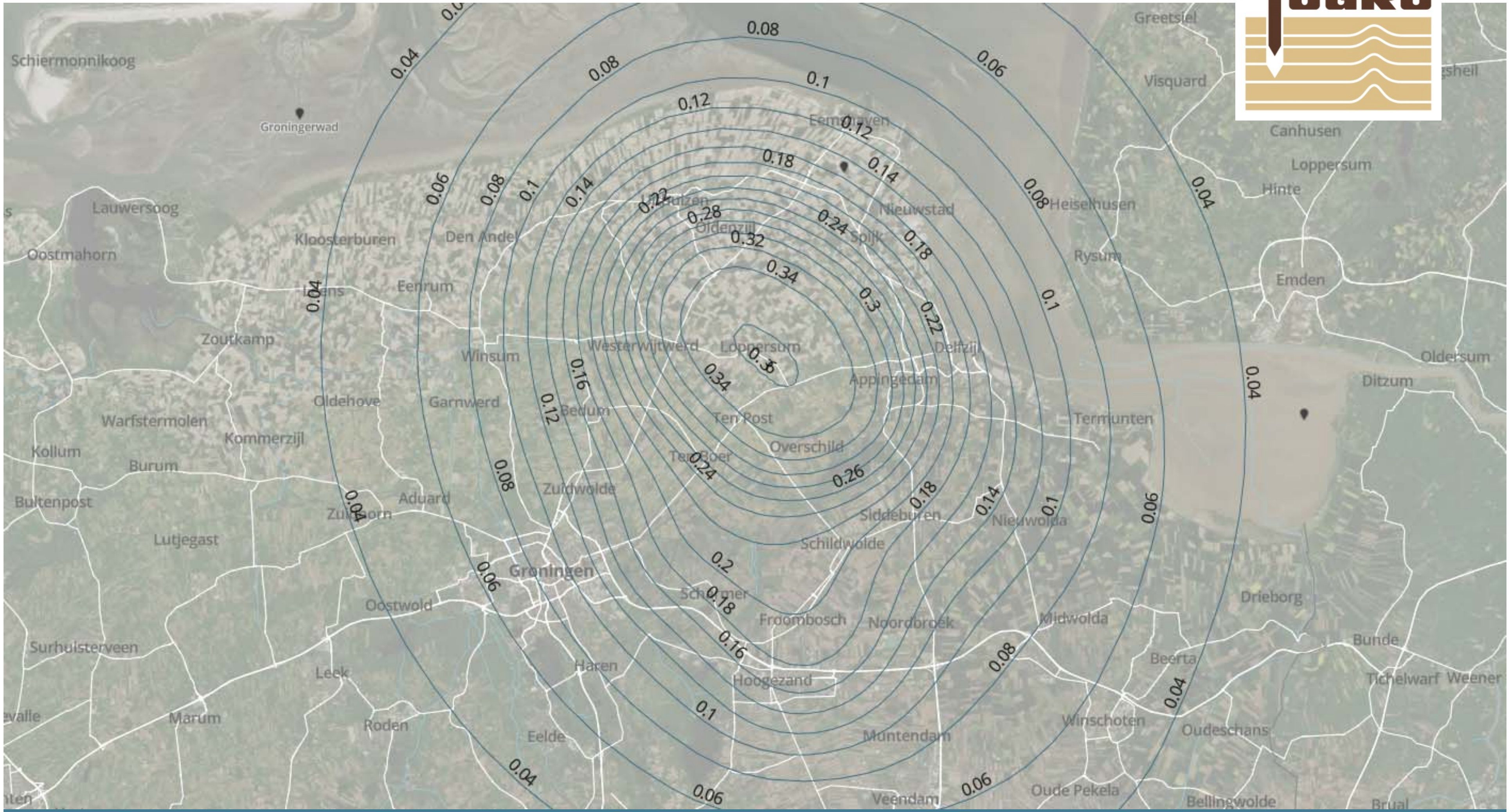


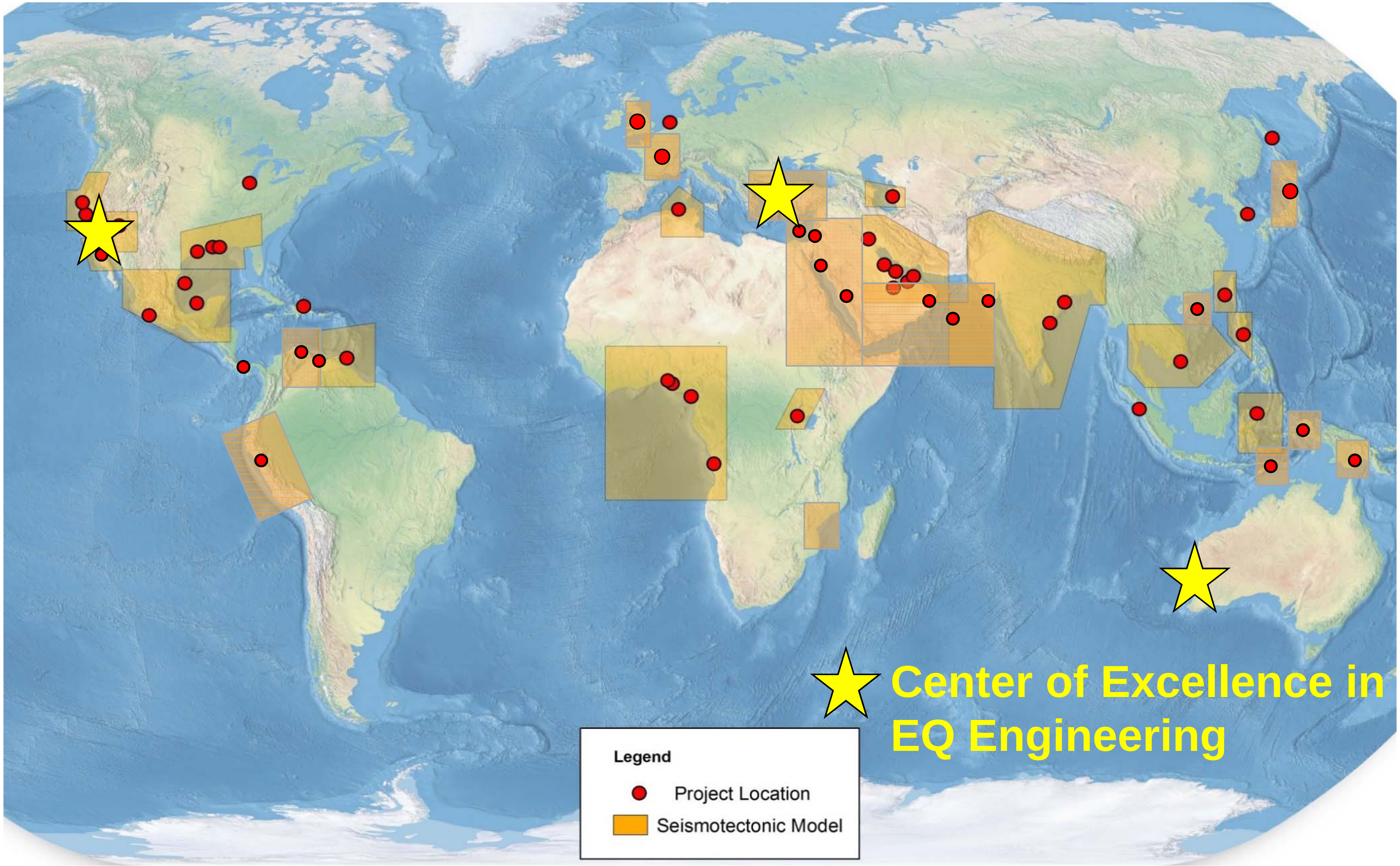
# Verhouding NPR9998 tot internationale praktijk

Klaas Siderius en Ben van der Kwaak

# Inhoud

- Introductie Fugro Earthquake Engineering Group
- Ontwikkeling van de NPR
- Vergelijking NPR
- Voorbeelden van berekeningen uit de praktijk

# Fugro Earthquake Engineering Worldwide Experience



# European Earthquake Group – Who We Are

EQ Engineering : 7 engineers (4 PhD, 3 MSc) based in Turkey and Greece

Geohazards : 12 seismologists and geologists (10 PhD, 2 MSc) based in France and Turkey

EQ group world (geotechnical) ca. 25 PhD and 15 MSc

Onderscheidende eigenschappen

- Entire Spectrum of Earthquake Services
- Highly Specialized Earthquake Group
- Cutting Edge Dynamic Numerical Modeling Capabilities

# Geotechnical Earthquake Engineering Services

- Site Characterization
  - Geotechnical, Geophysical Data Integration
  - GIS Based Site Characterization
- Development of Design Ground Motions
  - Seismic Source Modeling
  - Seismic Hazard Analyses (Probabilistic and Deterministic)
  - Development of design spectra and ground motions
  - Site Response Analyses
- Earthquake Effects and Related Hazards
  - Liquefaction, Lateral Spreading and resulting Ground Movements
  - Seismic Slope Stability / Embankment Movements
  - Fault Displacement Hazard
- Soil-Structure Interaction Analyses (Static & Dynamic)
  - Shallow foundations (footings, mat foundations)
  - Deep foundations (Piles, drilled shafts)
  - Retaining systems, Buried structures

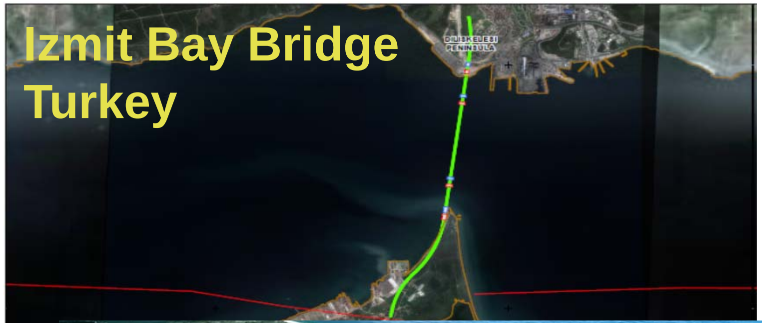
**Emphasis in Numerical Modeling**

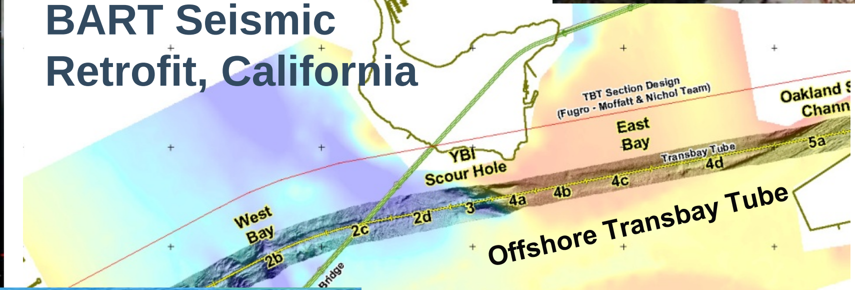
# Selected Major Infrastructure Projects


