# Liquefaction Mapping for Induced Seismicity based on geological and geotechnical features

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ABSTRACT
The depletion of the Groningen Gas Field in The Netherlands is known to cause induced seismicity. Until the end of 2016, the largest magnitude earthquake registered had a moment magnitude of 3.6. Ongoing production is expected to increase the seismic hazard. The subsoil in the area consists of several Holocene and Late Pleistocene geological formations, locally containing extensive layers of sand, making this area potentially sensitive to liquefaction. The mapping of the liquefaction susceptibility for this area is presented in this paper, based on (a) geological features, (b) an area wide geological model and (c) an extensive database of site investigations, consisting of exploration boreholes and CPT's.

Large deposits of loose sand are found in the Holocene formations in the northern part of the province of Groningen (close to the Waddenzee) and around the city of Groningen. For each of the formations the risk for liquefaction is identified based on the characteristics of the formation; including the age of the formation, the percentage of fines in the formation, the occurrence of (multiple) thin layers of cohesive material, the over-consolidation ratio and the depositional environment. The results presented are used for prioritization of risk assessments related to buildings and infrastructures with respect to liquefaction.

## 1. INDUCED SEISMICITY IN THE GRONINGEN FIELD

The Groningen Gas Field is one of the largest gas fields in the world. Since its discovery in 1959, over 2000 billion $m^3$ natural gas have been produced in the north of The Netherlands. The first gas-production-induced seismicity event was observed in 1986, after which the number and severity of the events has grown significantly and over the last decades started to be of growing concern. Between 1986 and July 2016, about 1000 events have been recorded by the Royal Dutch Meteorological Institute (KNMI) related to this gas field. All current seismicity events occurred at a 'shallow' depth of approximately 3 km. Magnitudes up to $M_W = 3.6$ have been recorded.

Based on expectations for future production, several groups have delivered seismic hazard maps for The Netherlands. The latest PGA levels to be expected in the coming period are in the order of 0.22g (1:475 year return period) according to Spetzler & Dost (2016) and NAM (2016). Despite the relatively low magnitude, these PGA values are still high enough that liquefaction cannot be ignored, especially since the Groningen subsoil consists of young deposits of loose sand with a high ground water table. For this purpose, a detailed study in the Groningen subsoil is performed, mapping the liquefaction sensitive areas.

## 2. RISK OF LIQUEFACTION

### 2.1 Liquefaction sensitivity

The occurrence of liquefaction of sand layers may potentially lead to loss of strength of the soil and settlements of surface and structures. Liquefaction susceptibility is defined here as the probability that the subsoil at a particular location may liquefy under a given earthquake loading. For the liquefaction mapping presented in this paper the focus is on the liquefaction susceptibility of the soil in Groningen, i.e. the occurrence of sand layers, their thickness, their depth and geological and geomechanical characteristics. The estimated liquefaction potential and settlement risks related to foundations or structures are not part of this paper and will be presented at a later stage once a Groningen specific assessment method has been derived.

The liquefaction susceptibility of a specific sand layer is determined by the density of the soil, depositional environment, age of the deposit, overconsolidation of the sand layers (previous overburden or ageing). Also the presence of fines (both cohesive and non-cohesive), grain size distribution, coefficient of uniformity, cementation and particle shape (sphericity, roundness) play a potential role. Most of the factors mentioned will influence the cone penetration test (CPT) values, although the exact relationship is not known for all of them. In the assessment presented, CPT values are used directly to determine the liquefaction susceptibility. Specific attention has been given to geologically weighted clustering of the CPT values to account for regional variability. The most relevant factors influencing the liquefaction susceptibility are described in the following section.

### 2.2 Liquefaction parameters from geology

One of the most important aspects of the liquefaction susceptibility is the density of the soil: densely packed sand is less likely to liquefy than loosely packed sand. The cone-tip resistance measured in CPT's can be used as a proxy for the soil density. Therefore, since a large amount of

CPTs are available in The Netherlands, the liquefaction assessment for Groningen is based on CPT data.

The Holocene deposits in Groningen date roughly between 0 and 12 thousand years BP. The age of the Pleistocene deposits ranges from 12 thousand years to 1.6 million years BP. Age and over consolidation may significantly decrease the liquefaction susceptibility of the sand layers, according to for example Arango & Kramer (1994) and Andrus et al. (2009). Cementation is expected to be correlated with age: the higher the age, the more cementation may have taken place. However, to what degree age influences the susceptibility to liquefaction, varies with the depositional environment of the sediment body.

