論文の内容の要旨

論文題目　The Origin of Near-Fault Ground Motion Pulses and Their Significance for Seismic Design

(震源近傍強震動パルスの成因と耐震設計におけるその重要性)

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Ground motions recorded in the near-fault area can present significant differences from those observed at the larger distances from the seismic fault. Presence of strong coherent long-period ground motion pulses recorded at some of the stations corresponding to a specific geometry of the fault-station configuration can be referred as being a distinctive characteristic of the near-fault ground motions that was widely discussed in the previous studies. These pulses can strongly affect the duration and spectral content of ground motions, thus being able to produce larger demand to the structures than ordinary records.

This study focuses on identifying the conditions contributing to the generation of the near-fault ground motion pulses for the earthquakes with different faulting styles. We aim to answer the question of how source parameters such as direction of rupture propagation, fault geometry, and the slip distribution affect the generation of the broadband near-fault ground motion pulses. The ability to predict the ground shaking for an expected future earthquake is an indispensable instrument in the mitigation of seismic hazard, and providing the guidelines for seismic design procedures. Taking this into consideration we also attempt to address the issue of how the obtained information can be further used in improving the simulation procedures for providing the ground motion time series relevant to the needs of seismic design.

In order to achieve these objectives, we estimated the detailed source process of two recent moderate damaging earthquakes from European and Middle East regions. These two events are the 2003 Bam, Iran (M_w 6.5) strike-slip faulting earthquake, and the 2009 L'Aquila, Italy (M_w 6.3) normal faulting earthquake. The earthquakes were characterized by significant damage concentrated in the area close to the causative fault, and by presence of ground motion pulses on velocity records from the near-fault stations. According to the analysis of the exceptional ground motions from European and Middle East regions both events are providing an important contribution to the database of largest recorded ground motions in the area.

We estimated the kinematic source processes of these damaging moderate size events from waveform inversions of the low-frequency seismological datasets recorded at both teleseismic and near-field distances. Given the significant amount of the available data, the source model of the 2009

L'Aquila event was further analyzed in the broadband frequency range using the empirical Green's function method in order to determine the broadband source characteristics accounting for the high-frequency ground motion generation. The conditions that contribute to the generation of the near-fault velocity pulses were then investigated by means of forward simulation for the assumed fault rupture scenarios based upon an inferred broad-band model.

The Bam earthquake (M_w 6.5) occurred on 26 December 2003 in southeastern Iran, causing a tremendous disaster in the city of Bam. A remarkable PGA of 988 cm/s^2 in the vertical component and two ground motion pulses in the horizontal components were recorded inside the damaged city. Previous analyses showed that the earthquake was caused by a subsurface rupture on an unknown strike-slip fault. In this study we attempted to determine the precise fault location and source process of the 2003 Bam earthquake by performing the waveform inversion of teleseismic and strong motion data, both individually and jointly. We examined the general features of the fault location and source process by analyzing the teleseismic displacement waveforms and determined the detailed features and fault geometry by inverting the three components of strong motion velocity records. The final estimate of the source process of the 2003 Bam earthquake is obtained by a joint inversion of the datasets. According to our results, a single fault model characterized by an appropriate location of the hypocenter, rake angle variations, and the Rayleigh-like speed of the rupture front can satisfactorily explain the three components of strong motion records at the BAM station, including the large fault normal velocity pulse. The latter one is well explained by the forward directivity effect of the rupture propagating towards the city of BAM at a high speed. The resulted model suggests that severe damage to the city of Bam can be attributed to a shallow rupture aggravated by the directivity effect, and a significant number of the poor quality buildings.