SFOBB, CA


Soyo Cabinda Bridge, Angola

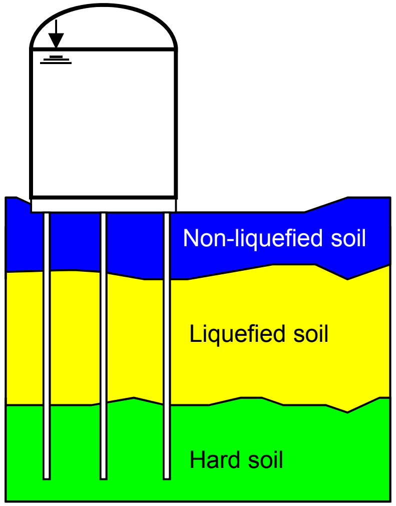

Presidio Parkway, CA


Izmit Bay Bridge
Turkey

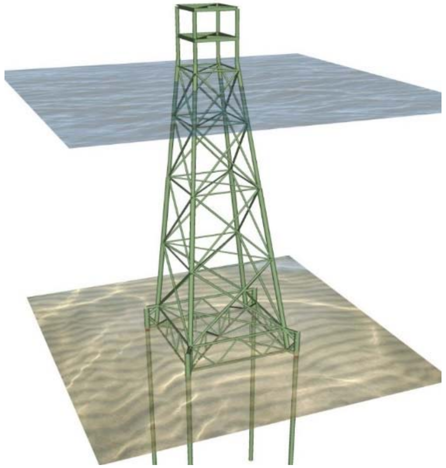

BART Seismic Retrofit, California


Istanbul New Airport
Preliminary Earthworks Design

# Selected Energy Projects

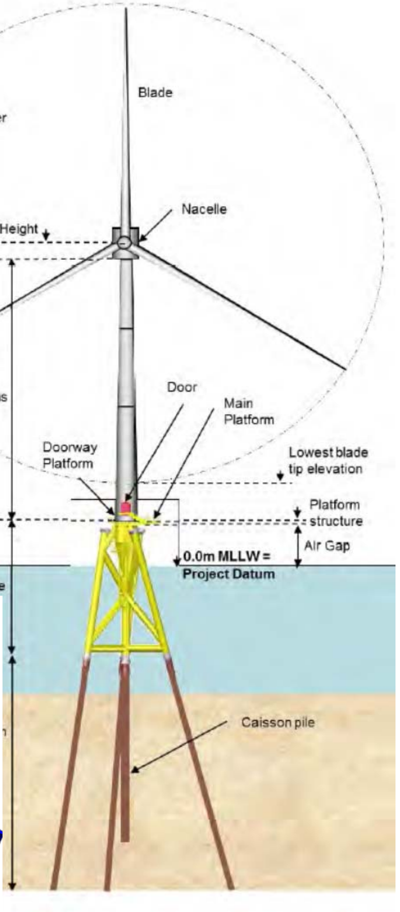


**LNG Storage Tank**
**(Wheatstone LNG, Australia)**



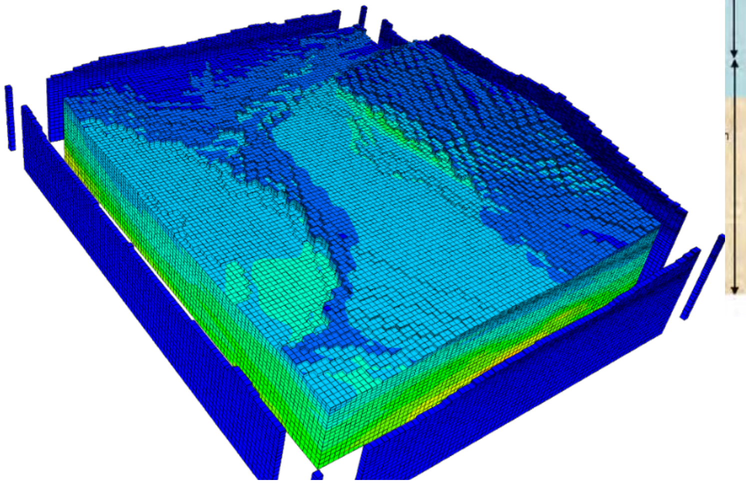
**Exploration Platform**
**(Offshore Trinidad)**

**Exploration Platform**
**(Offshore SE Asia)**



**Wind Turbine Generator**
**(Offshore Virginia)**

**Pipeline Fault Characterization Studies**
**(Turkey)**



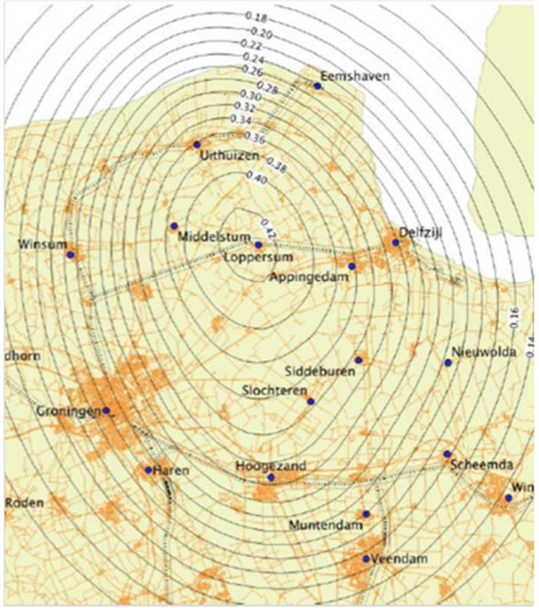
**Diablo Canyon Nuclear Power Plant**
**3-D Site Response Analyses**

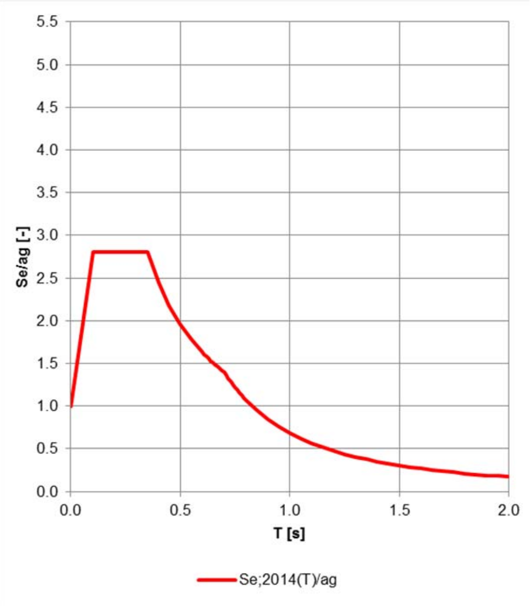
# Ontwikkeling van de NPR: Interim advies mei 2014

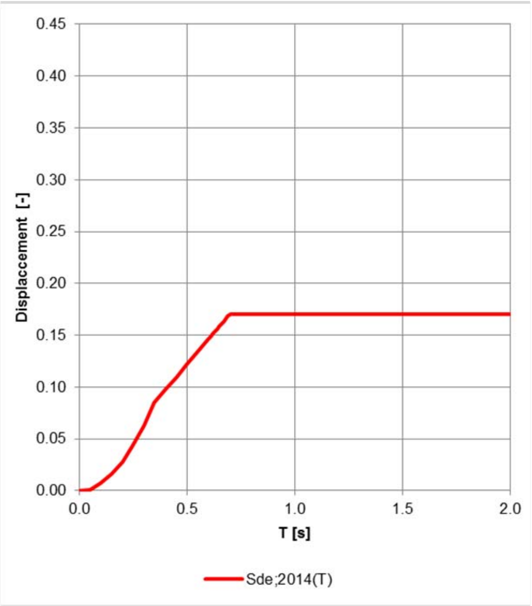
$a_{g;ref;max}$ = 0,42 [g]

| Parameter | Getalwaarde |
|---|---|
| S [-] | 1,0 |
| $T_B$ [s] | 0,10 |
| $T_C$ [s] | 0,35 |
| $T_D$ [s] | 0,70 |

$$S_{De}(T) = \frac{S_e(T)}{a_{g;ref}}\left[\frac{T}{2\pi}\right]^2$$





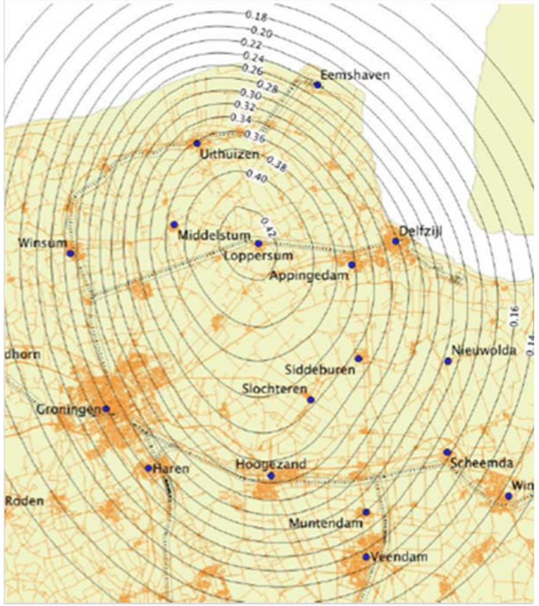


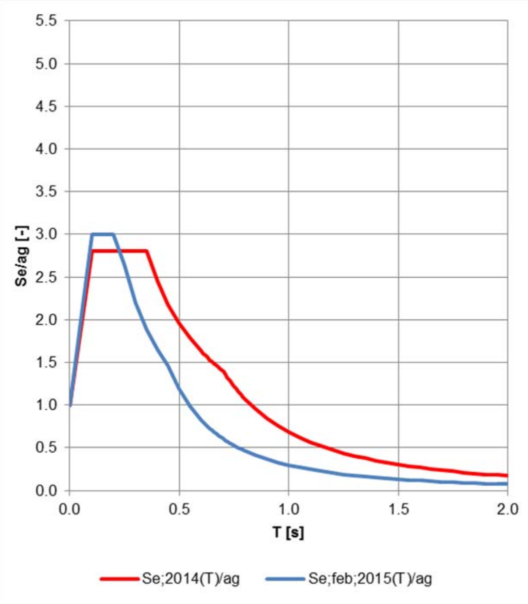
# Ontwikkeling van de NPR: Ontw. NPR 9998:2015

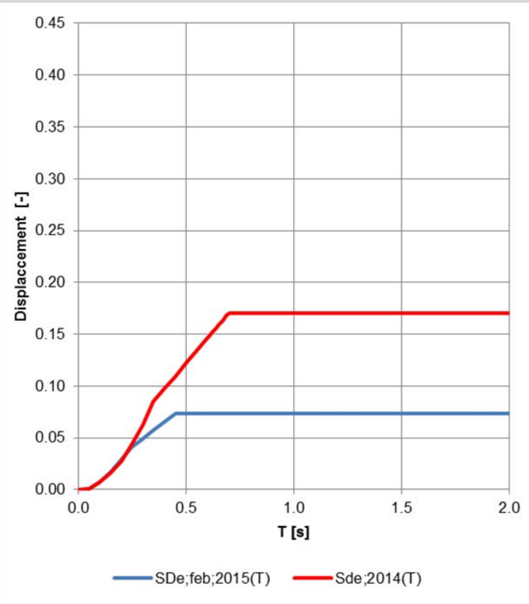
$a_{g;ref;max}$ = 0,42 [g]

| Parameter | Getalwaarde |
|---|---|
| S [-] | 1,0 |
| $T_B$ [s] | 0,10 |
| $T_C$ [s] | 0,22 |
| $T_D$ [s] | 0,45 |

$$S_{De}(T) = \frac{S_e(T)}{a_{g;ref}}\left[\frac{T}{2\pi}\right]^2$$







# Ontwikkeling van de NPR: NPR 9998:2015(dec)

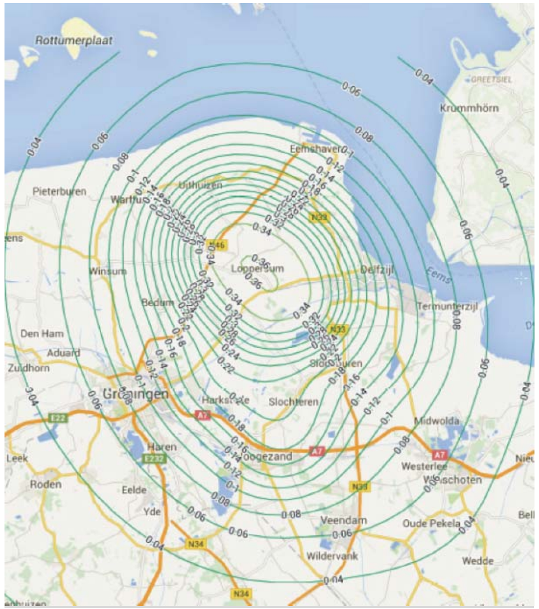
$a_{g;ref;max}$ = 0,36 [g] zonder niet-lineaire site-effecten

