Study on strength estimation of soil cement used in the embedded pile method by electrical resistivity measurement

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Abstract. Problems caused by poor quality control and quality assurance of the pre-boring embedded pile construction, such as on domestic apartment house, is still occurring nowadays. An adequate consideration for invisible risks inside or below the ground is important in pile foundation construction therefore the demand for advanced and reliable quality assurance is increase in the future. In this research, to understand the quality of the construction at early stage, the compressive strength of cement-soil mixture of pile construction after 28 days is estimated using electrical resistivity value of the mixture. More accurate measurement for electrical resistivity value is conducted by inserting the electrodes without using potassium chloride solution as a catalyst. The result showed that there is a certain tendency in the electric resistivity value at the early age regarding to the type of soil (sand, clay) mixed in. The most accurate estimation was achieved from the electric resistivity value at the first day and several days onwards, and from the compressive strength after 3 days.

1. Introduction
The purpose of this research is to study the utilization of electrical resistivity measurement to predict compressive strength and to perform quality control of cement slurry used in bored precast pile construction technique [1][2][4][5]. This paper consists report and recommendation for electrical resistivity measurement technique [3], quantification and estimation technique of electrical resistivity, compressive strength estimation formula based on electrical resistivity value and quality control method using strength prediction of cement slurry through indoor/laboratory and field examination [3][4][5].

2. Laboratory experiment of soil cement mixture
The electrical resistivity measurement methods were decided prior to laboratory examination. The following three patterns of electrical resistivity measurement methods were performed at the same time and suitable method is studied.

1. At 28 days from pouring without removing cell and no pore water.
2. Only measure bleeding water at early stage by making hole with diameter same as cell in specimens. After that stage, 0.1% KCl solution is used as pore water.
3. Using KCl solution with the same electrical resistivity value as specimen right after poured into cell. After that stage, the same procedure as number 2.

Considering actual soil configuration, cement slurry only, cement with sand, cement with clay and cement with sand and clay, three variants of mixture is used for laboratory examination. Electrical conductivity meter and schematic view of measurement are shown in Figure 1.
2.1 Laboratory examination mixture using cement slurry

Electrical resistivity value change with time shown by Figure 2 gives information that electrical resistivity value is tends to be the same regardless of mixture and cement amount. For mixture curing age of one day, electrical resistivity value is greatly affected by pore water for method number 1 and number 2, therefore, method number 1 is recommended for electrical resistivity measurement. In addition, temperature change also influences electrical resistivity value.

Figure 2. Electrical resistivity value change with time

Relationship between compression strength and electrical resistivity value measured by method number 1 as shown by Figure 3 resulted to conclusion that relation between $\frac{q_{u28}}{\rho_{28}}$ and $\frac{q_{u3}}{\rho_{3}}$ was more correlative than $\frac{\Delta q_{u}}{\Delta \rho}$ and $\frac{q_{u3}}{\rho_{3}}$. In other hand, measurement methods number 2 and 3 also had similar result, therefore, compression strength estimation formula using relationship between $\frac{q_{u28}}{\rho_{28}}$ and $\frac{q_{u3}}{\rho_{3}}$ is recommended. Here, $q_{u}$ is compressive strength, $\rho$ is electrical resistivity and subscript number indicates specimen curing age in day(s) unit.

Method 1: 
$$q_{u28} = \{0.1058 \cdot (\frac{q_{u3}}{\rho_{3}}) + 8.8964\} \cdot \rho_{28}$$  \hspace{1cm} (1)

Method 2: 
$$q_{u28} = \{3.3823 \cdot (\frac{q_{u3}}{\rho_{3}}) + 63.551\} \cdot \rho_{28}$$  \hspace{1cm} (2)

Method 3: 
$$q_{u28} = \{0.5807 \cdot (\frac{q_{u3}}{\rho_{3}}) + 9.3560\} \cdot \rho_{28}$$  \hspace{1cm} (3)