In overconsolidated sand (or ice-pushed sands /lateral moraines) the horizontal stress becomes larger and for sand with the same (relative) density the cone tip resistance increases. This will result in an underestimation of the liquefaction susceptibility. On the other hand, overconsolidation is expected to increase the liquefaction resistance, Ishihara and Takatsu (1978). From the above it follows that it is not clear if in overconsolidated sands the use of correlations for normally consolidated sands is conservative or optimistic, and if so to what extent. As overconsolidated sands are also older sands both aspects need to be considered. In the following descriptions of the geological formations present in the subsurface of Groningen, it is indicated whether the deposits have been exposed to ice-sheet loading.

Grain size is often suggested to be a criterion for liquefaction susceptibility. Mostly a graph from Tsuchida is used, see e.g. Ishihara (1985). Other parameters that may influence the liquefaction susceptibility are the fines content and the coefficient of uniformity (d60/d10). The fines correction proposed by Idriss & Boulanger (2008) and Boulanger & Idriss (2014) can be used to account for this effect on the liquefaction susceptibility.

## 3. GEOLOGY OF THE GRONINGEN AREA

### 3.1 Main characteristics

The shallow subsurface (upper 200 meters) of the Province of Groningen and surroundings is built-up mainly by marine Holocene deposits underlain by Pleistocene glacial and fluvial deposits. During the two penultimate glaciations the Scandinavian ice-sheets grew large enough to cover the northern parts of The Netherlands. Deposits of these two glacial episodes form a major part of the geological record. Three main sand-bearing geological formations have been identified to be potentially relevant for the occurrence of liquefaction in Groningen. These are the Holocene Naaldwijk Formation, and the Pleistocene Boxtel and Eem Formations.

Based on both the young age and tidal depositional environment of this formation, the sandy parts in the Naaldwijk Formation may be particularly susceptible to liquefaction. The sands are unconsolidated and the formation has not been exposed to ice-sheet loading and consists of relatively clean sand. The Boxtel Formation consists of several types of deposits, including various types of aeolian deposits, small scale fluvial deposits, slope deposits, lacustrine deposits and organic deposits. Cementation has been observed to occur. The lower, older part often exhibits high cone resistances which may be attributed to ice-sheet loading. The Eem Formation is not overconsolidated by ice-sheet loading. The deposits are comparable to those of the Naaldwijk Formation, but with a higher age. Tidal channels are the main lithological units within the Eem Formation, and can reach a thickness of over 10 m. The channels are filled with layered sand, often intercalated with organic and clay layers. Details of the sedimentary history are given in (Bosch et al., 2014).

Figure 2 shows a cross section of the area (North to South) with the different formations and Figure 3 shows the depth of the base and total thickness of the Naaldwijk Formation from the GeoTOP 3D geological subsurface model. Similar maps for the other formations are also available in Maljers et al., 2016 and reproduced specifically for the liquefaction mapping in Korff et al. (2016).

### 3.2 Specific deposits: layered soils

Part of the Naaldwijk tidal deposits in Groningen contain very thin irregular layers of clay/silt material, known as “Flaser beds.” An example of this type of sand deposit is shown in Figure 1. Flaser beds consist mainly of sands as they are deposited in high-energy tidal environments.

These layers can be characterized as laminated, quasi regular sequences of mud (clay/silt mixtures) and (fine) sand. The thickness of the clay/silt bands is typically 3 – 15 mm and the horizontal spread 10 – 20 cm. This kind of layering is hard to detect by CPT because of the small size of the layers relative to the cone diameter. Moreover, the measured resistances in the sand layers will be reduced by the less stiff and weaker layers compared with “clean sand”, which results in an underestimation of the sand density, leading to overestimation of the liquefaction susceptibility.

Figure 1. Example of “Flaser beds”

## 4. LIQUEFACTION MAPPING

### 4.1 Determination of sand densities

For the above-mentioned geological formations, a geological model was built for the Groningen field based on over 5700 CPTs, the 3D geological layer (voxel) model GeoTOP (Stafleu et al., 2011, 2012) and various other sources, such as borings from a large scale drilling campaign. Compared to an earlier paper by the same authors (Korff et al. 2015), the geological model and the liquefaction mapping have been updated and new CPTs have been added.

