Liquefaction Hazard Due to Induced Seismicity: Groningen Pilot Study

RUSSELL A. GREEN¹, PETER J. STAFFORD², BRETT W. MAURER³, ADRIAN RODRIGUEZ-MAREK¹, JULIAN J. BOMMER², BENJAMIN EDWARDS⁴, STEVE J. OATES⁵, PAULINE P. KRUIVER⁶, GER DE LANGE⁶, POURYA OMIĐI⁷, TOMAS STORCK⁷, STEPHEN J. BOURNE⁵, JAN VAN ELK⁸

¹Department of Civil and Environmental Engineering, Virginia Tech, Blacksburg, VA, U.S.
²Department of Civil and Environmental Engineering, Imperial College London, London, U.K.
³Department of Civil and Environmental Engineering, University of Washington, Seattle, WA, U.S.
⁴School of Environmental Sciences, University of Liverpool, Liverpool, U.K.
⁵Shell Global Solutions International B.V., Rijswijk, the Netherlands
⁶Deltares, Delft, the Netherlands
⁷Alten, Capelle aan den Ijssel, the Netherlands
⁸Nederlandse Aardolie Maatschappij B.V. (NAM), Assen, the Netherlands
Acknowledgements

- This study has also significantly benefited from enlightening discussions with colleagues at Shell, Deltares, Arup, Fugro, Beca, and on the NEN liquefaction task force

- Funding:
  - National Science Foundation
  - Nederlandse Aardolie Maatschappij B.V. (NAM)
Outline

• Background

• Evaluating Liquefaction Hazard
  • Potential biases in “simplified” liquefaction evaluation procedure
  • Updated stress reduction factor, $r_d$, relationship
  • Updated number of equivalent cycles, $n_{eq}$, and Magnitude Scaling Factor, MSF, relationships
  • Updated “simplified” liquefaction evaluation procedure
  • Ishihara Inspired Liquefaction Potential Index, LPI$_{ish}$

• Groningen Liquefaction Hazard Pilot Study
  • Probabilistic Liquefaction Hazard Analysis
  • Linking LPI$_{ish}$ and Differential Settlement

• Summary and Conclusions
Background

- Discovered in 1959; gas production began in 1963
- Field is operated by Nederlandse Aardolie Maatschappij B.V. (NAM), a joint venture of Shell and Exxonmobile
- 7th largest field in world based on initial reserves. Approximately 70% of reserves have been extracted; 13th largest field in world based on remaining reserves
- Approximately 93% of gross revenues are paid to the Dutch state in taxes; to date approximately 1 trillion euros have been paid to the Dutch state
- First earthquake in the region linked to gas production occurred in 1986; first earthquake linked to production at the Groningen field occurred in 1991
- Largest earthquake to date: August 2012, M3.6 Huizinge earthquake
- Largest PGA recorded to date: 0.11 g, January 2018 M3.4 Zeerjip earthquake
Background
historic seismicity
Background
geologic profile

Reference horizon (NS_B)

Gas reservoir and earthquake source
Activity Rate in Groningen

Cumulative number per year

- Moment Magnitude
  - 3.5-4.0
  - 3.0-3.5
  - 2.5-3.0
  - 2.0-2.5
  - 1.5-2.0
Background

January 2018, M3.4 Zeerjip earthquake motions (PGA = 0.11 g)

(courtesy of J. Bommer)
Evaluating Liquefaction Hazard
“Simplified” Liquefaction Evaluation Procedure

\[ \text{FS} = \frac{\text{Capacity}}{\text{Demand}} = \frac{\text{CRR}_{M7.5}}{\text{CSR}^*} \]

\[ \text{CSR}^* = 0.65 \left( \frac{a_{\text{max}}}{g} \right) \left( \frac{\sigma_v}{\sigma_v^0} \right) r_d \left( \frac{1}{\text{MSF}} \right) \left( \frac{1}{K_s K_s^*} \right) \]

- amplitude
- duration

![Graph showing liquefaction and no liquefaction data points](image-url)
“Simplified” Liquefaction Evaluation Procedure
magnitude distribution of liquefaction/no liquefaction case histories
“Simplified” Liquefaction Evaluation Procedure
magnitude distribution of liquefaction/no liquefaction case histories
“Simplified” Liquefaction Evaluation Procedure
Magnitude Scaling Factors (MSF)
“Simplified” Liquefaction Evaluation Procedure

potential biases

\[ FS = \frac{\text{Capacity}}{\text{Demand}} = \frac{\text{CRR}_{M7.5}}{\text{CSR}^*} \]

