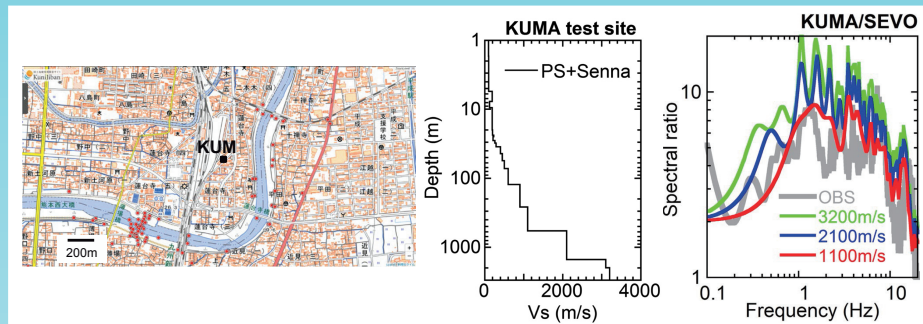


Earth, Planets and Space

Effects of Surface Geology on Seismic Motion (ESG):
General State-of-Research



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Yours sincerely,

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PREFACE

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Special issue “Effects of surface geology on seismic motion (ESG): general state-of-research”

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1 Introduction

To understand and predict the behaviors of strong ground motions incurred during devastating earthquakes, studies focused on the “effects of surface geology (ESG) on seismic motions” (following tradition, herein contracted as: “ESG”) have progressed steadily in the last three decades. These ESG studies typically involve in situ measurements of the wavefield and commonly apply both analytical and computational approaches. Concurrently, improvements in ESG-related research can be readily attributed to the proliferation of openly accessible strong motion data, as well as advances in computational power. Nevertheless, there remain significant shortfalls in our understanding of the epistemic and aleatory uncertainties associated with the ESG as demonstrated by phenomena from recent deadly earthquake-related site effects. Thus, investigations toward addressing these deficiencies should be underscored in future earthquake-related disaster mitigation efforts.

This special issue of *Earth, Planets, and Space* (EPS) is dedicated to the ongoing efforts by the International

Association of Seismology and Physics of the Earth's Interior (IASPEI) and the International Association of Earthquake Engineering (IAEE) that champion activities promoting studies related to the ESG. For over three decades, the IASPEI/IAEE oversaw six international ESG symposia that were hosted by local organization committees (LOCs) of the IASPEI/IAEE Joint Working Group on the ESG (JWG-ESG). Held in Odawara, Japan (1992), the inaugural gathering was dubbed as “ESG1”; going forward, ESG2 was held in Yokohama, Japan (1998); ESG3 in Grenoble, France (2006); ESG4 in Santa Barbara, United States (2011); and ESG5 in Taipei, Taiwan (2016). At the time of this publication, the 6th IASPEI/IAEE International Symposium on the Effect of Surface Geology on Seismic Motion (ESG6) was the latest gathering. Due to complications from the COVID-19 pandemic, ESG6 was originally planned to be held in Kyoto, Japan from 30 August–1 September 2021, but instead occurred as a virtual event held on the originally intended dates (Matsushima et al. 2024).

The first and third ESG symposia (ESG1 and ESG3; late 1980 s to early 1990 s) conducted blind studies (also known as blind predictions or trials) and fundamentally involved participants and researchers who were tested on their abilities to predict subsurface velocity structures, and to simulate observed ground motions using undisclosed site recordings that were later revealed to have been recorded in the Ashigara Valley, Japan. At about the same time (1987), a well-known blind prediction study involving the special deployment of an array of stations began at Turkey Flat, California (Real and Cramer 1992; Cramer and Real 1992; Cramer 1992). After nearly two decades, the study was able to gain traction when the

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array recorded the 2004 Mw 6.0 Parkfield Earthquake and produced mixed results (Real et al. 2006). Following these ESG-related endeavors, several similar major European benchmark tests were conducted, such as the Site EffectS assessment using AMbient Excitations (SESAME) (SESAME 2004), the INTERcomparison of methods for site PARAMeter and veloCITY proFile Characterization (INTERPACIFIC) (Garofalo et al. 2016a; 2016b), and PREdiction of NON-LINear soil behavior (PRENOLIN) (Régnier et al. 2018). In 2018, Asten et al. (2022) led an international pool of participants who took part in phased-blind trials on estimating seismic site conditions sponsored by the Consortium of Organizations for Strong Motion Observations Systems (COSMOS) to assess uncertainties when estimating shear-wave velocity (V_S) profiles obtained from microtremor observations. Data were incrementally released in four phases to 34 analysts, consisting of individuals and teams, with a wide range of experiences (graduate-level students to professional and academic experts). As a complement to the findings of Asten et al. (2022), COSMOS published a suite of international guidelines for applying noninvasive geophysical techniques to characterize seismic site conditions (Yong et al. 2022). Following tradition, the ESG6 LOC conducted a blind prediction test related to select recordings of the 2016 Kumamoto Earthquake sequence and the seismic site condition of a target recording location (Matsushima et al. 2024).

The ESG6 Symposium yielded submissions of more than 100 papers that originated from 21 countries. As mentioned, ESG6 was the most recent of successive JWG-ESG symposia since the inaugural 1992 ESG1 held in Odawara, Japan (JWG-ESG 1992). After the 2016 ESG5 Symposium in Taipei, Taiwan, the JWG-ESG organized a special issue published by the journal EPS entitled “Effect of surface geology on seismic motion: Challenges of applying ground motion simulation to seismology and engineering”, in which 18 papers were made available online in 2017 (Wen et al. 2018). For the 2021 ESG6 Symposium, the JWG-ESG observed tradition and published this current EPS special issue about recent ESG studies to share and disseminate the state of the art and knowledge in this important research field.

The members of the ESG6 Local Organizing Committee (LOC) encouraged authors, who have directly contributed papers to the ESG6 Symposium, to submit their manuscripts to this special issue. The LOC also encouraged submissions to ESG6 participants who wished to contribute other relevant papers about ESG related studies on ground motion prediction. In summary, 31 publications were associated with this special issue and were made available online from 2023 to 2024. Among them, three articles (Matsushima et al. 2024; Chimoto et al.

2023; Tsuno et al. 2023) were dedicated to describing the blind prediction exercise that was one of two main features of the ESG6 activities; the other activity being data usage as originated in Japan. Primarily, the ESG6 LOC was motivated to provide readers with important up-to-date information about Japanese seismological products and to further current capabilities to predict and assess uncertainties associated with Japanese ground motion recordings, as well as to distribute data (and metadata) for the ESG6 blind test exercise (Matsushima et al. 2024; Chimoto et al. 2023; Tsuno et al. 2023). Other articles herein are grouped by their commonality in subject matter. This collection of open-access articles is expected to attract a broad spectrum of readers and is intended to stimulate discussions about new paradigms that influence future ESG studies. Going forward, we hope that the state of art and knowledge described in this special EPS issue on ESG6 will further promote research on the quantitative prediction of strong motions for earthquake hazard mitigation.

2 Brief introduction of collected papers

2.1 ESG6 LOC blind prediction report

We curated three summary reports from the LOC of the ESG6 Symposium that were related to the blind prediction experiment (Chimoto et al. 2023; Matsushima et al. 2024; Tsuno et al. 2023). Matsushima et al. (2024) cast the premise, as well as the overview of the full ESG6 blind prediction test exercise. The 2016 Kumamoto, Japan earthquake and a target recording site (KUMA) in Kumamoto city were selected as the test location for the exercise. The first phase of the blind test (BP1) is to characterize the subsurface structure under the target site, according to a common set of prerecorded microtremor and surface wave data. To establish a reliable exercise, Matsushima et al. (2024) assembled the earthquake data and conducted geophysical and geotechnical surveys in and around the site, as well as performed velocity logging in a 39 m deep borehole. Then, the preferred one-dimensional (1-D) V_S model was constructed and provided for procedures in the second and third steps of the blind test to predict earthquake ground motions for a moderate event (BP2) and the mainshock (BP3) of the 2016 Kumamoto Earthquake.

Chimoto et al. (2023) summarized the results in BP1. There were 28 participants (some in teams) who applied various surface wave analytical methods; notably, the SPatial Autocorrelation Coefficient (SPAC) technique was the most common approach used. Results by participants were presented statistically (standard deviation, σ , with respect to frequency, f); their submitted dispersion curves ($\sigma < 40$ m/s for $f > 3.4$ Hz; $\sigma < 20$ m/s for $f > 20$ Hz) and shallow V_S structures appeared to successfully

estimate the V_S in the top 30 m from the surface with a low standard deviation ($\sigma < 45$ m/s) from preferred V_S profile derived from the borehole measurement (Matsushima et al. 2024). However, further development of the techniques for estimating velocities for substrates at greater depths (to 1500 m depth) was recommended as large variations in predicted V_S ($\sigma = 786$ m/s) were observed.

Tsuno et al. (2023) summarized the predicted results of weak and strong ground motions at the KUMA target site of the blind prediction exercise for BP2 and BP3 by the participants. The authors compared all submitted simulations with observations for ground motions consisting of foreshocks, aftershocks, and the mainshock of the 2016 Kumamoto Earthquake sequence. The methods used for predictions were unrestricted; hence, there were 1-D, 2-D, and 3-D theoretical methods, as well as approaches that rely on Green's function, spectral ratio, etc. The authors compared participant-derived estimates of peak ground velocity (PGV) and/or peak ground acceleration (PGA), acceleration and/or velocity duration, Fourier spectrum, pseudo-velocity response spectrum, and/or site amplification factors. They found that the observed values were mostly within the range of $\pm$ one standard deviation (on average) of all the predictions in both the cases of weak and strong ground motions. The results of the mean absolute percentage errors for these indices suggested that the applied methods performed well for predicting weak and strong ground motions for all three recording components in the range of factors that are one-half to twice the observations. The authors also compared the accuracy of predictions for the categorized methods and found that scores by the 2-D and 3-D methods in the frequency range of 0.5–1 and 1–2 Hz for all its categorized blind predictions were higher than the scores by the other methods. They also observed that the goodness-of-fit score for the portions of the wave train after the S-wave arrivals by the 2-D and 3-D methods is higher than that by the 1-D method. The authors suggested that these differences indicated the predictions by the 2-D and 3-D methods accounted for the basin-induced and/or basin-transduced surface waves excited by the 2-D and/or 3-D geometry of the basin.

2.2 ESG6 blind prediction phase 1 (BP1) related studies

There are four individual papers related to the blind prediction exercise described as BP1, where all the participants were asked to delineate a velocity profile at the target site KUMA (Chimoto et al. 2023; Matsushima et al. 2024). Mercerat and Mikesell (2023) investigated the validity of their method that combines active-source multi-channel analysis of surface waves (MASW), ambient noise (microtremor) cross-correlation, and

microtremor horizontal-to-vertical-spectral ratio (mHVSR) techniques to invert both active and passive multi-station data to model the velocity profile at the target site of KUMA. First, the Rayleigh wave dispersion curve was obtained using classical cross-correlation techniques to analyze ambient noise data; then, the dispersion curve was combined with classical MASW analysis of data recorded from the active seismic linear array of vertical geophones. The resultant dispersion curve was found to be in good agreement with the dispersion curve related to the preferred model of the ESG6 LOC, at portions of the substrate in the first few hundreds of meters. They found that the mHVSR method was useful because the joint inversion of mHVSR and Rayleigh wave dispersion data facilitated the determination of the velocity profile to the depth of the basement unit deeper (> 1.4 km). Through the subsequent release of the P–S logging results by the ESG6 LOC, the authors revisited the submitted results and identified the misinterpretation of higher mode Rayleigh waves as the fundamental mode in the high-frequency range. They proposed to use both active and passive multi-component seismic data to effectively identify the surface wave modes, which may not be present in either data set as the expected seismic excitations may not be captured solely on the vertical component.

Using the earthquake-to-microtremor ratio (EMR) single-station method, Nagashima et al. (2023a) calculated the horizontal-to-vertical spectral ratio of mHVSR (abbreviated as mHVR in Nagashima et al. 2023a), which were then converted into a pseudo earthquake horizontal-to-vertical spectral ratio (eHVSR) and was their basis for the inversions of V_S and P-wave velocity (V_P) structures as guided by the diffuse field concept (DFC) for earthquakes (e.g., Nagashima et al. 2014). The authors found their theoretical eHVSR calculated from the velocity structures was successful in reproducing pseudo eHVSR in the frequency range of 0.1–22 Hz. Despite some minor differences in the horizontal site amplification factor around the maximum peak frequency (0.8–1 Hz), the Nagashima et al. (2023a) inverted structure was found to be closely aligned with the characteristics of the preferred model and the averaged model of results produced by all the blind prediction participants.

Asten et al. (2023) estimated the V_S profile at KUMA using the direct-fitting multi-mode spatially averaged coherency (MMSPAC) method and the spatially averaged coherencies (krSPAC) method on passive data for a seven-station nested triangular array with apertures ranging from 1–962 m that were released from the ESG6 LOC. The data allowed the authors to conduct analyses in the frequency range of 0.3 to 38 Hz, allowing depth sensitivity from 2 m to over 1000 m. The results were

presented as a layered earth model which has time-averaged shear wave velocities for top 30 m and 300 m ($V_{S30} = 189$ m/s and $V_{S300} = 584$ m/s, respectively). Their mHVSr showed two significant peaks at 1.2 and 0.35 Hz, which the authors claimed are indicative of major V_S contrasts at depths 26 m and 750 m (respectively) for their estimated model. Evidence of lateral variation in V_S was detected at a depth range of 100–350 m (lower V_S under the eastern part of the survey area). The authors also suggested that an anomalous mHVSr peak for the north-west vertex of another part of the array can be explained by a possible change in basement structure or V_S at depths greater than at an order of 750 m.

