Statistical Estimation of Soil Type Using Cross-plots of S-wave Velocity and Resistivity in Japanese Levees

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Outline of Integrated Geophysical Method for Levee Safety Assessment

• The method consists of a surface-wave method and resistivity methods, such as a capacitively-coupled resistivity method or an electro-magnetic method.
• The surface-wave method provides S-wave velocity structure of levee body and fundation.
• The capacitively-coupled resistivity method or the electro-magnetic method provides resistivity structure of levee body and foundation.
• A cross-plot analysis of S-wave velocity and resistivity estimates soil type of levee body and foundation.
Surface-wave Method Using Land Streamer

Statistical Estimation of Soil Type Using Cross-plots of S-wave Velocity and Resistivity in Japanese Levees
In CCR, capacitors are used as electrode and metallic stakes are not used. The OhmMapper was used as a CCR instrument.
S-wave Velocity and N-value (blow-count) obtained by SPT

\[ N = 1.7 \times 10^{-4} \times V_s^{2.1} \]
20% Grain Size (D20) and Resistivity
S-wave velocity and Resistivity for Levee Safety

• From the Archie’s equation, resistivity of soil mainly indicates soil type.
• S-wave velocity is mainly affected by shear strength or porosity.
• Safety of levees can be evaluated by S-wave velocity and resistivity.

<table>
<thead>
<tr>
<th>Resistivity</th>
<th>Soil type</th>
<th>S-wave velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Clayey</td>
<td>Low (loose)</td>
</tr>
<tr>
<td>Low</td>
<td>Sandy</td>
<td>High (tight)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Resistivity</th>
<th>Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Safe (tight, clayey)</td>
</tr>
<tr>
<td>Low</td>
<td>Danger (loose, sandy)</td>
</tr>
</tbody>
</table>
S-wave velocity and Resistivity for Levee Safety

- A soil type (clay, sand or gravel) or grain size distribution (clay contents or $D_{20}$) is the most important information for levee safety evaluation from an engineering point of view.
- The soil type or the grain size distribution is used in many engineering analyses.
- In most of such analyses, the soil type or the grain size distribution is obtained by the borings or laboratory tests.
- Physical properties obtained through the geophysical methods (e.g. S-wave velocity or resistivity) do not directly relate to the soil type and the grain size distribution.
- We are going to estimate the soil type in terms of a statistical approach using geophysical and geotechnical data collected in Japan.
Statistical Estimation of Soil Type

- Soil type of levee body and foundation is statistically estimated using cross-plots of S-wave velocity and resistivity in Japan.
- S-wave velocity and resistivity are collected from surface wave methods and resistivity methods.
- Total survey line length of the geophysical methods is about 600km on 37 rivers in Japan.
- The blow counts and soil types are collected from about 400 boring logs carried out on geophysical survey lines.
- The total number of extracted data is about 4000.
Example of Geophysical Sections

S-wave velocity

Resistivity

Statistical Estimation of Soil Type Using Cross-plots of S-wave Velocity and Resistivity in Japanese Levees
## Statistical Estimation of Soil Type Using Cross-plots of S-wave Velocity and Resistivity in Japanese Levees

