Building with the Subsurface for realizing cost-efficient infrastructure

Construire avec le sous-sol pour réaliser une infrastructure à coût avantageux

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ABSTRACT: The paper introduces the concept of 'Building with the Subsurface' for optimising constructions to profit from subsurface conditions. The concept fits in the framework of Value Engineering. A case study for a road on soft soil illustrates the concept. Subsoil heterogeneity is expressed in sets of discrete synthetic subsoil profiles, suitable for geotechnical design calculations with conventional tools. The case study shows that the uncertainty in the whole life cost of the road ranges between ±10% and ±30%, depending on lithology and sensitivity of the construction method to subsoil uncertainty. Adding local site investigation to subsoil data from public sources reduces the uncertainty.

RÉSUMÉ : L'article introduit l'idée de 'Construire avec le Sous-sol' afin d'optimiser les constructions en profitant des conditions du sous-sol. Le concept s'inscrit dans le cadre de l'Ingénierie de Valeur. Le cas d'une route construite sur sol compressible illustre le concept. L'hétérogénéité du terrain est exprimée par des jeux de profils synthétiques discrets qui conviennent aux calculs géotechniques menés avec des outils conventionnels. L'étude de cas montre que l'incertitude sur le coût de la route pendant toute sa durée de vie varie entre ±10% à ±30%, selon la lithologie et la sensibilité de la méthode de construction aux incertitudes liées au sous-sol. Ajouter aux données du sous-sol de source publique une reconnaissance de sols locale réduit l'incertitude.

KEYWORDS: Subsurface model, Value Engineering, geological uncertainty, cost estimate, roads, soft soil, piled embankments.

1 BUILDING WITH THE SUBSURFACE AND VALUE ENGINEERING

Reduction of subsoil related risks has been an important issue for the past few years in the Netherlands. The potential economic benefit is estimated at 1.5 % of the construction sector turnover (van Staveren, 2006). However, entrepreneurs in the construction sector are easier stimulated by opportunities than by problems. Value engineering is an acknowledged method for identification of options for cost reduction. Value engineering saved between 6 and 8% of the total construction costs in U.S. highway projects in the past five years (US DoT FHWA, 2011). This paper focuses on the potential of the subsurface to realize cost savings in infrastructure construction.

The lithology, engineering properties and hydrology of the subsoil determine the feasibility of construction methods and their costs. Critical parameters may concern foundation depths, the continuity of an impervious layer or geotechnical properties.

These critical parameters are often not adequately and systematically mapped in the current Dutch site investigation practice. The usual approach is based on CPT's with typical centre-to-centre distances of 100 m, and soil sampling in borings even wider apart. Although this will provide a general idea of the soil profile and properties, heterogeneity will still cause substantial uncertainty. The more expensive way out is to use construction methods that are robust with respect to geological heterogeneity, such as piled embankments.

Three key elements of realizing more cost-effective infrastructure are (1) knowing the potential heterogeneity, (2) knowing its impacts on construction methods and costs and (3) reducing the impacts. This concept is called 'Building with the Subsurface', i.e. optimising constructions to profit from subsurface conditions. The impacts of subsurface uncertainty on construction costs are made explicit during the process. This allows informed decisions to be made on additional site investigation and finally, the selection of a construction method on the basis of costs, and uncertainty in costs. A Value Engineering / 'Building with the Subsurface' study can be performed in any project stage, but will be most rewarding in the feasibility stage. Usually the alignment or corridor will have been set in this stage. Choices regarding construction methods, materials and mitigation of impacts on the surrounding area are still open. The main outputs of the feasibility stage will be cost estimates, a time schedule for construction, and recommendations for mitigation of impacts.

Table 1 illustrates activities of the 'Building with the Subsurface' concept in the context of Value Engineering. This scheme is applied in the following virtual case study, using actual geological and geotechnical data.

2 EXAMPLE: FEASIBILITY STUDY OF A ROAD

2.1 *Preparation phase*

A 2x2 lane road is to be constructed in the soft soil area around Rotterdam Airport (Figure 1). The time available for construction may be ½, 1 or 2 years, to be decided later.

