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Liquefaction Mapping for Induced Seismicity in the Groningen Gas Field

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ABSTRACT

The depletion of the Groningen Gas Field in The Netherlands is known to cause induced seismicity. Until mid-2015, the largest magnitude earthquake that occurred had a moment magnitude of 3.6. Ongoing production is expected to increase the seismic hazard and corresponding median PGA levels and earthquake duration. The subsoil in the area consists of several Holocene and Late Pleistocene geological formations, locally containing extensive layers of sand. One specific feature of the Holocene deposits is the occurrence of well-layered fine sandy tidal flat sediment. The mapping of the liquefaction potential 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. An outlook is given to future work on assessing the liquefaction risk.

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 has 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. As of June 2015, more than 600 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 on the Richter scale up to M_L = 3.6 have been recorded. The seismicity displayed in Fig. 1 clearly shows a growing trend in the number of events of M_L>1.5.

Based on expectations for future production, several groups have delivered seismic hazard maps for The Netherlands. Median PGA levels to be expected in the coming period of about 5 years are in the order of 0.2 g, while 1:475 year return period values for 2013-2016 are in the order of over 0.4g according to Dost et al (2013) and NAM (2013). Despite the low magnitude, these relatively high PGA values potentially make liquefaction an important mechanism, 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.

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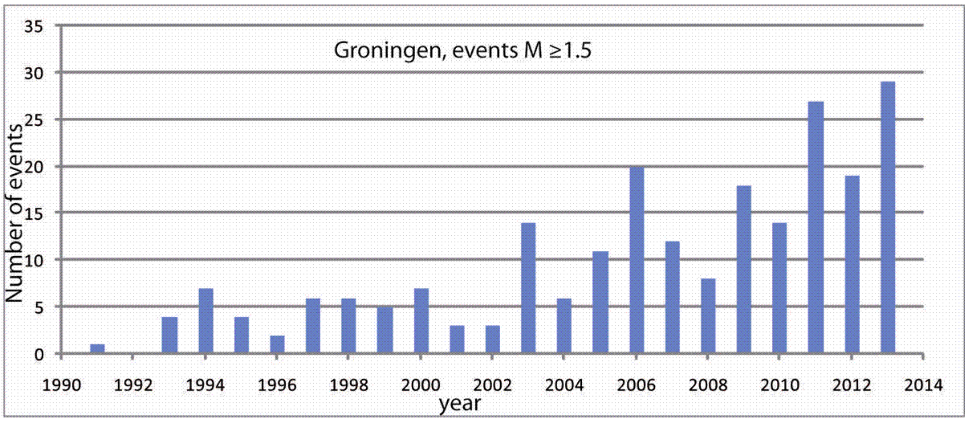

Figure 1. Seismicity in the Groningen field (from: KNMI)

Risk of Liquefaction

The potential occurrence of liquefaction of sand layers may lead to loss of strength of the soil and settlements of surface and structures. The consequences of liquefaction can be serious and mitigating measures expensive. Therefore a sound understanding of the liquefaction potential is required. Liquefaction potential is defined here as the probability that the subsoil at a particular location may liquefy under a given earthquake vibration. For the liquefaction mapping presented in this paper the focus is on the liquefaction potential of the soil in Groningen, i.e. the existence of sand layers, their thickness, their depth and geological and geomechanical characteristics. The calculation of the amount of liquefaction and the risks related to foundations or structures are not part of this paper and will be presented at a later stage once a specific assessment method for application to the Groningen earthquakes and site conditions has been derived.

The liquefaction potential of a specific sand layer is mainly determined by the density of the soil, the depositional environment, the age of the deposit and 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) potentially play a role. Most of the factors mentioned will influence the cone penetration test (CPT) values, although the exact relationship is not known for all of these. In the assessment presented, CPT values are used directly (no corrections) to determine the liquefaction potential. 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 potential and the way that they have been derived are described in the following section.

