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PARAMETERIZATION OF GEOLOGICAL MODELS FOR REGIONAL SITE RESPONSE AND LIQUEFACTION POTENTIAL INDICATORS

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ABSTRACT

We have built two regional geological models - covering over 1,000 km^2 - that serve as input for the seismic hazard and risk analysis of the onshore gas field of the Groningen region, the Netherlands. The first model describes the liquefaction potential indicators and the second model contains the layer model and parameterization for site response analysis. Earlier published papers focused on the construction of the models. The emphasis of the current paper is on the parameterization of both models. The liquefaction potential indicator consists of the cumulative thickness of loosely, moderately and densely packed sand in the top 40 m. This parameter was derived from the cone resistance values in the database of ~ 5,700 Cone Penetration Test (CPT) soundings. The geological model for site response consists of vertical voxel stacks corresponding to the GeoTOP model and extended to ~ 800 m depth using scenarios. These voxel stacks serve as input for site response calculations which requires information about shear wave velocity, unit weight, overconsolidation ratio, plasticity index, undrained shear strength, median grain size and coefficient of uniformity. These parameters were either derived based on local data from Seismic CPTs, CPTs or grainsize analyses. The empirical relations from literature were modified to fit the local Groningen characteristics of the soil. The parameterization was derived for the combinations of stratigraphy and lithology that are present in the region. Although our approach to schematize geology and to parameterize the geological models was developed for the region of Groningen, the general approach can be applied to other regions.

Keywords: Geology; liquefaction; model parameterization; site response.

1. INTRODUCTION

The Groningen region in the northern part of the Netherlands has experienced induced seismicity during the last decades as a result of gas extraction from the onshore gas field. The largest earthquake to date was the Huizinge earthquake in 2012 with a local magnitude of 3.6. This earthquake initiated a study program to better understand and subsequently mitigate the seismic hazards and risks associated

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with the exploitation of the gas field. As part of this study program, we have built two geological models that serve as input for the seismic hazard and risk analysis. The models have a regional coverage spanning an area of more than 1,000 km^2.

The first geological model describes the liquefaction potential indicators and the second geological model consists of the characterization and layer model for site response calculations. The geological setting is elaborately described in Kruiver et al. (2017b) and summarized in section 2. The models consist of a schematization part (e.g. the geometry of the layers) and a parameterization part (e.g. assignment of characteristic values for relevant parameters to those layers). Many parameters were derived from the database of ~ 5,700 Cone Penetration Tests (CPT). The schematization was published by Kruiver et al. (2017a, b). This conference paper focusses on the parameterization of the models and is described in section 3. Empirical relations from literature were modified to fit local (or regional) conditions, such is suggested to be superior to literature relationship charts by Lunne et al. (1997). The schematization and the application of the models and its use in the Groningen seismic hazard and risk are included in section 4. Future improvements and conclusions are provided in sections 5 and 6.

2. GEOLOGICAL SETTING

The northern part of the Netherlands borders the North Sea. The geology is extensively described in Kruiver et al. (2017b) and references therein. In summary, the Cenozoic sedimentary infill of the North Sea Basin is influenced by two recent ice ages and sea level fluctuations. The Elsterian glaciation produced deep erosive subglacial features (‘tunnel valleys’) which were filled with sands and clays of the Peelo Formation and subsequently buried by younger sediments. The second glaciation (Drenthe Substage of the Saalian glacial) produced the till sheet that constitutes the Drenthe plateau. Although the region has a relatively flat topography with elevation differences up to 25 meters, the ridge-and-valley relief is still present in the landscape stretching from the city of Groningen towards the South-East (Hondsrug). During the last ice-age (Weichselian), the region was not covered by ice-sheets but a widespread superficial blanket of aeolian cover sands (Boxtel Formation) formed that in many places marks the top of the Pleistocene deposits. During interglacial periods, when sea-level was higher than during ice-ages, a large part of Groningen formed the coastal plain of this sea. The most recent Holocene deposits typically consist of stacked vertical sequences of tidal clays and sands that are often thinly bedded and are intermittent with peat layers and soil horizons. The typical Holocene succession is (from old to young): Nieuwkoop Formation, Basal Peat Bed; Naaldwijk Formation, Wormer Member; Nieuwkoop Formation, Hollandveen Member; Naaldwijk Formation, Walcheren Member. The Holocene sediment thickness varies from approx. 20 m in the northern part to being absent in the southern part of the region.

3. PARAMETERISATION OF GEOLOGY

3.1 CPT derived parameters

The median depth of the CPTs in the database is 30 m. The dominant quality class of the CPT's used in the correlations was according to the Dutch Standard NEN 5140 class 2, and after introduction of the national ISO standard NEN-EN-ISO 22476-1, class 3.