Manakou et al. (2023) determined V_S by combining data from passive- and active-source field investigations for BP1. They analyzed vertical components of microtremor records using the SPAC method and data from a seven-station nested triangular array. They calculated cross-correlation coefficients and determined dispersion curves, which they assumed to correspond to the fundamental mode of Rayleigh waves. Simultaneously, they analyzed seismograms from the active-source seismic profile. By combining these results, their dispersion curve was characterized by phase velocities varying from 150–1920 m/s in the frequency range from 0.5–32 Hz. They calculated the 1-D theoretical Transfer Function (TF) from their V_S profile and compared the TF with the observed mHVSr curves. The higher peak frequencies at 1.0 Hz and 1.5 Hz in the TF were found to correspond to the 2nd and 3rd peak frequencies of the observed mHVSrs. However, the apparent difference in the fundamental resonant frequencies at 0.3–0.35 Hz in mHVSrs and 0.5 Hz in TF suggested that a basin deeper than the inverted bedrock depth was needed for the KUMA site.

2.3 ESG6 blind prediction (BP2 & BP3) related studies

There are five individual papers related to the BP2 and BP3 phases, where all the participants predicted weak and strong motions at the target site KUMA (Tsuno et al. 2023). Here are brief summaries of these paper collected in the special issue.

Based on the previous work of Nozu and Nagasaka (2017) and others, Nagasaka (2023) reported the results of his ground motion simulations as a part of the BP2 and BP3 exercises using corrected empirical Green's functions. This simulation method combined simple source and path factors with empirical site amplification and phase factors directly extracted from the pseudo point source to generate realistic site-specific ground motions. First, a region-wide spectral inversion was performed to obtain the Q-value and site amplification factors. Then, synthetic ground motions using a small Japan Meteorological Agency seismic intensity-scale magnitude

($M_{JMA}4.8$) earthquake for ten K-NET and KiK-net sites (in addition to the KUMA site) for the BP2 exercise was calculated. Next, by minimizing the errors between the observed and synthetic spectra for the target event of M_W 5.5, the source parameters were determined. The author found good agreement in both time and frequency domains for nine sites out of 11 sites used for evaluation. He then calculated synthetic ground motions for the M_W 6.1 event (largest foreshock) as part of the BP3 exercise. As before, he performed synthetic calculations for the M_W 7.1 mainshock. The author concluded that synthetics for the foreshock and mainshock were found to explain the observed ground motions at KUMA and other stations fairly well. Comparisons with predictions by other methods and the sensitivity to the rupture scenario were also presented.

Nozu (2023a) simulated ground motions for an M_W 5.9 earthquake at the target site KUMA for BP2 and estimated the Fourier amplitude spectrum from the spectral ratio between KUMA and a nearby JMA site. The Fourier phase spectrum was approximated by the spectrum of another event at KUMA. Comparison between the estimated and recorded ground motions after the blind prediction revealed that the estimated ground motions were consistent with the observed ground motions, implying the effectiveness of his approach. To simulate ground motions at KUMA for the M_W 6.5 foreshock and M_W 7.3 mainshock of the 2016 Kumamoto earthquake sequence as part of BP3, the author conducted effective stress analyses to account for soil nonlinearity. Comparisons between the estimated and recorded ground motions after the blind prediction indicated that the predictions for low-frequency components were overestimated, and the high-frequency components were underestimated. The strong soil nonlinearity considered in the effective stress analyses was determined to be the main cause of these discrepancies.

Nagashima et al. (2023b) estimated weak and strong ground motions based on DFC for earthquakes for BP2 and BP3. The spectral amplitudes of the three-component incident waves at the reference rock site were estimated from the vertical motions observed on the surface, assuming the generation of a diffused field for a single earthquake record. This estimation was then used for predicting the ground motions at the target site KUMA, also by considering the dynamic deformation characteristics of the soil. The authors demonstrated that they succeeded in obtaining the overall spectral intensities of all components at the frequency range between 1 and 10 Hz that corresponded to the observed ground motions.

Hailemichael et al. (2023) reproduced ground motions from the M_W 6.5 and the M_W 5.9 Kumamoto earthquake using a 2-D ambient vibration (AMV; also known

as ambient noise) derived V_S profile and 1-D ground response analyses. AMV data were analyzed using multiple surface wave methods to extract the dispersion curves of both Rayleigh and Love waves, as well as the ellipticity curves of Rayleigh waves. The joint inversion of dispersion and ellipticity curves to derive the V_S profile provided valuable insights into the presence of significant seismic impedance contrasts, including a deep interface located at approximately 1.5 km depth. The V_S profile was then used to perform 1-D equivalent-linear simulations of the M_W 5.9 aftershock, and both equivalent-linear and non-linear simulations of the M_W 6.5 foreshock at the target site. Using quantitative goodness-of-fit metrics based on time–frequency signal representation, the authors found a fair-to-good match between 1-D predictions and observations for the M_W 6.5 foreshock, but a poor match for the M_W 5.9 aftershock. The acceleration response spectra overestimated the ground motions for the M_W 5.9 earthquake, while simulations for the M_W 6.5 event significantly underestimated ground motions for the foreshock, especially in the non-linear domain. The authors hypothesized that spectra inherent within the input motion, which featured amplification at low (< 0.6 Hz) and intermediate frequencies (1–2 Hz), correlate to the discrepancies between 1-D predictions and observations.

Régnier et al. (2024) presented results of two different empirical approaches to estimate the strong ground motion at the target site KUMA (soft soil site) from the observed ground motion at a reference hard rock site (SEVO) for the foreshock (M_W 6.5) and mainshock (M_W 7.3) of the Kumamoto 2016 sequence as part of their BP3 exercise. Their method estimated the non-linear transfer function between a reference rock and a sedimentary site by modifying the linear transfer function derived from weak motion recordings. In their approach, nonlinearity is calculated based on a machine learning tool applied to a wide collection of Japanese weak and strong motion recordings. Next, nonlinearity is considered based on a site-specific parameter related to an average nonlinear site response. The acceleration time series were derived by using the time delay between the arrivals at the rock and site stations, and a minimum phase assumption for the site transfer function. After the predictions were made blindly, the authors compared both simulations with the actual ground motions recorded at KUMA during the two events, together with the range of all other predictions performed during the BP3 exercise. The authors claimed that their purely empirical methods provided a viable approach for predicting non-linear site response. More specifically, they found that the performance of these approaches is at least comparable to those of the

numerical simulation methods for the foreshock and slightly worse for the mainshock.

2.4 Delineation of phase velocity and velocity profile inversion in general

Cho (2022) analyzed the passive data distributed by the ESG6 LOC using the standard SPatial AutoCorrelation (SPAC) method to validate the approach developed by Cho and Iwata (2021). The Cho and Iwata (2021) approach was based on the relation between the array radius and the upper limit wavelength normalized by the array radius (NULW). Cho and Iwata (2021) suggested that (1) random errors in the SPAC coefficients and phase velocities are generally small even for very long wavelengths relative to the array radius; (2) consequently, the signal-to-noise ratio (SNR) becomes a crucial factor determining the NULW for the analysis of the SPAC method; thus, (3) the relation $(\text{NULW}) \propto \sqrt{(\text{SNR})}$ holds. Based on the statistical data obtained by Cho et al. (2021) and together with the BP1 data, it was shown that the NULW strongly depends on the array size, either small (radius r less than a few tens of meters) or very small (r about 1 m or less) arrays or both, the NULWs of which are dramatically larger than those of both middle (r about 100 m) and large (r about 500 m or more) arrays. According to Foti et al. (2017), NULWs from 4–6 times remained valid for arrays with radii larger than several tens of meters. However, the authors demonstrated that the empirical array size dependency of NULWs for small/very small arrays, as well as the large variations appearing in NULWs, can be explained by the effects of soil attenuation. Nevertheless, it is considered that the self-noise of a recording system also plays an important role. As a logical consequence (also shown empirically), the practicality of very small arrays increases as the soil gets softer (i.e., the S-wave velocity gets lower).

Sánchez-Sesma et al. (2023) introduced a theoretical derivation of Green's function, which was proposed for the velocity profile inversion or site amplification evaluation. They presented a new closed analytical solution in the frequency domain based on the principle of equipartition of energy. They found that the imaginary parts of Green's tensor components equal the average cross-correlations of the fields generated by the uniformly distributed multiple incidences of P- and S-body waves and Rayleigh waves with amplitudes weighted by partition factors. They validated their findings by comparing synthetic seismograms of well-known solutions for point sources. Their paper suggested that the concept of the diffuse fields is a robust basis for understanding the behavior of a realistic medium.

With their study area located on the Yufutsu Plain of Japan, Nakagawa et al. (2023) introduced a combined

method of MASW for active source, SPAC for microtremors, and autocorrelation function (ACF) analysis for the strong-motion data to invert S-wave velocity structures at the Kyoshin Network (K-NET) station of HKD126. Additional data recorded from three temporary accelerometer stations with sensors at the surface and at the seismological bedrock depth were also used. Their motivation is to determine the primary cause of the severe structural damages suffered by the Hokkaido Electric Power Company power plant because the HKD126 station in the town of Mukawa recorded strong-motion data with most energy in a predominant frequency range of 0.5–1.0 Hz during the 2018 Hokkaido Eastern Iburi earthquake (Mw 6.6). The validity of the estimated structures from the shallowest depth to the seismic bedrock was verified based on the differences between the observed arrival time difference and theoretical travel time difference for the S-wave initial motions. They estimated the seismic bedrock of the four stations to be at a depth of 7–10 km.

Labuta et al. (2023) determined the dimensions of the Mýtina maar (broad, low-relief crater) volcanic structure in West-Bohemia, Czechia using ambient vibration analysis. Ambient vibration data used in this study were collected by deploying two seismic arrays at two locations to estimate the V_S velocity structure of the crater infills. Array-1 was deployed to estimate the maar's lacustrine sediments. Array-2 was deployed to estimate the V_S of volcanic breccia. Additionally, active-source-induced vibrations were recorded along a transect, to map seismic response from the center to the border of the diatreme infills. For creating the 3-D velocity model, the seismic velocities at the selected sites of the Mýtina maar were estimated using array measurements. The development of elastic 3-D material parameters (P-wave velocity, S-wave velocity and density) of Mýtina maar was based on the density model in Mrlina et al. (2009) and the inverted velocity profiles at Array-1 and Array-2 were used for the lacustrine sediments and breccia, respectively. By using the simplified 3-D viscoelastic velocity model developed in this study, the synthetic ambient vibrations were simulated by the finite difference method. The simulated response fit both measured fundamental frequencies and the amplification levels, and the maximum depth of the crater was estimated to be at least 800 m.

Kimura et al. (2023) introduced a technique for direct estimation of phase velocity using records obtained through an arbitrarily shaped array. Array data were processed using a complex coherency function (CCF), where CCF was defined as the normalized cross spectrum of the microtremor records observed simultaneously by two receivers. The particle swarm optimization method, one of the metaheuristic optimization methods, was applied

and optimal values were provided for the phase velocity and other unknown parameters. Approximate representations of the stochastic properties for the unknown variables were analytically derived based on the discrete representation of the CCF, for a case where the arrival directions of microtremors were treated as random variables following a uniform distribution. Kimura et al. (2023) validated their method using both numerical simulations and actual observation records.

In pursuit of examining the applicability of DFC on earthquakes occurring outside the conceptual setting of Japan (Kawase et al. 2015), Ashayeri et al. (2023) presented a study on the inaugural application of the DFC using ground motions recorded in the tectonic and geologic environment of Iran. The authors produced velocity structures estimated from inversion codes developed by Nagashima et al. (2014) and Ashayeri et al. (2023). Both codes were run on recordings from three stations that are part of the Iranian Strong Motion Network (ISMN); data from one Japanese (KiK-net) station were used as the benchmark for their study. Both codes also calculated the theoretical eHVS curves based on DFC, but they differ in their respective search space parameterization and error-minimization algorithms. Empirical nonlinear site amplification functions were then estimated based on records from the M_W 7.3 Kermanshah mainshock and on the modified V_S structure that included shear modulus degradation in the shallow layers of the linear ground response analyses for two ISMN stations.

2.5 Empirical method for SAF evaluation

The site amplification study by Dhakal et al. (2023) applied the spectral inversion technique on earthquakes recorded by the S-net ocean bottom (OB) seismic network in the Japan Trench area to estimate key properties of the earthquake source spectra, path attenuation, and site factors from the horizontal-component S-wave portions of the recordings. They showed that the source spectra followed the ω^{-2} source model generally well, and estimated magnitudes were mostly within ± 0.3 magnitude units of the catalog magnitudes. Path-averaged quality factors were generally frequency-dependent and were somewhat larger than those in past studies. Amplification factors at a few OB sites in the shallow water regions were comparable with the theoretical ones computed from the 1-D subsea model.

Nakano and Kawase (2023) explored the spatial properties of site amplifications based on the generalized inversion technique (GIT) using Fourier amplitude spectra (FAS), as well as pseudo-velocity response spectra (pSv). The spatial distributions of S-wave site amplifications (SA-S), especially within large sediment basins (e.g., the Kanto and Osaka Basins in Japan), were found

to be relatively similar in proximate areas for long-period ground motions ranging from 2–8 s, suggesting that site amplifications can be easily predicted using an empirical approach through spatial interpolation of properties obtained by the GIT. A prediction procedure was proposed for site amplification for the entire duration from the SA-S at an arbitrary site. Nakano and Kawase (2023) found that SA-S in pSv was more or less similar to SA-S in FAS, however, when they calculated the site amplification for the whole duration (SA-W), their resultant pSv failed to capture the effects of the long duration of ground motions inside a large basin; they do not recommend the use of pSv for the prediction of entire duration of ground motion.

Nozu (2023b) studied the site amplification factors at several sites in the northern part of Hokkaido, Japan by using the GIT and spectra for a large-magnitude event at a very large distance. Prior to this paper, the author found that sites in the Soya region, Northern Hokkaido, with large site amplifications in the low-frequency range by GIT extended to both the eastern and western sides of the region. Such large amplification on the eastern side is contradictory to their shallow crustal velocity structures where rock outcrops are expected to occur. Hence, the author used records of the 24 May 2013 Mw 8.3 Sea of Okhotsk earthquake to validate the site amplification factors in a low-frequency range in that region. Because the epicentral distance of this event was greater than 1300 km with respect to the closest seismic station sited in Hokkaido, the expectation is that the difference in raw spectral amplitude at different stations represents the difference of the site amplification factors. The author found that the observed Fourier spectra for the S-wave part clearly indicated that the region of large site amplification in the low-frequency range extended to the eastern side as corroborated in the GIT site amplification factors.

