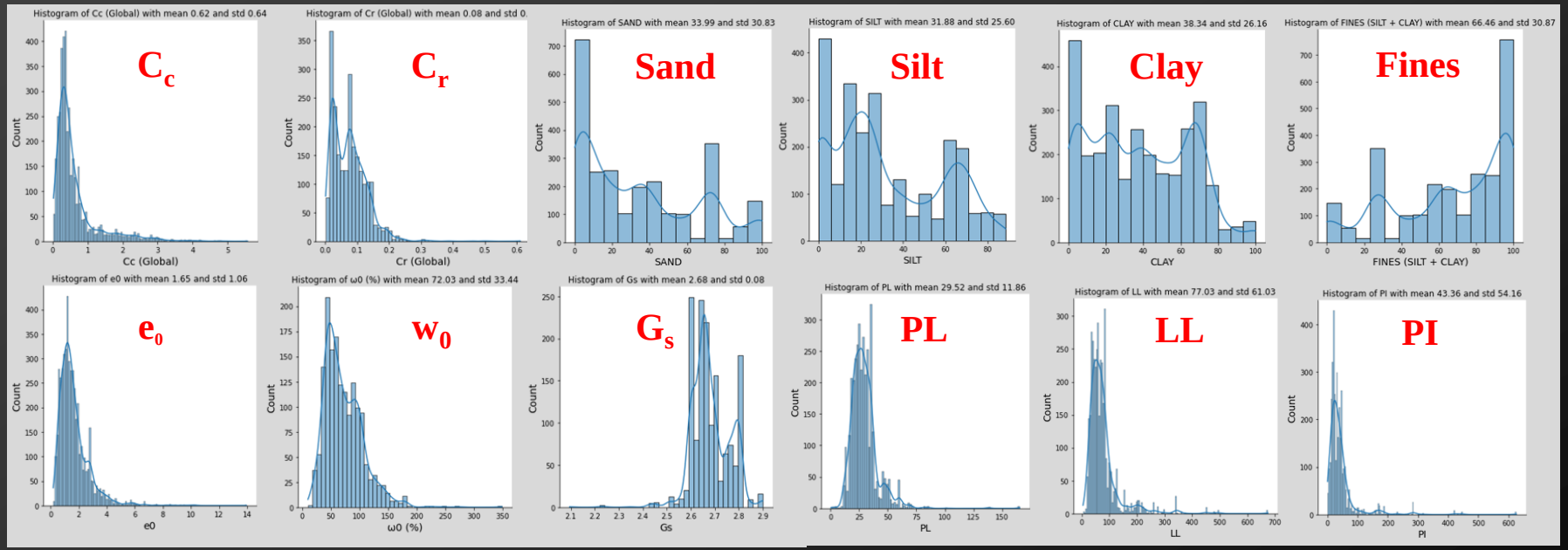

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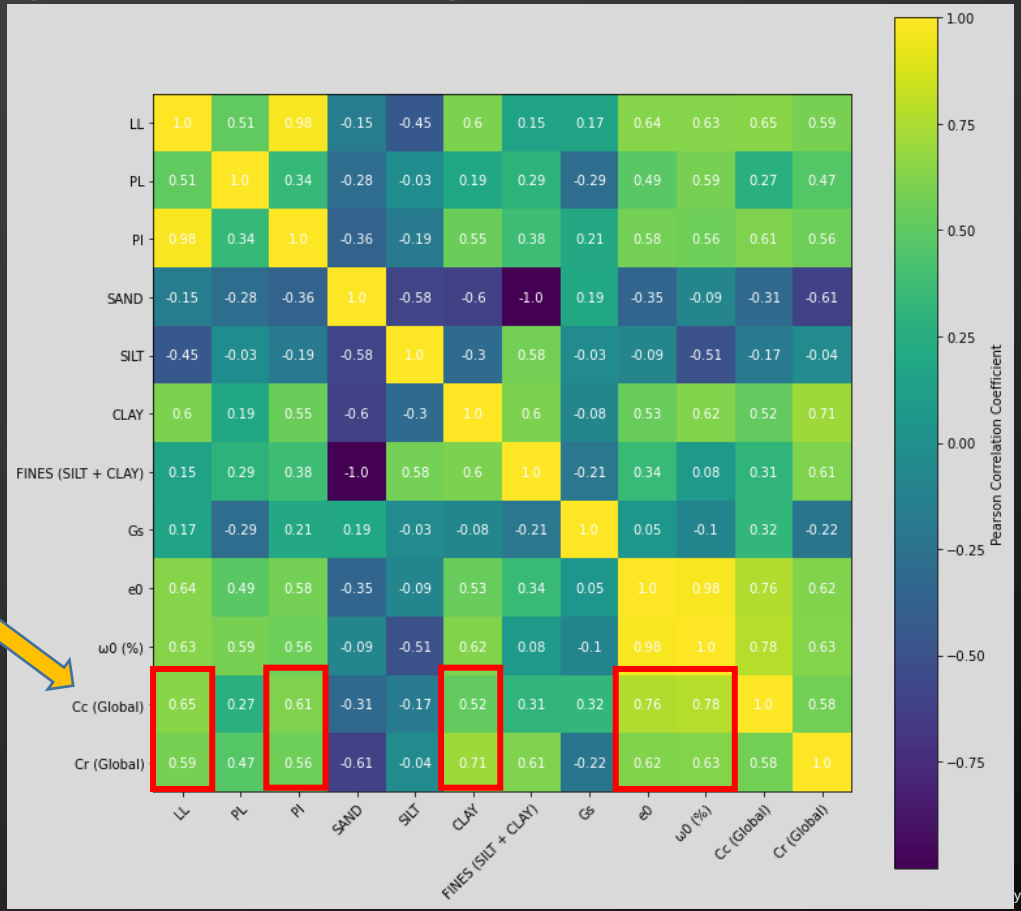
Engineering-Based Digital Twin Model

Correlation matrix of features in database



Increasing correlation

Strong correlation of compressibility (Cc) with:

