Neural networks approach and microtremor measurements in estimating peak ground acceleration due to strong motion

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Abstract

Peak ground acceleration is a very important factor that must be considered in construction site for examining the potential damage resulting from earthquake. The actual records by seismometer at stations related to the site may be taken as a basis, but a reliable estimating method may be useful for providing more detailed information of the strong motion characteristics. Therefore, the purpose of this study was by using back-propagation neural networks to develop a model for estimating peak ground acceleration at two main line sections of Kaohsiung Mass Rapid Transit in Taiwan. Additionally, the microtremor measurements with Nakamura transformation technique were taken to further validate the estimations. Three neural networks models with different inputs including epicentral distance, focal depth and magnitude of the earthquake records were trained and the output results were compared with available nonlinear regression analysis. The comparisons exhibited that the present neural networks model did have a better performance than that of the other methods, as the calculation results were more reasonable and closer to the actual seismic records. Besides, the distributions of estimating peak ground acceleration from both of computations and measurements might provide valuable information from theoretical and practical standpoints. © 2002 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Strong ground motion has a significant influence on the construction site which must be considered for a practical engineering designer. In particular, the peak ground acceleration (PGA) is one of the key factors for analyzing the potential damage resulting from earthquake. In general, the detailed seismic record is not easy to obtain in a short period of time, whereas the experimental technique such as microtremor measurement may be employed to provide further useful results in the investigation area [1–3]. Therefore, the estimation of PGA using numerical techniques based upon available actual earthquake data and on-site measurements is become a valuable topic for studying in the field of earthquake engineering as well as in the area of civil engineering.

Collected from several checking stations, the actual seismic records usually consist of some major earthquake relative information such as location, distance, depth, magnitude and PGA in different directions. These data are randomly distributed for each earthquake at each station, which may not be used without analyzing by scientific methods. Conventionally, the most common used method for this problem is nonlinear regression analysis, which mainly includes Kanai, Jayner and Boore, and Campbell three forms [4]. In each form, a simple statistical model based on the available data may be derived to describe the tendency of PGA with other parameters at the station. However, this method needs to assume a function form in advance, and may not be good enough to provide predictions in a particular construction site, which is different from the checking station. In contrast, by learning the characteristics of past records, the artificial neural network are powerful pattern recognizers and classifiers, which are capable of estimating engineering parameters not only at checking point but also at a particular point using spatial relationship in the calculation process [5,6]. Although the neural networks can be applied in many fields, the application for estimating the ground peak acceleration due to earthquake is still rarely seen, so it deserves more exploring in this important engineering area.
In order to supply information for obtaining more reliable predictions, the microtremor measurements with Nakamura transformation technique provide a way to enhance the numerical predictions. Caused by moving vehicle, river, wind, and activity of volcano, the microtremor is occurred on the earth surface from time to time, and the resulting elastic vibration on the ground surface can be measured by using suitable equipment (e.g. SPC-35F, [7]). In the comparison of results between strong motion and microtremor data, controversies did exist that can be found in some research papers [8–10], but many reports have been published to positively support this experimental method [11–15]. As more precisely measuring instruments have been developed in the recent years, in addition to several advantages such as low cost, easy to use and wide range of applications, this technique is popularly accepted for both academic researchers and practical engineers.

The objectives of the present study are at first is to estimate the PGA using back-propagation neural networks, in accordance with the actual records by seismometer at each station of Kaohsiung city obtained from Central Weather Bureau Seismological Center (CWBSN), Taiwan. The inputs in the neural networks calculation includes three parameters, they are: epicentral distance, focal depth and magnitude, respectively. Three models with different parameters in the input layer are trained to check their coefficient of correlation, and a better estimation model is achieved from computational experiments. The outputs obtained are also compared with available nonlinear regression analysis to prove the ability of neural networks model. Next, the estimation is sent to several sections at the two major lines of Kaohsiung Mass Rapid Transit (KMRT), namely Red line and Orange line, using multiple training sets of strong motion at checking stations around the estimating section. Finally, the technical results obtained from microtremor measurements for these two major line sections are taken to make comparison for further enhancing the numerical estimations. The research results may prove the feasibility of using neural networks and microtremor on-site tests in this type of problem, and may provide an important reference for the relative engineering fields.

