Recent Developments in Characterizing Liquefiable Sandy Soils in the Field and Laboratory

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Outline

1. Present results from recent (2013) in-situ liquefaction testing in Christchurch, NZ with T-Rex in terms of $r_u - \log \gamma$ at given N’s.

2. Investigate the dynamic response of the sand skeleton using the combined field and extrapolated $r_u - \log \gamma$ relationship ($N = 30$ cycles) with the effective-stress, $G - \log \gamma$ relationship determined from dynamic laboratory testing of the actual soil.

3. Briefly present the $\tau - \gamma$ curves determined from the $G - \log \gamma$ relationships with and without pore water pressure.

4. Very briefly introduce improvements in:
   - modeling ($G/G_{\text{max}} - \log \gamma$) of sands (SP, SW and SM),
   - combined dynamic and cyclic laboratory testing, and
   - next-generation field liquefaction testing.

5. Conclusions

6. Acknowledgments
2010-2011 Canterbury Earthquake Sequence

Christchurch Area

CBD

Legends

- 3.0 – 3.9
- 4.0 – 4.9
- 5.0 – 5.9

★ Sep. 2010, $M_w = 7.1$
★ Feb. 2011, $M_w = 6.2$
★ Jun. 2011, $M_w = 5.9$
★ Dec. 2011, $M_w = 6.0$

Notes:
We acknowledge the New Zealand geoset project and its sponsors EQC, GNS Science and LINZ for providing data.
Severe Liquefaction in Suburbs

Sand Ejecta

from Prof. Misko Cubrinovski
1. Example: Field Shaking Tests at Site 6 and Associated Dynamic and Cyclic Laboratory Tests

 Legends

- Moderate to severe liquefaction
- Low to moderate liquefaction
- Liquefaction on roads (predominantly, no/localized liquefaction on properties)

Sites 3 & 4

Heathcote River

Avon River

Christchurch CBD

Site 6

Christchurch Cathedral
Plan View of Site 6 with Natural Soil Test Panel
(Ariel Photograph Before Homes Removed)
Pre-Shaking Crosshole Testing in Progress to Characterize Soil

Note: General arrangement used as the field verification procedure.
Pre-Shaking Characterization of Soil: Direct-Push Crosshole Seismic Testing to Determine $V_p$ and $V_S$

Vertical Impacts (Seismic Source and Timing Trigger)

Source #1 (S1)

Source #2 (S2)

~2.5 m + for testing at Site 6 in NZ

$V_p^+$ (m/s)

$V_S^+$ (m/s)

$V_S^*$ is stress-corrected for T-Rex

$V_S^*$ is stress-corrected for T-Rex
Generalized Field Set-Up: T-Rex Shaking of an Embedded Array of Sensors

- Static Loading
- Dynamic Shaking

Instrumented Zone

Not to scale
Creating the Embedded Array of Sensors: Pushing Geophones and Pore-Pressure Transducers with T-Rex

[T-Rex]

Hydraulic Push/Pull Cylinder

Sensor Installation

bentonite
cable
sensor
Generalized Arrangement of Sensors to Evaluate $r_u$ versus Time (N) and $\gamma$ versus Time (N)

(a) Cross Section

(b) Instrumentation
In Situ Non-Linear Testing of Liquefiable Soils

Shallow In Situ Non-linear Testing of Liquefiable Soils
24-hr Process of Sensor Installation and Staged Loading with T-Rex at the Natural Soil Test Panel

(a) Install Sensors, Vertical Static Loading, and Demobilization

(b) Staged, Horizontal Shaking with T-Rex
Natural Soil Test Panel at Site 6:
Stage 5 - Pore Water Pressure Ratio, $r_u$, versus Time

Shaking: 100 cycles at 10 Hz; Stage 5; Peak Horizontal Force ~ 91 kN (20,500 lbs)

Depth = 2.1 m

Notes:

$$r_u = \frac{u_{\text{excess}}}{\sigma_v'}$$

$$\text{CSR} = \frac{\tau}{\sigma_v'}$$

$$G = \frac{\tau}{\gamma} \quad \Rightarrow \quad \tau = G \left( \gamma \right)$$
Stage Testing at Natural Soil Test Panel, Site 6:

$\text{r}_u$ versus Log $\gamma$ after 30 Cycles of Shaking at Each $\gamma$

- **PPT 9P, Depth 2.1 m,**
  - $V_p = 1,700 \text{m/s}$,
  - $V_S = 139 \text{m/s}$

