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Observational method applied to the decision optimizing of foundation method in Kujala Interchange on silty clay subsoil

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Abstract. Observational method is a powerful approach to dealing with uncertainty in subsoil conditions. In the presented case study, Kujala Interchange, constructing test embankments and applying the observational method enabled to replace many initially planned pile slab foundations with ground-supported road embankments. The residual settlements of these embankments were controlled by means of preloading accompanied with monitoring. This paper demonstrates how a decision tree analysis can be employed to assess the feasibility of constructing the test embankments. The prior probability of acceptable settlements of the ground-supported embankments is estimated for a typical soil profile in Kujala area via Monte Carlo simulation. This prior probability is then updated via monitoring results and Bayes' Theorem. Lastly, the expected costs of each design alternative are derived based on their respective probabilities and the actual cost savings acquired at Kujala Interchange. The results of the decision tree analysis confirm that constructing the test embankments and minimizing the pile foundations was the optimal decision in this case study. In sum, this paper shows how the observational method can be employed to reduce the expected costs and environmental impact of foundation design characterized by significant uncertainty in subsoil conditions. However, it is concluded that besides monetary costs, one should also include non-monetary consequences such as carbon dioxide emissions.

Keywords: Observational method, Decision tree, Road embankment, Bayes.

1 Introduction

Geotechnical engineers have developed many strategies to deal with uncertainty. According to Christian [1], they include: (1) ignoring it, (2) being conservative, (3) using the observational method, and (4) quantifying uncertainty. The second approach, conservatism, has been widely used with satisfactory results, but it may result in non-economical design solutions in challenging site conditions. Hence, in projects with higher level of uncertainty and greater difficulties to predict the geotechnical behavior, the observational method (OM) might be more suitable [2, 3]. This recommendation to consider OM is also given by the Eurocode 7 for Geotechnical Design [4].

In Kujala Interchange, which is a part of Highway 12 in Finland, the considerable uncertainty in the geotechnical properties of the silty clay subsoil conditions led the designers to apply observational method. The uncertainty in subsoil properties was partly caused by the high sensitivity of silty layers, which led to sample disturbance. As a result, field vane and oedometer tests were deemed unreliable. Thus, the epistemic uncertainty in both stability and settlement predictions was lowered by monitoring of two 4-5.5 meters high test embankments. Besides the test embankments, settlement monitoring was performed in other road sections in the interchange area also during the construction process. As a result, most of the initially planned pile slab foundations could be replaced by ground-supported road embankments; the residual settlements were decreased by applying preloading. In addition, lightweight fills made of recycled foamed glass were used in transition zones. This optimization of foundation method led to construction cost savings of six million euros (6 M€) compared to the initial road plan estimate; compared to the initial plan, the amount of pile slabs was reduced to one third, and the amount of lightweight fills became 1.5 times larger.

This paper utilizes a decision tree analysis to quantify the expected costs of different foundation method alternatives in the case of Kujala Interchange (conservative design versus optimized design, i.e., minimized pile foundations). In addition, this paper demonstrates how one can rationally evaluate whether it is an optimal decision to apply observational method (to construct the test embankments) or not. In sum, this case study shows how the observational method together with decision tree analysis can be employed to reduce both monetary costs and environmental impact of design cases with low quality site investigations.

2 Project description

Kujala Interchange area forms the Eastern border of Part 1B in Highway 12, Southern Ring Road of Lahti. Part 1B was assessed to be technically the most challenging part of the project. Hence, the selected procurement model was an alliance, which is considered to be suitable model for executing a complex project with considerable risks [5]. VALTARI alliance is formed by the owner parties (Finnish Transport Infrastructure Agency, City of Lahti and Municipality of Hollola) and the service providers Skanska Infra Oy and Pöyry Finland Oy. The geotechnical design of Kujala Interchange was provided by Pöyry Finland Oy, and Skanska Infra Oy was the constructor.

