Simulation of earthquake wave for aseismic check of a nonlinear structure considering non-stationary characteristic of earthquake motion

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学 位 論 文 要 旨

SUMMARY

This dissertation has mainly presented three numerical methods of simulating non-stationary wave for aseismic check of structures, in which simulated earthquake, referred to as critical earthquake, causes greater response on a given nonlinear structure than that of an observed record of an actual earthquake, referred to as target. As criticality measure, response displacement of structure has been focused on. The critical earthquake was simulated in such a way that satisfied restriction conditions regarding amplitude characteristics of target including peak acceleration and envelope curve, as well as its frequency characteristics comprising the area under power spectral density (PSD) function and the predominant frequency. Using target, the simulation was conducted on a given structure, which can be a single-degree-of-freedom (SDOF) or a multi-degree-of-freedom (MDOF) system. Concerning target, four observed records of 1995 Hyogoken-Nanbu (Japan), 2000 Tottoriken-Seibu (Japan), 1978 Tabas-e-Golshan (Iran) and 1990 Manjil-Rudbar (Iran) earthquakes have been employed throughout this study, of which a record of the first earthquake, named as Kobe record, and a record of the third earthquake, named as Tabas record, both with peak acceleration more than 800 gal were frequently utilized. The major results of the studies obtained all through the dissertation are summarized as follows. Some suggestions for aseismic design of structures are presented, along with proposals for future studies.

In Chapter 1, the general scope of the dissertation, and a review of past studies on

critical excitation were presented.

In simulating critical earthquake, it was presupposed that the site condition of structure is same or similar to that where target is observed. Connected with exploring the site condition, Chapter 2 was devoted to microtremor measurements carried out after 2002 Changureh-Avaj (Iran) earthquake. The tremors were measured on the ground surface in Abdareh Village and on a typical adobe house in Tablashkin Village to analyze relation between earthquake motion and damage on adobe houses, which relatively survived in a part of Abdareh, whereas in the other parts of it were completely destroyed. Although adobe houses are very vulnerable even to mild earthquakes, it was concluded that a remarkable difference in ground conditions in that part of Abdareh was the main reason for relatively less damage being done to adobe houses there.

In Chapter 3 several issues related to phase characteristic of earthquake motion have been addressed. In simulating critical earthquake by the second method, to be described below in Chapter 4, phase spectrum of target is utilized. It was emphasized that the phase spectrum is not determined readily from the ratio of imaginary to real parts of the Fourier transform, and then method of determining true phase spectrum was proposed. In simulating earthquakes with different phase spectra it was revealed that phase spectrum affects the shape of time history, and within the accuracy of the calculations causes up to 20% difference in acceleration response spectrum. In the phase difference concept, general equations of expected and variance time histories of phase wave compatible with arbitrary distribution of probability density function of phase difference were developed. Applying these equations on Gaussian and beta distributions by different parameters proved correspondence of the variance time history with envelope of the acceleration time history. By modifying phase characteristic of a given earthquake record, some attempts for enlarging response of a considered nonlinear structure were examined, of which some simulated earthquakes showed up to 30% greater response displacement. However, comparing to the given record, Fourier amplitude spectrum of the simulated earthquakes increased. The chapter ended with describing Masing-type nonlinear structural response analysis method utilized throughout the dissertation, after which developed general equation of yield displacement for SDOF structures was introduced, and used in the following chapter.

Chapter 4 dealt with three numerical methods of simulating critical earthquake. In the first method of amplifying specified frequency components of PSD function, after dividing time duration of target into several time intervals, their PSD graphs were modified according to the natural period of considered structure which might be prolonged at some time interval(s). At each time interval, from the modified PSD graph a stationary artificial earthquake with uniformly distributed phase within $0 \sim 2\pi$ was generated and multiplied by envelope curve of target to get a non-stationary critical wave. Critical earthquake in the first method was assembling of the critical waves obtained at each time interval. By two introduced ways, continuity between the adjacent critical waves can be maintained. Using a target for which upper and lower limits of probable acceleration response spectra have been estimated, and by employing relationship between acceleration response spectrum and PSD function, it was revealed that the modified PSD graph of target corresponding to whole time history is within its upper and lower limits. By applying the first method on several structures using different targets, wide applicability of the method was confirmed. The remained part of the chapter is devoted to explanation of the second and third methods both followed by an application example. The latter two methods based on drift of specified component(s) of non-stationary PSD and multi-filter functions of target to peak acceleration time of target. The specified components correspond to and around the natural frequency of considered structure. The non-stationary PSD function was determined using a narrow band filter and smoothed by moving average method. The multi-filter function in method 3 is similar to non-stationary PSD function, but employs acceleration time history of the filter instead of energy. In this method with the aim of reducing high peak of PSD function of simulated earthquake, a nonlinear elastic filter with soft spring type force-displacement relationship was utilized. The chapter comes to an end by applying the 3 methods on a structure and comparison of them. It was concluded that: 1) applicability region of the first method is wide, but because of determining parameters by a random process, in satisfying restriction conditions many trials are necessary; 2) when synthesis of target from its non-stationary PSD function has good accuracy especially in peak acceleration, it is easy to simulate critical earthquake by the second method. However, this method did not show effectiveness for structures whose natural frequencies are apart from the predominant frequency of target; 3) simulation of critical earthquake by the third method is effective when target contains wide band frequency contents. In this case, unlike the second method we simulated critical earthquakes for different structures.

