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Mapping liquefaction based on CPT data for induced seismicity in Groningen

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ABSTRACT: The depletion of the Groningen Gas Field in The Netherlands is known to cause induced seismicity. Until mid-2018, the largest magnitude earthquake that occurred had a moment magnitude of 3.6. The subsoil in the area consists of several Holocene and Late Pleisto-cene geological formations of shallow marine, lagoonal to fluvio-glacial origin, locally containing extensive layers of sand. The mapping of the liquefaction potential for this area is presented in this paper, based on (a) a high resolution regional geological layer model (GeoTOP, depth < 50m) and (b) an extensive database of site investigations, consisting of exploration boreholes and CPT's. 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 layers of cohesive material, the over consolidation ratio and the depositional environment. Mapping is based on the Groningen specific assessment by Green et al. (2018a,b) and a database of over 5000 CPTs.

1 INDUCED SEISMICITY IN THE GRONINGEN FIELD

The Groningen Gas Field is one of the largest onshore 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 October 2018, over 1200 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 to date with PGA levels of up to 0.1g.

Based on continuing production the the PGA levels to be expected are maximum 0.38g (1:2475-year return period) according to Spetzler & Dost (2017). Despite the relatively low magnitude, these PGA values are still high enough that liquefaction cannot be ignored, especially as the Groningen subsoil consists of young deposits of loose sand with a very shallow ground water table. For this purpose, a detailed study in the Groningen subsoil is performed, mapping the liquefaction sensitive areas. Compared to previous work on this topic (Korff et al 2016, 2017), the liquefaction assessment has been extended with more CPT data, the liquefaction assessment method of Green (Green et al, 2018a,b) and the derivation of related liquefaction potential index parameters, such as LPI_{ISH} (Maurer et al, 2015a).

2 RISK OF LIQUEFACTION

2.1 *Liquefaction susceptibility*

For the liquefaction mapping presented in this paper the focus is on the liquefaction susceptibility of the subsoil in Groningen, i.e. the occurrence of sand layers, their thickness, their depth, their extent and geological and geomechanical characteristics. The liquefaction susceptibility of a specific sand layer is determined by the density of the deposit, depositional environment, age of the deposit, over-consolidation of the sand layers (previous overburden or ageing). In addition, the presence of fines (both cohesive and non-cohesive), grain size distribution, and 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 deposit: densely packed sand is less likely to liquefy than loosely packed sand. The cone-tip resistance measured in CPTs 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.

Age, various diagenetic processes 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. 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. For the mapping done in this study, an estimate of the beneficial effect of ageing on the liquefaction resistance of Pleistocene sands has been made. This is achieved by multiplying the Cyclic Resistance Ratio (CRR) following from the selected liquefaction assessment method with a factor K_{DR} as follows:

$$CRR_k = CRR \cdot K_{DR} \tag{1}$$

The value of K_{DR} depends on the reference age, the age at which K_{DR} = 1. The commonly used correlations have a reference age of 10 to 20 year. The available databases for determining the $CRR_{7.5}$ value do not include the (geotechnical) age of the deposits. However, some authors claim that the $CRR_{7.5}$ line is mainly determined by young deposits. For instance, Maurer et al (2014) states that the reference age of the CRR line is likely in the order of 1 to 100 year.

Depending on the (geotechnical) age of the deposit the literature data suggest for the Pleistocene a value of K_{DR} between 1.3 (t = 20,000 years) and 1.4 (t = 425,000 years). Although some ageing in the Holocene deposits may be present as well, it is not common practice to use an ageing factor for the Holocene sandy deposits. Therefore, the no ageing factor is used for the Holocene deposits. In the mapping for this study the values used for K_{DR} is 1.3 for Pleistocene sand and 1.0 for Holocene sand.

Other important parameters that may influence the liquefaction susceptibility are the fines content and the coefficient of uniformity (d_{60}/d_{10}). The fines correction proposed by Boulanger & Idriss (2014) is often used to account for this effect on the liquefaction susceptibility:

$$FC = 80 \cdot (I_C + C_{FC}) - 137 \tag{2}$$

In this I_C is the soil behaviour index according to Robertson (2009). C_{FC} is a fitting parameter, C_{FC} = 0 gives the best-estimate for FC and C_{FC} = +/-0.29 give the one standard deviation value. Figure 1 compares this relation with data from Groningen. No clear relation between FC and I_C is observed. Therefore in this study a simple approach of FC= 0% for I_c <2.05 and FC= 20% for I_C >=2.05 is used in absence of reliable grain size analyses for each CPT.

