Practical framework for settlement predictions for the rehabilitation of roads on compressible soils

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Abstract: Many municipalities in the Netherlands are faced with large settlements of the infrastructure. When the settlements for a road have exceeded one of the usability criteria, they will be rehabilitated and brought back to their original level. By adding a layer of sand the construction costs will be small, but the process of settlement will accelerate. Other options, like using lightweight filling materials or underpinning the construction, are far more expensive. In order to evaluate the relative cost-effectiveness of these other options, an accurate settlement prediction is necessary. At the same time, the total construction costs of these roads and therefore the allowable expenses for site investigation and desk studies are limited. In this paper, a practical framework is presented to perform accurate settlement predictions for these situations. The project location and the available historical data are considered to avoid excessive site investigation and knowledge gaps. In the framework a quantitative measure is available for the accuracy of the settlement prediction.

Résumé: Beaucoup de municipalités dans les Pays Bas sont confrontées à de grands consolidations de l'infrastructure. Quand les consolidations pour une route ont excédé un des critères de viabilité, ils seront rehabilité et apportés de nouveau à leur niveau original. En ajoutant une couche du sable les coûts de construction seront petits, mais le processus de la consolidation accélèrent. D'autres options, comme utiliser les matières d'agrégation légères ou des pilotis, sont plus chères. Afin d'évaluer la rentabilité relative de ces autres options, une prévision précise de consolidation est nécessaire. En même temps, tous les coûts de construction de ces routes et donc dépenses permises pour des études de recherche et de bureau d'emplacement sont limités. En cet article, un cadre pratique est présenté pour exécuter des prévisions précises de xonsolidation pour ces situations. L'endroit de projet et les données historiques disponibles sont considérés comme éviters des lacunes de savoir excessive. Dans le cadre une mesure quantitative est disponible pour l'exactitude de la prévision de consolidation.

Keywords: geotechnical engineering, infrastructure, planning, settlement, urban geosciences

INTRODUCTION

Large parts of the Netherlands are made up of deposits of soft clays and peat of up to 15 meters thickness. Historically, many villages were started on sandy infills of rivers or on loamy deposits of glacial origin. Especially since about 1950 many villages have expanded outside of the historical boundaries and have built in the areas with soft peat and clay deposits. The municipal engineering departments responsible for maintenance of the public roads in many of these districts are now confronted with high maintenance costs. These maintenance costs are high because premature rehabilitation (premature in terms of the state of the paving) of the above-surface and sub-surface infrastructure is required. The reasons for this are trifold:

- Excessive differential settlements of the road surface causes safety problems;
- Excessive absolute settlements of the road, combined with the high ground water levels in the peaty polders, require the road to be prematurely raised to prevent damage by freezing or to allow residents easy entering or exit of their houses (see Figure 1);
- Damage to subsurface infrastructures like sewer, gas and water pipes and electricity and television cables. The costs involved with prematurely renewing the sewage system are of the same order of magnitude as the costs involved with replacing the road itself.

Especially for the smaller municipalities in areas with thick peat deposits, with up to 25.000 inhabitants, these costs have driven several to the brink of bankruptcy. The problem is actually one of inheritance; when the municipalities originally expanded into the soft soil areas, not enough effort was put into reducing the residual settlements after construction. In a few years time, large settlements occurred after which the roads were rehabilitated (i.e. raised and repaved) by adding a layer of sand. This of course only accelerated the settlement process. At present, there is not only more knowledge about predicting the settlement process, but also there are construction techniques that do not load the subsoil as much as a layer of sand does (e.g. using lightweight construction materials or expanded polystyrene (EPS)).

However, this increased knowledge of predicting settlements is generally not available to the small municipalities, where a very limited number of civil engineers are responsible for many things besides geotechnical engineering. Therefore, the performed settlement calculations are often rather unreliable. Also, the recent construction techniques that reduce settlements require a much higher initial investment that is only economically interesting when it can be proved that the maintenance costs during the lifetime of the road are lower when compared to using the classical approach of using heavy construction materials like sand. This combination of sources of uncertainty makes it very difficult for these municipal civil engineers to confidently choose the appropriate rehabilitation technique for each project.