During a CPT sounding, the cone tip resistance q_c and the friction ratio (R_f) are measured. Empirical relations between q_c and R_f and derived parameters such as unit weight or undrained shear strength are summarized in Lunne et al. (1997). These empirical relations are adjusted to fit the regional characteristics of the Groningen soils using the flow chart in Figure 1. The depth intervals in the CPT are classified in terms of stratigraphy (e.g. Naaldwijk, or Peelo) and lithology (peat, clay, sandy clay and clayey sand, fine sand and medium&coarse sand), as a combination referred to as a “unit”. This is either done automatically (section 3.1.1) for a large CPT database or manually on a smaller CPT database (sections 3.1.3 – 3.2). The relevant empirical relation is applied to obtain values for the desired parameter. Next, all parameter values for one unit are assembled for further analyses. This can be e.g. a nomogram (section 3.1.1) or a plot of the parameter versus vertical effective stress (section 3.1.2 – 3.2). For each unit, the Groningen specific relation is determined. This can either be a constant or a linear relation with vertical effective stress. Some units are not well represented in the CPT database, generally because the unit occurs at greater depth and occurs in the CPTs to a limited extent only. In this case, the empirical relation from a similar unit is selected, based on expert judgment and supported by literature if available.

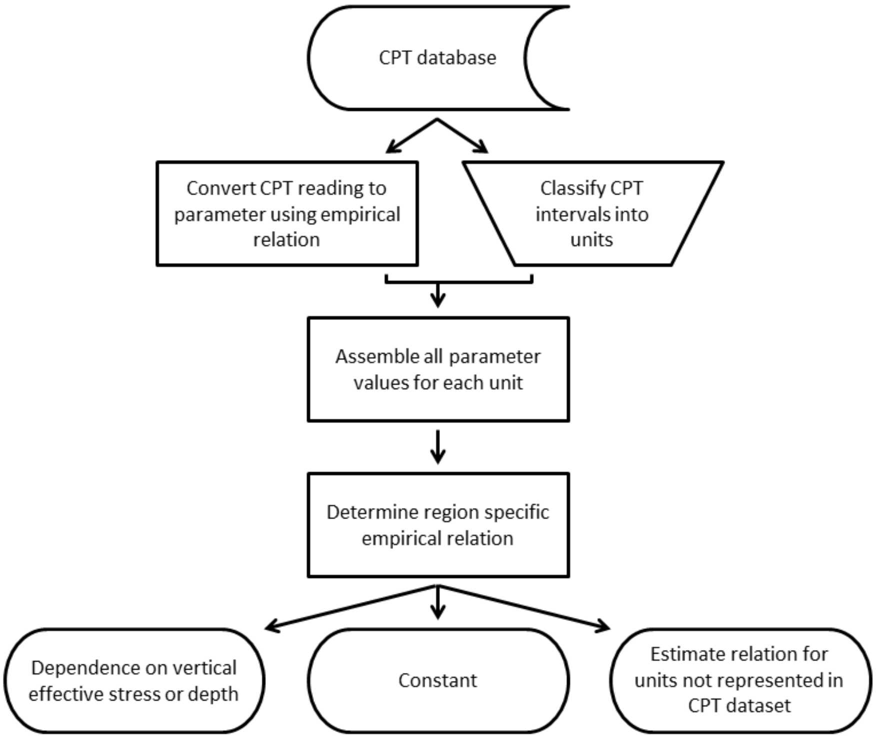

Figure 1. Flow chart of steps to obtain region-specific empirical relations for CPT parameters.

3.1.1 Lithology

There are several methods available to convert CPT data into an interpretation of simplified lithological units, such as the soil behavior charts developed by Robertson (1990), Douglas & Olson (1981) and Schmertmann (1978). The methods in literature are described as generalized representations of empirical correlations. However, different geological terrains and sediments in the subsoil will result in variations of the lines dividing the various lithologies. Site specific correlations with data obtained from soil samples are considered to be better suited for high risk applications (Lunne et al. 1997). Therefore, the classification was adjusted for the local conditions. Especially the correct classification of peat requires adjustment of the lithology divisions in the Groningen setting. For this study, a large number of CPTs without pore pressure sensor records was used. The method of Douglas & Olson (1981) appeared to be most appropriate to classify the unconsolidated sediments in the Groningen subsoil with the CPT data. For this, the density distributions of q_c-R_f pairs were divided by lines separating simple lithological units (Figure 2) by correlation with nearby Groningen boreholes with reliable lithology logs.

3.1.2 Relative density for sand

Relative density is used as an indicator of the packing of sand. This packing is relevant for liquefaction, because generally loosely and occasionally moderately dense packed sands can be sensitive to liquefaction. The relative density is influenced by factors such as grain shape, sorting, cementation and stratification. In earlier engineering projects, the methods of Lunne and Christofferson (1983) and Villet and Mitchell (1981) proved to yield the most reliable results. The relative density according to Lunne and Christofferson (1983) is given by:

$$Dr = \frac{1}{2.91} * \ln\left[\frac{q_c * 1000}{61 * (\sigma)^{0.71}}\right] * 100\% \qquad (1)$$

where Dr is the relative density in percentages, q_c is the cone tip resistance in MPa and σ is the effective stress in kPa.

