Deltares

Non reversible aspects of soil behaviour during earthquakes

(KEM 05a & KEM 14)

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January 2022

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KEM 5a

Cumulative effects of repetitive earthquakes on soil settlement

Research questions KEM 5a

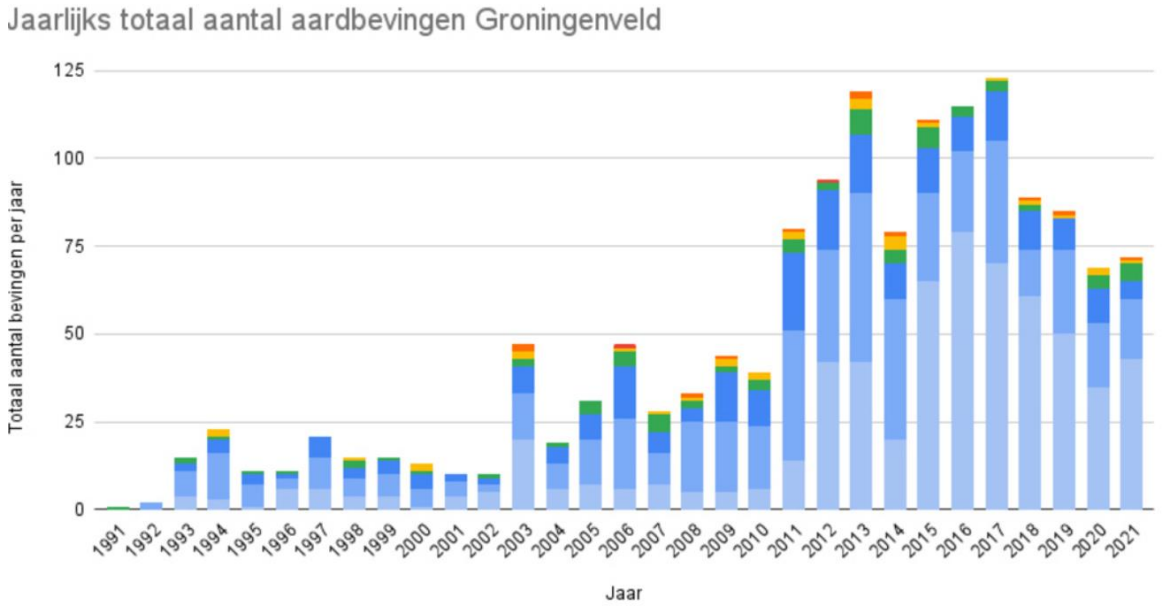
Main question

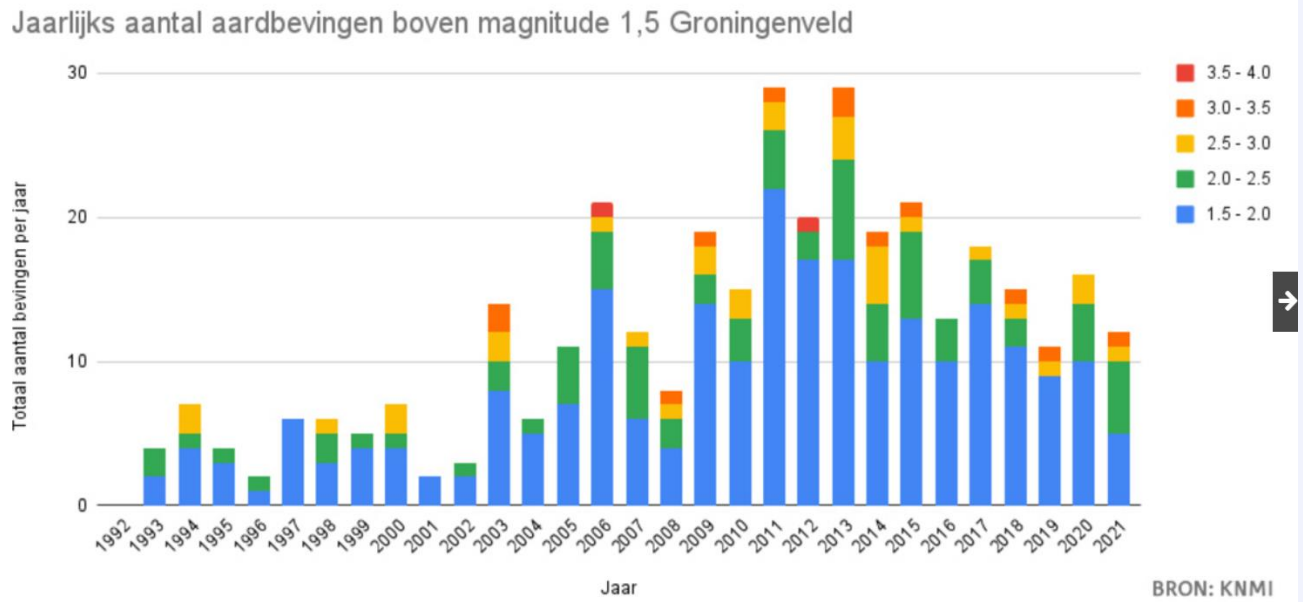
- What is the effect of repetitive earthquakes on settlement?

Detailed questions

- What effects on near surface sediment settlement can be expected due to repetitive earthquake tremors?
- Can the effect of repetitive earthquakes tremors cause damage to buildings (in relation to the specific situation in the Netherlands)?
- If so, can the effect of repetitive earthquakes tremors be tested and quantified?
- Can the effects of repetitive earthquake tremors be disentangled from other comparable processes common in soft soils in the Netherlands?

Number of earthquakes





Source: https://www.knmi.nl/over-het-knmi/nieuws/jaaroverzicht-aardbevingen-2021

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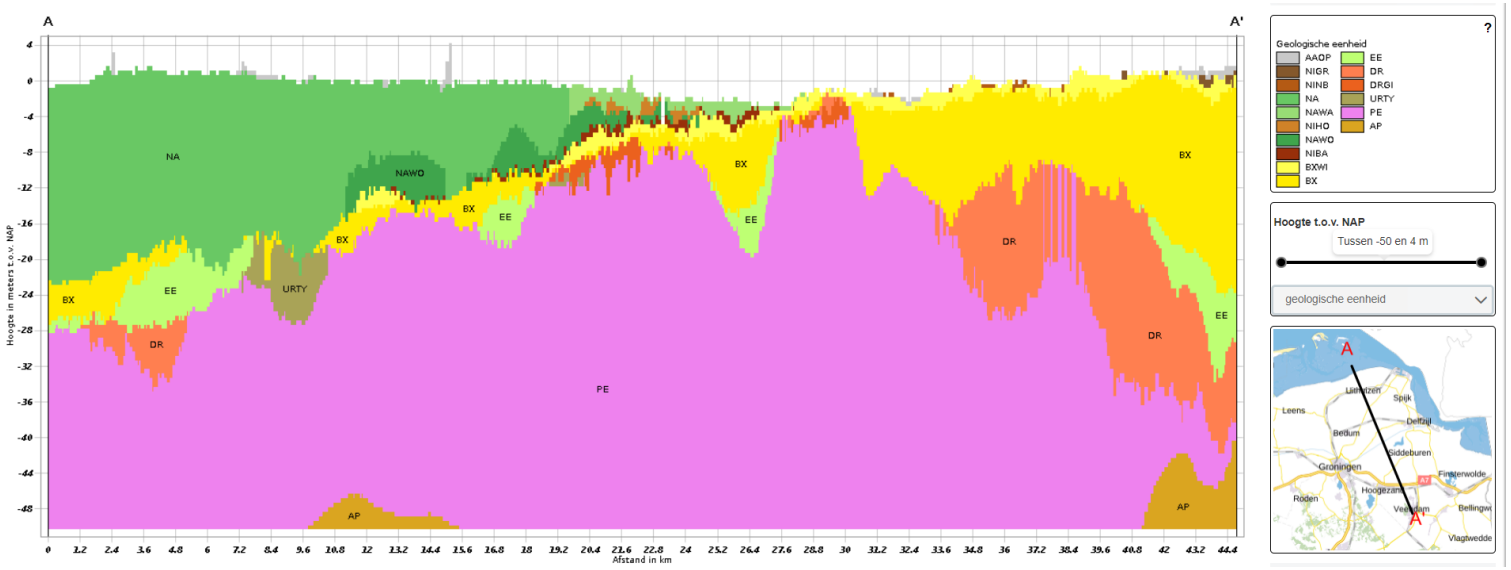
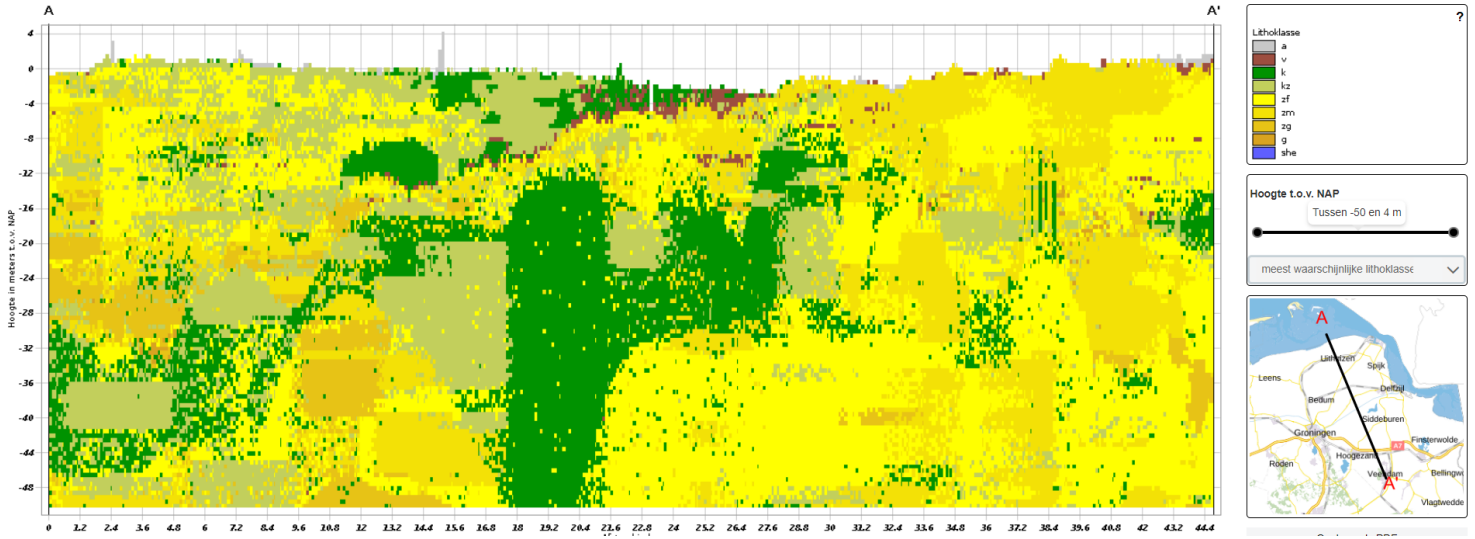
Subsoil conditions, N-S profile