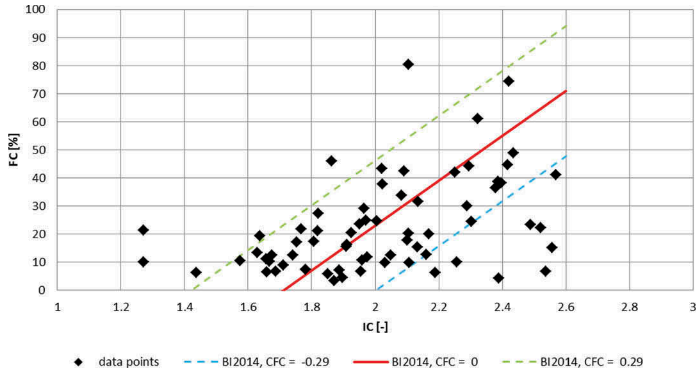

Figure 1. Groningen specific values of Ic – FC pairs, data from Deltares files.

2.3 *Liquefaction potential*

The liquefaction assessment procedure derived by Green et al (2018a, b) is based on Groningen specific determination of two parameters in the Boulanger & Idriss (2014) method, the MSF and r_d factors. These MSF and r_d factors have been derived based on site response analyses for a pilot area in Groningen. The site response analysis is combined with an energy-based comparison of events of different magnitudes, significant duration ($D_{5\text{-}75}$) and rupture distance/site-to-source distance (Rrup). The results of the analysis by Green (Green et al, 2018a,b) are as follows:

- Groningen specific MSF values, depending on v_{s12}, Maximum Magnitude M and PGA.
- Groningen specific r_d values, depending on v_{s12}, PGA and Maximum Magnitude M.

The Groningen-specific relationships have been determined for the pilot study area. (Green et al, 2018a,b) recommends to use the results of zone 801 for r_d and zone 1032 for MSF, for the rest of Groningen. This approach has been applied to the mapping in this study. In the formulas the value for Maximum Magnitude is taken as M=5. This value follows from the deaggregation of the Groningen hazard based on Spetzler (2017). V_{s12} values are based on the geological model by (Kruiver, 2017 a, b), see Figure 2a.

In this study the LPI_{ish} is used as a screening tool for the consequences of liquefaction. Details on LPI_{ish} can be found in Maurer et al 2015. The LPI_{ish} framework was chosen because it has been shown to yield more accurate predictions of the severity of surficial liquefaction manifestations than competing indices.

3 GEOLOGY OF THE GRONINGEN AREA

The shallow subsurface (upper 200 meters) of the Province of Groningen and surroundings is built-up mainly by shallow marine to lagoonal 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

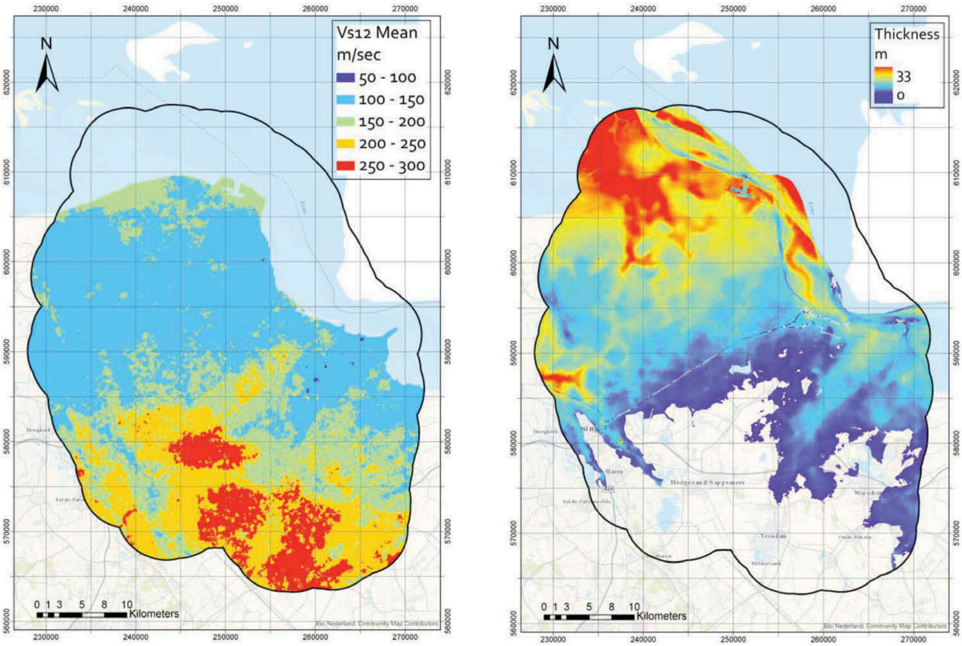

Figure 2. V_{s12} mean value (Kruiver, 2017a) (a) and thickness of the Holocene Naaldwijk Formation (Maljers et al., 2016) (b) in the geological model of the subsurface.

part often exhibits high cone resistances which may be attributed to ice-sheet loading. The Eem Formation is not over-consolidated 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 2b, 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).

