

Accurate Prediction of Wave-induced Seabed Liquefaction at Shallow depths using Multi-Artificial Neural Networks

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ABSTRACT

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In past decades, considerable effort has been devoted to the phenomenon of wave-induced liquefaction, because it is one of the most important factors for analysing the seabed and designing marine structures. As waves propagate and fluctuate over the ocean surface, energy is carried within the medium of the water particles. This energy could be transmitted into the seabed, which results in the rather complex mechanisms of soil behaviour and significantly affects the stability of the seabed.

The prediction of wave-induced seabed liquefaction has been recognised by coastal geotechnical engineers as an important factor when considering the design of marine structures. All existing models have been based on conventional approaches of engineering mechanics with limited laboratory work.

In the authors' previous study, a Single Artificial Neural Network (SANN) was applied for the prediction of wave-induced seabed liquefaction. It had been demonstrated that SANN model's performance can be accepted in engineering practice with large liquefaction depth. However, it failed if the liquefied depth is very small such as less than 1 m. Therefore, in the present study, the Multi Artificial Neural Network (MANN) model was introduced. The simulation results indicate that the MANN model can provide more accurate prediction of the wave-induced maximum liquefaction depth between 0 to 1m. This study has shown the capacity of the proposed MANN model and provides coastal engineers with another effective tool to analyse the stability of the marine sediment.

ADDITIONAL INDEX WORDS: *Single Artificial Neural Networks, Multi Artificial Neural Networks, Wave-induced seabed liquefactions*

INTRODUCTION

During the past decade, AI (Artificial Intelligence) technologies especially ANN (Artificial Neural Network) skills have been applied to coastal engineering fields, such as prediction of water quality parameters (Maier and Dandy, 1996), generation wave equations based on hydraulic data (Yonas et al 1998) and tide-forecasting using artificial neural networks (Lee & Jeng, 2002).

Wave-induced seabed liquefaction is profound interest to marine geotechnical and coastal engineers because of its influence on vertical movement of sediment. This sediment movement in the vicinity of a structure causes the instability of the structure. Numerous investigations of liquefaction have been carried out in the past. Bjerrum (1973) was possibly the first person that considered the wave-induced liquefaction occurring in saturated seabed sediments. Later, Nataraja et al. (1980) suggested a simplified procedure for ocean wave-induced liquefaction analysis. Recently, Rahman (1997) established the relationship between liquefaction and characteristics of wave and soil. He

concluded that liquefaction potential increases with degree of saturation and increase of wave period. Jeng (1997) examined the wave-induced liquefied state for several different cases, including Zen & Yamazaki's (1991) field data. He found that no liquefaction occurs in a saturated seabed, except in very shallow water with large waves and seabed with very low permeability. For more advanced poro-elastoplastic models for wave-induced liquefaction potential, the reader can refer to Sassa & Sekiguchi (2001) and Sassa et al. (2001). All aforementioned investigations have been reviewed by Jeng (2003). In summary, all previous investigations for wave-induced liquefaction potential in a porous seabed have been based on various assumptions of engineering mechanics, which limits the application of the model in realistic engineering problems.

The major difference between general engineering mechanics approaches and ANN models for the estimation of the wave-induced liquefaction is the procedure. Conventional models for wave-induced liquefaction procedures always involve complex mathematical calculations with numerous variables, such as shear

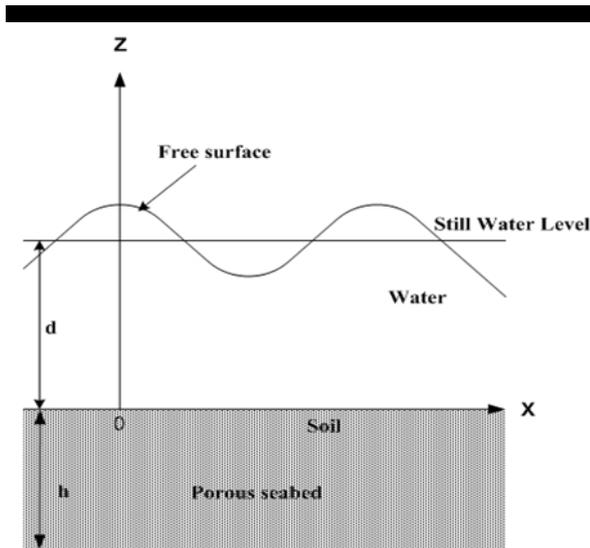


Figure 1. Definition of wave-seabed interaction

modulus, degree of saturation and Poisson ratio etc. However, ANN model can be simply built on the learnt knowledge of a database without complex mathematical procedures. The ANN model only requires accurate data, which include input and output data.