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>N-value</th>
<th>S-wave velocity (m/sec)</th>
<th>Resistivity (ohm-m)</th>
<th>Soil type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3</td>
<td>42</td>
<td>230</td>
<td>226</td>
<td>Gravel</td>
</tr>
<tr>
<td>2.3</td>
<td>9</td>
<td>230</td>
<td>256</td>
<td>Gravel</td>
</tr>
<tr>
<td>3.3</td>
<td>8</td>
<td>220</td>
<td>339</td>
<td>Gravel</td>
</tr>
<tr>
<td>4.4</td>
<td>10</td>
<td>259</td>
<td>378</td>
<td>Gravel</td>
</tr>
<tr>
<td>5.5</td>
<td>8</td>
<td>223</td>
<td>262</td>
<td>Gravel</td>
</tr>
<tr>
<td>6.3</td>
<td>8</td>
<td>223</td>
<td>262</td>
<td>Gravel</td>
</tr>
<tr>
<td>7.3</td>
<td>6</td>
<td>220</td>
<td>134</td>
<td>Sand</td>
</tr>
<tr>
<td>8.3</td>
<td>23</td>
<td>243</td>
<td>134</td>
<td>Gravel</td>
</tr>
<tr>
<td>9.3</td>
<td>20</td>
<td>247</td>
<td>134</td>
<td>Gravel</td>
</tr>
<tr>
<td>10.3</td>
<td>24</td>
<td>247</td>
<td>93</td>
<td>Sand</td>
</tr>
<tr>
<td>11.3</td>
<td>20</td>
<td>297</td>
<td>93</td>
<td>Gravel</td>
</tr>
<tr>
<td>12.3</td>
<td>29</td>
<td>311</td>
<td>80</td>
<td>Gravel</td>
</tr>
<tr>
<td>13.3</td>
<td>33</td>
<td>311</td>
<td>80</td>
<td>Gravel</td>
</tr>
<tr>
<td>14.3</td>
<td>31</td>
<td>307</td>
<td>80</td>
<td>Gravel</td>
</tr>
<tr>
<td>15.3</td>
<td>35</td>
<td>307</td>
<td>73</td>
<td>Gravel</td>
</tr>
<tr>
<td>16.3</td>
<td>19</td>
<td>307</td>
<td>73</td>
<td>Gravel</td>
</tr>
<tr>
<td>17.3</td>
<td>39</td>
<td>307</td>
<td>73</td>
<td>Gravel</td>
</tr>
</tbody>
</table>
Cross-plot of Vs and Resistivity

<table>
<thead>
<tr>
<th>S-wave velocity (m/sec)</th>
<th>Resistivity (ohm-m)</th>
<th>Soil type</th>
</tr>
</thead>
<tbody>
<tr>
<td>230</td>
<td>226</td>
<td>Gravel</td>
</tr>
<tr>
<td>230</td>
<td>256</td>
<td>Gravel</td>
</tr>
<tr>
<td>220</td>
<td>339</td>
<td>Gravel</td>
</tr>
<tr>
<td>259</td>
<td>378</td>
<td>Gravel</td>
</tr>
<tr>
<td>223</td>
<td>262</td>
<td>Gravel</td>
</tr>
<tr>
<td>223</td>
<td>262</td>
<td>Gravel</td>
</tr>
<tr>
<td>220</td>
<td>134</td>
<td>Sand</td>
</tr>
<tr>
<td>243</td>
<td>134</td>
<td>Gravel</td>
</tr>
<tr>
<td>247</td>
<td>134</td>
<td>Gravel</td>
</tr>
<tr>
<td>247</td>
<td>93</td>
<td>Sand</td>
</tr>
<tr>
<td>297</td>
<td>93</td>
<td>Gravel</td>
</tr>
<tr>
<td>311</td>
<td>80</td>
<td>Gravel</td>
</tr>
<tr>
<td>311</td>
<td>80</td>
<td>Gravel</td>
</tr>
<tr>
<td>307</td>
<td>80</td>
<td>Gravel</td>
</tr>
<tr>
<td>307</td>
<td>73</td>
<td>Gravel</td>
</tr>
<tr>
<td>307</td>
<td>73</td>
<td>Gravel</td>
</tr>
<tr>
<td>307</td>
<td>73</td>
<td>Gravel</td>
</tr>
</tbody>
</table>

Statistical Estimation of Soil Type Using Cross-plots of S-wave Velocity and Resistivity in Japanese Levees
Resistivity and S-wave velocity from 400 Boring Logs

Levee body (unsaturated)

Foundation (saturated)
Statistical Estimation of Soil Type Using Cross-plots of S-wave Velocity and Resistivity in Japanese Levees
Polynomial Approximation of Soil Type

• Polynomial approximation (curved plane) is used to estimate the soil type from the correlation between S-wave velocity and resistivity.

• In the approximation, the soil type is represented by discontinuous numbers one (clay), two (sand) and three (gravel).

• Polynomial equation is a function of S-wave velocity ($V_s$) and resistivity ($\rho$) and yields a continuous value $S$ between one and three.

$$S = aV_s^2 + bV_s + c \log 10(\rho)^2 + d \log 10(\rho) + eV_s \log 10(\rho) + fV_s \log 10(\rho)^2 + gV_s \log 10(\rho) + h$$

• Coefficients of equation are optimized by least squares method.
## Soil Type and Represented Numbers