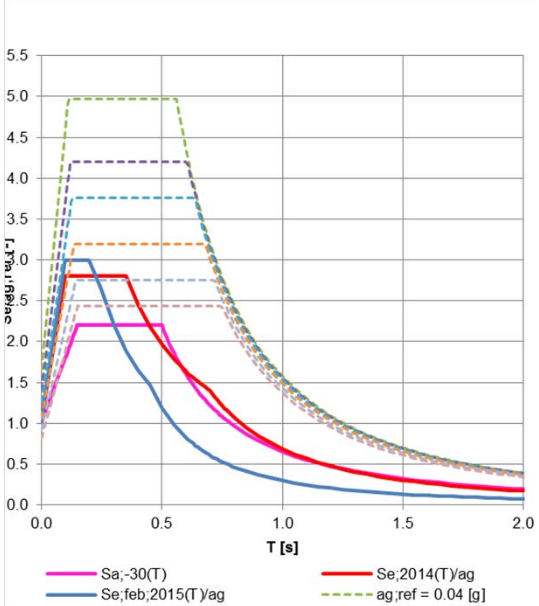
$T_B$ en $T_C$ afhankelijk van $a_{g;ref}$

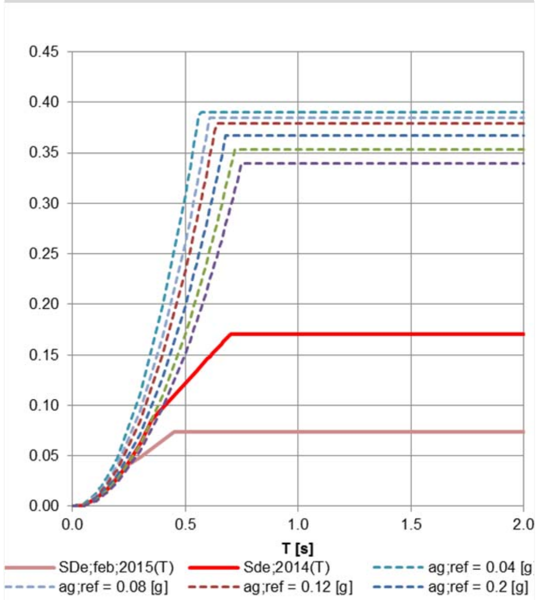
Indeling “speciaal”, “normaal”

Response spectrum op diepte gegeven in NPR

$$S_{De}(T) = \frac{S_e(T)}{a_{g;ref}}\left[\frac{T}{2\pi}\right]^2$$







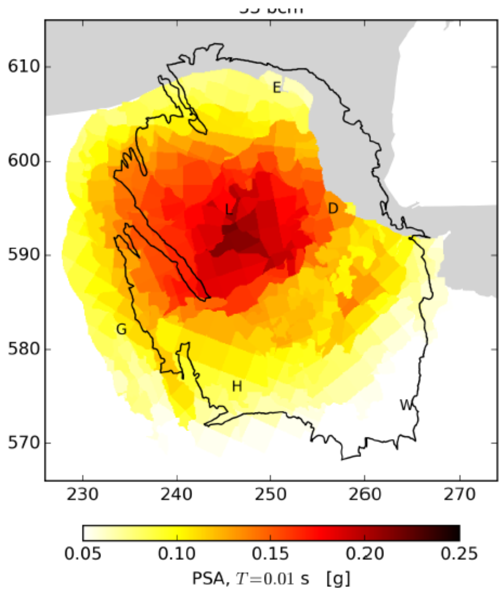
# Ontwikkeling van de NPR: NPR 9998:2016/2017 (Toekomst?)

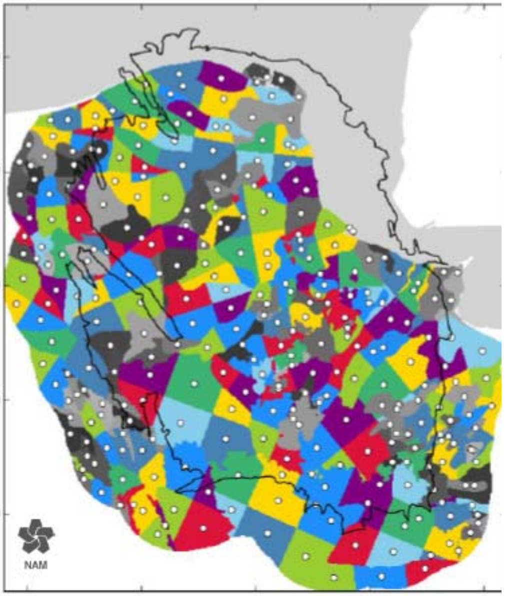
Model V2, periode 2016 – 2021 (chance of exceedance 10 % in 50 years) PGA = 0,21 [g]

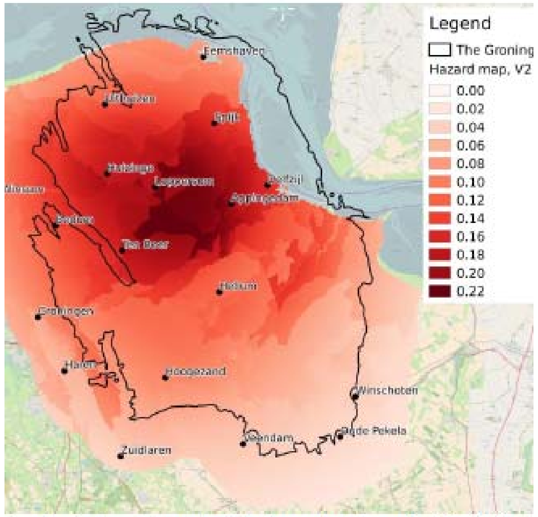
NAM PGA hazard map

KNMI PGA hazard map

Verschillend “source model” t.o.v. NAM



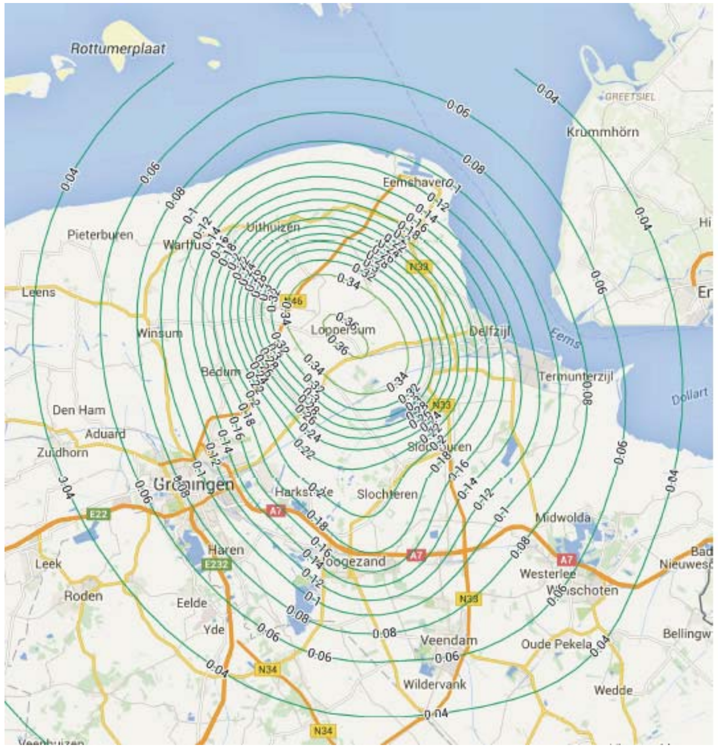


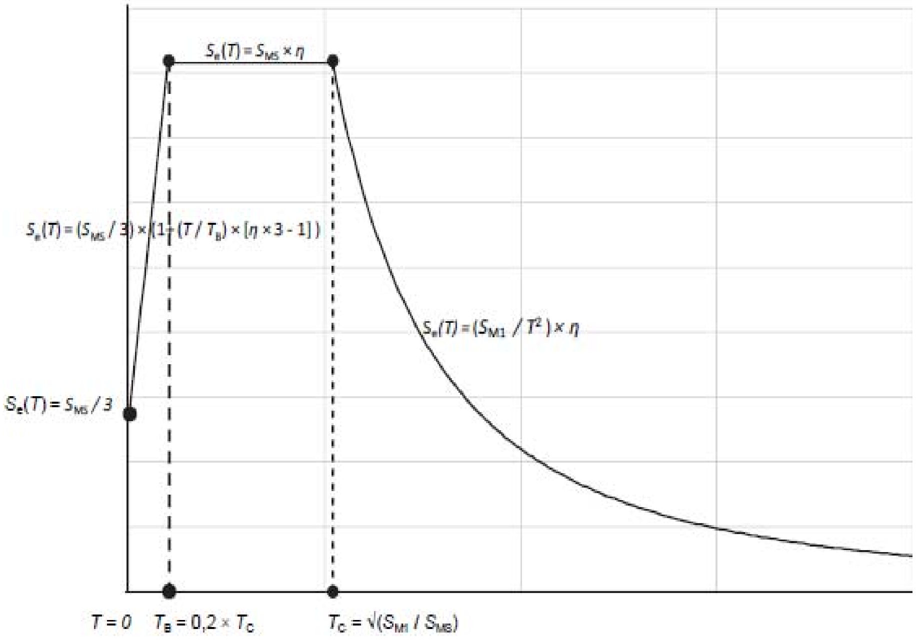


*tic seismic hazard map for Groningen for the period T = 0.01 s.*
*Eurocode 8, max PGA = 0.22 g. The black solid line indicates*

# NPR 9998:2015

- Richtlijn voor het bepalen van de seismische belasting
  - Referentie versnellingen $a_{g,ref}$ waarden op kaart
  - Horizontaal en verticaal elastisch ontwerp response spectrum aan oppervlakte
  - Uitgangspunten beschikbaar voor het uitvoeren van site response spectrum in de vorm van een response spectrum op diepte ($v_{s,30}$ = 300 m/s





# Vergelijking NPR

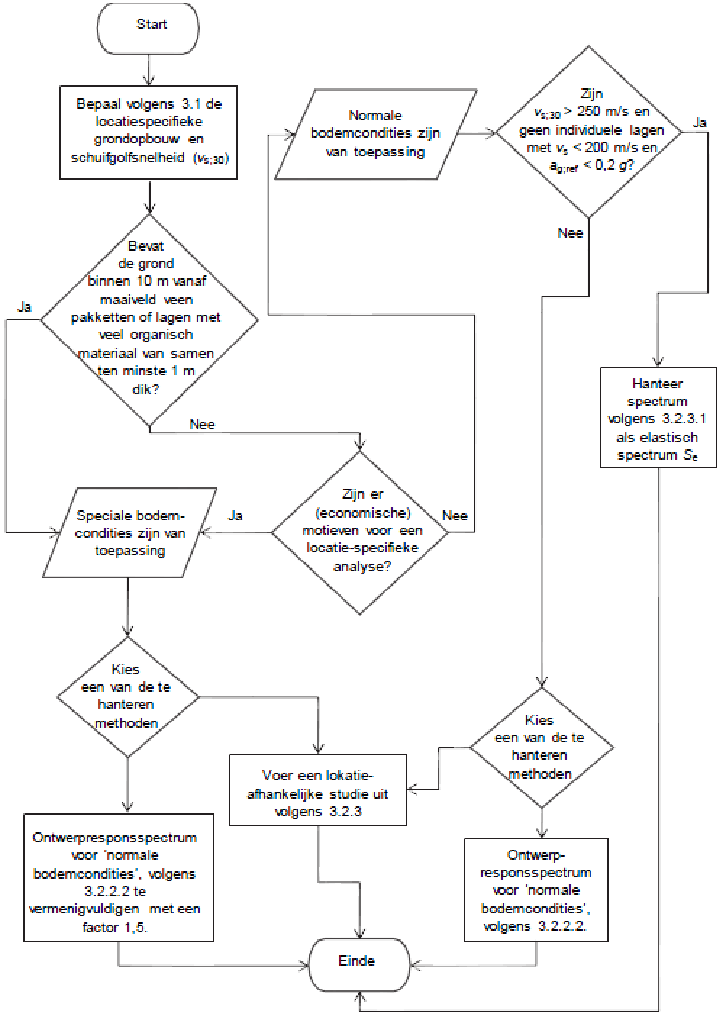
NPR indeling in 2 (of 3) verschillende bodem classificaties

