Ground motion prediction is an important element in seismic hazard analysis. However, the availability of recorded strong ground motion data is limited, particularly for large events in near-source regions. Recently, several physics-based ground motion simulation approaches have been developed, which may be useful for understanding the effect of earthquake source on near-source ground motion characteristics. In this study we investigated the sensitivity of near-source ground motions to finite earthquake source processes with pseudo-dynamic source models, based on 1-point and 2-point statistics of earthquake source parameters. We simulated ground motions for Mw 6.6 and 7.0 vertical strike-slip events using pseudo-dynamic source models derived from multiple sets of input source statistics, and investigated the characteristics of near-source ground motions relative to the input source statistics. Our results show that the effect of earthquake source on near-source ground motions can vary depending on the locations of near-source stations. The variability of ground motion intensities derived from multiple sets of input source statistics is greater in the forward directivity region. This pattern is also consistent for pseudo-spectral accelerations with various periods. The pseudo-dynamic source modeling method with 1-point and 2-point statistics seems to be an efficient framework for understanding the effect of earthquake source on near-source ground motion characteristics.

This paper is submitted for the first author (Ms. Donghee Park) to obtain Ph.D degree. It would be grateful if the manuscript is reviewed in a timely manner.
Dear Editor,

We sincerely appreciate the editor and two anonymous reviewers’ thoughtful comments and tried to consider them as much as possible when we revised our paper. Given the uncertainty of input models in currently available dynamic and pseudo-dynamic modeling approaches, we think that it is important to understand the sensitivity of near-source ground motions to the possible range of input models in finite earthquake modeling. We found two main criticisms in the reviewers’ comments. The first one is that the input models we used in the pseudo-dynamic source modeling are somewhat virtual rather than based on rupture dynamics. This is not true because our input models are fully based on the previously developed pseudo-dynamic source model (Song, GJI, 2016). We tried to clarify this misunderstanding in the revised manuscript. The second concern is that the sensitivity analysis of near-source ground motions is lacking detailed outcomes and also too much synthetic without data comparisons. We partially agree with this perspective and included additional analyses with PSAs at multiple periods and also with empirical GMPEs. We would like to again claim that the sensitivity analysis of near-source ground motions to input source models is an important work, given the uncertainty of input models in the pseudo-dynamic and dynamic source modeling. We hope that our revised version of the paper mostly fulfill the reviewers’ requests.

Sincerely,

Seok Goo Song
Associate editor:

This paper has been reviewed by two referees (Reviewer 1 and 3). The reviewer 2 reviewed the electronic supplement only, who accepted as it is. The two reviewers from the paper have provided very critical comments. Reviewer 1 has the strongest criticism recommending to reject the paper. The reviewer 3 recommends major revision. The main concern from reviewer 1 is that the paper has too much modeling features, making the paper rather technical. Most of the inputs are virtual (or proxies) and no justifications of the parameterizations are provided. The results can not be judged whether they are consistent or not with reality. Perhaps comparing with GMPEs could help on it. In addition, reviewer 1 is concerned about whether the pseudo-dynamic model is still dynamically compatible after removing some of the cross-correlations between parameters. Reviewer 3 is more positive thinking that the content of the papers has useful contribution to the community dedicated to synthetic ground motion, nevertheless, reviewer 3 think that some of the analyses should be clarified to be more accessible to BSSA readers. For example, Figures 8-11 should be clarified and, perhaps, replotted. Furthermore, the authors spend much of the paper describing the set-up for the source variations and only a few pages analyzing the resulting ground motions. One way to enhance their analyses would be to investigate spatial variations of ground motions.

=> Thank you for the editor’s thoughtful comments and concise summary of the reviewers’ comments. We responded to the raised issues below to the reviewers’ comments.

On the line of the reviewers comments, it is clear that the paper is in the verge of being rejected. The paper needs significant additional research or tests to be suitable for publication. I think the authors can still do it, so I recommend major revision. I strongly recommend the authors to address, in the revised version, all the commend, criticism and recommendations one by one.
Reviewer #1: Review of paper "Investigating the characteristics of near-source ground motions using pseudo-dynamic source models derived with 1-point and 2-point statistics of earthquake source parameters" by D. Park et al.