Liquefaction Parameters from Geology

One of the most important aspects of the liquefaction potential is the density of the soil: 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 CPTs are available in large numbers 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 overconsolidation may significantly decrease the liquefaction susceptibility of the sand layers, according to for example Andrus et al. (2009). The effect of ageing is expected to be cementation and/or soil formation in the sediments. 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. For the present study it is assumed that age and cementation are reflected in the cone-tip resistance values, but in future more detailed corrections might be used.

In overconsolidated sand (or horizontally forced sand/lateral moraine) the horizontal stress becomes larger and for sand with the same (relative) density the cone tip resistance increases. This will result in an overestimation of the liquefaction potential. On the other hand, overconsolidation is expected to increase the liquefaction resistance, as stated by 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 section describing the geological formations present in the subsurface of Groningen, it is indicated whether the deposits have been exposed to ice-sheet loading. No specific correction is suggested at this moment, but could be added later.

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 (d_{60}/d_{10}). The fines correction proposed by Idriss & Boulanger (2008) and Boulanger & Idriss (2014) can be used to account for this effect on the liquefaction potential. One particular feature of the tidal deposits in Groningen is that they contain thin layers of clay/silt material, known as “Flaser beds.” An example of this type of sand deposit is shown in Figure 2. These layers can be characterized as laminated, quasi regular sequences of clay/silt 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 relative density. However, an accurate estimation of the soil properties based on CPT data is crucial in order to assess the liquefaction potential. Therefore a correction factor for multiple thin layers is to be developed.

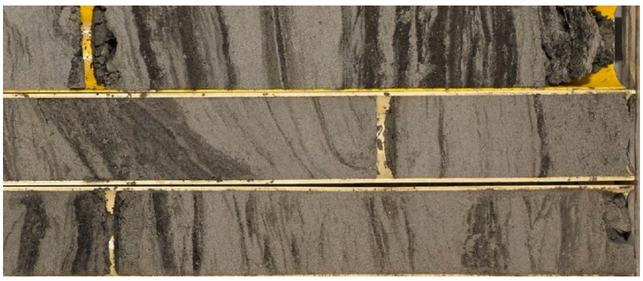

Figure 2. Example of a 66 mm core through so called “Flaser beds”

Geology of the Groningen Area

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 uncemented and the formation has not been exposed to ice-sheet loading. 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-load. The deposits are comparable to those of the Naaldwijk Formation, but of 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. Figure 3 shows the depth of the base and total thickness of the Naaldwijk Formation from the GeoTOP 3D model of the subsurface; similar maps for the other formations have also been used in the liquefaction mapping.

