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Data-driven approach to modelling bearing behaviors of OWT foundations

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Abstract

Proper estimation of offshore piles is vital to the life and permanence of the foundation in question. However, due to the uncertainties of soil parameters in the field, the offshore piles are greatly affected. The source of soil uncertainties may come from various reasons, such as lack of uniformity between in-situ test and laboratory experiment; spatial variability of soil profile and rationality of the constitutive model, etc. Traditional statistical analysis which is based on Monte Carlo, is time-consuming and laborious. Though Bayesian theorem provides ways to understand and update the uncertainties, the amount of the inference analysis is still computationally heavy, thus bringing big challenges for the pile design. Additionally, to mimic the geotechnical structures and bearing behaviors as accurate as possible, digital twin is seeping into all kinds of engineering problems, enabling to evolve over time to persistently represent a unique physical asset and achieving data-driven decision making process. However, state-of-the-art digital twins are still relying on considerable expertise and deployment resources, leading to an only one-off implementation and remaining limitation on providing adaptive digital models on unique offshore piles.

In this thesis, we hope to introduce Markov Chain process involving in Bayesian inverse analysis to speed up the calculation and provide reasonable posterior results for the soil parameters. Besides, as a mathematical and rigorous foundation, probabilistic graphical model is introduced to support the transition from custom defined model towards accessible digital twins at scale. Based on such flexible asset-specific models, the entire loading life-cycle can be incorporated into a digital twin forming a unified and accessible foundation for a wide range of offshore piles. Combined with monitored data, the proposed dynamic updated digital twin provides rapid analysis results for reliable soil parameters and enables intelligent decision making on the pile bearing behaviors.

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Chapter 1

Introduction

1.1 Background

Proper estimation of offshore piles is vital to the life and permanence of the foundation in question. However, due to the uncertainties of soil parameters in the field, the offshore piles are greatly effected. The source of soil uncertainties may come from various reasons, such as lack of uniformity between in-situ test and laboratory experiment; spatial variability of soil profile and rationality of the constitutive model, etc. Traditional statistical analysis is based on Monte Carlo, which is time-consuming and laborious. Even if Bayesian theorem provides a possible tool to understand and update the uncertainties for the priors, the amount of the inference analysis is still computationally heavy, thus bring big challenges for the pile design. One typical soil profile can be shown in fig. 1.1, it can be seen that:

- Fluctuating untrained shear strength curve indicates the spatial variability
- Non-uniformity exists between in-situ test and laboratory experiment

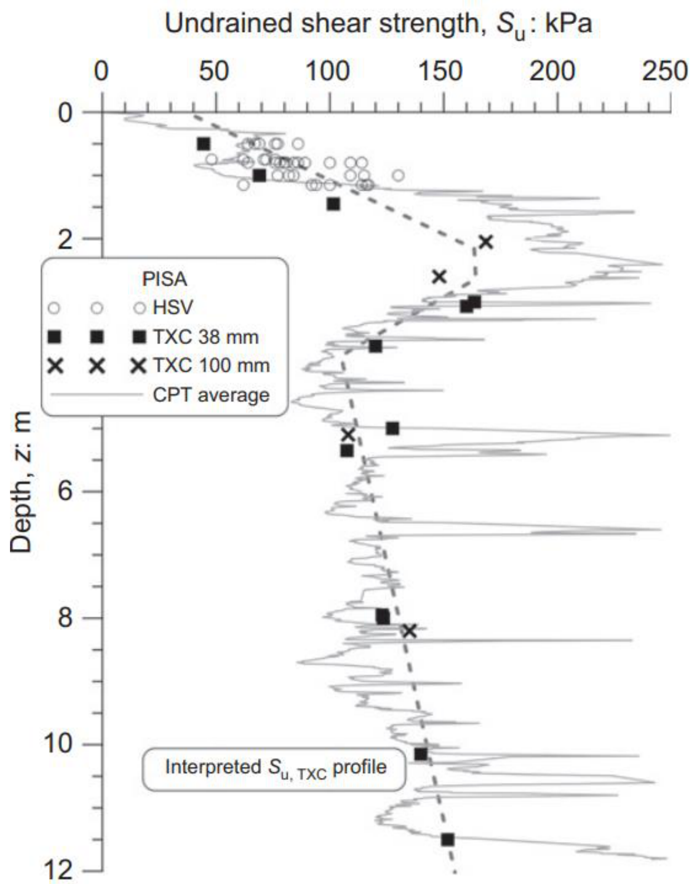

Figure 1.1: Untrained strength profile at Cowden (Zdravković et al., 2020)

1.2 Challenges

Bayesian theorem provides a possible tool to understand and update the uncertainties for the priors as shown in eq. (1.1).

$$P(A|B) = \frac{P(B|A) \cdot P(A)}{P(B)} \tag{1.1}$$

$P(A|B)$: posterior: Distribution of soil parameters;$P(B|A)$:likelihood: observed data and FE simulation based on priors; $P(A)$: prior: Soil parameters from lab/field. The challenges are:

- The amount of Inference analysis is time consuming (each soil layer can contain 2 to 14 parameters)
- How to get the best possible soil parameters distribution, based on the given priors, while avoiding extreme calculations.