For liquefaction considerations, such as the prediction of seismic liquefaction potential, back-propagation neural networks have been widely used by Goh (1995). Later, Juang & Chen (1999) predicted seismic liquefaction potential from the cone penetration field test data. Lately, Jeng et al. (2003) predicted earthquake-induced liquefaction using the ANN model. In the authors' previous study (Jeng et al 2004), a Single Artificial Neural Network (SANN) was applied for the prediction of wave-induced seabed liquefaction. However, this study concluded that the SANN model failed to predict the liquefaction depth when it is very shallow i.e. less than 1 m. (Jeng et al 2004). Therefore, in the present study, the Multi Artificial Neural Network (MANN) model was applied. The simulation results indicate that the MANN model can provide a more accurate prediction of the wave-induced maximum liquefaction depth between 0 to 1m. This study has shown the capability of the MANN model and provides coastal engineers with another effective tool to analyse the stability of the marine sediment.

WAVE-INDUCED SEABED LIQUEFACTION

In this study, we consider an ocean wave propagating over a porous seabed of infinite thickness. The definition of the problem is illustrated in Figure 1. Considering a two-dimensional wave-seabed interaction problem, and treating the porous seabed as hydraulically isotropic with the same permeability. Biot (1956) presented a general set of equations governing the behaviour of a linear elastic porous solid under dynamic conditions. They are summarized in the tensor form below

$$\sigma_{ij,j} = \rho \ddot{u}_i + \rho_f \ddot{w}_i \quad (1)$$

$$-p_{,i} = \rho_f \ddot{u}_i + \frac{\rho_f}{n} \ddot{w}_i + \frac{\rho_f g}{k_z} \dot{w}_i \quad (2)$$

Table 1: Input data for the poro-elastic model

Soil Characteristics	
Soil permeability (k_z)	$10^{-4}, 5 \times 10^{-4}$ (m/s)
Seabed thickness (h)	From 10 m or various
Shear modulus (G)	10^7 N/m ²
Poisson ratio (μ)	0.4
Porosity (n)	0.35
Degree of saturation (S)	0.95, 0.975, 0.99 and 1
Wave Characteristics	
Wave period (T)	8.00 sec or various
Wave height (H)	7.5 m or various
Water depth (d)	50m or various

$$\dot{u}_{i,i} + \dot{w}_{ii} = -\frac{n}{k_f} \dot{p} \quad (3)$$

where the subscripts "i, j" denote the derivation which respect to the i- and j- directions, respectively, p is pore pressure, u and w are the displacements of solid and relative displacements of solid and fluids; $1/k_f$ is the compressibility of pore fluid, which is defined by

$$\frac{1}{k_f} = \frac{1}{2 \times 10^9} + \frac{1-S}{P_{wo}} \quad (4)$$

where S is the degree of saturation, P_{wo} is the absolute water pressure.

Estimation of Liquefaction

It has generally been accepted that when the vertical effective stress vanishes, the soil will be liquefied. Thus, the soil matrix loses its strength to carry load, and consequently causes seabed instability.

Based on the concept of excess pore pressure, Zen and Yamazaki (1991) proposed a criterion of liquefaction, which has been further extended by considering the effects of lateral loading (Jeng, 1997)

$$-\frac{1}{3}(1 + 2K_o)(\gamma_s - \gamma_w)z + (P_b - p) \leq 0 \quad (5)$$

where K_o is the coefficient of earth pressure at rest, which is normally varied from 0.4 to 1.0, and 0.5 is commonly used for marine sediments (Scott, 1968). In (5), γ_s is the unit weight of soil, γ_w is the unit weight of water, and P_b is the wave pressure at the seabed surface, which is given by

$$P_b(x,t) = \frac{\gamma_w H}{2 \cosh kd} \cos(kx - \omega t) \quad (6)$$

where, H is the wave height and d is the water depth.

The input data for the wave-induced seabed liquefaction calculation which establishes the ANN model, are shown in Table 1. As seen in Table 1, the database was compiled from the potential range of wave and soil conditions most likely to induce seabed liquefaction.

MULTI NEURAL NETWORK MODEL FOR SHALLOW DEPTH SEA BED LIQUEFACTION

A multi-artificial neural network (MANN) model was introduced, which extends the single artificial neural network (SANN) model developed in the authors' previous study (Jeng et al 2004). The major difference between the SANN model and the MANN model is the number of networks used. The SANN model is comprised of only one network which is used for the whole database, and the MANN is composed of various networks depending on the range of the database. Hence it is better suited to the predication of shallow liquefaction seabed depth.