Recently, over 25 municipalities, together with public utility companies, engineering consultants and knowledge institutes, have started a project to develop the tools that allow municipal engineers to choose the optimal maintenance strategy for these roads on soft soils. One of the first tools that was developed is a practical, quantitative framework for the assessment of the quality of a settlement prediction. This framework is discussed in the remainder of this paper.

Figure 1. Within ten years after construction, the road settled the height of three steps. Photograph taken in 2004 in the municipality of Boskoop, the Netherlands.

GOAL OF THE FRAMEWORK

Generally, a new maintenance strategy has to be determined when the current road cannot function according to specifications, e.g. because excessive settlements significantly decrease the usability of the road. The economic consequences of the choice of maintenance strategy are dominated by the choice of the road foundation type. When choosing the optimal road foundation type in a settlement sensitive area, the accuracy of the settlement prediction is a dominant factor. At the same time, performing a settlement prediction is not straightforward and small errors in input parameters or model schematization can cause a large error in the settlement prediction. Municipal civil engineers as well as the third-party civil engineers who are generally involved in these small road construction projects generally do not have a sufficiently detailed knowledge of the subtleties of the settlement predictions to successfully navigate the pitfalls.

The framework is a tool for both municipal civil engineers as well as third-party civil engineers that helps determine the required effort for producing a suitably accurate settlement prediction. The framework is specifically developed for settlement predictions that are made in order to choose between traditional, heavy road rehabilitation methods and lightweight or weight-neutral road rehabilitation methods.

OUTLINE OF THE NEW FRAMEWORK

After many discussions with municipal civil engineers, it was decided to develop a framework that could be used to assess the accuracy of a settlement prediction made by a third-party, e.g. an civil engineering consultant, in order to establish the validity of the results. The framework could also be used by the consultant as a guideline for the settlement predictions. By following the framework, a detailed settlement prediction can be made for a construction of relatively heavy materials on a soft soil foundation. When different construction methods are analyzed for their life-cycle costs, the variant using heavy construction materials will be the most sensitive for any errors.

On the basis of expert knowledge and the analysis of four test cases, a flow chart was developed describing the steps in the settlement prediction and the consequences for the accuracy of the analysis. The main flow chart is depicted in Figure 2. This flow chart is divided into five main categories, which will be briefly discussed below. The framework and flow chart is described in more detail in Maccabiani (2005a).

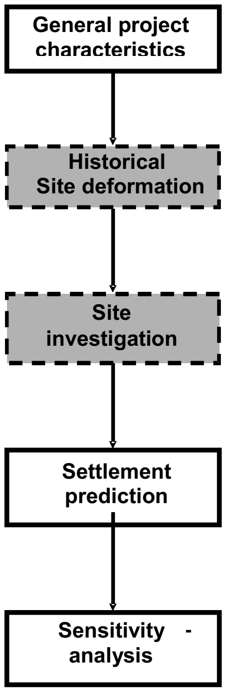

Figure 2. Main flowchart for the framework.

General project characteristics

Since the framework is meant to aid the municipal civil engineer in obtaining a settlement prediction of suitable accuracy, an attempt is made to ensure that all relevant project characteristics are determined before the settlement prediction is performed. This includes the explicit formulation of the expectation of the municipality for the assumptions and quality of the work done by the third-parties. In a time where competition among civil engineering consultants is done mainly on the basis of whoever accepts the task for the lowest price, carefully specifying the assumptions and expectations has unfortunately been proven to be required. Several general characteristics include:

- The required road level after rehabilitation;
- The allowable absolute settlements during the lifetime of the road construction, calculated from a pre-determined date. Practical measures for the allowable settlements are the minimum required distance between road level and groundwater level, or the maximum distance between the road level and the level of the doorsteps of the neighbouring houses;
- The required type of settlement prediction: based on averaged settlement parameters or based on statistically determined representative values of the settlement parameters, in accordance with Dutch standards (NEN 1991). The latter type obviously favours lightweight constructions and constructions on pile foundations when the life-cycle costs are considered;
- The restriction on, and properties of, the construction materials to be used in the analysis, e.g. the volumetric weight of the existing road foundation materials;
- The phreatic levels in the polder during summer and winter. These levels are actively maintained by the local water board.