The study should identify the alignment of the road running approximately north-south in the 10 km^2 area, the whole life costs and their uncertainty. Whole life costs are the sum of construction costs of earthworks, drainage and pavement and costs of subsoil related maintenance. Construction methods will be selected on the basis of the 90% upper limit of their whole life cost. Also, the 80% confidence interval of the cost estimate should be within ±15% of the average value. 'Uncertainty' is thus expressed as the half width of the 80% confidence interval.

2.2 *Information Phase*

The elevation of the road surface will be 0.5 m above ground level. The 1:50,000 geological map indicates that the subsoil consists of 15 to 20 m of Holocene soft peat and clay over Pleistocene sands. Peat was excavated in part of the area, and artesian pressures are present in the underlying Pleistocene sands. The surface water table is at 0.6 m below ground level.

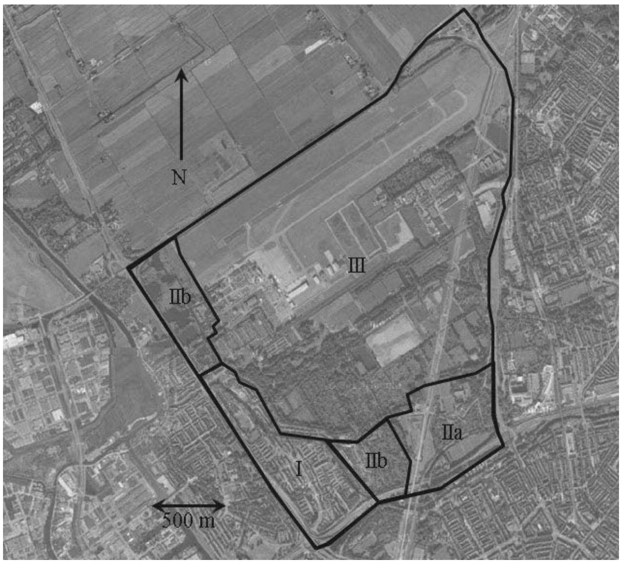

Figure 1. Project area with subdivision according to subsoil lithology.

2.3 *Function Analysis Phase*

The road administrator demands that post-construction settlements should not exceed 0.15 m in 30 years, to prevent differential settlements from compromising driver comfort.

Construction should not create connections between surface water and the Pleistocene aquifer. The feasibility stage of the project will not consider relocation of utility networks.

2.4 *Creative Phase*

Two construction methods will be considered in the study: a basal reinforced piled embankment and traditional construction, using prefab vertical drains and a sand fill with temporary surcharge.

2.5 *Evaluation and Selection Phase*

The main failure mechanisms identified for the traditional construction method are: excessive post-construction settlements and differential settlements, contamination of surface water and water in the Pleistocene aquifer, damage to constructions and utility networks. Failure mechanisms for piled embankment construction include: insufficient end bearing capacity of the piles, failure of piles or load transfer platform. Shared failure mechanisms are: instability of embankment slopes, insufficient bearing capacity of pavements and verges, and noise and vibration nuisance during construction.

A subsoil hazard is defined as the likely occurrence of a subsoil phenomenon that promotes failure. Figure 2 identifies these subsoil phenomena for the project area. This simplified geological section is redefined in terms that geotechnical engineers can understand (Baynes, 2005). Table 2 lists the associated subsoil hazards. On the basis of expert judgement and local experience both construction methods were considered feasible, and included in the further process.

2.6 *Development Phase, first stage*

A sensitivity analysis was performed to determine which parameters have the largest contribution to the uncertainty in whole life costs of the traditional construction method. Variations of peat thickness, total thickness and unit weight of the soft layers, compression parameters and consolidation coefficient account for 95% of the variation of the costs. These critical parameters were selected for the further study.