- Normaal (spectrum afhankelijk van $a_{g;ref}$)
- "Speciaal" (normale spectrum x 1,5)

Speciale bodemcondities: *soils which do not satisfy "normal" soil conditions*

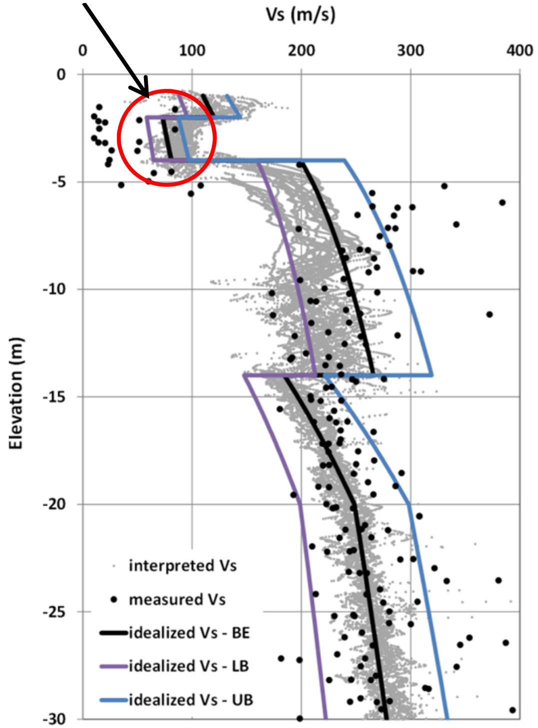
similar to EC8 site classes *E*, *$S_1$*, *$S_2$* (*special study is required*)

similar to ASCE7-10 site classes *E*, *F* (*special study is required*

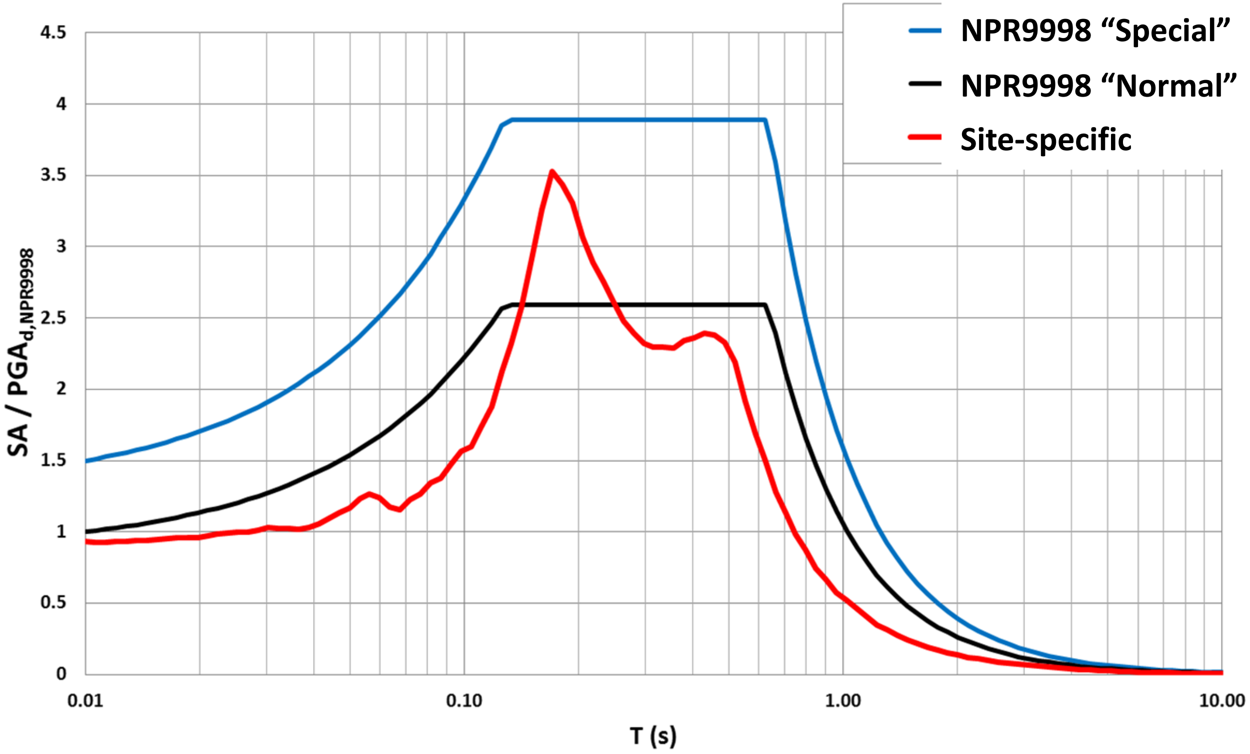


**Figuur 3.2 — Procedure voor de bepaling van een geschikt elastisch responsspectrum**

# NPR 9998:2015 – Site conditions


**peat layer**

example project site in Groningen



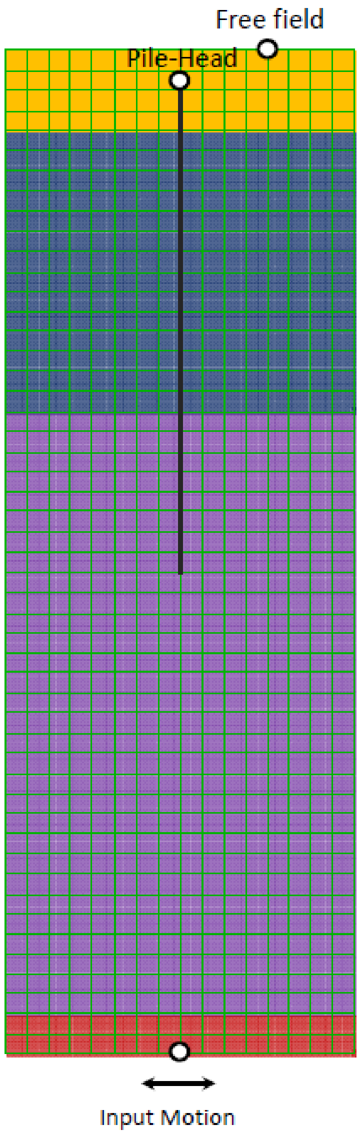
**NPR9998:** Response Spectrum $_{\text{special}}$ = **1.5** x Response Spectrum $_{\text{normal}}$

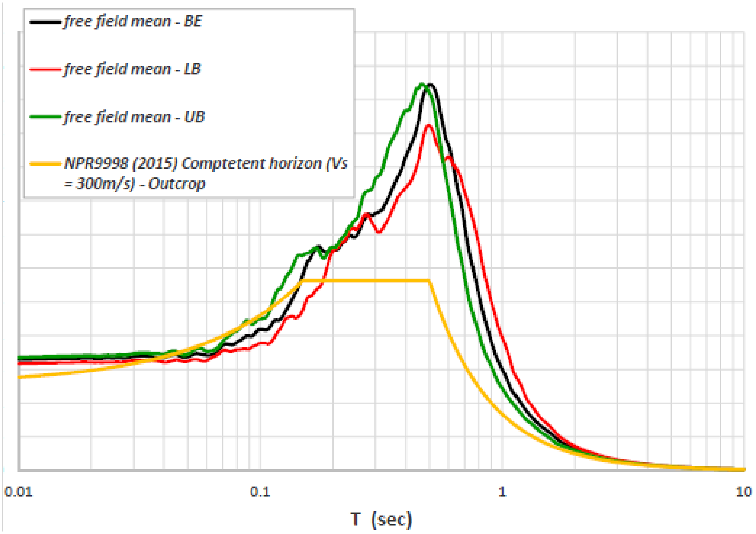
**application of 1.5 factor may be very conservative**

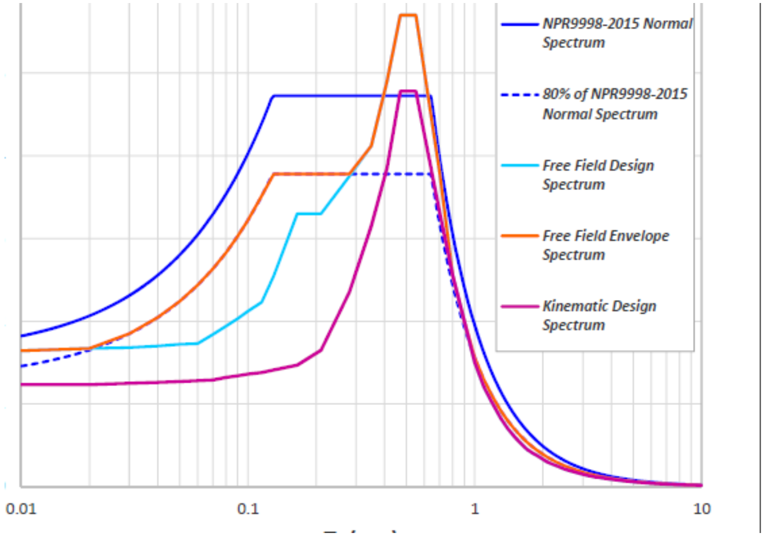
# Site Response Analyse

Total stress analysis free-field

Kinematic total stress analysis







# Samenvatting – Site Response Analyses

- Locatie specifieke analyse zou moeten worden uitgevoerd voor speciale bodem condities

- Spectra uit de norm / richtlijn kunnen (te) conservatief zijn

- Locatie specifieke analyses moeten worden overwogen bij
  - Belangrijke projecten
  - Wanneer optimalisaties voordelen opleveren

- De geschikte site response techniek dient te worden geselecteerd gebaseerd op
  - Bodemcondities
  - Geometrie
  - Grootte van de belasting

# Liquefaction Triggering Evaluation

- Stress approach → “Capacity” vs. “Demand”

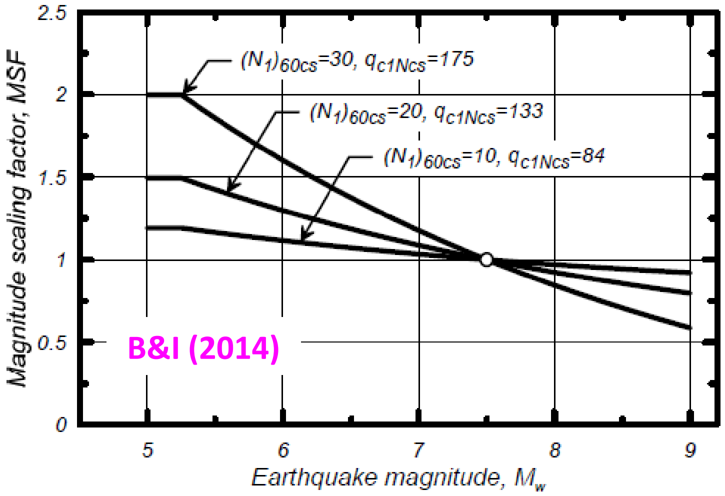
- Factor of Safety
  - FS = Resistance / Loading (Demand)