The relative density according to Villet and Mitchell (1981) is given by:

$$Dr = \frac{[qc + 0.0000088 * \sigma^2 - 0.0055 * \sigma]}{[0.205 * \sigma - 0.0001969 * \sigma^2]} * 100\% \qquad (2)$$

At the transition from clay to sand or sand to clay a transition zone is present where in the sand layer the measured cone resistance is decreased by the clay layer. Therefore, the cone tip resistance was corrected prior to conversion to relative density. The correction was based on the statistical comparison between the average q_c of top and bottom 20 cm of a sand layer and the average q_c of the unaffected part of a sand layer. The difference was a factor of around 2.5. Hence in our study, the Groningen-specific correction factor of 2.5 was applied.

Relative density values calculated using (1) are slightly higher than using (2). Classification into sand packing is given in Table 1 (ISO/DIS 14688-2, 2017). In our study, the classes of 'very loose' and 'loose' were combined, as well as the classes of 'dense' and 'very dense'. The Lunne and Christofferson (1983) derived Dr for values < 65% (indicating moderately and loosely packed sand) is more conservative. Therefore, in the following analyses Equation 1 was used for Dr.

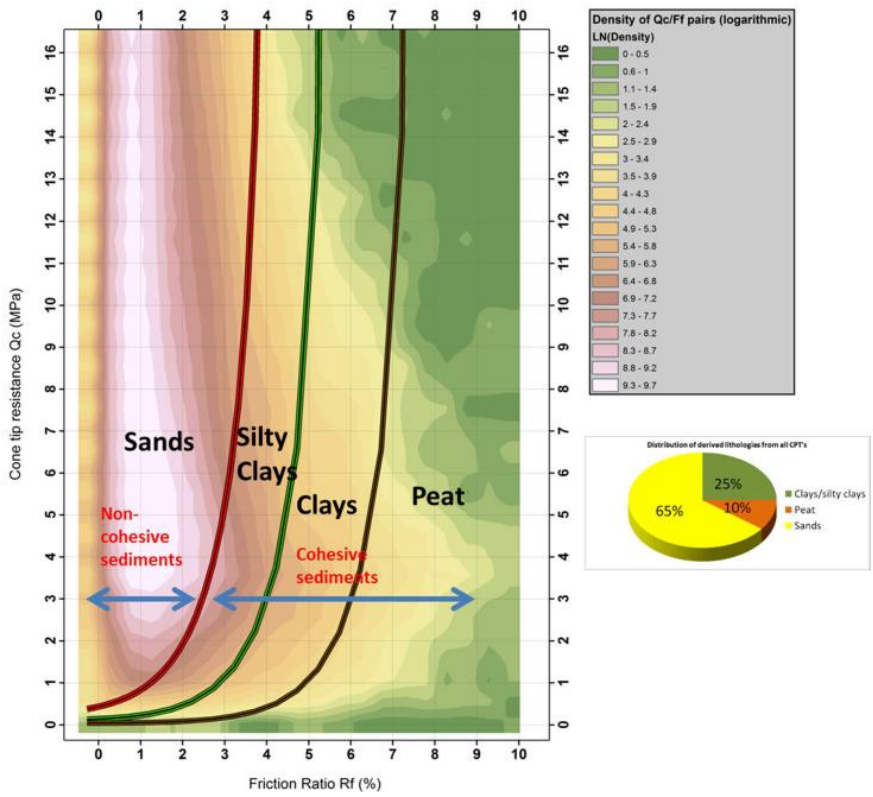

Figure 2. Density (logarithmic) of q_c-R_f pairs in the Groningen CPT data base, representing all lithologies. The dividing lines between lithology types were adjusted from the nomogram of Douglas & Olson (1981) to fit the local conditions. The pie diagram shows that sandy lithologies dominate in this data set.

Table 1. Classification of sand packing using relative density Dr

Packing	**Dr (%)**
Loose	< 35
Moderate	35 – 65
Dense	> 65

3.1.3 Unit weight

One of the input parameters for site response analysis is the unit weight. For the shallow depth range down to approximately 30 m below the surface, the unit weights were estimated from a subset of 31 CPTs that were manually classified in terms of lithostratigraphical unit and lithological class. All cone tip resistance values from the CPTs from one combination of lithostratigraphical unit and lithoclass ("unit" for short) were assembled and converted to unit weight using Lunne et al. (1997) and regional correlations with sample data. The average unit weight was calculated for each unit. For units that were not represented in the CPTs, a value for unit weight from a comparable geological unit was selected. An exception to this procedure is the unit weight of peat, because literature correlations typically lead to an overestimation for peat. This parameter was estimated from local correlations encountered in Dutch peats and statistical weighting, e.g. leading to a unit weight of 10.8 kN/m^3 for Holland Peat.