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Represented number</th>
<th>Number of data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Levee body</td>
</tr>
<tr>
<td>Clay</td>
<td>1.0</td>
<td>221</td>
</tr>
<tr>
<td>Sand</td>
<td>2.0</td>
<td>199</td>
</tr>
<tr>
<td>Gravel</td>
<td>3.0</td>
<td>143</td>
</tr>
<tr>
<td>Total</td>
<td>-</td>
<td>563</td>
</tr>
</tbody>
</table>

Statistical Estimation of Soil Type Using Cross-plots of S-wave Velocity and Resistivity in Japanese Levees
S-wave velocity and Resistivity

Levee body

Statistical Estimation of Soil Type Using Cross-plots of S-wave Velocity and Resistivity in Japanese Levees
Polynomial Approximation

Levee body

Statistical Estimation of Soil Type Using Cross-plots of S-wave Velocity and Resistivity in Japanese Levees
S-wave velocity and Resistivity

Foundation

Statistical Estimation of Soil Type Using Cross-plots of S-wave Velocity and Resistivity in Japanese Levees
Polynomial Approximation

Foundation

Statistical Estimation of Soil Type Using Cross-plots of S-wave Velocity and Resistivity in Japanese Levees
Polynomial Approximation

Statistical Estimation of Soil Type Using Cross-plots of S-wave Velocity and Resistivity in Japanese Levees

Levee body (unsaturated)

Foundation (saturated)

S-wave velocity (m/s)

Resistivity (ohm-m)

Clay
Sand
Gravel

:Clay
:Sand
:Gravel

Statistical Estimation of Soil Type Using Cross-plots of S-wave Velocity and Resistivity in Japanese Levees
**Polynomial Approximation of Soil Type**

\[ S = a v_s^2 + b v_s + c \log_{10}(\rho)^2 + d \log_{10}(\rho) + e v_s \log_{10}(\rho) + f v_s \log_{10}(\rho)^2 + g v_s \log_{10}(\rho) + h \]

<table>
<thead>
<tr>
<th>Levee body</th>
<th>Foundation</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>-0.00000062</td>
</tr>
<tr>
<td>b</td>
<td>-0.0072263</td>
</tr>
<tr>
<td>c</td>
<td>0.5333744</td>
</tr>
<tr>
<td>d</td>
<td>-1.5275230</td>
</tr>
<tr>
<td>e</td>
<td>0.0000016</td>
</tr>
<tr>
<td>f</td>
<td>-0.0025515</td>
</tr>
<tr>
<td>g</td>
<td>0.0111545</td>
</tr>
<tr>
<td>h</td>
<td>1.7115340</td>
</tr>
</tbody>
</table>

Statistical Estimation of Soil Type Using Cross-plots of S-wave Velocity and Resistivity in Japanese Levees
Example of Estimation

Statistical Estimation of Soil Type Using Cross-plots of S-wave Velocity and Resistivity in Japanese Levees
Example of Estimation

Statistical Estimation of Soil Type Using Cross-plots of S-wave Velocity and Resistivity in Japanese Levees

Soil type
- Gravel (3.0)
- Sand (2.0)
- Clay (1.0)

Levee body
Foundation
Accuracy of Estimation

• Accuracy of estimation can be statistically evaluated by comparing the estimated soil parameter with actual soil.

• Data were grouped into four groups (1.0 to 1.5, 1.5 to 2.0, 2.0 to 2.5, 3.0 to 3.5) by the estimated soil parameter.

• In each group, the numbers of actual soil type (clay, sand, gravel) were counted as probability.
Accuracy of Estimation

Levee body

Foundation

Estimated soil parameter

0% 20% 40% 60% 80% 100%

1.0 to 1.5
1.5 to 2.0
2.0 to 2.5
2.5 to 3.0

Proportion

Estimated soil parameter

Levee body

Clay(1.0)
Sand(2.0)
Gravel(3.0)

Foundation

Clay(1.0)
Sand(2.0)
Gravel(3.0)

Probability

Statistical Estimation of Soil Type Using Cross-plots of S-wave Velocity and Resistivity in Japanese Levees
Conclusions

• The soil type of levee body and foundation was statistically predicted using the cross-plots of S-wave velocity and of resistivity.

• The results imply that the physical properties obtained by geophysical methods, such as S-wave velocity and resistivity, can be used not only for qualitative interpretation but also quantitative engineering analyses, such as slope stability or liquefaction analyses.

• Similar approaches can be applied to other purposes besides levee inspection and other countries besides Japan.

• It is important that any results of geophysical investigations are saved as a standard format and registered in database with adequate geotechnical or geological information.