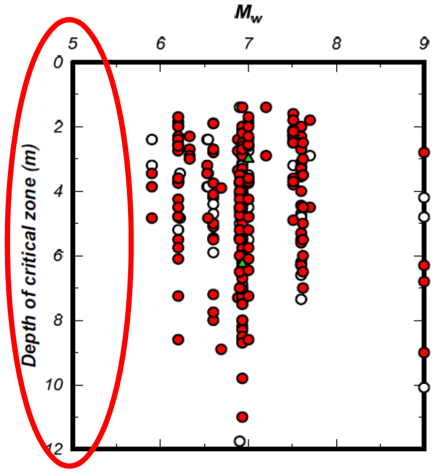
- Loading → Cyclic Stress Ratio (CSR)
  - Stress induced by earthquake ground motions
  - Obtained from simplified approaches
  - or from site-specific response analyses

- Resistance → Cyclic Resistance Ratio (CRR)
  - Stress required to trigger liquefaction
  - Determined based on analysis of case histories
  - Determined as a function of in-situ indices (e.g., CPT, SPT, Vs)
  - Also obtained from laboratory tests (site- or soil-specific)

# NPR 9998:2015 – Liquefaction triggering

- NPR9998 Guidelines:
  - very prescriptive
  - based on *Idriss & Boulanger (2008)* methodology
  - Magnitude Scaling Factor (MSF): function of $M_w$ and extrapolated to $M_w$=5
  - $MSF_{NPR} \neq MSF_{EC8}$
  - ageing effects not considered
- Other codes [EC8, ASCE7-10]:
  - less prescriptive
  - any well-established method may be used
  - Boulanger & Idriss (2014) MSF: function of $M_w$ **and** soil density ($D_r$, $q_c$)



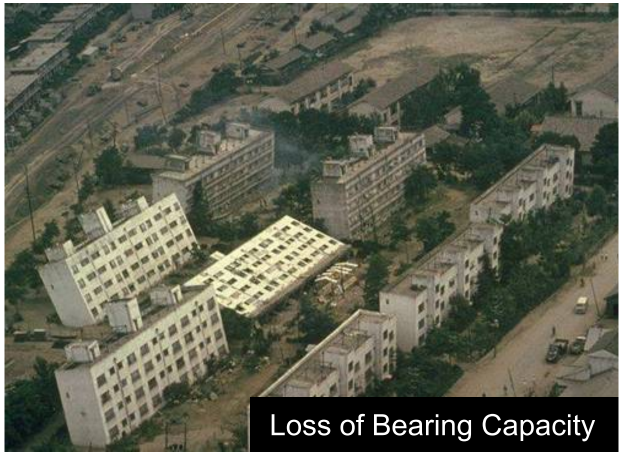


min $M_w$ of dataset: 5.8

# Observed Consequences of Liquefaction

- Loss of bearing support
- Settlements
- Loss of lateral support
- Uplift of buried structures
- Increased lateral pressures against retaining structures
- Slope Failure or Lateral spreading
- Lateral flows

Settlement / Tilting



Loss of Bearing Capacity

Lateral Spreading

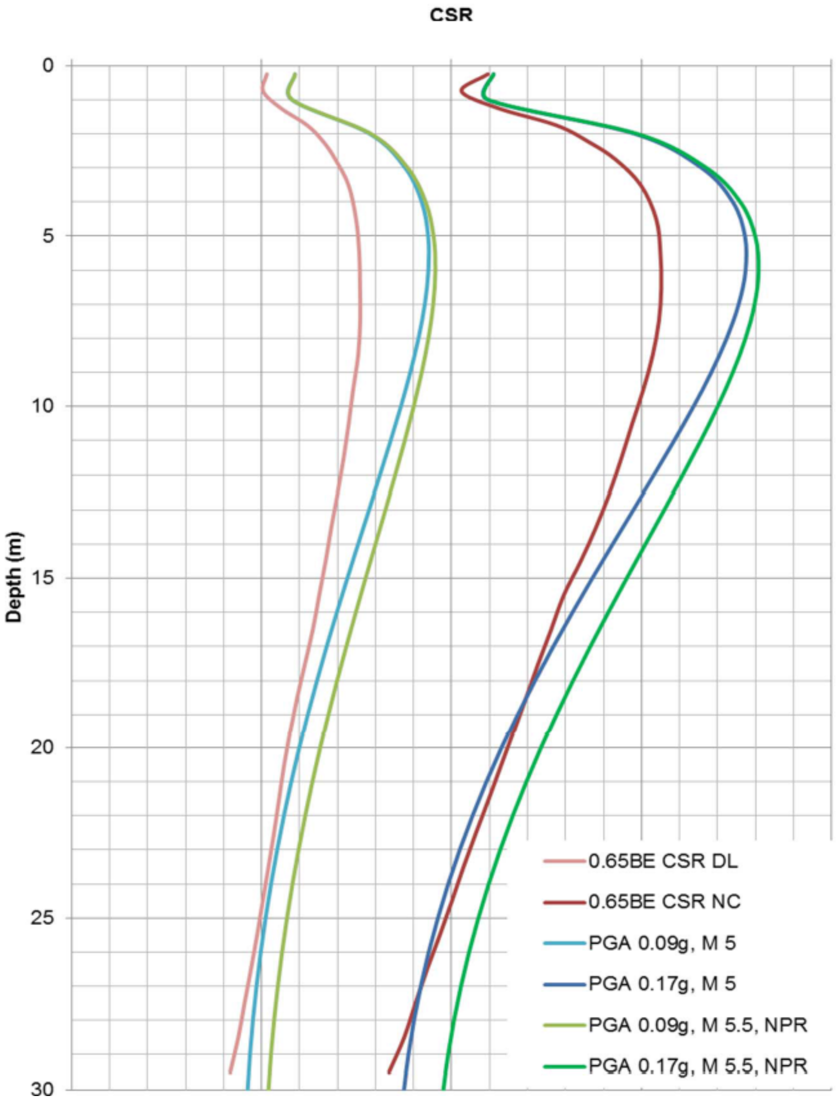
# NPR 9998:2015 – Liquefaction consequences

- NPR9998 Guidelines:
  - based on empirical correlations, some of them outdated
  - shear and volumetric strains according to *Yoshimine et al. (2006)*
  - pore water excess pressures provided as a function of FS ($\gamma_L$) [Marcuson et al., 1990]
    - may be overly conservative (based on reconstituted sample testing – no ageing considered)
  - residual strength due to liquefaction:
    - use of drained strength parameters (overly conservative)
- International Practice:
  - pore water excess pressures
    - advanced numerical nonlinear effective stress analysis (combined with sound engineering judgment is the most reliable path forward to evaluate the foundation/building performance)
  - residual strength due to liquefaction:
    - use of undrained strength parameters
    - even liquefied soils exhibit some residual strength

# CSR from Site Response Analyses

- Simplified triggering procedures estimate shear stress through PGA and $r_d$ → may significantly overestimate shear stress for Groningen, where high PGA is combined with high frequency content and short duration

- Site response analyses provide a direct, realistic estimate of shear stress induced from ground motion that can be entered in liquefaction triggering evaluations



# Summary - Consequences of Liquefaction

- Soil liquefaction may have catastrophic consequences on structures and life safety
- Liquefaction hazard should be assessed using different approaches depending on the severity of hazard, importance of structures, complexity of problem
- Simplified approaches may be used in desktop evaluations, however could be overly conservative
- Advanced numerical analyses allow for optimization:
  - Performance-Based Design (PBD)
  - Adequate assessment of *consequences* of soil liquefaction
  - Improved characterization of a system’s dynamic behavior
  - Identifying complex controlling mechanisms
  - Can lead to design optimization and potential cost savings

# Performance Based Design (PBD)

**Design objectives** in **current** building codes :
- life safety
- control damage in minor and moderate earthquakes
- no collapse in a major earthquake

Actual reliability of the design in achieving the objectives : **unknown**

**Performance based design**:
- explicitly quantified performance criteria considering multiple performance and hazard levels (e.g. settlements, displacements, storey drifts)

**PBD not addressed in NPR9998**

# Simplified vs Detailed Dynamic Analyses

– Simplified / Empirical methods → screening procedure

+ Can be performed fast at low cost
+ Assist in initial risk evaluation
+ Helps clients in cost / risk evaluation

- May produce overly conservative results → primarily based on PGA, may not accurately represent the demand in Groningen case → May lead to expensive design solutions

- Underestimate or miss key elements of dynamic behavior and may lead to design failures

# Simplified vs Detailed Dynamic Analyses

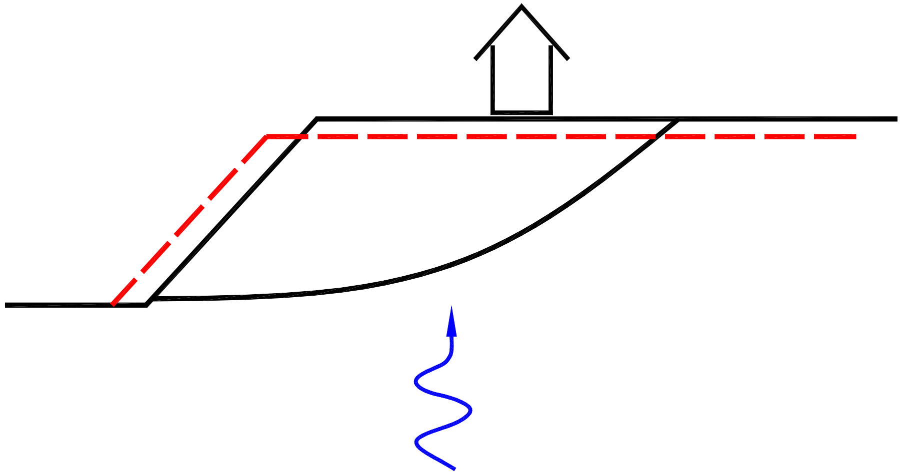
- Higher order analyses / Numerical modeling → Performance Based Design

  + Provide better assessment of actual demands
  + Identify critical failure mechanisms
  + Allow for better quantification of consequences
  + Allow to optimize design and reduce conservatism

  - Require earthquake engineering expertise
  - Require more time and budget at design stage

# Approaches for Evaluation of Slope Stability

- Pseudo-static Approach (Limit Equilibrium Analyses)
  - Factor of Safety (FOS) calculation
  - Yield acceleration (ky)
- Deformation Analyses
  - Simplified approaches (e.g., empirical methods)
  - Advanced numerical analyses (e.g., Finite Element, Finite Difference)



# Simplified Seismic Displacement Procedures

- Based on deformable block (modified Newmark) models
- Empirical equations based on a large number of simulations
- Provide estimates of seismically-induced permanent slope displacements
  - Slope displacement → index of performance

  - Bray and Travasarou (2007)
  - Nonlinear fully coupled stick-slip deformable sliding block model
  - Based on thousands of analytical simulations
  - 688 recorded ground motions used (because the primary source of uncertainty is the input ground motion)
  - Validated through re-examination of 16 case histories
  - Can be implemented rigorously within a fully probabilistic framework or used deterministically to evaluate seismic displacement potential