3.1.4 Undrained shear strength S_u

Undrained shear strength S_u can be estimated by the following the empirical relation from Lunne et al. (1997):

$$S_u = \frac{q_c - \sigma_{v0}}{N_k} = \frac{q_{net}}{N_k} \tag{3}$$

where σ_{v0} is the total vertical stress and N_k is an empirical load bearing factor. Generally, a value of 14 was chosen as recommended by Lunne et al. (1997). A plot of S_u versus effective vertical stress for Peelo clay is included in Kruiver et al. (2017b).

For several units, laboratory data became recently available (Van Essen, 2017). The samples were taken at the Eemskanaal levee in the province of Groningen, in the toe and the crest of the levee. Cone penetration tests were also performed at these locations. The combination of laboratory data and CPT soundings enables the calibration of empirical relations between CPT parameters and undrained shear strength S_u for Groningen for the sampled units. This was possible for three soil types: Naaldwijk clay, Holland peat and Basal peat.

For Naaldwijk clay, the CPT derived S_u using N_k = 17 follow the laboratory S_u much better than the earlier assumed N_k = 14 (Figure 3). Therefore, the more conservative N_k = 17 was applied to the CPT data resulting in the following empirical relation between S_u and σ'_{v0} (both in kPa):

$$S_u = 0.31\,\sigma'_{v0} + 10 \tag{4}$$

The Holland peat and Basal peat members are well represented in the laboratory data and less abundant in the CPT data set (Figure 4). The quality of the CPT data set is also adversely influenced by the thin dimension of the peat layers. For both types of peat, the laboratory data show considerably less scatter and are regarded as better representatives of S_u values than the CPT-derived S_u. Therefore, the empirical relation between S_u and vertical effective stress was based on the linear regression through the laboratory data. This resulted in the following empirical relations between S_u and σ'_{v0} (both in kPa) for Holland peat (Equation 5) and Basal peat (Equation 6):

$$S_u = 0.39\,\sigma'_{v0} + 8 \qquad \text{Holland peat} \qquad (5)$$

$$S_u = 0.47\,\sigma'_{v0} + 5 \qquad \text{Basal peat} \qquad (6)$$

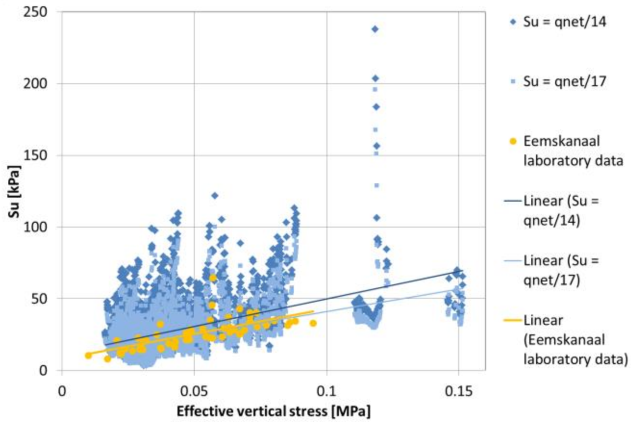

Figure 3. CPT derived and laboratory data for S_u for Naaldwijk clay, including linear regression lines.

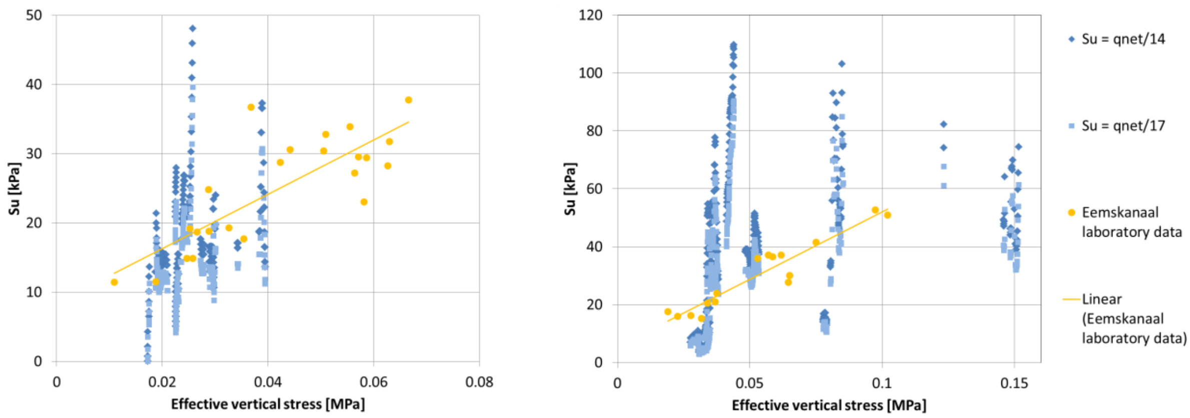

Figure 4. CPT derived (blue) and laboratory data (orange) for S_u including linear regression line. Left: for Holland peat. Right: for Basal peat.