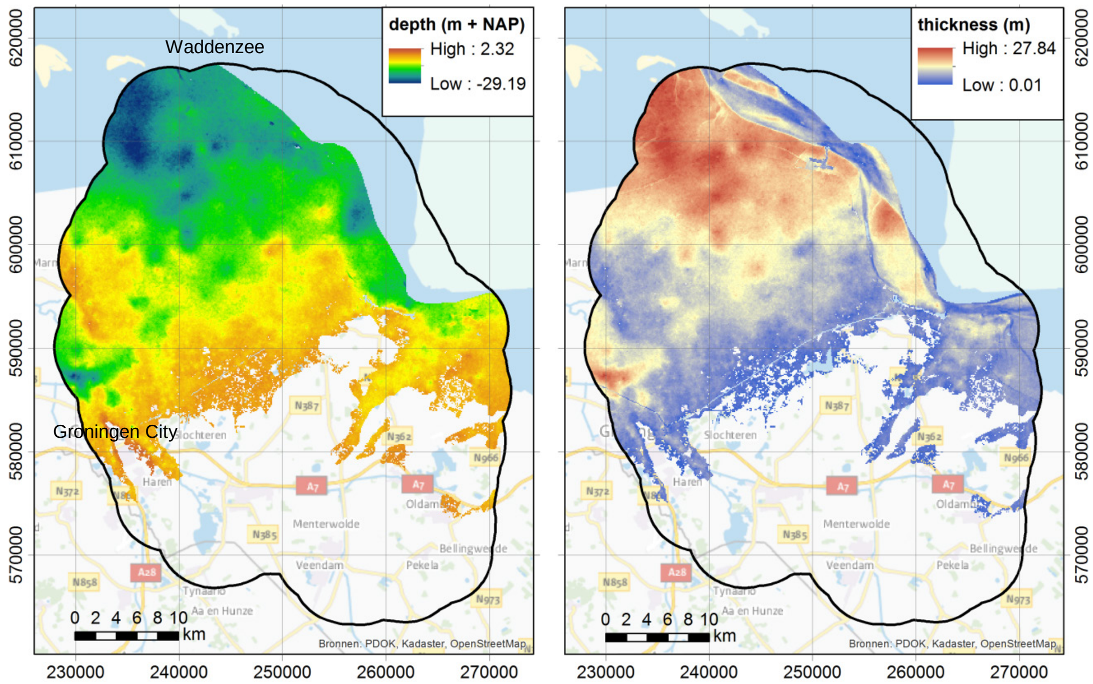

Figure 3. Depth of the base (left) and total thickness (right) of the Naaldwijk Formation in the 3D model of the subsurface. NAP is Dutch reference level (appr. mean sea level)

Liquefaction Mapping

For the above mentioned geological formations, a geological model was built for the Groningen field based on over 5000 CPTs, on the beta version of the 3D geological layer model GeoTOP (Stafleu et al., 2011) and various other sources, such as borings from a large scale drilling campaign. From the 3D lithostratigraphic model only those geological formations were included 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) as described above. The maximum depth below the land surface taken into account was 20 m.

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). After this, relative densities of the identified sand layers were determined according to Lunne & Christofferson (1983) and Villet & Mitchell (1981). The resulting relative density values calculated for Groningen by Lunne & Christofferson are on average about 8% higher than those calculated by Villet & Mitchell. For loose and medium dense sands, the Lunne & Christofferson parameter is more conservative, whereas this is reverse for higher relative densities. 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%.

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 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.

Loose sands are widely occurring in the Naaldwijk Formation, especially in the thicker parts of the formation; see Figure 4 (top). Subareas are defined, based on the thickness of the Naaldwijk Formation, to group the CPTs in zones of 5 m thickness contour intervals. This was done to simplify the estimation of loose sands thickness at locations within such a subarea in terms of statistically reliable mean values derived from Gaussian-like symmetric distributions. The intervals and an example of the distribution over one of the zones is shown in Figure 5. The mean of the thickness of the sand deposits (loose, medium and dense together above NAP-20m) in the Naaldwijk formation is less than 1 or 2m in the South of the area. The total thickness increases to almost 20 m close to the Waddenzee in the North.

Table 1 shows the mean thicknesses of loose, moderate and dense sands in each of the subareas, including the total sand thickness in the Naaldwijk Formation. It is obvious that 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.

In the Pleistocene deposits loose sands are mainly present in the western part, near the city of Groningen and the northern part, see figure 4 (bottom). The mean thickness of Pleistocene sands is around 2 m for loose sands, 4.5m for medium dense sand and 6.5m for dense send respectively.

Table 1 Total sand thickness in the Naaldwijk Formation in the five subareas.

Zone	**Average thickness**	**%loose sand**	**%medium dense sand**	**% dense sand**
1	19.3	30	48	22
2	11.4	32	46	22
3	4.0	44	39	17
4	1.9	26	38	36
5	1.7	14	31	55