Geological cross section



Geotechnical cross section

Data from GeoTop

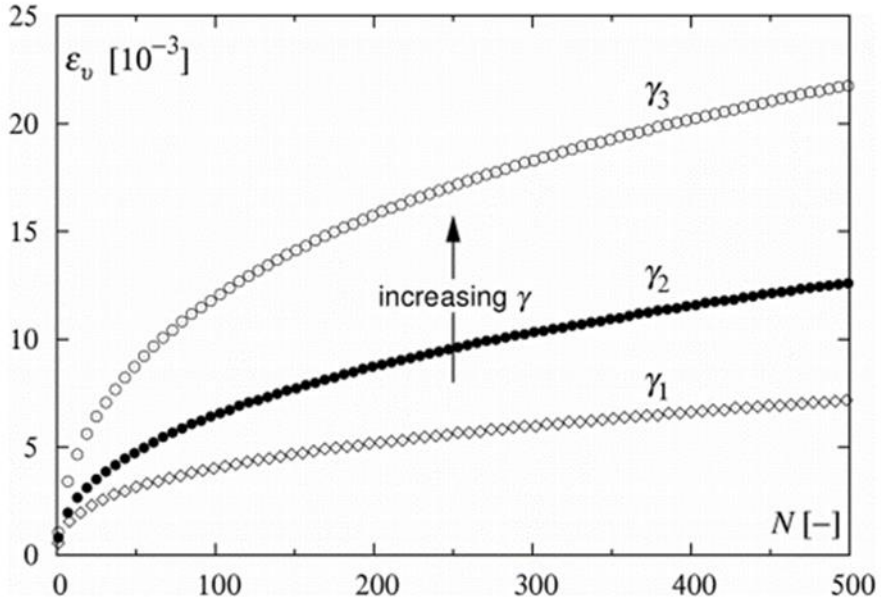
Literature data

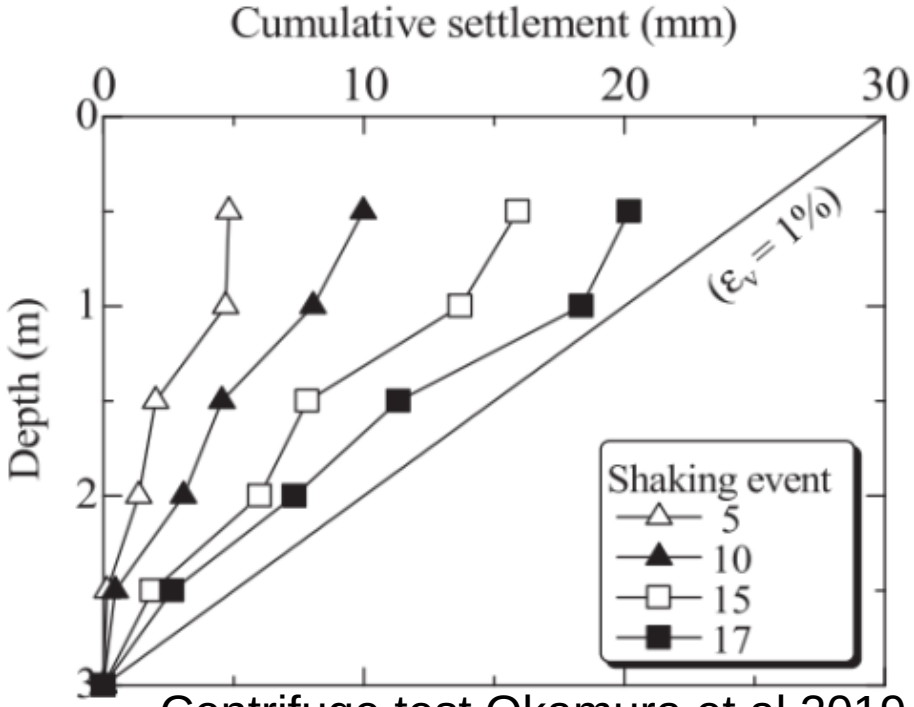
- Little to no information in literature
- Densification increases with number of cycles, but rate of densification decreases.

Therefore:

- Focus on soil behaviour during cyclic loading

  -> sand / clay / peat
- Use results geo-centrifuge tests

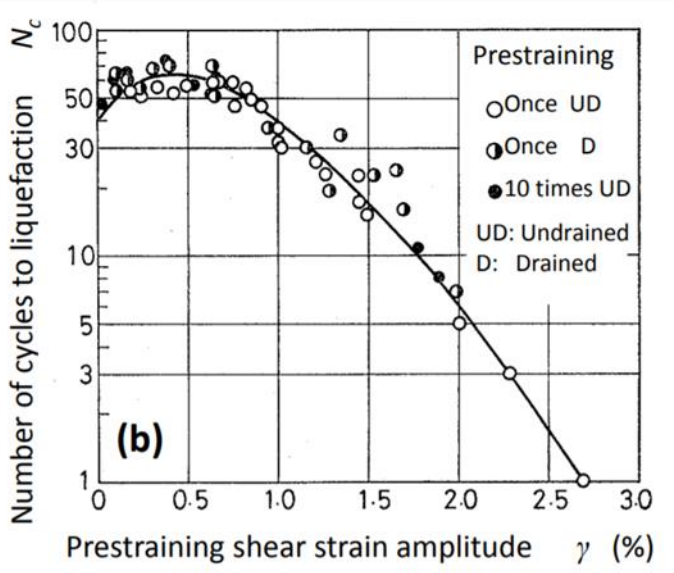




Centrifuge test Okamura et al 2019

Sand: liquefaction (effect pre-shearing)

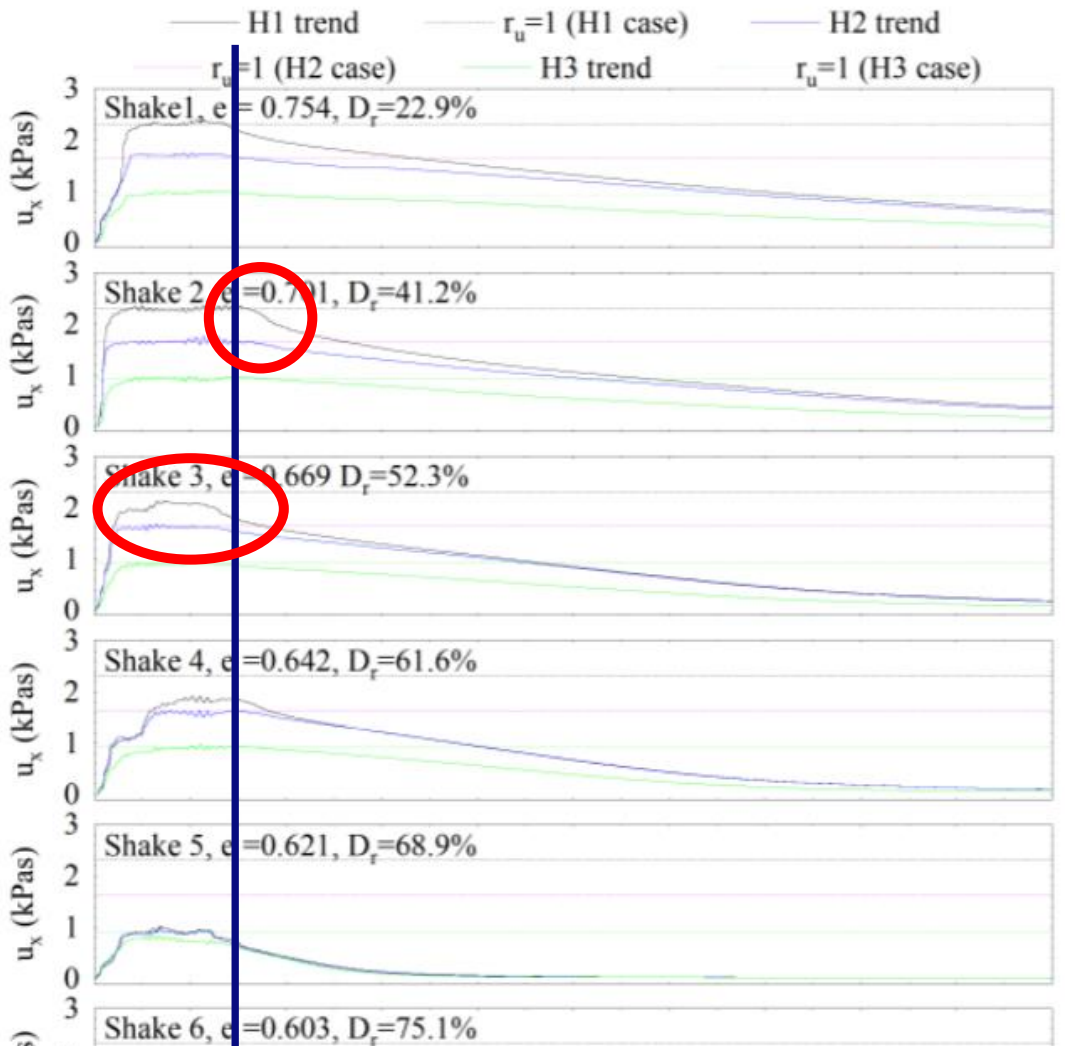
Results CTX tests,
with pre-shearing



(Suzuki, Toki 1984)

Small pre-shear: positive
Large pre-shear: detrimental

Results shaking table tests, with several events



event 2: longer duration period full liquefaction

event 3, 4, 5, 6: decrease amount of liquefaction, both amount and duration

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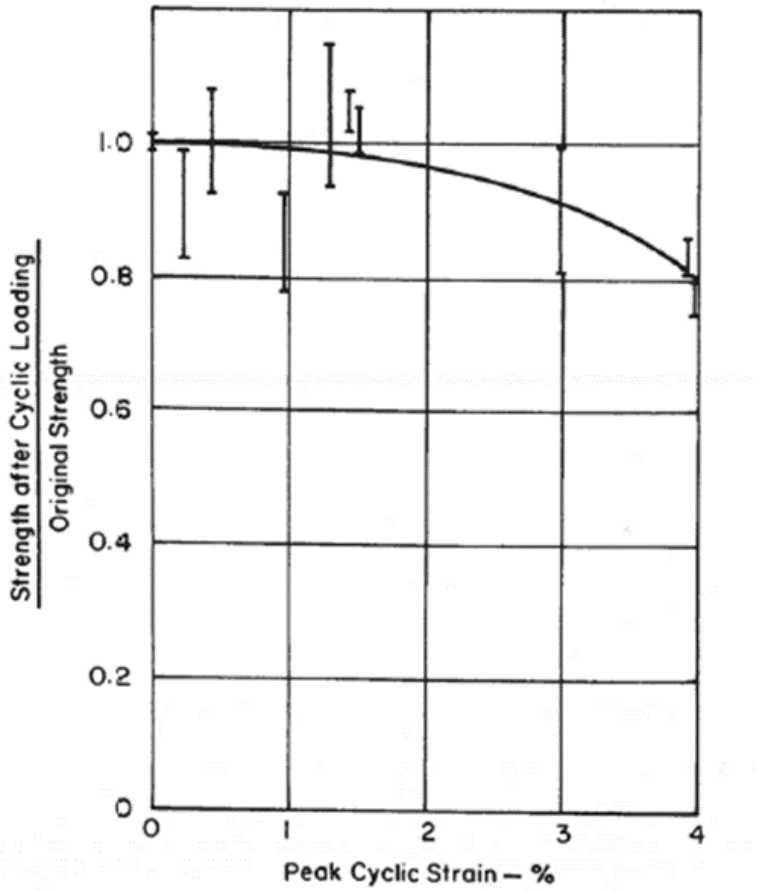
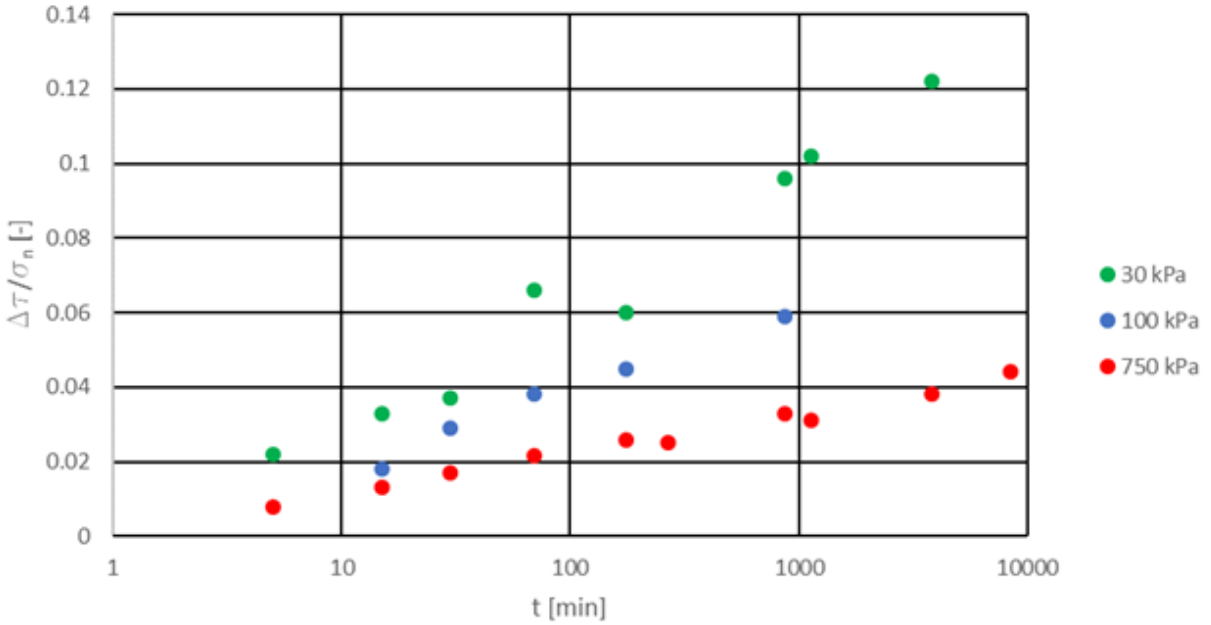
Clay: loss and regain of strength