From the 3D lithostratigraphic model only those geological formations were included in the mapping that are considered to be relevant for liquefaction. A selection of the available CPT data set was made to include just these geological formations and members containing sandy lithofacies (depositional environments). The maximum depth below the land surface taken into account was 20 m.

Firstly, the regional boundaries of the formations were derived from the geological model. As a next step, the CPT data was interpreted into simple lithological units based on the method by Douglas & Olson (1981). For the sand layers only (leaving out some but perhaps not all of the Flaser beds), relative densities were determined. The relative density of the (relatively clean) sand deposits is estimated from CPT data according to the methods of Lunne & Christofferson (1983). The classification of loose, medium dense and dense sands follows the generally agreed values in the literature of <35% indicating loose sands, medium dense sands between 35% and 65% and dense sands > 65%.

For transition zones between sand and clay layers, a thin layer correction was applied by comparing the average CPT values within the ‘unaffected’ part of the sand layer, with the CPT values along a zone of 20 cm in the top and 20 cm at the bottom of a sand layer. Statistical analysis of the recorded Qc values in the top and bottom zones as compared to the Qc mean values in the sand layer indicated that a factor of about 2.5 exists between these zones. Since both the bottom and the top zones are used, there is no bias in these values for depth or thickness of the layer. This factor is applied to correct the underestimated Qc values in these top and bottom zones of the sand layers, see Figure 4. Since the factor that was found is higher than the factor found from literature (lower estimates around 1.5 based on Youd et al (2001) we compared the results of the densities with correction factor of 1.5 and 2.5 and found very small differences (5% averaging over all the sand layers).

The computation in the previous step results a classification of the CPT values in loose, medium dense and dense sands over the entire depth range. To give a meaningful estimation of the sensitivity to liquefaction over larger areas, the sand density classes must be grouped into meaningful units. As argued above the properties of

