DERIVING SCENARIOS FOR STOCHASTIC CHARACTERISATION OF THE SUBSURFACE

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General

Water defence systems are made for operating conditions which are assumed to be rare and may not have occurred yet at a location or in an area. The local performance of a water defence system during extreme, rare, events depends on local conditions, including the local subsurface, which is a part of any water defence system. The interaction of processes during extreme high water can depend on the conditions in the subsurface which in turn depend upon, sometimes details of, the subsurface build-up and its local variation. Information on the local subsurface build-up is therefore necessary, preferably in a flexible form allowing incorporating detail where necessary and possible.

The schematisation of the subsurface described here is developed to support mitigation actions taken during and immediately preceding extreme high water conditions at water defences. The method allows for efficient incorporation of "new" information, and for local analysis of details in the subsurface build-up by experts during emergencies. The approach and procedure described here also provide relevant information for regular qualification checks of water defences for which it is already used in The Netherlands. The method has similarities with the "total geology" approach described in Fookes (1997).

In geotechnical engineering the subsurface at a site in lowland terrain is often considered to be represented by the vertical sequence of properties in an individual soil investigation point, i.e.a CPT or borehole location. Often the vertical sequence of properties to be used in the analysis is chosen from among several investigation points after a selection criterium, e.g. the average or the worst condition. Alternatively horizontal interpolation, qualitatively or quantitatively, of boundaries between layers or properties between adjacent observations is used to cover unprobed locations. These interpolation procedures, however, easily violate some well known properties of the systematics in the build-up of the subsurface, notably non-stationarity in the subsurface at the relevant dimensions, and easily underestimate the very high sampling density required to represent the variation actually present without excessive uncertainties. The method for schematisation presented here provides a direct path from original data, supplemented by available knowledge, to the input for quantitative analyses, including probabilistic assessments. To quantitatively deal with the inherent limitations regarding the detail that can be known about the relevant spatial variation of properties in the subsurface, the schematisation presents the information on the subsurface as scenarios, possible realisations, with estimates of the probability of their occurrence. These scenarios are set up in a format suitable for the quantitative analysis methods.

Approach

The relevant properties of the materials in the subsurface show a strong spatial variation for civil engineering applications. The spatial variation in properties is commonly represented by dissecting the subsurface in discrete units, layers, each with an assumed homogeneous distribution of property values. The dimensions of the units discerned depend on the application, notably (i) its sensitivity for the values of the properties, (ii) the information on the subsurface available, and (iii) the safety margins allowed for in the application. Schematising the subsurface therefore requires geotechnical information and knowledge. The necessary information on the subsurface can be obtained from data in combination with knowledge on the systematics in the build-up. As data coverage is in general very low for the subsurface, additional information is usually called upon. An increase in the knowledge on the systematics in the subsurface of an area reduces the dependency on data at the site, and can add substantial detail in information on the soil involved. The schematisation of the subsurface therefore requires combining geotechnical expertise, specifying the required detail and sensitivity, with local expertise or formal knowledge on the actual conditions in the subsurface.

In case of an emergency a suitable schematisation of the subsurface may be required, and it may have to be generated at very short notice based on already compiled data and information, or must have been prepared in advance. Where a schematisation has to be made at very short notice a team comprising an experienced geotechnical engineer and an experienced geologist has to be available. Such a team is also required if additional detail on specific aspects of the subsurface is needed.

Most of the information on the variation in the subsurface at a location comes from boreholes and CPTs. In order to adequately map the spatial variation in the subsurface for flood defence applications, a spacing between the boreholes and CPTs over the area of the structure about 25 m or less would be required if additional information on systematic aspects of the variation cannot be obtained and used. Such additional information, however, is, or can be made available at very short notice in lowland areas such as The Netherlands at suitable detail for many applications. Moreover, not all variation in the subsurface need be known for an application and geotechnical experience can indicate which aspects of the strong spatial variation must be known. For civil engineering applications it often suffices to have a good overview of the possible ways the subsurface is built up at a site, and of parameter value ranges for the properties that can be present. These possible combinations of build-up and properties at a site can then be represented by scenarios. Each of the scenarios for a site can be assigned a probability of being encountered at the site, such as a stretch of a water defence structure. Characterisation of the subsurface with scenarios is notably appropriate where insufficient data are available at a site and extensive experience, local or in similar settings, is or can be made available. This experience can be formal or well-trained intuition based on in depth local experience.