Historical information

The current state of the road can yield valuable information about the compressibility of the soil beneath the road construction. This information can be used to raise the accuracy level of a new settlement prediction. This part of the framework helps determine the value of that historical information. Analysis of the historical information reveals the knowledge gaps that have to be addressed, e.g. through site investigation. In more detail, two questions are addressed. The first question is if the current road surface shows any differential settlements, and if these differential settlements can be explained from either the maintenance record, known heterogeneity in the subsurface, or otherwise. The second question is if the settlement process matches the predictions that were made for the existing road. If the predictions match the actually observed settlement, measured at least two, but preferably more times during the settlement process, and if the boundary conditions haven't changed considerably, then little additional site investigation will be necessary for the new settlement prediction.

Table 3 shows a flowchart for this section of the framework.

Site investigation

After guiding the analysis of the available historical data, the framework helps determine the appropriate amount and type of site investigation. The goal of the site investigation is to complete the geotechnical subsurface model including the layering, the relevant geotechnical properties of those layers and the water pressures acting on those layers. The extent of the site investigation depends on the amount and quality of the historical information, on the actual problems observed with the existing road surface and on the level of accuracy required for the settlement prediction. Based on the analysis of available historical information, the framework advises on the priority of the following goals for the site investigation:

- Heterogeneity in the horizontal plain (i.e. different geological structures or different effects of preloading)
- Heterogeneity in the vertical plain (i.e. identification of layers with different compressibility or hydraulic conductivity)
- Compressibility properties of the relevant geotechnical layers
- Water pressures, both phreatic and in any aquifers
- Volumetric weights of soil and construction materials
- Preconsolidation pressure profile
- Amount, type and properties of previously used construction materials

Once the goals for the site investigation have been identified, the framework indicates the type and amount of site investigation that can be used to reach those goals. The type of site investigation speaks for itself, but determining *a priori* the amount of site investigation necessary is rather difficult. In this framework, the results of another Dutch study (CUR 2003) were used as a guideline. A practical framework for the determination of the required extent of the site investigation is currently under development as part of the aforementioned project.

Table 2 shows a flowchart for this section of the framework.

Geotechnical parameters

The section of the framework on the geotechnical parameters focuses on the ways in which the parameters for the settlement prediction can be determined from the site investigation and how they affect the accuracy of the total analysis. Four main categories have been identified for the determination of the relevant parameters:

- Through statistical analysis of multiple measurements according to the NEN (1991) methodology. In this methodology, the average parameter value is reduced according to the variation in the available test results and based on the number of tests. Unfortunately, this requires 8 to 10 tests to prevent too great a reduction of the average value;
- Through the use of correlations, determined with project data, e.g. by back-analysis of the deformation behaviour of the structure or in-situ bulk characteristics;
- Through the use of 'standard' correlations, e.g. between volumetric weight and a,b,c-isotache model parameters for compressibility (Den Haan, 1994);
- Through the use of values reported in literature or based on 'engineering judgment', e.g. estimations of the volumetric weight on the basis of soil type without any tests on local materials or general relationship between horizontal and vertical permeability.

Table 4 shows a flowchart for this section of the framework.

Settlement prediction

The section in the framework on the settlement prediction itself deals with the choice for the settlement model. Using a more advanced settlement model like the a,b,c-isotache model (Den Haan, 1994) will yield more accurate results compared with a simple 1 dimensional Terzaghi solution, if the input parameters for the more advanced model have been determined with sufficient accuracy. Also, the manner in which the residual settlement caused by the existing construction is incorporated in the settlement prediction plays an important role as this residual settlement is likely to be significant.

Table 6 shows a flowchart for this section of the framework.