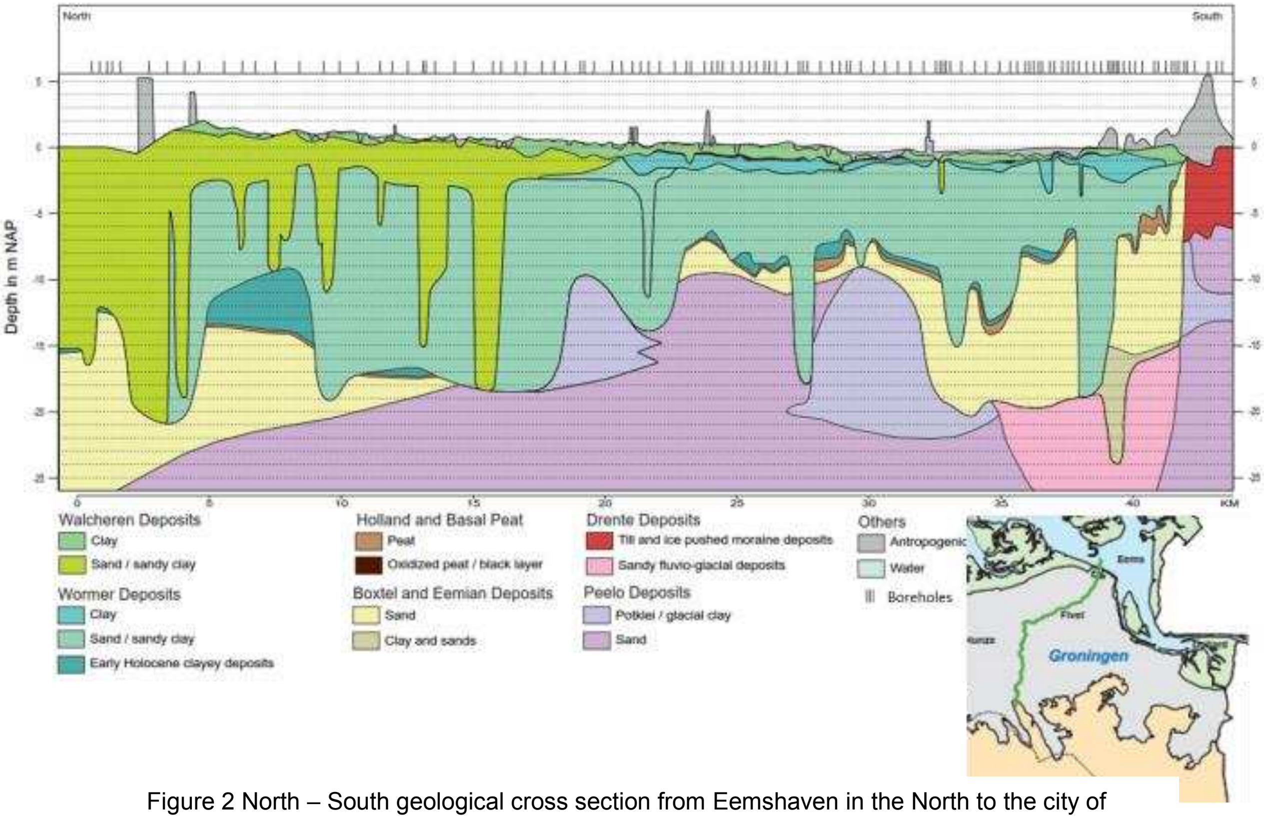

Figure 2 North – South geological cross section from Eemshaven in the North to the city of Groningen in the south to a depth of 25 m. The Naaldwijk Formation (Walcheren/Wormer) in green, Boxtel in yellow and Pleistocene in purple (from: Vos, 2015).

the sand are related to depositional environment and age. Both are included in the definition of geological formations, hence it makes sense to group according to geological formations. For every CPT, the sand density classes were grouped according to formation boundaries by subdividing the CPT record using the depth of the base and the top of the relevant formations at that location.

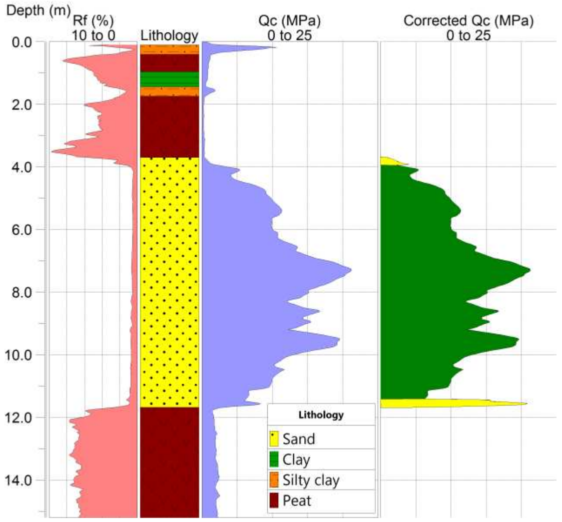

Figure 3. Example of original and corrected CPT for layered soil

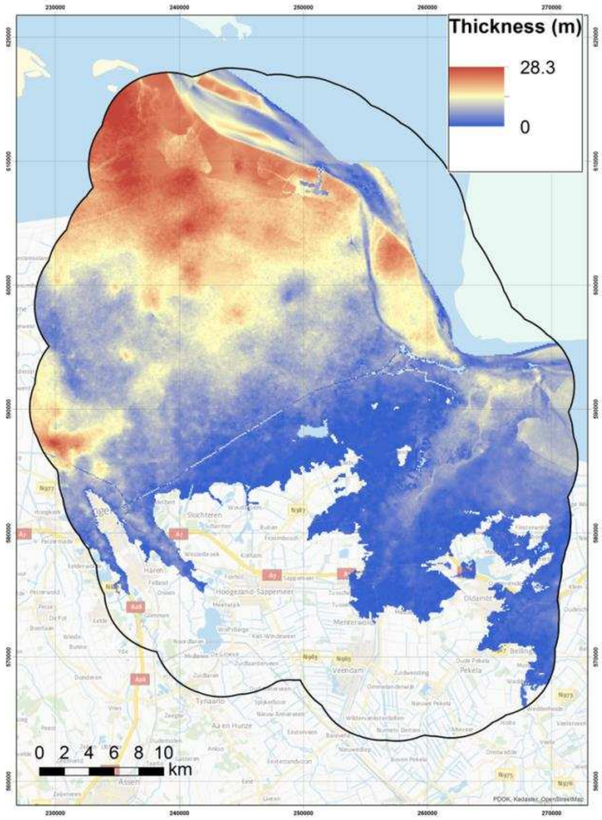

Figure 4. Thickness of the Holocene Naaldwijk Formation in the GeoTOP 3D model of the subsurface. (Maljers et al., 2016)

## 4.2 Results: Sand densities in Holocene Deposits

The presented geological mapping of liquefaction susceptibility is mainly based on thousands of CPT's and on the Dutch 3D geological model GeoTOP (from TNO). The results are presented as maps showing the distribution of the thickness of loose, medium dense and dense sand layers in separate geological areas based on stratigraphy and lithology. This has the advantage that the geological origin, which is known to be related to liquefaction influencing parameters such as depositional environment, age and overconsolidation, can explicitly be taken into account.

