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Mapping Geotechnical Risks for Infrastructural Works in Deltaic Areas

Arjan VENMANS [a] , Jeroen SCHOKKER [b], Roula DAMBRINK [b], Denise MALJERS [b] and Jan Jaap HEEREMA [c]
[a] *Deltares, P.O. Box 177, NL-2600 MH Delft, the Netherlands*
[b] *TNO - Geological Survey of the Netherlands*
[c] *Ministry of Infrastructure and Environment, Rijkswaterstaat, the Netherlands*

Abstract. This paper presents method and first results of a study to quantify and communicate geotechnical risk for highway construction on soft soil and large building pits associated with infrastructural works in the Netherlands. A set of easy-to-read maps will inform the end users, geotechnical consultants at the Dutch Ministry of Infrastructure and Environment, in the early stage of projects of the most important subsoil-related geotechnical risks and their spatial distribution. The method involves risk identification, risk assessment, identification of critical geological features contributing to this risk, and development of maps reflecting the magnitude of the geotechnical risk. Geological information is derived from the detailed 3D geological model GeoTOP. GeoTOP allows quick data assessment and creation of maps on a regional to nationwide scale. Close cooperation between geologists, geotechnical engineers and end users is the key success factor in application of the method. Geotechnical consultants will use the maps to identify risks, determine early risk mitigation measures and design site-investigation schemes.

Keywords. Quantifying geotechnical uncertainty, management of geotechnical risks, geology, GeoTOP, 3D modelling

1. Introduction

Geotechnical risks of construction projects are caused by unwanted events related to specific ground conditions. Like other risks, geotechnical risks need to be identified and addressed in a systematic risk management process in order to prevent time and budget over-runs, damage to property and loss of human life. Baynes et al. (2005) show that geomorphological and geological studies in the early project stages greatly contribute to reducing geotechnical risks. However, a hectic project start and a lack of subsoil data, geological and geotechnical expertise complicate daily practice.

Rijkswaterstaat, the executive branch of the Dutch Ministry of Infrastructure and Environment, has initiated a study to quantify uncertainty caused by ground conditions. A set of nationwide maps will express the amount of uncertainty from different sources of geotechnical risks.

The maps will allow geotechnical engineers of Rijkswaterstaat to rapidly identify and quantify subsoil-related risks, communicate these risks to project managers, and take appropriate measures. Notably, greater-than-average risks will be identified. The maps will typically be used in the pre-feasibility phase, when a site investigation is yet to be carried out.

The study has been a joint effort of geotechnical engineers and engineering geologists at Rijkswaterstaat and Deltares, and geologists of TNO - Geological Survey of the Netherlands (Sman et al., 2013; Venmans et al., 2014). The methodology developed can be used for several types of constructions, like road embankments and building pits. This paper presents the methodology, identification of critical ground conditions and production of pilot maps depicting these conditions, using the construction of a road on soft soil as an example.

2. Methodology

The methodology is best used in a framework for management of geotechnical risks such as the GeoRM approach developed by Geo-Impuls (Van Staveren et al., 2013). The GeoRM approach is an extension of the generic RISMAN risk management approach (van Well-Stam et al., 2004), focused on geotechnical risks. Table 1 gives the 6 steps of the GeoRM method. Baynes (2010) defines several sources of geotechnical risk: project management, contractual and technical risk. Consistent application of the GeoRM approach will account for the 'project management' and 'contractual' sources of geotechnical risks. The methodology described in this paper addresses the 'technical' sources of geotechnical risks as part of steps 1 to 3 of the GeoRM approach. The 'technical' sources of geotechnical risks are related to design models, mass and material properties, and geological conditions. The methodology will be illustrated in Section 4 using an example.