Table 1. Activities in a Value Engineering study, applying the ‘Building with the Subsurface’ concept

Value Engineering study	‘Building with the Subsurface’ process	Acquisition of geological and geotechnical data
Preparation Phase	Bring together a multidisciplinary team Create commitment with stakeholders and decision makers Define output of the study	
Information Phase	Collect information on design Collect geotechnical data	Topography, general geomorphology, geology and hydrology, surface elevation
Function Analysis Phase	Collect and analyse data on end user specifications, impacts on the surrounding area, natural and manmade hazards	
Creative Phase	Prepare a long list of construction methods and materials	
Evaluation and Selection Phase	Define failure mechanisms for construction methods Define and assess subsoil hazards for construction methods Assess feasibility of construction methods Prepare a shortlist of construction methods	
Development Phase	Define design methods for evaluation of failure mechanisms Define critical parameters of the subsurface model Collect all available geological and geotechnical data Synthetize sets of discrete soil profiles; define average values and uncertainty of all critical parameters Perform design calculations for all soil profiles Analyse the design results in terms of the output of the study Optimize the design and the construction methods	*First stage* Data on geology, geotechnical parameters and hydrology from public sources *Second stage* Local site investigation
Presentation Phase	Present the output in maps, 3D models Select preferred construction methods and materials	
Implementation Phase	Update the list of subsoil hazards, define actions for mitigation of hazards Present recommendations for later site investigation	

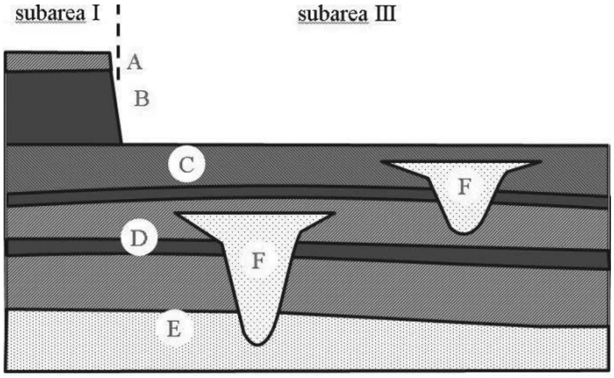

Figure 2. Simplified geological section showing subsoil phenomena relevant to failure.

Table 2. Subsoil hazard associated with phenomena in Figure 2.

Unit / phenomenon	Subsoil hazard
A. Clay cover / man-made deposits	Differential settlements due to old surcharges and buried sand filled channels Large (post-construction) settlements
B. Peat	Large (post-construction) settlements
C. Mudflat deposits: sand, silt, clay with intermediate peat layers	Differential settlements due to buried sand filled channels Large (post-construction) settlements
D. River deposits: sand, silt, clay with intermediate peat layers	Differential settlements due to buried sand filled channels Large (post-construction) settlements
E. Pleistocene river deposits: sand	Artesian pressure Varying bearing capacity
F. Buried sand filled channels	Differential settlements Contact with Pleistocene deposits; artesian pressure

Modelling of the lithological variation is based on 76 borings, 96 CPTs and layer boundaries of the GeoTOP 3D geological model, all obtained from the Dutch national DINO database. The information density of 10 verticals per km^2 is considered sufficient for compilation of a representative subsoil model, but will not allow detailed mapping of heterogeneity.

The project area is divided in 4 subareas (Figure 1), each with a different set of discrete subsoil profiles. Each profile is a synthetic stack of scenarios for the layers Pleistocene deposits, river deposits, mud flat deposits, peat and man-made deposits. The total number of combinations can be huge, because up to 4 scenarios can be identified for every layer. Two hundred profiles remain for the entire project area after elimination of improbable or identical subsoil profiles. These profiles represent the subsoil variation in the area, made accessible for design calculations with conventional tools. Weighted averages and standard deviations can be determined, by estimation of the frequency of occurrence of the profiles.

Figure 3 gives an example of part of the discrete subsoil profiles synthesized for subarea I. The main difference between the areas is the peat layer that is thicker in subarea I than in subareas IIa and IIb, and has been excavated in subarea III. In subarea IIb the layer is more clayey than in subarea IIa.