Loss of strength

(Thiers, Seed 1968)



Regain of strengt in time

(Doglioni and Simeone 2011)

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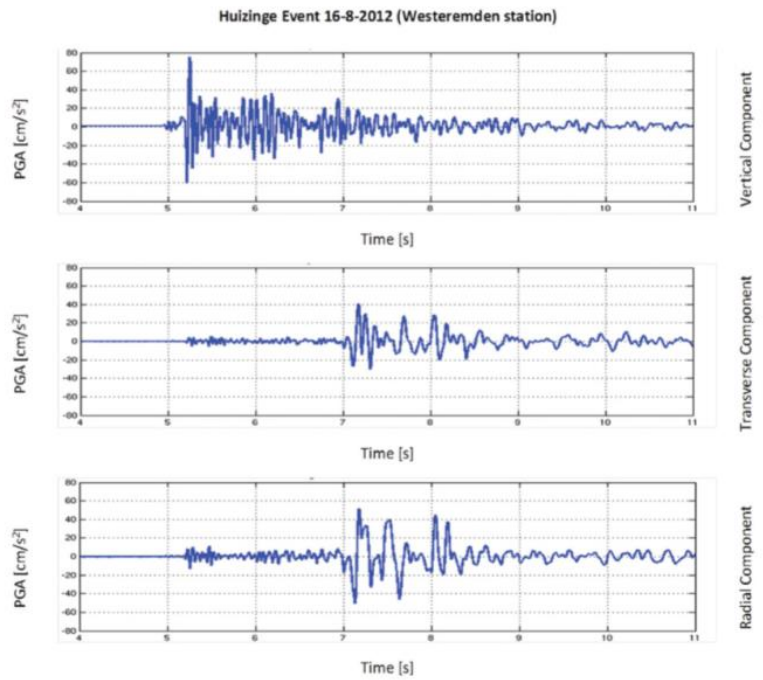
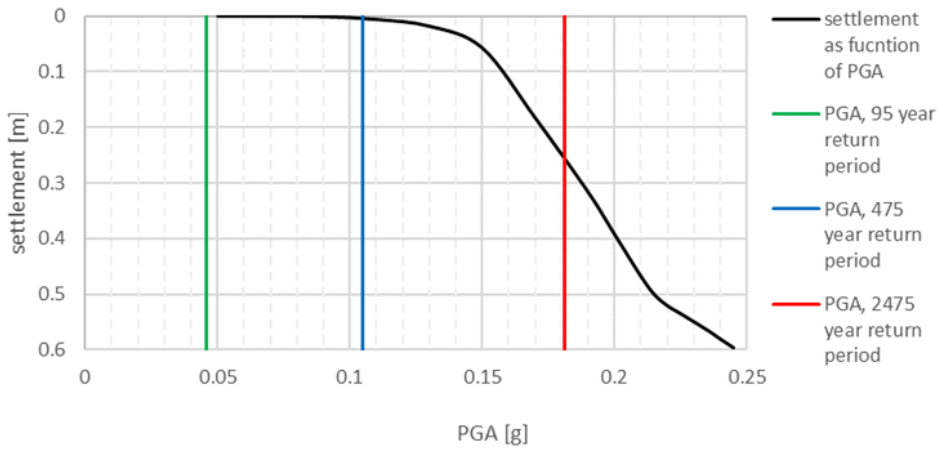
Sand: application to Groningen

- Rate of densification may decrease with subsequent earthquakes
- Settlement due to densification will be instantaneous

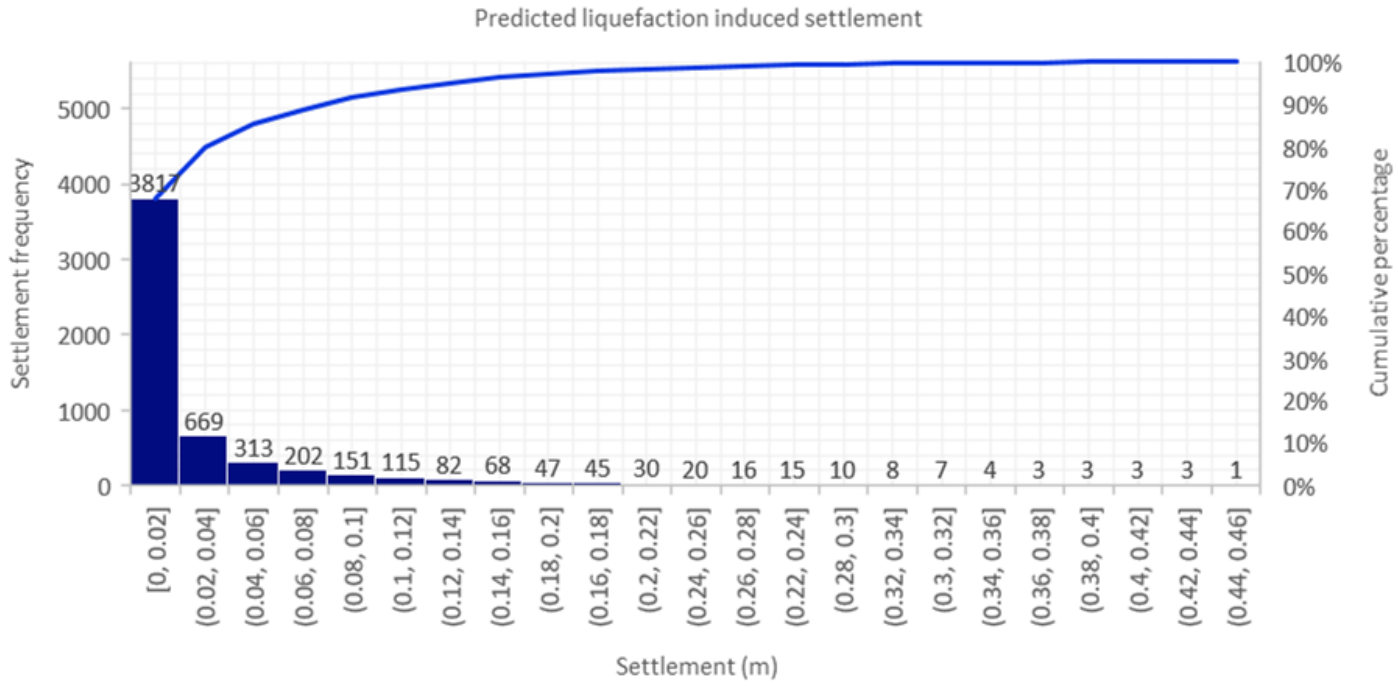


- But: low PGA so far
  - Uncertain if already some densification occured
  - Uncertain if effect pre-shearing is already present



Sand: Settlement to date in Groningen

- Free field settlement, using Yoshimine approach
- No measured data, estimated from available models
- Estimated free field settlement for design earthquake limited



Pareto diagram computed settlement Groningen wide, V6, 2475 year return period

Clay: application to Groningen

- Low PGA so far
  - Uncertain if any degradation occurs

    even if: effect will be negligible or small
- No information on settlement, will be difficult to distinguish from normal consolidation settlement

Answers to questions (KEM 5a)

- What effects on near surface sediment settlement can be expected due to repetitive earthquake tremors?
  - In sand: cumulative settlement; in clay: no or only minor loss of strength
- Can the effect of repetitive earthquakes tremors cause damage to buildings (in relation to the specific situation in the Netherlands)?
  - Not for the earthquakes to date, could happen for future (if stronger) earthquakes
- If so, can the effect of repetitive earthquakes tremors be tested and quantified?
  - Can be tested with cyclic tests on soil samples or geo-centrifuge tests

    recommendation: assess shear strain amplitude due to present day earthquakes

    option: install extensometers
- Can the effects of repetitive earthquake tremors be disentangled from other comparable processes common in soft soils in the Netherlands?
  - In sand: possible as a ‘jump’ in settlement
  - In clay: bearing capacity: possible as a ‘jump’, for settlement: uncertain

KEM 14

Liquefaction hazard and risk quantification

Research questions and objective KEM 14

Questions from the public: Is it possible that for Groningen type earthquakes (PGA's, PGV's) liquefaction occurs? If so, what effect can be expected for buildings and infrastructure in Groningen?

Previous work in NPR9998 and at NAM.nl already describes how to assess liquefaction for Groningen.

Main follow up questions in KEM14:

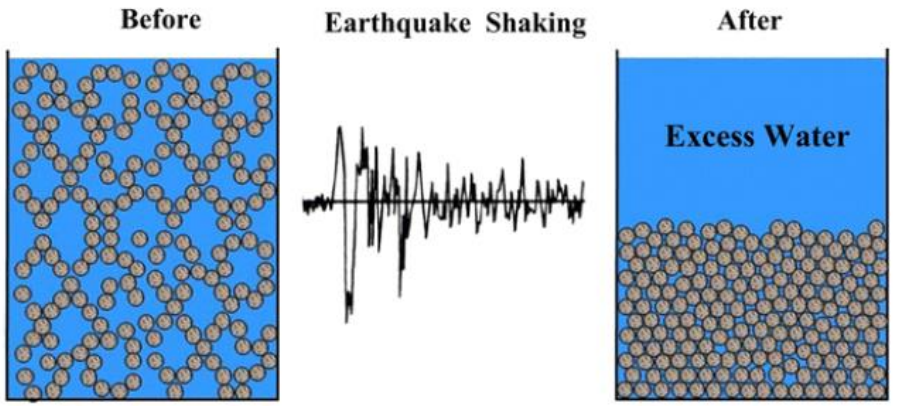
- Is there a method to link the probability of liquefaction to the risk for building damage?
- What is the validity of such a link?

Liquefaction

Definition:
The act or process of transforming any substance into a liquid. In cohesionless soils, the transformation is from a solid state to a liquefied state as a consequence of increased pore pressure and reduced effective stress.