The effects of these subsurface scenarios on the functioning, including probability of failure of the water defence structures can be evaluated, quantitatively or qualitatively. The probability of a scenario being encountered at a site can be combined with other aspects in the probability of e.g. failure of the structure and be weighed against the required safety level. The so-called schematisation factor (Deltares, 2011a) is a tool for a rational weighing of the combination of the various probabilities in loads and strengths versus the required safety level in terms of the probability of failure allowed.

Schematisation of the subsurface using scenarios for the build-up of the subsurface is taken here as the appropriate method for flood defence structures in The Netherlands, where the subsurface has been studied in considerable detail and wide experience with water defences exists. The procedure sketched below is based on availability of a database with borehole logs and CPT results with a suitable spatial coverage.

Procedure

Scenarios

The procedure for schematizing the subsurface aims at establishing scenarios representing the build-up and properties of the subsurface for a stretch of water defences in lowland terrain. The scenarios in this section represent the relevant characteristics of the subsurface for e.g. slope failure and piping as determined with the "piping rule" (Deltares, 2011b) for dikes. The detail and further specifics incorporated in the scenarios depend on those applications. Each scenario is valid for a certain stretch of the dike. Approximate indications of the location for which a scenario holds suffice, at least initially before mitigating measures are designed, and in subsequent project stages refinements can be incorporated.

The subsurface build-up in a scenario for a location is represented here by a continuous vertical stack of units, layers, of soil which completely describes the depth interval of the stack. It is noted that each depth in the depth interval of a stack is occupied by only one unit. If the occurrence of alternative units is possible in a depth interval at a location, alternative stacks with the mutually exclusive units for this depth exist: scenarios. For each location along the stretch the probability of a specific unit being encountered, i.e. of occurrence, can be determined. The probability of a unit being encountered can be either a rough or a detailed estimate, depending on the data and information coverage used, and after the sensitivity of the dike for the alternatives. Where alternative units can occur in a certain depth interval the probability of occurrence of all these alternatives is approximated by data supported expert guesses, or data coverage alone where sufficient data are available to derive statistics from for the site. The possible stacks of units at a location can be determined from the possible occurrence of units there. The probabilities of the individual units at a location can be combined for a stack to determine the probability of occurrence of the entire stack, which is the probability of occurrence of the subsurface build-up scenario. A scenario can be extended beyond only the vertical stack, and incorporate other features such as local 2- or 3-dimensional transitions and variation patterns. However, this lies beyond the scope of this contribution.

In stretches of water defences with very limited spatial variation, one or a few scenarios may suffice to represent the subsurface for safety assessments. In other stretches the number of possible alternatives can be high. In short stretches fewer alternatives, scenarios, in the schematisation are necessary to represent the possible build-ups of the subsurface than in longer stretches.

The implications of a scenario for an actual safety level can be evaluated using stochastic methods involving the probabilistic evaluation of the performance of the structure, and statistics on parameter values of properties and geometry. The scenarios can also be used with the abovementioned schematisation factor (Deltares, 2011a).

Necessary data

Direct observations of the subsurface are necessary to provide suitable detail for locating the various types of build-up possible for an area. These observation can be CPTs, borehole data, areal geophysical data, and specific terrain data. Geophysical data is usually employed to support the information from CPT and borehole data. Terrain data can help to delineate the area within which subsurface data are meaningful for a project site, e.g. a present river valley or a tidal inlet zone. Availability of borehole and CPT information is critical for most applications, however, and, unless geophysical data have proven to provide sufficient certainty, are indispensable in characterizing the subsurface in lowland terrain. The following is therefore based on CPT and borehole data, but other data can be incorporated directly or used as supporting material.