Chapter 2

State of the Art

2.1 Markov Chain

As shown in fig. 2.1, Markov Chain is involved in Bayesian inference calculation and can therefore reduce the analysis time and provide reasonable posterior results.

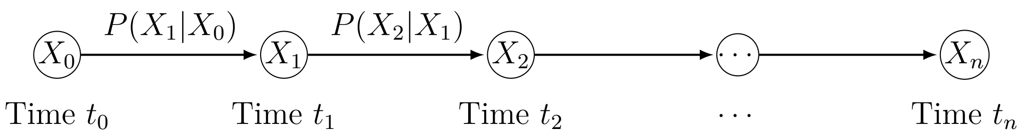

Figure 2.1: Markov Chain process

Markov Chain has two main features:

- State transition of Markov chains depends only on the current state, thus simplifying the modeling process
- Given the current state, a state transition probability distribution can be used to infer the likelihood of the next state

Thus, the properties of Markov Chain will bring two advantages:

- Adapt to more complex models (with increasing soil parameters)
- Iterative updating of parameter estimates because of Markov Chain's property (enables updating the priors through Bayesian inference in stage)

2.2 Partially observed Markov decision process (POMDP)

As shown in fig. 2.2, based on Markov Chain, with introducing Rewards and Actions, it can form the basis of Partially observed Markov decision process.

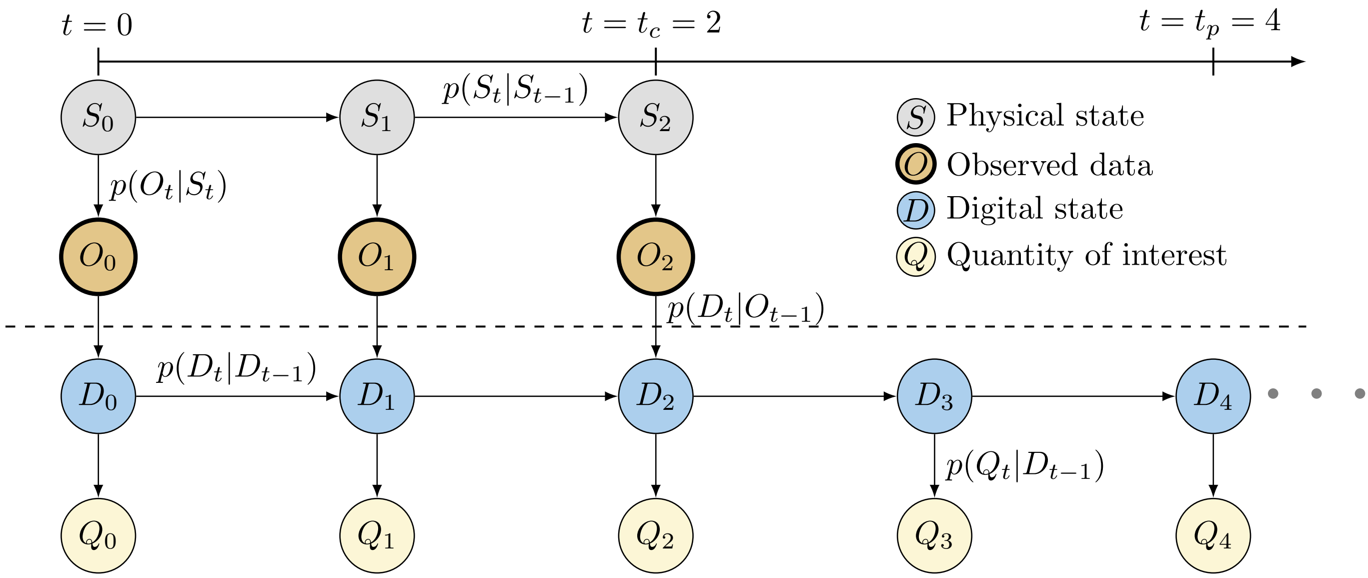

Figure 2.2: Untrained strength profile at Cowden (Kapteyn et al., 2021)