2. Description of investigation area

Taiwan, an island, is about 400 km long from tip to tip and 130 km wide at its broadest points. It is located in the intermediate boundary region of Philippine sea plate and Eurasia plate. The occurrence of strong motion has a very high possibility in this area due to extrusion of two plates. For instance, the recent big one with magnitude 7.3 in Richter scale, occurred at central part of Taiwan on 21 September 1999 [16], resulted in tremendous casualties and structural damages, which is equivalent to about USD 10 billion property losses. Meanwhile, ideally situated on the southern coastline is the vibrant city of Kaohsiung, which is Taiwan’s second largest city, foremost industrial center, and largest international port, with 1.5 million populations and has many traditional architectures and modern high-rise buildings. Although the big one did not hit the city directly, the chain reaction of the ground strong motion did have a significant influence on this city. The reliability of old or new structures against earthquake becomes a critical issue, which is concerned for both relative governments and people living in this city.

At present in Kaohsiung city, the major engineering project in progress is the construction of mass rapid transit system. The original plan of KMRT system consists of four lines, with a total of 77.7 km. Fig. 1 shows two main lines. The Red line has a length of 28.3 km in north–south direction, and the Orange line has a length of 14.4 km in east–west direction. The former line to be constructed includes 19.8 km underground works and 8.5 km trestle works, whereas the entire underground works are planned for the latter line. Kaohsiung is located in a weak seismic zone, and the actual design value of PGA is 0.23g, which is greater than 0.14g for underground structures based on the safety design code. Therefore, it is expected that the effect of ground strong motion may be reduced as most of the construction works for these two main lines are in underground stations and tunnels. However, for the sake of safety, it may still require further engineering analysis from different point of view under a conservative manner.

Based on the on-site boring test, sampling and laboratory work [17,18], the Red and Orange lines are situated in the recent alluvial sediments, and the distributions of various soil textures mainly may contain sandy silt, low compressibility clay and their mixtures. A detailed classification of soil types and groundwater level may be found from the soil profiles along two main lines [19]. In this study, for the investigation area, there are 12 sections (R01–R12) and 5 sections (O01–O05) for Red line and Orange line, respectively, and they are divided according to the distribution of soil layers. In addition, there are 17 recording stations around the city that can provide the actual seismic data for multi-purpose of technical analysis. The checking stations in this region are established after 1993, the recorded data range from 6 to 36 times, which may not be sufficient, but provide a minimum requirement for reference in this study.


Because the neural computing has the advantage of using field or experimental data directly without simplifying assumptions, and the nonalgorithm method is capable of executing massive computation in a parallel environment, so this approach has been extensively developed in recent years. In particular, the back-propagation neural networks, which uses a specific learning law for updating the weightings of each layer in accordance with the errors
from the network output, is frequently applied to solve various types of engineering problems due to its simplicity [20–28]. From these references, it can be found that the multi-layered neural networks may include input layer, hidden layer and output layer. For the basic algebraic equation of each layer, it may be written as:

\[ Y_j = \Phi(\sum W_{ij}X_i - \theta_j) \]  

where \( Y_j \) is the output of neuron \( j \), \( W_{ij} \) represents the weight from neuron \( i \) to neuron \( j \), \( X_i \) is the input signal generated for neuron \( i \), \( \theta_j \) is the bias term associated with neuron \( j \), and the nonlinear activation function \( \Phi \) is assumed to be a sigmoid function as \( \Phi(x) = 1/(1 + e^{-x}) \), which will make the operating process continuous and differentiable.