The paper presents parametric study of various input parameters of the employed pseudo-dynamic rupture source model introduced by Song et al. (2014) and Song (2016) on simulated ground motions. In particular, after setting up the model, the authors perturb some of the parameters (e.g., correlation lengths, cross-correlations between source parameters) and analyze their respective impact on mean values and variability of PGV around the fault. These tests are performed on two hypothetical strike slip earthquakes of Mw6.6 and 7.0. The paper is clearly written and easy to understand.

In my view, the paper is too much oriented on the particular modeling method, with no attempt to provide any general conclusions, which makes the paper rather technical. Most of the parameters are rather virtual (or proxies), such as correlation lengths of peak slip rates or crosscorrelations, so that it is not easy to understand the actual connection between rupture physics and the resulting ground motions, especially its variability. The authors do not comment much on it although the abstract promises to provide "understanding the effect of earthquake source on near-source ground motion characteristics".

Thanks for the insightful comments on the general aspect of the paper. However, we need to point out that the input parameters used in our pseudo-dynamic source modeling are not virtual, but fully based on Song (GJI, 2016). We performed the perturbation analysis of the input source statistics models because we expect that there is still a certain level of uncertainty in the input models due to the uncertainty of dynamic rupture modeling such as stress parameters and friction, etc. We added comments to the revised manuscript to justify the perturbation analysis of 1-point and 2-point statistics in our study.

The modeling is purely synthetic with no comparison with observations (e.g., GMPEs), so one cannot judge whether the parameter sensitivity is significant or not. Moreover, the choice of the tested values of the model parameters are not justified (no bounds on suitable values are given). Even the aim of the changes is not clear because the parameters are supposed to stem from dynamic models, so changing them means that the pseudo-dynamic model does not have to be necessarily dynamically compatible anymore. I point out that exactly the feature of being dynamically compatible is the one that is supposed to make the present model superior to the classical kinematic rupture models. This issue is especially evident when some of the
cross-correlations between parameters are removed - can such model be still considered as pseudo-dynamic?

=> We added comparison analysis with empirical GMPEs to check the significance of the parameter sensitivity. As we stated above, dynamic models have their own limitations such as the uncertainty of input models and friction laws, which is one of the main motivations for our perturbation analysis. We do not claim that the perturbed models are still dynamically compatible, but we aim to understand the sensitivity of ground motions when a certain component of pseudo-dynamic source models are missing. Regarding the perturbation range, we agree that it is not easy to set up standardized reasonable ranges at this point. We considered a relatively large range of variations to cover the upper bound of the uncertainty in the study. In addition, a main goal of this paper is to understand the ‘relative’ difference of near-source ground motion sensitivity, depending on target regions such as forward and backward directivity zones. Thus we set aside the absolute level of the perturbation range for future studies. We agree that these perspectives are not clearly stated in the initial manuscript, thus added comments to the revised text to clarify it.

I have also the following additional comments:

- It is not clear how the parameters of the pseudo-dynamic model were selected. They seem to be not adopted directly from Song (2016), so how did the authors determine them?

=> The pseudo-dynamic source parameters used in the study are fully based on Song (2016).

- The modeling concerns two earthquakes, for which all the parameter values are given, but in absolute numbers (values). This narrows the use of the model to basically those two event sizes because it is not clear how to choose the parameters for other magnitudes. In other words the model does not involve any magnitude scaling. Is such model suitable for strong motion prediction or to understand the near source ground motion characteristics?

=> In Song (2016), the source statistics are conditioned on the mean slip, which is scaled with magnitude. Thus, the input parameters of the original pseudo-dynamic source models (i.e., before perturbation) are actually scaled with magnitude.

- The original pseudo-dynamic model of Song et al. (2014) was derived from statistical analysis of numerous dynamic rupture models. It is striking that although the dynamic models
of Song et al. (2014) had very smooth slip distribution (which is a common feature of
dynamic models in general), the present rupture models have very rough slip distributions.
Why it is so? Are such models still compatible with the rupture dynamics?

=> We think that the phase information needs to be included in the source characterization to
completely mimic the smooth slip distribution of the dynamic modeling. In the pseudo-
dynamic modeling, auto-correlation (i.e., amplitude spectrum) is only considered so far, thus
the continuation of the large slip may not be fully reproduced in the pseudo-dynamic source
modeling. In Song et al. (2014), they used the slip distribution directly from the dynamic
models and pseudo-dynamically simulated temporal source parameters such as rupture
velocity and peak slip velocity, conditioning on the dynamic slip model, for direct
comparisons with the dynamic modeling and understanding of the temporal source
parameters. In Figures 6 and 7 of Song (2016), we can observe a similar pattern of slip
distributions with this study.