- **Liquid limit (LL)**
- **Plasticity index (PI)**
- **Clay content (Clay)**
- **Initial void ratio (e0)**
- **Initial moisture (w0)**

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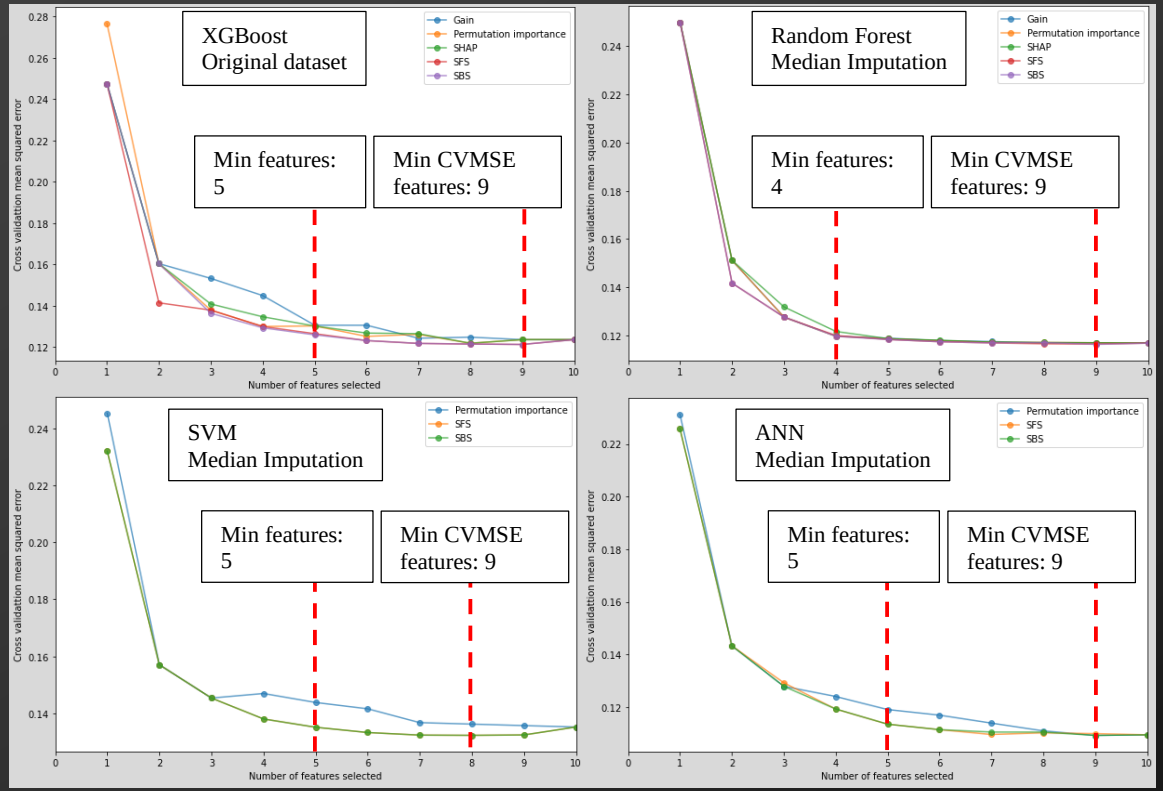
Engineering-Based Digital Twin Model