2.3 Digital Twin

Generally, Digital Twin can be divided into two main parts, including (1) calibration and assimilation (2) Prediction, as shown in eq. (2.1) and eq. (2.2).

$$\begin{aligned} &p(D_0, ..., D_{t_c}, Q_0, ..., Q_{t_c}, R_0, ..., R_{t_c}|o_0, ..., o_{t_c}, u_0, ..., u_{t_c}) \\ &= \prod_{t=0}^{t_c} [\phi_t^{update} \phi_t^{QoI} \phi_t^{evaluation}] \end{aligned} \tag{2.1}$$

$$\begin{aligned} &p(D_0, ..., D_{t_p}, Q_0, ..., Q_{t_p}, R_0, ..., R_{t_p}, U_{t_c+1}, ..., U_{t_p}|o_0, ..., o_{t_c}, u_0, ..., u_{t_c}) \\ &\propto \prod_{t=0}^{t_p} [\phi_t^{dynamics} \phi_t^{QoI} \phi_t^{evaluation}] \prod_{t=0}^{t_c} \phi_t^{assimilation} \prod_{t=t_c+1}^{t_p} \phi_t^{control} \end{aligned} \tag{2.2}$$

Chapter 3

Focus of the Work

3.1 Objectives

Introduce Markov Chain process involving in Bayesian inverse analysis to reduce the inverse analysis time and provide reasonable posterior results for the soil parameters. Based on Markov Chain process, we also introduce the Reward function and Action function to form the basis of digital twin. Combined with monitored data, the proposed probabilistic graph model-Partially Observed Markov Decision Process can be used to mimic and predict the pile bearing behaviors.

Chapter 4

Work Plan

4.1 Stage 1

Calibrate the models in fig. 4.1 with partially observed Markov decision process.

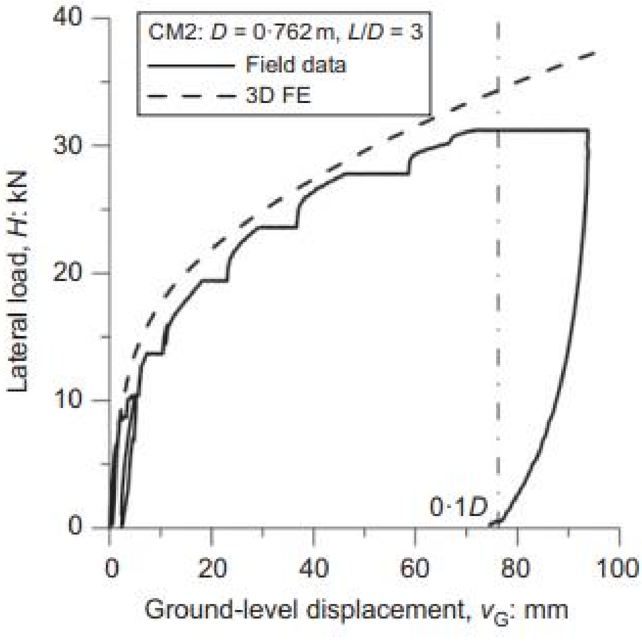

Figure 4.1: CM2 pile load displacement in (Zdravković et al., 2020)

- Software: ICFEP-Likelihoods and observed data.
- Constitutive model: clay in (Zdravković et al., 2020) and sand in (Taborda et al., 2020).
- Consider the soil profile variance-Create the random field (scale of fluctuation in ICFEP).

Objective: Ensure the soil parameters in digital model can reveal unique characteristics of piles.

4.2 Stage 2

In operational Phase, Based on Partially observed Markov decision process method, continue the assimilation process: extend the digital twin capability to capture the piles response during loading.

4.3 Stage 3

Extension to Prediction

4.4 Time plan

Table 4.1: PhD timeline

month	0	3	6	9	12	15	18	21	24	27	30	33	36	39	42	45	48
Literature review	✓	✓	✓														
Numerical modelling (Data collection)		✓	✓	✓	✓	✓	✓										
Statistics Methods learning		✓	✓	✓	✓	✓	✓	✓	✓								
Statistics analysis calibration			✓	✓	✓												
Statistics analysis assimilation						✓	✓	✓	✓	✓	✓						
Statistics analysis prediction												✓	✓	✓			
Thesis writing															✓	✓	✓
Journal/Conference								✓				✓					✓

References

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Taborda, D. M., Zdravković, L., Potts, D. M., Burd, H. J., Byrne, B. W., Gavin, K. G., … others (2020). Finite-element modelling of laterally loaded piles in a dense marine sand at dunkirk. *Géotechnique*, *70*(11), 1014–1029.

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