3.1.5 Overconsolidation ratio OCR

No laboratory tests for OCR were available at the time of starting the site response calculations. Therefore, representative values for geological units were derived from the subset of geologically classified CPT soundings. For OCR, a data set of 88 CPTs corresponding to the Seismic CPT (SCPT) data set was used. The OCR was estimated for clay from the normalized total cone resistance following Robertson and Cabal (2015), using the relationship suggested by Kulhawy & Mayne (1990), adjusted for Robertson's Soil Behaviour Index I_c:

$$OCR = k\left(\frac{q_t - \sigma_{v0}}{\sigma'_{vo}}\right) \qquad (7)$$

where σ_{v0} and σ'_{v0} are the total and the effective vertical stresses, respectively, and k is a parameter that is set to 0.33. The linear relation between effective vertical stress and OCR was derived if a sufficiently large number of OCR values was available for a unit. Otherwise, a constant OCR value was assumed. An example of OCR from CPT data is given in Figure 5 for Peelo clay. In this case, the data were not extrapolated outside the data range. This means that a minimum OCR of 4 and a maximum OCR of 6 was assumed.

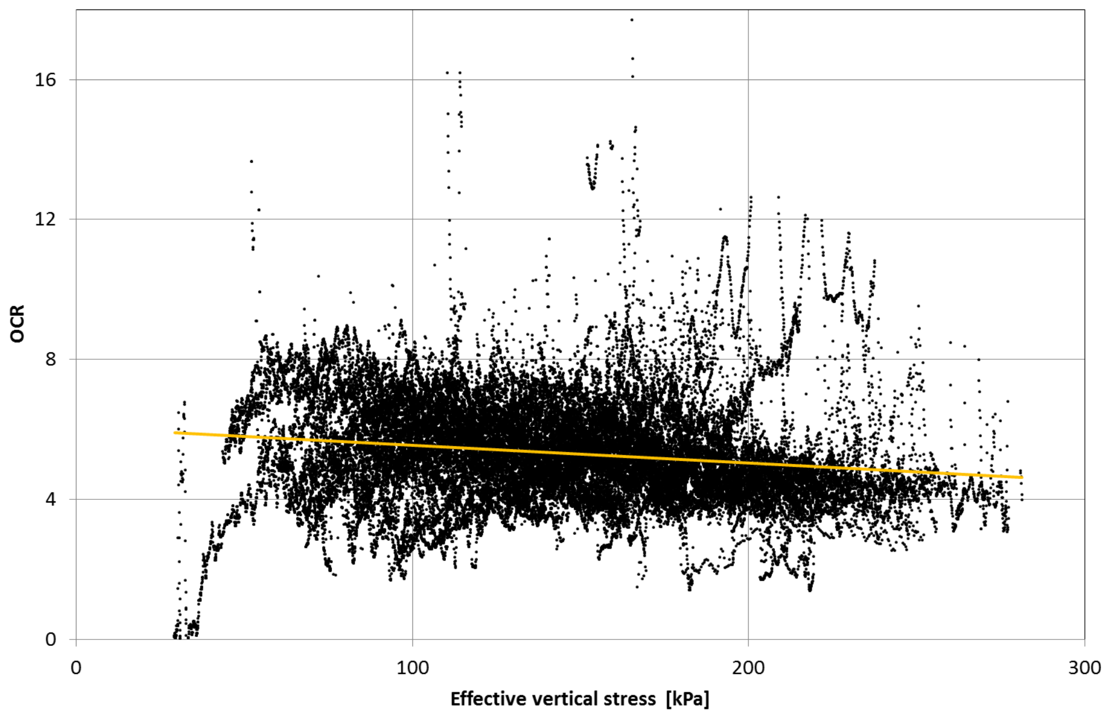

Figure 5 OCR for Peelo clay, derived from CPT data and related to effective vertical stress. The black dots are data points, the orange line is the linear regression line.

3.1.6 Plasticity Index I_p

The plasticity index I_p was only available for a few samples of Naaldwijk clay. The relationship between I_p and the undrained shear strength to overburden stress ratio from Skempton in Grace et al. (1957) was used to extrapolate the parameter to the entire Holocene clay profile. For Pleistocene and Tertiary clays this relationship is not suitable. In these cases, I_p was estimated using expert judgement based on values measured elsewhere in the Netherlands and from Sorensen & Okkels (2013) who gathered data in the Danish region of the North Sea Basin.