4 LIQUEFACTION MAPPING

4.1 *Soil classification, formation and layer boundaries*

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 borehole logs from a large-scale drilling campaign. From the 3D lithostratigraphic model only those geological formations were included in the mapping, considered to be relevant for liquefaction. A selection of the available CPT data set (comprising of in total 3234 CPTs of at least 15 m deep) was made to include just these geological formations and members containing sandy lithofacies (depositional environments). The maximum depth below the land surface to be considered 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 Robertson (2009). Stresses were determined using the phreatic depths derived from the geological model (reference) and the following (wet) unit weights: 17 kN/m^3 for sand layers, 16 kN/m^3 for clay and 11 kN/m^3 for peat layers.

For transition zones between sand and clay layers, a 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 2.4 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 3. Correction factors for local friction Fs and friction ratio Rf were found to be 2.0 and 0.7 respectively.

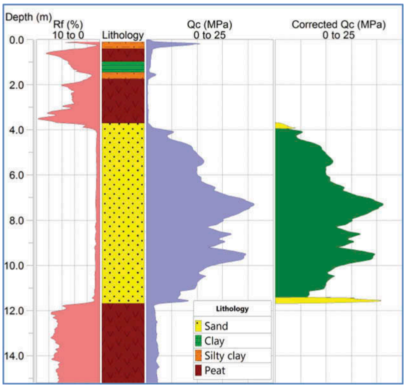

Figure 3. Example of original and corrected CPT for layered soil.

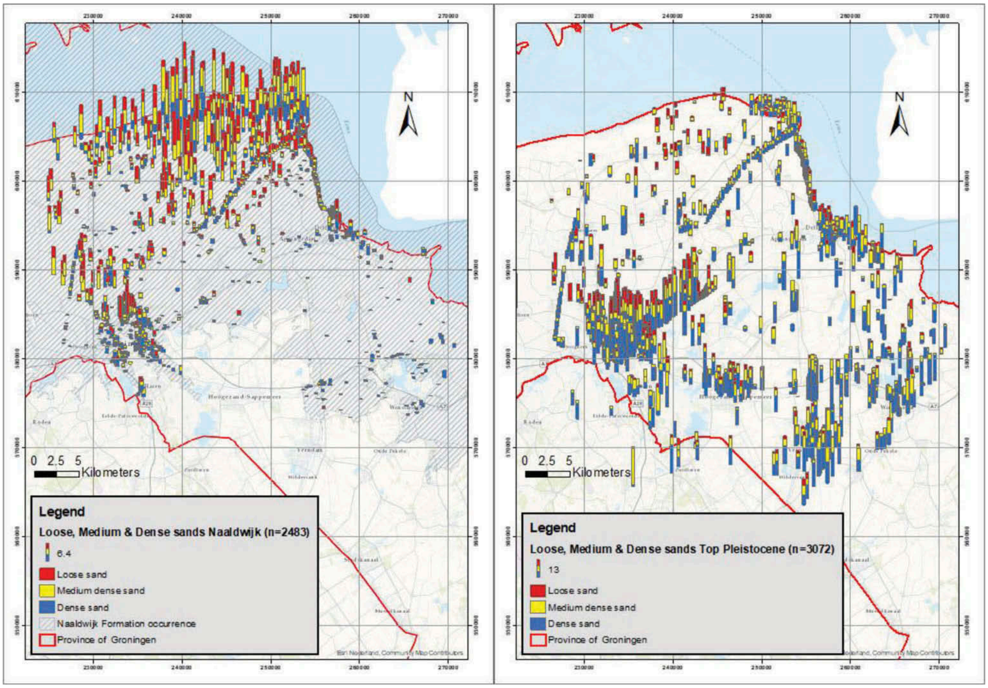

Figure 4. Stacked bars showing the total thicknesses of loose (red), medium dense (yellow) and dense (blue) sand in the Naaldwijk Formation (a) and Pleistocene sand (b). (Length of the bar indicates the total sand thickness in m).

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

Formation / depth interval	Total thickness (average, in m)	% loose sand	% medium dense sand	% dense sand
Naaldwijk	3	32	41	27
0-5m	1.3	22	40	38
5-10m	1.9	38	43	19
10-15m	2.0	37	40	23
15-20m	1.9	37	43	20
Boxtel	5.1	10	28	62
Eem	3.3	34	43	22

4.2 *Determination of sand densities*

The computation in the previous step results in a classification of the CPT values into loose, medium dense and dense sands over the entire depth range. The relative density 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 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.

