Development of Deep Learning Methods for Real-Time Earthquake Predictions of Building Time-History Responses and Site Spectra

著者	Ahmed Alaaeldean Mohammed Abdelhaleam Torky
学位授与機関	Tohoku University
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アーマド アラデン モハマド アブデルハリム トオーキイ
氏　　　　　名　Ahmed Alaaeldean Mohammed Abdelhaleam Torky
研究科，専攻の名称　東北大学大学院工学研究科（博士課程）都市・建築学専攻
学位論文題目 Development of Deep Learning Methods for Real-Time Earthquake Predictions of Building Time-History Responses and Site Spectra (地震時の建物時刻歴応答およびサイトスペクトルの即時予測のための深層学習手法の開発)
論文審査委員　主査　東北大学准教授　大野 晋　　東北大学教授　前田　匡樹
東北大学教授　　五十子 幸樹

論文内容要約

Strong ground motions have caused serious damages to structures and harm to communities in the past. Real-time assessment is necessary to alert systems of the impending danger to facilitate earthquake damage mitigation. Responses of a structure and/or an occupied site is necessary for rapid approximation of human injury, occupancy level of buildings, and estimation of property loss. Conventional numerical methods in engineering are computationally expensive and inadequate in complex situations, therefore, faster prediction methods that do not sacrifice accuracy are required. Historically recorded data is abundant in Japan; hence, data-driven methodologies are promising and could be sufficient in reducing computational time of complex tasks associated with real-time seismic assessment.

Artificial intelligence (AI) methods have matured enough to promise substantial gain at adequacy and rapidness of assessing complex problems in real-time compared to traditional approaches. A modern branch of machine learning (ML) is Deep Learning (DL) which uses artificial neural networks to detect high-level patterns in Big Data and provide function approximators to quickly predict sequential values, which is useful at handling real-time seismic sequences. Due to its superiority in nonlinear functional modelling, early implementations of DL in earthquake engineering focused on classifying earthquakes in real-time and improving ground motion parameters. The promise of this data-driven method is further investigated in this thesis. The main objective is to develop new rapid and highly reliable DL algorithms that can predict building and site responses due to strong ground motions.

This thesis is organized in to 5 main chapters to deliver the development of data-driven algorithms for real-time building response and site spectra estimation. *Chapter 1* introduces the Research Background with selected range of literature review in relevant artificial intelligence methods, relevant implementations in the earthquake engineering field, wavelet transform technology applied to building response, and current and modern earthquake early warning systems that process real-time observation data. From the obtained research background and problem statements, the research objectives and contents were devised and clearly explained.

Chapter 2 provides multiple machine learning methods to predicting seismic response of buildings. A sliding window algorithm for acceleration time-history representation is presented, and the

machine learning methods are compared for their time-series and Fourier spectra accuracy. The addressed sequence learning algorithms are Deep Neural Networks (DNN), Recurrent Neural Networks (RNN), Long Short-Term Memory (LSTM), and Levenberg–Marquardt Recurrent Neural Networks (LM-RNN). RNN-type networks contain feedback loops with recurrent connections between hidden layers of the network to enhance sequence learning tasks. The performance of conventional and modern neural networks are compared for a building with seismic response displaying resonance phenomena and significant higher modes. LSTM neural networks outperformed other supervised learning techniques at estimating the structural response time-series and Fourier spectra for testing data. LSTMs could maintain "memories" across thousands or millions of discrete time steps, which can be useful for subsequent earthquake events.

Chapter 3 explains a novel enhancement to inelastic seismic response prediction of structures using multiple-component features. Convolutional-LSTMs (ConvLSTM) units, originally used for weather forecasting, are proposed as an expansion to the capabilities of LSTM algorithms; however, the network architectures are re-engineered for adequate predictions for seismic signals. Also, the discrete wavelet transform (DWT) is proposed as an adequate feature engineering method for the proposed data-driven algorithms. The framework from the previous chapter is upgraded to compare 4 new hybrid model architectures, and the new sequence learning method is implemented on an industrial level building. Models that mainly included ConvLSTM layers underperformed in terms of computational time and accuracy. However, with model improvements, such as appending LSTM layers to the end of the model pipeline, and adequate DWT decomposition filtering, models reached satisfactory accuracy and could be suitable for real-time inference or with artificial earthquakes. The optimum architecture model (ConvLSTM-LSTM) is compared to the performance and capabilities of multi-degree of freedom analysis and an appropriate variant of Kalman filter (Augmented Kalman filter). ConvLSTM-based models were shown to be superior at capturing a range of natural frequencies.

Chapter 4 explains the implementation of an enhanced method for impending ground motions at sites for earthquake early warning (EEW) systems. The method relies on Fourier amplitude or pseudo-velocity response spectra, rather than strong motion parameters (PGA, shaking intensity, etc.). The DL architecture in this chapter is composed of a hybrid convolutional neural network (CNN) and LSTM architecture. The methodology forecasts target-site spectra from real-time observations of sites in near proximity of the earthquake event (front-sites). CNN-LSTM models can learn spectral features between sites and predicting evolved Target-site spectra several seconds ahead of S-wave arrival and in some cases even before tremors are felt. The shaking intensity scale by the Japan Meteorological Agency (JMA) is computed from site spectra using a developed intensity acceleration response spectra relationship. Noteworthy, seismic intensity is a byproduct of this methodology. Five case studies of different seismogenic regions and sites' amplifications are employed to evaluate the proficiency of this method in terms of spectra accuracy, seismic intensity accuracy, and available warning time (before S-wave arrival at Target-sites). This deep learning technique was able to learn site-site amplification effects from spectral series computed purely from observed acceleration records. This proves that this sophisticated technique can find site-site spectral relations without geological, source, or path information. The converged forecasts of this method are compared to empirical ground motion prediction equation output. Results demonstrated that CNN-LSTM is more reliable and robust compared to conventional GMPE methods. Finally, limitations of this method are discussed.

Chapter 5 discusses the main conclusions of the thesis are that the developed data-driven algorithms were rapid and precise at predicting building's seismic response and site ground motion spectra due to earthquakes. Each chapter's conclusion is summarized including accomplished concepts and findings. The benefits of each chapter are explained briefly, then prospects stemming from this research are clearly stated.