3. GeoTOP

Regional geological information is derived from the subsurface model GeoTOP (Stafleu et al., 2011, 2012; Van der Meulen et al., 2013). GeoTOP schematises the upper 30 to 50 m of the subsurface in voxels of 100 x 100 x 0.5 m. The model currently provides estimates of geological unit and lithological class (including grain-size classes for sand) per voxel, based on 100 equiprobable model realisations. The main data source of GeoTOP is the database DINO with approximately 500,000 digitally available borehole descriptions. Regionally important third-party datasets are also included. The use of cone penetration test data as additional model data source is yet in an incipient stage.

The GeoTOP modelling workflow involves three basic steps:

1. Coding all borehole information in terms of geological unit and lithoclass.
2. 2D interpolation to construct geological unit boundaries, resulting in a layer-based model.
3. 3D stochastic simulation to predict lithoclass for each of the voxels within the geological units, resulting in a voxel model.

GeoTOP was developed because heterogeneity in the Holocene coastal and fluvial deposits could not be accurately represented in layer-based models. Incorporating this variability is crucial for understanding ground behaviour and thus for successfully applying model results to geotechnical applications. To derive information on a specific geological phenomenon, voxels have been selected based on their properties and calculations have been made on vertical voxel stacks.

GeoTOP modelling is carried out per region. At current, GeoTOP is available for large parts of Western, Central and Northern Netherlands (Figure 1). Nationwide coverage should be reached in the following years. The model results can be accessed online for free (www.dinoloket.nl).

Table 1. Methodology for mapping geotechnical uncertainty as part of the GeoRM approach.

Step	Action
Risk identification workshop, main input from geotechnical engineers (generic for a road, building pit, etc.)	
1	Collection of data – determine type of geotechnical construction: road, building pit, etc.
2	Identification of 'technical' sources of geotechnical risks:
	2.1 Identify unwanted geotechnical events and underlying causes for all construction methods
	2.2 Identify geological phenomena associated with these events and causes.
3	Generic qualification and classification of risks:
	3.1 Compile an overall list of unwanted geotechnical events and underlying causes for all construction methods.
	3.2 Estimate the consequences of the unwanted geotechnical event and underlying causes for the main project performance indicators time, budget, quality, environment, public image and safety.
	3.3 Determine risk = probability x consequences, rank risks and select the top risks that will be mapped. Add all risks to the risk register.
	3.4 Determine what regional to nationwide data are available describing the geological phenomena causing the unwanted geotechnical events.
Map preparation workshop , main input from geologists	
3	Site specific qualification and classification of risks:
	3.5 Collect geotechnical, geological and geohydrological data for the selected top risks.
	3.6 Quantify the probability of the unwanted geotechnical event occurring by relating the probability to properties of the geological phenomenon. Determine the legend to be used in the maps.
	3.7 Prepare the maps.
	3.8 Prepare a schematic cross-section showing the geological phenomena.
Subsequent GeoRM steps (outside the scope of the methodology presented in this paper)	
4	Identify and deploy mitigation measures for all risks that are not acceptable.
5	Evaluate the remaining risk profile after the mitigation measures have taken effect.
6	Transfer the risk file to the next phase of the project.

4. Application to Road Construction on Soft Soil

This chapter illustrates the application of the methodology to road construction on soft soil. A 22 x 21 km large area North-East of Rotterdam was selected as pilot area (Figure 1). The pilot area contains both fluvial and coastal deposits.

Figure 1. GeoTOP coverage (grey) ultimo 2014. Black box indicates pilot area.

The risk assessment for roads on soft soil in this area has resulted in pilot maps for the six underlying causes contributing most to geotechnical risk. Paragraph 4.1 focuses on the process of identification and classification of risks related to ground conditions. As an example, paragraph 4.2 focuses on the preparation of the pilot map for short-distance variation in foundation-level depth, leading to a risk for insufficient bearing capacity for piled embankments.

The steps used refer to the steps in Table 1.

4.1. Risk Identification and Classification

4.1.1. Step 1: Type of Geotechnical Construction

The maps will be produced for 2x2 lane highways with elevation 1 m above the original ground surface.