Conservative estimates of the geotechnical parameters are derived from correlations with lithology and inferred volume weights. Variation coefficients of compression parameters are estimated at 23%; the consolidation coefficients are assumed to vary by a factor 2.

Actual CPTs are entered directly in the foundation design of the piled embankments, rather than synthetic subsoil profiles.

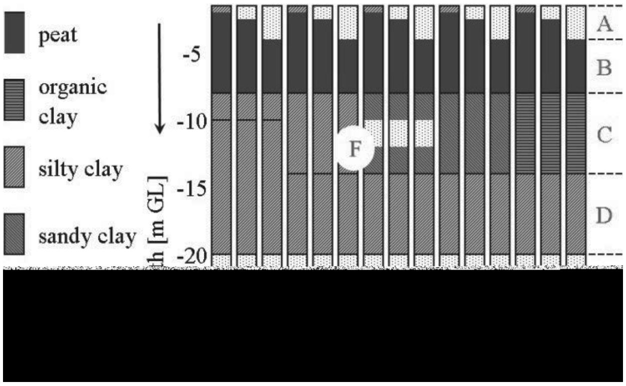

Figure 3. Part of the synthetic soil profiles for subarea I.

The analyses for the traditional method are performed in batch using the software MRoad (Venmans et al., 2005), that combines analytical settlement calculations using an isotache model with automatic determination of whole life cost. The standard deviation of the whole life costs is derived by summation of the variance caused by subsoil heterogeneity and the variance caused by permutations of the other design parameters around their average values. The variance caused by subsoil heterogeneity is reduced for length effects along the road alignment. Subsoil profiles for the soft layers are assumed to differ every 50 m. Foundation characteristics of the Pleistocene sand layer are found to vary over distances less than 20 m in the design of the piled embankment.

Settlements in the traditional method are in the order of 2.20 m in areas I and IIa, with standard deviations of 1 m. In areas IIb and III the top peat layer is much thinner or missing, and settlements are smaller, 1.40 m and 1.00 m respectively. Standard deviations are around 0.30 m.

Post-construction settlements are highly variable in all subareas, with values up to 0.40 m in 30 years for the traditional method with 1 year surcharge time. However, the average values satisfy the design specification of 0.15 m. Uncertainty in compression parameters and consolidation coefficients is the main source of the uncertainty in the post-construction settlements. The post-construction settlements for a surcharge time of 2 years are smaller than the 0.15 m in all locations.

Table 3 summarizes the results of the cost calculations. The design of the piled embankment is the same for all areas, because no systematic trends can be observed in the foundation characteristics of the Pleistocene sand layer.

Table 3. Whole life costs of 500 m road for different areas.

Cost parameter	I	IIa	IIb	III
Traditional method, 1 year surcharge time				
Average	676 k€	659 k€	612 k€	562 k€
90% upper limit	815 k€	816 k€	796 k€	697 k€
Uncertainty	21%	24%	30%	24%
Traditional method, 2 year surcharge time				
Average	687 k€	668 k€	588 k€	550 k€
90% upper limit	762 k€	752 k€	646 k€	598 k€
Uncertainty	11%	13%	10%	9%
Basal reinforced piled embankment				
Average	1601 k€	1601 k€	1601 k€	1601 k€
90% upper limit	1692 k€	1692 k€	1692 k€	1692 k€
Uncertainty	6%	6%	6%	6%

The average whole life costs for the traditional method and their upper limits differ up to 25% between subareas. The average whole life costs for a 1 year and 2 year surcharge time are more or less equal. The 90% upper limit is much higher for the 1 year surcharge time, corresponding to 20 to 30% uncertainty. This large uncertainty is due to the large uncertainty in maintenance costs. However, the uncertainty in compression parameters and consolidation coefficients is the fundamental cause of the uncertainty in the whole life costs, since maintenance costs are related to post-construction settlements. The whole life costs for the piled embankment are much higher than for the traditional method for this particular case. The difference mainly depends on the length of the piles and may be smaller in other cases. The uncertainty in whole life costs of the piled embankment is limited to 6% and is mainly due to uncertainty in the unit costs of construction materials.