The allowable settlements in Kujala Interchange during service time were defined by the Finnish Transport Infrastructure Agency. The maximum total settlement for road embankments was either 300 mm (class V1) or 400 mm (class V2) during 50 years of operation. The maximum change in longitudinal grade (slope) was set to 0.6 percentage points (p.p) in 50 years and 0.8 p.p./50 years for classes V1 and V2, respectively. In transition zones, no more than half of this maximum change in grade is allowed. Due to this limit, the maximum total settlement was set to 50 mm/50 years at the transitions to the piled structures.

The subsoil in Kujala area consists of 10-25 meters of clay and silt. Between the fine-grained soil and bedrock, there is a few meters thick layer of glacial till. The groundwater depth is at 0.3-2 meters. The thickness of top clay layer (dry crust) is 2-4 meters. The water content of clay and silt layers is 30-90 %, and the liquid limit is approximately equal or slightly greater than the water content. The clay fraction is 30-70 %. The undrained shear strength is in the scale of 20-50 kN/m^2 in clay and silt layers and up to 200 kN/m^2 in the dry crust layer. The sensitivity is mostly in the scale of 10, but in some silt-rich layers, the sensitivity is up to 60. The overconsolidation ratio (OCR) is mostly in the scale of 1.5-2 but higher (OCR=4-6) in the dry crust layer.

Two instrumented 4-5.5 meters high test embankments were constructed in order to increase the reliability of settlement predictions. These embankments will remain as a part of final interchange ramp structures. The monitoring data was collected for six months before starting the construction at the area; settlements, horizontal displacements (via inclinometers) and pore pressure measurements were recorded every 2-4 hours. The data collection was continued for almost 1.5 years. Besides monitoring, an extensive ground investigation program was planned with special focus on ensuring the best possible quality. The settlement predictions were then calibrated using the newly collected data, and it turned out that the subsoil conditions were more favorable than what the preliminary ground investigation implied. Consequently, these test embankments and other monitoring in the area (i.e., observational method) allowed for minimizing the pile foundations in Kujala Interchange.

3 Observational method

The principles of *observational method* were first defined by Peck [6], based on a methodology applied by Terzaghi. Peck [6] states that the observational method can enable considerable savings in time or money, or provide the needed assurance for the safety (reliability) of the design. Terzaghi, who applied this method successfully, called it the ‘learn-as-you-go’ method [6]. Christian [1] summarizes the basis of the observational method as follows: “It involves (1) considering possible modes of unsatisfactory performance or other undesirable developments; (2) developing plans for dealing with each such development; (3) making field measurements during construction and operation to establish whether the developments are occurring; and (4) reacting to the observed behavior by changing the design or construction process.”

According to Peck [6], observational method is often used to provide affirmation that enough time has elapsed for a certain desirable outcome. In the case of preloading, the desirable outcome would be that enough settlements occur during the available consolidation time in order to minimize the settlements that would occur during the operation time. Peck [6] continues, that the observational method can only be used if the engineer can alter the design during construction. Consequently, the specifics of the contract between the owner and the constructor may pose limitations to the usage of observational method. The strength in alliance model, which was the model applied in Kujala Interchange, is that the communication between the constructor, designer and owner parties is proficient, and optimizing the design solutions is encouraged for by means of bonus and sanctions scheme. The service-providing parties can earn bonuses via working towards solutions that are accordance with the agreed key objectives [5].

Peck [6] also notes that in some cases the probability of most unfavorable conditions is so high that the usage of observational method is simply not economical. In other words, if the expected probability of needing contingency actions is too high with respect to their cost, the observational method does not provide more favorable option than the conventional design [7]. That is, the engineer should have a prior position that the actual conditions are more favorable (or the same) as predicted before the observations. In the case of Kujala area, the prior position based on engineering judgement was that the geotechnical properties of the silty clay subsoil should be more favorable than what was indicated by the preliminary ground investigations. Moreover, the uncertainty in OCR forced the engineers to consider the most unfavorable conditions (subsoil in OCR=1 state mostly). As noted by Terzaghi [6], this conservatism-based approach to deal with high uncertainty can be uneconomical.