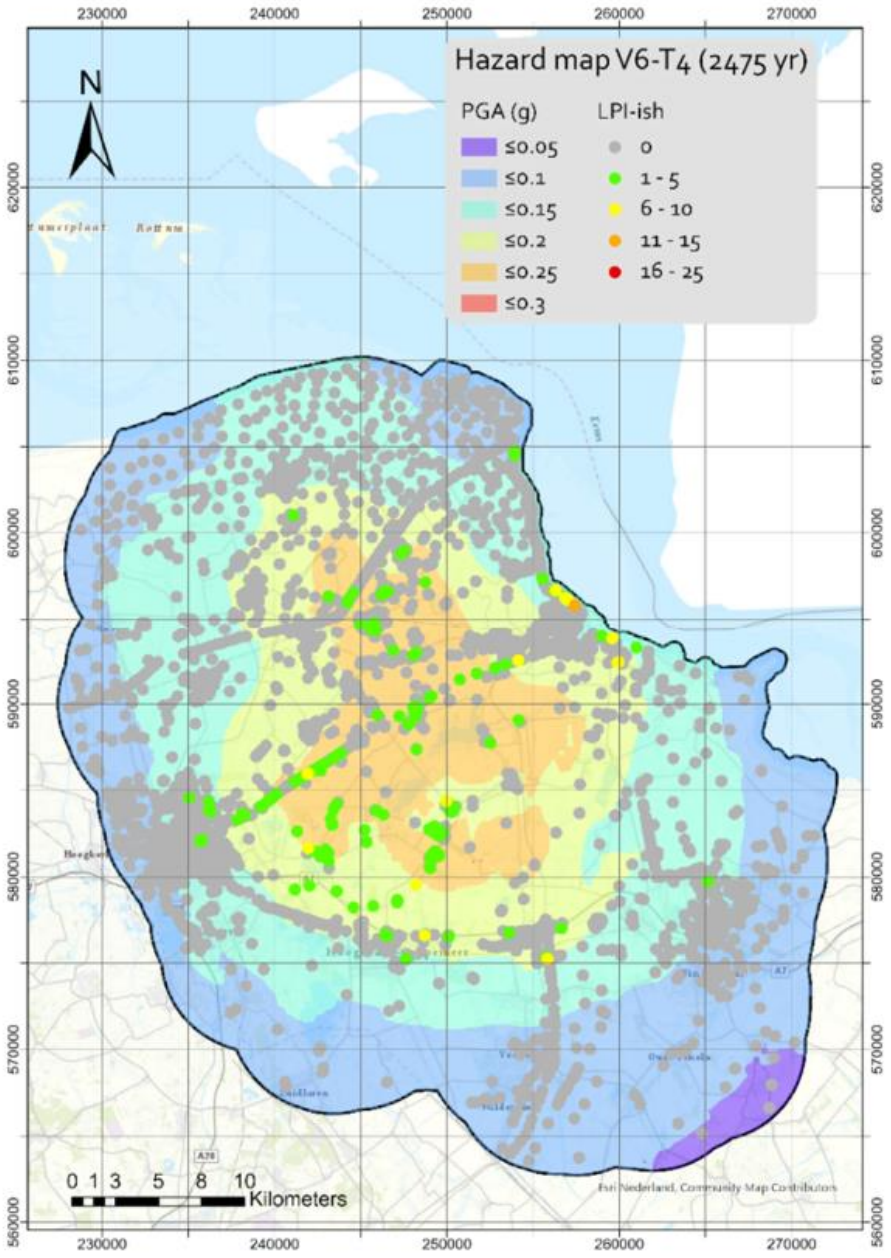
*(*Marcuson, 1978*)*

Consequences liquefaction
- Loss of bearing capacity => large deformation, failure
- Densification => settlement



Liquefaction, Roermond 1992 earthquake

Liquefaction assessment Groningen



Already analysed by NPR9998, results available at https://seismischekrachten.nen.nl/map.php

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Approach used in KEM 14

- Initial approach: use index parameters
  - link damage to a well established index parameter (e.g.), advantage: it takes into account thickness liquefied layer and effect of depth liquefied layer, no need for multiple complex SSI calculations

- Required:
  - Selection relation damage and index parameter
  - Thresholds for index parameter

Index parameters from literature

- LPI (Liquefaction Potential Index)
- LPI_{ish} (Ishihara inspired Liquefaction Potential Index)
- LSN (Liquefaction Severity Number)
- LDI (Lateral Displacement Index)
- LBS (Liquefaction induced Building Settlement index)
- IAM (Induced dAmage Measurement)

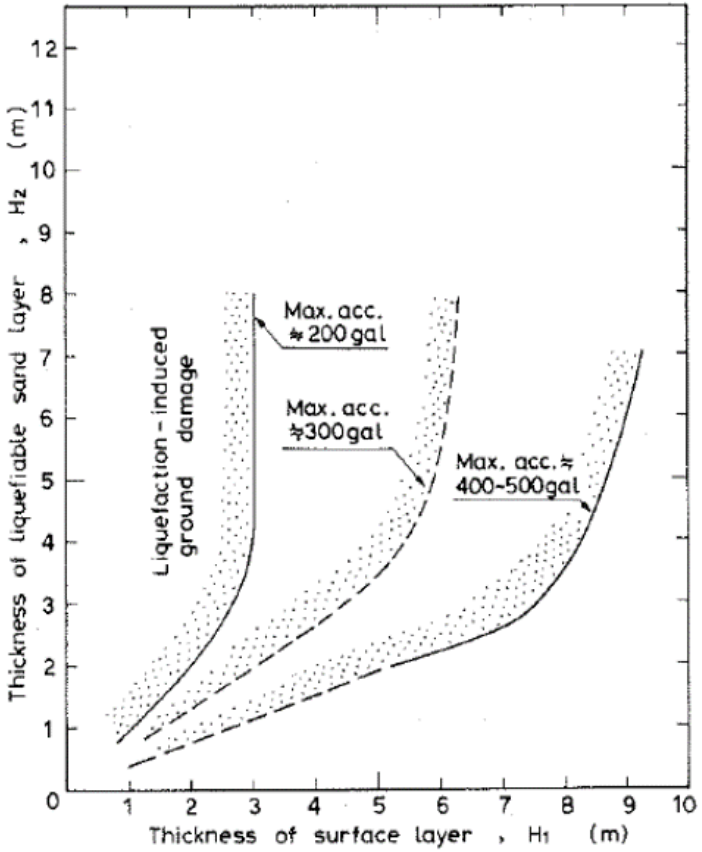
LPI and LPI_{ish} are widely used, others mainly or only used by their originators

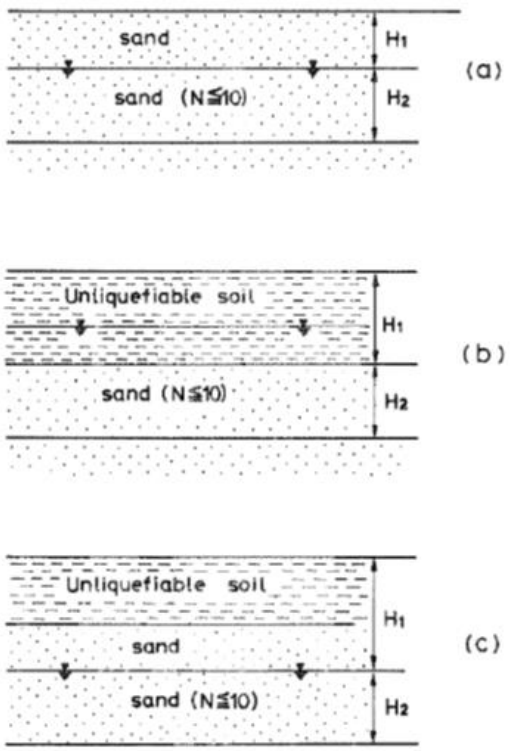
Calculation of LPI and LPI_{ish} (Ishihara inspired LPI)

$$LPI = \int_0^{20\ m} F(z)W(z)\,dz$$

F(z) function of resistance against liquefaction, F(z) is 0 (no liquefaction) to 1 (full liquefaction)
W(z) is depth function (10-0.5z)

LPI_{ish} is an extension of LPI – different weight function and non-liquefiable crust



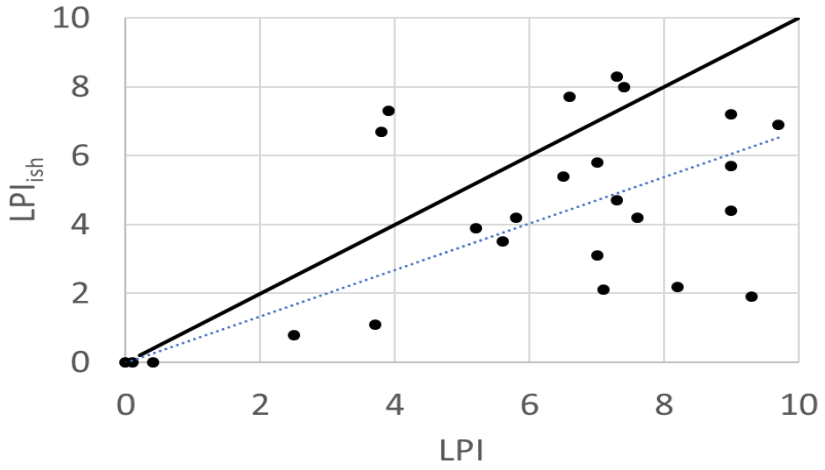


Boundary curves for site identification of liquefaction induced damage, from Ishihara (1985).
NB 1 gal = 1 galileo = 1 cm/s^2 = 0.01 m/s^2 ≈ 0.001 g

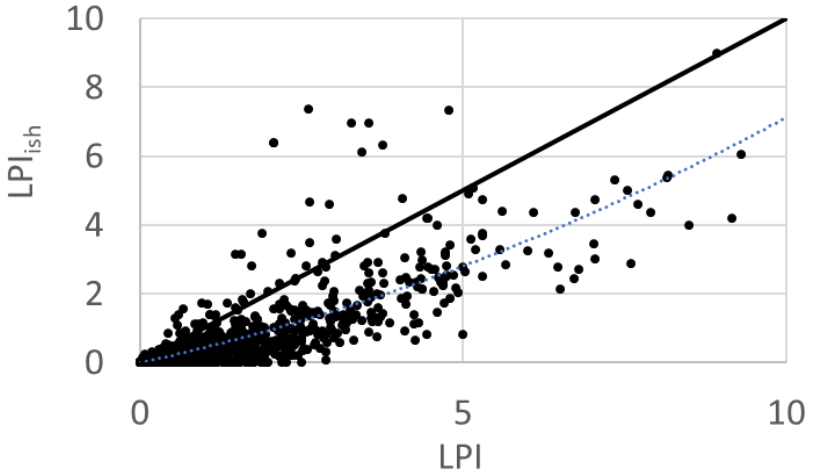
Relation LPI and LPI_{ish} to severity

- Commonly used classification LPI
  - LPI < 5: no to minor liquefaction manifestation
  - LPI > 15 : severe liquefaction severe liquefaction manifestation
  - No direct link with building damage

- Commonly used classification LPI_{ish}
  - No reports or papers linking LPI_{ish} to severity of liquefaction
  - Common approach is to use same values as for LPI



(based on Maurer et al 2015 database)



(based on Groningen database)

