京都大学	博士（　　工　　学）	氏名	WANG　ZIQIAN
論文題目	Integrated Study on Seismological Site Effects Based on Empirical Methods Considering Linear and Nonlinear Soil Behaviors （経験的手法に基づく地盤の線形および非線形挙動を考慮した地震時地盤増幅特性に関する総合的研究）		

（論文内容の要旨）

This thesis concentrates on estimating the horizontal site amplification factor (HSAF) considering linear or nonlinear soil behaviors at sites with ground motion recordings. When seismological waveform simulation is performed for estimating ground motion at a site of interest, three effects should be considered: source, path, and site effects. HSAF, which represents the site effect, is essential especially for estimating the soil amplification factors in seismological waveform simulation. HSAF reflects the amplification of seismological waveforms from the seismological bedrock to the Earth's surface in terms of frequency domain. If this factor is not considered, the seismological waveform will be significantly underestimated in time domain. Precise evaluation of HSAFs is always an essential task for earthquake engineers. This thesis consists of six chapters and mainly proposes two methodologies for practical HSAF evaluation in case of linear and nonlinear soil behaviors. HSAFs in linear soil behavior cases ($HSAF^{L}$) estimated by the proposed approach is validated as superior to several existing methods. HSAFs in nonlinear soil behavior cases ($HSAF^{N}$) are estimated in a convenient way, based on a novel strategy.

Chapter 1 provides a general introduction to this thesis, briefly introducing some disastrous historical earthquakes in Japan, the concept of site effects and HSAFs, and the overview of linear or nonlinear soil behavior to seismological waveforms. The purpose and structure of this thesis are described.

Chapter 2 introduces the datasets utilized in this thesis. Three different databases are applied in Chapters 3 to 5. All the raw data are provided by Kyoshin Network (K-NET) and Kiban Kyoshin Network (KiK-net), installed and maintained by the National Research Institute for Earth Science and Disaster Resilience (NIED). The data from Jan 1, 1996, to Jan 1, 2020, are considered. More than 140,000 events with peak ground acceleration (PGA) of 4 to 15 cm/s^2 and more than 5,300 events with PGA greater than 100 cm/s^2 are utilized in this thesis. These data are collected from 1,550 observation stations throughout Japan. The largest PGA among utilized events is over 2,400 cm/s^2.

Chapter 3 describes a hybrid methodology for estimating $HSAF^{L}$. First, the similarity distribution between the horizontal-to-vertical spectral ratio of earthquakes ($HVSR_E$) and HSAF is explored. Based on such similarity distribution, the HSAF of a target site can be derived. This strategy is termed the "similarity method". The effectiveness of the similarity method is somewhat sensitive to the time-averaged shear wave velocity for the upper 30m (V_{S30}). HSAF is derived using the vertical amplification correction function without considering V_{S30} (VACF) and considering V_{S30} ($VACF_{VS30}$). Subsequently, the geometrical averaging on the above-mentioned HSAFs calculated by two different approaches is performed in order to acquire a new HSAF. This methodology involving geometric average with VACF

is termed “Hybrid method 1” and with $VACF_{VS30}$ is termed “Hybrid method 2”. Hybrid method 2 is very convenient for deriving $HSAF^{L}$, and the effectiveness of the Hybrid method 2 is superior to presently used approaches. In addition, a favorable comparison between observational waveforms and waveforms estimated considering the Hybrid method 2 is provided. A favorable comparison between $HSAF^{L}$ calculated by the Hybrid method 2 and that extracted by the ground motion model is also provided.

Chapter 4 depicts a methodology for estimating $HSAF^{N}$ using data of Kinki area of Japan. 119 sites were selected in total. All sites have at least one record with PGA greater than 100 cm/s^2, and at least five records with PGA of 4-15 cm/s^2. More than 7,000 records with PGA of 4-15 cm/s^2 and 227 records with PGA greater than 100 cm/s^2 were used. First, it was found that the difference between $HVSR_E$ in nonlinear cases ($HVSR_E^N$) and $HVSR_E$ in linear cases ($HVSR_E^L$) can be approximately regarded as a shift, from $HVSR_E^L$ to $HVSR_E^N$, both on amplitude and frequency axes. α and β are defined to represent the shift on the frequency and amplitude axes, respectively. Subsequently, the relationships between PGA versus α and β were explored. The nonlinear correction function (NCF) was proposed based on the relationships. $HVSR_E^N$ can be reproduced based on NCF, and then $HSAF^{N}$ can be derived based on the reproduced $HVSR_E^N$ and VACF. This methodology for deriving $HSAF^{N}$ is named the “VACF-NCF hybrid method”. The effectiveness of the VACF-NCF hybrid method has been proved based on the comparison with the HSAF calculated by an equivalent linear method considering frequency dependent characteristics of stiffness and damping (e.g. DYNEQ).