4.1.2. Step 2.1/2.2: Unwanted Geotechnical Events and Associated Geological Phenomena

Common construction methods for roads on soft soil involve application of prefabricated vertical drains, piled embankments or light-weight fill materials. Not all construction methods are sensitive to the same geological phenomena. For instance, thickness and lithology of the soft soil deposits are the geological phenomena determining settlement under the weight of a sand fill, but these will hardly affect the design of a piled embankment.

Table 2 shows unwanted geotechnical events for roads on soft soil that are related to subsoil characteristics. For these events several underlying causes have been identified and linked to specific geological phenomena. This type of table is best produced in a workshop by a team of geotechnical engineers and geologists.

Table 2. Causes and geological phenomena contributing most to geotechnical risks for roads on soft soil.

Cause	**Geological phenomenon**
Large (post-construction) settlements of sand fills	
Over-optimistic assessment of lithology	Long term settlement, estimated from layer thickness and lithology
Over-optimistic assessment of settlement and settlement rate	Proportion of peat in the upper 3 m
Over-optimistic assessment of soil permeability	Proportion of organic clay and clayey peat in total thickness of soft soil
Vertical drains cannot penetrate densely-packed shallow sand bodies	Shallow Holocene sand layers underlain by soft soil
Large (post-construction) differential settlements of sand fills	
Buried sand bodies with dimensions smaller than the average spacing of verticals in a site investigation	Shallow and narrow buried sand channels of river systems, crevasse splays
Insufficient bearing capacity for piled embankments	
Foundation level varies over short distances	Loose sand layers directly on top of densely-packed Pleistocene sand layers

4.1.3. Step 3.1/3.2/3.3: Overall List, Consequences and Risk

Table 2 is the basis for an overall list of all unwanted geotechnical events, underlying causes and associated geological phenomena for selected construction methods. Next, a team of experts assesses consequences of the unwanted event on time, budget, quality, environment, public image and safety. An example of the scoring system is given in Table 3.

Table 3. Example of scoring system for consequences of unwanted events.

Consequence for budget – loss [%]	Consequence for time – delay [months]	Score
0	None	1
0 - 3	0 - 1	2
3 - 7	1 - 2	3
7 - 15	2 - 4	4
15 - 33	4 - 6	5
> 33	> 6	6

After scoring events and causes, the events are ranked according to the sum of the scores of the associated causes. In case total scores of the events are approximately equal, further criteria may be applied to select the most important events. These criteria may be the probability that damage will actually be inflicted, or the degree to which Rijkswaterstaat or contractors can control the risk.

4.1.4. Step 3.4: Available Regional to Nationwide Subsurface Data

The unwanted geotechnical events and underlying causes that contribute most to geotechnical risks ('top risks') for roads on soft soil are selected for map preparation. In this step relevant data needs to be selected from the TNO databases. Ideally, the data are directly related to the relevant geological phenomenon. For instance, the geological phenomenon 'proportion of peat in the upper 3 m' (see Table 2) can be directly derived from the lithoclass information in GeoTOP. However, the phenomenon 'proportion of organic clay and clayey peat layers in total thickness of soft soil' (Table 2) refers to soil types that are not represented as a separate lithoclass in GeoTOP. In this case, the proportion of fluvial deposits has been adopted as alternative, because these deposits are known to contain abundant organic strata.

4.2. Map Preparation

4.2.1. Step 3.5: Collect Data

The pilot map presented in this paper relates to the unwanted geotechnical event "insufficient bearing capacity for piled embankments" (Table 2), which scored highest in the risk assessment performed. One of the underlying causes is expected to be "foundation level varies over short distances" and the associated geological phenomenon is "loose sand layers directly on top of densely-packed Pleistocene sand layers". To develop this map the geological framework of the area has been compiled.

The pilot area is characterised by the presence of 10 to 15 m of Holocene fine-grained fluvial and coastal deposits and peat on top of coarse-grained Pleistocene deposits. Within the Holocene clay and peat sequence, sandy fluvial channel-belt deposits occur.