3.2 Seismic CPT and shear wave velocity

The shear wave velocity V_S model for the top 50 m of sediments was derived from a set of 87 seismic CPTs (SCPTs). This is described by Kruiver et al. (2017a) and summarized in this section. The scheme to derive Groningen-specific V_S relations for units was determined using a slight adaption of Figure 1. The SCPT intervals were classified in terms of units. No empirical relation between CPT parameters was needed to obtain V_S values, because they were directly measured during the SCPT sounding. The relation between V_S and the confining stress σ'_0 for each unit was determined following a functional form suggested by Sykora (1987):

$$ln\, V_S = ln\, V_{S1} + n\, ln\left(\frac{\sigma_o'}{p_a}\right) \qquad (8)$$

where σ_o' is the confining stress, p_a is atmospheric pressure, $ln\, Vs_1$ is a parameter that represents the shear-wave velocity at a confining stress equal to one atmosphere, and n is the slope that defines confining stress dependence. Depending on the number of datapoints and the expected dependence of confining stress, the V_S relation for a unit falls into one of the three groups: (i) V_S depends on confining stress according to Equation 8 with values for $ln\, Vs_1$ and n based on SCPT data; (ii) V_S depends on confining stress according to Equation 8 with estimated values for $ln\, Vs_1$ and n based on literature and expert judgement; (iii) constant V_S.

The deeper V_S models are derived from seismic data (Kruiver et al. 2017a). The V_S models for the various depth ranges were spliced to obtain V_S profiles for the full depth range required for site response calculations.

3.3 Other types of parameters

TNO Geological Survey of the Netherlands conducted a campaign to map and characterize sediments in terms of physical and chemical characteristics (Bosch et al., 2014) for geological units occurring in the upper 30 to 40 meters below surface. About 2,000 samples were taken in the northern part of the Netherlands. The grain size distributions, organic matter content, permeability and geochemistry were determined in the laboratory. This resulted in a table with - amongst other parameters - the median grain sizes D_{50} and coefficients of uniformity C_u, together with standard deviations, for a wide range in formations (Bosch et al., 2014). These tables were used to extract the relevant D_{50} and C_u for the units in Groningen in order to construct the Modulus Reduction and Damping curves for the site response analyses for sand.

4. SCHEMATISATION OF GEOLOGY AND APPLICATION OF PARAMETERISATION

4.1 For liquefaction potential indicator model

The relevant lithology for liquefaction is sand. All CPTs were automatically interpreted in terms of lithology (see section 3.1.1) and the sand intervals were identified. The properties of the sand are related to the depositional environment and the age of the sediment. For example, Holocene Naaldwijk sand (marine tidal flat deposits) is expected to have different properties from Pleistocene Boxtel sand (periglacial aeolian and local fluvial deposits). Therefore, the sand intervals were classified in terms of stratigraphic unit. Because of the vast amount of CPTs, this could not be done manually. About 4,300 out of the total of 5,700 CPTs were suitable for the analysis, i.e. containing both q_c and R_f and had a length of more than 5 m. We used the detailed geological model GeoTOP of the Geological Survey of the Netherlands for the automatic determination of stratigraphy. The GeoTOP model consists of "volume pixels" called voxels of 100 m x 100 m in horizontal direction and 0.5 m depth. The attributes of each voxel are the lithostratigraphical unit, the statistical probabilities of the lithoclasses and the most likely lithoclass (Maljers et al. 2015; Stafleu and Dubelaar, 2016). Combining the sand intervals from the CPTs and the GeoTOP models resulted in a dataset of sand intervals with associated stratigraphy. The workflow is visualized in Figure 6.

Next, the CPT readings for each sand layer were converted to relative density (see section 3.1.2) and classified in terms of loosely, moderately or densely packed sand using Table 1. For each CPT, the cumulative thickness of these three classes of sand packing was determined. In summary, after performing the processing steps from Figure 6, each CPT had cumulative thickness of loosely, moderately and densely packed sand for all formations represented in the CPT. These data were further analyzed by plotting on a map for the spatial distribution. Maps are included in Kruiver et al (2017b) and Korff et al. (2017) and are not reproduced here because of space limitations. The maps show that the thickest cumulative sand thickness in the Naaldwijk Formation is concentrated in the north of the Groningen area and is composed of loosely, moderately or densely packed sands of similar proportions. Units of Pleistocene age deposits are present in the southern part of the study area and these deposits are mainly composed of dense sands in the top 20 m.

Additionally, the relative contributions of the classes of packing were analyzed (Kruiver et al. 2017b; Korff et al. 2017). The marine Naaldwijk and Eem Formations have the highest proportion of loosely packed sand (31 and 38%, respectively). The other units contain 5 to 17% loosely packed sand. Accordingly, the Naaldwijk and Eem Formations are more sensitive to liquefaction than the other units.