2.6 Strong-motion prediction considering ESG

Graves (2022) presented a validation approach for a deterministic-stochastic hybrid simulation method intended for use as a physics-based broadband strong motion prediction. In addition to slip distributions, this approach also sampled variations in average rupture speed, down-dip fault width, and slip rise time. He validated the Graves-Pitarka (GP) approach using near-fault data from 12 California and Baja California earthquakes, where magnitudes ranged $5.9 \leq M_w \leq 7.3$. A total of 240 realizations are computed for each earthquake and compared with recorded ground motions from near-fault sites. Simulated ground motions are compared to the observations using a pseudo-spectral acceleration goodness-of-fit metric. Parameters for the lowest misfit cases are then tabulated to develop

relations for estimating median values and ranges for future applications. The reported results reinforced the importance of adequately sampling ranges of rupture parameters when performing validations, as well as when simulating ground motions for future events.

Petukhin et al. (2016) adopted a nonlinear source inversion method to construct a characterized source model of the 2016 Kumamoto earthquake, consisting of several Strong Motion Generation Areas (SMGA). To accelerate these calculations, they applied pre-calculated Green's Functions (GFs) estimated by the reciprocity method in the 3-D Japan Integrated Velocity Structure Model (JIVSM) (https://www.jishin.go.jp/evaluation/seismic_hazard_map/lpshm/12_choshuki_dat/; in Japanese; last accessed: 18 April 2025). The JIVSM model is validated by comparison of aftershock records. The authors used target sites limited to locations close to the fault. One of the advantages of this approach is the consistency of the inverted model with the characterized model that can be used for strong motion prediction. An important point of the inversion scheme is to describe the Kostrov-like slip velocity functions inside each SMGAs. Physical constraints for the range of the source parameters are applied. The authors succeeded in reproducing a strong westward velocity pulse at KMMH16 that caused severe damage in Mashiki, as well as short-period (> 1.5 s) waveforms at other sites near the fault.

To quantitatively reproduce observed ground motions that severely damaged the building stock of downtown Mashiki, Japan during the 2016 Mw 7.0 Kumamoto Earthquake, Fukutake et al. (2023) performed non-linear ground motion analyses to determine whether sub-surface soils liquefied. To emulate ground motions, 1-D non-linear effective-stress time-history analyses and simulated out-crop input motions based on the DFC for three locations were applied. These sites included: a KiK-net station (KMMH16) with both surface and down-hole sensor pairing; a free-field surface recording site (GS-MSK-2) with supplemental PS-logging borehole data at the GS-MSK-2 location, as well as at two other nearby PS-logging sites (GS-MSK-1 and GS-MSK-3); and a non-free-field station (MTO) housed on the ground floor of the Mashiki Town Office. Their analyses sufficiently replicated the recordings by KMMH16 where acceleration and velocity were observed to be more than 1000 Gal and 100 cm/s, respectively; the authors also surmised that no liquefaction occurred in the sub-soil of MTO despite the expectation of nonlinear soil behaviour at this site. For GS-MSK-2, the authors showed that soil liquefaction did occur where thick subsurface layers were known to be saturated with a shallow water table due to its proximity to the Akitsu River and observations of sand boils.

Ito et al. (2023) adopted the statistical Green's function method to model the ground motions for the 1944 Mw 8.2 Tonankai earthquake. Their statistical Green's function was constructed based on the GIT reflecting the medium and event-specific characteristics as statistical deviations from the average. The authors extracted seismological bedrock spectra at one reference site to compute the amplification at all other sites to demonstrate the merit of substitution for the empirical Green's function in the broadband frequency range. Then, a complex finite source model with random slip distribution and random rupture velocity perturbation was constructed. The authors succeeded in demonstrating the realistic simulation in the frequency range from 0.1 to 20 Hz.

Using strong motion data observed during the 2016 Kumamoto earthquake sequence in Japan, Tsuno et al. (2024) investigated the applicability of the on-site P-wave early earthquake warning (EEW) method on ground motions recorded near the source fault region. Because their method was based on site-specific ratios of S- to P-wave phases, P-wave arrivals with appropriate time-window lengths were found to be necessary to robustly predict S-wave phases for various sizes of earthquakes recorded in the sequence. Though reports about the behavior of non-linearity in soils underlying downtown Mashiki were widely observed, the authors reported that their EEW method was (instead) predominantly affected by the variability of the P- and S-waves relationship as influenced by source and path effects. Specifically, they found that the variability of the relationship of the P- and S-waves is greater at the seismic bedrock interface and at the ground surface. Hence, they concluded that site effects mask the effect of non-linearity of soil deposits.

2.7 Numerical and empirical modeling of 2-D/3-D ESG

Oprsal et al. (2023) modeled seismic wave propagation with a finite difference method using a 3-D structural model of the Osaka basin. The authors speculated that strong surface waves in the region are not directly generated by deep earthquake sources; instead, they originate by refraction occurring predominately at the edges of the bedrock-sediments interface. The objective of this research was to model observed surface Love waves generated in the eastern part of the basin that propagate approximately westward and were recorded by several surface stations. For these stations, the 3-D finite-difference modeling provided a good fit with the observed motions in terms of waveform amplitude and arrival time for the most detailed 3-D velocity model. The model contains the topmost 50–250 m structure with the lowest V_S at 250 m/s. The semblance analysis of the synthetic wave field revealed that the respective synthetic surface wave is a result of interfering waves arriving in OSA and WOS

stations from the northeast and southeast directions. Tests revealed that the synthetic wave field was extremely sensitive to the presence of the superficial 50–250 m thick low-velocity structure which was only a small fraction of the propagating surface wavelength and occupies only part of the surface area. The ability to model the surface wave in terms of amplitude and time arrival validated the 3-D structural model for long-period Osaka Bay earthquake scenario computations.

Petukhin and Iwasaki (2023) tuned source parameters of small earthquakes to validate the JIVSM of the Osaka basin. For source tuning, they adopted pre-calculated 3D GFs by adopting the reciprocity method, which substantially reduced the calculations required, compared to a full inversion of the source mechanism, depth, and source duration (rise time). Waveforms recorded by seismic stations at bedrock sites surrounding the Osaka basin were used. One of the merits of using bedrock sites at basin edges for the source tuning was the necessity for simulated input wavefields on the basin edges. The authors were able to remove the trade-off between source solution and wave propagation from source to site, which was possibly due to the inaccuracy of the velocity structure model. By mapping the distributions of misfit values for major earthquake-engineering metrics inside the Osaka basin, the authors succeeded in identifying areas in the basin that require additional tuning of the velocity model.

Sgatonni et al. (2023) introduced a signal rotation method for mHVSr analyses that was applied to microtremor recordings. The authors demonstrated the effectiveness of their technique for revealing 2-D resonance patterns, identifying resonance modes, and determining axes of seismic motions within buried geological structures. They were able to distinguish signals with 2-D resonances from those of 1-D based on inspections of data from individual spectral components of recorded motions. Determinations about the principal axes of motion were achieved through azimuthal analyses and alignments of the horizontal components. The authors tested their approach using a large number of single-station microtremor measurements in the Bolzono alluvial sedimentary basin and showed that seemingly complex resonance patterns can be simplified by interpreting these phenomena as 2-D resonances within slices of valley cross-sections.

Miyanaga and Yamanaka (2023) used numerical models of surface waves for the exploration of river embankments using 3-D shallow soil models with different subsurface shapes and S-wave velocities. The focus of this study was on the effects of surface and subsurface irregularities to the propagation and dispersion characteristics of Rayleigh waves generated by a surface source and observed at points along the crest of the embankment.

Rayleigh wave dispersion curves derived along the embankment crest were found to be contaminated by reflected waves and the amount of contamination was found to be affected more by the position of the velocity boundary at the bottom edge of the embankment rather than the surface topography. When the velocity boundary is close to the ground surface, especially at the toe of the slope, the effect of reflected waves was sufficiently large to generate biases in the phase velocity estimates.

2.8 A review of ESG related studies

Kawase et al. (2023) reviewed historical investigations about the ESG and outlined key elements required for reliable quantifications of site amplification factors (SAFs). Then, the authors introduced various emerging techniques for broadband quantitative evaluations of SAFs through their use of recorded ground motions primarily from dense Japanese accelerometer networks. From their own investigations, the authors recommended that researchers on ESG-related topics should refer to the five basic guidelines proposed in their conclusions for a more robust implementation of techniques to delineate SAFs in a specific region of interest, such as the use of Fourier spectra instead of response spectra.

3 Conclusions

This preface—entitled Effects of Surface Geology on Seismic Motion (ESG): General State of Research—introduces the special issue of *Earth, Planets, and Space* and 31 papers, which were curated from the 6th IASPEI/IAEE International Symposium on the Effect of Surface Geology on Seismic Motion (ESG6). Since 1992, six international ESG symposia were hosted by LOCs of the IASPEI/IAEE JWG-ESG. Despite the impacts of the COVID-19 pandemic, the papers of this special issue represent a major milestone for the LOC of ESG6. Following tradition, this issue includes a dozen papers related to the ESG6 blind prediction test on select recordings of the 2016 Kumamoto earthquake sequence and the seismic site conditions of a target recording location. Thus, the remaining 19 papers are published on state-of-the-art applications of geophysical site characterization methods by the developers, as well as articles by experts, on topics relating to uncertainty as stemming from site characterization and site response analyses. This collection of articles will naturally bring about more questions and elucidate the need to continue these activities for the foreseeable future. Going forward, we hope to follow the lead by IASPEI/IAEE to champion efforts that address shortfalls in our understanding of the epistemic and aleatory uncertainties as associated with the ESG.

Acknowledgements

We would like to express our sincere appreciation for the help and patience of the editorial team of EPS, especially Prof. Sagiya, the Editor in Chief during the editing process of this special issue.

Author contributions

The generic part of the main text was written by HK and edited and approved by the other authors. HK, AY, HA, and SM contributed to write the summary of each article that was handled by the editor in charge. HK and AY contributed to editing and revising the manuscript. All authors read and approved the final manuscript.

Funding

Not applicable.

Availability of data and materials

Not applicable.

Declarations

Ethics approval and consent to participate

Yes, we all have checked and approved.

Consent for publication

All authors have agreed to the publication of the manuscript.

Competing interests

The authors declare that they have no competing interests.

Received: 11 May 2025 Accepted: 20 May 2025

Published: 22 July 2025

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Unified approach for evaluation of horizontal site amplification factors with special reference to history of studies on the effects of surface geology on seismic motion

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Earth, Planets and Space 2023, **75**:95 DOI: 10.1186/s40623-023-01849-w

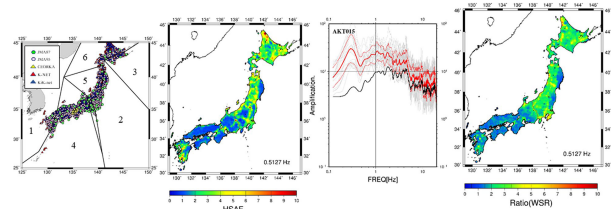
Received: 15 November 2022, Accepted: 20 May 2023, Published: 9 June 2023



Abstract

Following the 1923 Kanto earthquake in Japan, Japanese researchers noticed the strong effects of surface geology on seismic motion (ESG) and began to investigate these effects to quantify the site amplification factors (SAFs) associated with soft surface sediments. On the other side of the Pacific Ocean, ESG received limited attention until the 1985 Michoacan, Mexico earthquake revealed significant long-period amplification inside Mexico City that manifested as the source of devastating damage to high-rise buildings. Since then, seismologists and earthquake engineers have performed a lot of studies on various ESG issues worldwide. We have not yet reached common conclusions on how to quantitatively predict SAFs over a broad frequency band of engineering interest, 0.1 to 20 Hz, for moderate to strong input from different types of earthquakes in different tectonic settings. However, we found here several basic guidelines useful for successfully modeling ground motions as a common approach to ESG studies. First, in this letter, we briefly review our history of understanding ESG, which is closely related to the key settings required for reliable quantifications of SAFs, and then introduce various emerging techniques for broadband quantitative evaluations of SAFs based on the vast amount of observed ground motions primarily from dense Japanese strong-motion networks. Based on the findings of our investigation and the physical relationships behind the parameters, the authors would like to recommend that researchers on ESG and related topics would refer to the five basic guidelines proposed in the conclusions for the successful implementation of techniques to delineate SAFs in a specific region of interest, such as the use of Fourier spectra instead of response spectra. We have started applying the proposed techniques to regions outside Japan. The implementation of the statistical validation exercises will follow.

Keywords: Surface geology, Diffuse field concept, Horizontal-to-vertical spectra ratio, Subsurface structure, Earthquake-to-microtremor ratio, Vertical amplification correction



Graphical abstract

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Array-size dependency of the upper limit wavelength normalized by array radius for the standard spatial autocorrelation method

Ikuo Cho

Earth, Planets and Space 2022, **74**:75 DOI: 10.1186/s40623-022-01641-2

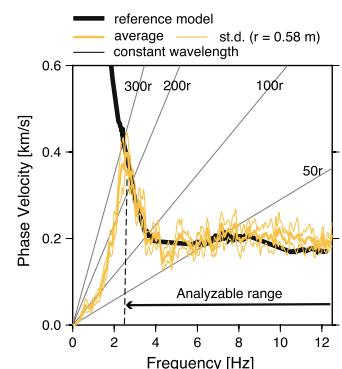
Received: 30 November 2021, Accepted: 3 May 2022, Published: 23 May 2022



Abstract

This study has shown for the analysis of the standard spatial autocorrelation (SPAC) method that the upper limit wavelength (ULW) normalized by the array radius (normalized ULW, NULW) strongly depends on the array size if we include small (radius r less than a few tens of meters) and very small (r about 1 m or less) microtremor arrays in addition to conventional larger arrays. First, field data of microtremor arrays were analyzed to demonstrate the possible use of small/very small arrays. Specifically, it was shown that, (i) even in the case of a very small array, random errors in the analysis results for very long wavelengths relative to the array radius are kept in an acceptable range for practical use; (ii) the signal-to-noise ratio (SNR) is a crucial factor determining the NULW; and (iii) an equation determining the NULW applies, namely the relation $(\text{NULW}) \propto \sqrt{(\text{SNR})}$ holds through very small to large arrays. The field data used are those distributed for blind prediction (BP) experiments for an international symposium (BP data), which consist of high-quality microtremor array data with various radii from very small ($r=0.58$ m) to large ($r=555$ m). It was then shown that SNRs of the BP data, and consequently the NULWs, increase with a decrease of array radius. Statistical data obtained from a few hundred arrays in our previous research also exhibit a similar tendency. The BP data lie around the maximum values of these distributions, showing the high quality of the BP data as well as supporting the array-size dependency of the NULW. Finally, the BP data were processed to identify the characteristics of the soil attenuation. It was found that the array-size dependency of NULW, as well as the large variations in NULW, can generally be explained by soil attenuation. It is plausible that the SNR of small/very small arrays are generally determined by the soil attenuation if the self-noise of the recording system is excluded. A logical conclusion drawn from these results, and also empirically supported, is that the practicality of very small arrays increases as the soil gets softer.