**Depth = 2.1 m**

**Shaking Stages:**
- Stage 1;
- Stage 2;
- Stage 3;
- Stage 4;
- Stage 5

**Legend:**
- Medium Sand
- Silt
- Sandy Silt
- Silty Fine Sand
- PPT

**Graph:**
- Pore Pressure Ratio, $r_u$ (%)
- Shear strain (%)
- $N = 30$
- $r_u > 0$
2a. Modeling the Loading of the Natural Soil Test Panel Before T-Rex Shaking: Depth 2.1 m

**Pre-Shaking Field Stage:**

1. $G_{\text{max}}$ (No T-Rex)

**From Field $V_s$:**

$G_{\text{max}} = 38.1 \text{ MPa}$

$\sigma'_o = 16.5 \text{ kPa}$, $V_s = 139 \text{ m/s}$
Modeling the Loading of the Natural Soil Test Panel
Before T-Rex Shaking: Depth 2.1 m

\[ G_{\text{max}}^* = 48.2 \text{ MPa} \]
\[ \sigma_o' = 26.5 \text{ kPa}, V_S = 156 \text{ m/s} \]

Pre-Shaking Field Stage:
(1) ♦ \( G_{\text{max}} \) (No T-Rex)
(2) ● \( G_{\text{max}}^* \) (With T-Rex)
Modeling the Loading of the Natural Soil Test Panel Before T-Rex Shaking: Depth 2.1 m

\[
\frac{G}{G_{\text{max}(T-Rex)}} = \frac{1}{\left(1 + \left(\frac{\gamma}{\gamma_r}\right)^a\right)^b} = \frac{1}{\left(1 + \left(\frac{\gamma}{0.017\%}\right)^{0.96}\right)^{0.55}}
\]

Pre-Shaking Field Stage:
(1) ♦ \(G_{\text{max}}\) (No T-Rex)
(2) ● \(G_{\text{max}}^*\) (With T-Rex)
(3) – \(G-\log(\gamma)\) (Pre-Shaking)

Lab RCTS

Field \(r_u = 0\)
2b. Modeling the Loading of the Natural Soil Test Panel During T-Rex Shaking: with Measured Values of $r_u$

- $G_{\text{max}}^* = 48.2 \text{ MPa}$
- $\sigma_o' = 26.5 \text{ kPa}$
- $G/G_{\text{max}}^* = 0.91$
- $N = 30$
- Depth = 2.1 m
- $r_u = u_{\text{excess}}/\sigma_v'$
- $r_u = 0.0 \%$
- CSR = 0.03

Shaking Stages: Stage 1
Modeling the Loading of the Natural Soil Test Panel During T-Rex Shaking: with Measured Values of $r_u$

- $G_{\text{max}}^* = 48.2 \text{ MPa}$
- $\sigma_0' = 26.5 \text{ kPa}$
- $G/G_{\text{max}}^* = 0.68$
- $r_u < 0.1 \%$
- $\text{CSR} = 0.14$

**Equation:**

$$r_u = \frac{u_{\text{excess}}}{\sigma_v'}$$

- $N = 30$
- Depth = 2.1 m
- If $r_u = 0$

**Shaking Stages:**

- Blue Circle: Stage 1
- Green Circle: Stage 2
Modeling the Loading of the Natural Soil Test Panel During T-Rex Shaking: with Measured Values of \( r_u \)

- \( G_{\text{max}}^* = 48.2 \text{ MPa} \)
  - \( \sigma_o' = 26.5 \text{ kPa} \)
- \( G_{\text{max}} = 48.0 \text{ MPa} \)
  - \( \sigma_o' = 26.3 \text{ kPa} \)
- \( \frac{G}{G_{\text{max}}} = 0.56 \)
- \( N = 30 \)
- Depth = 2.1 m
- \( r_u = \frac{u_{\text{excess}}}{\sigma_v'} \)
- \( r_u = 0.8 \% \)
- CSR = 0.22

Shaking Stages:
- Stage 1
- Stage 2
- Stage 3
Modeling the Loading of the Natural Soil Test Panel During T-Rex Shaking: with Measured Values of $r_u$

- $G_{\text{max}}^* = 48.2 \text{ MPa}$
  - $\sigma_0' = 26.5 \text{ kPa}$
- $G_{\text{max}} = 46.4 \text{ Mpa}$
  - $\sigma_0' = 24.6 \text{ kPa}$
- $N = 30$
- Depth = 2.1 m
- $r_u = \frac{u_{\text{excess}}}{\sigma_v'}$
- $r_u = 7.3 \%$
- CSR = 0.33

