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論文題目	Simulation of Strong Ground Motions in Mashiki Town, Kumamoto, Based on the Seismic Response Analysis of Soils and the Dynamic Rupture Modeling of Sources （地盤応答解析および動力学的震源モデルに基づく熊本県益城町における強震動シミュレーション）		

（論文内容の要旨）

It is indispensable to validate a unified approach to earthquake damage prediction in order to enable a quantitative assessment of future seismic hazard and risk. The sequence of the 2016 Kumamoto earthquake caused a devastating disaster in downtown Mashiki, Kumamoto Prefecture, Japan. According to the survey results of the Architectural Institute of Japan (AIJ), a damage belt spread mainly in the east-west direction in the area between the Prefectural road No. 28 and the Akitsu river in downtown Mashiki. This thesis consists of 10 chapters and aims to answer three important questions raised from the damage distribution in Mashiki: a) What was the contribution of local site amplifications to create the damage belt? b) What was the seismic performance of local buildings during the mainshock? c) What was the contribution of the source process to the strong ground motions during the mainshock? By answering these questions, the approach to earthquake damage prediction will be validated.

Chapter 1 is the introduction of research background and purposes of the study. This chapter describes the detailed information about the 2016 Kumamoto earthquake, the damage caused by the earthquake, and related research results. The problems to be solved in this study are also described and the content of this thesis is presented.

Chapter 2 illustrates the microtremor observations at 86 sites in downtown Mashiki and results of analyses of Microtremor Horizontal-to-Vertical spectral Ratios (MHVRs). It was found that the fundamental frequencies obtained from MHVRs show higher values in the northeastern side (up to 4.6 Hz) but lower values in the southwestern side (<1.0 Hz).

Chapter 3 presents the analysis of Earthquake Horizontal-to-Vertical spectral Ratio (EHVR) and pseudo EHVR (pEHVR), which is the transformed version of EHVR from MHVR. pEHVRs, MHVRs, and EHVRs are compared at and around the strong motion sites in Mashiki, and pEHVRs are found to be the good choice to be used for the identification of subsurface velocity structures in a wide area of Mashiki.

Chapter 4 explains the identified subsurface velocity structures in Mashiki. Inversion of the pEHVRs and EHVRs in Mashiki was carried out by using a hybrid heuristic search method. The depth distribution of the engineering bedrock was derived from the inversion results and the distribution of the time-averaged shear wave velocity of top 30m underground was generated. The results show that the stack of soft layers is thicker in the southwestern part, especially for the area close to the Akitsu river.

Chapter 5 explains the methodology and result of the estimation of strong ground motions in Mashiki by using the linear ground response analysis (LA) and the equivalent-linear ground response analysis (ELA). The distribution of the peak ground acceleration (PGA) and the peak ground velocity (PGV) in Mashiki was obtained. It was found that the PGVs in the southwestern area are larger than the other areas. This is consistent with the distribution of the building damage.

Chapter 6 illustrates the estimation of strong ground motions in Mashiki by using the nonlinear analysis (NA) with liquefaction. This chapter introduces two models to consider the nonlinear soil response, namely the Ramberg−Osgood model for representing the soil nonlinear property and the “bowl model” for considering the effect of the excess pore water pressure. The nonlinear properties of shallow subsurface layers at four borehole drilling sites were analyzed and the sand properties for Mashiki sites were classified into four categories. The estimated PGV distribution shows characteristics similar to the ELA results in Chapter 5. Most of the liquefaction sites are close to the river and this result is similar to the observed results.

Chapter 7 reports the estimated construction periods of existing buildings in Mashiki. The buildings of Mashiki were classified into four categories based on their construction periods: before 1950, 1951−1970, 1971−1980, and after 1981. The results show that the percentage of old buildings in the central part of Mashiki is larger than that in the other areas in Mashiki. This means that the age distribution also contributes to the creation of the observed damage belt.