Loose sands widely occur in the Naaldwijk Formation, especially in the thicker parts of the formation, see Figure 5. Subareas are defined, based on the thickness of the Naaldwijk Formation, to group the CPTs in zones of 5 m thickness contour intervals.

In the Naaldwijk formation the average total sand thickness rapidly increases towards the north. The same applies to the average thickness of loose sands, but also the medium dense sands become more important and even dominant. Most accumulated thicknesses do not surpass approximately 1.5m, with the distribution of the loose sand thickness shown in Figure 6 and Table 1.

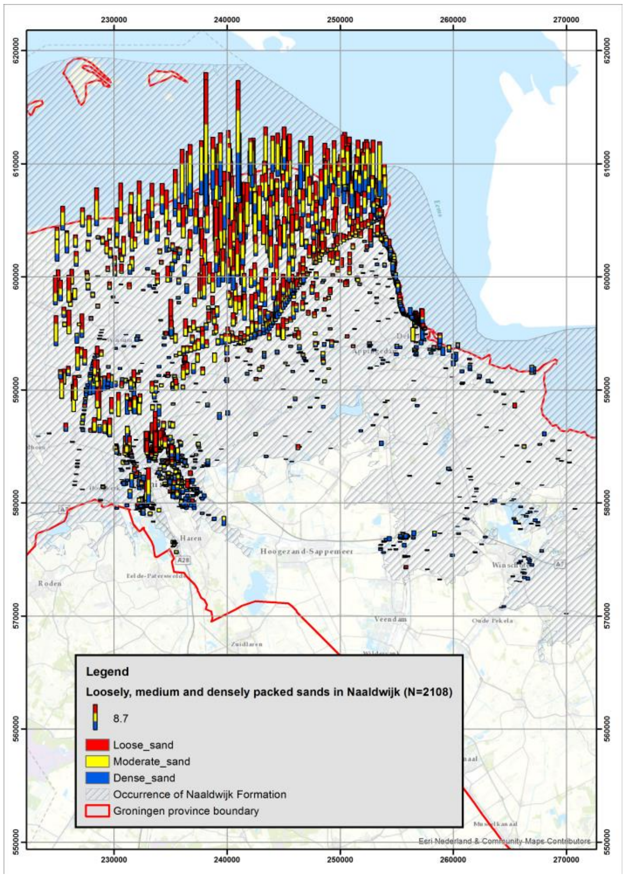

Figure 5. Stacked bars showing the total thicknesses of loose (red), medium dense (yellow) and dense (blue) sand in the Naaldwijk Formation. (Length of the bar indicates the total sand thickness).

Table 1. Total average sand thickness in the Naaldwijk Formation and percentages of loose, medium dense and dense sands, for the whole formation and per 5m depth intervals

| Zone | Total thickness (average, in m) | % loose sand | % medium dense sand | % dense sand |
|---|---|---|---|---|
| Naaldwijk | 4 | 38 | 38 | 24 |
| 0-5m | 1.8 | 28 | 37 | 35 |
| 5-10m | 2.4 | 37 | 38 | 25 |
| 10-15m | 2.8 | 33 | 36 | 31 |
| 15-20m | 2.8 | 32 | 36 | 32 |