Generally, uncertainty in the whole life costs is caused by a combination of uncertainty in the geotechnical parameters, and the sensitivity of the construction method to this uncertainty. The contribution of subsoil heterogeneity to the overall uncertainty is minor. The effects of variations between individual soil profiles or CPTs are strongly reduced by averaging along the road alignment.

2.7 *Presentation Phase*

The traditional method with 2 years surcharge time is the preferred construction method, based on the 90% upper limit of the whole life costs. The costs of 500 m road are visualised on a 500x500 m^2 grid in Figure 4. The figure also shows the location of the north-south alignment with the lowest costs. The piled embankment method will be preferred if the time available for construction is ½ year or 1 year. The traditional method with 1 year surcharge time is not eligible because of the excessive uncertainty in the costs.

Figure 4. Whole life costs per 500x500 m^2 grid cell and preferred alignment of road.

2.8 *Local site investigation*

The project manager decides to perform an additional site investigation along the alignment shown in figure 4, aiming to reduce the uncertainty in the whole life costs of the traditional construction method with 1 year surcharge time. The site investigation is targeted at reducing the uncertainty in compression parameters and consolidation coefficient. The costs of the site investigation campaign are very modest compared to saving 1 year in construction time.

2.9 *Development Phase, second stage*

A new data set with CPTs, borings and laboratory data is obtained for part of area III. The centre-to-centre distance of the CPTs is approximately 50 m, an increase in data density by a factor 40. Soil profiles are interpreted directly from CPT characteristics, and validated with the lithology observed in the borings. The compression constants determined in laboratory tests represent a 10% higher compressibility. The consolidation coefficients are up to 5 times higher compared to the initial parameter set. The variation coefficient of the new set of compression parameters is slightly lower at 20%; the variation in consolidation coefficients varied by a factor 2, as in the initial parameters set.

The design calculations are performed as in the earlier phases, for a surcharge time of 1 year. The settlements are 10% higher than in the initial calculations, the post-construction settlements are compatible. However, the uncertainty in the post-construction settlements was reduced from 0.17 m in the initial calculations to 0.02 m. This is caused by the significantly higher consolidation coefficients. Consolidation is completed well within the surcharge time of 1 year in all soil profiles, with only a small amount of creep compression occurring after construction. The favourable parameters also allowed a reduction of surcharge height from 2.50 m to 1.50 m, thus reducing construction cost.

The average whole life costs for 500 m road are 523 k€, a 7% cost reduction as compared to the initial calculations for subarea III. The 90% upper limit is 560 k€, representing an uncertainty in the whole life costs of 7% only.

Based on these results, the traditional construction method with 1 year surcharge time is the best option for area III.

3 CONCLUSIONS AND RECOMMENDATIONS

The example shows that application of the ‘Building with the Subsurface’ concept in a Value Engineering study is successful. The concept can identify construction methods that fulfil all requirements, achieve cost savings, and increase the reliability of cost estimates. The method for subsoil modelling on the basis of synthetic soil profiles can successfully quantify heterogeneity using the conventional tools of geotechnical engineers.

The uncertainty in cost estimates mainly depends on uncertainty in soil parameters and the sensitivity of the construction method to these uncertainties. The cost estimate appears to depend less on lithological heterogeneity. A data density of 10 verticals/km^2 appears to be sufficient to reduce uncertainty in cost estimates for the traditional construction method, even though lithological heterogeneity in the Rotterdam Airport is high.

Value Engineering studies should include at least one target parameter related to the uncertainty in cost estimates, rather than focus on average cost only.

A general data set of compression and consolidation parameters should be established by systematically collecting laboratory and field observations, to reduce uncertainty in geotechnical parameters for feasibility studies.

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