Sources of limitation in use of the procedure

\[ \text{CSR}^* = 0.65 \left( \frac{a_{\text{max}}}{g} \right) \frac{\sigma_v}{\sigma_{v0}} \frac{1}{r_d} \frac{1}{\text{MSF}} \frac{1}{K_\sigma K_\alpha} \]

amplitude duration
Bias in in stress reduction factor, $r_d$
Bias in stress reduction factor, $r_d$
Updated Worldwide $r_d$ Relationship

$$
r_d = (1 - \alpha) \exp \left( \frac{-z}{\beta} \right) + \alpha
$$

$$
\alpha_1 = \exp(b_1 + b_2 M + b_3 V_{s12})
$$

$$
\beta_1 = \exp(b_4 + b_5 M + b_6 V_{s12})
$$

$$
\alpha_2 = \exp(b_1 + b_2 M)
$$

$$
\beta_2 = b_3 + b_4 M
$$
Updated Worldwide $r_d$ Relationship
Updated Worldwide $n_{eq}$ Relationship
Computation of $n_{eq}$
Comparison of Traditional and Alternative Implementation of P-M Hypothesis
Updated Worldwide $n_{eq}$ Relationship

\[ r = -0.41 \]

\[ r = 0.12 \]
Updated Worldwide MSF Relationship

\[ MSF = \left( \frac{n_{eq, M7.5}}{n_{eq, M}} \right)^b \]
Updated Worldwide MSF Relationship

\[
MSF = \left( \frac{n_{eq \ M7.5}}{n_{eq \ M}} \right)^b
\]

- \( b \approx 0.34 \)

Contour of constant \( \Delta W \)
Updated Worldwide $n_{eq}$ Relationship

$$MSF = \left( \frac{14}{n_{eq}(M, a_{max})} \right)^{0.34} \leq 2.02$$

$$\ln(n_{eq}) = a_1 + a_2 \ln(a_{max}) + a_3 M + \delta_{event} + \delta_{profile} + \delta_0$$

$$\sigma_{\ln(MSF)} = b \cdot \sqrt{\sigma^2_{\ln(n_{eq, M7.5})} + \sigma^2_{\ln(n_{eq, M})} - 2 \cdot \rho \cdot \sigma_{\ln(n_{eq, M7.5})} \sigma_{\ln(n_{eq, M})}}$$
Updated Worldwide MSF Relationship
Updated Worldwide MSF Relationship
Updated “Simplified” Liquefaction Evaluation Procedure
Updated “Simplified” Liquefaction Evaluation Procedure
(other than $r_d$ and MSF all other relationships are from BI14)
Ishihara Inspired Liquefaction Potential Index (LPI_{ish})
Ishihara Inspired Liquefaction Potential Index ($LPI_{ish}$)

\[
LPI_{ish} = \int_{H_1}^{20m} F(FS) \cdot w(z) \, dz
\]

\[
F(FS) = \begin{cases} 
  1 - FS & \text{if } FS \leq 1 \land H_1 \cdot m(FS) \leq 3 \\
  0 & \text{otherwise}
\end{cases}
\]

\[
m(FS) = \exp \left( \frac{5}{25.56(1-FS)} \right) - 1
\]

\[
w(z) = \frac{25.56}{z} ; \quad z \text{ in } m
\]
Groningen Liquefaction Hazard Pilot Study
Liquefaction Pilot Study Area
Site Amplification Zones
Liquefaction Pilot Study Area

• Pilot study area selected to simultaneously satisfy three criteria:
  o proximity to the region of highest shaking hazard, i.e., Loppersum;
  o sampling of areas with thick, shallow deposits of young, loose sands; and
  o sampling of multiple site amplification zones
Liquefaction Pilot Study Area

Loosely packed sands in Naaldwijk Formation and Pleistocene Formations

Accumulated thickness in m.
- 0.0 - 0.5
- 0.6 - 1.0
- 1.1 - 2.0
- 2.1 - 5.0
- 5.1 - 10.0
- 10.1 - 25.0

Red line: Loppersum municipality
Black ellipse: Loppersum (town)
Black rectangle: Liquefaction Pilot study area
Development of Groningen-Specific $r_d$, $n_{eq}$, and MSF relationships

- 110 sites, Vs profiles down to NS_B (depth ~800 m)
- 3840 ground motions
  - $M^{3.5}$ to $M^{7.0}$, $\Delta M = 0.5$
  - Horizontal distance to fault, R: 0.1 to 60 km, $\Delta \log(R) = 0.2$
  - 8 azimuths radially around fault
  - Hypocentral depth: 3 km (reservoir depth)
- ~425,000 equivalent linear site response analyses, ShakeVT2
Field-Wide $V_s$ Model

- Typical profile includes fine sands, clays, and silts
- Peat layers are present in some regions
- Soil-type information is extracted from GeoTOP model and geological models
- Generally very soft near-surface deposits
Framework for the ground motion model