Observational method has not been widely used in Finland; the usage has been increasing in the field of rock engineering, but in foundation engineering the systematic use has been more scarce. In his master thesis research, Bäcklund [8] interviewed industry representatives during years 2012-2013 and concluded that the main reason for the rare applications of observational method has been that the geotechnical designers do not fully understand its principles or possible benefits. Nevertheless, the observational method has been successfully applied in other Nordic countries (e.g. [2]). In order to study which is more effective, the observational method or conventional design, one can apply decision optimizing methods such as decision tree analysis [7].

4 Decision tree analysis

A *decision tree* is an organized graph that presents the information available for the decision making [9]. It is formed by two basic components: alternatives and outcomes [10]. Different events arise from the outcome nodes (chance nodes), and one can assess the probability of these outcomes. Fig. 1 presents a basic decision tree for two alternative designs (a_i) for Kujala Interchange with their possible outcomes, consequences and their respective probabilities (P_{ij}).

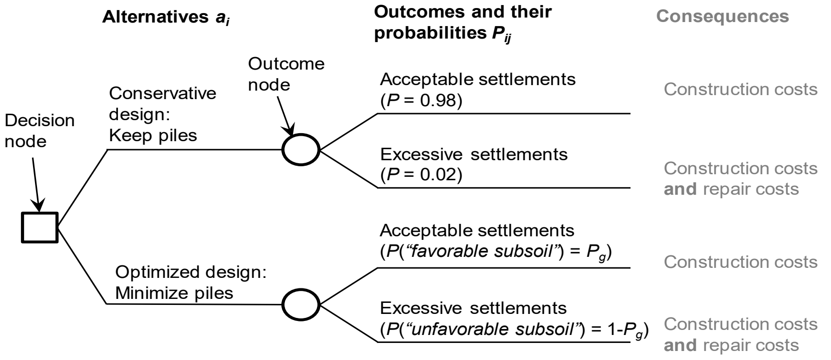

Fig. 1. Basic decision tree for the serviceability limit state design of a road foundation (modified after Gilbert et al. [10]).

The probability of excessive settlements in the case of conservative design ("keep the piles") is usually low; it is here assumed that there is P=0.02 probability in the case of a design consisting mostly of end-bearing piles supported by the bedrock. On contrary, the probability of excessive settlements in the case of ground-supported embankments is usually much greater. In this study, 'minimize piles' (Fig. 1) refers to an optimized design in which pile slab foundations are replaced with ground-supported road embankments at all sections in which it is feasible given the design criteria and the available knowledge on the subsoil conditions. This optimized design will require more site investigations and monitoring compared to over-designing (i.e., "keep the piles").

When the consequences can be defined as monetary costs or value, a common procedure is to adopt the decision criterion known as *maximum expected monetary gain* [11, 12]. In other words, the optimized decision is the design alternative with the smallest expected monetary cost (or the greatest value). This *expected monetary cost* of the ith design alternative $E(a_i)$ is derived by weighting the total cost of each outcome (C_{ij}) by its probability P_{ij} [11]:

$$E(a_i) = \sum_j P_{ij} C_{ij} \tag{1}$$

Besides monetary costs, one can also include other consequences such as environmental impact or human health risks. A common procedure is to then combine all the attributes to a single monetary value, or, alternatively, to a utility value [10].