Shaking Stages:

- Stage 1
- Stage 2
- Stage 3
- Stage 4
Modeling the Loading of the Natural Soil Test Panel During T-Rex Shaking: with Measured Values of $r_u$

- $G_{max}^* = 48.2$ MPa
- $\sigma'_o = 26.5$ kPa
- $r_u = 17.0\%$
- $CSR = 0.45$
- $G/G_{max} = 0.29$

- $G_{max} = 44.0$ MPa
- $\sigma'_o = 22.0$ kPa

- $N = 30$
- $\text{Depth} = 2.1$ m
- $r_u = u_{\text{excess}}/\sigma'_v$

Shaking Stages:  
- Stage 1;  
- Stage 2;  
- Stage 3;  
- Stage 4;  
- Stage 5
Predicting the Response of the Natural Soil Test Panel at High Levels of Shaking: with Estimated Values of $r_u$.

- $G_{\text{max}}^* = 48.2$ MPa
  - $\sigma_o' = 26.5$ kPa
- $G_{\text{max}} = 40.4$ MPa
  - $\sigma_o' = 18.6$ kPa
- $r_u = 30\%$
  - CSR = 0.48
- $G/G_{\text{max}} = 0.24$

N = 30
Depth = 2.1 m
$r_u = u_{\text{excess}}/\sigma_v'$

Shaking Stages:
- Stage 1;
- Stage 2;
- Stage 3;
- Stage 4;
- Stage 5

Predicted Shaking Results:
- Stage 6
Predicting the Response of the Natural Soil Test Panel at High Levels of Shaking: with Estimated Values of $r_u$

- $G_{\text{max}}^* = 48.2$ MPa
  - $\sigma_o' = 26.5$ kPa
- $G_{\text{max}} = 26.9$ MPa
  - $\sigma_o' = 8.1$ kPa
- $r_u = 69\%$
  - CSR = 0.33
- $G/G_{\text{max}} = 0.16$

**Predicted Shaking Results:**
- Stage 6
- Stage 7 ($G/G_{\text{max}}^* = 0.09$)

**Shaking Stages:**
- Stage 1
- Stage 2
- Stage 3
- Stage 4
- Stage 5

**N = 30**
- Depth = 2.1 m
  - $r_u = u_{\text{excess}}/\sigma_v'$

**Excess Pore Pressure Ratio, $r_u$ (%) vs. Shear Strain (%)**

Shear Modulus, $G$ (MPa) vs. Excess Pore Pressure Ratio, $r_u$ (%)
2d. Comparing the Response of the Natural Soil Test Panel at High Levels of Shaking: with and without $r_u$

Predicted Shaking Results:
- Stage 6
- Stage 7

$G_{\max}^* = 48.2 \text{ MPa}$
$\sigma_o' = 26.5 \text{ kPa}$

$r_u = 69\%$
$CSR = 0.33$

If $r_u = 0$

Due to $r_u$

$N = 30$
Depth = 2.1 m
$r_u = u_{\text{excess}}/\sigma_v'$

Shaking Stages:
- Stage 1
- Stage 2
- Stage 3
- Stage 4
- Stage 5

Predicted Shaking Results:
- Stage 6
- Stage 7
3. Combining the Laboratory $G/G_{\text{max}} - \log \gamma$ Data (a) and the In-Situ $r_u - \log \gamma$ Data (b)
Combining the Laboratory $G/G_{\text{max}} - \log \gamma$ Data (a) and the In-Situ $r_u - \log \gamma$ Data (b)

**Laboratory RC Test**

**In-Situ T-Rex Shaking Test**
Creating the $\tau - \gamma$ Curve for $r_u = 0$ from the Laboratory $G/G_{\text{max}} - \log \gamma$ Data and the In-Situ $G_{\text{max}}$ *

Shear Stress vs. Shear Strain at $\sigma_0' \sim 28$ kPa
(Represents In-Situ Condition)
Creating the $\tau - \gamma$ Curve for $r_u > 0$ from the Laboratory $G/G_{\text{max}} - \log \gamma$ Data and the In-Situ $G_{\text{max}}$*

Shear Stress vs. Shear Strain at $\sigma_0' \sim 28$ kPa
(Represents In-Situ Condition)

