Intelligent seismic risk mitigation system on structure building

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Abstract. Indonesia located on the Pacific Ring of Fire, is one of the highest-risk seismic zone in the world. The strong ground motion might cause catastrophic collapse of the building which leads to casualties and property damages. Therefore, it is imperative to properly design the structural response of building against seismic hazard. Seismic-resistant building design process requires structural analysis to be performed to obtain the necessary building responses. However, the structural analysis could be very difficult and time consuming. This study aims to predict the structural response includes displacement, velocity, and acceleration of multi-storey building with the fixed floor plan using Artificial Neural Network (ANN) method based on the 2010 Indonesian seismic hazard map. By varying the building height, soil condition, and seismic location in 47 cities in Indonesia, 6345 data sets were obtained and fed into the ANN model for the learning process. The trained ANN can predict the displacement, velocity, and acceleration responses with up to 96% of predicted rate. The trained ANN architecture and weight factors were later used to build a simple tool in Visual Basic program which possesses the features for prediction of structural response as mentioned previously.
Keywords: artificial neural network, mitigation, seismic, structural analysis

1. Introduction

Indonesia is one of the high-risk seismic-zone in the world, which refers to the geographical region with the most active tectonic plate and volcanic activities on earth as known as the Pacific Ring of Fire. This results in a high tendency of strong ground motion to occur due to earthquake in the Pacific Ring of Fire region. In 2004, a whopping 9.3 Richter-scale mega quake struck Aceh on the Western Coast of Sumatera Island, which then followed by a tsunami that travelled several kilometers inland. In 2009, a devastating 7.9 Richter-scale earthquake hit Padang City, also the Western Coast of Sumatera Island. Recently in March 2016, another 7.8 Richter-scale earthquake hit Southwest of Sumatra and the ground motion was felt on the whole Sumatera Island [1]. In all the aforementioned cases, the property damage was severe and the casualty was huge.

The spectral hazard maps for Sumatra and Java islands was developed by [2]. Two hazard levels for representing 10% and 2% probability of exceedance (PE) in 50 years ground motions were analysed for Sumatra and Java. The analysis implemented some improvements in seismic hazard by considering the latest seismic activities around Java and Sumatra. The authors also proposed a revision of the seismic hazard map in Indonesian Seismic Code SNI 03-1726-2002 which partially adopts the concept of UBC 1997 [3].

The new revision Indonesian seismic code as known as SNI 03-1726-2012. According to [4], prior to 2012, the seismic design criteria for buildings in Indonesia is based on map with ground motion

spectral accelerations of 10% probability of being exceeded (PE) in 50 years. The seismic design criteria and map was hazard-based without considering uncertainty from collapse capacity of building structures. Otherwise, in the new seismic design criteria included 2% PE in 50 years, defined as Maximum Considered Earthquake (MCE). In the new code has adopted the most recent data and current state of knowledge in probabilistic and deterministic seismic hazard assessment methodologies, and using the most recent ground motion predictive equations.

The new MCE ground motion parameter for 1.0 second spectral acceleration, site class B with 5% of critical damping as shown in Figure 1.
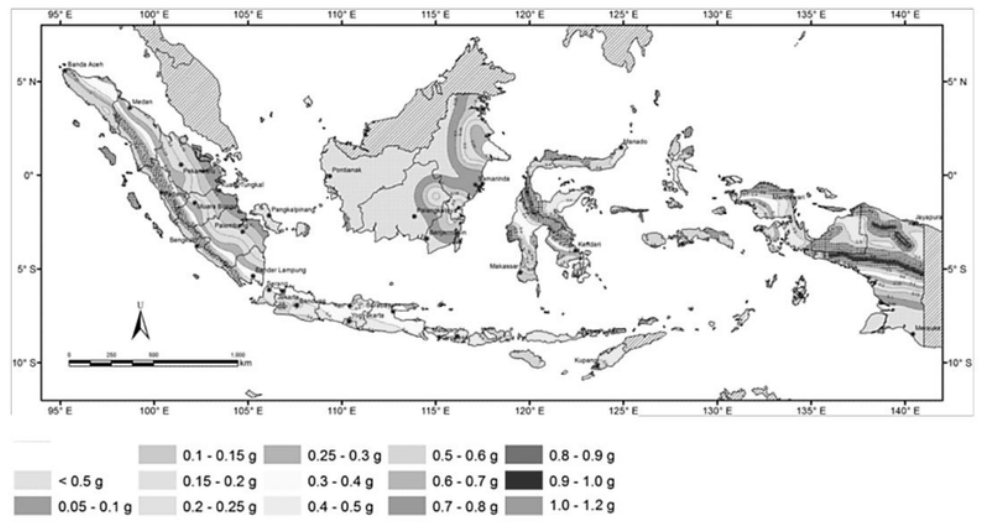

Figure1. Spectra design map of Indonesia for 1 second spectral acceleration with 5% [5].