In the simple case presented in Fig. 1, the expected monetary costs of the optimized design alternative for Kujala Interchange are:

$$E\left(a_{minimize\ piles}\right) = C_{constr.} P_g + (C_{constr.} + C_{repair})\left(1 - P_g\right) \tag{2}$$

$$\rightarrow E\left(a_{minimize\ piles}\right) = (C_{constr.} + C_{repair}) - C_{repair} P_g \tag{3}$$

Where C_{constr} is the cost of construction, C_{repair} is the cost of repair and other costs created by excessive settlements, P_g is the probability of acceptable settlements and $(1-P_g)$ is the probability of excessive settlements. Probability g is later referred to as the 'probability of favorable subsoil conditions'. Fig. 2 presents the expected relative cost of the two alternatives (optimized design and 'keep the piles' alternative).

In Kujala Interchange area, the expected cost of keeping the piles does not depend on the probability of favorable subsoil conditions P_g, because the end-bearing piles are supported by the bedrock. On the other hand, the expected cost of fully optimized design (minimizing the piles) decreases linearly as the probability of favorable subsoil conditions P_g increases. At P_g=1, the relative cost of optimized design is zero, whereas the expected cost of keeping the piles is 6M€ greater. This difference (6M€) corresponds to the actual cost savings acquired in Kujala Interchange by replacing two thirds of the initially planned pilings with ground-supported embankments).

At P_g=0, the intercept of expected cost for optimized design ($E(a_{\text{minimize piles}})$) is defined by the assumed costs of construction and repair (C_{constr} + C_{repair}). At these low values of g, the risk of both excessive settlements and stability issues is so large that the conservative design ('keep the piles') is usually preferred. Hence, the lowest value for C_{repair} should be in the scale of 1.5 times the construction costs (dotted line in Fig.

2); at low values of P_g, the expected cost of 'keep piles' is then lower and thus optimal. However, the authors estimate that the actual monetary repair cost of excessive settlements would be lower; thus, it is assumed that C_{repair} here includes other consequences also, such as contingency actions required by low stability, environmental impact, and repair works' consequences to road users.

Given the assumed relative costs of excessive settlements, minimizing the piles becomes more optimal when P_g is larger than 0.2−0.4. In the following sections, the site-specific probability of favorable subsoil conditions (P_g) for Kujala area is assessed.

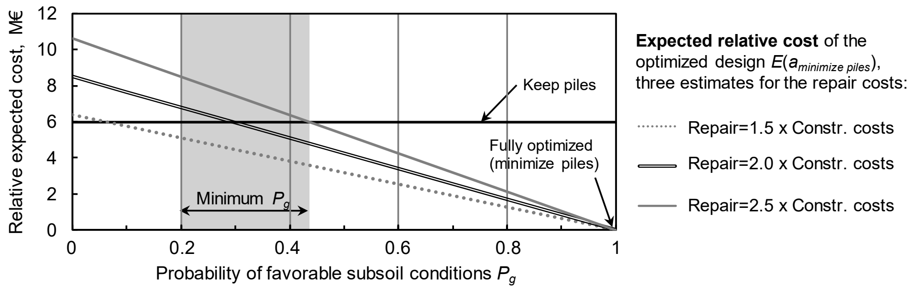

Fig. 2. Expected relative costs for the alternative designs (keep piles versus minimized piles).

5 Decision optimizing for Kujala Interchange

5.1 Prior probability of favorable subsoil conditions

In order to study the feasibility of constructing the test embankments, the probability of acceptable settlements (that is, the probability of favorable subsoil conditions P_g) must be high enough. In order to assess this probability, the prior distribution of residual settlement was estimated for a typical soil profile in Kujala.

The preliminary ground investigations in Kujala area revealed that the subsoil is mostly silty clay with a few layers with higher clay content. Taken into account the ground elevation (+80 meters above sea level) and geographic location, one can estimate that the subsoil may represent somewhat overconsolidated Baltic Ice Lake sediment. For this sediment type, prior distributions of geotechnical properties are available in the literature. Alternatively, one could utilize a probability of favorable subsoil conditions based on local expertise or other prior knowledge such as established correlations between water content and compressibility index, for example.

