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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 (σ< 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 (σ= 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 ± 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 northwest 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.

Hailemikael 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 contracts, 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 nonlinear 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 (NULW) $\propto \sqrt{(\mathrm{SNR})}$ 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 eHVSR 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 $5.9 \leq Mw \leq 7.3$. 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 subsurface 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.

Sgattoni 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.

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