The back-propagation neural networks are basically a gradient descent method, and two parameters called as the learning rate \( \eta \) and the momentum factor \( \alpha \), are usually introduced in the iterative calculation process as the following equation:

\[ W_{ij}^n = W_{ij}^{n-1} + \eta \delta_j X_i + \alpha \Delta W_{ij}^{n-1} \]  

where \( \delta_j \) is the error signal for neuron \( j \), \( \Delta W_{ij}^{n-1} \) denotes the adjusting weights between neurons \( i \) and \( j \), meanwhile the symbols \( n \) and \( n-1 \) are the current and the most recent training step, respectively. In general, the learning rate and momentum parameters may accelerate convergent speed and may smooth oscillations in weight corrections during training. But these two parameters

Fig. 1. Sketch of the investigation area.
require some computational experiments to determine their better values for fitting in the case study. Furthermore, to evaluate the effectiveness of neural networks model, the coefficient of correlation \( r \) may be used and defined as follows

\[
 r = \frac{\sum_{i=1}^{m} (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{m} (x_i - \bar{x})^2 \sum_{i=1}^{m} (y_i - \bar{y})^2}}
\]

where \( x_i \) and \( \bar{x} \) are the record and its average values, \( y_i \) and \( \bar{y} \) are the estimated and its average values, and \( m \) denotes the number of data in the analysis.

Now in the present study, three neural networks models, as shown in Fig. 2, are trained according to the actual seismic records in Kaohsiung area (17 stations). Three input parameters including epicentral distance, focal depth and magnitude are used for the models where: Model 1 uses each of the parameters, Model 2 uses the combinations of two parameters, and Model 3 takes the whole parameters as the inputs, respectively. In addition, the learning rate \( \eta = 0.8 \) and the momentum factor \( \alpha = 0.8 \) are chosen in the training process due to their relatively better tendency of convergence based upon computational experiments. From the neural networks computations for vertical, north–south, and east–west directions at different stations, as shown in Figs. 3–5, it can be found that the average coefficient...
of correlation for Model 1 is lower than 0.6, and Model 2 has the average coefficient between 0.6 and 0.9, but Model 3 has the highest average coefficient which is over 0.95. Therefore, the results from Model 3 can achieve the best estimation, and by comparing the converted results in horizontal direction with other nonlinear regression analyses [3], including Kanai form, Jayner and Boore form, and Campbell form is exhibited in Fig. 6. It can be seen that the coefficient of correlation trained by neural networks Model 3, can reach up to 0.972, which is higher than the coefficients between 0.6 and 0.7 obtained from three regression forms. This comparison demonstrates the ability of neural networks in this case study, and the same model will be used for further estimations.

4. Microtremor measurements and ground peak acceleration estimations

The ambient vibration on-site test, frequently applied in the field of civil engineering, is mainly used for identifying the dynamic characteristics of structures, predominant frequency, amplification factor, and material properties of the stratum. In this study, a measurement system SPC-35F provided by National Center for Research on Earthquake Engineering (NCREE) of Taiwan is taken for microtremor measurements in the investigation area. The principle of analyzing ambient vibration surveys is based on the Nakamura technique, and the major equations for
estimation may be written as:

\[ b_{EW}(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \frac{SRB_{EW}(\omega)}{SRA_{EW}(\omega)} \left( \int_{-\infty}^{+\infty} a_{EW}(t)e^{-i\omega t} dt \right) e^{i\omega t} d\omega \]  \hspace{1cm} (4)

\[ b_{NS}(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \frac{SRB_{NS}(\omega)}{SRA_{NS}(\omega)} \left( \int_{-\infty}^{+\infty} a_{NS}(t)e^{-i\omega t} dt \right) e^{i\omega t} d\omega \]  \hspace{1cm} (5)

where \( a_{EW}(t) \) and \( a_{NS}(t) \) are recorded accelerations in the EW and NS directions at station A, \( SRA_{EW}(\omega) \) and \( SRA_{NS}(\omega) \) are frequency spectral ratios from microtremor measurements in the EW and NS directions at station A. Meanwhile, \( b_{EW}(t) \) and \( b_{NS}(t) \) are estimated accelerations in the EW and NS directions at station B, \( SRB_{EW}(\omega) \) and \( SRB_{NS}(\omega) \) are frequency spectral ratios from microtremor measurements in the EW and NS directions at station B. Hence, the estimation of strong motion characteristics using microtremor measurements is simply based upon the Fourier transform and its inverse transform in the frequency and time domains.