Sensitivity analysis

Finally, this section addresses the use and value of sensitivity analyses. Since many important parameters are often only based on engineering judgment or a limited number of test results, a sensitivity analysis can show the robustness of the prediction and therefore the usefulness in choosing between different construction techniques. Both very advanced methods, like Monte Carlo analyses, and very straightforward methods, like manually studying the robustness of the settlement prediction for changes in the most sensitive input parameters, can be employed. In most current settlement predictions however, a sensitivity analysis is not performed.

SETTLEMENT PREDICTION ACCURACY RATING (SPAR)

The framework explains the steps that have to be taken in order to perform an accurate settlement prediction when a relatively heavy road is constructed on very compressible soils. Since this option is the most sensitive for errors in the settlement prediction and also requires the lowest initial investment to construct, special care is needed to avoid decisions based on erroneous predictions.

However, in many cases either the prediction will be made by third parties who might not follow the framework entirely. Some guide is needed for the municipal civil engineer to asses the effect of digression of the framework on the accuracy of the prediction. When heavy construction types are excluded from the analysis for any reason, some guide is needed to asses the *required* accuracy for the settlement prediction.

For these reasons, a Settlement Prediction Accuracy Rating (SPAR) was developed alongside the framework, ranging from 0 to 100. The rating can increase according to the choices made in the flow charts for the sections 'Historical information', 'Site investigation' and 'Settlement prediction' and by performing a sensitivity analysis. The SPAR scores have been appointed to the different steps in the flow charts by the authors. The SPAR was verified in four projects (Maccabiani, 2005b), but it should be evident that further verification might lead to different weights to the steps in the flow charts. The maximum score for each section is listed in Table 1. This means that if the site investigation is done perfectly and for example 40 points are awarded, this score has to be reduced to 30.

Table 1. Maximum SPAR points per category in the framework

Section	maximum SPAR
Historical information	30
Site investigation	30
Settlement prediction	20
Sensitivity analysis	20
Total	**100**

INTERPRETATION OF THE SPAR

As mentioned in the previous paragraph, the accuracy required in the settlement predictions depends on the type of constructions that are considered. If the construction types using heavy materials like sand are not considered, the settlement prediction generally will not require the determination of all relevant parameters in the same level of accuracy. The relationship between the type of construction and the accuracy of the settlement predictions has been determined based on the personal consulting experiences of the authors as well as detailed study of four test cases (Maccabiani, 2005b). These four test cases can only give a general relationship and the study of more test cases is required.

The resulting relationship is graphically depicted in Figure 3. The red line in Figure 3 corresponds with the minimum required SPAR rating for a certain type of road foundation. For example for an EPS foundation which is to be designed as a floating foundation, relatively little effort has to be put into the determination of parameters. The most important parameters are the residual settlements as a consequence of the current road foundation and the volumetric weights of the materials to be replaced by the EPS blocks. For a road foundation made of sand, a high SPAR rating is required since inaccuracy in many more parameters can have larger consequences for the accuracy of the settlement prediction.

Remarkably, this is very different from the current practice in most municipalities. A road with an EPS foundation requires a much higher initial investment and therefore more funds are made available for the geotechnical design process. For a road with a sand foundation, the logic is reversed. It is therefore not surprising that the problems as described in the introduction have arisen.

CONCLUSIONS

The framework for settlement predictions presented in this paper is a practical tool for both municipal civil engineers and civil- or geotechnical engineering consultants to get a suitably accurate result for a particular situation. The associated SPAR rating method allows both a quantitative description of the accuracy of the settlement prediction as well as a way to asses the importance of extra efforts on the total accuracy of the analysis. The framework takes the project properties and the historical information into account, so that a good balance is obtained between thoroughness and economy.

Currently, the framework and SPAR rating is largely based on settlement theory and personal experience of the authors. They have been verified by analysis of four projects. Further verification will be needed to fine-tune the framework and SPAR rating.

