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

Canterbury Earthquake Sequence

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, $M_w = 6.0$

CBD

Christchurch Area
Severe Liquefaction in Suburbs

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

Legend:
- **Red**: Moderate to severe liquefaction
- **Yellow**: Low to moderate liquefaction
- **Pink**: Liquefaction on roads (predominantly, no/localized liquefaction on properties)
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 $V_s$
Generalized Field Set-Up: T-Rex Shaking of an Embedded Array of Sensors
Creating the Embedded Array of Sensors: Pushing Geophones and Pore-Pressure Transducers with T-Rex
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

Vertical Static Load, kips

~ 60

Install Sensors

Overnight Consolidation Period

Constant Static Load During Consolidation and Shaking Periods

Demob

0

1:00 p

7:00 p

8:00 a

11:00 a

Time

Day 1

Day 2

(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 $\sim$ 91 kN (20,500 lbs)

Depth = 2.1 m

Notes:

$$r_u = \frac{u_{excess}}{\sigma_v'} ; \quad \text{CSR} = \frac{\tau}{\sigma_v'} ; \quad G = \frac{\tau}{\gamma} \quad \rightarrow \quad \tau = G \left( \frac{\gamma}{\gamma} \right)$$
Stage Testing at Natural Soil Test Panel, Site 6: $r_u$ versus Log $\gamma$ after 30 Cycles of Shaking at Each $\gamma$

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

N = 30

Shaking Stages: • Stage 1; ■ Stage 2; ◆ Stage 3; □ Stage 4; ○ Stage 5
2a. Modeling the Loading of the Natural Soil Test Panel Before T-Rex Shaking: Depth 2.1 m

G_{max} = 38.1 \text{ MPa}, \text{ From Field } V_S
\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

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

Pre-Shaking Field Stage:
1. \( G_{\text{max}} \) (No T-Rex)
2. \( G_{\text{max}} \) (With T-Rex)
3. \( G\text{-log}(\gamma) \) (Pre-Shaking)
2b. Modeling the Loading of the Natural Soil Test Panel During T-Rex Shaking: with Measured Values of $r_u$

- $G_{max}^* = 48.2 \text{ MPa}$
- $\sigma_o' = 26.5 \text{ kPa}$
- $G/G_{max}^* = 0.91$
- $\sigma_v' = 0.0\%$
- $CSR = 0.03$

N = 30
Depth = 2.1 m

Excess Pore Pressure Ratio, $r_u(\%)$

Shear Strain (%)

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

Shear Modulus, $G$ (MPa)

Greatest Shear Modulus, $G_{\text{max}}^* = 48.2$ MPa

Effective Stress, $\sigma_0' = 26.5$ kPa

$G / G_{\text{max}}^* = 0.68$

$r_u < 0.1\%$

CSR = 0.14

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

If $r_u = 0$

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

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

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 $r_u$

- $G_{\text{max}}^* = 48.2$ MPa
- $\sigma_o' = 26.5$ kPa
- $G_{\text{max}} = 46.4$ MPa
- $\sigma_o' = 24.6$ kPa
- $r_u = 7.3\%$
- $\text{CSR} = 0.33$

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

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 \( r_u \)

- **Stage 1**: \( G_{\text{max}}^* = 48.2 \text{ MPa} \), \( \sigma_o' = 26.5 \text{ kPa} \)
- **Stage 2**: \( G_{\text{max}} = 44.0 \text{ MPa} \), \( \sigma_o' = 22.0 \text{ kPa} \)
- **Stage 3**: \( r_u = 17.0\% \) CSR = 0.45

- **N = 30**
- **Depth = 2.1 m**
- **\( r_u = \frac{u_{\text{excess}}}{\sigma_v'} \)**

**Shear Strain (%)**

**Shear Modulus, G (MPa)**

**Excess Pore Pressure Ratio, \( r_u \), %**
2c. Predicting the Response of the Natural Soil Test Panel at High Levels of Shaking: with Estimated Values of $r_u$

Predicted Shaking Results:
- Stage 6

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

**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
\(r_u = u_{\text{excess}}/\sigma_{v'}\)
Predicting the Response of the Natural Soil Test Panel at High Levels of Shaking: with Estimated Values of $r_u$