Seismological Model

Inversions of recorded data

Non-linear AF model

Ground motions simulated at NS_B horizon for range of M & R

Recordings

Linear TF and AF

Reservoir

NS_B

(Courtesy of J. Bommer)
Groningen-Specific (zone-specific) $r_d$

$$r_{d-Gron} = 1 - \frac{A_{rd}}{1 + \exp\left[-\frac{\ln(z) - (\beta_2 + \beta_6 \cdot M)}{(\beta_3 + \beta_7 \cdot M)}\right]}; \quad 0 \leq r_d \leq 1$$

$$A_{rd} = \beta_1 + \beta_4 \cdot \min[M, 6.5] + \beta_5 \cdot \ln\left(\frac{a_{\text{max}}}{g}\right) + \beta_9 \cdot V_{s12}$$

for $a_{\text{max}} \leq 0.3 \text{g}$

$$A_{rd} = \beta_1 + \beta_4 \cdot \min[M, 6.5] + \beta_5 \cdot \ln\left(\frac{a_{\text{max}}}{g}\right) + \beta_8 \cdot \ln\left(\frac{a_{\text{max}}}{0.3g}\right) + \beta_9 \cdot V_{s12}$$

for $a_{\text{max}} > 0.3 \text{g}$

$$\sigma_{rd} = \frac{\beta_{10}}{1 + \exp\left[-\frac{\ln(\max[z,5]) - (\beta_2 + \beta_6 \cdot M)}{(\beta_3 + \beta_7 \cdot M)}\right]}$$
Groningen-Specific (zone-specific) $r_d$
Groningen-Specific (zone-specific) MSF

\[ MSF_{Gron} = \left\{ \frac{7.25}{n_{eqM}(M,a_{max},V_{s12})} \right\}^{0.34} \leq 2.04 \]

\[
\ln[n_{eqM}(M,a_{max},V_{s12})] = \begin{cases} 
\alpha_1 + \alpha_2 \cdot \ln\left(\frac{a_{max}}{g}\right) + \alpha_4 \cdot M + \alpha_5 \cdot V_{s12} & \text{for } a_{max} \leq 0.3g \\
\alpha_1 + \alpha_2 \cdot \ln\left(\frac{a_{max}}{g}\right) + \alpha_3 \cdot \ln\left(\frac{a_{max}}{0.3g}\right) + \alpha_4 \cdot M + \alpha_5 \cdot V_{s12} & \text{for } a_{max} > 0.3g 
\end{cases}
\]

\[ \sigma_{\ln(MSF_{Gron})} = 0.34 \cdot \sigma_{\ln(n_{eqM})} \]
Groningen-Specific (zone-specific) MSF
Probabilistic Liquefaction Hazard Analysis

Monte Carlo Simulation of Earthquake Scenarios (100k scenarios per site)
Probabilistic Liquefaction Hazard Analysis

- Seismological model comprises 5 sequential stochastic elements
- Ground motion model comprises 2 sequential stochastic elements
- Liquefaction model comprises 2 sequential stochastic elements

(Courtesy of S. Bourne)
Probabilistic Liquefaction Hazard Analysis

- Seismological model comprises 5 sequential stochastic elements
- Ground motion model comprises 2 sequential stochastic elements
- Liquefaction model comprises 2 sequential stochastic elements

\[ r_d \text{ relationship} \rightarrow \text{MSF relationship} \rightarrow \text{Liquefaction triggering} \rightarrow \text{LPI}_{\text{ish}} \text{ hazard curve} \]

- Stress reduction coefficient given earthquake magnitude, ground surface acceleration, Vs profile, and \( r_d \) and other depths
- Magnitude Scaling Factor given earthquake magnitude, ground surface acceleration, Vs profile, and \( r_d \)
Parameter Correlations: Depth and $r_d$-MSF

At a given depth, $r_d$ & $n_{eq}$ correlated
Logic Tree Description of Epistemic Uncertainty

- **$M_{\text{max}}$**
  - $M_{\text{max}} = 6.8$
    - $p = 0.11$
  - $M_{\text{max}} = 5.4$
    - $p = 0.43$
  - $M_{\text{max}} = 4.5$
    - $p = 0.46$

- **GMM Median-$\tau$**
  - Upper
    - $p = 0.3$
      - Upper-central
        - $p = 0.3$
      - Lower-central
        - $p = 0.3$
    - Lower
      - $p = 0.1$

- **GMM $\phi$**
  - Upper
    - $p = 0.5$
  - Lower
    - $p = 0.5$

- **AF**
  - $p = 1$

- 3 factors
- $3 \times 4 \times 2 \times 1$ levels
- 24 full-factorial combinations
Probabilistic Liquefaction Hazard Analysis
Linking $LPI_{ish}$ and Differential Settlement
Summary & Conclusions

- Natural gas production in the Groningen field has resulted in induced seismicity
- Seismic hazard is dominated by small magnitude events $M < 5$
  - Semi-empirical “simplified” liquefaction evaluation procedures based predominantly on cases histories $M > 6.25$
  - Potential bias exists in $r_d$, MSF, and $CRR_{M7.5}$ relationships in existing procedures
  - An updated simplified liquefaction evaluation procedure developed for worldwide tectonic events
- Same approach used to develop Groningen-specific $r_d$ and MSF relationships
  - $r_d$ and MSF relationships functions of $M$, $a_{max}$, and $V_{s12}$
  - $r_d$ and MSF correlated with depth and with each other
- Probabilistic Liquefaction Hazard Analysis performed using Monte Carlo approach
- Liquefaction hazard pilot study shows a moderate liquefaction hazard in Zandeweer, and no-to-minor liquefaction hazard elsewhere in the pilot study area
Thank You