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A value of information framework for offshore wind site investigations

Leon Kučinić[1], Irina Stipanović[2], Ken Gavin[3], Mario Bačić[4]

[1,2]INFRA PLAN KONZALTING d.o.o., leon.kucinic@infraplan.hr, Irina.stipanovic@infraplan.hr

[3] Delft University of Technology, k.g.gavin@tudelft.nl

[4] University of Zagreb, Faculty of Civil Engineering, mario.bacic@grad.unizg.hr

Abstract

Geotechnical site investigations in projects of all scopes are governed more by budget constraints than actual requirements to resolve uncertainty of ground variability. This leads to under-designed or over-designed foundations. In the offshore wind context, where foundations account for 25–34% of total cost, the economic consequences of inadequate ground characterisation are significant. This paper proposes a Value of Information (VoI) framework to determine the optimal Cone Penetration Test (CPT) raster that builds on a probabilistic soil profile using Coupled Markov Chains (CMC) for stratigraphic uncertainty and Bayesian updating for strength parameter uncertainty. To turn these ground model properties into actionable insights, the probabilistic soil profile is propagated through an analytical structural response model to determine the required foundation steel volume and thus total construction costs. The optimal CPT raster is the configuration that optimises the expected reduction in project cost relative to additional investigation expenses. This paper presents a conceptual framework which will be further developed and validated on real site data during the PhD studies.

Key words: Value of Information, Site Investigation, Coupled Markov Chain, Bayesian Updating, Offshore Wind, Monopile Foundation, CPT

Model Vrijednosti Informacije za geotehničke istražne radove pučinskih vjetroelektrana

Sažetak

Geotehnički istražni radovi u projektima svih opsega prvenstveno su ograničena projektnim budžetom, a ne stvarnim zahtjevima za rješavanje nesigurnosti varijabilnosti tla. To dovodi do poddimenzioniranja ili predimenzioniranja temelja. U kontekstu pučinskih vjetroelektrana, gdje temelji čine 25-34 % ukupnih troškova, ekonomske posljedice neadekvatne karakterizacije tla su značajne. Ovaj rad predlaže okvir temeljen na vrijednosti informacija (VoI) za određivanje optimalnog rastera statičkog penetracijskog pokusa (CPT) koji koristi probabilistički profil tla pri čemu je stratigrafija modelirana uparenim Markovljevim lancima, a parametri čvrstoće Bayesovim ažuriranjem. Kako bi se svojstva ovog modela tla pretvorila u praktične rezultate, probabilistički profil tla propagira se kroz analitički model strukturnog odziva kako bi se odredio potreban volumen čelika temelja i time i ukupni troškovi gradnje. Optimalni CPT raster je konfiguracija koja optimizira očekivano smanjenje troškova u odnosu na dodatne troškove istraživanja. Ovaj rad predstavlja konceptualan model koji će se tokom doktorskog istraživanja dalje razviti i validirati sa stvarnim podacima.

Ključne riječi: vrijednost Informacije, terenski istražni radovi, upareni Markovljevi lanci, Bayesovo ažuriranje, pučinske vjetroelektrane, monopiloti, CPT

1 Introduction

One of the largest sources of financial and technical risk in civil engineering are soil conditions. Minimal investigation cost (as low as 0.025-0.3 % of total project cost) can lead to significant cost over-runs and delays down the project [1]. Site investigations represent the primary tool to address and reduce the uncertainty in projects when it comes to soil conditions. With increase in observed data, uncertainties can be reduced through updating mean values and decreasing distribution spread which will benefit the design and construction stages of the project [2]. However, there is always a trade-off between investigation efforts and improved knowledge of design soil parameters. Nevertheless, geotechnical site investigation scope is rarely adjusted to the anticipated variability of the ground, rather it is chosen to minimise initial costs. This practice can lead to significant consequences on both ends of design spectrum: a geotechnical structure can be under-designed due to non-conservative geotechnical model, therefore risking structural failure or over-designed due to the excess of conservatism, and by that wasting materials and costs [1].

These consequences are accentuated in offshore wind projects, where foundations account for 25 to 34 % of total project cost [3]. Monopiles, large diameter tubular steel piles, are the most common type of foundation for offshore wind turbines, and their design is sensitive to soil parameters which amplifies the impact of ground model uncertainty on the project economics. This is compounded further by the transition to deeper water and more complex ground conditions which result in significant challenges beyond conventional geotechnical engineering practice [4].