One of the many factors that affect the aftermath of earthquake disaster is the resilience of the infrastructure building against the strong ground motion [6]. Critical infrastructure-buildings such as hospital, school, power plant office, and governmental building are most likely multi-storey buildings which are very prone to seismic loading. During strong ground motion, multi-storey building might collapse in brittle-way that endangers its occupant's due to the massive dead weight, especially for Reinforced Cement Concrete (RCC) building. Furthermore, in case of tall building is not designed properly will experience excessive displacement (storey-drift) that cause discomfort and might damage non-structural components such partition wall, window, and door which blocks evacuation passage. Due to these facts, multi-storey building shall be designed properly to exhibit ductile behaviour and controlled deformations during strong ground motion.

Seismic-resistant building design requires structural analysis to be performed first, to obtain some building response characteristics, such as storey displacement (drift), velocity, and acceleration. However, such structural analysis could be very difficult, especially for 3D building structural models. For complex building structure, the structural analysis will require the involvement of finite element structural analysis program which is very costly and time consuming to learn and operate.

Artificial Neural Network (ANN) is a mathematical model inspired by its biological neural network counterpart. The ANN system comprises of several processing layers and neurons. Just like the biological neural network, the connection and signal transfer between neurons and layers enable the ANN system to process the given input signal into appropriate outputs, which is later called prediction. ANN possesses the capability to predict output based on any given input in which the mathematical relationship between the input and output parameter is nonlinear, complex, and often vague.

The output layer of the ANN consists of output neurons that represent the output parameters to be predicted. The difference between the predicted output value and the target value (the true value according to learning data set) is the error of the ANN system. ANN neuron's functionality is analogue to the biological neuron. The synapse strength in biological neural network is represented by the weight factor in the ANN system. The initial values of the weight factors are usually random, which later modified through a process called ANN training, iteration, or learning process. The ANN learning process requires a set of data to 'train' the ANN before it is ready for testing. The trained ANN system is expected to possess the capability to predict outputs based on any given inputs at decent accuracy. The commonly adopted criteria to evaluate the performance of the ANN system are Mean-Squared-Error (MSE) and Coefficient of Correlation (R) are computed using (1) and (2), respectively.

$$MSE = 0.5 \, (T_i - Y_i)^2 \tag{1}$$

$$R = \frac{n \sum T_i Y_i - (\sum T_i)(\sum Y_i)}{\sqrt{n(\sum T_i^2) - (\sum T_i)^2} \, \sqrt{n(\sum Y_i^2) - (\sum Y_i)^2}} \tag{2}$$

Where: T_i = target value based on learning data set;
       Y_i = predicted output value; and
       n = the number of data sets.

This research aims to predict the structural response includes displacement, velocity, and acceleration of multi-storey building in the region of seismic hazard maps of Indonesia using an Artificial Neural Network (ANN) tool. The final software was designed to be user friendly, simple-to-use, lightweight, and performs faster. The previous study [7] discussed prediction of structural response based on the seismic hazard maps of Sumatera. The study was successful to predict the story drift of multi-storey building in all the capital cities of the provinces in Sumatera. The prediction capability of the ANN-based system was achieved through a vigorous learning process with over 4000 of data sets. Meanwhile, other researchers have applied an Artificial Neural Networks to predict response spectra such as [8], and to generate the artificial earthquake such as [9], [10] and [11]

2. Research Method
The prediction system based on an ANN analysis, which requires an amount of learning data sets to perform the training, validation, and testing process. In this research, the ANN data sets were generated by performing structural analysis on several varieties of building the structure model, soil condition, and seismic location. In the following sub-sections, the methodology used in this research will be described in detail.

The multi-storey building structure models are reinforced cement concrete (RCC) moment frames combined with shear walls. In this research, 3 variations of building height are adopted: 10 storeys (Model 1), 15 storeys (Model 2), and 20 storeys (Model 3). The inter-storey height is 4.5 meters at base and 4 meters at other storeys.

Modal response spectrum analysis was performed to obtain the responses of the building structure models (storey displacement, velocity, and acceleration). The seismic load was included as seismic response spectrum plot which shows the relationship between the design structure acceleration (S_a) and the structure's period of free vibration (T). The S_a vs. T plot varies with soil condition and seismic location. In this research, 34 capital cities and 13 other cities in Indonesia were selected as seismic location with 3 soil conditions (soft, medium, and hard soil). By adopting 47 cities in Indonesia with 3 possible soil conditions, 141 seismic response spectrum plots were obtained (e.g Banda Aceh City is shown in Figure 2). For each seismic load, 10 building response data were generated from modal response spectrum analysis from Model 1, 15 data from Model 2, and 20 data from Model 3, which sums

up to 45 data. Therefore, as many as 6345 data sets (141 x 45) were generated from the whole structural analysis process.
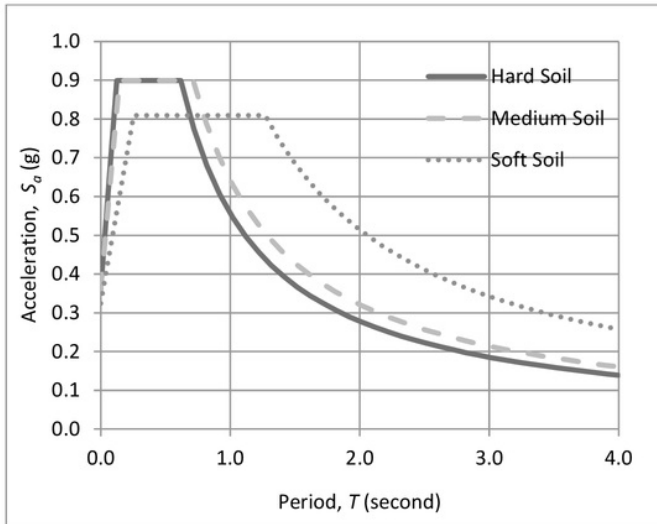