# Advanced Numerical Analyses

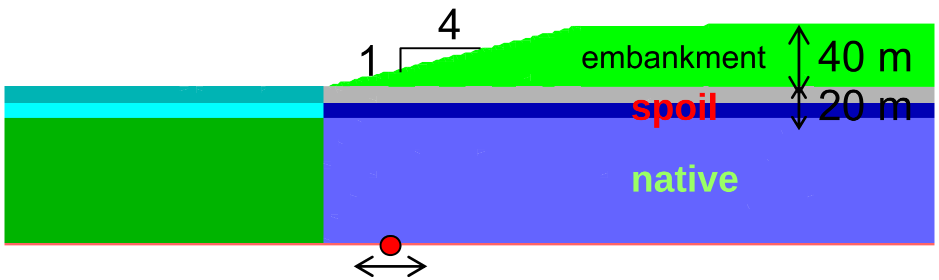
- Should be considered:
  - For important structures
  - For complex geometry
  - To provide more refined deformation estimates and failure modes
  - To optimize design

- Can help address:
  - Potential for cyclic strength degradation
  - Progressive failure conditions
  - Time-dependence of slope instability

# Example Dynamic Slope Stability (No Liquefaction)

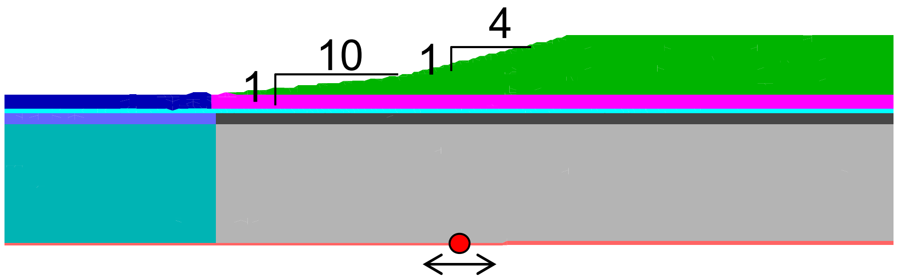
***Without Berm***

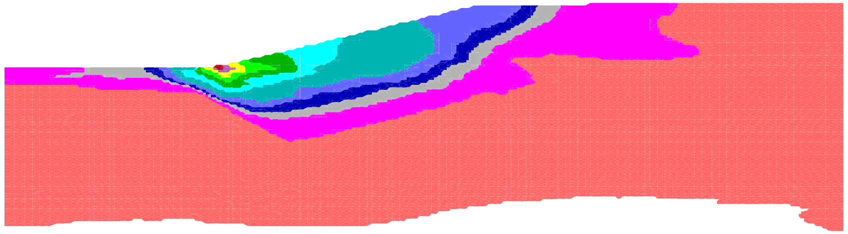
Static FS = 1.4

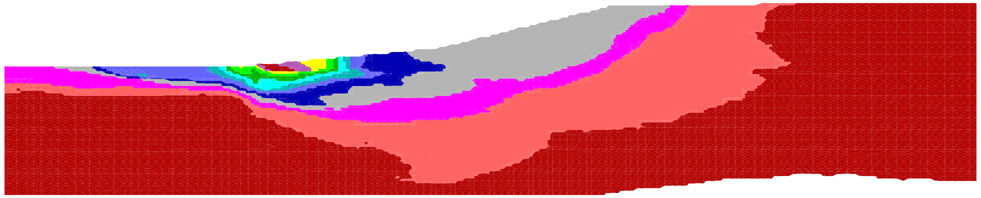


***With Berm***

Static FS = 1.5







**At the Crest**: $X_{displ} \approx$ 50cm
**40m from the Crest**: $X_{displ} \approx$ 27cm

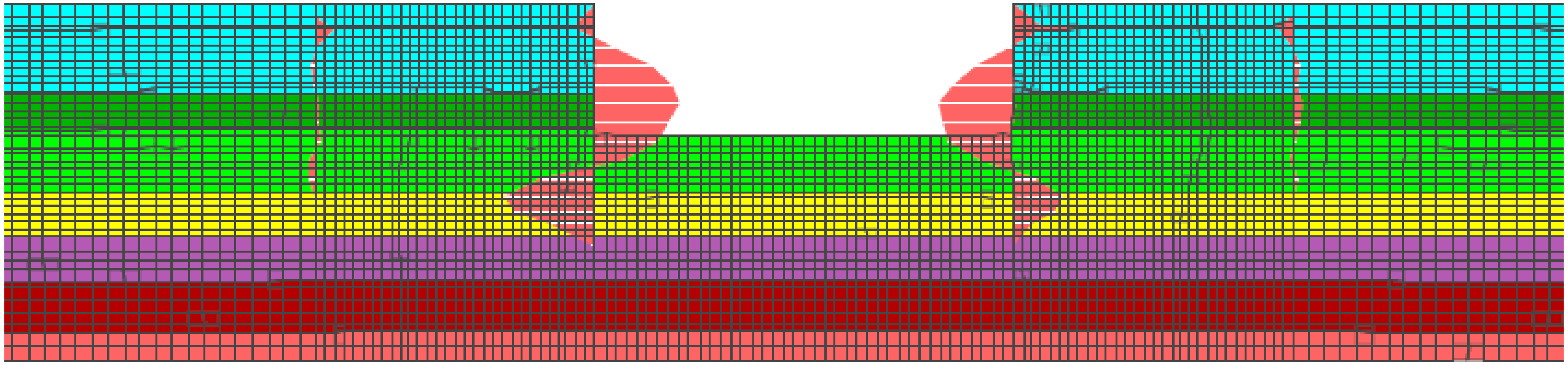
**At the Crest**: $X_{displ} \approx$ 17cm
**40m from the Crest**: $X_{displ} \approx$ 12cm

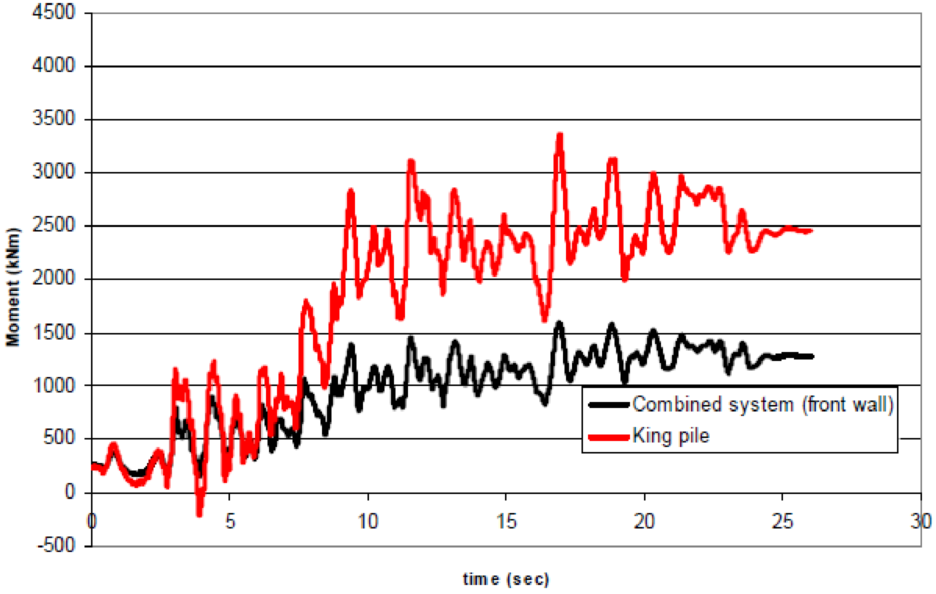
# Dynamic Analyses of Retaining Structures

- Simplified Approach
  - Mononobe-Okabe Method for estimation of Active Dynamic Pressures based on PGA
  - Newmark-type Approach for earthquake-induced movement evaluations
  - Can be too conservative and lead to overdesign of walls
  - Can miss/underestimate critical failure mechanisms
  - For cases in which the wall seismic design result appears to be excessively conservative relative to past experience in earthquakes, there are no simple solutions; numerical dynamic soil structure interaction (SSI) modeling may need to be considered

- Soil Structure Interaction Approach
  - Models both the soil and the retaining structure
  - Provides direct estimates of moment and shear on the wall
  - Identifies critical failure mechanisms
  - Optimized design

# Example Evaluation of Bulkhead Stability



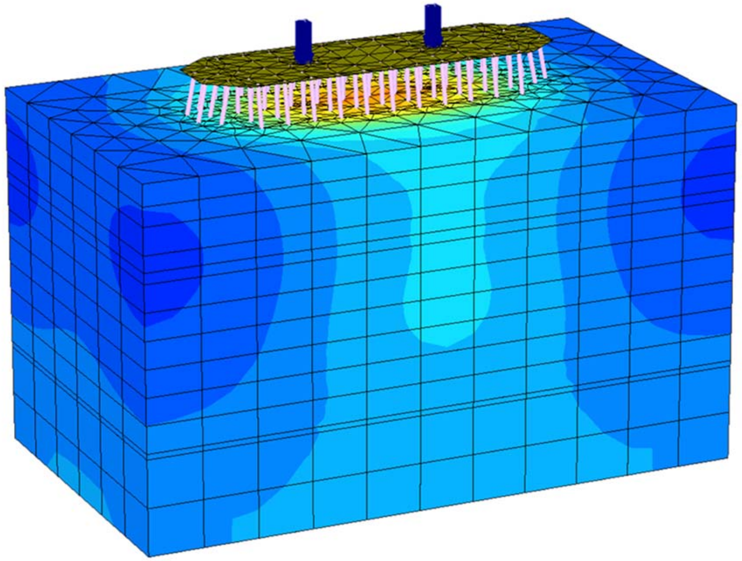


# Soil Structure Interaction

- Presence of stucture can influence the characteristics of “free field” ground motions

- “Free Field” ground motions → ground motion in soil, not influenced by presence of structure

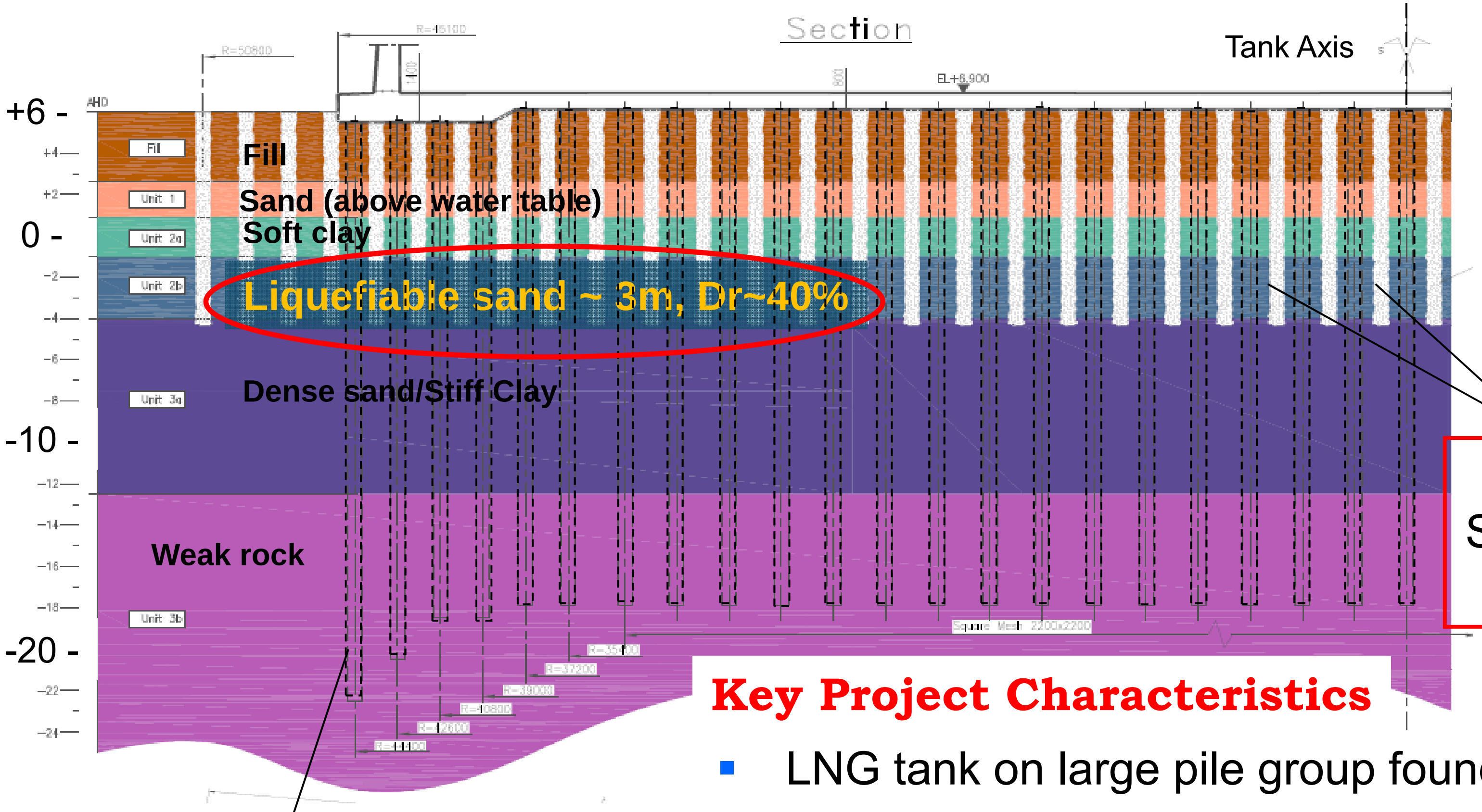
- Soil-Structure Interaction: the process during which the response of the soil influences the net motion of the structure and the response of the structure influences the motion of the soil