A quantitative decision support framework for required additional investigation can have significant impact on the final project design quality and total project costs, while narrowing down parameters distributions. Value of Information (VoI) analysis is already a common practice across various industries such as healthcare, oil & gas, economics, and is gaining popularity in civil engineering [5, 6]. Recently, VoI has been applied to geotechnical site investigation, where additional data is modelled as reducing the uncertainty and improving design outcomes [5]. Pre-posterior decision analysis quantifies the expected benefit of additional information before it is acquired.

In this paper, a framework is developed based on VoI for optimising Cone Penetration Test (CPT) raster for offshore wind turbines on monopiles which will enable rational and quantitative decision on the location and number of additional CPT sites.

2 Value of information framework

The proposed framework optimises the number and position of CPT investigations for an offshore wind farm by maximising the VoI in regard to the investigation costs. The financial metric is the expected cost of steel in the monopile foundation, which is primarily driven by the maximum bending moment induced by lateral loading, as this governs the required structural dimensions and thus the steel volume. Visualization of the framework process is shown in Figure 1. The framework begins with the existing data: regional geology mapping, geophysical investigations and any existing CPTs or boreholes. From this, an initial probabilistic soil profile is constructed at every point of the site. Stratigraphic uncertainty is modelled with Coupled Markov Chains (CMC) which are built from initial geological and geophysical data and calibrated on existing CPT and borehole investigations. Uncertainty in soil strength parameters is modelled using probabilistic distributions, where prior distributions are informed by geology, geophysics, and literature, and are updated to posterior distributions using CPT measurements and borehole data.

After that, a Monte Carlo analysis is used to propagate uncertainty of the probabilistic soil profile which turns strength parameters and stratigraphy into distribution of maximum bending moments, through the use of analytical p-y Winkler beam model.

For each of the candidate CPT locations, the expected VoI is evaluated as the predicted reduction in steel cost. Each new investigation point constrains the CMC model, while its CPT resistance values narrow the Bayesian posterior distribution of strength parameters. The benefit of new CPT extends beyond its location, narrowing the posterior distribution of surrounded area within a distance governed by scale of fluctuation.

Candidate location which maximizes cost reduction relative to investigation cost is selected. The process is repeated until the VoI of the next CPT falls below its mobilisation cost.