Since electrical resistivity value tends to change regarding to time (curing age), compressive strength can be estimated using $\rho$ value from early curing age until reached final curing age (28 days). Electrical resistivity changes due curing age is observed to decide the suitable time for estimating the compressive strength as shown by Figure 4. Relationship between $\rho_{1}$ and $\rho_{28}$ recommends equation 4, equation 5 and equation 6 for estimating $\rho$ value. In addition, considering $\rho$ value at early age and onwards due to pore water existence, relationship between $\rho_{0}$ and $\rho_{1}$ is used for measurement method 1 and $\rho_{1}$ vs $\rho_{1}$ for method 2 and 3 recommends equation 7 – equation 9 for estimating $\rho$ value. Therefore, equation 4 – equation 9 is used for estimating electrical resistivity value ($\rho$).
Method 1: \[ \rho_{28} = 7.8687 \cdot \rho_3^{1.5779} \]  
Method 2: \[ \rho_{28} = 0.8950 \cdot \rho_3^{0.153} \]  
Method 3: \[ \rho_{28} = 3.5787 \cdot \rho_3^{1.1367} \]  

Method 1: \[ \rho_3 = 0.0015 \cdot \rho_0^{-2.483} \]  
Method 2: \[ \rho_3 = 1.8722 \cdot \rho_1^{1.1642} \]  
Method 3: \[ \rho_3 = 4.0211 \cdot \rho_3^{1.5936} \]  

Subsequently, estimation formulation for compressive strength prediction was also attempted. Equation 10 is formulation recommended by Japan Society of Civil Engineering (JSCE) [6], is used and applied for laboratory examination in this research. Where \( \alpha \) and \( \beta \) is material constants and \( t \) is specimen’s curing age. Calculation of performed by linear interpolation of \( q_u(28)/q_u(t) \) vs \( t \) recommended by JSCE (Figure 5) and listed in Table 1.

![Figure 3. Relationship between \( \Delta q_u/\Delta \rho \) and \( q_u3/\rho_3 \) and \( q_u28/\rho_{28} \) and \( q_u3/\rho_3 \)](image)

![Figure 4. Relationship between \( \rho_3 \) and \( \rho_{28} \) and \( \rho_0 \) and \( \rho_3 \)](image)

**Table 1. Laboratory experiment mixture condition**

| Sample condition (W/C) | \( \alpha \) | \( \beta \) |
|------------------------|-------------|-------------|
| 60%                    | 0.84        | 4.86        |
| 80%                    | 0.68        | 9.53        |
| 100%                   | 0.79        | 6.08        |
| Average                | 0.77        | 6.6233      |

\[ q_u(t) = q_u(28) \times \frac{t}{\alpha x t + \beta} \]  

Estimation of compressive strength using equation 1 to equation 9 and laboratory compressive strength test are attempted and the result is compared as shown by Figure 6. Estimated value and measured value are nearly consistent for measurement method 1. Estimated value is larger than measured value for method 2 while Measured value is larger than estimated value for method 3. Hence, method 1 is possible and recommended for estimating electrical resistivity value.
Figure 5. Relationship of $t$ and $t_{qu_{28}}/qu_{t}$ (left) and Figure 6. Comparison of measured vs predicted value of compressive strength (right)

2.2 Laboratory examination mixture using sandy soil and clayey soil

Laboratory examination for sandy and clayey soil assumption are performed and the procedures are shown by Figure 7 and mixture condition listed in Table 2. Electrical resistivity value changes by material age (time) for sandy soil is different from cement only and cement with clay soil due to precipitation influence. For clay soil, specimen is expanding and cracks occurs during curing process causing variation in electrical resistivity value. Furthermore, for clay soil, the viscosity of the soil cement slurry was very high therefore the compressive strength test could not performed as shown by Figure 8.

![Figure 7. Soil cement mixing procedure](image)

| W/C ratio (%) | Mud water ratio | Cement milk : mud water | Replacement soil percentage (%) |
|---------------|-----------------|-------------------------|---------------------------------|
| 60            | 1.5             | 1:3                     | A                               |
| 60            | 1.5             | 1:5                     | B                               |
| 60            | 1.5             | 1:10                    | C                               |
| 100           | 1.5             | 1:2                     | D                               |
| 100           | 1.5             | 1:2.5                   | E                               |
| 100           | 1.5             | 1:2                     | F                               |

Compressive strength estimation for sandy soil specimen are also conducted using the same procedure as cement slurry only specimen and recommended formulation, equation 11 ~ equation 19 and equation 10, and comparison between measured and estimated value is shown by Figure 9. As a result, for every measurement method, compressive strength prediction is possible even when sand is mixed. There was specimen with large error of compressive strength value, however, bleeding water effect during curing process might cause this phenomenon.