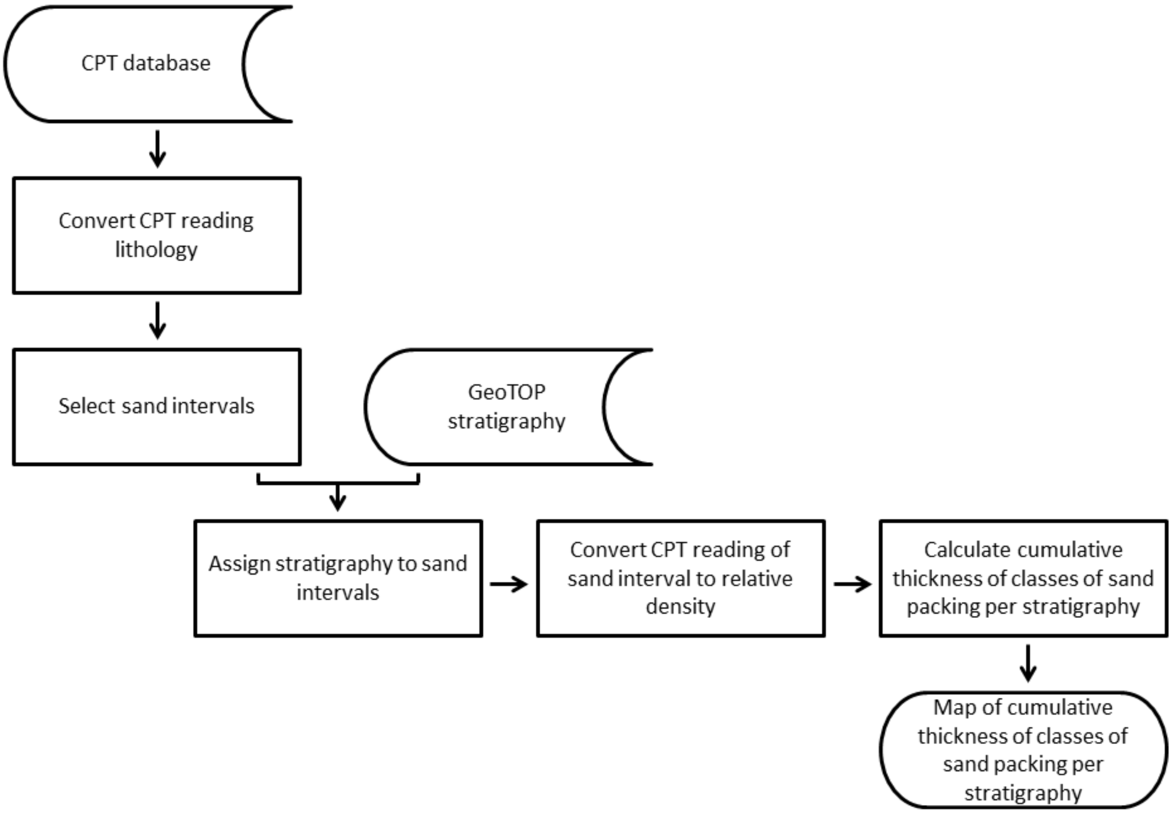

Figure 6. Flow chart of steps to obtain relative densities from CPTs for liquefaction potential analysis.

4.2 For site response model

The parameterized geological model for site response is input for the site response calculations. One-dimensional soil columns of stratigraphy and properties are required as input. Therefore, the aim of the geological model for site response was to provide both geometry of layers (stratigraphy) and the assignment of relevant parameter values to the layers. The approach was described in Kruiver et al. (2017a) and summarized here. The work flow to obtain parameterized soil columns (voxel stacks) is shown in Figure 7.

The data available consisted of models from TNO Geological Survey of the Netherlands, such as the GeoTOP model, the Digital Geological Model (DGM, Gunnink et al. 2013), the regional geohydrological model (REGIS II, Vernes & van Doorn, 2005) and the digital terrain model AHN (open data, www.ahn.nl). Additionally, the borehole descriptions and CPTs from the DINO database (www.dinoloket.nl) were used. Because of the difference in data density, the geological model has two levels of detail. The shallow level (from surface to ~ 50 m depth) is based on the detailed GeoTOP model (based on boreholes), combined with the vast amount of individual shallow borehole descriptions and CPTs in the area. The stratigraphy is taken from the GeoTOP model and zones of similar geology are defined. The deeper level is (> 50 m depth) is based on a limited number of borings and the less detailed DGM and REGIS II model. Because of the uncertainty in layering in this depth interval, scenarios of stratigraphy are defined with a probability of occurrence for each scenario. The two depth ranges are spliced to obtain the layer definition of each vertical voxel stack. This is done by combining the GeoTOP stratigraphy with one of the scenarios. Scenario selection is random, but satisfying the probability of each scenario in a zone.

The properties of each layer need to be defined for site response calculations. The parameter values of OCR and I_p and undrained shear strength (for clay and peat) and D_{50} and C_u (for sand), as well as V_S and unit weight (all lithologies) are required. These are assigned to each layer using the empirical relations that were fine-tuned for Groningen (sections 3.1.3-3.3). This results in one parameterized voxel stack per 100 m x 100 m grid cell which is input in the site response calculations. The site response analysis and its use in the Ground Motion Model are described in Rodriguez-Marek et al. (2017) and Bommer et al. (2017) respectively.