Chapter 5 describes an attempt to improve NCF proposed in Chapter 4. The data used in Chapter 4 was only gathered from the Kinki area of Japan, and NCF proposed in Chapter 4 was obtained without considering the site classification. In Chapter 5, data collected at 1,065 sites from entire Japan is used out of the whole database described in Chapter 2. Thus, NCFs proposed in Chapter 5 can be understood to be more creditable than those proposed in Chapter 4. Moreover, two types of NCFs were proposed in Chapter 5, namely, NCF considering site classification and NCF without considering site classification. Either of them can be used to reproduce $HVSR_E^N$. Subsequently, $VACF_{VS30}$, which was proposed in Chapter 3, was utilized to transform the reproduced $HVSR_E^N$ to $HSAF^{N}$. In addition, the relationships between the peak ground velocity (PGV) or PGV/V_{S30} versus the shift were provided. A presently used 1-D theory for $HVSR_E$ calculation preliminary validates the presence of shifts on the frequency and amplitude axes.

Chapter 6 provides conclusions of this thesis. This thesis concentrated on the estimation of HSAF under both linear and nonlinear soil behaviors. The methodologies applied in Chapters 3 to 5 are novel and can be used to improve the accuracy of HSAF estimation. The $HSAF^{L}$ and $HSAF^{N}$ estimated by the proposed method in this thesis is expected to be used to improve the accuracy of seismic waveform simulation for estimating ground motions at a site of interest.

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（論文審査の結果の要旨）

地震動予測のためには、震源、伝播経路、サイトの３つの特性を考慮する必要があり、サイト特性としては地震基盤から地表までの地盤構造による水平地震動の増幅率（Horizontal Site Amplification Factor:HSAF）を評価することが重要となる。建築物の構造設計時の設計用入力地震動評価のためには、建設地点の HSAF を精度良く評価することが不可欠である。本論文は、地震動観測記録から地盤の線形および非線形挙動を考慮した HSAF を簡便な方法で推定する手法を提案することを目的としたもので、得られた主な成果は次の通りである。

１．地盤の線形挙動を考慮した HSAF（$HSAF^{L}$）を推定するための新しいハイブリッド手法を提案した。この手法は、地震動の水平上下スペクトル比（$HVSR_{E}$）の複数地点間の類似度から類似する $HSAF^{L}$ を探査する手法と、表層 30m の時間平均 S 波速度（V_{S30}）を考慮した上下動増幅率補正関数（Vertical Amplification Correction Function:VACF）を用いて $HVSR_{E}$ から $HSAF^{L}$ を求める手法を組み合わせたもので、それぞれの手法で得られた $HSAF^{L}$ を幾何平均することで最終的な $HSAF^{L}$ が求められる。この手法により求められる $HSAF^{L}$ は、従来の方法と比べてより精度の高い推定が出来ることが検証された。

２．地盤の非線形挙動を考慮した HSAF（$HSAF^{N}$）を求める手法を、近畿地方の地震動観測記録を用いて開発した。まず、地盤が線形挙動から非線形挙動となったときの $HVSR_{E}$ の振動数と振幅の変動に着目し、それぞれの変動度である α と β および最大加速度との関係から非線形補正関数（NCF）を同定した。この NCF を用いることで非線形挙動時の $HVSR_{E}$ が求められ、さらに VACF で補正することにより、$HSAF^{N}$ が求められる。

３．近畿地方の地震動観測記録を用いて開発した手法を全国の地震動データセットに適用し、さらに地盤分類を考慮した NCF を用いることで、$HSAF^{N}$ を推定する手法を拡張した。その有効性を確認した。

以上の内容を要約すると、本論文は建築物の構造設計時の設計用入力地震動評価に不可欠な水平地震動の深い地盤域での増幅率を簡便でありながら高精度に推定する手法を提案しその妥当性を実証することにより、今後の設計用入力地震動評価の高度化に大きく貢献するもので、学術上、実際上寄与するところが少なくない。よって、本論文は博士（工学）の学位論文として価値あるものと認める。また、令和５年１月２４日、論文内容とそれに関連した事項について試問を行って、申請者が博士後期課程学位取得基準を満たしていることを確認し、合格と認めた。