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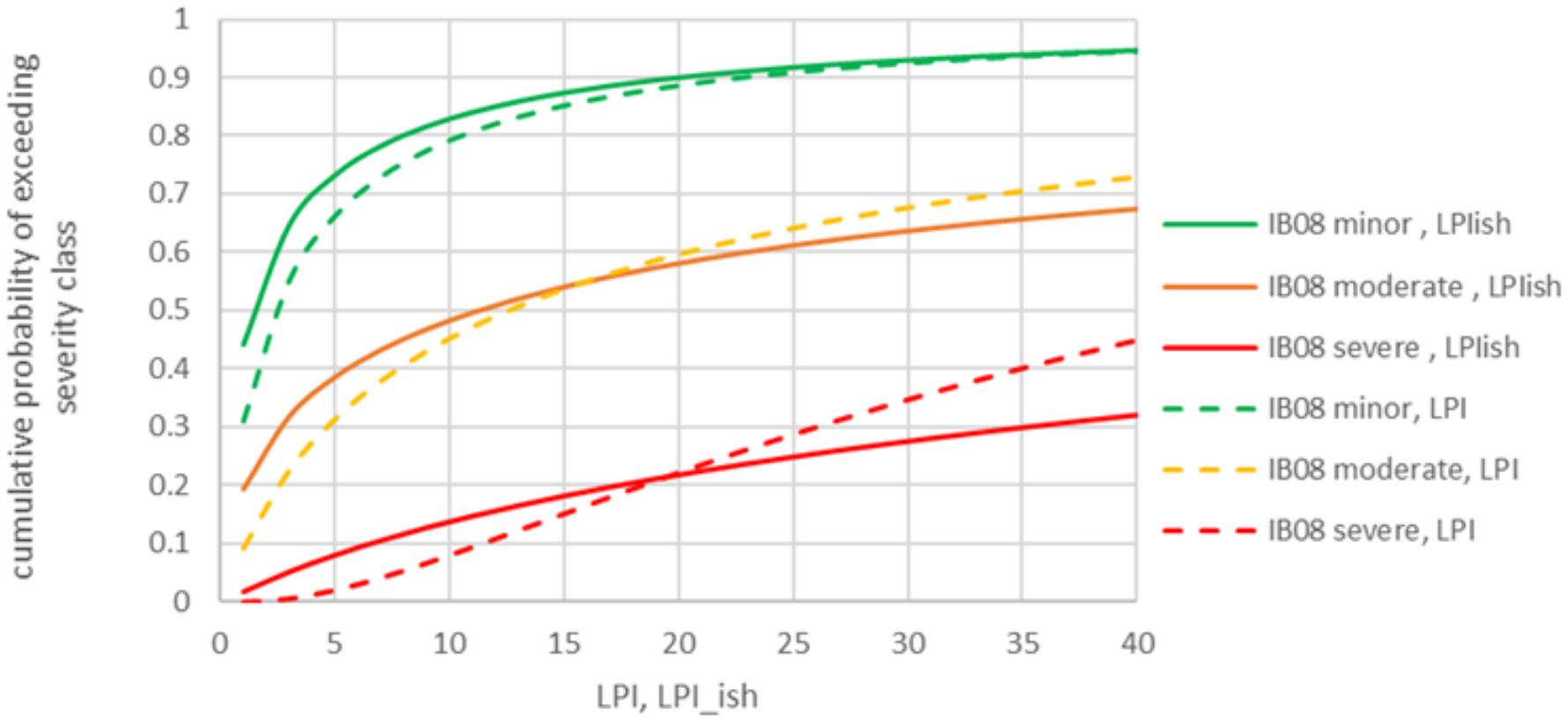
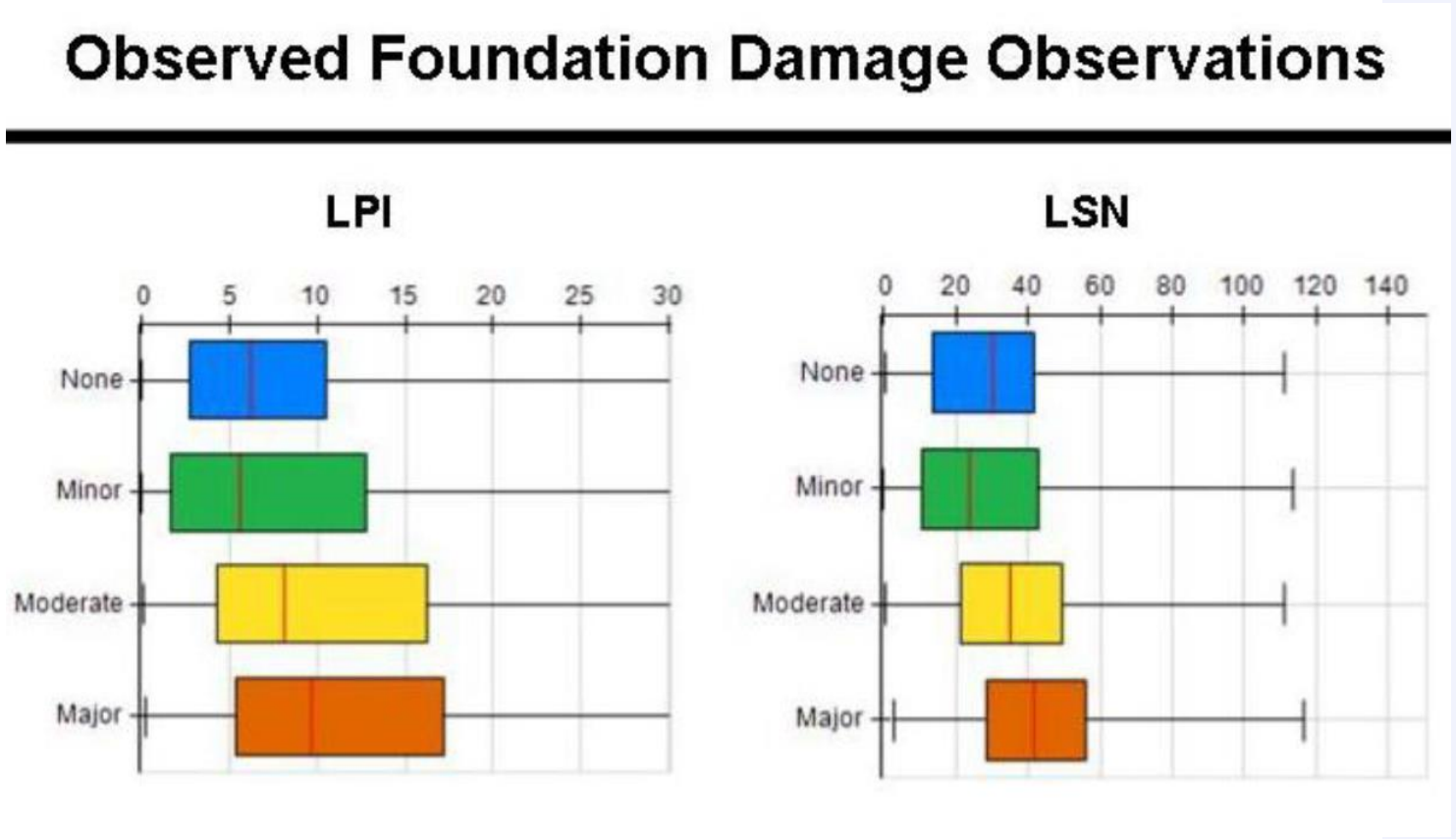
Fragility curve linking LPI_{ish} to surface manifestation of liquefaction



(Data from Maurer et al 2017)

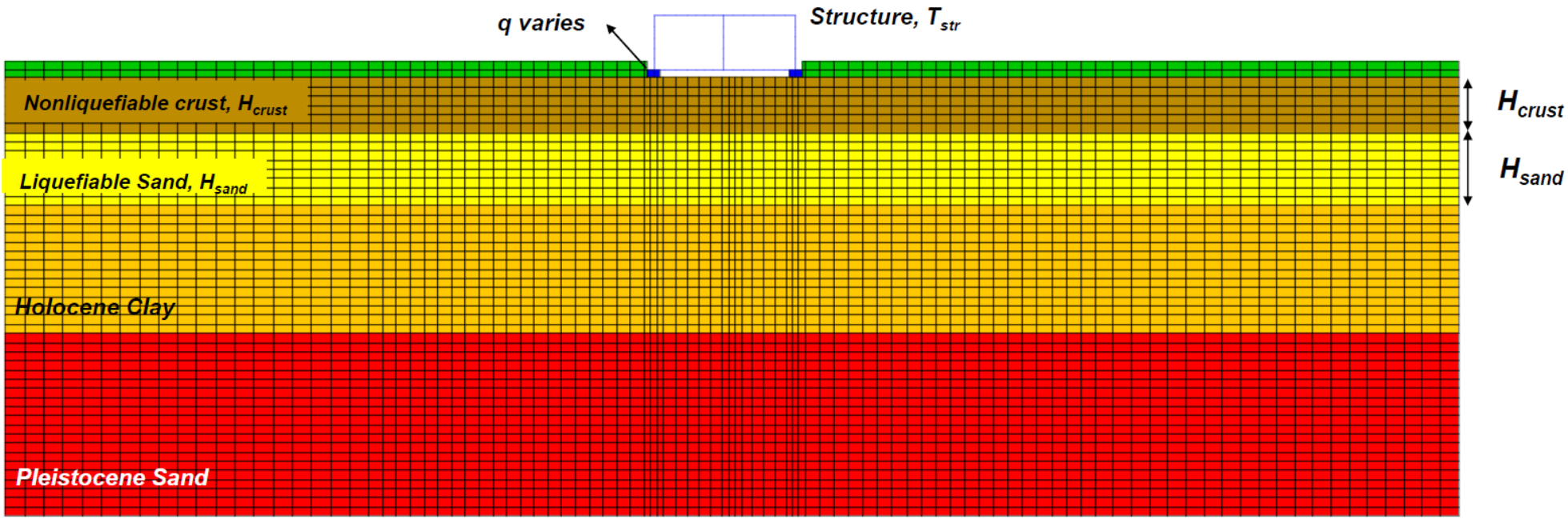
Link LPI to building damage

- Investigated by Tonkin+Taylor (2012) using database CES (Canterbury Earthquake Sequence, Christchurch 2010/2011)
- Relating building damage to LPI and LSN
- General trend is that damage increases with increasing LPI
- however: weak correlation
- Not such an investigation available using LPI_{ish} as index parameter



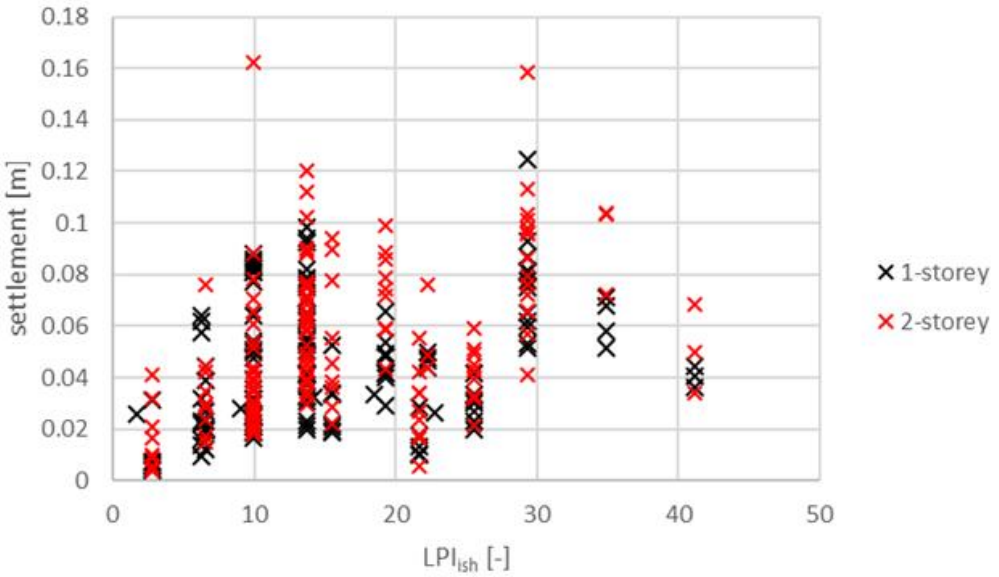
FEM calculations for NPR9998

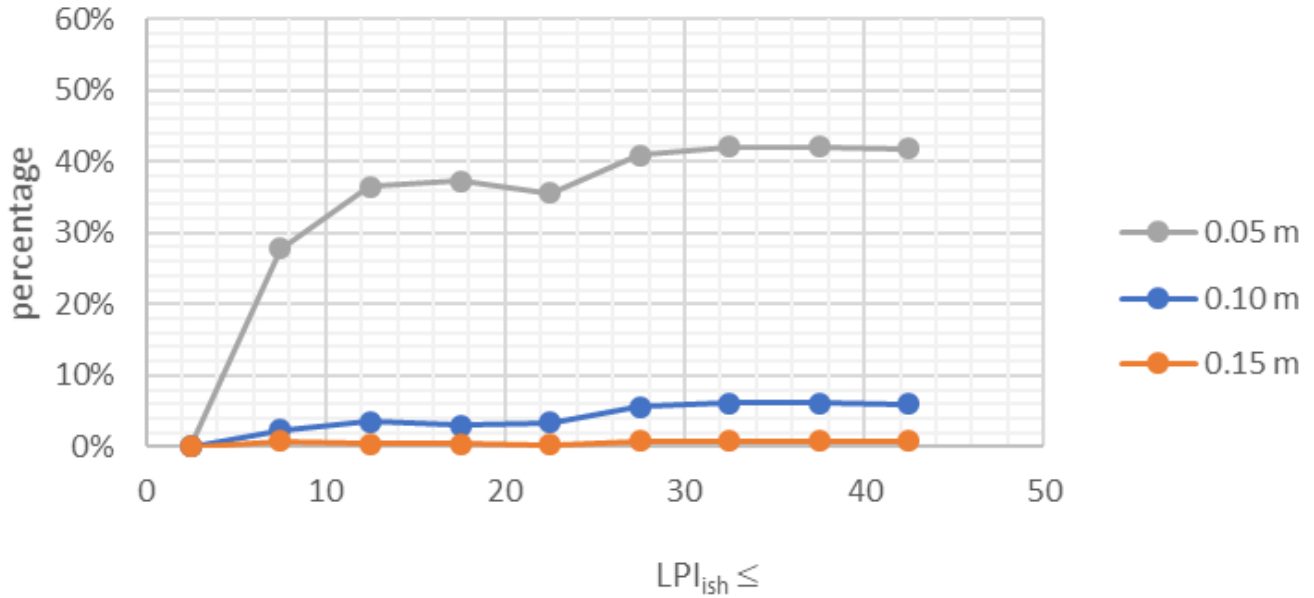
- Aim of FEM calculations was to assess foundation settlement
- Variation of subsoil conditions and input signal
- Result was an expression for assessing amount of foundation settlement (is incorporated in NPR9998)