In case the local experience is limited and dedicated knowledge on systematics in the subsurface of the area is not mobilized the data coverage should be about as indicated in the two cases below, notably:

- site investigation results, CPT and borehole data, with spacing not more than 150 m along at least larger parts of the water defence structure investigated, and more than about 15 quasi-regularly distributed observations per km^2 in a zone along the water defence structure about 2 km wide (such as the DINO database, at TNO, for The Netherlands) in similar terrain (notably local relief and landscape);
- alternatively about 30 regularly distributed observations per km^2 in a zone along the water defence structure about 2 km wide (such as the DINO database, at TNO, for The Netherlands) in similar terrain (notably local relief and landscape).

In case extensive local experience (10 year work directly involving subsurface data in the area) or dedicated knowledge on the systematics of the subsurface of the area is mobilised the spatial coverage should be about at least 8 observations per km^2. The limited data coverage is possible since indications from the observations combined with expert knowledge on the area provide information concerning not directly observed features in the vicinity.

Activities for generating the schematisations

The procedure consists of the following activities which are given below in approximate sequence of execution, notably:

Determine, and register the depth intervals of the various well recognizable lithologies (soil types) in all borehole logs and CPT results (use of correlation of CPTs with nearby borehole data is preferred in lowland terrain, since the reliability of general purpose correlation charts is insufficient for discriminating the common soil types).

From the range of depths of all depth intervals of the lithologies discriminate any apparent depth and thickness categories in the intervals for each lithology. Note downward transitions from sand to clay or peat separately as for sand intervals only the upper boundary is considered initially. For lithological intervals with a large variation in thickness in a specific depth range (top, base or average depth of the interval) categories of thickness and for depth range can be discriminated for the lithology, which applies notably for coarser, sand units. Expert knowledge allows identification and discrimination of specific features in borehole logs and CPT data where specific detail can refine schematisation of geometry or assigning soil properties.

Plot and subsequently approximately delineate in map view the occurrence of the intervals of the depth categories of each of the various lithologies to determine their spatial distribution in the 2 km wide zone along the dike. Boundaries in the delineation are located such that all observations representing notable adverse conditions are circumscribed with a wide margin, which depends, of course, on the local data density. Expert knowledge on the features that are delineated can improve the spatial resolution significantly.

Determine layers in the investigated area, the water defence and the 2 km wide zone, by combining recursively depth and lithology categories, while maintaining spatial coherencies, and aiming at optimising the number and detail of the resulting layers which will be used in the scenarios for geotechnical assessments.

If the data coverage is less than about 50/km^2 within 1 km from the dike, check for possible adverse undetected features, lithologies or depth and thickness outliers, with experts.

Estimate the probability of occurrence of each layer in the relevant delineated zones, and of the complementary alternatives at the same or overlapping depth intervals.

Determine the possible vertical stacks of layers by combining the overlaps of delineated zones, and noting the alternatives in scenario resulting from the layers that occupy the same or overlapping depth interval. Note that sand and clayey sand units can have considerable thickness, and replace other lithologies over a sometimes > 10 m thick depth interval.

Determine the probability of occurrence of each of the possible stacks along the dike section by combining (multiplication) the probabilities of all of the layers present in the stack.

Identify the locations along the dike where the probability of or more scenarios changes (it is recommended to cluster these locations as much as possible initially, in order to reduce the complexity of the resulting zoning map for the dike). Give the location of scenario changes or the stretches with a specific set of scenarios a unique identification and geographical position.

Layers and optimisation

The minimum layer thickness used in scenarios for slope stability and the piping rule is about 0.5 m except for layers known to have large continuous spatial extent and which have important influence on permeability or strength. In The Netherlands the so-called Basal Peat layer is such a layer notably affecting geohydrological conditions.

The number of scenarios for a stretch multiply by the number of alternatives that exist for each depth interval. For example, in a total thickness of 15 m in a stretch of dike the number of depth intervals with a choice between 2 or more alternatives can be over 4, which results in at least 16 scenarios which may have to be evaluated. If one of those depth intervals is a sand unit for which 3 thickness categories exist (e.g. 2, 5, and 8 m) the total number of scenarios amounts already to 24. Optimizing the number of layers from a geotechnical perspective is therefore imperative in this approach. The schematisation should focus on the variation in the geotechnically dominating layers. Where competing geotechnical sensitivities exist, separate schematisation such as for piping and slope stability should be considered. E.g. a thick soft clay layer may be an issue for slope stability, but may have a positive effect with respect to piping.