To evaluate the model performance, three different values were used to distinguish the prediction of seabed liquefaction depth. These are Root Mean Square Error (RMSE), Scatter Index (SI) and Correlation Coefficient (R²). These parameters are defined as follows

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (L_A - L_P)^2} \quad (7)$$

$$SI = \sqrt{\frac{RMSE}{L_o}} \quad (8)$$

$$R^2 = \frac{\sum (L_o - \bar{L}_o)(L_t - \bar{L}_t)}{\sqrt{\sum (L_o - \bar{L}_o)^2 \sum (L_t - \bar{L}_t)^2}} \quad (9)$$

$$\bar{L}_o = \frac{\sum L_o}{n} \quad (10)$$

$$\bar{L}_t = \frac{\sum L_t}{n} \quad (11)$$

where L_o is the maximum liquefaction depth from the poro-elastic model, L_t is the maximum liquefaction depth from the ANN model and n is the number of maximum liquefaction depth. In general, the correlation coefficient (R^2) values are used for the accuracy of the prediction. However, results in this study indicate that it is very difficult to evaluate the model using only the correlation coefficient. Therefore, the Root Mean Square Error (RMSE) was adopted, as well as the Scatter Index (SI) defined in Equations (7) and (8).

RESULTS

A multi-artificial neural network (MANN) model was investigated for the improvement of the accuracy of the existing ANN model, and numerical experiments were conducted to demonstrate the capability of the proposed MANN model for the prediction of wave-induced liquefaction. The MANN has a similar training procedure to the SANN model, but the data used for training is divided differently depending on the range of the training datasets. The occurrence of wave-induced liquefaction depends on soil and wave parameters. It is clearly shown that the overall performance of maximum liquefaction depth prediction of the seabed using single artificial neural network (SANN) models are working well (Figures 2 and 5). However, when we investigate the overall results of the SANN model for shallow liquefaction range depth sections as shown in Figures 3 and 6, the SANN model fails to predict values in the zero to 1m liquefaction depth

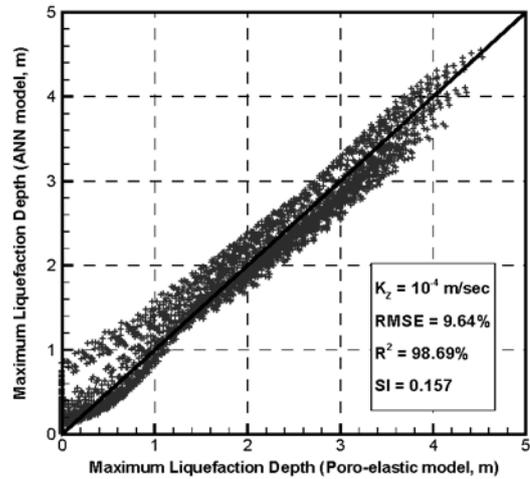


Figure 2. Comparison of the wave-induced maximum liquefaction depth by the SANN model versus poro-elastic model ($K_z = 10^{-4}$ m/sec)

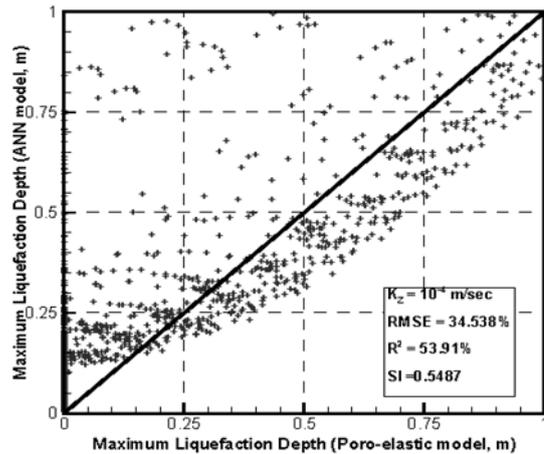


Figure 3. Comparison of the wave-induced maximum liquefaction depth between 0 to 1 m by the SANN model versus poro-elastic model ($K_z = 10^{-4}$ m/sec)

even though this is one of the most accurate prediction results in each soil permeability case. Therefore, the MANN model is applied to deal with the same range as the SANN model cases from 0 to 1 m.