- The difference between models SSM 2-1 and 2-2 is not clear. According to Tab. 2 the
difference is just in the random seed. However, the random seeds are varied in the 30
realizations of each of the model. This needs to be clarified.

=> Correct. In terms of source statistics, they (SSM 2-1 and 2-2) are the same. We just want
to test the effect of random seeds since our comparisons were performed with the mean and
standard deviation of 30 scenario models.

- Some of the kinematic models seem somewhat suspicious. For example in Fig. 3 (cont.)
there are models with large areas of zero (or almost zero) Vmax, although the same areas
contain large slip. How large is the rise time at such points? Are those rupture models still
meaningful (and dynamically compatible)?

=> In Figure 3 (cont.), three models except the second one (corr_13) do not have a cross-
correlation matrix between slip and peak slip velocity. Thus it is natural that there is no link
between the areas of large slip and large peak slip rate. In the second model (corr_13), we can
observe some correlation patterns between the area of large slip and large peak slip rate. But
as the reviewer clearly pointed it out, there is a large fraction of very small peak slip velocity
zone. This pattern often happens when the standard deviation is relatively large compared to
the mean since we truncated the negative Vmax and set them to a minimum number (here 1
cm/s). Since we also set the maximum of the risetime to 10 seconds, the region of the very
low peak slip velocity is re-adjusted to satisfy the maximum risetime before the synthetic
ground motion calculation. We agree that we need to improve this issue by adopting some non-Gaussian and non-negative distributions for 1-point statistics later.

- What velocity model is considered? Does it affect the rupture velocities, or are the ruptures supershear at shallow depths? If so, what is the impact on the radiated ground motions?

=> We used the same velocity model in Song et al. (2014). There may be a slight portion of the supershear rupture zone at the very shallow depth, but we don’t think it affects our results significantly.

- Remark: Autocorrelation function has its maximum for zero lag in general, so the parameters RDx and RDz of Eq. (1) must be zero for autocorrelations by definition.

=> Correct.

For all mentioned above, I suggest rejection of the paper from publication in BSSA.
Reviewer #3: Comments and suggestions to the authors:

The authors investigate the effect on earthquake ground motions (PGV) of varying the source features of kinematic rupture models, through the statistical distributions of rupture parameters (1-point statistics) and their correlations (2-point statistics). Source inversions have little ability to resolve these correlations, and understanding the assumptions of these source parameters for synthetic ground motion applications are important to applying these methods for seismic hazard analyses. The authors' study focuses on perturbations to one method of specifying the kinematic rupture of Mw=6.6 and 7 earthquakes. The study is a useful contribution to the field of forward modeling of synthetic ground motions for hazard applications.

Analyzing the ground motion volumes from many source realizations is challenging, and the authors have previously contributed to statistical means to describe rupture models. In this paper, they focus on peak ground velocities, to simplify the analysis; however, it should be emphasized that the resulting features described in this paper may not apply to other metrics of ground motion (e.g., PSA, at short- or long-periods).

=> Good point. We also performed additional tests for PSAs with multiple periods in the revised manuscript.

Minor comments and suggestions:

- Abstract, line 33: Suggest replacing "more dominant" with "greater"

=> Replaced

- I was curious (and suspect other readers may also be curious) to understand why the magnitudes of historic earthquakes, including recent events, were presented in local magnitudes and not moment magnitude. Similarly, please explain why local GMPEs are developed for ML and not Mw, which will be familiar to more readers

=> Since the moment tensor inversion technique was routinely adopted in Korea, the size of major events with magnitude larger than 3.0 have been determined with the moment magnitude. But mostly small events occur in the low seismicity region such as the Korean peninsula, the local magnitude measured by the maximum amplitude of body waves have been conventionally used. Actually the GMPEs developed by stochastic ground motion
modeling were formulated with Mw although they used the local earthquake data scaled by the local magnitude.

- Lines 158-163: Define variables (Vr, Vmax) at first use

  => Fixed

- Lines 190-191: The paper references earlier publications in describing methods. I think it would be appropriate to summarize details here, so that readers do not need to refer earlier papers to understand the basic features of the study

  => Actually the second and third paragraphs in the ‘pseudo-dynamic source modeling’ section describe the details of the previous studies.