In this study, prior distributions for compressibility properties given by Löfman and Korkiala-Tanttu [13] were mostly utilized. The prior distribution for OCR was modified after Gardemeister [14]. Regarding the coefficient of creep (coefficient of secondary compression $C_{\alpha\varepsilon}$), no prior distribution for Baltic Ice Lake sediments was available; hence, a general prior distribution for clay soils given by Löfman [15] was used. The probability distribution of residual settlement in Kujala area was estimated via Monte Carlo simulation (30 000 simulations) in @RISK software [16]. The input parameters for random variables are presented in Table 1.

Table 1. Input parameters for the random variables used in Monte Carlo simulation.

Input†	Unit	Distribution Type	Min	Mode /Mean	Max	Standard deviation	COV (%)
OCR	-	Truncated lognormal	1.00	1.20/1.80	6.00	0.869	48.2
C_c	-	Lognormal	0.00	0.200*/0.586*	+∞	0.6003*	102
C_s	-	Lognormal	0.00	0.044*/0.077*	+∞	0.0523*	67.9
γ	kN/m^3	Truncated normal	11.0	17.7/17.7	25.0	1.119	6.32
$C_{\alpha\varepsilon}$	%	Triangle	0.00	1.30/1.71	3.82	0.793	46.4
GW	m	Triangle	0.50	1.00/1.17	2.00	0.312	26.7
H	m	Triangle	3.50	4.50/4.50	5.50	0.408	9.07
γ_{fill}	kN/m^3	Normal	-∞	20.0/20.0	+∞	1.000	1.00

†*OCR* = Overconsolidation ratio; C_c = compression index; C_s = swelling index; γ = unit weight of soil; $C_{\alpha\varepsilon}$ = coefficient of secondary compression; *GW* = depth of groundwater level; *H* = height of the embankment; γ_{fill} = unit weight of fill material (crushed rock).

*Arithmetic statistic.

The residual settlement was calculated for a typical soil profile in Kujala area: a 15 meters deep clay-silt basin. The OCR in dry crust is usually 5-7 times greater than in deeper soil layers [14], and this was taken into account by applying a decreasing pre-consolidation pressure with σ'_p=200 kN/m^2 at the ground surface and minimum around depth of 4 m. The maximum value of σ'_p was chosen to be in the same scale as the value determined from two good/fair quality oedometer tests (at 5 m and 10 m) performed in the preliminary ground investigation program. The mode values of σ'_p, effective in-situ stress and embankment load are presented in Fig. 3 (left).

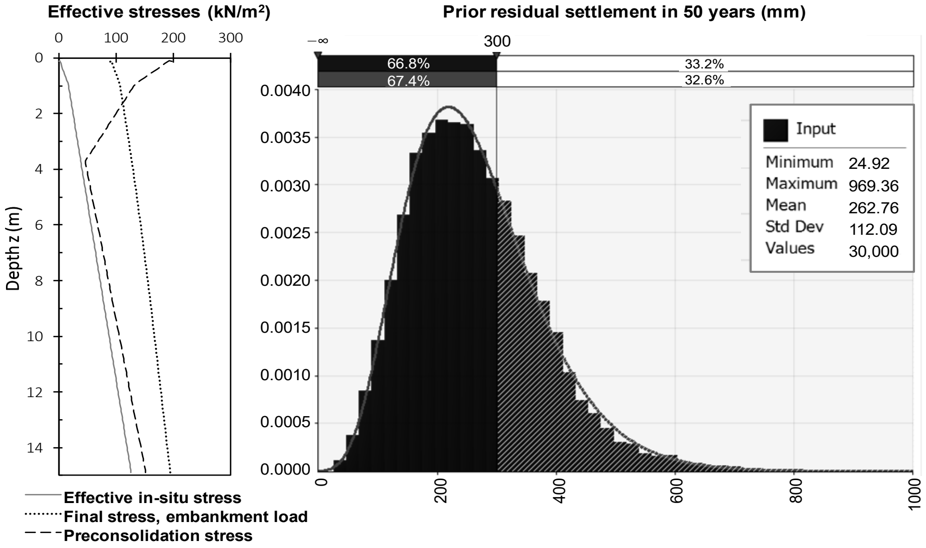

Fig. 3. Mode values of effective stresses (left) and the prior residual settlement (right).