The L'Aquila earthquake occurred on 6 April 2009 at 01:32:40 UTC in the Abruzzo region of Central Apennines, Italy. As reported by Istituto Nazionale di Geofisica e Vulcanologia of Italy (INGV), the earthquake was generated by normal faulting on a fault system running parallel to the axis of the Apennine Mountains, and had a moment magnitude (M_w) of 6.3. Regardless of the fact that the magnitude of the event was not the largest that have occurred in the Apennines, the 2009 L'Aquila earthquake can be considered one of the most disastrous events there. Over 300 people were killed, about 1000 people were injured, and thousands of buildings and houses were destroyed and damaged. Most of the damage occurred within the city of L'Aquila, located close to the hypocenter, and the villages of Paganica and Onna, located further southeast. The event was followed by a significant aftershock activity that extended over the length exceeding 30 km in northwest-southeast direction.

The 2009 L'Aquila earthquake provided an unprecedented amount of seismological records from a normal faulting event, making the study of its source process an important issue for understanding and quantifying the seismic hazard due to normal faulting events. The values of PGA > 0.6 g, recorded at the near-fault stations located on the hanging wall of the source fault are representing the largest PGAs instrumentally recorded for an earthquake in Italy, as well as the largest values observed for a normal faulting event in European and Middle East regions. All of these near-fault ground motion records are presenting characteristic pulse-like velocity motions.

We developed a source model for the L'Aquila event, by performing waveform inversions of teleseismic and strong motion data in a frequency range of 0.05 to 0.5 Hz, and estimating the broadband modeling using the EGF method in the frequency range of 0.2 to 10 Hz. The resulted source model; location of the main asperity and the SMGA are in agreement with the results presented by other authors as well as the aftershock distributions. We confirmed that location of the main slip area about 8 km southeast from the hypocenter is the robust feature of the inversion. The determined SMGA is in agreement with the existing empirical source scaling relationships for inland crustal earthquakes implying a stress drop of around 10 MPa, confirming that the 2009 L'Aquila earthquake provided a stress drop that corresponds to the events recorded in the Central and Southern Apennines. The results of our analysis show as well correlation with the observed macroseismic intensities reported by INGV. The maximum MCS intensities of IX-X are reported southeast of the hypocentral location, with the value of X corresponding to the city of Onna.

In order to get an insight into the origin of the velocity pulses observed at the near-source stations during the 2009 L'Aquila earthquake, we carried out forward simulations for assumed fault rupture scenarios. The scenarios are based on the broadband source model determined by the EGF analysis. We tested the contribution of the along strike versus up-dip rupture propagation, the influence of the different assumptions of the rupture starting point, and the relative position of the rupture are and the city of L'Aquila. The results of the forward simulations confirmed that both along-strike and up-dip rupture propagation in the direction of station contribute to generation of the near-fault ground motion pulses. We could also identify that the radial rupture propagation towards the site is the main condition of ground motion pulse generation for the near-fault stations from both the hanging wall and the foot wall sides of the fault. For the hanging wall stations located above the rupture "focusing effect" could be confirmed as being another mechanism for the pulse generation. The analysis also pointed out that the along-strike propagation towards the site and the focusing effect are the main candidates for the worst case rupture scenarios of the pulse generation for the city of L'Aquila.

The results of the forward simulations support the idea of a more complex mechanism for the near-fault pulse generation in the dip-slip faulting events than that of the forward rupture directivity effect in case of the strike-slip faulting. These differences should be appropriately reflected in the procedures of the ground motion estimations for the seismic design.

In the final part and as one of the major conclusions of the study, we proposed a scheme of evaluating near-fault ground motions by summarizing our main results of the analyses related to the principal aspects of the generation mechanism of ground motion pulses. The scheme can be used to provide an estimate of a synthetic ground motion for an analysis of an engineering structure at a given site if the basic information about a fault to be considered (e.g., style of faulting) is available or a valid assumption about it can be made. The main contribution of the present thesis to the proposal constituting the suggestion of performing the evaluation of the pulse-like ground motions in case of dip-slip fault separately for the foot wall and hanging wall locations of the site, taking into consideration the relative location of the site and the assumed rupture area. This will result in including the rupture scenarios corresponding to the focusing effect and the radial rupture propagation.