The scenarios can be easily expanded and adapted to incorporate additional data or information on the subsurface. Apart from possible redefinition of units, this can involve redistribution of the stretches for which a combination of scenarios holds. Locally added borehole or CPT information will in general result in making certain scenarios more likely, or even exclusive, and other less likely in a stretch of dike or part of an section.

Involving expert knowledge on the systematics in the subsurface in the area together with geotechnical expertise can significantly reduce the time and effort in the schematisation in this procedure, while increasing the accuracy. Apart from the information on the systematics in the arrangement of layers in the subsurface the expert knowledge can make use of the indications in the borehole and CPT data in reducing uncertainty and concerning features missed by the available exploration data. The combination with geotechnical expertise can much enhance the optimisation towards definition of geotechnically relevant features in the subsurface.

Remarks on justification of the procedure

Schematising the subsurface for practical application in not only civil engineering, but also in mineral, groundwater and hydrocarbons extraction, eludes an adequate formal, quantitative description. The inadequacy results from both a lack of a statistically relevant number of direct observations given the actual relevant variation in the subsurface, and absence of a suitably defined model of the systematics in the subsurface in which the observations have a well defined role. A substantial part of the inadequacy can be overcome by generating, or using an existing suitable model of the systematics in the subsurface, and specifying the way in which available observations fit in the elements of the systematics. Such a suitable model of the systematics is only well possible in sufficient detail for civil engineering for an area of limited extent (i.e. areas of 5 to 25 km^2). The model of systematics limits not only the amount of observations necessary for an appropriate schematisation of the subsurface, but also gives relevant information for applications directly (e.g. materials to be reckoned with, nature of stacks of layers, general regional trends). The method presented here relies on the specific aspects of the systematics in the subsurface in lowland terrains, and provides for a way to make use of it without the necessity to know details of the model, while, at the same time, allowing for incorporation of such details where available. However, an explicit description of the model of the systematics in the subsurface for individual dike stretches requires excessive amounts of work; comparable to a surgeon having to explain the various aspects and interrelations of all the tissues that are dissected during an operation. This aspect of the method has therefore never been put to an explicit test so far. (Note that none of the other methods for schematising the subsurface on regular basis on the basis of sparse data has passed tests with positive results. Justification of the method can, apart from theoretical considerations, be found in the findings thus far (several thousands of kilometers in The Netherlands), showing that it has described the subsurface very well for locations for which soil investigation results have become available, or when matched with existing soil data. Improvement of the quantitative probabilistic description with the method can be notably achieved by inserting more definite information on spatial dimensions of units in the subsurface, and notably the trends in the influences on these dimensions. Incorporating this information would enable more definite quantification of the statistics for probabilistic analyses.

Example

In figure 1a sketch of a relatively simple configuration of the subsurface is given showing the units that can be encountered in an area where a dike is located, and which can occur at the dike. The units shown in the figure are the result of the steps 1 to 5 of the activities listed above. The stretches in which the various units can be encountered are indicated in the figure, as are the stretches in which certain stacks of units can be encountered, i.e. the segments for which the scenarios are given. In Table 1 the probabilities of encountering a unit in the indicated stretch are given, and in Table 2 the stacks possible in the stretches 1 to 3 for the scenarios are listed with the probability of occurrence as derived with the procedure described above. It is noted that Figure 1 does not show all the possible scenarios listed in Table 2. Figure 1 is also not a hypothetical geotechnical profile nor does it show all scenarios that can occur with the given probabilities for the units. A comprehensible sketch for a stretch of dike in which all possible scenarios occur in a geometrically realistic setting would be very complicated to set up, unless the geological and geotechnical profile connotation is dropped.

In figure 1 two clearly different thicknesses for units 2 and 6 are indicated. This variation is not incorporated explicitly in the assessment here, but such variation can be relevant. If the thickness variation is not translated in separate scenarios, the application determines whether the thick or the thin alternative is selected, or whether an intermediate is more appropriate. In this case it is assumed that the units 2, 4 and 6 are sand units and that the difference between the units does not necessitate separation leading to additional scenarios.