Normally, MANN experiments would include more than one neural network for dealing with each level of liquefaction depth, however in this study, we are mainly concentrating on shallow depth. Hence to apply the MANN to this study, the SANN model for the range of 0-1 m was used for the testing procedure. Figures 4 and 7, clearly show that the results for each range of maximum liquefaction depth predicted for the MANN models agree with the numerical calculation depths. It is demonstrated that maximum liquefaction depth ranges between 0 to 1 m have a good agreement between the MANN and poro-elastic models when compared to the SANN model. It is also shown that the correlation of the MANN model and the poro-elastic model is over 97% for most ranges and RMSE values are dramatically decreased when

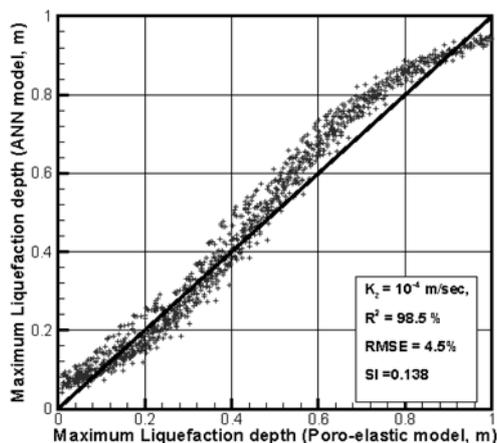


Figure 4. Comparison of the wave-induced maximum liquefaction depth between 0 to 1 m by the MANN model versus poro-elastic model ($K_z=10^{-4}$ m/sec)

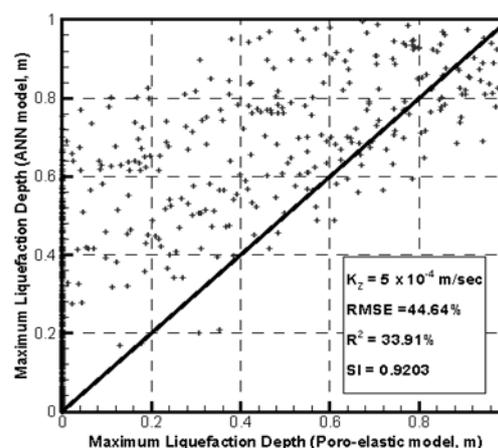


Figure 6. Comparison of the wave-induced maximum liquefaction depth between 0 to 1 m by the SANN model versus poro-elastic model ($K_z=5 \times 10^{-4}$ m/sec)

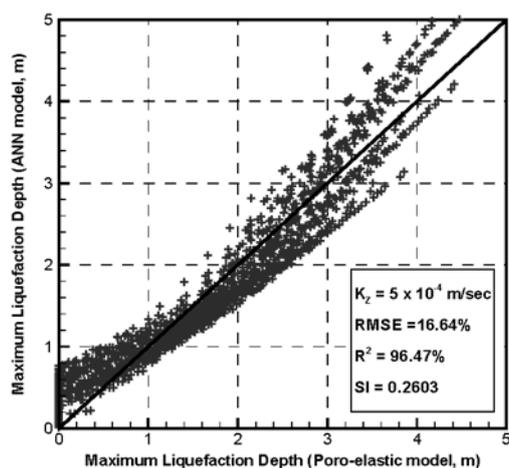


Figure 5. Comparison of the wave-induced maximum liquefaction depth by the SANN model versus poro-elastic model ($K_z=5 \times 10^{-4}$ m/sec)

compared to the SANN model. These figures illustrate that the differences in predictions of the maximum depths are within the $\pm 10\%$ range, which is acceptable for an engineering application.

CONCLUSION

This paper discusses performance of the single artificial neural network (SANN) model for the prediction of liquefaction depth. Even if results of the SANN model can be accepted in the engineering view, we are still faced with the problem of prediction of shallow liquefaction depth. Therefore, we investigated the use of the Multi-Artificial Neural Network (MANN) model for the liquefaction depth range 0 to 1 m, where the SANN models failed.

The results clearly indicate that the MANN model successfully predicted the wave-induced liquefaction depth for the range 0 to 1 m, where the SANN model failed to achieve high accuracy.

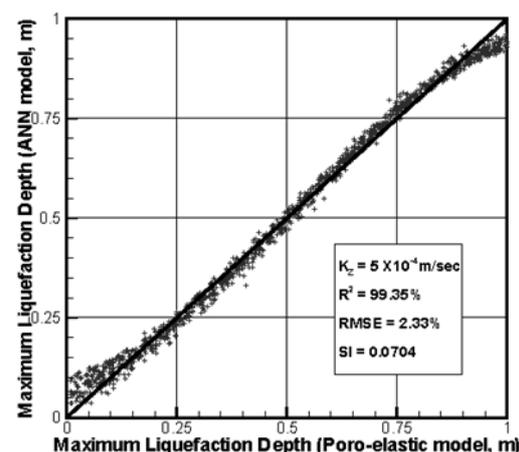


Figure 7. Comparison of the the wave-induced maximum liquefaction depth between 0 to 1 m by the MANN model versus poro-elastic model ($K_z=5 \times 10^{-4}$ m/sec)

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