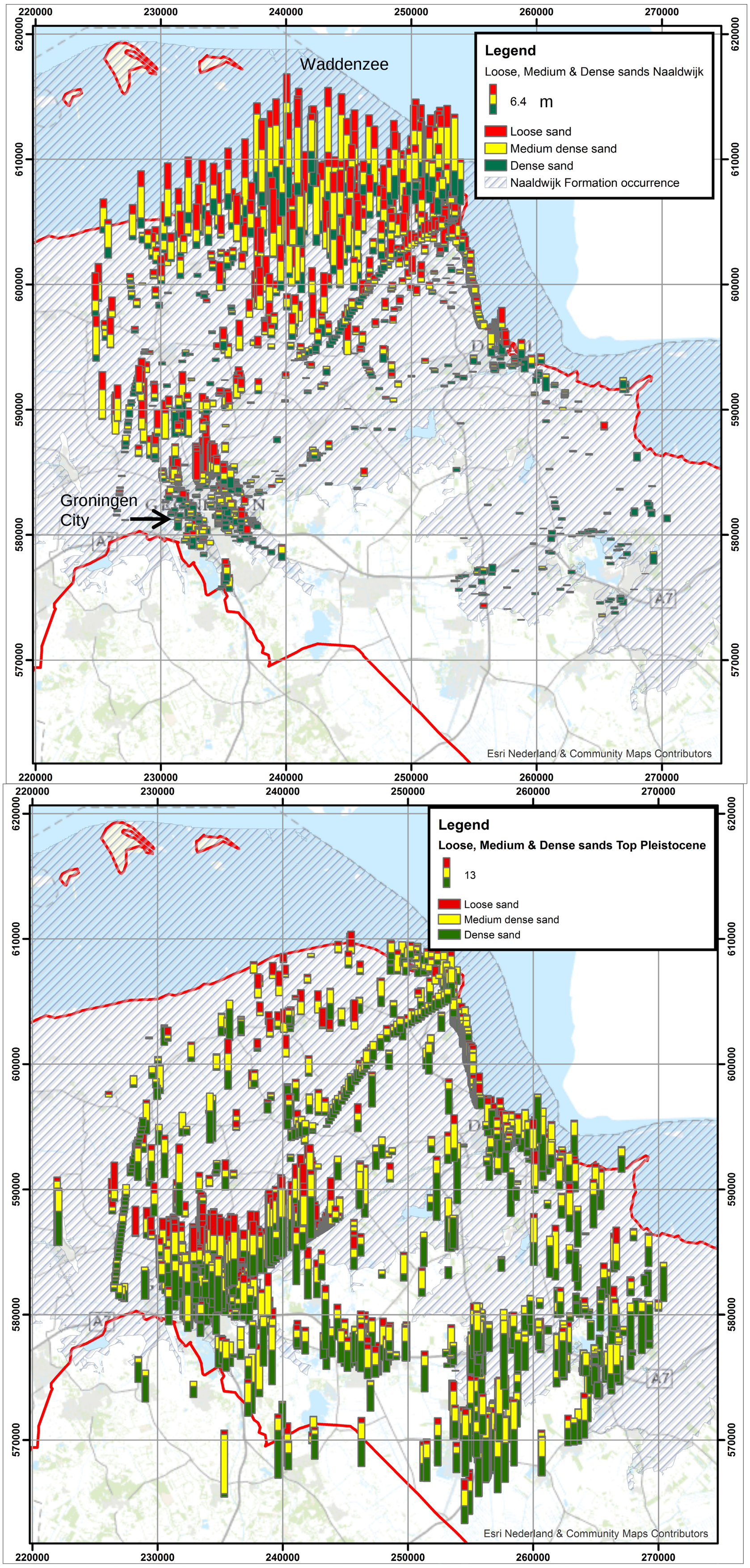

Figure 4. Stacked bars showing the total thicknesses of loose, medium dense and dense sand in the Naaldwijk Formation (top) and Pleistocene formations (bottom)