Keywords: Surface geology, Blind prediction, Microtremor, SPAC method, Surface wave, S-wave, SNR, Noise, Phase velocity, Attenuation



Graphical abstract

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Using a grid-search approach to validate the Graves–Pitarka broadband simulation method

Robert Graves

Earth, Planets and Space 2022, **74**:186 DOI: 10.1186/s40623-022-01742-y

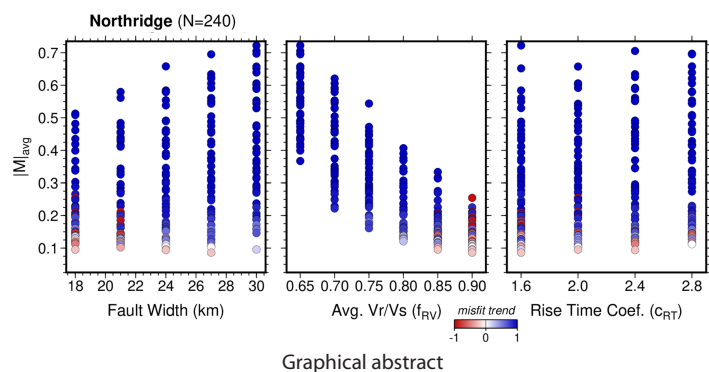
Received: 17 May 2022, Accepted: 16 November 2022, Published: 14 December 2022



Abstract

This work assesses the ability of the Graves–Pitarka simulation approach to reproduce observed ground motions for 12 California and Baja California earthquakes. A total of 240 realizations are computed for each earthquake and compared with recorded strong motions from near-fault sites. In addition to spatial variability in slip, each realization samples from discrete combinations of average rupture speed, rise time, and down-dip fault width. Ground motions for each realization of a given earthquake are compared to the observations using a pseudo-spectral acceleration goodness-of-fit (GoF) metric. Parameters for the lowest misfit cases are then tabulated to develop relations for estimating median values and ranges for future applications. The results are generally consistent with published scaling relations for estimating rupture dimensions as a function of magnitude. Additionally, I find the average rise time scales as $2.3 \times \alpha_T \times 10^{-9} \times M_o^{1/3}$ (M_o is seismic moment in dyne-cm) and average rupture speed as $(0.765 \pm 0.075) \times \alpha_T^{-1} \times V_s$ (V_s is local shear wave velocity), where α_T is a mechanism adjustment ranging from a value of 1.0 for pure strike-slip to 0.9 for pure reverse-slip cases. There are cases where slightly different combinations of parameters produce equally good fits to the observations, demonstrating the non-uniqueness of using a single GoF metric in this approach. Nonetheless, the results reinforce the importance of adequately sampling ranges of rupture parameters when performing validations, as well as when simulating ground motions for future events.

Keywords: Broadband simulation, Kinematic rupture, Strong ground motion, Grid-search validation



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Estimation of source, path, and site factors of S waves recorded at the S-net sites in the Japan Trench area using the spectral inversion technique

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Earth, Planets and Space 2023, **75**:1 DOI: 10.1186/s40623-022-01756-6

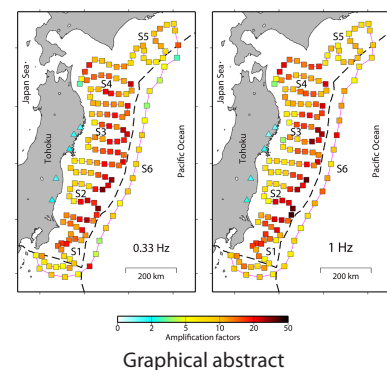
Received: 27 June 2022, Accepted: 17 December 2022, Published: 3 January 2023



Abstract

S-net is a large-scale ocean bottom (OB) network in the Japan Trench area, consisting of inline-type 150 observatories equipped with seismometers and pressure gauges. Among them, 41 observatories have been buried about one meter beneath the seafloors in the shallow water regions (water depth < 1500 m). We analyzed the strong-motion data recorded at the S-net sites from earthquakes with magnitudes $3.5 < M_w \leq 7$ and focal depths < 70 km to understand the site amplification effect on the recorded motions. We used the spectral inversion technique and obtained some fundamental properties of the earthquake source spectra, path attenuation, and site factors from the horizontal-component S-wave portions of the recordings. We obtained that the source spectra followed the ω^{-2} source model generally well, and the estimated magnitudes were mostly within ± 0.3 magnitude units of the catalog magnitudes. The stress drops increased systematically with the focal depths, and the values for the shallow earthquakes in the Pacific Plate were higher than those for the interplate earthquakes with comparable focal depths. The path-averaged quality factors were generally frequency-dependent and were somewhat larger than those in the past studies. The peak site frequencies ranged between about 0.2 and 10 Hz, while the peak amplification factors ranged between 10 and 50. Even though the peak frequencies and amplification factors differed from site to site, the peak frequencies were mostly higher than 2 Hz at the outer trench stations, while they were lower than 2 Hz at many inner trench stations. The amplification factors at a few OB sites in the shallow water regions were comparable with the theoretical ones computed from the 1-D subsea model. The amplification factors at intermediate frequencies (~ 0.3 to 2 Hz) generally increased with P-wave travel time in the sediments estimated from the multi-channel seismic survey. At about 20% of the sites (mainly at the unburied stations), spurious site spectra were recognized at frequencies higher than about 4 Hz. If the site spectra between 4 and 10 Hz are required, using only the X-component records is recommended.

Keywords: Site amplification, Path effects, Stress drops, Spectral inversion, S-net, Ocean bottom seismographs, Japan Trench



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Characterized source model of the M7.3 2016 Kumamoto earthquake by the 3D reciprocity GFs inversion with special reference to the velocity pulse at KMMH16

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Earth, Planets and Space 2023, **75**:16 DOI: 10.1186/s40623-023-01768-w

Received: 2 June 2022, Accepted: 7 January 2023, Published: 30 January 2023

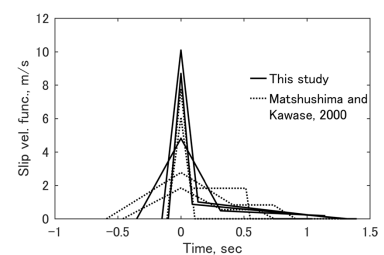


Abstract

The 2016 Kumamoto earthquakes caused severe damage centering on the Mashiki residential area. The velocity waveforms at station KMMH16 in Mashiki, during the M7.3 mainshock, show large pulses. We found that severe damage in Mashiki may be the result of the strong westward velocity pulse. The question raised is how the near-fault ground motions with strong velocity pulse at KMMH16 were generated during the mainshock. We focus on the characterized source model with Strong Motion Generation Areas (SMGA). Empirical Green's function (EGF) method is widely used for source modeling in this case. However, in case that the target site is located just near the fault in nodal plane of source mechanism (like KMMH16), mechanism of the EGF event should perfectly fit mechanism of the mainshock, which is a rare case. Therefore, instead of using EGFs, we used theoretical 3D Green's functions. Our approach is a nonlinear source inversion. This method requires calculation of waveforms and comparison with observations for many source models. To accelerate these calculations, we use pre-calculated GFs by the reciprocity method in the JIVSM velocity structure model. By comparison with aftershock records, we validated this structure for periods as short as 1.5 s. Target sites are limited to sites close to the fault: KMM005, KMM006, KMMH14, and KMMH16.

First, we look for an initial SMGA source model by the grid search method applied to relatively long-period (> 3 s) waveforms and coarse grid of source parameters. Then, we tune that source model to fit observed short-period waveforms with the simplex search method. Necessary physical constraints for the range of the source parameters are applied here. The important point in our inversion scheme is to describe the Kostrov-like slip velocity functions inside each SMGAs by using two triangles. The resulting source model agrees well with other inversion results. We found that the observed westward pulse at KMMH16 is the result of the constructive interference of two pulses from SMGA1 and SMGA2, located in Hinagu fault and southwestern segment of Futagawa fault.

Keywords: 2016 Kumamoto earthquake, Source inversion, Reciprocity method, Strong-motion generation area, Characterized source model, Recipe for strong-motion prediction, Source time function



Graphical abstract

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A new closed analytical solution for the elastodynamic half-space Green's function

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Earth, Planets and Space 2023, **75**:29 DOI: 10.1186/s40623-023-01780-0

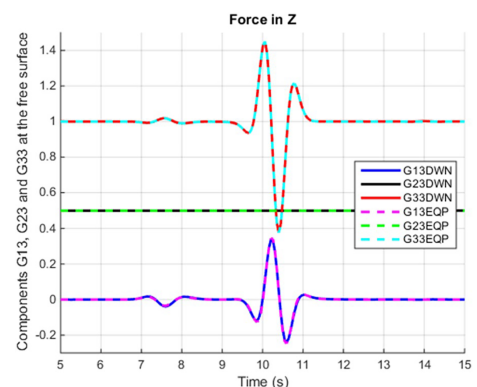
Received: 8 October 2022, Accepted: 27 January 2023, Published: 27 February 2023



Abstract

The elastodynamic half-space Green's function has been the subject of research for more than a century since the Lamb's classical solution. Here, we revisit the problem and present a new closed analytical solution, in frequency domain, based upon the Principle of Equipartition (EQP) of Energy. This principle asserts that the imaginary parts of the Green's tensor components equal the average cross-correlations of the fields generated by the uniform incidence of P and S body waves and by Rayleigh surface waves with amplitudes weighted by partition factors. The real part of the Green's function is the Hilbert transform of the imaginary part. We validate our results by comparing synthetic seismograms of well-known solutions for surface and buried forces and discuss the implications of this new solution. Constructing synthetic diffuse fields is a first step for identifying them in nature.

Keywords: Elastic half-space, Elastodynamic Green's function, Equipartition, Cross-correlations, Synthetic diffuse fields



Graphical abstract

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A look at the blind Kumamoto experiment: combining active and passive seismic observations to avoid Rayleigh-wave mode misidentification

E. Diego Mercerat* and T. Dylan Mikesell

Earth, Planets and Space 2023, **75**:31 DOI: 10.1186/s40623-023-01785-9

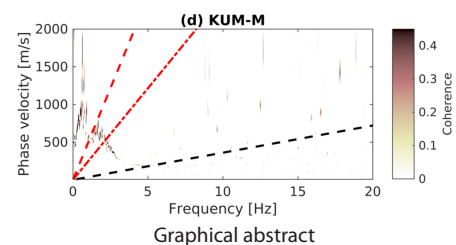
Received: 17 November 2022, Accepted: 11 February 2023, Published: 3 March 2023



Abstract

We present our pathway through participation in the blind Kumamoto exercise, particularly the Step 1 of site characterization. The combination of passive and active seismic imaging techniques is used to image the velocity profile beneath the KUMA site. The estimation of the broadband Rayleigh wave dispersion curve is based on cross-correlations of ambient seismic noise and analysis of active seismic shots. We calculate correlations from the entire time series (only vertical components) of each seismic array after classical pre-processing of ambient noise data. Then, a passive seismic section is constructed using all available stations pairs and stacking the cross-correlation traces with similar interstation distances. The obtained passive seismic section is analyzed using a high-resolution Radon transform to obtain the dispersion image of Rayleigh waves traveling through the KUM-LL, KUM-M and KUM-SM arrays. Then, the information is merged and interpolated to obtain the final broadband dispersion curve. In addition, active source seismic data are used with the high-resolution Radon technique to constrain the model at shallow depths (< 30 m). Then, a broadband dispersion image is constructed with significant energy from 0.9 Hz to 45 Hz. The final dispersion curve is inverted using the non-linear neighborhood algorithm. Using just the fundamental mode Rayleigh wave, a first model with normal velocity variation in depth is obtained that corresponds well with the preferred model provided by the organizing committee. The addition of a mHVS curve in a joint inversion better constrains the deeper part of the model (> 1 km). After comparison of the submitted dispersion curve to the theoretical dispersion curve for the preferred model (Step 4 of the blind test), the authors note that there was a clear misinterpretation in the fundamental mode of their submitted results, especially at frequencies higher than 5 Hz. Using both fundamental (only visible in the passive data set) and first overtones of Rayleigh waves (only visible in the active seismic data set) a refined velocity model could have been inferred, but we decided to keep our first submitted result. This detailed interpretation should be further studied as dispersion images from forward and backward hammer shots are quite different, which may indicate strong variations in the geometry and/or shear-wave velocities of the first meters of the subsurface.