Chapter 5 covered experiments conducted to verify theoretical results of simulation, namely greater response of a considered structure due to critical earthquake than target. For this purpose, a steel pure frame model structure with scale factor of 1:8 accompanied with a viscous damper was employed. The utilized damper was a set of small-size dampers mainly made for radio controllers, in which the required damping ratio can be established by changing the inside oil. For simulation of critical earthquake, nonlinear parameters as well as the damping ratio of the model were necessary. Nonlinear parameters including yield displacement and the ratio of post-yield to initial stiffness were determined by static experiment. And, free vibration test was performed to confirm the natural frequency of 5 Hz and to determine the damping ratio of 2% of the model. Using the shortened Kobe record as target with the predominant frequency near to 5 Hz, a critical earthquake was simulated by the first method, and shaking table experiments were carried out. For each case of target and critical earthquake, five shaking table tests were carried out, all of which were in good agreement with theoretical analysis. In comparison with target, the average result represented about 60% greater response of the model due to critical earthquake even with less PA. From the five tests, for each target and critical case one output wave (recorded on the shaking table) that coincided well with the corresponding input wave (to the shaking table) was selected and compared with each other. Satisfying all the restriction conditions, the selected critical earthquake showed some 70% greater response than target.

Owing to inherent uncertainties in forthcoming earthquakes, a robust design is necessary especially for certain important (costly and/or potentially hazardous) structures that consequent damage or failure could be a tremendous catastrophe. The concept of critical earthquake can be taken into account for aseismic check of structures. In this study, it was focused on simulation of critical earthquake, and revealed that a simulated earthquake while satisfies the assumed restriction conditions may cause several ten percents greater response than a deterministic (target) record observed during past earthquakes. Nevertheless, there still exist certain problems in the aspects concerned. First, it seems necessary to evaluate that how realistic critical earthquakes simulated by the presented methods are. Secondly, it should be considered that if site condition where the considered structure is constructed in differs with that of observed target record, what modification should be imposed to the simulation process. And finally, if influential active faults are already known in the site of structure, how corresponding parameters of which can be taken into account.

学位論文審査結果の要旨

本学位論文に対し、審査委員が個別に面接と試問を行うとともに、第1回審査会で論文の内容について検討し、審査方針を決定した。さらに平成16年1月29日に行われた口頭発表後に第2回審査会を開き、協議の結果、以下のように判定した。

構造物の耐震性照査においては、1995年兵庫県南部地震などで得られた加速度波形を振動数領域で振幅調整して用いるように推奨されることが多い。しかし構造物の振動特性によっては推奨地震波形よりもさらに大きな応答をもたらす地震波形の存在することが考えられる。そこで本研究では地震波形と非線形構造物の振動特性が時間と共に変化することを考慮して、地震の最初から最後まで系が共振に近い状態で、より大きく応答するような地震波形の作成手法を数値実験的に検討、開発している。このときシミュレートされた加速度波形の最大値や包絡線、スペクトル密度などは原波形のそれらとの間で、ある制約条件を満足するようにしている。また2002年イラン・チャングレーアヴァジ地震の震害調査をし、構造物の震害と地盤条件の関係を常時微動計測により評価するとともに、先の手法にイランの構造物特性と地盤条件を導入する際の、基本的データを収集している。さらに振動台によるモデル実験により、シミュレートされた地震波形の妥当性を導いている。

以上の研究成果は耐震性照査用地震波形の信頼性を増し、また構造物の耐震性向上にも直接的に貢献するなど、工学上有用な知見を得ていることから、本申請者は博士（工学）の学位を受けるに値する、と判定した。