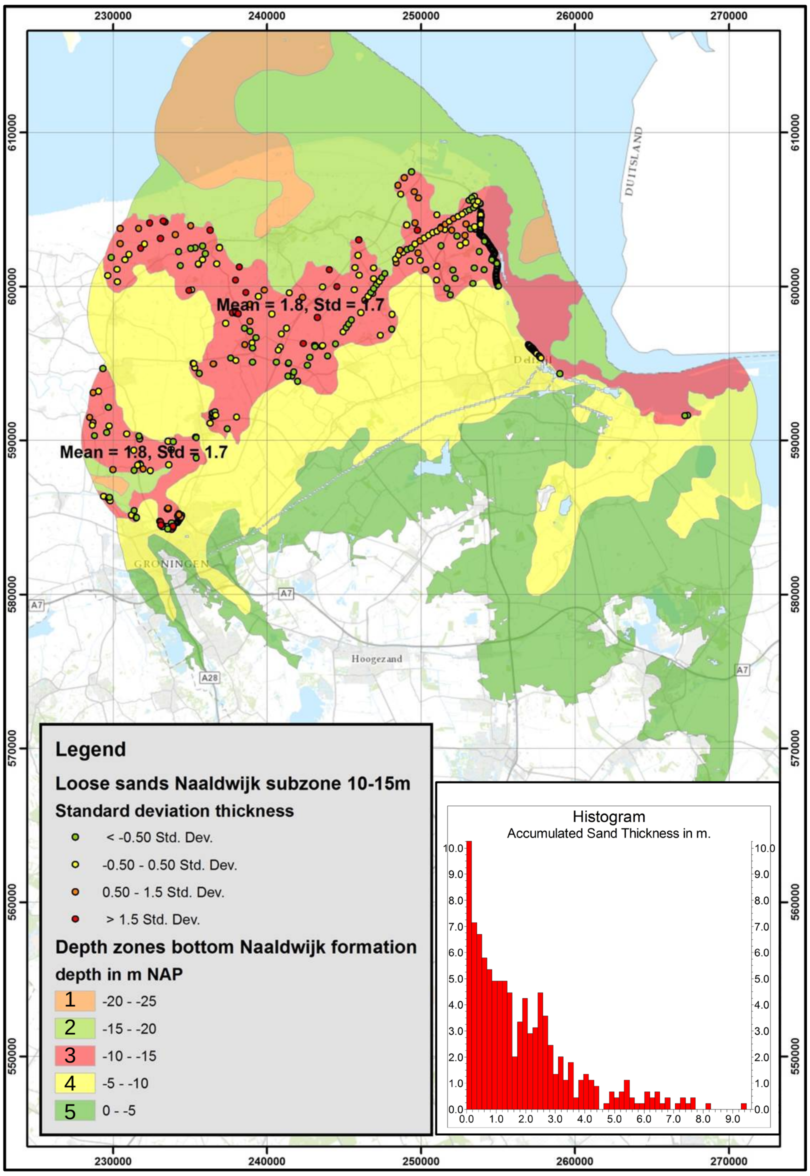

Figure 5. Deviation from the mean of accumulated thicknesses of loose sands in the Naaldwijk Formation in depth 10 - 15m

Discussion and Future Developments

The presented geological mapping of liquefaction potential is mainly based on CPT's and on the Dutch 3D geological model GeoTOP (from TNO). The results are presented as maps defining the distribution of the thickness of loose, medium and dense sand layers in separate geological areas based on stratigraphy and lithology. This has the advantage that geological origin, which is known to be related to liquefaction influencing parameters such as depositional environment, age and overconsolidation are implicitly taken into account. This also gives the opportunity for future determination of formation-specific liquefaction potentials.

The relative density of the soil (based on CPT value and stress level) is presented in this model as the main factor determining the liquefaction potential. Future work needs to determine the link between density and liquefaction potential and the actual risk (with consequences for structures). In particular for the Flaser beds in the tidal flats, the measured CPT value may not be a sufficient parameter to determine the liquefaction potential and experiments are currently undertaken to come to a multiple thin layer correction suitable for these specific alternating layers.

Conclusions

The liquefaction potential for the Groningen area, based on over 5000 CPTs, shows that 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 spatial distribution of the relative sand densities in the Naaldwijk Formation approach Gaussian distributions when grouped into zones based on the average thickness of the formation (for the thicker zones).

The liquefaction potential is separately mapped for each of the geological formations, leaving room for formation specific interpretations in future based on influencing factors such as age or overconsolidation. Currently there are no reliable methods to deal with the specific Flaser beds, consisting of very thin alternating sand and clay layers. The results presented can be used for prioritization of risk assessments related to buildings and infrastructures with respect to liquefaction.

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