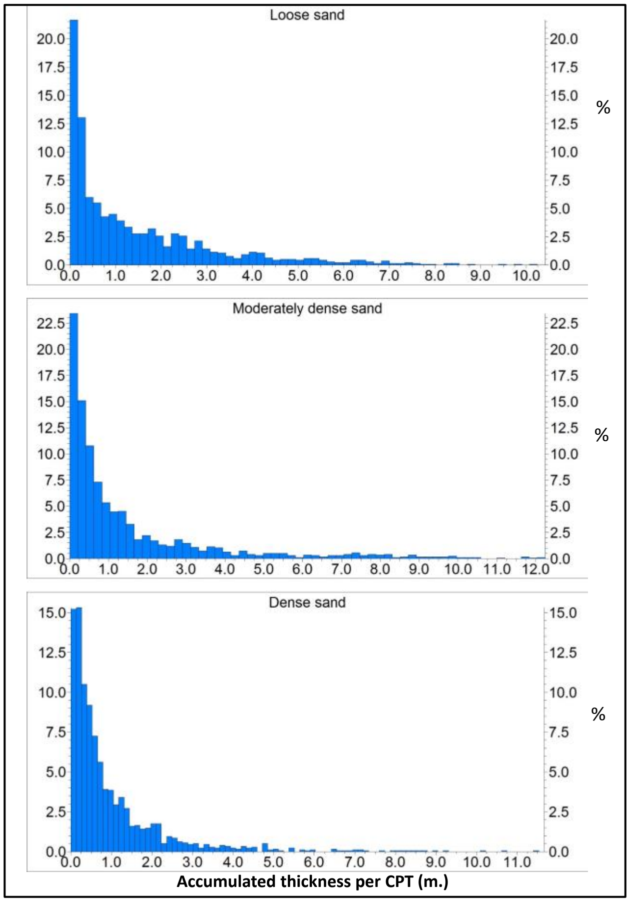

Figure 6 Histograms of the accumulated thickness of loose, medium dense and dense sands in the upper 20 m of the Naaldwijk Formation. Frequency in %.

## 4.2 Results: Sand densities Pleistocene Deposits

In the Pleistocene deposits loose sands are mainly present in the western part, near the city of Groningen and the northern part, see Figure 8. The dominance of medium dense and dense sand in the top of the Pleistocene is also well expressed in the histograms of accumulated thicknesses in Figure 8. Dense sands reach thicknesses of a few meters, sharply contrasting with the sand thicknesses in the overlying Naaldwijk Formation.

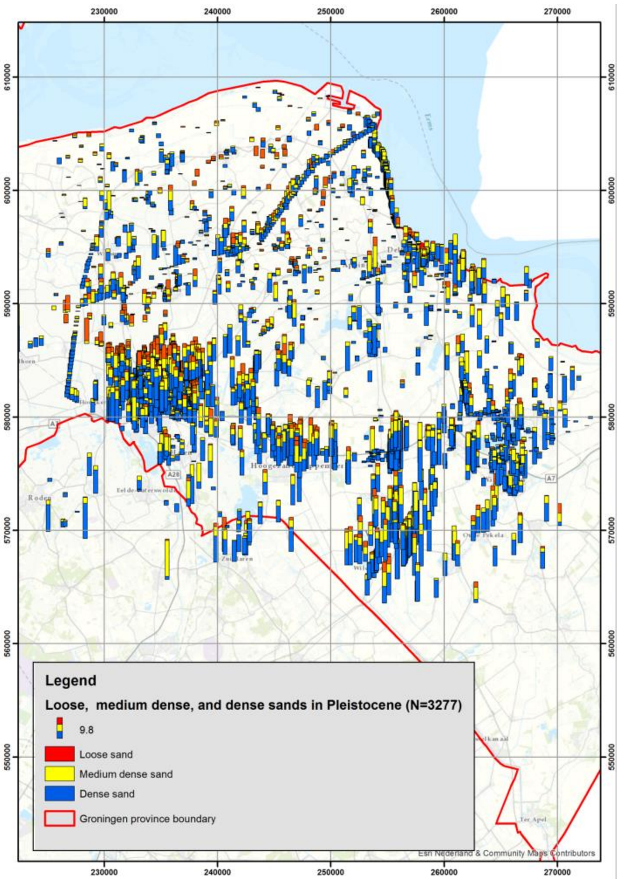

Figure 7. Stacked bars showing the total thicknesses of loose (red), medium dense (yellow) and dense (blue) sand in the Pleistocene sand between 0 and 20 m below the surface (Length of the bar indicates the total thickness).

Table 2 shows the mean thicknesses of loose, medium dense and dense sands, including the total sand thickness in the Boxtel and Eem Formation.