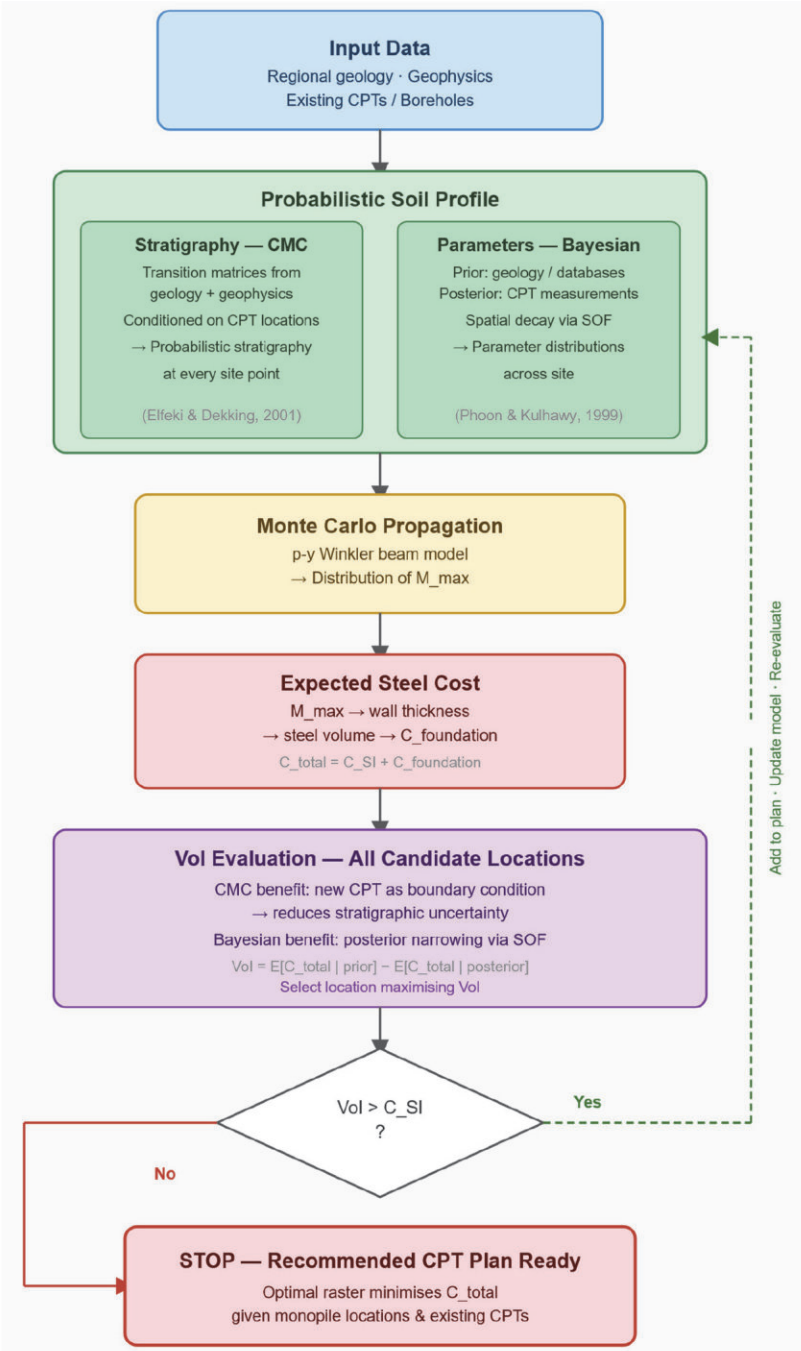

Figure 1. VoI Framework Workflow

3 Probabilistic characterisation of soil profile

Soil is a natural material formed through a long and complex geological processes that are still ongoing. Because of that, soil properties vary both in horizontal and vertical direction across almost any site [7]. Since in-situ investigation only give data in a form of a localized point, any properties between two known points are inherently uncertain. Therefore, a probabilistic soil profile is built through two sequential steps. Firstly, stratigraphic uncertainty is addressed using Coupled Markov Chains which is then followed by Bayesian updating of soil strength parameters.

3.1 Stratigraphic uncertainty: Coupled markov chains

Between two CPT locations, exact stratigraphy remains uncertain as point measurements cannot resolve what can be between them [8]. Spatial variability exists because properties and geometric features such as stratification, voids and discontinuities are spatially heterogenous [7]. Instead of assuming a deterministic stratigraphy, the CMC model can be used to assign probabilities to all possible stratigraphic configurations [9]. Markov chain is a stochastic model in which the state at any step depends only on its immediate predecessor, which makes it applicable to modelling discrete geological variables. CMC extends this into two dimensions, vertical chain to capture variation with depth, and horizontal chain to capture lateral variation coupled with a joint transition probability:

$$\Pr(Z_{i,j} = S_k \mid Z_{i-1,j} = S_l,\ Z_{i,j-1} = S_m) = C \Pr(X_i = S_k \mid X_{i-1} = S_l)\ \Pr(Y_j = S_k \mid Y_{j-1} = S_m) \qquad (1)$$

Where $Z_{i,j}$ is soil state at cell (i,j), S_k, S_l, S_m are possible geological states, X_i is the horizontal Markov Chain, Y_j is the vertical Markov Chain and C is a normalising constant ensuring the probabilities sum to one.
Transition matrices are calibrated from geological maps and geophysical survey data. CPT observations represent a fixed boundary condition at a given point, and each additional investigation point narrows down the possible solution and pushes it toward true formation [9].

3.2 Strength parameter uncertainty: Bayesian updating

Once the stratigraphy uncertainty is addressed, strength parameters still remain uncertain. This uncertainty stems from three primary sources: inherent variability due to natural geological processes, measurement error caused by equipment and operator defects and transformation uncertainty where measurements, in this case CPT values are converted into strength parameters through empirical correlation models [7].

Prior to site investigations, parameter distribution can be derived from geological maps, regional guides and published databases which will all have broad distributions and reflect the initial high uncertainty [10]. The distribution is then updated using CPT measurements. CPT provides cone resistance values with depth of the soil. These can be then transformed, through established empirical correlations, into strength parameters. Bayes' theorem then combines the prior distribution with this new measurement to produce a posterior distribution which is narrower and better constrained than the prior:

$$f(\theta \mid D) = \frac{L(\theta \mid D) f\left(\theta\right)}{\int \cdots \int L(\theta \mid D) f\left(\theta\right) d\theta} \tag{2}$$

where f (θ | D) is the posterior probability density function of θ representing the combined knowledge, L(θ | D) is the likelihood function indicating the probability of observing data D given θ, and f(θ) is the prior probability density function representing the initial knowledge about θ before any site-specific measurements are taken.