Keywords: Seismic interferometry, Ambient noise, Site characterization, Surface waves



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Subsurface structure identification at the blind prediction site of ESG6 based on the earthquake-to-microtremor ratio method and diffuse field concept for earthquakes

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Earth, Planets and Space 2023, **75**:35 DOI: 10.1186/s40623-023-01791-x

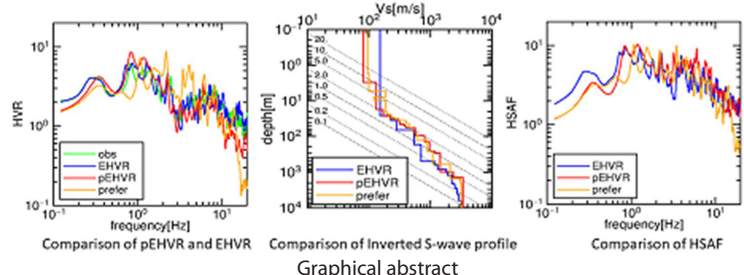
Received: 25 September 2022, Accepted: 23 February 2023, Published: 13 March 2023



Abstract

We participated in the blind prediction exercise organized by the committee of the blind prediction experiment during the 6th International Symposium on Effects of Surface Geology on Seismic Motion (CBP-ESG6). In response to the committee's request, we identified the ground velocity structure from microtremors observed at a target site as the first step of the exercise. First, we calculated the horizontal-to-vertical spectral ratio of microtremors (MHVR) at the target site from the distributed microtremor data collected in the vicinity of the target site in Kumamoto Prefecture. Then, we converted the MHVR into a pseudo horizontal-to-vertical spectral ratio of earthquake (pEHVR) using the previously proposed and validated earthquake-to-microtremor ratio (EMR) method, where an empirically obtained EMR is used to convert MHVR into pEHVR. Next, we inverted the S-wave and P-wave velocity structures based on the pEHVR and the diffuse field concept for earthquakes. The theoretical EHVR calculated from the identified velocity structure reproduced the pEHVR quite well in the frequency range of 0.1–22 Hz. After the collection of the blind prediction results by all the participants, the CBP-ESG6 released the observed earthquake records, a preferred model based on the P-S logging data from the in-situ borehole measurement combined with the generic deeper structure, and the average of all the predicted structures by the participants. Notably, our inverted structure was found to be close to the preferred model and the averaged one of all the blind prediction participants, despite some minor differences in the horizontal site amplification factor around the maximum peak frequency at 0.8–1 Hz.

Keywords: Diffuse field concept, Horizontal-to-vertical spectra ratio, Subsurface structure, Earthquake-to-microtremor ratio



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Blind study site assessment of shear-wave velocity at Kumamoto City, Japan, using direct-fitting SPAC methods

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Earth, Planets and Space 2023, **75**:40 DOI: 10.1186/s40623-023-01801-y

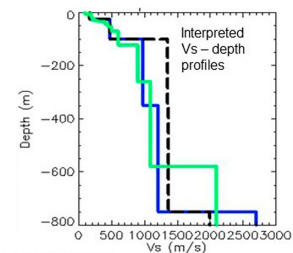
Received: 28 September 2022, Accepted: 6 March 2023, Published: 20 March 2023



Abstract

The study used data acquired by the ESG6 Blind Prediction Step BP1 Working Group for purposes of facilitating a comparison of interpretation methods for obtaining shear-wave velocity profiles (V_s) from array observations of microtremor (passive seismic) noise. This work uses the direct-fitting MMSPAC method and the krSPAC method on passive seismic data supplied from four seven-station nested triangular arrays with apertures ranging from 1 to 962 m, located within Kumamoto City, Japan. The data allow a useful frequency range of 38 Hz down to 0.3 Hz, giving depth sensitivities from 2 m to > 1000 m. Results are presented as a seven-layer model which has time-averaged shear wave velocities for top 30 m and 300 m of $V_{s30} = 189$ m/s and $V_{s300} = 584$ m/s, respectively. HVSR spectra show two significant peaks at 1.2 and 0.35 Hz which are indicative of major V_s contrasts at depths 26 m and 750 m. The MMSPAC method (and its krSPAC variant) also proved viable on one asymmetric array where four of the seven stations were corrupted by incoherent low-frequency noise. Indications of a lateral variation in V_s could be detected due to the non-concentric geometry of the four arrays, and also from variations in HVSR spectra at stations of the largest array. Further analysis in step 4 of the blind trials, making use of geological data and a Preferred model supplied to participants, showed apparent discrepancies between the Preferred and our BP1 model for the upper 40 m where a supplied PS log appears to be inconsistent with geological data and the blind BP1 model. At low frequencies 0.5–2.5 Hz dispersion data and the BP1 model suggest that use of the Rayleigh effective mode is superior to use of the fundamental mode in deducing the V_s model at depths below 100 m. The method of direct fitting of model and observed SPAC spectra used in MMSPAC also enabled the use of a bandwidth 0.5–38 Hz for interpretation, which is a wider bandwidth than that achieved by other participants for use of passive seismic data alone.

Keywords: Site effect, Microtremor, Passive seismic, SPAC, MMSPAC, krSPAC, Blind prediction



Green: Blind project committee Preferred model
Blue: This paper, best fit using multimode SPAC method with Rayleigh effective mode modeling
Black: poorer fit observed when modeling is limited to Rayleigh fundamental mode only

Graphical abstract

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Examination of one-dimensional S-wave velocity structure using strong-motion data for high-seismic-intensity area during the 2018 Hokkaido Eastern Iburu earthquake

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Earth, Planets and Space 2023, **75**:42 DOI: 10.1186/s40623-023-01802-x

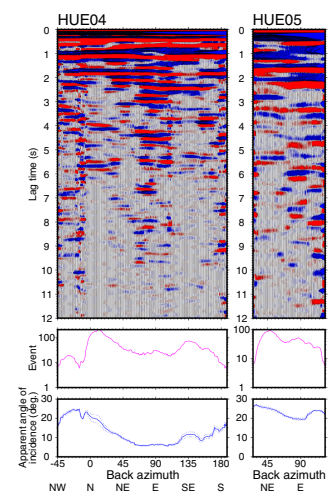
Received: 1 November 2022, Accepted: 7 March 2023, Published: 22 March 2023



Abstract

The Yufutsu Plain, a sedimentary basin surrounded by mountains, is located in the southern part of the Ishikari-Yufutsu Lowlands, Hokkaido, Japan. The Hidaka arc–arc collision zone, located in the eastern part of the Yufutsu Plain, forms the Hidaka Mountain range in central Hokkaido, with the Ishikari–Teichi–Toen Fault Zone of the Ishikari–Yufutsu Lowlands on the west side, which forms part of a major geological boundary that extends in the north–south direction. The 2018 Hokkaido Eastern Iburu earthquake (M_w 6.6) occurred at 03:08 JST on September 6, 2018, in this arc–arc collision zone. The K-NET HKD126 station in Mukawa Town, which is close to the severely damaged basin margin area, recorded strong-motion data with strong power for a predominant frequency of 0.5–1.0 Hz during the main shock. The peak ground acceleration was 661 cm/s^2 in the east–west direction. The site amplification characteristics of the shallow S-wave velocity structure, which was estimated from microtremor array observations and surface wave explorations, were one of the causes of this strong ground motion. It is essential to accurately estimate the depth of the seismic bedrock and basin margin to evaluate the long period of large earthquakes. In this study, we used strong-motion data recorded at HKD126 and three temporary strong-motion stations near the basin margin area to tune the deep S-wave velocity structure. First, we performed microtremor array observations and surface wave explorations to estimate the S-wave velocity structure to a depth of 1 km beneath the station at the hill site because a detailed shallow structure is not available for this site. Then, with a combination of the estimated S-wave velocity structure and the existing structure, we tuned the deep structures based on an autocorrelation function analysis using strong-motion data. The validity of the estimated structures from the shallowest depth to the seismic bedrock was verified based on the differences between the observed arrival time difference and theoretical travel time difference for the S-wave initial motion. We estimated the seismic bedrock of the four stations to be at a depth of 7–10 km. In addition, an autocorrelation function analysis suggests topological bedrock undulations.

Keywords: 2018 Hokkaido Eastern Iburu earthquake, S-wave velocity structure, Temporary strong-motion observation, Autocorrelation function analysis, Microtremor array observation, Multi-channel analysis of surface waves



Graphical abstract

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Influence of low-velocity superficial layer on long-period basin-induced surface waves in eastern Osaka basin

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Earth, Planets and Space 2023, **75**:55 DOI: 10.1186/s40623-023-01804-9

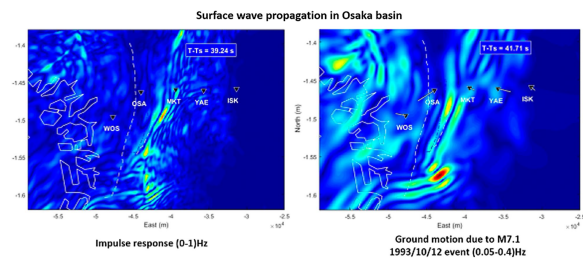
Received: 26 September 2022, Accepted: 9 March 2023, Published: 11 April 2023



Abstract

The long-period strong ground motions with periods above 1 s have, in the case of farther or deeper earthquakes, potential to cause serious damage to structures with low eigen frequency, such as long bridges, oil tanks, or artificially damped structures, such as high-rise buildings. This work focuses on wave propagation due to the deep large earthquake representing rare deep damaging events of the region, with relatively sparse data coverage, studied for simple geological models computed by 2D finite differences. We model the wave propagation by finite differences using up-to-date 3D structural model of the Osaka basin. The strong surface waves in the region are not directly generated by these deep sources, but they originate by refraction mostly at the edges of the bedrock–sediments interface. The objective of this research is to model observed surface Love wave generated in the eastern part of the basin that propagates approximately westwards and is recorded by several surface stations. At these stations, the 3D finite-difference modeling provides a good fit with the observed surface wave in terms of waveform, amplitude, and arrival time for the most detailed 3D velocity model that contains topmost 50–250 m structure with the lowest S-wave velocities of 250 m/s. The semblance analysis of the synthetic wave field reveals that the respective synthetic surface wave is a result of interfering waves arriving in OSA and WOS stations from NE and SE directions. Performed tests reveal that such a synthetic wave field is extremely sensitive to the presence of the superficial 50–250 m thick low-velocity structure which is only a small fraction of the propagating surface wave length and occupies only part of the surface area. The ability to model the surface wave in terms of amplitude and time arrival validates the 3D structural model for long-period Osaka Bay earthquake scenario computations.

Keywords: Long-period ground motions, Basin-edge generated surface waves, Low-velocity superficial layer, Finite-difference modeling, Hybrid modeling, Deep earthquake, Osaka basin



Graphical abstract

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Strong ground motion simulations of the 2016 Kumamoto earthquakes using corrected empirical Green's functions: methods and results for ESG6 blind prediction Steps 2 and 3 with improved parameters

Yosuke Nagasaka

Earth, Planets and Space 2023, **75**:61 DOI: 10.1186/s40623-023-01815-6

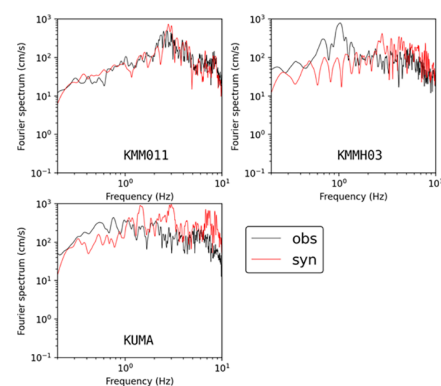
Received: 19 October 2022, Accepted: 7 April 2023, Published: 23 April 2023



Abstract

This paper describes the methods and results of the strong ground motion simulations for three earthquakes from the 2016 Kumamoto earthquake sequence using corrected empirical Green's functions. The target earthquakes were an aftershock (M_w 5.5), the largest foreshock of the sequence (M_w 6.1), and the mainshock (M_w 7.1). The corrected empirical Green's function method was used in the simulations. This simulation method combines simple source and path factors with empirical site amplification and phase factors to generate realistic site-specific strong motions. Simulations were originally conducted to participate in blind prediction exercises in ESG6. Although the simulations performed in this study were based on the models submitted to the blind prediction committee, several modifications were made after the blind prediction exercise. First, the observed records at the target site of the blind prediction called KUMA were used to compare observed and synthetic strong ground motions. In addition, a regional spectral inversion was conducted to obtain a more appropriate Q -value and site amplification factor. Synthetic strong motions were found to explain the observed strong ground motions at KUMA and other stations. Comparisons with predictions by other methods and the sensitivity to the rupture scenario were also discussed. These results provide useful information for applying the corrected Green's function method to strong ground motion simulations.

Keywords: 2016 Kumamoto earthquake sequence, Strong ground motion simulation, Corrected Green's function method, Spectral inversion, Site amplification factor, Blind prediction



Graphical abstract

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The spatial properties of the site amplifications of S-waves by generalized spectral inversion technique and the correction method of the site amplifications considering the contribution of later arrivals after major S-waves

Kenichi Nakano* and Hiroshi Kawase

Earth, Planets and Space 2023, **75**:65 DOI: 10.1186/s40623-023-01800-z

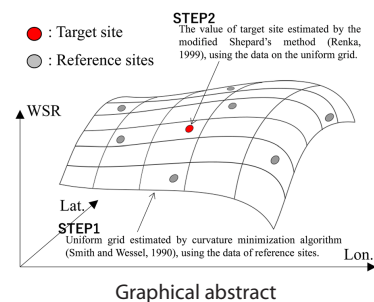
Received: 30 September 2022, Accepted: 5 March 2023, Published: 4 May 2023



Abstract

Site amplification is an important component of strong ground motion prediction as it differs among sites, reflecting its specific local subsurface geology. Here, we confirm that site amplifications are similar in a neighborhood area over a long period. However, few studies have investigated the spatial properties in a wide region (i.e., the whole of Japan). In this study, we explored the spatial properties of site amplifications based on the generalized inversion technique (GIT) using Fourier amplitude spectra (FAS) as well as pseudo-velocity response spectra (pSv) as the latter is an important index for engineering purposes and the most similar type of response spectra to FAS. The spatial distributions of S-wave site amplifications (SA-S), especially within large sediment basins (e.g., the Kanto and Osaka Basins in Japan), were found to be relatively similar in proximate areas for a long period ranging from 2 to 8 s. This suggests that we could easily predict the site amplifications using an empirical approach through spatial interpolation based on the properties obtained by the GIT. Furthermore, we propose a prediction procedure for site amplification for the whole duration from the SA-S at an arbitrary site. We used the correction function, which converts the SA-S to the site amplification for the whole duration (SA-W), including an S-wave portion and a subsequent portion. This function is called the whole-duration to S-wave spectral ratio (WSR) and is stable in terms of spatial properties. As we could estimate the SA-S either by theoretical transfer functions or observed microtremors, we can easily predict the SA-W based on the proposed WSR concept. We found that SA-S in pSv is more or less similar to SA-S in FAS, however, SA-W in pSv fails to capture the effects of the long duration of ground motions inside a large basin so that we cannot recommend to use pSv for the prediction of whole duration of ground motion.