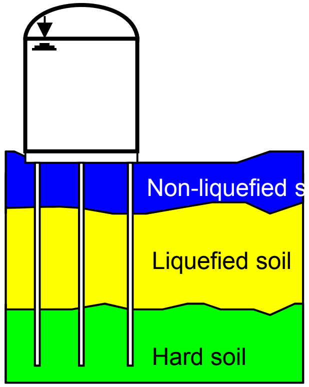


# Soil Structure Interaction

- Analytical Methods
  - Simplified approach → Spectral analyses
  - Time history analyses
    - Direct Method
    - Sub-structuring Method
- Free-field vs. Kinematic Motion
- Geotechnical Input
  - Earthquake motion (free-field, kinematic motion)
  - Soil element and soil spring
- Structure Input
  - Geometry and property of embedded foundation
  - Superstructure

# LNG Tank Founded on Liquefiable Soils





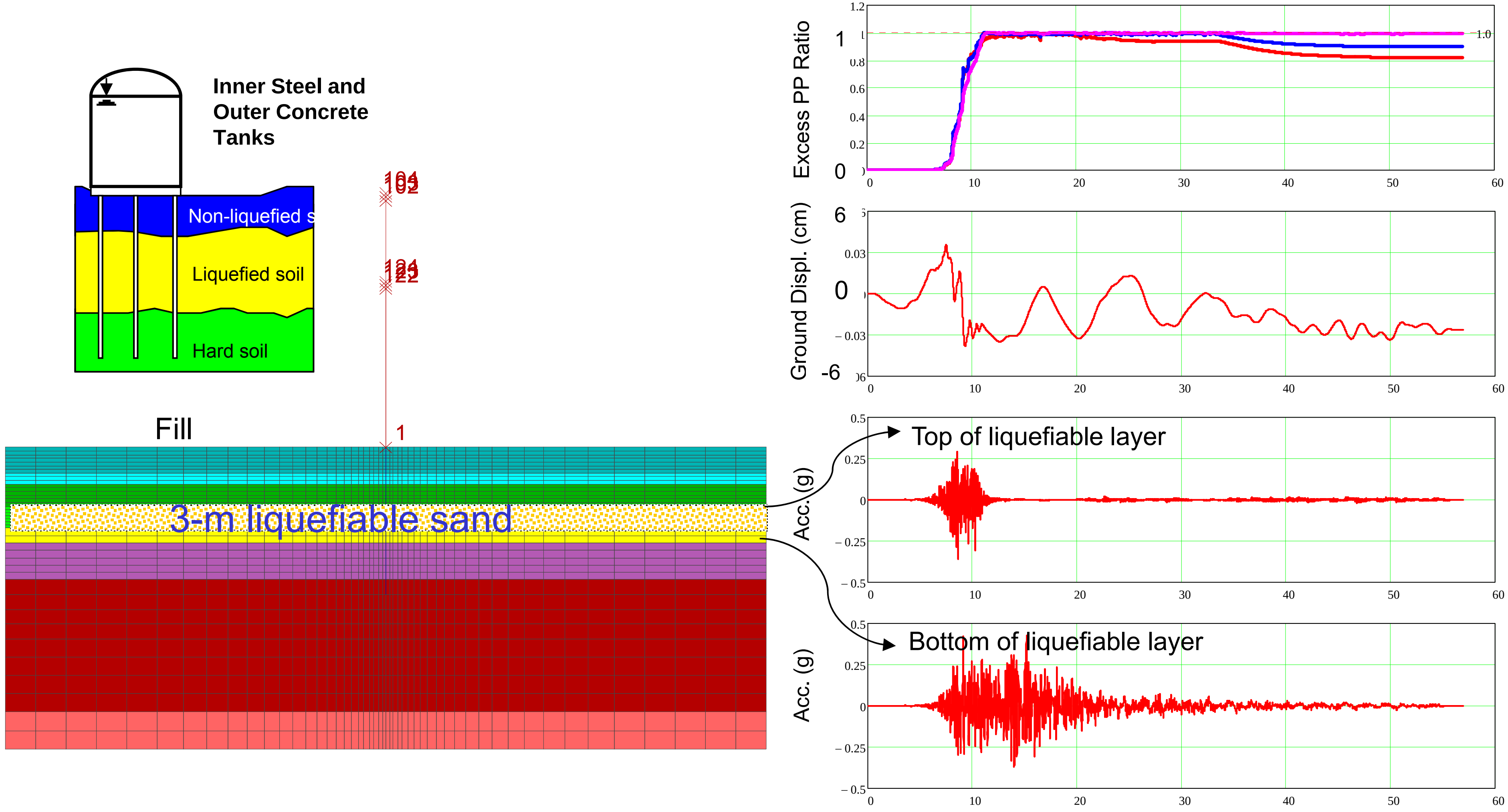
Tentative
Stone Column
Retrofit

850 steel pipe piles
D= 0.75m, Spaced @ 3.5D
Anchored in weak rock

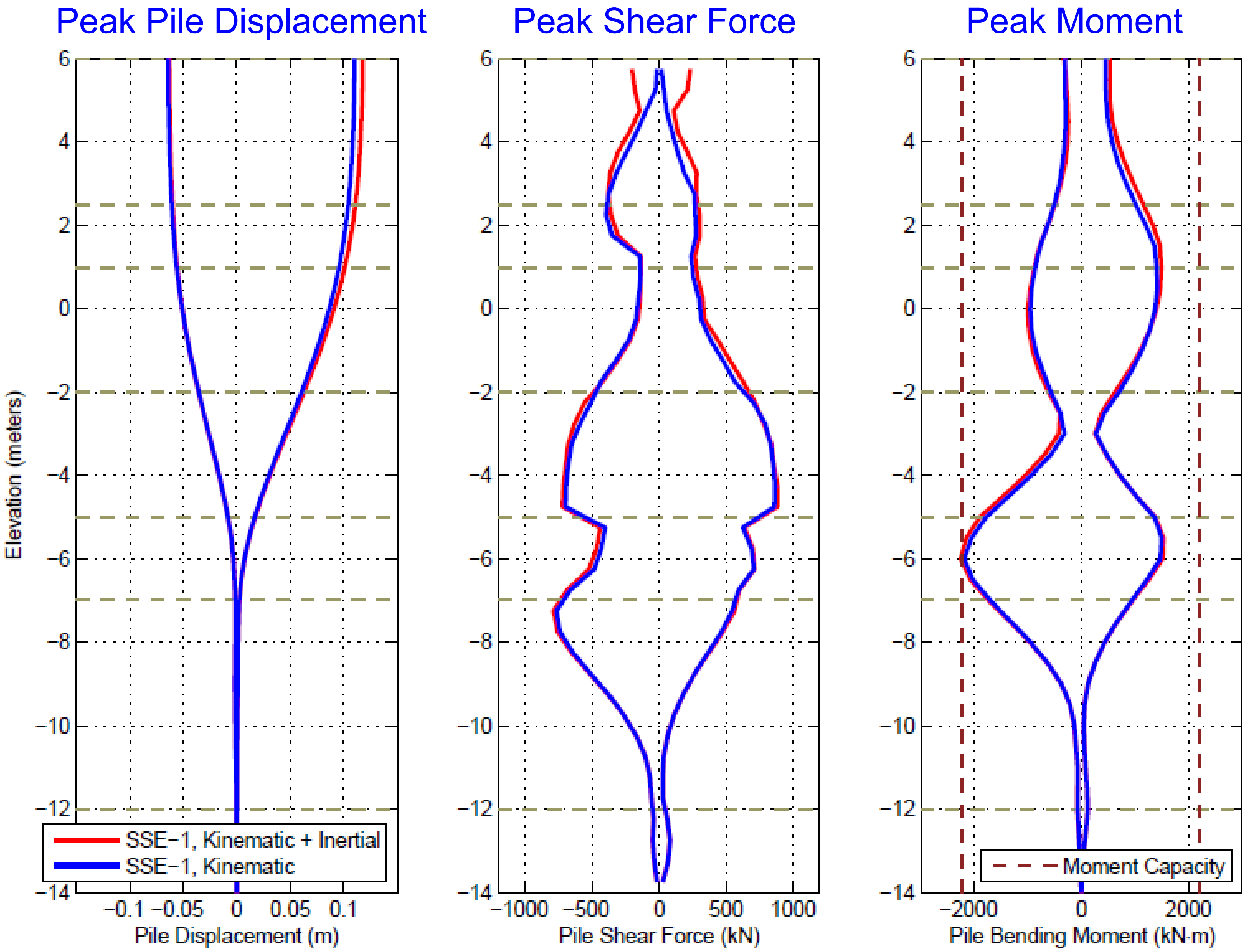
## Key Project Characteristics

- LNG tank on large pile group foundation
- Loose liquefiable layer at ~8m depth
- PGA 0.45g for Safe Shutdown event
- Liquefaction-induced kinematic loads on piles
- Is liquefaction mitigation necessary?