Chapter 8 shows the results of building damage probabilities (DP) in Mashiki, based on the estimated strong ground motions by ELA and NA. The estimated DP by NA showed a distribution closer to the AIJ field survey results. This means that a higher DP zone appears at the southwestern area of Mashiki. The site-specific strong ground motions and building construction periods were found to be two influential factors of the building damage distributions during the Kumamoto earthquake.

Chapter 9 explains the strong ground motions simulated by the dynamic rupture analysis of the mainshock. A set of parametric studies were performed using finite difference calculations with a slip-weakening dynamic fault rupture model to find the relationships of the assumed stress drop and the resultant slip amount. It was found that the forward directivity effect has a significant influence to produce the large PGA and PGV along the direction of rupture propagation, the peak slip velocity increased greatly inside the asperity as rupture propagates and the high PGV on the surface was created by the high slip-velocity areas, but not by the large slip areas. These findings, together with the inverted slip distribution on the fault segment beneath Mashiki, suggested that the observed high PGV at Mashiki was caused by the strong rupture directivity from the asperity immediately beneath Mashiki. Peak values of estimated ground motions by the rupture dynamics analysis at KiK-net Mashiki (KMMH16) were similar to the observed ones. The estimated seismological bedrock motions at KMMH16 and Mashiki Town Hall (KMMP58) were almost identical. Moreover, PGV and PGD distributions showed clear effects of rupture directivity. It also resulted in a significant amplitude in the east-west component of the gound motions in Mashiki.

Chapter 10 provides the discussions and conclusions of this thesis.

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（論文審査の結果の要旨）

本論文は、2016年熊本地震の際に熊本県上益城郡益城町中心部において東西方向に帯状の建物被害集中域が生じた生成原因を解明するために、観測に裏付けられた物理モデルを用いて震源から建物被害までを考慮した手法により被害を再現することで、一連の予測手法を検証することを目的としている。そのために、益城町中心部全域の推定地盤構造と観測記録から逆算した基盤波を用いた非線形応答解析により面的な強震動を再現し、それを入力として建設年代を考慮した木造被害推定を行うことにより手法の検証を行うとともに、動力学的震源モデルにより震源破壊過程と観測地震動の特徴との関係を明らかにしたもので、得られた主な成果は次の通りである。

１．益城町の 86 地点における微動観測記録より換算した擬似地震動水平上下スペクトル比を用いて各地点の地盤構造を推定し、その地盤構造に KiK-net 益城地点での観測記録から逆算した基盤波を入力して、線形、等価線形、非線形の地盤応答解析を実施したところ、液状化を的確に考慮できる非線形地盤応答解析による最大速度分布が最も観測被害分布と対応が良いことを示した。

２．益城町における木造家屋の建築年代を４年代区分に分けて推定したところ、被害が顕著であった益城町中心部では 1950 年以前の建築年代の割合が益城町の他の領域に比べると高いことを示した。非線形地盤応答解析による地表での推定強震動と、建築年代を考慮した被害予測建物群モデルを用いた非線形応答解析を組み合わせて建物被害率を算出した結果、観測被害分布をよく説明できることが明らかとなった。このことから、益城町における建物被害の主な要因は表層地盤による地震動の非線形増幅特性と建築年代であることを明らかにした。

３．動力学的震源モデルに基づく熊本地震本震の地震動シミュレーションから、益城町全域において地震基盤における地震動は同一と見做せることを明らかにした。また、益城町での地表での地震動の最大速度が大きくなった原因は、益城町直下に位置する、すべり速度が大きい領域から放出された地震動が、破壊伝播の指向性効果によって増幅された影響が大きかったことを明らかにした。

以上の内容を要約すると、本論文の成果は、地震時の建物被害を推定するために必要な一連の予測手法を検証したこと、および 2016 年熊本地震におけるの被害発生要因を明確にしたことにあり、今後の強震動予測及び地震被害予測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３年１月２１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。