Method 1: $q_{u_{28}}=(0.2514 \cdot (qu_{3}/\rho_{3})+0.6748) \cdot \rho_{28}$  
Method 2: $q_{u_{28}}=(0.451 \cdot (qu_{3}/\rho_{3})+0.5002) \cdot \rho_{28}$  
Method 3: $q_{u_{28}}=(0.9578 \cdot (qu_{3}/\rho_{3})+2.9513) \cdot \rho_{28}$

Method 1: $\rho_{28}=0.2807 \cdot \rho_{28}^{2.071}$  
Method 2: $\rho_{28}=0.7269 \cdot \rho_{28}^{0.2769}$  
Method 3: $\rho_{28}=0.9634 \cdot \rho_{28}^{0.572}$

Method 1: $\rho_{2}=0.5048 \cdot \rho_{2}^{0.284}$  
Method 2: $\rho_{2}=0.0946 \cdot \rho_{2}^{0.7377}$  
Method 3: $\rho_{2}=0.7643 \cdot \rho_{2}^{-0.599}$
2.3 Laboratory mix examination assuming actual ground

Laboratory mixing experiment assuming actual soil condition was performed using sand and clay mixed together with mixing conditions listed in Table 3. The experiment results lead to inconsistent change of electrical resistivity value with time along with large variation. Similar method to predict compressive strength of the specimen using relationship between $q_{u28}/\rho_{28}$ and $q_{u3}/\rho_3$ also applied in this procedure and came to results that equations 20~28 are recommended for compressive strength prediction. Comparison between predicted value and measured value shown by Figure 10.

Method 1: $q_{u28} = (0.2662(q_{u3}/\rho_3)+1.9764)\rho_{28}$ (25)
Method 2: $q_{u28} = (4.1042(q_{u3}/\rho_3)-81.007)\rho_{28}$ (26)
Method 3: $q_{u28} = (2.8788(q_{u3}/\rho_3)-51.029)\rho_{28}$ (27)

Method 1: $\rho_{28} = 3.2724\rho_{3}^{0.6215}$ (28)
Method 2: $\rho_{28} = 66.139\rho_{3}^{3.2056}$ (29)
Method 3: $\rho_{28} = 278.01\rho_{3}^{4.427}$ (30)

Method 1: $\rho_3 = 0.5048\rho_0^{0.2804}$ (31)
Method 2: $\rho_3 = 0.7679\rho_1^{0.7792}$ (32)
Method 3: $\rho_3 = 0.4656\rho_1^{0.6635}$ (33)

| W/C ratio (%) | Mud water amount ratio | Cement milk : mud water | Sand : clay | Replacement soil percentage (%) |
|---------------|------------------------|-------------------------|-------------|---------------------------------|
| 60            | 1.6                    | 1:1                     | G           | 3:7                             | 100                              |
| 60            | 1.6                    | 1:1                     | H           | 6:4                             | 100                              |
| 60            | 1.6                    | 1:1                     | I           | 8:2                             | 100                              |

Measurement method 1 and 2 gives prediction with high accuracy, however not with method 3. It is understood that the mixture of sand and clay has moderate density and reduce bleeding process, therefore increase accuracy in measuring electrical resistivity and improves accuracy of prediction formulation.
3. Outdoor experiment

3.1 Examination of pile hole at the construction site.

Bored pile construction site in Arahama, Kashiwa city of Niigata prefecture is selected for outdoor experiment. The specifications were bored pile hole with diameter of 530mm, depth of 20m and with W/C ratio of 60%. Collection of unsolidified sample was carried out from overflow and mortar plant and the universal water sampler shown in Figure 11 and was conducted from depth of 2.5m, 5.0m, 10m, and the specific resistance value on the ground are measured. Soil until depth of 15m was sandy soil. At the same time, electrical resistivity value near depth of 5.0 m was also measured using custom made electrical conductivity meter with cord length of 30 m.

Changes of electrical resistivity value was rapid as shown by Figure 12. Is it believed that summer season condition caused the acceleration of specimen curing process. Figure 12 also shows that the temperature rise is extremely low inside the hole, the influence of the outside air is small at the depth of 5.0m and the influence on the quality by the temperature is not significant.