Feature selection for Cc prediction

- **All 4 machine learning technique showed min. 4~5 features for good prediction of compressibility (Cc).**
- **In good agreement with correlation matrix.**

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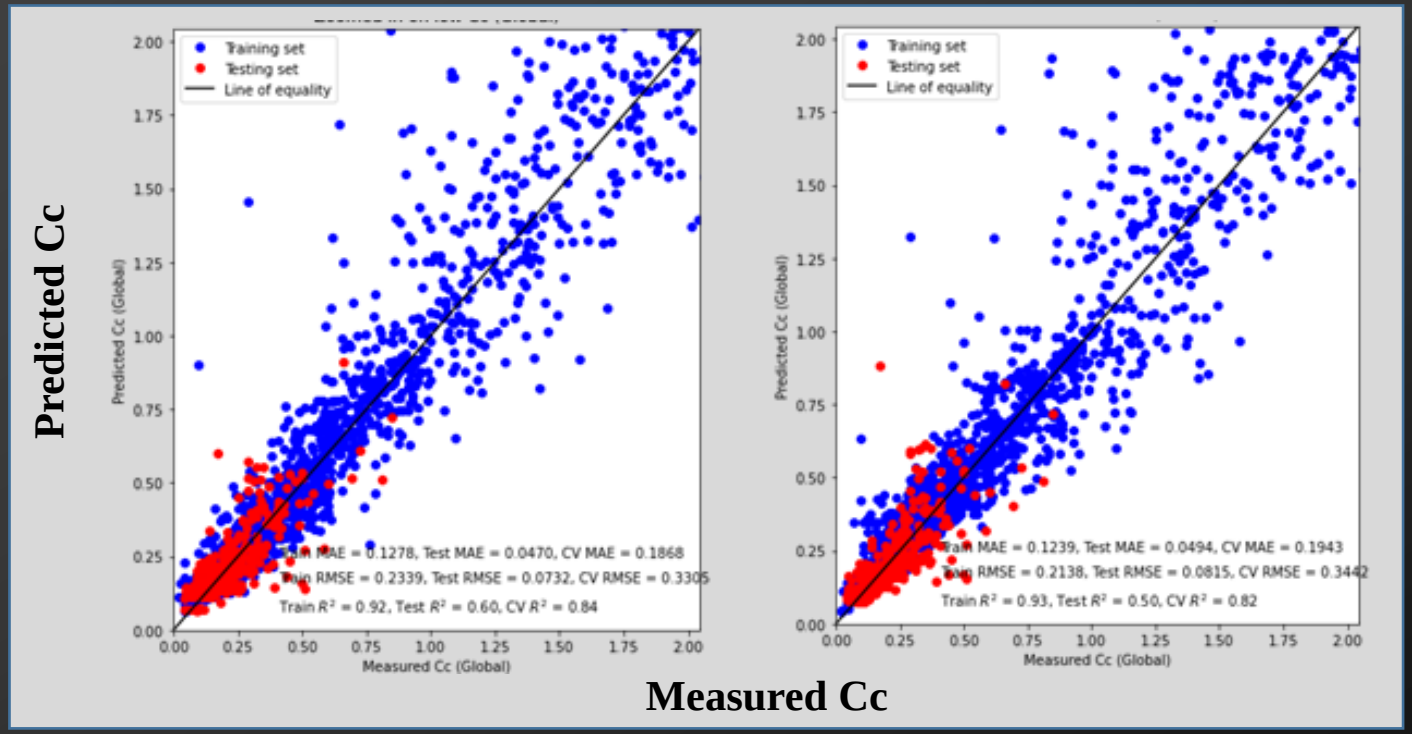
Engineering-Based Digital Twin Model



