Effective Stress Analysis to Evaluate Ejecta Severity at Sandy and Silty Soil Sites

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Sediment Ejecta

1. Case Histories: 2010-2011 Canterbury EQs
   *Inconsistent assessment with current procedures*

2. Physical Process: Back-Analysis
   *Use effective stress analyses to gain insight*

3. Quantify its severity
   *Ejecta Potential Index (EPI)*

Source: M. Cubrinovski (UC Canterbury)
M$_{w}$ 6.2 2011 February Christchurch

**Underestimated Case**
- $R_{rup}$: 4.7 km
- PGA: 0.38 g
- Estimation: Moderate
- Observation: EXTREME

**Overestimated Case**
- $R_{rup}$: 5.7 km
- PGA: 0.34 g
- Estimation: Severe
- Observation: NONE

Why?

The sunk car

2011 Christchurch Rupture
Bradley & Cubrinovski (2011)
Occurrence of Liquefaction Ejecta Related to CPT Profile

van Ballegooy et al.
Tonkin & Taylor
for the EQC
M_w 6.0 June 13, 2011 Christchurch Earthquake

Original Video Duration: 3 mins 27 sec
Location: Christchurch Suburb

https://youtu.be/rRVK5NJJE2qE
Physical Process of Sediment Ejecta

- **Crust Layer**: Impermeable
  - **Liquefiable Layer**: (Fully Drained Soil)
  - **Denser Layer**: (Fully Drained Soil)

**Equations**:

- Initial total head (Steady state) \( h_{exc} = \) 0

\[ h_{exc} = h_T - h_o \]

Red Zone: \( h_{exc} > h_{icr} \)

- Upward seepage-induced piping condition at the ground surface

**Key Terms**:

- **\( h_{exc} \)**: Excess pressure head (m)
- **\( h_{icr} \)**: Critical head to cause piping condition \( (i > i_{cr}) \) at ground surface
Effective Stress Analysis (ESA) OpenSees v3.0

Crust

Water level

Dry Nodes

Computed response $\{\ddot{u}, \dot{u}, u, p\}$

Saturated Nodes

Equal DOF (tied nodes)

Reduced Integration

Solid-fluid saturated porous medium (u-p element)

Displacement and Pore Pressure Nodes

Stack of quad elements

Solve for

At Corner:
- displacement ($u$)
- velocity ($\dot{u}$)
- acceleration ($\ddot{u}$)
- pore pressure ($p$)

At Center:
- $\frac{\tau_{xy}}{\sigma'_{vo}}$ (CSR)
- $\gamma_{xy}$

L-K (1969) Dashpot

Shear stress time history $\sigma_{xy} = c \dot{u}$

Elastic half-space & outcrop motion

Vertical Fixity

Computed response

Equation $\sigma_{xy} = c \dot{u}$
Constitutive Models

PM4Sand & PM4Silt
(Boulanger & Ziotopoulou 2017, 2018)

Based primarily on CPT data

For:

\[ I_B > 32: \] PM4Sand (Sand-Like)

\[ 22 < I_B < 32: \] PM4Silt \((r_{u-max} = 0.99)\)

\[ I_B < 22: \] PM4Silt (Clay-Like)

* Hutabarat & Bray PEER Report for more detail on PM4Sand & PM4Silt parameters
At each time step when $h_{exc} > h_{icr}$, the area is given by:

$$\text{Artesian Flow Potential (m}^3) = \int_{\text{Datum}}^{\text{GWL}} (h_{exc} - h_{icr})^2 \, dz$$

$i > i_{cr}$, cause piping
Progressive cracks at crust

For thicker liquefaction,
More RED Shaded Area
Greater Artesian Pressure
More Water Volume
180 Seconds of Dynamic ESA simulation

Shirley

St. Teresa

Time 179.84 sec

AFP (m$^3$)

0.0 0.5 1.0 1.5 2.0

high AFP value after shaking stop t>50 s due to upward seepage

Time 179.88 sec

thicker liquefaction, but not enough artesian pressure (AFP = 0) to crack crust layer & eject sediment

Depth (m)

0 2 4 6 8 10 12 14 16 18 20 22 24 26

q$_f$ (MPa)

Disp. (m)

Excess Head (m)

Base Motion

Accel (g)

0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0

Time (s)

0 20 40 60 80 100 120 140 160 180
Ejecta Potential Index (EPI)
Artesian Flow Potential integrated over time

\[ EPI(\text{m}^3.\text{s}) = \int_{0}^{t_d} \int_{\text{Datum}}^{GWL} (h_{exc} - h_{icr})^2 \, dz \, dt \]

Measure of hydraulic gradient, critical layer thickness, and volume of water over time

<table>
<thead>
<tr>
<th>Site</th>
<th>Event</th>
<th>LSN</th>
<th>Observation</th>
<th>EPI (m³.s)</th>
</tr>
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<tbody>
<tr>
<td>Shirley Darfield</td>
<td>3</td>
<td>NONE</td>
<td>0</td>
<td></td>
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<tr>
<td>St. Teresa</td>
<td>44</td>
<td>NONE</td>
<td>0</td>
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<td>Shirley Christchurch</td>
<td>15</td>
<td>EXTREME</td>
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<tr>
<td>St. Teresa</td>
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<tr>
<td>Shirley June</td>
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<td>SEVERE</td>
<td>83</td>
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<tr>
<td>St. Teresa</td>
<td>14</td>
<td>NONE</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Extending the analysis duration is important to understand the full story
Evaluation of EPI

23 Well-investigated sites
(BH, CPT, VsVp, GWL, Photos)

Well-documented case histories
(22 New Zealand + 1 Japan)

4 Shallow-crustal earthquakes
23 well-investigated sites forming 46 case histories:

- 3 Extreme: $\text{EPI} > 120$
- 6 Severe: $40 < \text{EPI} < 120$
- 10 Moderate: $10 < \text{EPI} < 40$
- 3 Minor: $2 < \text{EPI} < 10$
- 24 None: $\text{EPI} < 2$

90% of cases estimated correctly
10% of cases with minor inconsistencies
Conclusions

Post-shaking water flow is important, because the primary driving mechanism is *upward seepage-induced piping*.

Severity of sediment ejecta influenced by:
- Drainage contrast ($c_v$ profile)
- Excess head (pressure)
- Duration (piping)

Ejecta Potential Index (EPI):
- 46 case histories (23 sites & 4 earthquakes)
- 90% well-estimated
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