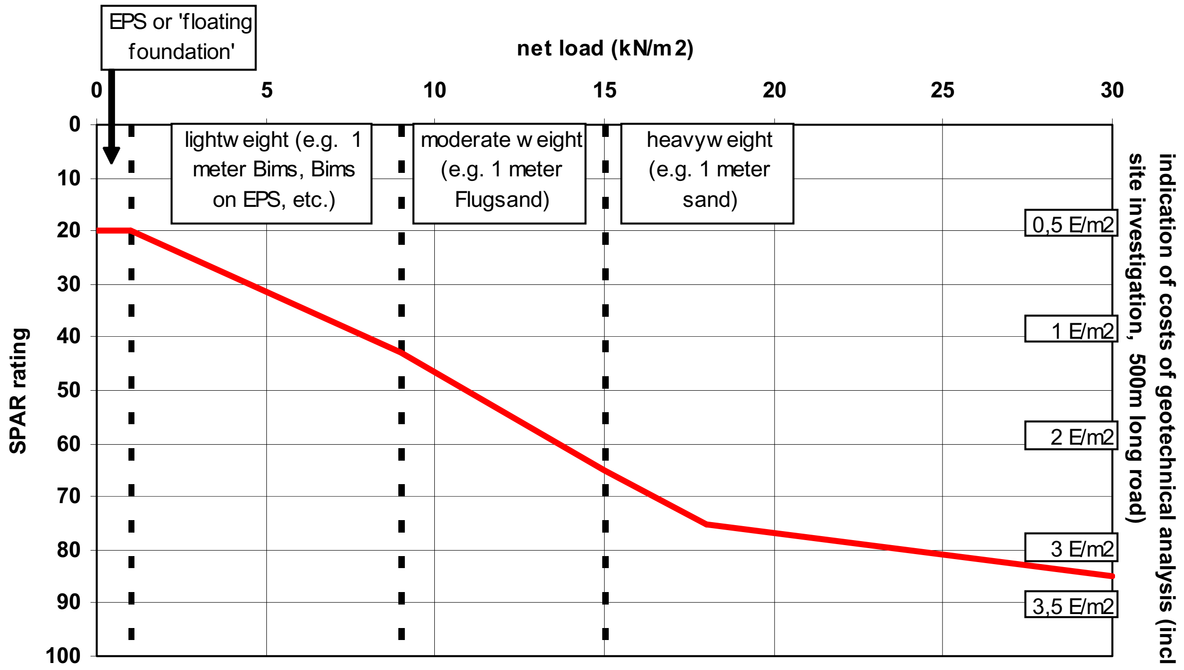

Figure 3. Relationship between the type of road foundation, the required Settlement Prediction Accuracy Rating and the estimated costs for the geotechnical analysis and site investigation.

FLOW CHARTS AND SCORING TABLES

This section holds the flow charts and the scoring tables from the framework. With this information, the framework and SPAR rating can be used. The full version of the framework and SPAR rating, as described by Maccabiani (2005), contains many more details and nuances that go beyond the scope of this paper. Most details and nuances deal with situations where the answer in the flow charts is not a simple 'yes' or 'no', as is the case in many if not all practical projects. However, all details and nuances add to the complexity of the framework. Since the framework is presented as a *practical* framework for municipal engineers, the flow charts and scoring tables presented here should be a sufficient improvement over the current working practice.

Table 2: Site investigation flow chart and scoring table (after CUR 2003).

S1: **Plan the site investigation**		
	S1.1: Determine the goals for the site investigation, based on the necessary parameters and the analysis of the historical data	
	S1.2: Analyse any literature, preliminary site investigation results	
	S1.3: Determination of the amount and type of site investigation per parameter necessary	
S2: **Carry out site investigation. Is the site investigation carried out in a phased manner, allowing the site investigation programme to be adaptable to previously obtained results?**		
	S2.1: **If yes**, score: 8	
	S2.2: **If no**, score: 0	
S3: **Interpret site investigation (for phased site investigations, repeat from 2)**		
	S3.1: Determine relevant subsurface layers. Was the site investigation density more determination (borings, CPTs) per 100 meter of road?	
		S3.1.1: **If yes**: score 5
		S3.1.2: **If no**, but local site investigation was used: score 2.5
		S3.1.3: **If no**, because only general knowledge (e.g. geological maps) were used: score 0
	S3.2: Determine relevant geohydrological properties using local site investigation: score: 5	
	S3.3: Determine relevant parameters for the settlement prediction	
	S3.4: Is the thickness of the existing road foundation determined using local site investigation or based on detailed technical drawings?	
		S3.4.1: **If yes**: score 10
		S3.4.2: **If no**: score 0

Table 3. Historical information flow chart and scoring table.