Keywords: Generalized inversion technique, Pseudo-velocity response spectra, Fourier amplitude, Site amplification, Spatial distribution, WSR



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Validation of the Osaka basin velocity model by waveform simulation using sources inverted with reciprocal Green's functions

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Earth, Planets and Space 2023, **75**:69 DOI: 10.1186/s40623-023-01824-5

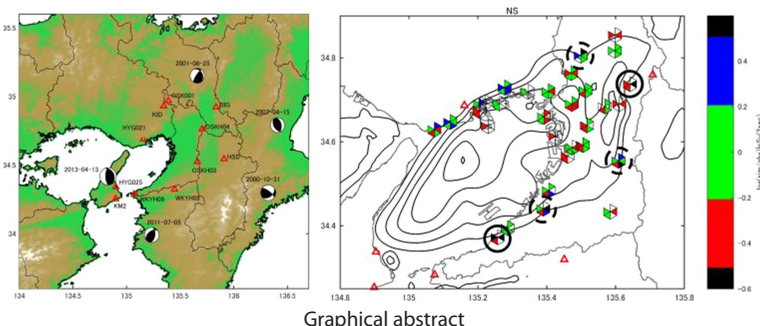
Received: 28 September 2022, Accepted: 15 April 2023, Published: 4 May 2023



Abstract

To advance the methodology for validating velocity models by waveform comparison, we estimated source parameters for small magnitude earthquakes that can be approximated by point sources. Instead of using published source models, we used the reciprocity method to calculate 3D Green's functions using the target velocity structure itself, and then inverted the earthquake sources. This method greatly reduces the calculations required compared to a full inversion of the source mechanism, depth, and source duration (risetime), making it possible to reproduce input ground motions in the target basin. Here, we validated the Japan Integrated Velocity Structure model of the Osaka basin using five earthquakes around the Osaka basin; these earthquakes allowed us to investigate the impact of the incident waves' propagation directions. We first estimated source parameters using records at control bedrock sites surrounding the Osaka basin to reproduce the input ground motions. Then, we conducted a 3D finite-difference simulation for sites within the basin. By mapping the distributions of misfit values for individual waveforms, peak ground velocities, and response spectra, we were able to identify areas in the basin that require additional tuning of the velocity model.

Keywords: Osaka basin model, FDM waveform simulation, Reciprocity method, Velocity model validation



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An experimental approach to unravel 2D ground resonances: application to an alluvial-sedimentary basin

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Earth, Planets and Space 2023, **75**:74 DOI: 10.1186/s40623-023-01825-4

Received: 22 May 2022, Accepted: 17 April 2023, Published: 10 May 2023

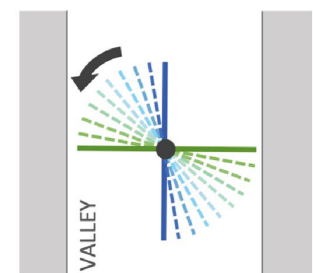
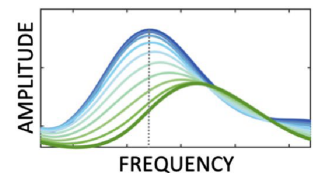


Abstract

The study of ground resonances is important to assess seismic site amplification and to infer information on the geometrical and mechanical properties of the resonating structures. 1D- and 2D-type resonances imply different dynamic behavior that can be distinguished by inspecting the individual spectral components of single-station microtremor measurements. Typically, 2D resonance modes develop along cross-sections of deep sediment-filled valleys and consist of longitudinal, transverse and vertical modes that can be identified as spectral peaks when ground motion is recorded parallel to the axes of the valley. In the case of more complex geometries, such as sedimentary basins, resonance modes are more difficult to predict and depend on the unknown complexity of the buried bedrock geometry. We show how a simple signal rotation procedure applied to single-station microtremor recordings reveals the underlying 2D resonance pattern. The method allows assessing the axes of motion of buried geological structures and identifying 2D resonance modes along these axes. Their directionality, frequency and amplitude features are then analyzed to extract information on the bedrock geometry. We test our method in the Bolzano alluvial-sedimentary basin and we observe that apparently complicated resonance patterns may be simplified by locally referring to the simplest description of the phenomenon as 2D resonance of a valley slice. The bedrock morphology can be decomposed into 2D-like geometries, i.e., excavated channels, and the observed resonances develop within cross-sections of these channels.

Keywords: Site effects, Vibration modes of sedimentary basins, 2D resonance, Directional analysis, Single-station microtremor measurements

2D resonance peaks along different directions



Graphical abstract

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Predicted results of the velocity structure at the target site of the blind prediction exercise from microtremors and surface wave method as Step-1, Report for the experiments for the 6th international symposium on effects of surface geology on seismic motion

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Earth, Planets and Space 2023, **75**:79 DOI: 10.1186/s40623-023-01842-3

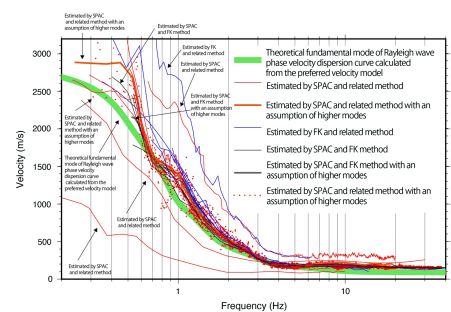
Received: 12 October 2022, Accepted: 3 May 2023, Published: 12 May 2023



Abstract

1D velocity profiles at a strong motion station in the northern part of the Kumamoto plain, Japan, were submitted in Step-1 of the blind prediction exercise of strong ground motions in the sixth international symposium on effects of surface geology on seismic motion (ESG6). Individual participants were requested to estimate a 1D S-wave velocity profile of sedimentary layers from the given data obtained by microtremor array explorations and surface-wave explorations at the site. This paper reports the target site, methods used by the individual participants, and the submitted results. More than half of the participants estimated the phase velocities of the Rayleigh-wave in the frequency range from 0.53 to 29.8 Hz. The statistical analysis of the phase velocity dispersion curves indicates that the standard deviation was below 40 m/s at the frequencies above 3.4 Hz, and it was below 20 m/s above 20 Hz. The S-wave velocity profiles are also similar to a depth of 20 m. The standard deviation was below 45 m/s. The average S-wave velocity in the top 30 m from the surface is 207.3 ± 60.7 m/s for the submitted profiles. The large variation is related to the introduction of the near-surface low velocity layers. The large variation of the S-wave velocities was found in the deep part. The average S-wave velocity at a depth of 1500 m was 2674 m/s with the standard deviation of 786 m/s. We compared 1D amplifications for the submitted profiles. Common peaks can be identified at 0.3–0.4 Hz and 1–2 Hz, excluding two teams. However, the amplifications vary much in the frequency range higher than 4 Hz. Through the experiment, it was found that the dispersion curves and the shallow S-wave velocity structures are estimated with a low standard deviation among the participants. Further development of the techniques for deep S-wave velocity profiling was found to be required.

Keywords: S-wave velocity, Microtremor exploration, Surface-wave exploration, Rayleigh-wave dispersion, Inversion, Kumamoto plain



Graphical abstract

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Modelling the seismic response of the Mýtina maar volcanic structure

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Earth, Planets and Space 2023, **75**:80 DOI: 10.1186/s40623-023-01822-7

Received: 6 October 2022, Accepted: 14 April 2023, Published: 12 May 2023

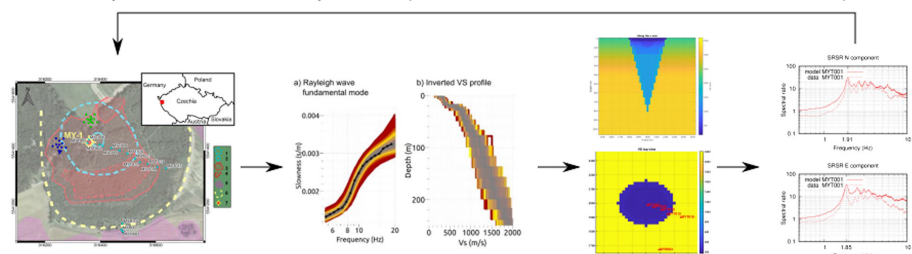


Abstract

In this study, we determine the properties of the maar volcanic structure using ambient vibration analysis. We performed several ambient vibrations surveys at Mýtina maar (West-Bohemia, Czechia) to map amplification by site-to-reference spectral ratios and to estimate average shear wave velocities by array methods. As the maar diatreme is formed by a deep concave body of broken rock, strong 3D resonances develop. The site-to-reference amplification factors reach a value of 20 in the central part of the maar. Using the noise data, we demonstrate possibility of mapping the lateral dimensions of the maar infills by ambient noise measurements. To understand these observations, we developed a simplified 3D viscoelastic velocity model and simulated synthetic ambient vibrations by the finite difference method. The simulated response fitted both, measured fundamental frequencies and the amplification levels. The maximum depth of the crater was estimated to be at least 800 m.

Keywords: Ambient vibrations, Site effects, 3D resonance, Spectral analysis, 3D numerical modelling, Maar volcanic structure response, Array measurements, Dispersion curves, F-K analysis

From field array measurements to F-K analysis and VS profile to creation of 3-D maar models to site-to-reference spectral ratio



Graphical abstract

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Quantitative strong motion simulations at three locations in downtown Mashiki during the 2016 Kumamoto Earthquake (Mw 7.0) based on the nonlinear ground response analyses with soil liquefaction

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Earth, Planets and Space 2023, **75**:87 DOI: 10.1186/s40623-023-01821-8

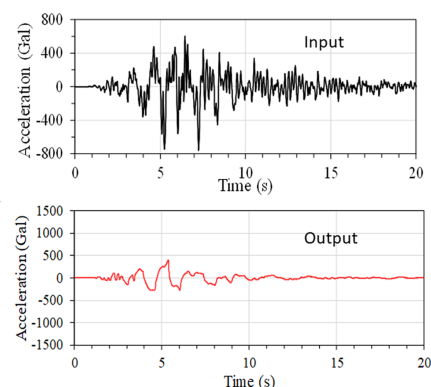
Received: 4 July 2022, Accepted: 14 April 2023, Published: 16 May 2023



Abstract

The mainshock of the 2016 Kumamoto Earthquake (Mw 7.0) caused extensive damage to buildings in downtown Mashiki, Kumamoto Prefecture, Japan. The heavy building damage in the area was associated with both strong ground motion and building response characteristics. Fortunately, there were two strong motion stations in the area and the observed records during the mainshock were distributed, showing peak ground velocities exceeding 100 cm/s on the surface. The level of shaking would be sufficient to make soft surface sediments nonlinear. To reproduce observed ground motions quantitatively, one-dimensional nonlinear effective-stress time-history analyses were conducted at three locations in downtown Mashiki. The input wave was employed as either the observed underground wave or simulated outcrop input motion based on the diffuse field theory. The main purpose of the study was twofold: to investigate the proper soil constitutive relationship and its nonlinear parameters based on the limited amount of in situ information, and to validate the method of input motion evaluation at the seismological bedrock level based on diffuse field theory. The nonlinear time history analyses using the on-site boring survey and the outcrop wave based on diffuse field theory showed that the waveform of the mainshock observed on the ground surface was explained with sufficient accuracy. In addition, the results of the effective stress analysis indicated that soil liquefaction might have occurred in the area with thick surface layers along the Akitsu River where the water table was considered to be quite shallow.

Keywords: Kumamoto earthquake, Observed strong motion, Nonlinear analysis, On-site boring survey, Soil liquefaction, Diffuse field theory



Simulation of acceleration waveforms on the ground surface at the liquefaction site (EW component)

Graphical abstract

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Estimation of phase velocity using array observation of microtremors with arbitrary shape

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Earth, Planets and Space 2023, **75**:88 DOI: 10.1186/s40623-023-01831-6

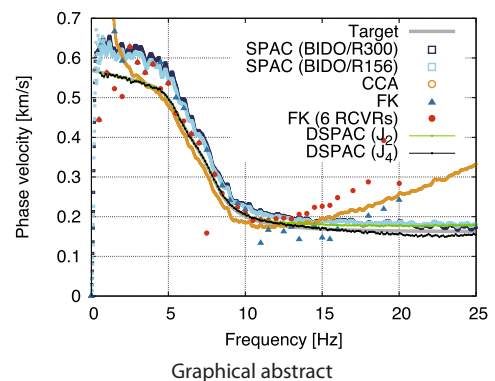
Received: 31 October 2022, Accepted: 22 April 2023, Published: 18 May 2023



Abstract

To estimate the phase velocity using the array observations of microtremors, some algorithms for the estimation include constraints on the array shape, such as equilateral triangles or the placement of receivers on a circle, in order to reduce the estimation error of the phase velocity. In the present study, a direct estimation technique is introduced for the phase velocity using records obtained through an array with an arbitrary shape based on a complex coherency function (CCF), where CCF is defined as the normalized cross spectrum of the microtremor records observed simultaneously by two receivers. The particle swarm optimization (PSO) method, one of metaheuristic optimization methods, is applied and optimal values are provided for the phase velocity and other unknown parameters. Approximate representations of the stochastic properties for the unknown variables are analytically derived based on the discrete representation of the CCF, for a case where the arrival directions of microtremors are treated as random variables following a uniform distribution. Furthermore, the validity of the proposed method is confirmed using numerical simulations and actual observation records.