The influence of CPT measurement on strength parameter distribution across whole site can be described as deterministic in the point of investigation, and decays spatially with distance. This correlation is characterized by scale of fluctuation [7] which defines the horizontal distance within which the soil properties show strong correlation. Beyond this distance, model falls back on the prior distribution. The function used to describe the form of decay is selected to best represent the spatial behaviour of strength parameters. Gaussian decay can be used for smoothly varying properties.

4 Structural response

To translate the probabilistic soil profile into a structural behaviour, The Beam on Nonlinear Winkler Foundation (BNWF) method, more commonly known as p-y method is used [3]. It represents one of the most widely used analytical methods for analysing laterally loaded piles. Premise is that soil reaction *p* at any depth is proportional to the pile-soil deflection, modelled as independent springs along the pile length. More advanced frameworks such as PISA are proposed for large diameter monopiles [11]. Key structural output used from these analyses is maximum mudline bending moment, which governs the required pile diameter and wall thickness and through that the steel mass of the foundation.

A representative set of soil profiles sampled through the use of Monte Carlo Method is propagated through the p-y model, with each of them giving a corresponding mudline bending moment as a result. These form the distribution of bending moment across the observed site. Addition of a new CPT simultaneously provides a new fixed boundary condition for the CMC and its stratigraphic realisations and narrows the posterior distribution of strength parameters through Bayesian updating. A further set of p-y analyses on the updated soil profile will result in reduction of the bending moment spread and therefore expected steel cost.

5 Value of information

The concept of pre-posterior decision analysis was formalised by Raiffa & Schlaifer [12] as a method to evaluate the utility of an experiment prior to its execution by computing the expectation of posterior outcomes across all possible results of an experiment. In engineering, this was adapted into a cost-minimisation framework: the optimal decision is the one that minimises total expected cost, where information collection and action decision are optimised jointly [13]. In construction industry, Bayesian decision analysis has been around since 1970s, particularly in the field of planning of operation and maintenance strategies [6]. Recently, VoI has been applied to geotechnical site investigation, where additional data is modelled as reducing the uncertainty and improving design outcomes [5].

This paper applies the same principle to the CPT raster optimisation for offshore wind monopile foundations. Total expected project cost is expressed as:

$$C_{total} = C_{SI} + C_{foundation} \tag{3}$$

Where C_{SI} is the cost of site investigations, $C_{foundation}$ is the foundation steel cost, which is determined through the distribution of soil properties. They govern the mudline bending moment in the analytical structural response model, which in turn is used to design pile wall thickness. Together with pile length and price of steel, it is used to calculate $C_{foundation}$.

Benefit of any CPT raster configuration can then be expressed as a reduction in total cost in relation to the prior state of knowledge:

$$VoI = E\left[C_{total}^{prior}\right] - E\left[C_{total}^{posterior}\right] \tag{4}$$

Decision variable that needs to be optimised is the CPT raster, number and spatial arrangement of additional sites. Candidate locations are constrained by existing CPTs and their area of influence. Planned locations of monopile foundations also provide an additional layer of economic constraint. Optimal raster is the configuration that minimises the C_{total}. These components brought together form a planning tool that enables rational, site-specific decisions on the scope of additional geotechnical investigation.

6 Conclusion

Geotechnical site investigations are critical to both structural performance and economic feasibility of projects, especially in offshore wind farms. Still, investment decisions are made on the basis of minimal requirements and rarely based on the analysis that quantifies the value additional site investigation can bring forth. A framework that speaks both to the design geotechnical engineer and investor, translating the investigation campaign into expected reductions in material costs has significant potential. This paper presents a preliminary description of such framework with basis in VoI and probabilistic ground modelling. Current formulation remains conceptual and is intended as a starting point for further development where assumptions will be refined as framework matures. The proposed framework is also applicable in scenarios where no site-specific investigation data are available. In such cases the initial probabilistic soil profile would rely on regional geology, published databases and expert judgement, which would result in larger prior uncertainty. Consequently, expected VoI of initial CPTs would be higher, and their value would decrease as model becomes better constrained. In the next research phase data from real sites will be used for the demonstration of each individual component in order to validate the framework and propose the implementation in practice.

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