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Statistical analysis for evaluating cyclic strength of cement-treated soils

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Abstract

This study presents a statistical analysis for evaluating the cyclic unconfined compressive strength of cement-treated soils. In laboratory tests on cement-treated soils, the strength of the specimens varies to some extent even though they are prepared in the laboratory. Therefore, the influence of the variation in specimen strength on the cyclic loading test results should be assessed in order to obtain the cyclic strength precisely. Moreover, the variability of the specimen strength results in non-failure specimen data even at a large number of loading cycles. In the present study, the binary regression approach is adopted for analyzing the cyclic loading test results to take into account the non-failure specimen data. In the binary regression approach, the cyclic loading test results are treated as having one of two possible forms, namely, 'failure' or 'non-failure', at prescribed cycles. The parameters in the binary regression model are related to the variability of the cyclic strength and the ratio of the cyclic strength to the unconfined compressive strength. The binary regression analysis results reveal that the variability of the cyclic strength approximately corresponds to the variability of the specimen strength. The non-failure specimen data is properly treated in evaluating the cyclic strength by adopting the binary regression analysis. Using the binary regression analysis approach proposed in this study, an unnecessarily large number of cycles to failure is not required in the cyclic loading tests. This reduces the experimental cost for obtaining the deterioration property of the materials.

Keywords: Cement-treated soil; Strength; Cyclic loading; Variability; Statistical analysis (**IGC**: D6)

1. Introduction

Ground improvement by cement mixing has been widely used for structural foundations and liquefaction mitigation methods. When employing cement mixing for structural foundations and liquefaction mitigation methods, cyclic loadings induced by the inertia forces of the structure and the soil mass are applied to the improved ground during an earthquake (Namikawa et al., 2007; Khosravi et al., 2016). These cyclic loadings are likely to degrade cement-treated soils. Therefore, the deterioration of strength is one of the major issues in the seismic design of ground improvement by cement mixing, and the mechanical properties of cement-treated soils subjected to cyclic loadings should be investigated to assess the internal stability of ground improvement by cement mixing.

Several researchers have conducted laboratory cyclic loading tests on cement-treated soils (Terashi et al., 1983; Nakajima et al., 1984; Sharma and Fahey, 2003; Viana

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da Fonseca et al., 2013). In the cyclic loading test results, the deterioration of the material strength with cyclic loading is usually represented as a plot of applied stress against the number of cycles to failure, which is known as an S–N curve. Terashi et al. (1983) conducted cyclic unconfined compression tests for cement-treated soil specimens prepared in a laboratory and provided the S–N curve based on the experimental results. The S–N curve shows a linear relationship between the applied stress and the logarithm of the number of cycles to failure. In the test results, the data varies widely and a few specimens do not fail in 2×10^5 cycles which was set as the number of cycles to runout. In their study, the data on the non-failure specimen was not considered when evaluating the S–N curve. Nakajima et al. (1984) also conducted cyclic unconfined compressive tests for cement-treated soil specimens prepared in a laboratory. As in the results provided by Terashi et al. (1983), the experimental results provided by Nakajima et al. (1984) show that there is a large variation in the relationship between the applied stress and the number of cycles to failure.

Previous experimental evidence suggests that the data obtained from cyclic loading tests for cement-treated soils varies widely even though the specimens are prepared in a laboratory. Such variability in the cyclic loading test results might be mainly induced by the variability of the unconfined compressive strength q_u of the specimens because the q_u of the specimens prepared using the same laboratory procedure varies to some extent. Kitazume et al. (2015) examined the influence of applying different molding techniques to the laboratory preparation of specimens on the strength of cement-treated soils. They showed that the coefficient of the variation values for q_u of the specimens prepared by the tamping method lies in the range of 0.05–0.18. This indicates that it is difficult to carry out cyclic loading tests with specimens having exactly the same strength. However, previous studies have never assessed the influence of the variation in q_u on the variation in the cyclic loading test results. An assessment of that influence is required to analyze the factors inducing the variation in the cyclic loading test results.

When the q_u of specimens varies in the cyclic loading tests, the specimens are likely not to fail under the cyclic stress that is determined from the mean of q_u. This indicates that the variation in q_u yields non-failure specimen data which was not considered when evaluating the S–N curve in previous studies. This implies that the S–N curve is likely to have been evaluated with bias. In particular, when the number of cycles to runout is not large, many non-failure specimens are yielded in the cyclic loading tests. Japanese Geotechnical Standard JGS2562 (JGS, 2012) recommends that the number of cyclic loadings to runout be 200 in order to determine the fatigue properties of rocks in cyclic triaxial compression tests. Although the recommended cyclic number is not large, that standard does not describe how to treat the data on runout specimens when determining the fatigue properties.

This study presents a statistical analysis for evaluating the cyclic strength q_{cyc} of cement-treated soils. The cyclic stress is defined here as the axial compression stress applied cyclically to a specimen under an unconfined condition. q_{cyc} is defined as the maximum value of cyclic axial compression stress σ_{max} causing failure at a specific number of cycles in the cyclic unconfined compression tests. In other words, q_{cyc} represents the cyclic unconfined compressive strength for a specific number of cyclic loadings. q_{cyc} is likely to become smaller than q_u because cyclic loading degrades the strength. Strength ratio R_s, defined as the ratio of the mean of q_{cyc} to that of q_u, is used as the deterioration index in this study.

In the binary regression approach, the experimental results are treated as having one of two possible forms, 'failure' or 'non-failure', at prescribed cycles to take into account the non-failure specimen data. In the analysis, σ_{max} is treated as an explanatory variable, and the parameters are calculated by the maximum likelihood method. The parameters in the binary regression model are theoretically related to the variations in q_{cyc} and R_s. Moreover, the error of the estimator obtained from the binary regression analysis is evaluated on the basis of the asymptotic normality of the maximum likelihood estimator, and the uncertainty involved in the estimated parameters is examined.

In order to demonstrate the benefits of the proposed method, the binary regression approach is adopted for analyzing the results of cyclic unconfined compression tests. The analysis results give R_s for denoting the deterioration of strength due to cyclic loading and the interpretation of the factors on the variability of q_{cyc}. The S–N curve is also evaluated as the sample regression line using only the failure specimen data obtained from the tests. Comparing the sample regression line to the binary regression analysis results, the reliability of the S–N curve obtained from the cyclic loading test results is examined without the non-failure specimen data.

This study suggests that the non-failure specimen data can be utilized to evaluate the cyclic strength by adopting the binary regression analysis. Using the binary regression analysis proposed in this study, an unnecessarily large number of cycles to failure can be avoided in the cyclic loading tests and the experimental cost to obtain the deterioration property of the materials can be drastically reduced.

2. Binary regression approach

2.1. Binary regression analysis

Using the binary regression approach (Nawata 1992), the experimental data can be treated as binary data and can take into account the results of the non-failure specimen data yielded in the cyclic loading tests. The binary regression analysis method for evaluating q_{cyc} at a specific number of cycles is described in this section. The ratio of maximum axial compression stress σ_{maxi}, applied in cyclic