The negative correlation between unit weight and compression indexes was taken into account by means of a copula function. The initial void ratio of soil was calculated using the compression index, based on a regression analysis performed for the Baltic Ice Lake sediment data analyzed by Löfman and Korkiala-Tanttu [13]. The compressibility of the dry crust was calculated by assuming that the modulus is 50 times the preconsolidation pressure (an empirical relation used in Swedish practice, e.g., [17]).

Fig. 3 (right) presents the histogram of residual settlement in millimeters. It was assumed, that this residual settlement accumulating during road service time of 50 years is a sum of 20 % of the primary consolidation settlement and 50 % of the estimated creep. In other words, it is assumed that 80 % of primary consolidation occurs already during the construction/preloading stage. Regarding the creep, only 50 % of the estimated creep settlement is included in the residual settlement for two reasons: Firstly, the prior distribution used for coefficient of creep included many soft clays and organic clays which are more prone to creep than silty clays (dominant in Kujala area) which are characterized by lower C_c and lower water content [17, 18]. Secondly, the applied surcharge preloading decreases the creep effects (e.g., [18]). Fig. 3 shows that the probability of settlements smaller than 300 mm is P_g=0.67. However, due to the limitations for differential settlements, a 300 mm limit cannot be applied to the whole area. Hence, it is assumed, that on average the prior probability of acceptable settlements is only P_g=0.25 (which corresponds to a probability of residual settlements being less than ≈180 mm).

5.2 Probability of favorable subsoil given the observations

Since the prior probability of favorable subsoil conditions is only P_g=0.25, one could consider the feasibility of acquiring more information about the actual subsoil conditions via monitoring of test embankments. In general, the additional cost of acquiring more information (e.g., via observational method) may be justified if it eliminates a considerable part of the uncertainty [11].

The reliability of field observations of a test embankment depends on their quality and the measurement period. On the other hand, the time required for a reliable total settlement prediction depends on consolidation properties of the compressing subsoil (drainage paths and permeability). Länsivaara [19] observed (based on 11 clayey soil sites in Finland), that that measurement period of one year usually leads to a very reliable settlement prediction, whilst six months perios led to a 'quite good' prediction at many sites. If one applies the verbal descriptions of uncertainty collected by Baecher and Christian [12], 'quite likely' and 'very likely, very probably' corresponds to probabilities P = 0.80 and P = 0.90, respecively.

In Kujala test embankments, the time reserved for settlement observations prior design update was 6 months; however, the observations were continued during construction also, in total over 16 months. In addition, the rate of consolidation (rate of excess pore pressure dissipation) was observed via piezometers. Combined with the settlement monitoring, the observations provide a rather reliable result. Hence, one can estimate that the probability of reliable settlement prediction (given the monitoring measurements) is at least 0.80 and up to 0.90.

The prior probability of favorable subsoil conditions ($P(G)=P_g$), given the monitoring observations that also indicate favorable subsoil conditions (A), can be updated with Bayes' Theorem. The updated, posterior probability is defined with:

$$P(G\,|\,A) = \frac{P(G)*P(\mathrm{A}\,|\,G)}{P(G)*P(\mathrm{A}\,|\,G)+P(\bar{G})*P(\mathrm{A}\,|\,\bar{\mathrm{G}})} \tag{4}$$

The definitions of these probabilities are given in Table 2. Scenario 1 represents an optimistic estimate of the reliability of monitoring-based settlement prediction, whereas Scenario 2 assumes that the probability of inaccurate or false interpretation is greater. For example, the primary consolidation might continue longer than what the measurements indicate, or, the creep might be more significant than what initially estimated.