XGBoost

Random Forest

- **Good prediction vs measured Cc values with R^2 of about 0.82.**

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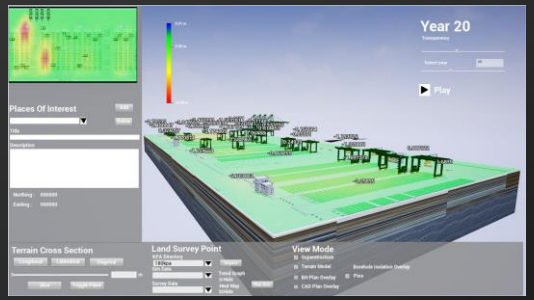
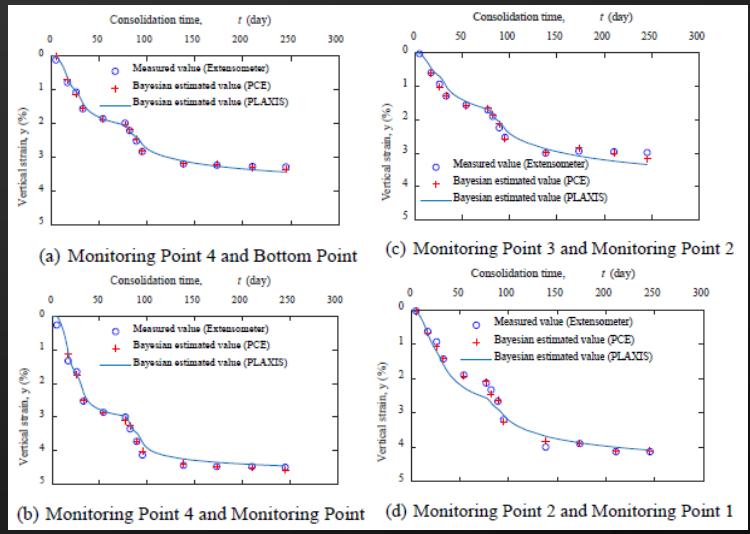
Engineering-Based Digital Twin Model

- **A digital twin, capable of refining soil parameters in numerical analysis with presence of actual ground settlement measurements over time.**
  - With progressively more field measurements, accuracy of prediction of settlement would improve via this automated feature in the digital twin.
  - Better facilitate anticipation of maintenance planning and minimise disruption to port operations.

Ground settlement with time from digital twin interface



Digitaland@Tuas user interface



Measured vs estimated settlement (Borehole 420A3)

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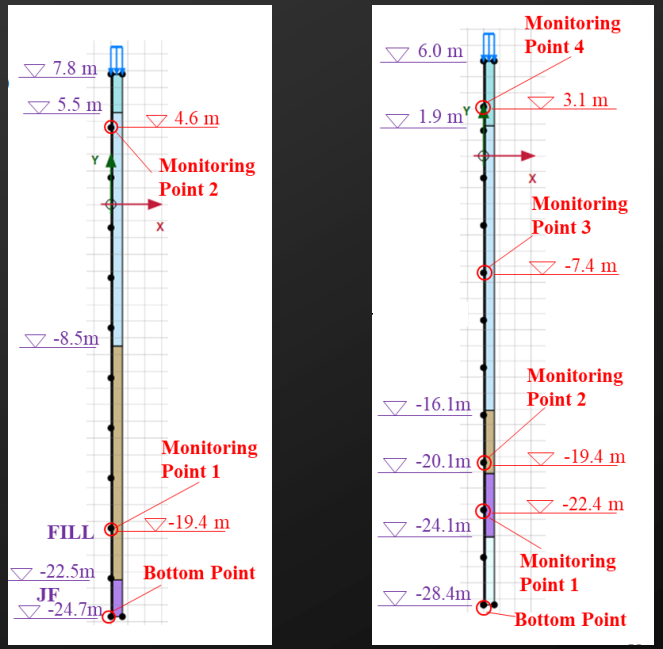
Engineering-Based Digital Twin Model