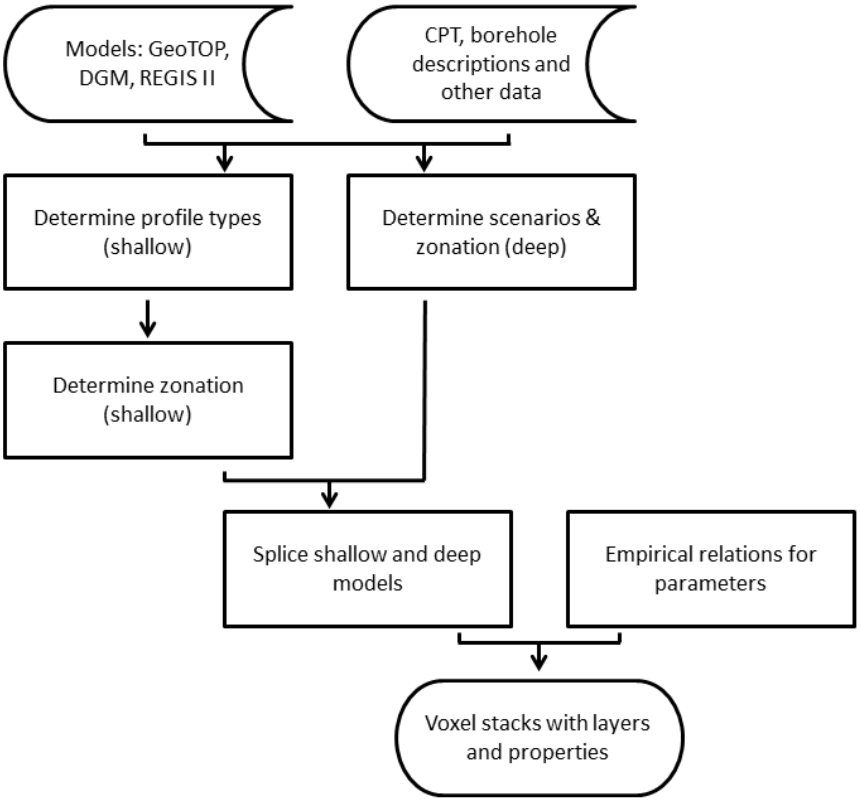

Figure 7. Flow chart of steps to obtain input for site response calculations.

5. FUTURE IMPROVEMENTS

Regularly, new data become available. Either specifically collected for the Groningen seismic hazard analysis and independently. For example, model development and improvement is a continuous process for TNO Geological Survey of the Netherlands. When new models become available, the geological models for liquefaction and site response can be updated. Additionally, laboratory analyses and CPT soundings are performed by several consultancy companies. It takes an effort to collect these data in order to be able to improve regional empirical CPT relations. The synchronization of various CPT databases is currently in progress.

For the mapping of the liquefaction potential indicator, future work needs to determine the relation between relative density and liquefaction potential and the actual risk with consequences for structures. Research on the thin layer correction is required to improve the interpretation. Recent experiments (van der Linden, 2016) show that a multiple thin layer correction may be suitable for these specific irregularly alternating layers. Ongoing experiments are conducted for higher stress levels.

Improvement of the deeper models for site response comes from new borehole descriptions and borehole logs of 70 recently placed 200 m geophone array boreholes for the KNMI monitoring network. These data will be used to improve the scenarios that are input for the deeper levels of the voxel stacks.

6. CONCLUSIONS

The seismic hazard and risk analysis of the Groningen gas field requires the best possible input data. The geological models presented are sophisticated, regional models that provide detailed input. The large amount of data in the form of statistical geological models, a CPT database, seismic CPTs and borehole descriptions allowed for the construction of detailed models. CPT readings were converted to relevant parameters using literature empirical relations. Following the recommendation of Lunne et al. (1997), we modified the empirical relations to fit the Groningen conditions. The two different geological models - for liquefaction and for site response - are tailored to their application. The liquefaction model extends to 40 m depth and focuses on the sand layers. CPT readings were converted to lithology and to relative density. This resulted in maps of loosely, moderately and densely packed sand and relative proportions of packing classes for the various formations in Groningen and serve as a proxy for regional sensitivity to liquefaction.

The geological model for site response consists of a set of vertical voxel stacks with parameter values assigned to each layer. Unit weight, OCR, S_u and I_p were derived from the CPT database. Additional laboratory measurements for S_u enabled further adjustment of empirical relations for Groningen conditions. The parameterized voxel stacks were input for the site response calculations that were incorporated in the Ground Motion Model that served as input for the seismic hazard and risk analysis. The geological model improved the Ground Motion Model significantly compared to earlier versions in which no differentiation of geology and soil behavior was included (Bommer et al. 2016, 2017).

7. ACKNOWLEDGMENTS

The building of the geological models and the parameterization was a team effort of Deltares and TNO Geological Survey of the Netherlands. Numerous geologists contributed to the models, too many to mention. Their expertise is greatly valued. The sharing of various data bases and project results allowed us to gather a sufficient amount of data to enable the derivation of region specific empirical relations. All contributors to the data supporting this paper are acknowledged.

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