4.2.2. Step 3.6/3.7/3.8: Quantify Probability, Map Preparation and Schematic Cross Section

The foundation level generally used for piled embankments in this area is formed by densely-packed Pleistocene fluvial sand, partly capped by thin floodloam deposits (Figure 2). Directly on top of these sediments, other sandy deposits may be present, e.g. Holocene channel-belt sand (a), Late-Pleistocene aeolian riverdune sand (b) or coversand (c). These sandy sediments are either very heterogeneous (channel-belt deposits) or loose (aeolian deposits). We assume that if these deposits comprise a thick layer, the risk of choosing a relatively shallow foundation level that has insufficient investigations are probably needed. The map is therefore based on the depth difference between the top of the loose sand and the densely-packed Pleistocene fluvial sand (Figure 3).

Based on expert assessment, a traffic-light type legend has been designed, running from low risk (green), meaning the absence of loose sand, to high risk (red), meaning a thickness of loose sand exceeding 5 m.

Geological structures clearly stand out on the resulting map: West-East oriented dune complexes occur as red streaks on the southern half of the map, whereas cover sand deposits show up more diffusely in the northernmost part. Sandy Holocene channel-belt deposits appear to be almost nowhere in direct contact with the Pleistocene sand in this area and are therefore hardly visible on the map.

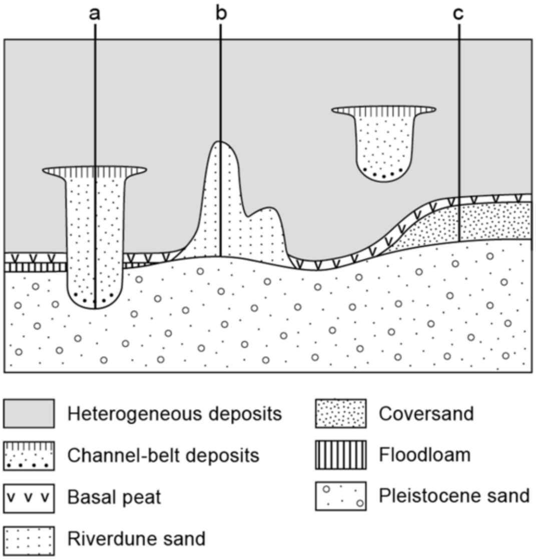

Figure 2. Schematic cross section showing subsurface features relevant for foundation of a road on soft soil in the pilot area. See text for more information.

5. Discussion and Recommendations

5.1. Discussion

The methodology presented in this paper greatly benefits from a multi-disciplinary approach, involving geotechnical engineers and engineering geologists to identify and classify risks, and geologists to quantify the associated geological phenomena.

Only part of the causes of geotechnical risks is related to ground conditions; the risk identification step also produced many risks caused by inappropriate design methods and construction errors. These risks can be added to the risk file for future mitigation in the design and construction stages of the project.

The 3D voxel model GeoTOP provides the best regionally available information on lithological variability down to a depth of 30 to 50 m below surface for the Netherlands. Without the use of GeoTOP most of these maps could not have been made.

Some unwanted geotechnical events are difficult to quantify because GeoTOP does not include the parameters describing the associated geological phenomena, e.g. proportion of organic clay and clayey peat. For those cases a work-around method was developed.

Not all unwanted geotechnical events can be quantified because essential information is lacking about the parameters of the associated geological phenomena, e.g. width of narrow buried sand channels and packing variability of Holocene sand.

5.2. Recommendations

In 2015 the methodology will be validated, comparing the results of the method to actual planned or realized projects. Validation needs to focus on assumptions regarding the characteristics of geological phenomena, e.g. to use the presence of fluvial deposits as an indicator for the presence of organic clay and clayey peat. Also, the amount of risks expressed by the maps and the map legends has to be checked against the risk perception of end users.

A next step is the preparation of nationwide maps. For this, it has to be tested if assumptions made in the pilot area can be upscaled to a nationwide scale. More likely, regionally diverse assumptions will have to be developed.