***H1:* does the existing road show differential settlements?**			
	H1.1: **If yes or unknown:** aim the site investigation at explaining the cause of these differential settlements (score: 0)		
	H1.2: **If no:** were differential settlements explicitly avoided when constructing the current road, e.g. by using different foundation thicknesses?		
		H1.2.1: **If yes:** are the initial assumptions that were made in the design of the present road known in detail, allowing their re-use?	
			H1.2.1.1: **If yes:** copy initial assumptions and use site investigation for any changed or unknown elements (score: 6)
			H1.2.1.2: **If no:** aim the site investigation at explaining the heterogeneity in compressibility (score: 4)
		H1.2.2: **If no:** soil compressibility profiles are homogeneous along the road; low priority for the site investigation to determine the horizontal heterogeneity (score: 8)	
***H2:* was the absolute settlement prediction for the current road accurate?**			
	H2.1: **If yes:** are the assumptions made for that prediction still accurate?		
		H2.1.1: **If yes:** copy initial assumptions and use site investigation for any changed or unknown elements (score: 18)	
		H2.1.2: **If no:** aim the site investigation at the changed assumptions (score: 14)	
	H2.2: **If no or no prediction available:** Aim site investigation at the determination of all relevant parameters for a detailed settlement prediction. Is the site's loading history known?		
		H2.2.1: **If yes:** back-calculation of settlement prediction parameters might be possible, limiting the extent of the required site investigation (score: 10)	
		H2.2.2: **If no:** full site investigation necessary (score: 0)	
***H3:* Does the new road foundation involve unloading of the subsoil?**			
	H3.1: **If yes:** determination of the pre-consolidation pressure is not necessary (score: 4)		
	H3.2: **If no:** the pre-consolidation pressure needs to be determined (score: 4 after determination of pre-consolidation pressure, otherwise score: 0)		
***H4:* Is extrapolation of settlement measurements possible to determine the residual settlements caused by the currently existing road?**			
	H4.1: **If yes:** estimate residual settlements using the settlement measurements (score: 8)		
	H4.2: **If no:** back-calculation using the initial height and the current height can be used (score: 0)		

Table 4: Parameter determination flow chart and scoring table (after CUR 2003).

***P1:* For the parameter in case, is there any actual in situ or laboratory measurement?**		
	P1.1: **If yes**: Can the parameter be determined using statistical procedures?	
		P1.1.1: **If yes**: use the statistical procedures
		P1.1.2: **If no**: attempt to confirm the accuracy of the parameters by back-analysis or correlation with nearby site investigation results
	P1.2: **If no**: Are there any 'standard' correlations available?	
		P1.2.1: **If yes**: use the most appropriate standard correlation available
		P1.2.2: **If no**: use values from literature or 'engineering judgment'

Table 5: SPAR scores per layer for parameter determination

Parameter determination score For each layer, determine the score. The final score is the average for all layers.	**Statistical analysis**	**Correlations based on project data**	**"Standard correlations"**	**Engineering judgement**
Volumetric weights	+7	+3	+1.5	+0
Compressibility parameters including pre-consolidation pressures	+7	+4.5	+1.5	+0
Permeability	+3	+3	+1.5	+0

Table 6: Settlement prediction.

Settlement prediction score for correctly using calculation method:	**Score:**
1D or 2D Terzaghi formula (or equivalent), no creep rule	3
1D or 2D Terzaghi formula (or equivalent), with simple creep rule	3
1D Koppejan, NEN-Bjerrum or isotache model	3
2D NEN or C_α-C_c model, not corrected for submerging	5
2D NEN or C_α-C_c model, corrected for submerging	7
2D Koppejan- or isotache model, not corrected for submerging of soil layers	10
2D Koppejan- or isotache model, corrected for submerging of soil layers	13
Settlement prediction score for explicitly using the residual settlement of the current road construction	7

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