Keywords: Microtremor survey, Arbitrary array shape, Array observation, Phase velocity, Numerical simulation, Complex coherency function (CCF), Direct spatial auto-correlation (DSPAC) method, Spatial auto-correlation (SPAC), Particle swarm optimization (PSO)



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Velocity structure above seismological bedrock estimated from earthquake recordings: an application of diffuse wave-field concept to strong motions in Iran

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Earth, Planets and Space 2023, **75**:94 DOI: 10.1186/s40623-023-01853-0

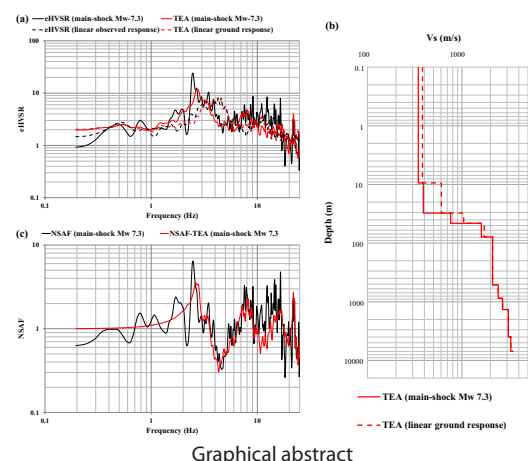
Received: 29 September 2022, Accepted: 28 May 2023, Published: 9 June 2023



Abstract

We present velocity structure inversion for three stations of Iranian Strong Motion Network (ISMN), and one KiK-net station that is used as a benchmark, for the application of diffuse wave-field concept in tectonic and geological setting of the west of Iran. This study compares the results of two existing computer codes for the velocity structure inversion at these sites. The computer codes use different search space parameterization, and error-minimization algorithms. Firstly, the available information on subsurface structure and surface geology from the strong motion stations is introduced. Then, ground motions of M_w larger than 4, with PGA of all components less than 50 cm/s^2 are used to calculate horizontal-to-vertical spectral ratios of earthquakes (eHVSR) at each station. The observed eHVSR curves are inverted for the velocity structure of the stations, and the results are compared with each other and the information of previous studies. Finally, the eHVSR curves of the mainshock records of the recent M_w 7.3 earthquake at two ISMN sites are investigated. The velocity inversion is repeated by considering the shear modulus degradation of several shallow layers. Empirical nonlinear site amplification functions are calculated based on the modified V_s structure and the V_s structure of the linear ground response for two ISMN stations.

Keywords: Diffuse field concept, Earthquake horizontal-to-vertical spectral ratio, Velocity structure inversion, Nonlinear site amplification function



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Strong-motion simulation for the 1944 Tonankai earthquake based on the statistical green's function method and stochastic representation of complex source process

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Earth, Planets and Space 2023, **75**:97 DOI: 10.1186/s40623-023-01847-y

Received: 3 August 2022, Accepted: 3 May 2023, Published: 15 June 2023

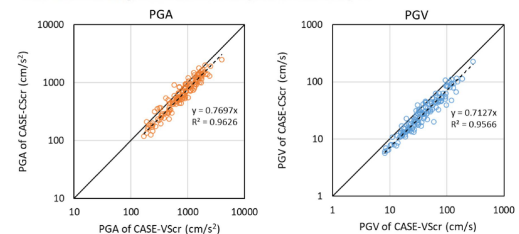


Abstract

Precisely evaluating the source, path, and site terms in a broadband frequency range is indispensable for quantitatively predicting strong motions. We conducted a generalized spectral inversion of strong motion in Japan to delineate both the spectral amplitude and phase characteristics for statistical Green's functions. To predict ground motion from future megathrust earthquakes, we also need to model a kinematic source with a stochastic representation of the slip and rupture velocities on the fault surface. In this fundamental study, we first reported the basic features of statistical Green's functions used for summation. We then demonstrated the construction of a kinematic source with distinctive strong-motion-generation areas with spatially random slip and rupture velocity variations. After the summation of statistical Green's functions following the constructed kinematic source, we found that the peak ground accelerations and peak ground velocities of synthetics for the Mw8.2 1944 Tonankai earthquake are in good agreement with those of the well-established empirical formula in Japan because the medians of the synthetic values are well within the average plus/minus one standard deviation of the formula. Based on the simulation results of conducted parametric studies, we observed relatively small but meaningful effects of random slip distribution, as well as relatively small effects of random rupture velocity perturbation. In conclusion, our implementation of the complex source model and the empirically obtained statistical Green's function used as an element source can be a viable combination for broadband (0.1 to 20 Hz) strong-motion simulations, realistic in terms of the amplitude and duration, without any hybrid scheme.

Keywords: 1944 Tonankai earthquake, Heterogeneous source model, Statistical Green's function

Comparisons of PGAs and PGVs for the calculated synthetics with slip variations (CASE-VScr) and without slip variations (CASE-CScr).



Graphical abstract

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Use of Fourier phase characteristics and effective stress analyses for post-earthquake ground motion estimation: application to ESG6 blind prediction steps 2&3 dataset and JMA accelerometric data

Atsushi Nozu

Earth, Planets and Space 2023, **75**:101 DOI: 10.1186/s40623-023-01854-z

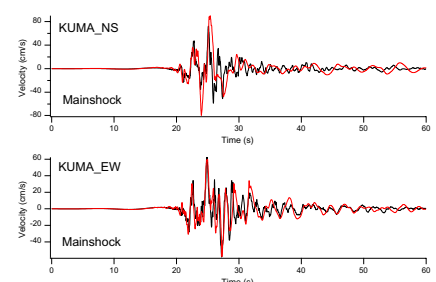
Received: 1 October 2022, Accepted: 28 May 2023, Published: 20 June 2023



Abstract

After the occurrence of a large earthquake, engineering seismologists are often requested to estimate strong ground motions at a site where strong motion data were not obtained. The goal of this study was to test the ability of a class of methods that uses Fourier phase characteristics for the post-earthquake ground motion estimation, making use of the precious opportunity provided by the ESG6 Blind Prediction Steps 2&3. It was also part of the goal of this study to test the performance of the effective stress analyses to account for soil nonlinearity. In addition to the dataset provided by the organizer of the blind prediction, the author used additional accelerometric data from a nearby JMA site. To simulate ground motions for an M5.9 earthquake at the target site "KUMA", the Fourier amplitude spectrum was estimated from the spectral ratio between KUMA and the nearby JMA site. The Fourier phase spectrum was approximated by the spectrum of another event at KUMA. Comparison between the estimated and recorded ground motions after the blind prediction revealed that the estimated ground motions were fairly consistent with the observed ground motions, indicating the effectiveness of the method when the rupture process of the target event is simple and the soil nonlinearity at the target site is not significant. To simulate ground motions at KUMA for the M6.5 foreshock and the M7.3 mainshock of the 2016 Kumamoto earthquake sequence, the author conducted effective stress analyses using a program called "FLIP" to account for soil nonlinearity. Comparison between the estimated and recorded ground motions after the blind prediction indicated that the low-frequency components were overestimated and the high-frequency components were underestimated. The strong soil nonlinearity considered in the effective stress analyses was the main cause of the discrepancy. One explanation for this result could be that the nonlinear soil behavior at KUMA during the foreshock and the mainshock was not a strong one. Another explanation could be that the effect of soil nonlinearity was already included in the records at JMA and the effect of soil nonlinearity was double counted in the results submitted by the author.

Keywords: Site effect, Fourier phase spectrum, Soil nonlinearity, Effective stress analysis, FLIP



Graphical abstract

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Estimation of weak and strong ground motions based on diffuse field concept for earthquake for steps 2 and 3 of blind prediction exercise

Fumiaki Nagashima*, Hiroshi Kawase, Kenichi Nakano and Eri Ito

Earth, Planets and Space 2023, **75**:104 DOI: 10.1186/s40623-023-01859-8

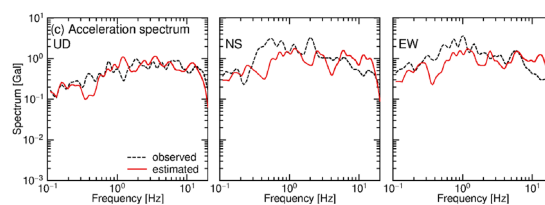
Received: 6 October 2022, Accepted: 10 June 2023, Published: 25 June 2023



Abstract

For the accurate prediction of earthquake ground motions, the investigation of three elements in its process, namely the source, path, and site effects, is crucial, and their accuracy and reliability should be evaluated. The Committee of the 6th Effect of Surface Geology on Seismic Motion Symposium conducted a blind prediction exercise to investigate the accuracy and reliability of estimating the subsurface velocity structure related to the site effect and for predicting weak and strong ground motions. We participated in a blind prediction exercise and estimated the weak and strong ground motions that occurred during the 2016 Kumamoto earthquake sequence. First, the velocity structures at a target site KUMA and our reference site EEB were identified based on the diffuse field concept for earthquake (DFCe). The identified velocity structures at KUMA and EEB reproduced the observed horizontal-to-vertical spectral ratios of earthquakes well and were considered to be able to reproduce the horizontal and vertical site amplification factors based on DFCe. Second, the incident waves at the seismic bedrock of EEB were estimated. For weak and strong ground motions, the spectral amplitudes of the three components of the incident waves were estimated from the vertical motions observed on the surface at EEB assuming the generation of a diffuse field for a single earthquake record and the linearity of the vertical amplification factor, even during strong shaking. Finally, the ground motions on the surface at KUMA were estimated using the incident waves estimated at the seismic bedrock, the inverted velocity structure, and the dynamic deformation characteristics distributed by the organizer of the blind prediction exercise for shallow soil sediments. The spectral amplitudes of the estimated strong ground motions were smaller at around 1 Hz and larger at around 10 Hz than the observed ones. However, the estimated overall spectral levels of all components corresponded to the observed ones. Although several parameters require further research, such as the damping factor of soil sediments, we have shown that the proposed method can estimate the overall seismic ground motions at a target site in the blind.

Keywords: Ground motion estimation, Blind prediction, Diffuse field, Horizontal-to-vertical spectral ratio, Seismic bedrock



Graphical abstract

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From ambient vibration data analysis to 1D ground-motion prediction of the Mj 5.9 and the Mj 6.5 Kumamoto earthquakes in the Kumamoto alluvial plain, Japan

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Earth, Planets and Space 2023, **75**:105 DOI: 10.1186/s40623-023-01848-x

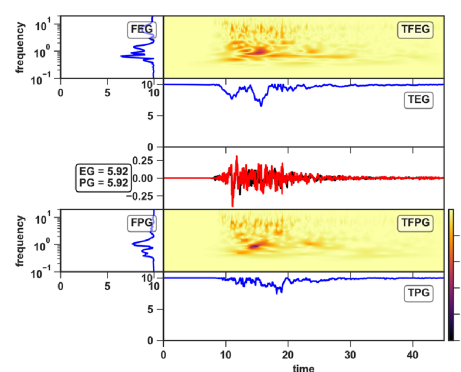
Received: 27 October 2022, Accepted: 20 May 2023, Published: 29 June 2023



Abstract

We present horizontal ground motion predictions at a soft site in the Kumamoto alluvial plain for the Mj 5.9 and Mj 6.5 Kumamoto earthquakes of April 2016, in the framework of an international blind prediction exercise. Such predictions were obtained by leveraging all available information which included: (i) analysis of earthquake ground motions; (ii) processing of ambient vibration data (AMV); and (iii) 1D ground response analysis. Spectral analysis of earthquake ground-motion data were used to obtain empirical estimates of the prediction site amplification function, with evidence of an amplification peak at about 1.2 Hz. Horizontal-to-vertical spectral ratio analysis of AMV confirmed this resonance frequency and pointed out also a low-frequency resonance around 0.3 Hz at the prediction site. AMV were then processed by cross-correlation, modified spatial autocorrelation and high-resolution beamforming methods to retrieve the 1D shear-wave velocity (V_s) structure at the prediction site by joint inversion of surface-wave dispersion and ellipticity curves. The use of low frequency dispersion curve and ellipticity data allowed to retrieve a reference V_s profile down to few thousand meters depth which was then used to perform 1D equivalent-linear simulations of the M 5.9 event, and both equivalent-linear and nonlinear simulations of the M 6.5 event at the target site. Adopting quantitative goodness-of-fit metrics based on time–frequency representation of the signals, we obtained fair-to-good agreement between 1D predictions and observations for the Mj 6.5 earthquake and a poor agreement for the Mj 5.9 earthquake. In terms of acceleration response spectra, while ground-motion overpredictions were obtained for the Mj 5.9 event, simulated ground motions for the Mj 6.5 earthquake severely underestimate the observations, especially those obtained by the nonlinear approach.

Keywords: Ambient vibration, Surface-wave dispersion, 1D ground response analysis, ESG6 blind test, Kumamoto earthquake sequence



Graphical abstract

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Predicted results of weak and strong ground motions at the target site of the blind prediction exercise as steps-2 and -3, Report for the experiments for the 6th international symposium on effects of surface geology on seismic motion

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Earth, Planets and Space 2023, **75**:130 DOI: 10.1186/s40623-023-01885-6

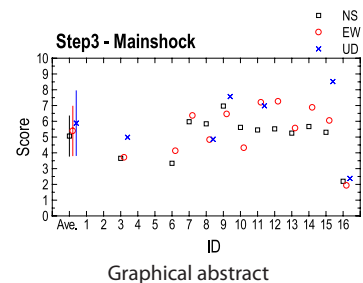
Received: 1 October 2022, Accepted: 19 August 2023, Published: 29 August 2023



Abstract

In this study, we compared observations and predictions submitted by participants for blind prediction experiments for ground motions using aftershocks, foreshock, and mainshock of the 2016 Kumamoto earthquake sequence, Japan, to improve our understanding of the quality of state-of-the-art methods on the reproducibility of the effects of surface geology on seismic motions. In the blind predictions, 1D, 2D, and 3D methods, Green's function methods, spectral ratio approaches, and other approaches were applied. As for PGA/PGV, acceleration/velocity duration, Fourier spectrum, pseudo-velocity response spectrum, and site amplification factors, the observed values are mostly within the range of average $\pm \sigma$ of all the predictions in the case of weak and strong ground motions. The results of the mean absolute percentage errors for these indices show that the applied methods can predict weak and strong ground motions for the three components in the range of one-half to twice the observations. The average goodness-of-fit (GOF) scores for weak and strong ground motions indicate either a very good fit (6.5–8) or a good fit (4.5–6.5) for the three components. Finally, examples of the categorized methods are quite limited; however, results indicate that the predictions by all the categorized methods can adequately reproduce weak and strong ground motions within either a very good or good fit. Although we could not find a significant difference in the results from the categorized methods, scores by the 2D and 3D methods in the frequency range of 0.5–1 and 1–2 Hz for all the blind predictions are higher than the scores by the other methods. The GOF score for the part after the S-wave by the 2D and 3D methods is higher than that by the 1D method. This supports that the predictions by the 2D and 3D methods due to the accounting of the proper geometry could reproduce the basin-induced and/or basin-transduced surface waves excited by the basin-edge effect more than the 1D method using the earthquake record observed at the reference site.