Table 2. Likelihoods used to update the probability of favorable subsoil conditions.

Outcome of monitoring observations	G: Actual subsoil conditions: Favorable (prior = P_g = 0.25)		$\bar{G}$: Actual subsoil conditions: Unfavorable (prior =1- P_g = 0.75)	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
A: Observations indicate favorable subsoil	**$P_1(\mathrm{A}\,|\,G)$ =0.90**	**$P_2(\mathrm{A}\,|\,G)$ =0.80**	**$P_1(A\,|\,\bar{G})$ =0.30**	**$P_2(A\,|\,\bar{G})$ =0.50**
$\bar{A}$: Observations indicate unfavorable subsoil	$P_1(\bar{A}\,|\,G)$ =0.10	$P_2(\bar{A}\,|\,G)$ =0.20	$P_2(\bar{A}\,|\,\bar{G})$ =0.70	$P_2(\bar{A}\,|\,\bar{G})$ =0.50

As there are two test embankments with somewhat different subsoil profiles, one can update the prior probability two times (two sets of independent measurement data). In the second update, the prior probability $P(G)=P_g$ in Eq. 4 is replaced by previously updated posterior probability $P(G\,|\,A)$. After the second update, the posterior probability of favorable subsoil (given monitoring results that indicate favorable conditions) is thus 0.75 in Scenario 1 and 0.46 in Scenario 2.

A similar updating process could also be performed to the case of monitoring results indicating unfavorable subsoil conditions (measured settlements are large and excess pore pressure dissipated slowly). This outcome would decrease the probability of favorable subsoil conditions even more ($P_g<0.25$). Hence, one can assume that if the monitoring indicates excessive settlements, the optimal decision by default is to keep the piles.

5.3 Optimal design according to the decision tree analysis

The final decision tree with the expected relative monetary costs is presented in Fig. 4. For all the alternative designs, the assumed repair costs (C_{repair}) was two times the construction cost of the fully optimized design (minimize the piles). The assumed cost of test embankments was 0.25 M€; in Kujala interchange, the actual cost of the test embankments was in the scale 0.20-0.25 M€. The lowest expected relative cost (corresponding to the optimal design alternative) is marked with bold font.

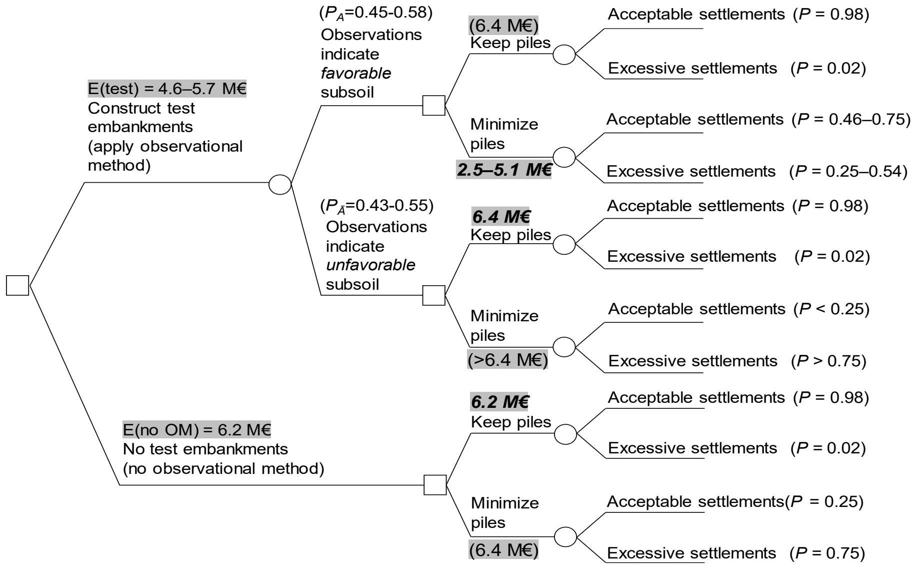

Fig. 4. Decision tree for applying the observational method with expected relative costs.