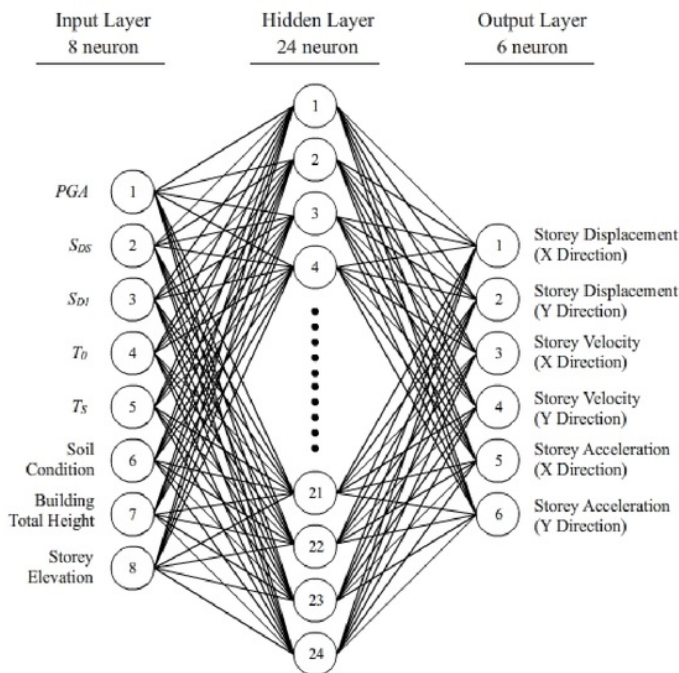**Figure 2.** Seismic response spectrum plot for Banda Aceh City [5].

Figure 3. Proposed backpropagation ANN architecture.

The proposed backpropagation ANN architecture on the prediction of building structure response in this research as shown in Figure 3. The ANN architecture consists of 3 layers: input layer with 8 neurons, hidden layer with 24 neurons, and output layer with 6 neurons. The input parameters are peak ground acceleration (PGA), design spectral acceleration at brief period (S_{DS}), design spectral acceleration at 1 second of the period (S_{D1}), the lower limit of period that results in maximum acceleration (T_0), the upper limit of period that results in maximum acceleration (T_S), soil condition, building total height, and storey elevation (base level was not included). Whereas, the output parameters are storey displacement, velocity, and acceleration in both orthogonal horizontal directions (X and Y).

3. Results and Discussion

The details on the MSE and R values obtained through the ANN learning process is tabulated in Table 1 and Table 2 after 1000 epochs during the ANN learning process.

Table 1. MSE after ANN learning process.

Parameters	Mean-Squared-Error (MSE)		
	Training	Validation	Testing
Displacement X	1.09×10^{-4}	1.01×10^{-4}	1.00×10^{-4}
Displacement Y	1.05×10^{-4}	0.96×10^{-4}	0.96×10^{-4}
Velocity X	2.05×10^{-4}	2.14×10^{-4}	1.96×10^{-4}
Velocity Y	1.99×10^{-4}	1.99×10^{-4}	1.98×10^{-4}
Acceleration X	4.04×10^{-4}	4.13×10^{-4}	3.80×10^{-4}
Acceleration Y	3.80×10^{-4}	3.93×10^{-4}	3.43×10^{-4}
Average	2.34×10^{-4}	2.36×10^{-4}	2.17×10^{-4}

Table 2. R Details after ANN learning process.

Parameters	Coefficient of Correlation (R)		
	Training	Validation	Testing
Displacement X	0.982	0.981	0.988
Displacement Y	0.982	0.981	0.988
Velocity X	0.972	0.964	0.982
Velocity Y	0.972	0.965	0.983
Acceleration X	0.928	0.901	0.957
Acceleration Y	0.928	0.899	0.959
Average	0.961	0.949	0.976

4. Conclusion

The comparison of displacement, velocity and acceleration data have been concluded based on MSE mean value and regression mean value of the network model. Both comparisons show the MSE mean value decreases since the epoch increases. Whereas regression value increases close to 1 since the epoch increases. According to the results, the neural networks' method based on the displacement data has the best performance rather than velocity and acceleration data. The reason describes the displacement is derived from second time to generate the acceleration. The displacement has simpler physic quantity rather than acceleration so the convergent is approached faster. Furthermore, both calculated MSE and R value indicate that the prediction performance of the trained ANN is sufficiently accurate. The ANN is a very promising tool to provide an early prediction on structural response such as story drift (displacement, velocity and acceleration at multi-story building in the region of Indonesia to assist further Finite Element Method analysis.

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