Keywords: Weak motion, Strong motion, Blind prediction, Validation, MAPE, GOF, Basin-edge effect, 2016 Kumamoto earthquake, Kumamoto Plain



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Effects of surface topography and subsurface structural irregularities of river embankments on Rayleigh wave propagation

Shuntaro Miyanaga* and Hiroaki Yamanaka

Earth, Planets and Space 2023, **75**:135 DOI: 10.1186/s40623-023-01884-7

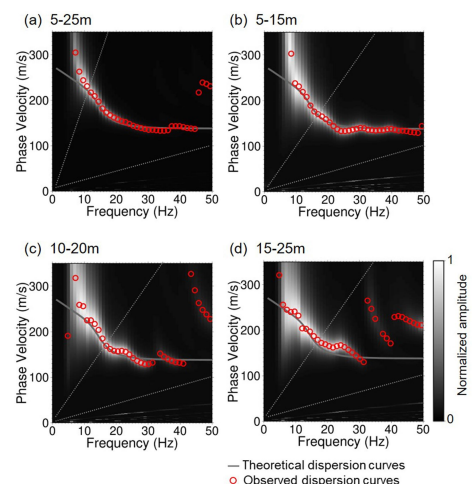
Received: 26 May 2022, Accepted: 19 August 2023, Published: 8 September 2023



Abstract

A numerical investigation of surface wave propagation in the surface wave exploration of river embankments is implemented using 3D shallow soil models with different subsurface shapes and S-wave velocities. The focus is on the effects of surface and subsurface irregularities on the propagation and dispersion characteristics of Rayleigh waves generated by a surface source and observed at points along the crest of the embankment. Rayleigh wave dispersion curves observed along the embankment crest are found to be contaminated by reflected waves, with the amount of contamination affected more by the position of the velocity boundary at the bottom edge of the embankment than the surface topography. When the velocity boundary is close to the ground surface, especially at the toe of the slope, the effect of reflected waves is sufficiently large to generate biases in the phase velocity estimates.

Keywords: Surface wave exploration, S-wave velocity, River embankment, Rayleigh wave, Dispersion curve



Graphical abstract

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Shear-wave velocity determination by combining data from passive and active source field investigations in Kumamoto city, Japan

Maria Manakou*, Zafeiria Roumelioti and Evi Riga

Earth, Planets and Space 2023, **75**:163 DOI: 10.1186/s40623-023-01916-2

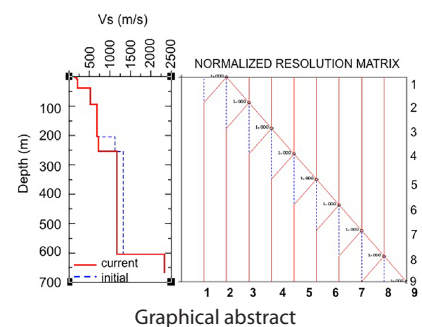
Received: 23 August 2022, Accepted: 3 October 2023, Published: 18 October 2023



Abstract

We present the 1D subsoil structure and local site effects at KUMA strong ground motion station in Kumamoto City, Japan. We analyze data from a field campaign conducted in the framework of the Blind Prediction BP1 test of the 6th IASPEI/IAEE International Symposium: Effects of Surface Geology on Seismic Motion. In parallel with other participants of the BP1 test, we process data from passive and active source measurements aiming to determine the shear-wave velocity, V_s , structure and the site response at KUMA station. Passive measurements are associated to five microtremor arrays. In each array, seven seismometers have been deployed in a common-center triangle shape, recording microtremors simultaneously for 1 to 2 h. The vertical component of microtremors was analyzed using the spatial autocorrelation (SPAC) method. Cross-correlation coefficients were computed for all station pairs available for each array. By fitting the average SPAC's coefficients to the first-kind zero-order Bessel function, J_0 , and assuming that microtremors primarily comprise fundamental mode Rayleigh waves, phase velocity dispersion curves were determined. Phase velocity values for frequencies > 15 Hz were obtained from data of a close-by active source geophone profile. We integrated the data with those of the passive measurements and obtained an experimental phase velocity dispersion curve. The resulting curve shows low velocity variation, from 150 to 200 m/s, in the surface layers, whereas significant dispersion appears in frequencies below 2.5 Hz. By inverting this curve, we achieved to determine the 1D shear-wave velocity structure at KUMA station. Site response characteristics were determined by applying the Horizontal-to-Vertical-Spectral-Ratios method. Significantly amplified peaks in the frequency range between 0.3 to 1.5 Hz dominate HVSR spectral ratios. These peaks correspond to resonant frequencies of soils and originate from different impedance contrasts within the substratum of the site.

Keywords: Microtremor, Blind prediction, Phase velocity dispersion curve, Fundamental mode of Rayleigh waves, Shear-wave velocity profile, Site response, Resonant frequency, Kumamoto Plain



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Application of the on-site P-wave earthquake early warning method based on site-specific ratios of S-waves to P-waves to the 2016 Kumamoto earthquake sequence, Japan

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Earth, Planets and Space 2024, **76**:32 DOI: 10.1186/s40623-024-01968-y

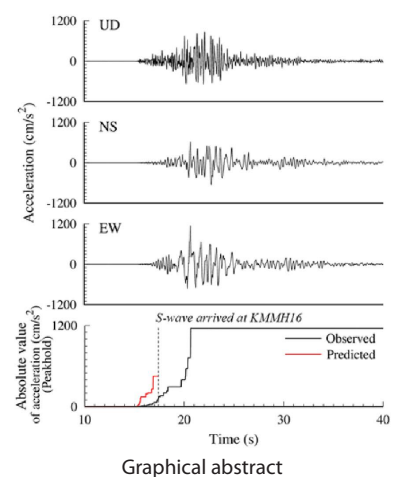
Received: 31 October 2022, Accepted: 19 January 2024, Published: 18 February 2024



Abstract

The on-site P-wave earthquake early warning (EEW) based on the site-specific ratios of S-waves to P-waves has been applied to large-sized offshore earthquakes, and the efficiency of the method has been validated. However, the method requires the P-waves including earthquake ground motions radiated from a large slip area while avoiding the inclusion of S-waves. In this study, we investigated the applicability of the on-site P-wave EEW method for ground motions near an earthquake source fault region, using strong-motion data observed during the 2016 Kumamoto earthquake sequence in Japan. At first, we examined the appropriate time-window length following the arrival of the P-waves. As a result, P-waves with a time-window length of 2.56 s after the arrival at most strong-motion stations were required at least to predict appropriately S-waves for the 2016 Kumamoto earthquake sequence, including the large-sized earthquakes. On the other hand, in the case of the large-sized earthquake as the mainshock (M_j 7.3), the method can predict within a brief time of 0.5 to 2 s in the operational use that strong ground motions exceeding a certain threshold (e.g., acceleration of 150 cm/s^2) will come. Moreover, we found that the method was not strongly affected by the non-linearity of soil deposits due to strong ground motions during the 2016 Kumamoto earthquake sequence. The variability of the relationship between P- and S-waves at the seismic bedrock influenced by the source and path effects is larger than the variability of the relationships between P-/S-waves at the seismic bedrock and at the ground surface by the site effects, and therefore, it hides the effect of the non-linearity of soil deposits.

Keywords: On-site EEW, P-wave, Site-specific ratio, Data length, Earthquake source fault region, Non-linearity, The 2016 Kumamoto earthquake sequence



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Investigation of the subsurface structure at the target site in Kumamoto, Japan, and the distributed data of the blind prediction exercise: report for the experiments for the 6th international symposium on effects of surface geology on seismic motion

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Earth, Planets and Space 2024, **76**:43 DOI: 10.1186/s40623-024-01958-0

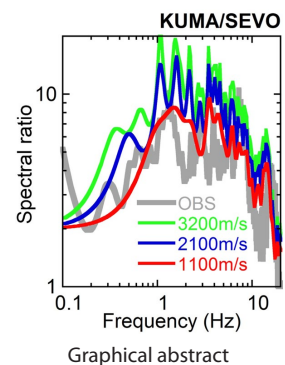
Received: 29 September 2022, Accepted: 5 January 2024, Published: 15 March 2024



Abstract

This technical report explains details on the results of the investigation to build a subsurface structural model and a selection of earthquake data at the target site of the blind prediction exercise for “The 6th International Association of Seismology and Physics of the Earth’s Interior/ International Association of Earthquake Engineering International Symposium on the Effect of Surface Geology on Seismic Motion (ESG6).” The selection process of the target site in the Kumamoto Plain, Japan, in ESG6 was explained with a historical review of the blind prediction tests in the previous ESG conferences. We have collected existing subsurface structural and earthquake data and conducted geophysical and geotechnical surveys in and around the target site to generate important velocity structure and the earthquake data used in the blind test. Microtremor data were obtained in triangular arrays ranging in side lengths from 1 to 962 m, and active surface wave data were derived along a 36-m line at the site. These data were provided for the prediction of a subsurface structural model in the first step of the blind prediction exercise. We also conducted a velocity logging in a borehole to a bottom depth of 39 m at the site and laboratory tests of soil samples from the borehole. We constructed a velocity profile of the shallow and deep sedimentary layers from a combination of the geophysical and geotechnical data at the site, and validated it by comparing the characteristics of the ground motion data from the moderate event. This “preferred velocity model” was provided as a standard model to the participants in the second and third steps of the blind prediction test to predict the earthquake ground motions of a moderate event and the mainshock of the 2016 Kumamoto earthquake.

Keywords: ESG6, Blind prediction, 2016 Kumamoto earthquake, Kumamoto City, Microtremor, Ground motion, P-S logging, In situ measurement



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Empirical approaches for non-linear site response: results for the ESG6-blind test

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Earth, Planets and Space 2024, **76**:109 DOI: 10.1186/s40623-024-02048-x

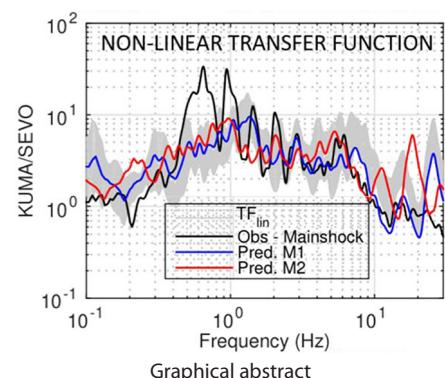
Received: 24 April 2023, Accepted: 17 July 2024, Published: 8 August 2024



Abstract

As a contribution to step 3 of the ESG6 blind prediction exercise, we present an application of two different, purely empirical approaches to estimate the strong ground motion at a soft site (“KUMA”) from the observed ground motion at a reference rock site (“SEVO”) for the two largest shocks of the Kumamoto 2016 sequence. The two methods estimate the non-linear transfer function between a reference rock and a sedimentary site by modifying the linear transfer function derived from weak motion recordings. The modification is based either on a machine learning tool based on a wide collection of Japanese weak and strong motion recordings and the associated site metadata (method 1), or on an estimate of a site-specific parameter related to an average non-linear site response (method 2). The acceleration time series are then derived at the sedimentary site of interest using an estimation of the time delay between wave arrivals at the rock and site stations, and a minimum phase assumption for the site transfer function. These predictions were made blindly, but after the ESG6 conference they could be compared both with the actual ground motion recorded at KUMA during the two shocks, and the average and range of all other predictions performed for this benchmark. Both of these purely empirical methods provide an honorable prediction of usual engineering ground motion parameters of the two target events. The performance of these two purely empirical approaches is at least comparable to those of the numerical simulation methods for the foreshock—if not better—and slightly worse for the (largest) mainshock. As the methods required only recordings of weak motions at the target and a referent sites and very simple description of the soil profile. The use of moderate motions to constrain the frequency shift prediction for the second method and the consideration of an alternative phase modification are possible ways to improvement.

Keywords: Site response, Non-linear soil behavior, Blind prediction, Empirical methods



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The region of large site amplification in Northern Hokkaido, Japan, extends to the eastern Soya Region

Atsushi Nozu

Earth, Planets and Space 2023, **75**:181 DOI: 10.1186/s40623-023-01936-y

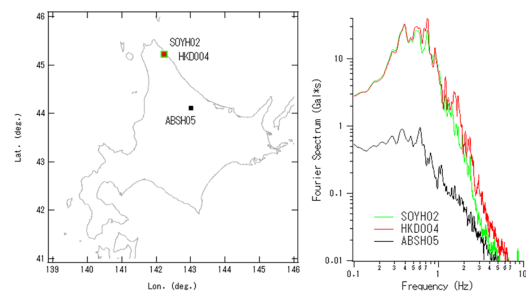
Received: 25 September 2022, Accepted: 17 November 2023, Published: 30 November 2023



Abstract

In the document titled “predominant period of long-period ground motions and the natural period of deep subsoil” by the Central Disaster Management Council, the west part of Northern Hokkaido facing the Sea of Japan is categorized as a region, where long-period (> 6 s) ground motions are predominant. In contrast, the document categorizes the east part of Northern Hokkaido as a region where short-period (< 1 s) ground motions are predominant. The J-SHIS velocity structure model also implies that a deep sedimentary basin is located in the west part of Northern Hokkaido, but not in the east part. However, the result of a past generalized inversion analysis was inconsistent with these general understanding and suggested that the region of large site amplification in the low-frequency range in Northern Hokkaido extends to the eastern Soya Region. It was preferable to check this result with an independent dataset. Therefore, in this study, the records of the May 24, 2013, $M_w 8.3$, Sea of Okhotsk earthquake were used to investigate the distributions of site amplification factors in Northern Hokkaido. Because this is a distant earthquake and the epicentral distance was greater than 1300 km even at the closest station in Hokkaido, it was assumed that the difference of ground motions at different stations represents the difference of the site effects. The Fourier spectra for the S wave part of this earthquake at K-NET and KiK-net stations clearly indicated that the region of large site amplification in the low-frequency range in Northern Hokkaido does extend to the eastern Soya Region. It is desirable in a future study to reveal the cause of the discrepancy between this amplification pattern and the existing velocity structure models.

Keywords: Ground motion, Site effect, Northern Hokkaido, The 2013 Sea of Okhotsk earthquake, Sedimentary basin, Subsurface structure



Graphical abstract

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