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# Reliability-based design of ground improvement for liquefaction mitigation

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**Abstract**

The main purpose of this research is to develop a calculation method to assess the probability of liquefaction and a reliability-based design method to mitigate the liquefaction in sandy grounds. The probability of liquefaction is evaluated with the proposed model by considering the spatial variability of the soil parameters and the statistical characteristics related to the occurrence of earthquakes. The liquefaction resistance is calculated from the SPT *N*-value, the median grain size, $D_{50}$, and the fines content, $F_c$, through the empirical relationship [Iwasaki T, Arakawa A, Tokida, K. Simplified procedure for assessing soil liquefaction during earthquakes. Proc Soil Dyn Earthquake Eng Conf 1982;925–39]. The statistical models for these three soil parameters are determined with the maximum likelihood method. The occurrences of earthquakes is modeled based on the maximum annual acceleration found in historical earthquake data records. In this study, the probability of liquefaction is evaluated multi-dimensionally using the cokriging method. Finally, the reliability-based design method is discussed in order to determine the optimum design for ground improvement using sand compaction piles (SCP) based on the calculated probability of liquefaction.


*Keywords:* Reliability-based design; Liquefaction resistance; Cokriging; Statistical model; Sand compaction pile

## 1. Introduction

This research discusses further developments in the evaluation method used to assess the probability of liquefaction by considering the spatial variability of the soil parameters and the statistical characteristics of earthquake occurrences found in historical earthquake records. In addition, the method is extended to a reliability-based design method for ground improvement.

There are many works which deal with reliability analyses and reliability-based designs to counteract liquefaction. Halder and Tang [1] calculated the probability of liquefaction by considering the variability of the soil parameters and the uncertainty of earthquake magnitudes. They evaluated the liquefaction resistance

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using relative density $D_r$. Fadris and Veneziano [2] proposed a regression model for liquefaction resistance based on the SPT-$N$ value, and evaluated the probability of liquefaction. Liao and Veneziano [3] also created a regression model to determine the probability of liquefaction with a logistic model. Fenton and Vanmarcke [4] performed a liquefaction reliability analysis considering the spatial variation in soil parameters and the stochastic characteristics of earthquake motion. They used the finite element method combined with the Monte Carlo method. Juang et al. [5] determined the CPT-based limit state function of liquefaction with an artificial neural network, and tried a reliability analysis based on that function [6].

Nishimura et al. [7] created a reliability-based design for ground improvement with a one-dimensional statistical model for the soil parameters. In their paper, the method is extended to be multi-dimensional with a geostatistical method, like a kriging [8]. However, almost none of the previous works, except for that by Fenton and Vanmarcke [4], assesses the multi-dimensional liquefaction risk. Thus, the characteristic point of this study is a multi-dimensional assessment.

As a basic evaluation method for the liquefaction risk, the safety factor method for liquefaction [9] is applied. Ordinarily, liquefaction resistance $R$ is simply determined by an empirical equation based on effective vertical stress $\sigma'_v$, SPT blow count $N$, median grain size $D_{50}$, and fines content $F_c$. The last three parameters generally have great spatial variability, and appropriate statistical models for these parameters are required for the liquefaction analysis. The models are determined three-dimensionally with the maximum likelihood method. These soil parameters are interpolated three-dimensionally on the statistical models with the cokriging method.

Dynamic load $L$, brought about by earthquakes, is determined based on the statistical model for the occurrence of earthquakes. The statistical model is determined from the maximum annual acceleration found in the historical earthquake records dating back to 1885. The maximum annual acceleration is drawn throughout the attenuation equation and the error in the attenuation equation is also considered in the analysis. The annual probability of liquefaction is evaluated with a statistical model for liquefaction resistance $R$ and dynamic load $L$. Resistance $R$ is simulated three-dimensionally based on the cokriged soil parameters. Generally, the statistical model for the acceleration is not accurate for large values. Therefore, a deterministic acceleration case for relatively large values is also simultaneously carried out for this shortcoming in this study.

Finally, the optimum ground improvement method is discussed. The sand compaction pile (SCP) method is employed as the ground improvement method. The total cost minimization method is used as the reliability-based design method. The relationship between the optimum sand replacement ratio and the importance of the structures is clarified.

## 2. Dynamic load

Dynamic load therefore, even $L$ is given by the following equation [9]:

$$L = \frac{\alpha_{max}\sigma_v}{980\sigma'_v} r_d \tag{1}$$

in which $\alpha_{max}$ stands for the maximum ground surface acceleration (Gal), $\sigma_v$ is the total vertical stress (kPa), $\sigma'_v$ is the effective vertical stress (kPa), and $r_d = 1 - 0.015\bar{z}$, where $\bar{z}$ is the depth (m) from the ground surface. The expected value $\alpha_{max}$ is given by the following attenuation equation for soft grounds [10]:

$$\bar{\alpha}_{max} = 403.8 \times 10^{0.265M_g} \times (\Delta + 30)^{-1.218}. \tag{2}$$

Here, $\bar{\alpha}_{max}$ is the expected value for $\alpha_{max}$, $M_g$ is the $JMA$ magnitude of the earthquake, and $\Delta$ is the epicentral distance from the source of the earthquake (km).

Kawashima proposed an attenuation model which corresponds to three types of grounds with different stiffness levels, respectively, and the adjusted accelerograms which consider the characteristics of the instruments, were employed to construct the model. Thus far, the locations of active faults around have been found the analytical site of this study. We adopt the Kawashima's model, therefore, eventhough the model is based on the data from before 1980s, and uses the epicentral distance.

Logarithmic maximum acceleration $\ln\bar{\alpha}_{max}$ is defined as the probabilistic parameter following extreme type III distribution [11].