Unit type	Unit stretch	Probability of occurrence
1	Z1	1.0
2	Z2	0.5
3	Z3	0.95
4	Z4	0.4
5	Z5	0.5
6	Z6a	0.5
6	Z6b	0.5
7	Z7	0.9
7	Z8/7	0.9
8	Z8	0.9
9	Z9	1.0

Table 1 (with Figure 1) Probability of occurrence (of being encountered by soil investigation) of the various units

segm	scen	unit stack	Pscen.	unit type	1	2	n2	3	n3	4	n4	5	6	7	n7	8	9
1	1	1-5-7-9	0.950		1									0.95			1
	1	1-5-7-9	0.050		1										0.05		1
				unit type	1	2	n2	3	n3	4	n4	5	6	7	n7	8	9
2	1	1-5-7-9	0.238		1		0.5					0.5		0.95			1
	2	1-5-9	0.013		1		0.5					0.5			0.05		1
	3	1-6-9	0.250		1		0.5						0.5				1
	4	1-2-6-9	0.250		1	0.5							0.5				1
	5	1-2-5-7-9	0.238		1	0.5						0.5		0.95			1
	6	1-2-5-9	0.013		1	0.5						0.5			0.05		1
				unit type	1	2	n2	3	n3	4	n4	5	6	7	n7	8	9
3	1	1-2-6-9	0.150		1	0.5					0.6		0.5				1
	2	1-6-9	0.150		1		0.5				0.6		0.5				1
	3	1-4-6-9	0.100		1		0.5			0.4			0.5				1
	4	1-2-4-6-9	0.100		1	0.5				0.4			0.5				1
	5	1-4-5-9	0.100		1		0.5			0.4		0.5					1
	6	1-2-4-5-6-9	0.100		1	0.5				0.4		0.5					1
	7	1-5-9	0.150		1		0.5				0.6	0.5					1
	8	1-2-5-9	0.150		1	0.5					0.6	0.5					1

Table 2 (with Figure 1) Stacks of units that can occur in the stretches 1 to 3 for which the scenarios are defined as stacks of units. The probability of occurrence of each of the units is given in Table 1 Where a unit can be present or not in a stack this is indicated by the unit number or the unit number preceded by the letter n, i.e. 4 and n4. For each scenario the probability is listed for each participating or absent unit in the stack. The column ´segm´ gives the segment number in Figure 1, ´scen´ gives the scenario number, ´Pscen´ contains the probability of occurrence of the scenario (the sum of the scenarios in a segment is 1.0).

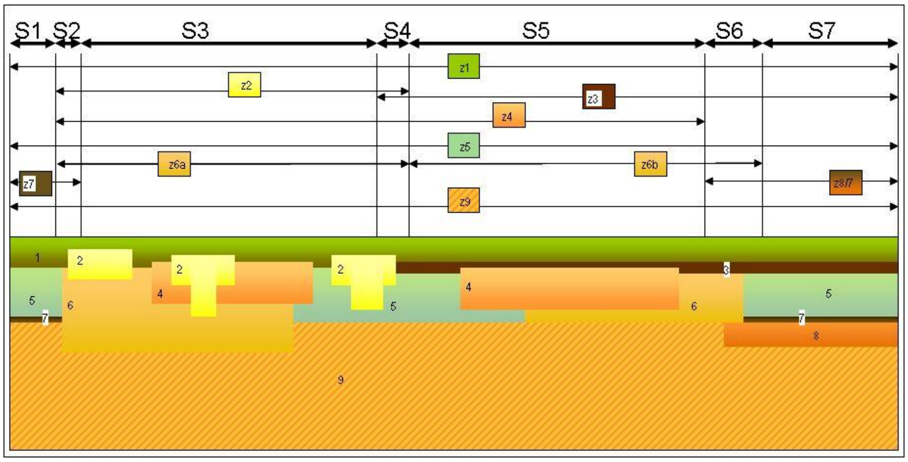

Figure 1 Sketch of a subsurface build-up in units of certain lithologies at various depths. The units are indicated by 1, 2, ..., 9, and the stretches, in which the units can be found with a certain probability are indicated by Z1, Z2, …, Z9. The stretches for which scenarios are defined are indicated by S1, … , S7. The probabilities of occurrence in the stretches are given in Table 1 and the stacks of units possible in the scenario stretches are given in Table 2.

References

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