The result of compressive strength value using prediction equation is shown as listed in table 4. An Accurate strength prediction performed by sample collected from inside the bored hole. In addition, it is possible to predict the compressive strength with an error of about 1.0 N / mm² for safety consideration. However, for sample collected from the plant gives more variation as effect of temperature change is believed to cause this large margin of error.

![Figure 11. Tools and sample collection](image)

![Figure 12. Electrical resistivity value and temperature change](image)

| Plant | Depth = 0m | Depth = 2.5m | Depth = 5.0m | Depth = 10.0m | Inside the hole |
|-------|------------|--------------|--------------|---------------|----------------|
| $\bar{q}_{38}$ (predicted) | 11.1 | 3.036 | 4.43 | 4.24 | 4.64 | 3.04 |
| $\bar{q}_{38}$ (measured) | 29.52 | 4.282 | 4.28 | 4.28 | 4.28 | 4.28 |
| $\rho_0$ (measured) | 0.122 | 0.333 | 0.273 | 0.273 | 0.261 | 0.333 |
| Equation used | 1.2.7.A | 10.13.16.A | 10.13.16.A | 10.13.16.A | 10.13.16.A | 10.13.16.A |
3.2 Laboratory mixing experiment using site soil
Soil sample also collected from the same construction site in Arahama, Kashiwazaki-shi, Niigata
prefecture. Sample was taken using from the bored hole depth of 21.0m (sandy soil) and 51.0m
(gravel ground) and cement milk with water cement ratio 60%. Similar mixture experiment was
conducted and the condition is listed in table 5. Electrical resistivity value is shown in Figure 13 and
mixture P and Q has different initial electrical resistivity value compare other mixture. The influence
of variation in gravel size of site soil is believed as a factor and temperature also has significant effect.

| W/C ratio (%) | Soil classification | Mud water amount ratio | Cement milk : mud water | Replacement soil percentage (%) |
|---------------|---------------------|------------------------|-------------------------|--------------------------------|
| 60            | Sand                | 1.6                    | 1:1                     | J 100                          |
| 60            | Sand                | 1.6                    | 1:1.5                   | K 150                          |
| 60            | Sand                | 1.6                    | 1:2                     | L 200                          |
| 60            | Gravel              | 1.7                    | 1:1                     | P 100                          |
| 60            | Gravel              | 1.7                    | 1:1.5                   | Q 150                          |
| 60            | Gravel              | 1.7                    | 1:2                     | R 200                          |

Compressive strength was also calculated using prediction formulation (equation 25 to equation 31)
and obtained the same results for every mixture sample. This is believed caused by large error of
predicted value when assumed \( \rho_0 \) was larger than soil electrical resistivity value. Based on this result,
it is necessary to collect more data on the electric resistivity value estimation formula and modify it to
an estimation formula incorporated to actual soil conditions.

4. Electrical Resistivity Measurement Based of Strength Prediction Recommendation
Based on performed laboratory experiment in this research, prediction formulation for compressive
strength of bored pile construction using electrical resistivity measurement procedure is recommended
by following diagram shown by Figure 14.

Figure 13. Electrical resistivity value and temperature change with time
Figure 14. Recommendation procedure for compressive strength prediction soil cement mixture

5. Conclusion
1. Electrical resistivity measurement method 1 was the most suitable method to predict compressive strength of cement milk or cement soil mixture.
2. Electrical resistivity value of specimen at early age tends to be consistent regardless to mixture configuration and cement amount if the particle size of soil is uniform to some extent.
3. The temperature change of the specimen is greater than Atmospheric temperature has more influence to temperature change of the specimens rather than the heat emission due to the hydration reaction.
4. The relationship between \( q_{us} / \rho_2 \) and \( qu / \rho_3 \) is better than \( \Delta q / \Delta \rho \) and \( qu / \rho_3 \).
5. It is possible to use measurement method 2 and 3 for laboratory experiment, however correction process is necessary.
6. Based on outdoor experiment, temperature change does not have significant effect to compressive strength.
7. It is necessary to perform another experiment to understand the influence of soil classification and particle size of soil to electrical resistivity value.
8. Equation 1 to equation 33 may be applied to predict compressive strength of actual condition, however accurate electrical resistivity measurement and measurement data accumulation is necessary.

6. References
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