$G/G_{\text{max}} = 0.65$
where $r_u = 0$

$G/G_{\text{max}} = 0.35$
$CSR = 0.43$

$G/G_{\text{max}} = 0.33$
$CSR = 0.40$

$G/G_{\text{max}} = 0.26$
$CSR = 0.43$

$G/G_{\text{max}} = 0.22$
$CSR = 0.48$

$G/G_{\text{max}} = 0.20$
$CSR = 0.48$

$G/G_{\text{max}} = 0.21$
$CSR = 0.76$

$r_u > 0$

Field Data Extrapolated

$\gamma_{\text{pp}}$

Creating the $\tau - \gamma$ Curve for $r_u > 0$ from the Laboratory $G/G_{\text{max}} - \log \gamma$ Data and the In-Situ $G_{\text{max}}$*

Shear Stress vs. Shear Strain at $\sigma_0' \sim 28$ kPa
(Represents In-Situ Condition)
4a. Improved Laboratory Testing and Modeling Using Combined Dynamic Resonant Column (RC) and Cyclic Torsional Shear (TS) Equipment

**RC Testing:**

1. More Data from Non-Plastic Sandy Soils.

2. Wide Range in Effective Confining Pressures, \( \sigma_0' = 0.14 \) to 14 atm.

3. Wide Range in Strains, \( \gamma \sim 10^{-5} \% \) to 0.3 \% or more.

4. Model for the \( G - \log \gamma \) Relationship is:

\[
G = G_{\text{max}} \left( \frac{1}{1 + \left( \gamma / \gamma_r \right)^a} \right)^b
\]
More Effective Constitutive Model for Sands (SP, SW, and SM)

Note: 1. Curves were extrapolated to $\gamma = 0.3\%$. 

Material: SP
TS Testing:

1. Testing Hollow Specimens.

2. Evaluating Effects of $S_r$ and $N$.

3. Determining $\gamma_t^{PP}$ (Threshold for Pore Pressure Generation).

4. Model for the $G - \log \gamma$ Relationship is

$$G = G_{\text{max}} \left( \frac{1}{1 + \left( \frac{\gamma}{\gamma_r} \right)^a} \right)^b$$
Pore Water Pressure Generation Data from Laboratory TS Test (0.54 atm, Strain = 0.05%, N = 30 cycles)
Evaluating the Threshold for Pore Water Pressure Generation, $\gamma_t^{PP}$, from TS Testing

S6(2.1m), SP, $D_r \sim 40\%$

$f = 0.5$ Hz

$N = 30$

Excess Pore Pressure Ratio, $r_u$, %

Shear Strain $\gamma$, %

0.3%
Comparing the Laboratory TS Testing Data and $\gamma_t^{PP}$ with Pore Pressure Generation Data from In-Situ T-Rex Shaking

![Laboratory RC Test](image1)

![Laboratory TS Test](image2)
4b. Improved Field Liquefaction Testing: SABW
Site 6-NS-1, Depth: 1.6 m, 100 Cycles per Stage
Soil Type: SP, FC = 3-12 %, $V_p = 1570$ m/s, $V_s = 117$ m/s

![Graph showing estimated range of field $G_{max}$ with T-Rex vs. shear strain.](chart)
Project in 2018 Between OSU and UT: Combined Shaking with T-Rex and Rattler Positioned Side by Side (1D and 2D Loadings)
Project in 2018 Between OSU and UT: Combined Shaking with T-Rex and Rattler Positioned Side by Side (1D and 2D Loadings)

Instrumented Zone (12, 3D Geophones)

Note: Already $2 \times \gamma_{\text{max}}$ in 1D Shaking

As typical in NHERI projects, piggy-back projects are welcomed.
Conclusions

1. Controlled, in-situ “liquefaction testing” involves large electro-hydraulic shakers (T-Rex and Rattler) to statically and dynamically load instrumented portions of the soil.

2. The generalized field test method is quite laborious, time consuming and still evolving. The method is not designed for routine testing; rather, for testing these hard-to-sample soils for which we have few field parametric studies.
Conclusions (Cont’d)

3. Field studies of the effects of various parameters on the pore-pressure generation ($r_u \log \gamma$) and shear-modulus nonlinearity ($G \log \gamma$ and $G/G_{max} \log \gamma$) of liquefiable soils are already contributing new knowledge. Parameters being studied include: $N$, $S_r$, $\gamma_t^{pp}$, and sands with and without plastic fines.

4. Improvements in modeling and combined dynamic and cyclic laboratory testing are also underway which will contribute to our understanding of these parameters.
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