**G_{max}^* = 48.2 MPa**  
$\sigma_0' = 26.5$ kPa

**G_{max} = 26.9 MPa**  
$\sigma_0' = 8.1$ kPa

$N = 30$

Depth = 2.1 m

$r_u = 69\%$

$CSR = 0.33$

$G/G_{max} = 0.16$

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

$G_{\text{max}}^* = 48.2 \text{ MPa}$
$\sigma'_o = 26.5 \text{ kPa}$
$ru = 69\%$
$\text{CSR} = 0.33$

Due to $ru$

If $ru = 0$

Comparing the Response of the Natural Soil Test Panel at High Levels of Shaking: with and without $r_u$

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

Shear Modulus, $G$ (MPa)

Excess Pore Pressure Ratio, $r_u$ (%)

Shear Strain (%)

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)

- **Laboratory RC Test**
  - Specimen
  - LVDT
  - Proximator Probe
  - Drive Plate
  - Magnet
  - Accelerometer

- **In-Situ T-Rex Shaking Test**
  - State Loading
  - Dynamic Shaking

**Notes:**
1. Points were extrapolated to $\gamma = 0.3\%$.
2. $\gamma_t^{pp}$ at $r_u = 0.3\%$.

**Graphs:**
- $G/G_{\text{max}}$ vs. $\gamma$
- $r_u$ vs. Log $\gamma$

**Data:**
- $S6 (2.1 \text{ m}) SP (\text{Avg Dr~40\%}) : \sigma_0' = 28 \text{ kPa}$
- Determined in Field

**Equations:**
- $G/G_{\text{max}} = \log \gamma$
- $(r_u = 0)$

**Excess Pore Pressure Ratio, $r_u$ %**
- RC Testing; $S_r \sim 20\%$
- Pore Pressure Ratio $r_u$

$\gamma_e$

References:
- Wang, 2018
Combining the Laboratory $G/G_{\text{max}} - \log \gamma$ Data (a) and the In-Situ $r_u - \log \gamma$ Data (b)

**Laboratory RC Test**

- Top Cap
- Specimen
- Base Pedestal ("Fixed Base")
- D = 5.1 cm
- $H = 10.2$ cm

**In-Situ T-Rex Shaking Test**

- Dynamic Shaking
- State Loading
- Instrumented Zone
- Not to scale

**Graph**

- Normalized Shear Modulus, $G/G_{\text{max}}$
- Shear Strain, $\gamma$, %
- Excess Pore Pressure Ratio, $r_u$, %

- S6 (2.1 m) SP (Avg Dr~40%) : $\sigma_0' = 28$ kPa

- $G/G_{\text{max}} - \log \gamma$ (Wang, 2018) ($r_u = 0$)

- $r_u - \log \gamma$ (N = 30 cycles)

- RC Testing; $S_r \sim 20$
- Pore Pressure Ratio $r_u$
- Determined in Field
- RC Corrected for $r_u > 0$
- Changed due to $r_u > 0$
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 $r_u = 0.5\%$
- $G/G_{\text{max}} = 0.35$ $\text{CSR} = 0.43$
- $G/G_{\text{max}} = 0.26$ $\text{CSR} = 0.62$
- $G/G_{\text{max}} = 0.21$ $\text{CSR} = 0.76$

Extrapolated Laboratory Data

Creating the $\tau - \gamma$ Curve from Laboratory $G/G_{\text{max}} - \log \gamma$ Data and the In-Situ $G_{\text{max}}^*$
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 $r_u = 0.5\%$

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

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

$G/G_{\text{max}} = 0.26$
$CSR = 0.62$

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

Extrapolated Field Data

$r_u > 0$
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:
   
   $$G = G_{\text{max}} \left(1/(1 + (\gamma/\gamma_r)^a)^b\right)$$
More Effective Constitutive Model for Sands (SP, SW, and SM)

S6 (2.1 m) (Avg Dr~40%) : $\sigma_0' = 28$ kPa

$G/G_{\text{max}} - \log \gamma$

(Wang, 2018)

$G/G_{\text{max}} - \log \gamma$

(Darendeli, 2001)

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

Material : SP

Excess Pore Pressure Ratio, $r_u$, %

Normalized Shear Modulus, $G/G_{\text{max}}$

RC Testing; $S_r \sim 20\%$

Darendeli, 2001

Wang, 2018
Improved Laboratory Testing and Modeling Using Combined Dynamic Resonant Column (RC) and Cyclic Torsional Shear (TS) Equipment

**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
   $G = G_{max} \left(1/(1 + (\gamma/\gamma_r)^a)^b\right)$
Pore Water Pressure Generation Data from Laboratory TS Test (0.54 atm, Strain = 0.05%, N = 30 cycles)