Table 2. Total sand thickness in the Boxtel and Eem Formation and percentages of loose, medium dense and dense sands.

| Zone | Total thickness (average, in m) | %loose sand | %medium dense sand | % dense sand |
|---|---|---|---|---|
| Boxtel | 5.5 | 13 | 27 | 60 |
| Eem | 3.3 | 33 | 39 | 28 |

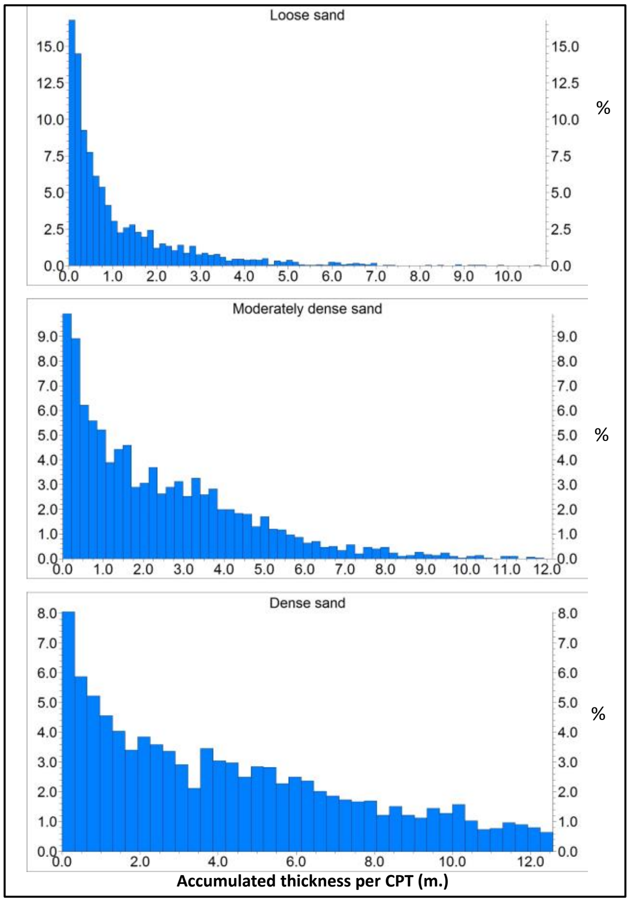

Figure 8 Histograms of the accumulated thicknesses of loose, medium dense and dense sands in the upper 20 m of the Pleistocene Formations. Frequency in %.

## 5. FUTURE DEVELOPMENTS

The relative density of the subsoil (based on CPT value and stress level) is presented in this model as the main factor determining the liquefaction susceptibility. Future work needs to determine the relationship between density and liquefaction susceptibility and the actual risk (with consequences for structures). In particular, for the sandy Flaser beds in the tidal flats, the measured CPT value may not be a sufficient parameter to determine the liquefaction susceptibility. Experiments undertaken (van der Linden 2016) show that a multiple thin layer correction may be suitable for these specific irregularly alternating layers. Further experiments are on-going along the same line, but for higher stress levels.

A further study could be used to determine the critical thickness of a loose sand layer to become susceptible to liquefaction and to determine whether the liquefaction susceptibility is influenced by intercalation between dense sand layers or clay layers, etc.

The effect of other factors than the relative sand density that influence the susceptibility to liquefaction should be incorporated, like overlying deposits.

## 6. CONCLUSIONS

Based on several thousands of CPTs, a detailed geological model and sedimentary characteristics of the formations, mapping of loose, medium and dense sands in the Groningen area of The Netherlands has taken place to identify the areas where liquefaction is most likely to occur in case of induced earthquakes that can be expected in the area.

The largest deposits of loose sand are found in the Holocene Naaldwijk Formation. In the Pleistocene formations, mainly the Eem Formation stands out in this respect. These deposits can be found in the North of Groningen (close to the Waddenzee) and around the city of Groningen). The total thickness increases to almost 20 m close to the Waddenzee in the North, of which at specific locations, up to 10 m may be identified as loose sand. In the Pleistocene layers the amount of loose sand is significant only in a belt from Groningen city towards the North and North East.

The spatial distribution of the relative sand densities in the Naaldwijk unit show that the thickest occurrences can be related to tidal flat and channel deposits in the north of the area.

The liquefaction susceptibility can be assessed more accurately, when aspects are taken into account such as the depositional environment, the presence of clay beds, sorting, grain size, age, thickness and type of under- and overlying deposits.

The results presented can be used for prioritization of risk assessments related to buildings and infrastructures with respect to liquefaction.

## 7. REFERENCES

Ahmadi, M.M. & P.K. Robertson (2005). Thin-layer effects on the CPT qc measurement. *Canadian Geotechnical Journal* 42, 1302–1317.

Andrus, R.D., Hayati, H. and Mohanan , N.P., (2009). Correcting Liquefaction Resistance for Aged Sands Using Measured to Estimated Velocity Ratio. *Journal of Geotechnical and Geoenvironmental Engineering* ASCE GT.1943-5606.0000025135(6), 735-744.