More information has to be acquired on parameters of the geological phenomena that are associated with important unwanted geotechnical events, e.g. width of narrow buried sand channels and packing variability of Holocene sand.

It has to be assessed how the maps are best incorporated in the workflow of Rijkswaterstaat to ensure optimal application by end users.

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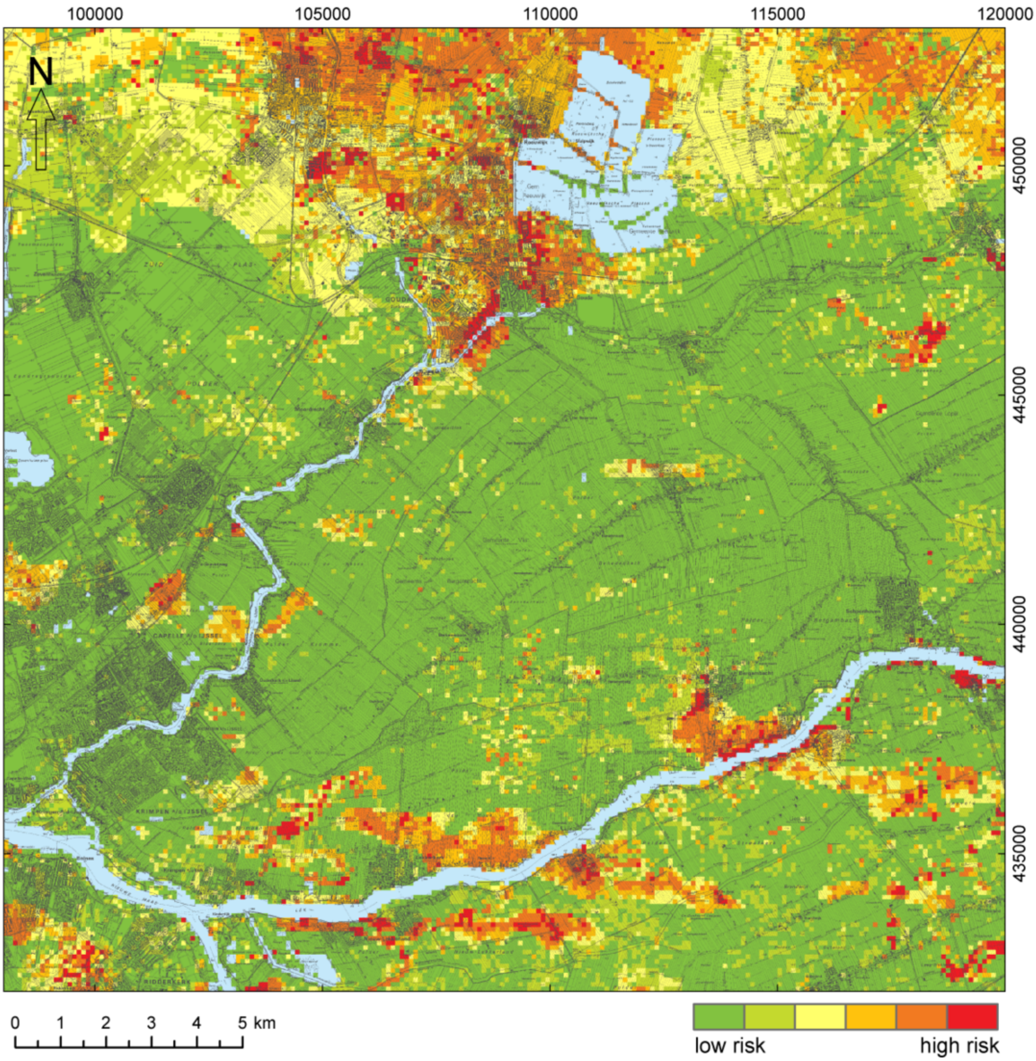

Figure 3. Risk of insufficient bearing capacity for piled embankments, based on the occurrence and thickness of loose sand layers causing short-distance variation in foundation level.

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