(Fugro 2018)

Results FEM calculations for NPR9998 re-analysis



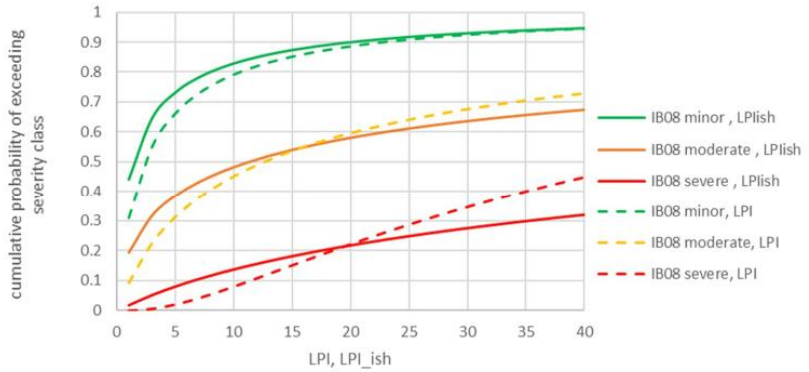


(Data from Chaloulos et al 2020)

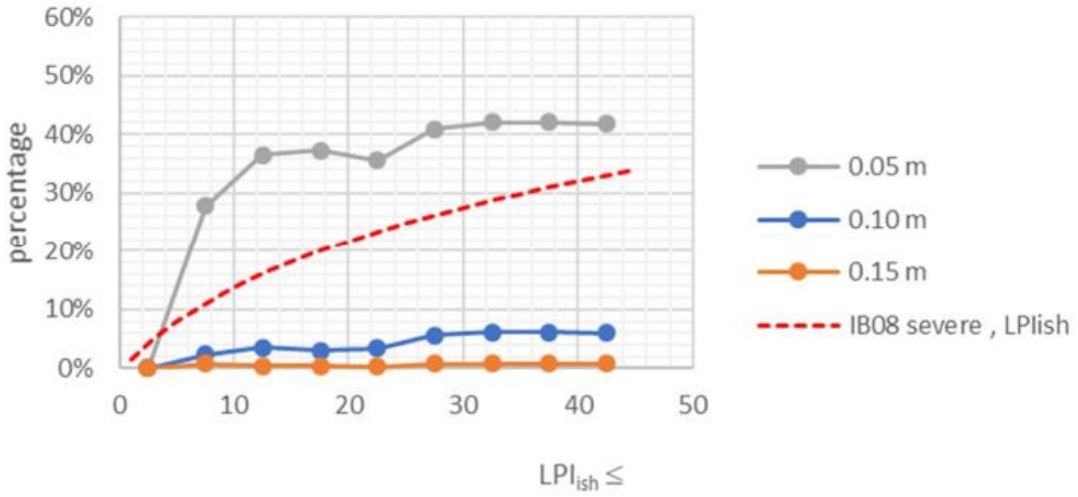
Selection threshold values for LPI_{ish} for model train

Procedure followed to select LPI_{ish} value for model train:

- Starting point are requirements in NPR9998
- Limit for **Near Collapse**: rotation 20 mm/m
  - Differential settlements 2/3 – 1 times total settlement
  - Building width: 5 m
  - This gives as limit for total settlement: 0.1 m resp. 0.15 m
  - 5% probability of exceedance
  - Result: LPI_{ish} = 25



- Limit for **building damage**
  - Use the 'standard' value: LPI_{ish} = 5



Summary of results / Answer to questions

Is there a method to link the probability of liquefaction to the risk for building damage?

What is the validity of such a link?

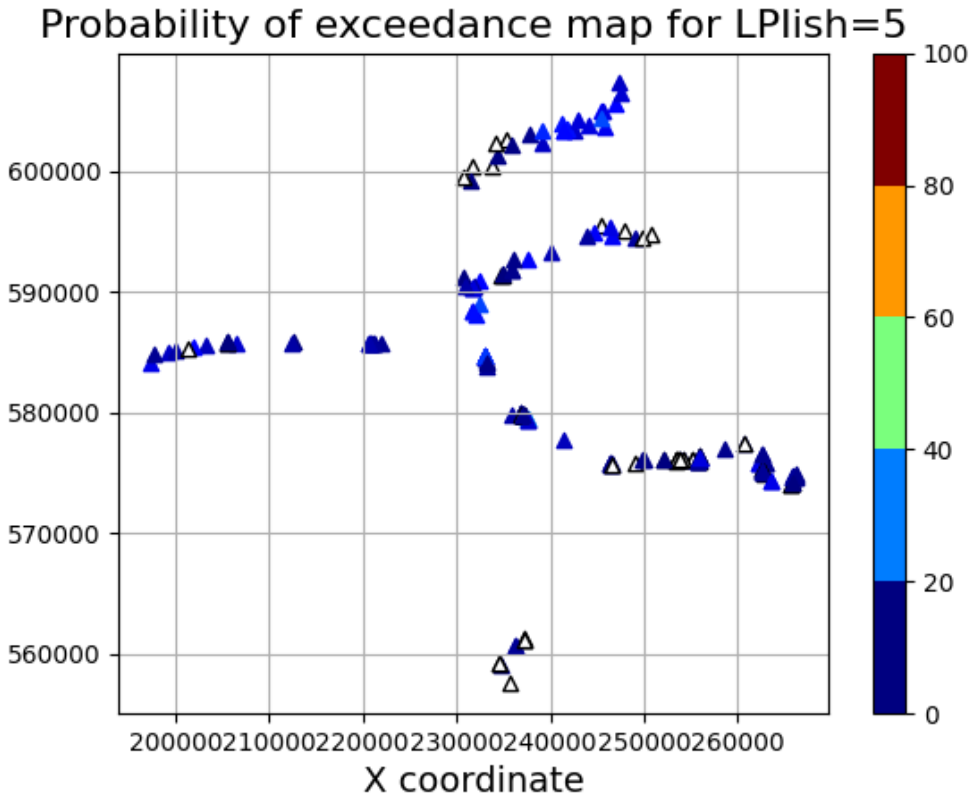
- LPI and $LPIi_{sh}$ are index parameters for surface manifestation of liquefaction
- $LPIi_{sh}$ is an extension of LPI, taking into account effect non-liquefied top layer
- Correlation LPI and building damage is poor
- No other index parameters give better correlation

- Indicative values can be given for use LPI_{ish} as damage indicator
- A more refined approach is recommended

Future work

- Recommendation
  - Develop a full probabilistic approach
  - Taking into account probabilistic approach for liquefaction ánd for buildings

- Work started at Deltares as part of the TURNKEY project (work in progress)



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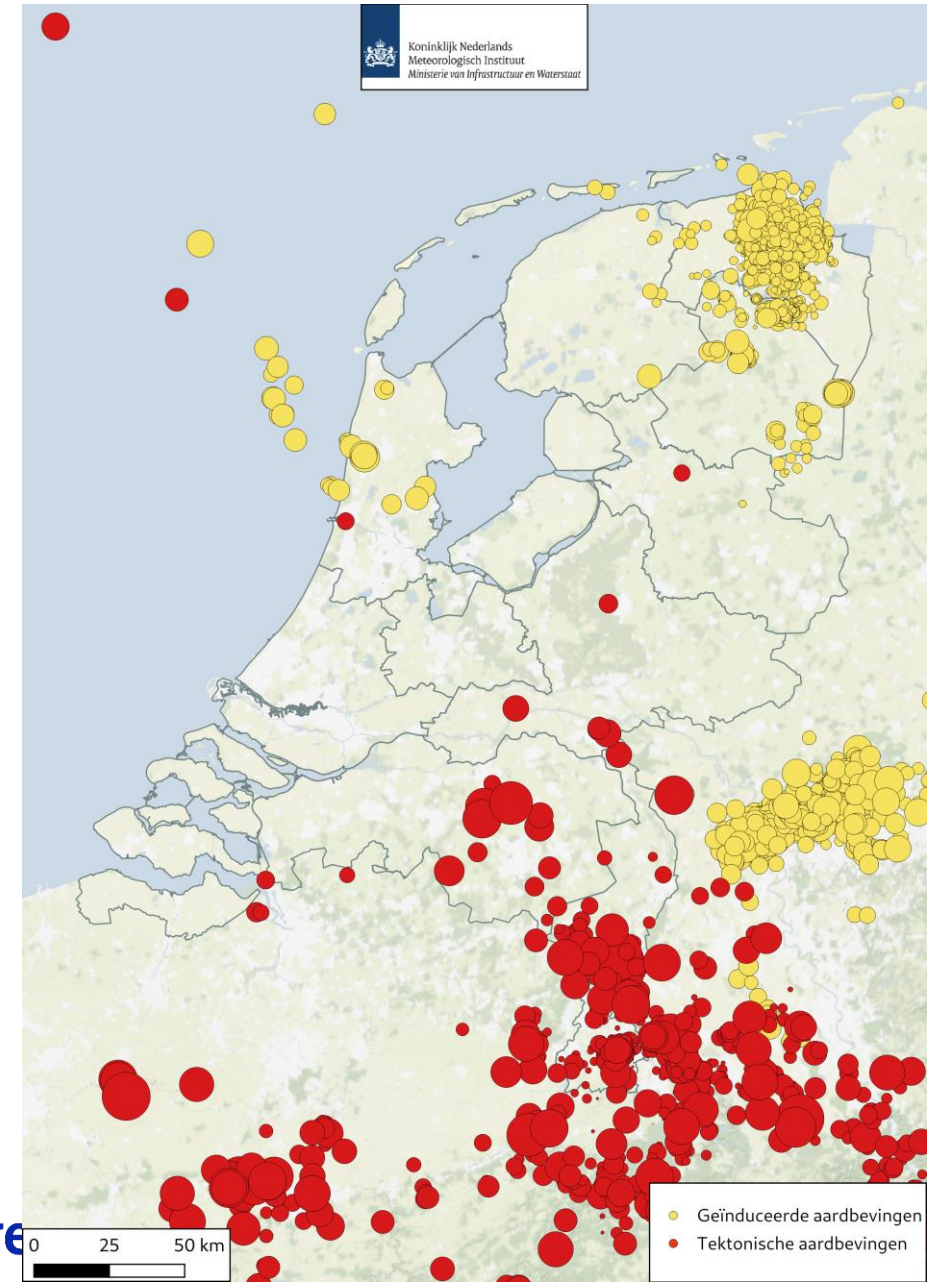
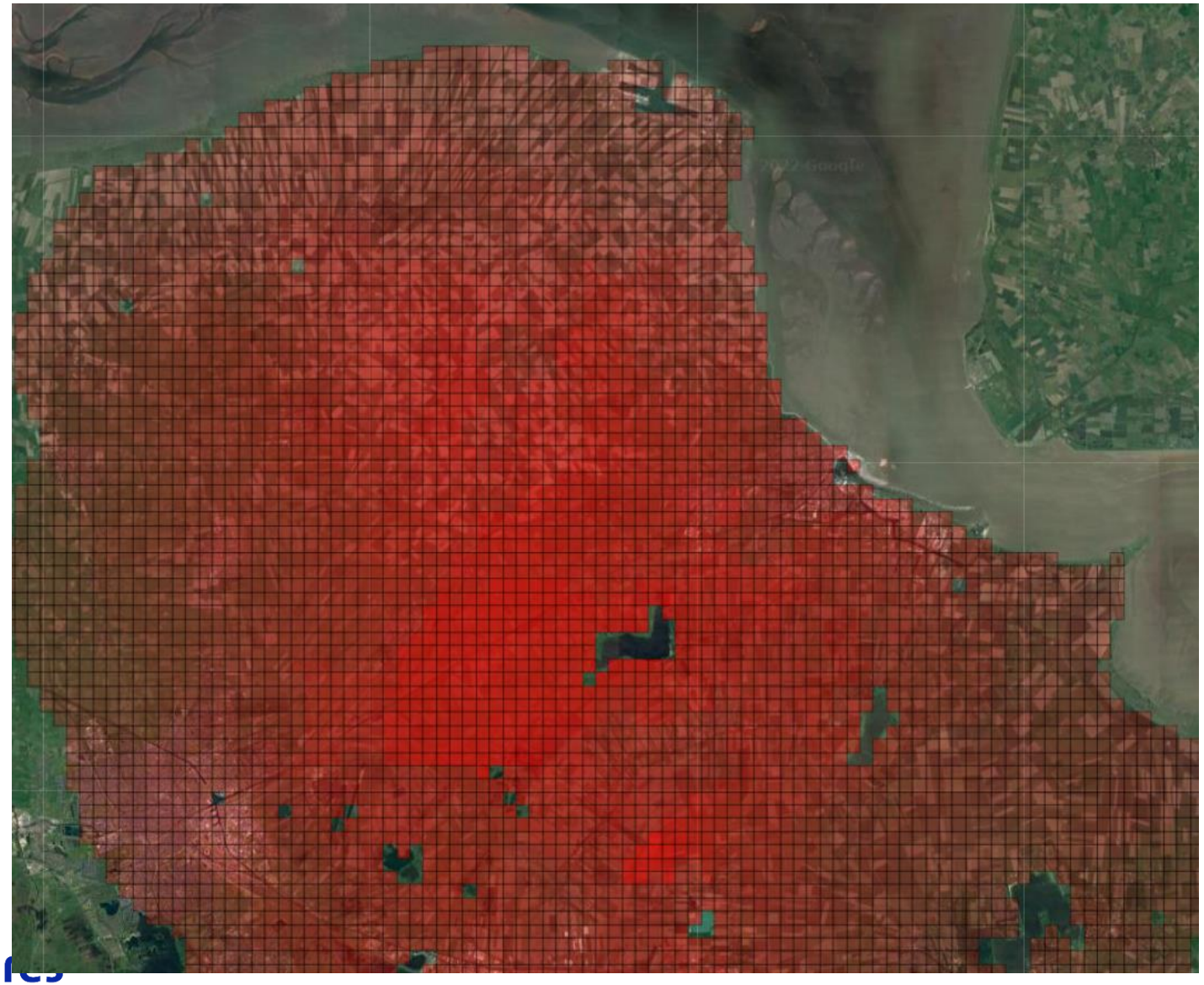