# Initial 2D Vulnerability Evaluations

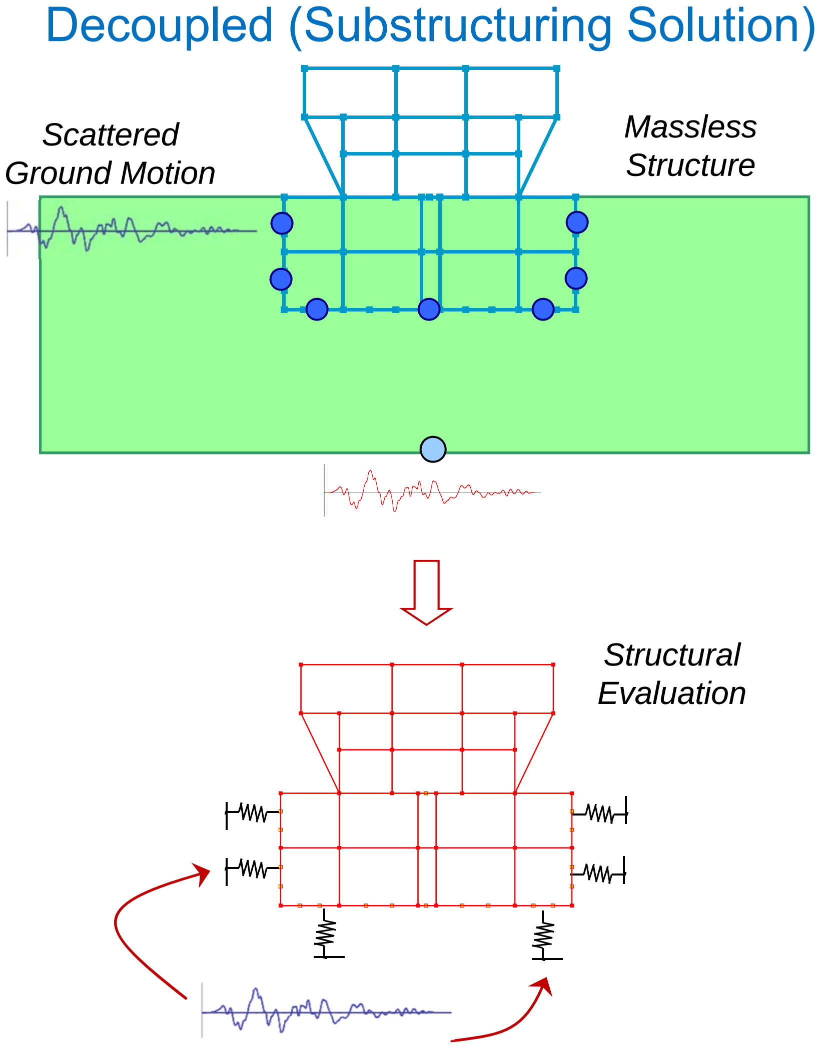


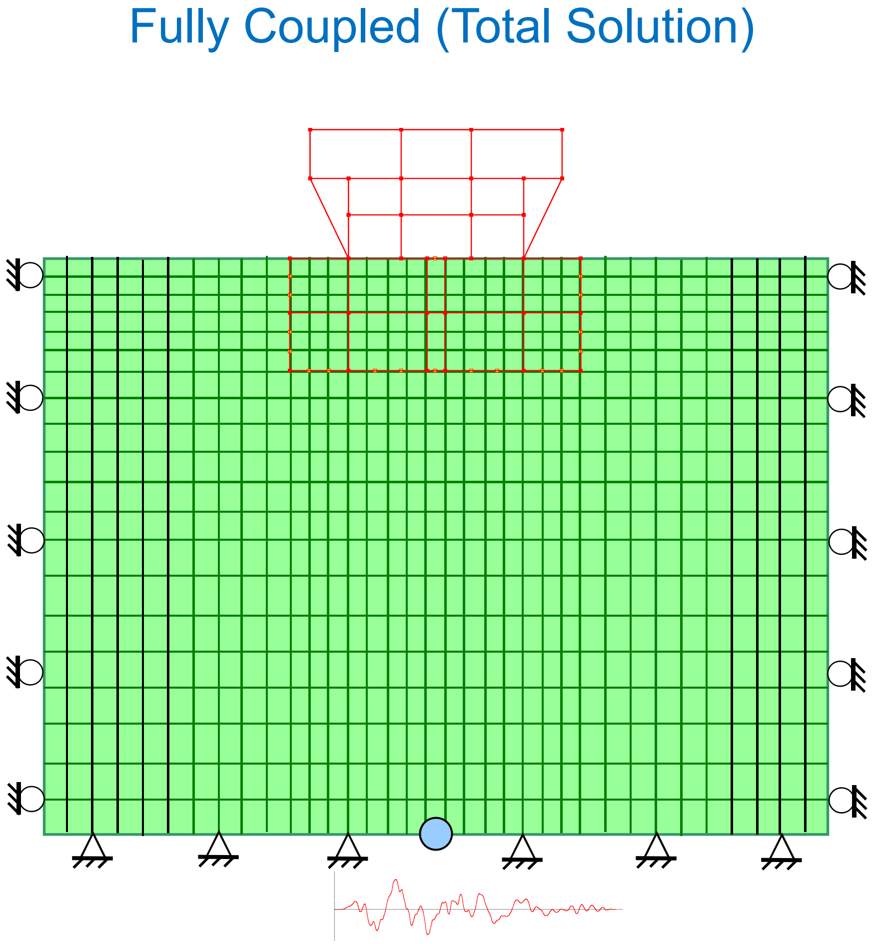
# Kinematic versus Inertial Demands



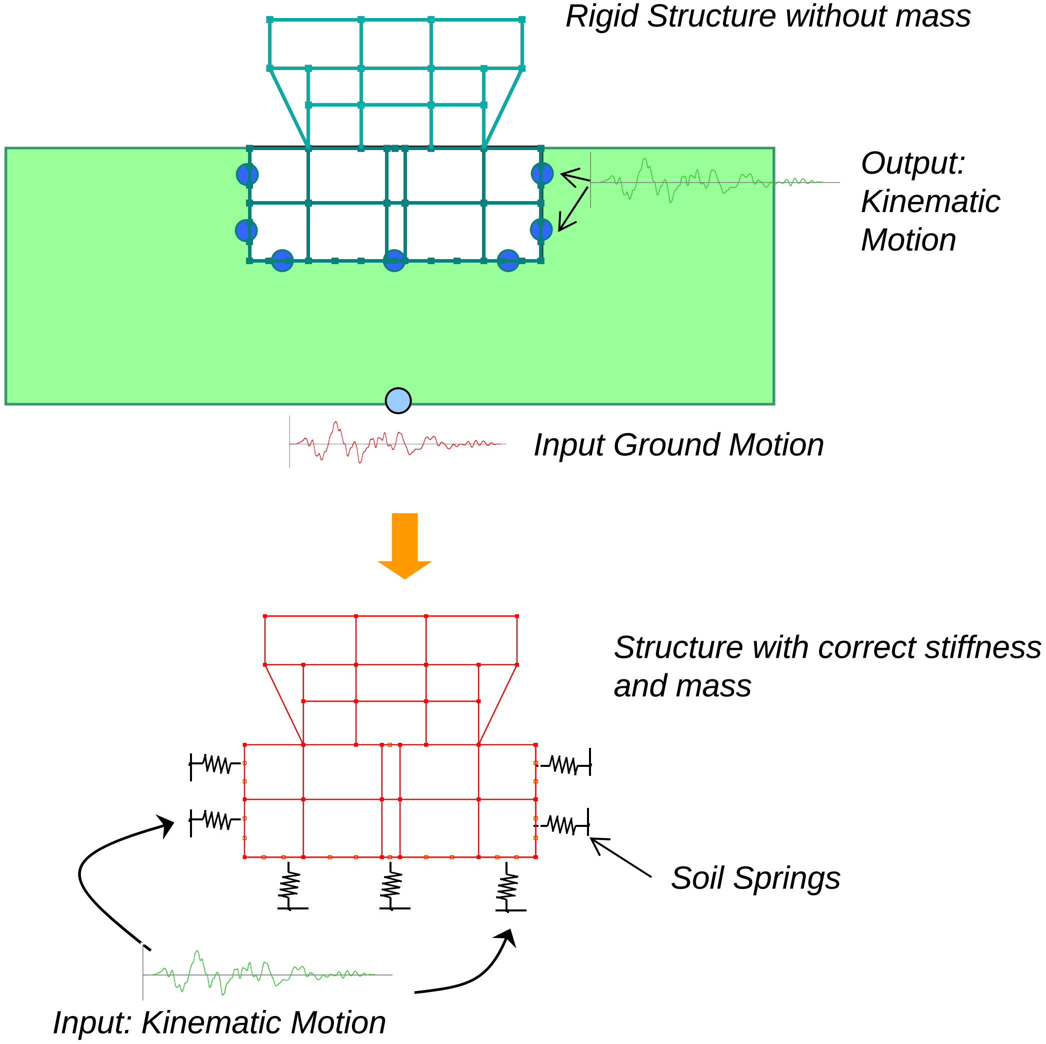
**liquefiable sand**

# SSI Analysis Methods


Decoupled (Substructuring Solution)

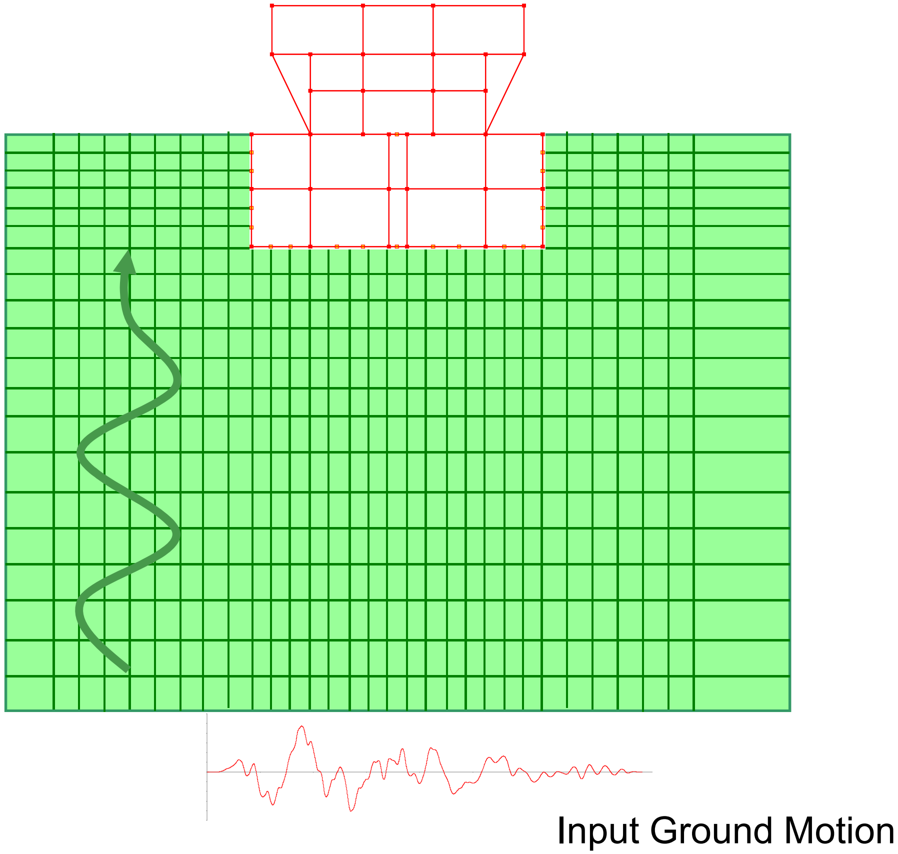

Fully Coupled (Total Solution)

# Time History Analysis – Sub-structuring Method



- A 2-step approach
- Step 1: derive kinematic motion with a rigid, massless structure
- Step 2: apply kinematic motion at the far-field end of the soil spring. The structure has real mass and internal stiffness.

# Time History Analyses – Direct Method



- In the Direct method, soil elements, foundation and superstructure are constructed in a single model
- Earthquake motion is input at the model base
- Seismic shear waves propagate upward through the soil to the surface and structure
- The foundation is shaken by the seismic waves
- Interaction between soil and foundation is modeled simultaneously, dynamic response from the foundation will also affect the soil response

# Summary SSI

- Use of simplified approaches may lead to overly conservative or inappropriate design

- Advanced numerical analyses allow for more rational and robust design by:
  - improved characterization of a system's dynamic behavior
  - Identifying complex controlling mechanisms

- Advanced numerical analyses can be performed efficiently and can lead to:
  - design optimization
  - potential cost savings

Klaas Siderius k.siderius@fugro.com
Ben van der Kwaak b.kwaak@fugro.com