Arango, I., Kramer, C., (1994). The importance of aging on the liquefaction resistance of sand deposits. *Proceedings of the NEHRP Conference and Workshop on Research on the Northridge*, California Earthquake of January 17, 1994

van den Berg, P. (1994). *Analysis of soil penetration*. Ph.D. thesis Delft University of Technology

Bosch, J.H.A., Harting, R., Gunnink, J.L., (2014). Lithologische karakterisering van de ondiepe ondergrond van Noord-Nederland (Topsysteem hoofdgebied 5). TNO 2014-R10680

Douglas, J. B. and R. S. Olsen (1981). Soil Classification using Electric Cone Penetrometer. *Symposium on Cone Penetration Testing and Experience, Geotechnical Engineering Division*, ASCE, St. Louis, p. 209-227.

Ishihara, K., Takatsu, H. (1978) Effects of overconsolidation and K0 conditions on the liquefaction characteristics of sands. *Proceedings of the First Caribbean Conference on Earthquake Engineering*, Port-of-Spain, Trinidad, 1978

Ishihara, K. (1985) Stability of natural deposits during earthquakes. *Proceedings 11th International Conference on Soil Mechanics and Foundation Engineering*, 1985, pp 321-376

Idriss, I.M. & R.W. Boulanger (2008). Soil Liquefaction during Earthquakes, Monograph MNO-12, Earthquake Engineering Research Institute, Oakland, CA, 261 pp.

Korff, M., Wiersma, A. Meijers, P., Kloosterman, F., De Lange, G., van Elk, J, Doornhof, D. (2015) Liquefaction Mapping for Induced Seismicity in the Groningen Gas Field, *6th International Conference on Earthquake Geotechnical Engineering*, Christchurch, New Zealand

Korff, M., Wiersma, A. Meijers, P., Kloosterman, F. & De Lange, G. (2016) Liquefaction sensitivity of the shallow subsurface of Groningen, 1209862-005, October 2016

van der Linden, T.I. (2016) Influence of multiple thin soft layers on the cone resistance in intermediate soils. MSc thesis TUDelft, 2016. uuid:756ae85e-c1a2-4d3e-b070-5f237d521699

Lunne, R., Christoffersen, H.P. (1983) Interpretation of cone penetrometer data for offshore sands. *Offshore Technology Conference*, paper OT 4464, Houston, USA, May 2-5, 1983

Maljers, D., Dubelaar, W, Stafleu, J., Busschers, F., Dambrink, R. and Schokker, J., (2016). Modelleerwerkwijze GeoTOP modelgebied Oostelijke Wadden en aandachtspunten GeoTOP versie 1.3, stand 11 maart 2016. TNO report 060.21052/01.06-1IVDe Mulder, E.F.J., Geluk, M.C., Ritsema, I., Westerhoff, W.E. & Wong, T.E. (2003) De Ondergrond van Nederland. Geologie van Nederland, deel 7. Nederlands Instituut voor Toegepaste Geowetenschappen TNO, Utrecht. 379 p.

NAM (2016) Technical Addendum to the Winningsplan Groningen 2016 Subsidence, Induced Earthquakes and Seismic Hazard Analysis in the Groningen Field, April 2016

Spetzler, J. & Dost, B. (2016), Probabilistic Seismic Hazard Analysis for Induced Earthquakes in Groningen, Update June 2016, KNMI.

Stafleu, J., Maljers, D., Gunnink, J.L., Menkovic, A. & Busschers, F.S. (2011). 3D modelling of the shallow subsurface of Zeeland,The Netherlands. *Netherlands Journal of Geosciences - Geologie en Mijnbouw* 90 - 4, p. 293-310. Available at: https://www.dinoloket.nl/meer-weten-over-GeoTOP

Stafleu, J., Maljers, D., Busschers, F.S., Gunnink, J.L., Schokker, J, Dambrink, R.M., Hummelman, H.J. & Schijf, M.L., (2012). GeoTOP modellering. TNO-rapport TNO 2012 R10991.

Vos, P.C., 2015. Origin of the Dutch coastal landscapes. PhD thesis, Utrecht University

Youd, T.L., & Perkins, D.M. (1978). Mapping liquefaction-induced ground failure potential, *Journal of the Geotechnical Engineering Division 104*, No. GT4, 433-446.