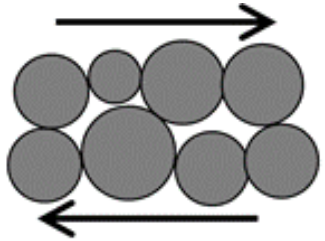
https://cdn.knmi.nl/knmi/map/page/additional/seismologie_aardbevingen_1911_2020_knmi_staand.png

Design PGA, V6, period T4, 2475 year return period



PGA_max = 0.25g
Design value decreasing with time
Max. PGA recorded is about 0.1g

I



Shear deformation of grain matrix

II

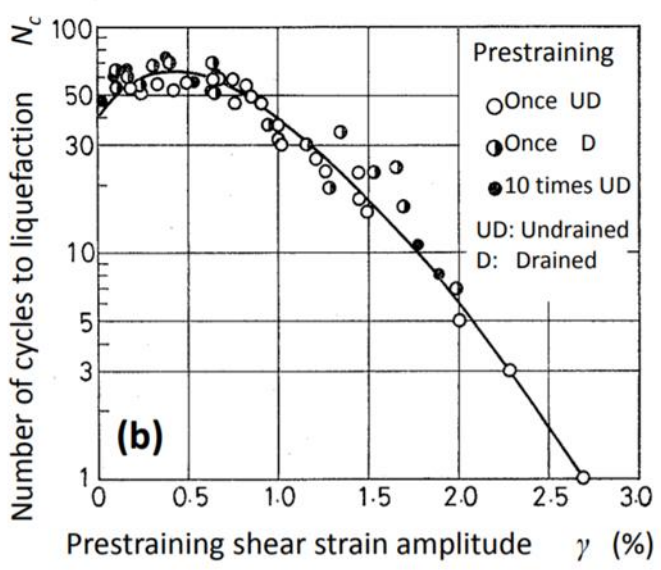
Grains want to move, pore water needs to move
→ water overpressure

III

When water has been drained, the grains are closer to each other → compaction

Sand: liquefaction (effect pre-shearing)

Results CTX tests,
with pre-shearing



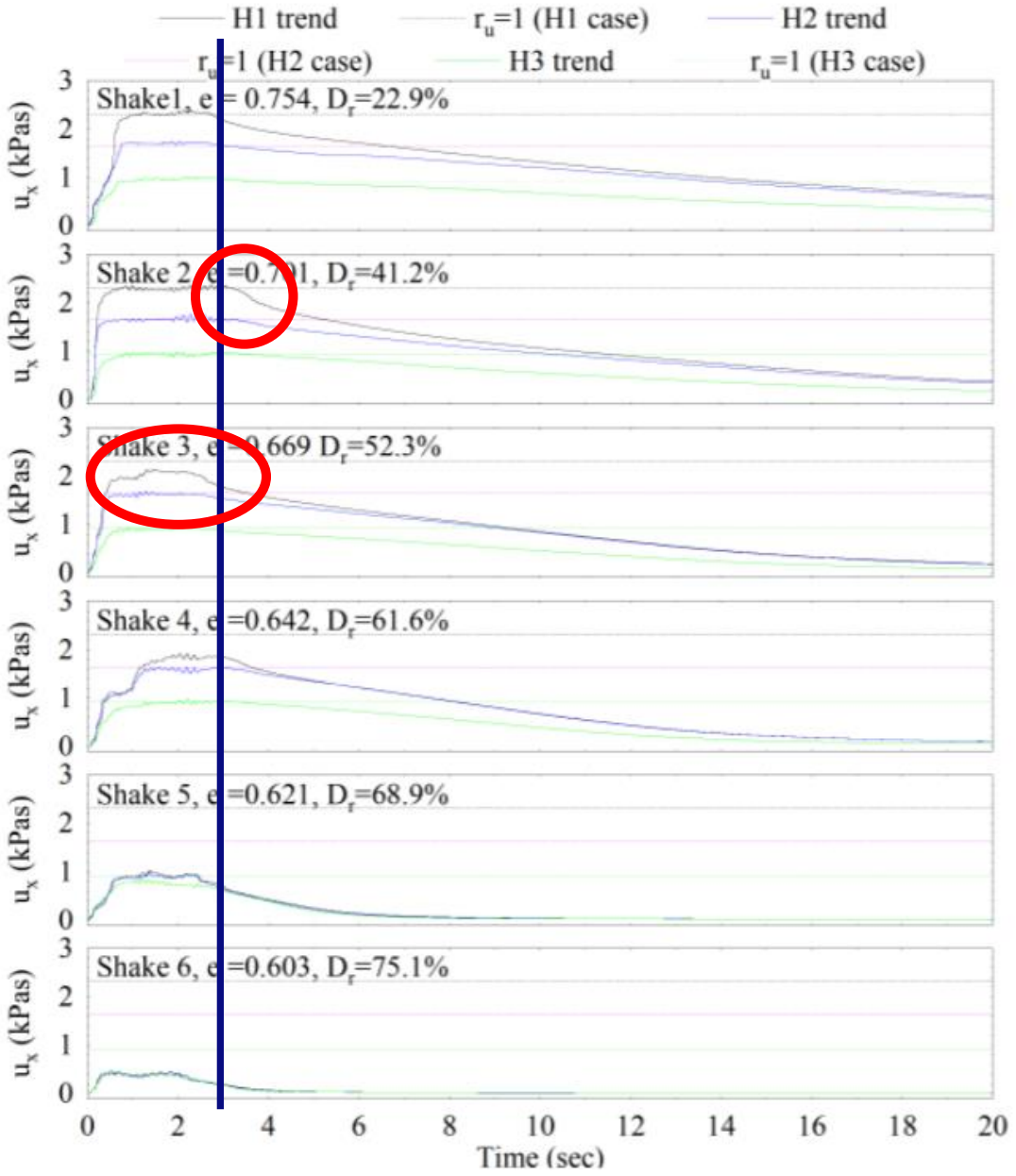
(Suzuki, Toki 1984)

Small pre-shear: positive
Large pre-shear: detrimental

Results shaking table tests, with several events

event 2: longer duration period full liquefaction

event 3, 4, 5, 6: decrease amount of liquefaction, both amount and duration



(Nepal et al 2020)

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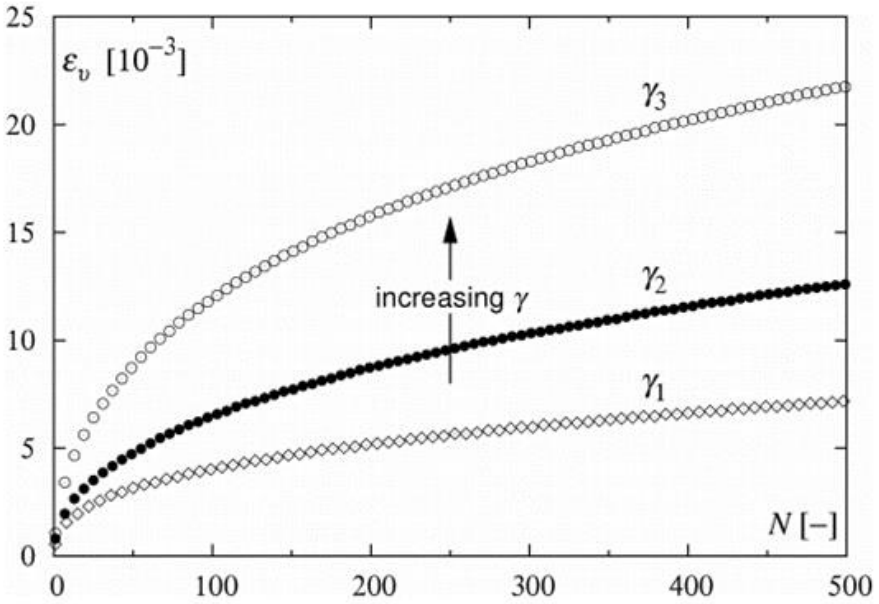
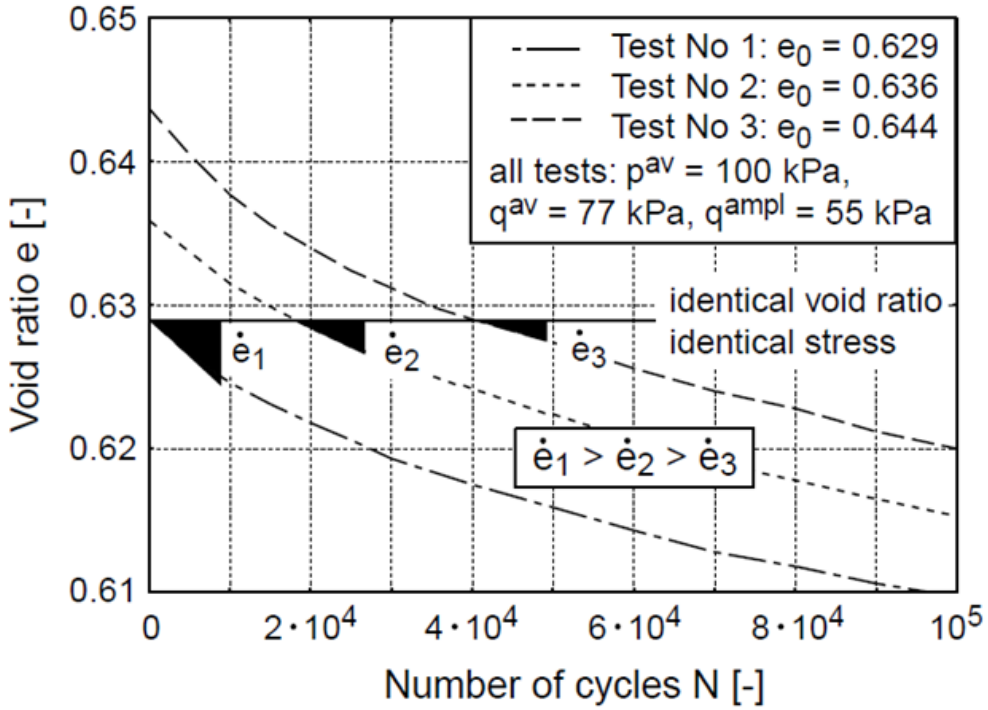
Sand: cumulative densification