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 is fully addressed, which is known to be related to liquefaction influencing parameters such as depositional environment, age and

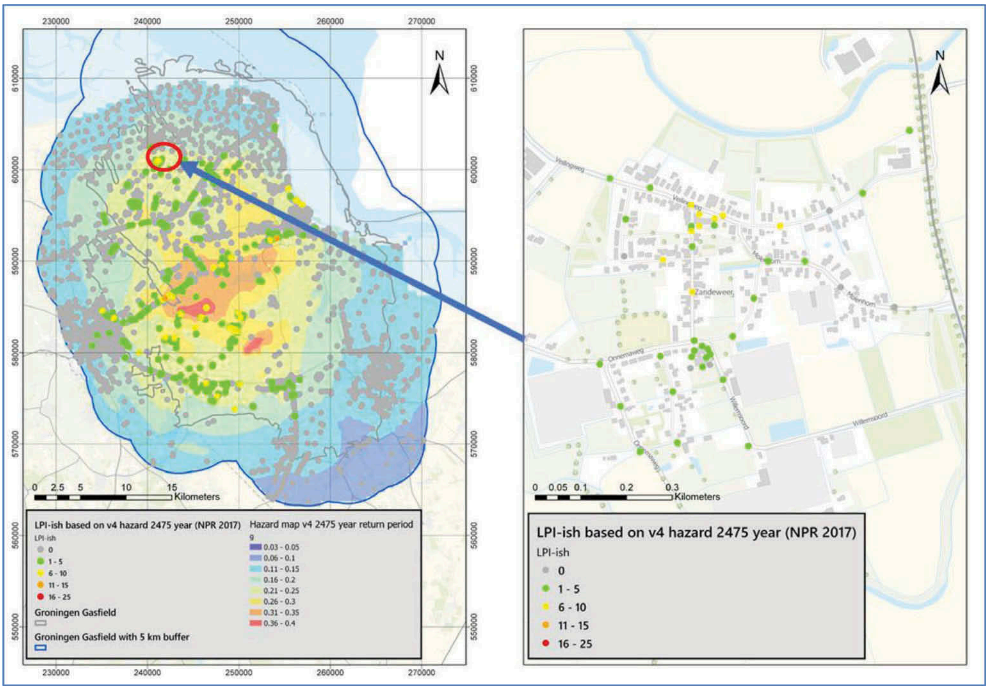

Figure 5. LPI$_{ish}$ map of Groningen based on the v4 hazard (NPR 2017) (left) with a detailed map of the town of Zandeweer in the northern part of Groningen as an example (right).

over-consolidation. Loose sands widely occur in the Naaldwijk Formation, especially in the thicker parts of the formation, see Figure 4a. The average total sand thickness rapidly increases towards the north. Accumulated thicknesses are presented in Table 1. In the Pleistocene deposits loose sands are mainly present in the western part, near the city of Groningen and the northern part, see Figure 4b. Dense sands reach thicknesses of a few meters, sharply contrasting with the sand thicknesses in the overlying Naaldwijk Formation. Note the high average total sand thickness and high percentage of dense sands in the fluvio-glacial formation of Boxtel. The interglacial Eem Formation resembles much to the Naaldwijk Formation.

4.3 *Determination of LPI_{ish}*

The liquefaction assessment method of (Green et al, 2018a,b) has been applied to determine the LPI_{ish} values for all CPTs (n=5467 after additional field campaigns in 2018) from the Groningen database and each relevant town in detail, see Figure 5. The hazard used is the 2017 v4 hazard PGA map for 2474-years return period, the common return period for foundation design for houses according to NPR998:2017. For most areas $LPI_{ish} < 5$, which means no serious risks are expected. For some places where $LPI_{ish} > 5$, additional investigations may be needed.

5 CONCLUSIONS

Based on 3234 CPTs in 2015, 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 been conducted to identify those areas where liquefaction is most likely to occur in case of induced earthquakes which are to be expected in the near future. The liquefaction potential is further assessed in 2018 based on 5467 CPTs, using the Groningen specific assessment procedure by (Green et al 2018a,b) and the derived LP_{Iish} values.

The most prominent deposits of loose sand are found in the Holocene Naaldwijk Formation. These deposits of young loose sands can be found in the northern part 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 formations, mainly the Eem Formation stands out in this respect of loose sand occurrences, as it resembles to the Naaldwijk Formation. In the Pleistocene layers the amount of loose sand is significant only in a belt from Groningen city towards the north and northeast. The aged Pleistocene fluvio-glacial Boxtel Formation in the southern part of Groningen, shows dominant thick horizons of dense sands as expected from geological point of view.

The highest hazard is found in the centre of the area, leading to a slightly different distribution of the LPI_{ish} values, concentrating around this centre. It can be seen that in many areas the risk for liquefaction is low (assuming this is the case for LPI_{ish} values <5).

The results presented can be used for prioritization of risk assessments related to buildings and infrastructures with respect to liquefaction and will be part of the NPR2018 update.

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