- **A digital twin, capable of refining soil parameters in numerical analysis with presence of actual ground settlement measurements over time.**
  - **Bayesian Updating of Soil Parameters**
    - First estimate of ground settlement based engineering numerical simulation on available data from borehole.
    - With progressive measurement of ground settlement, Bayesian updating carried out to fine-tune soil parameters for improved forecast of final settlement.



Borehole data

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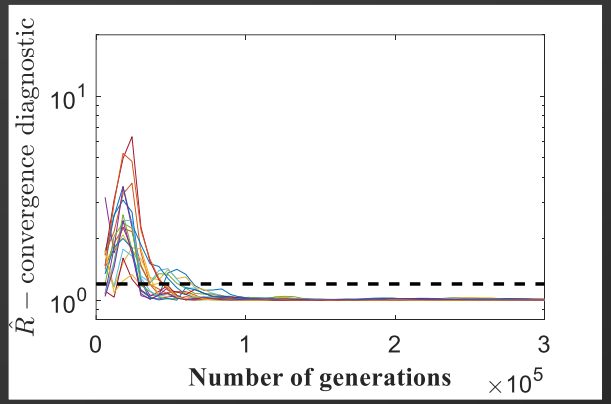
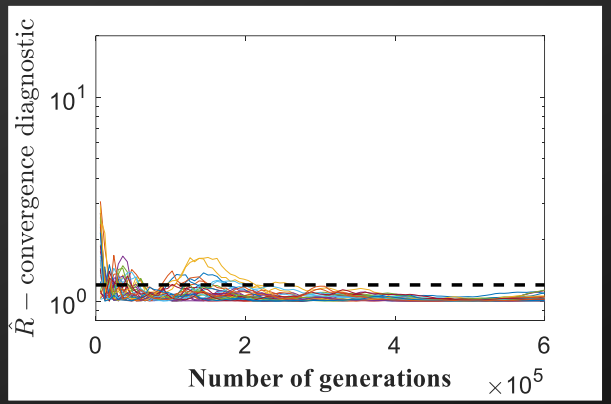
Engineering-Based Digital Twin Model

- **A digital twin, capable of refining soil parameters in numerical analysis with presence of actual ground settlement measurements over time.**

Borehole A



Borehole B



- Convergence after about ten to forty thousand of generations in surrogate model.

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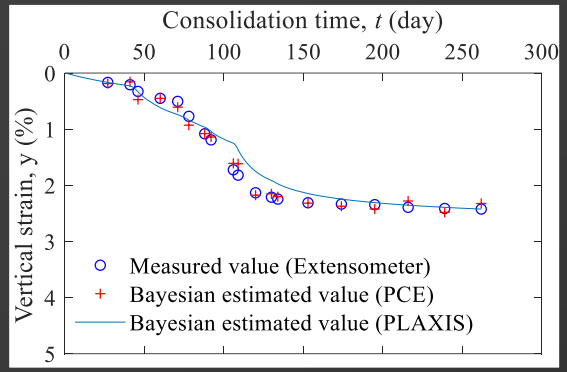
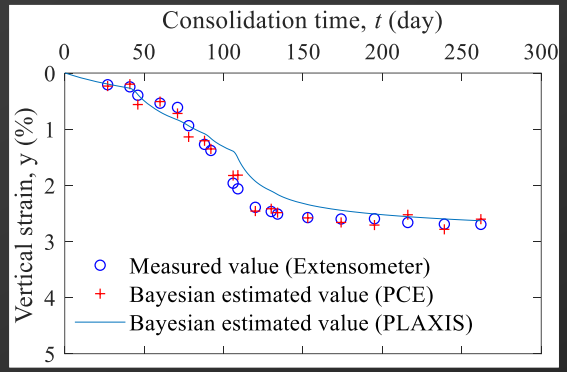
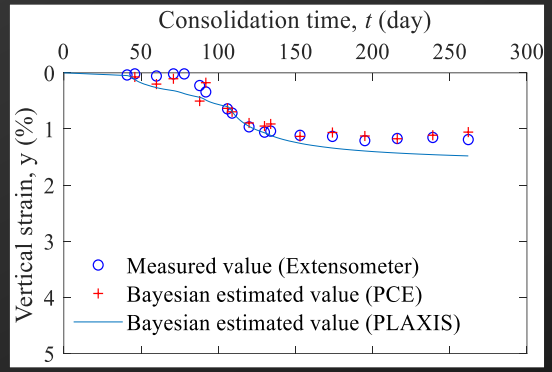
Borehole A