(Sawicki et al 2014)



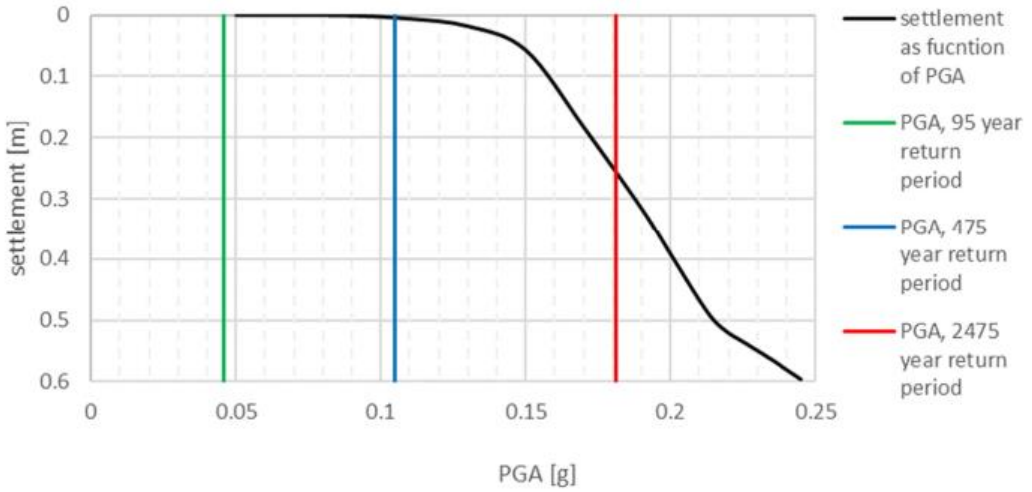
(Wichtmann et al 2005)

Rate of densification dereases with increasing number of cycles

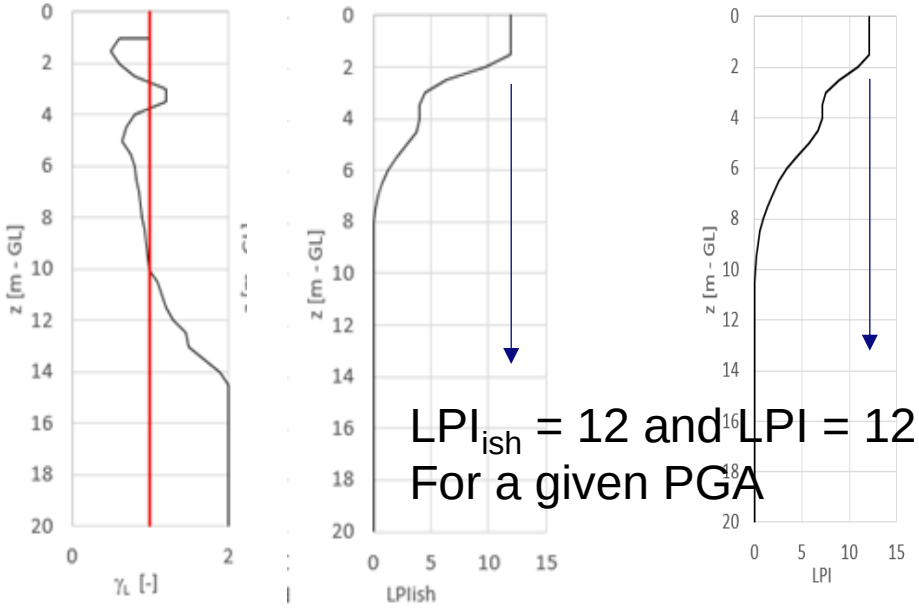
Example for Zandeweer

Liquefaction potential for every depth upto 20 m below surface

Fee field settlement based on sum of strain over depth



LPI/LP_{lish}: weighted function of sum of liquefaction potential



LPI_{ish} = 12 and LPI = 12
For a given PGA

Peat

- Less published data
- Same mechanisms as for clay

Summary

- No field data on cumulative settlement known
- From basic soil behaviour
  - Sand: possible cumulative settlements, decreasing rate of settlement
  - Clay/peat: minor loss of strength, regain of strength between earthquakes
- Model tests
  - On sand: confirm basic soil behaviour
  - On clay: no data

Answers to questions (KEM 5a)

- What effects on near surface sediment settlement can be expected due to repetitive earthquake tremors?
  - In sand: cumulative settlement; in clay: no or only minor loss of strength
- Can the effect of repetitive earthquakes tremors cause damage to buildings (in relation to the specific situation in the Netherlands)?
  - Depends on amount of settlement during present earthquakes
- If so, can the effect of repetitive earthquakes tremors be tested and quantified?
  - can be tested with cyclic tests on soil samples or geo-centrifuge tests

    recommendation: assess shear strain amplitude due to present day earthquakes

    option: install extenso meters
- Can the effects of repetitive earthquake tremors be disentangled form other comparable processes common in soft soils in the Netherlands?
  - depends on amount of settlement during earthquakes to date

    for sand: possible as a ‘jump’ in settlement

    for clay:

    bearing capacity: possible as a ‘jump’

    for settlement: uncertain

Severity of liquefaction

(Maurer et al 2015)

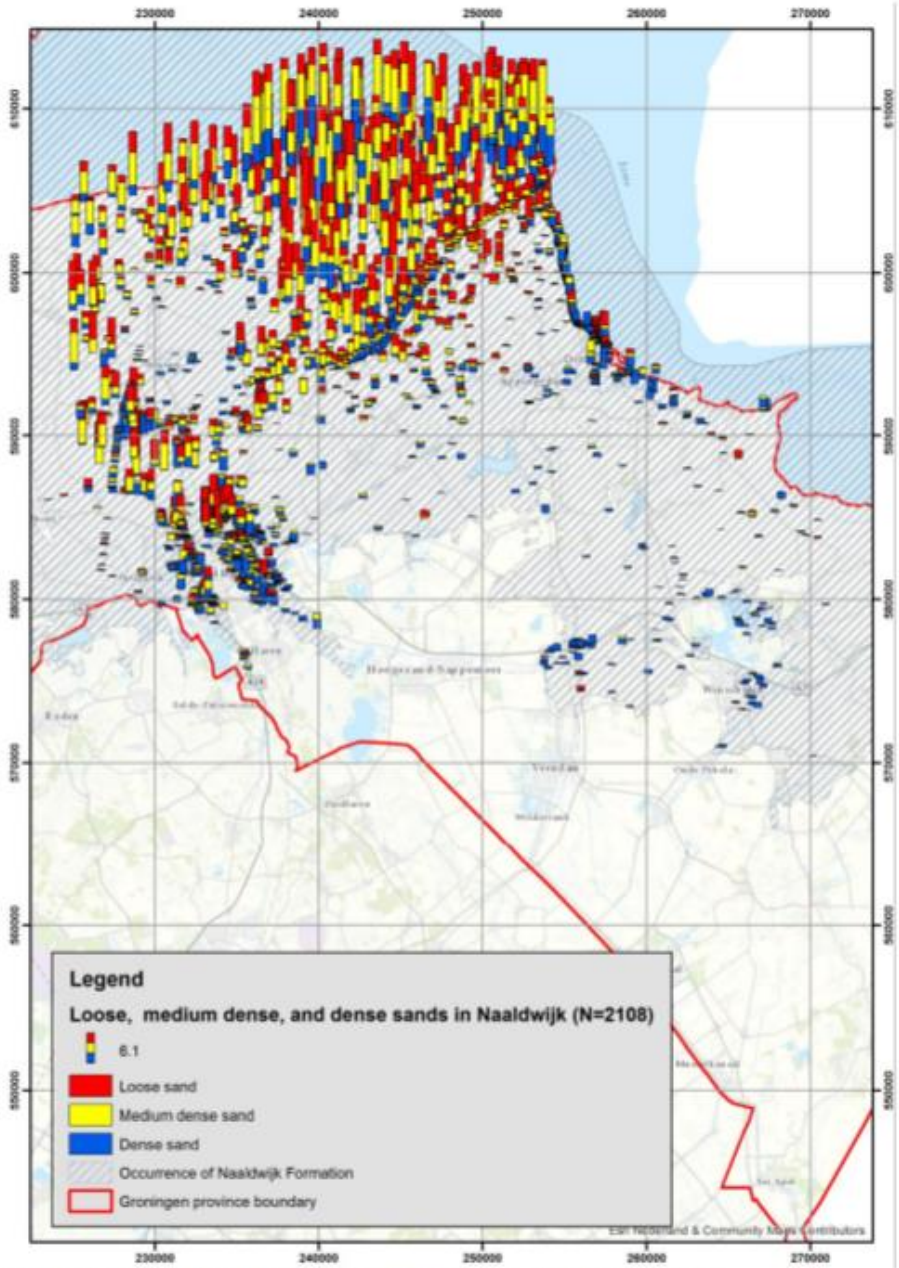
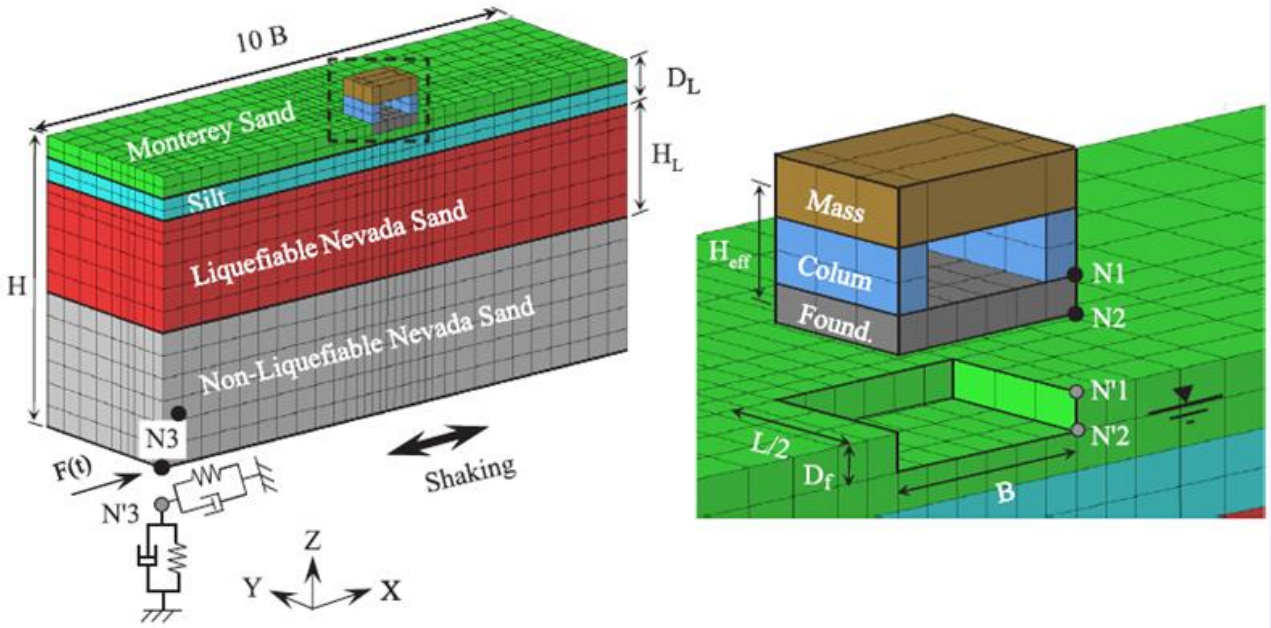


Figure 6.7 Distribution of loose, medium dense and dense sand in CPts in the Naaldwijk unit

Deltares report 1209862-005-GEO-0008-v3, 27 October 2016, final
Available at
https://www.nam.nl/feiten-en-cijfers/onderzoeksrapporten

Integrated modelling

- SSI modelling
  - Complex calculations
  - No known studies with both building and subsoil modelled in detail
  - In literature: simplified building, mat foundation



- Groningen specific calculations
  - 2D calculation
  - Aimed at obtaining foundation settlement
  - Damage state from (differential) settlement