Since the tremble of the earth is very small, and normally the acceleration at the ground surface is around \((10^{-6} – 10^{-4})g\), the ambient vibration measurement system has to be a system with very high sensitivity. To verify the reliability of the measurement system, a comparison of rock depth along 12 sections of Red line and 5 sections of Orange line obtained from estimations and boring tests [17,18] is shown in Table 1. Note that the estimation of rock depth is obtained by converting the predominant frequency from microtremor measurements [19]. Now, if a statistical \( t \)-test is performed for both of the confirming data in the table, then the calculated value \( t = 0.131 \) is in the acceptance interval \(-2.262 < t < 2.262\) with significance level \( \alpha = 0.05 \). Thus, the estimation of rock depth has a reasonable agreement with the actual boring results, which may provide a confidence for estimating PGA using microtremor measurements.

From the above illustrations of using neural networks and microtremor measurements, shown in Fig. 7 is the comparison of estimating PGA in different directions from both methods and the actual seismic records at checking stations. From the results, it can be found that the neural networks predictions are more effective than the microtremor measurements, as over 80% of available data from the former method are closer to the actual checking records. In general, most of the natural faults in Taiwan area are oriented in north–south direction, the strong motion has a tendency of movement in east–west direction caused by the extrusion of two plates in both east and west sides. Therefore, the predictions in E–W direction are roughly better than that of N–S direction, particularly in the use of neural networks approach.

Now for the evaluation of PGA along the Red line and the Orange line of KMRT, as no direct checking stations are located in these two main lines, the estimations may use the nearest station records as the reference and applied to a model for prediction. To this point, there is no problem for the method of ambient vibration on-site survey as Eqs. (4) and (5) discussed can be used for estimation within two locations. But in neural networks approach, a set of weights and bias values is obtained by training the actual seismic records from 2 to 4 checking stations.
stations in the neighborhood of estimating section on the main lines. Then, the output is the estimated result obtained by the input of parameters of testing section in the same model. To view the results more clearly, Figs. 8–13 are displayed as three-dimensional plots of PGA along the Red line and the Orange line sections. Although the difference of estimation using neural networks is smoother than that of microtremor measurements, the tendency is similar for both methods. Since there may involve many factors such as traffic, noise and soil conditions to affect the accuracy of on-site tests, the results obtained from neural networks are expected to be more reliable as this method takes the actual earthquake data for the basis. However, for the investigation area that lacks long term actual seismic records, the microtremor measurements may provide useful information to determine some of strong motion characteristics for the relative engineering fields.
5. Summary and conclusion

PGA is one of the strong ground motion characteristics and the key factor that ought to be considered in construction site for examining the potential damage caused by earthquake. In the present research, both back-propagation neural networks approach and ambient microtremor measurements using SPC-35F have been performed to estimate the PGA along two main lines (12 Red sections and 5 Orange sections) of KMRT in Taiwan. The actual seismic
records at several checking stations around the investigation area were employed as the basis for calculation or used as the purpose of verification.

Three input parameters including epicentral distance, focal depth and magnitude of seismic records in the neural networks model training proved to obtain highest coefficient of correlation if compared with other models, which used one or two parameters in the input layer. The comparison has also extended to show the neural networks prediction is better than the conventional nonlinear regression analysis such as Kanai, Jayner and Boore, and Campbell forms. Furthermore, the microtremor measurements with the use of Nakamura transformation technique has predicted rock depth reasonable agreement with the available boring...
tests. These comparisons have verified the capacity and the reliability of applying both methods for this complicated engineering problem.

From the estimated results of PGA in the investigation area, it might be found that the difference of estimation using neural networks was smoother than that of microtremor measurements, but the tendency was similar for both methods. Since there might involve many factors such as traffic, noise and soil conditions to affect the accuracy of on-site surveys, the results obtained from neural networks are expected to be more reliable as this method trained the actual recording data in the calculation process. However, for the investigation area that lacks long term actual seismic records, the microtremor measurements might provide important information to determine some of strong motion characteristics, which is useful in the relative engineering fields.

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