If no test embankments are built, the optimal decision is to keep the piles (if the probability of favorable subsoil conditions is only P_g=0.25). On the other hand, if the prior probability of favorable subsoil condition is updated using the monitoring, the expected cost of minimizing piles is only $E(a_{minimize\,piles}|A)$=2.5-5.1 M€ (lower than expected cost of keeping the piles, 6.4 M€). The lower expected cost corresponds to the highest assumed reliability of monitoring-based settlement prediction (Scenario 1, Table 2).

However, one potential outcome is that the monitoring results will indicate unfavorable subsoil conditions, which would lead to selecting 'keep piles' and thus losing the investments put into observational methods. The expected relative cost of test embankments and OM, E(test), can be calculated by considering the most optimal alternatives in both monitoring outcomes with [11]:

$$E(test) = P_A * E\left(a_{minimize\ piles}\right) + P_{\bar{A}} * E\left(a_{keep\ piles}\right) \tag{5}$$

Where $P_{\bar{A}}$ is the probability of monitoring results indicating unfavorable subsoil conditions given the prior probability of P_g=0.25 ($P_{\bar{A}}$=0.55 and $P_{\bar{A}}$=0.43 in Scenarios 1 and 2, respectively), and P_A is the probability of monitoring indicating favorable subsoil conditions (P_A=0.45 and P_A=0.58 in Scenarios 1 and 2). It was assumed that the probability of observations indicating unfavorable subsoil equals the complement of 'favorable' observations (Table 2). It should be noted that because the prior probability of favorable subsoil conditions is only 0.25, larger 'false positive' probability is actually beneficial from the perspective of ground-supported embankments.

Expected cost of constructing test embankments and applying observational method $E(test)$ is thus 4.6 M€ and 5.7 M€ for Scenario 1 and Scenario 2, respectively. This expected relative cost is less than the optimal decision in the alternative of no test embankments (keep piles, 6.2 M€). Thus, the decision to construct the test embankments is supported by the decision tree analysis.

6 Discussion

Fig. 4 shows that the probability of excessive settlements for the 'minimize piles' design with observational method is quite large (P=0.25−0.54). Hence, it should be noted that the optimal decision might be the conservative design instead, if the decision maker preferred risk minimization decision criteria instead of maximum expected monetary gain. All in all, the 'gray area' in which minimizing piles becomes more optimal than the conservative design (keeping the piles) is the most challenging from the perspective of decision-making. In this gray area, including other consequences besides the construction and repair work costs would support the robustness of decision optimizing. For instance, environmental impact such as greenhouse gas emissions should be included in the consequences also. In Kujala Interchange, the minimization of reinforced concrete piled slab foundations lowered the estimated carbon dioxide equivalent (CO_2eq) by approximately 7000-14000 tonnes. This minimization of piles caused an increase in the amount of lightweight fills, but the equivalent CO_2eq increase for the fill material used (recycled foamed glass) is only approximately 500 tonnes. Hence, it is clear that the overall climate change impact was reduced via the foundation method optimization.

7 Conclusions

This paper demonstrated how a decision tree analysis can be used to study the feasibility of applying the observational method in the foundation type optimization. In Kujala Interchange, the decision to construct the test embankments was supported by the decision tree analysis, even though the estimated prior probability of favorable subsoil conditions was only P_g=0.25. However, the most optimal decision can be quite sensitive to the assumed consequences of the unsatisfactory performance of the foundation.

By using real cost savings acquired in the Kujala Interchange case study, it was shown how the observational method can be employed to reduce the expected costs and environmental impact of foundation design. In particular, the observational method can be very effective in projects which are characterized by significant uncertainty in subsoil conditions.

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