Monitoring Point 2 and Bottom Point

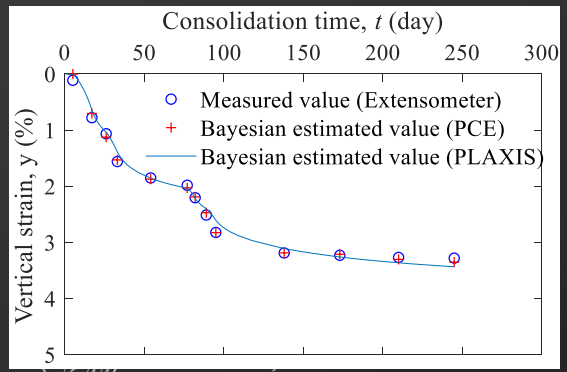


Monitoring Point 2 and Monitoring Point 1

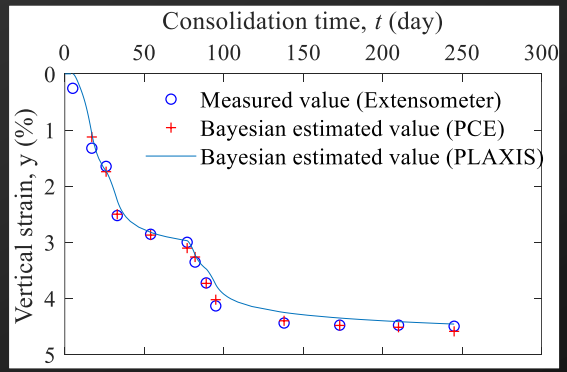


Monitoring Point 1 and Bottom Point

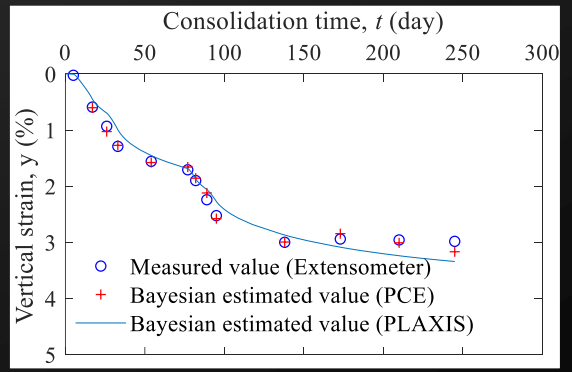
Borehole B



Monitoring Point 4 and Bottom Point



Monitoring Point 4 and Monitoring Point 3



Monitoring Point 3 and Monitoring Point 2

Closing Remarks

- **Impact of Research Work to the Industry:**
  - For Design Engineers:
    - Better anticipate of settlement using improved novel unit cell model.
    - Improved understanding and estimate of compressibility indices for different soil types obtained from machine learning techniques.
  - For Port Operator:
    - Facilitate maintenance planning and minimise disruption to port operations using Bayesian updating with inputs of progressively measured survey settlement.
  - For Developer:
    - Better anticipation of required ground improvement in land reclamation works in tender preparation.

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  - Reearch Fellow, Dr. Bi Jurong (now with Sea Limited)
  - Research Fellow, Dr. Shen Zhichao (now with South China University of Technology

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THANK YOU

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