- Line 236: The second author is Adrian Rodriguez-Marek and the citation should be to "Bray and Rodriguez-Marek"

  => Thank you for pointing it out. Corrected.

- Lines ~236-240: Ben-Menahem also describes the azimuthal variation of directivity effects in "Seismic Waves and Sources" and earlier references. These equations also describe effects of rupture velocity and source dimension. This work should probably be included here.

  => Thank you for the information. We cited them as well.

- Line 252: Why are logarithms base-2? Please briefly describe

  => We used the base 2 because it is easier to understand the ratio even after taking the logarithm. We briefly explained it in the text.

- Line 274: Somerville et al. and others have noted the period-dependence of the directivity pulse. The statement on Line 274 probably only holds for PGV within a range of earthquake magnitudes and should reflect this feature. Presumably, this observation also depends on the slip distribution (and dependence of asperity dimension on magnitude), which may also be addressed

  => Thank you for pointing it out. We rephrased the statement to consider your comments.
- Moschetti et al. (2017, BSSA) and Wirth et al. (2018, BSSA) have recently examined ground motion variability from source variations. There may be features of interest in these references.

=> Thank you for your recommendation. We went through the papers and cited them in the revised manuscript.

- Figures 8-9: Initially unclear to me what the x-axis represented. Clarify and improve labeling of x-axis

=> The x-axis is explained explicitly in the figure caption.

- Figure 13: Why not plot values as a function of azimuth instead of paths (e.g., A1, A2)

=> Modified.

- Data and Resources: Is this rupture generator publically available? If so please indicate a URL. This would increase use by other researchers and allow more vetting of the code.

=> The code is not publicly available yet, but it can be accessed by requesting the corresponding author of the paper. We indicated it in the ‘Data and Resources’ section.
Sensitivity analysis of Investigating the characteristics of near-source ground motions using pseudo-dynamic source models derived with 1-point and 2-point statistics of earthquake source parameters

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Abstract

Ground motion prediction is an important element in seismic hazard analysis. However, the availability of recorded strong ground motion data is limited, particularly for large events in near-source regions. Recently, several physics-based ground motion simulation approaches have been developed, which may be useful for understanding the effect of earthquake source on near-source ground motion characteristics. In this study we investigated the sensitivity characteristics of near-source ground motions controlled by finite earthquake-source processes utilizing pseudo-dynamic source modeling, based on 1-point and 2-point statistics of earthquake source parameters. We simulated ground motions for $M_w$ 6.6 and 7.0 vertical strike-slip events using pseudo-dynamic source models derived from multiple sets of input source statistics, and investigated the characteristics of near-source ground motions relative to the input source statistics. Our results show that the effect of earthquake source on near-source ground motions can vary depending on the locations of near-source stations. The variability of ground motion intensities derived from multiple sets of input source statistics is greater more dominant in the forward directivity region. This pattern is also consistent for pseudo-spectral accelerations with various periods. The pseudo-dynamic source modeling method with 1-point and 2-point statistics seems to be an efficient framework for understanding the effect of earthquake source on near-source ground motion characteristics.
38

Introduction

39 It has been noted that the Korean Peninsula belongs to a stable seismic zone in comparison
40 with active seismic zones, such as the western United States and neighboring Japan. However,
41 according to historical earthquake data that covers approximately 2,000 years, it is known that
42 there was a time period in which many large earthquakes (Modified Mercalli Intensity, MMI >
43 VII) occurred in the southeastern region of the Korean Peninsula (Lee and Yang, 2006). As
44 instrumental earthquake data have been accumulated since 1905, it is also known that moderate
45 earthquakes (M_s=5.0) took place several times, and caused damages more than 5
46 times (e.g., the Ssanggyesa earthquake (M_s=5.0) on June 4, 1936, the Hongsung earthquake
47 (M_s=5.0) on October 7, 1978, the Gyeongju earthquakes (M_s=5.1, M_s=5.8) on September 12,
48 2016, and the Pohang earthquake (M_s=5.4) on November 15, 2017. Even though an earthquake
49 of M_s 6.0 or greater, which might cause serious damages, have not taken place in the last century,
50 predicting potential seismic hazards has become a more important issue after the occurrence of the
51 Gyeongju earthquake (M_s=5.8) on September 12 2016, which is considered to be the largest
52 earthquake in South Korea since the initiation of instrumental recordings (i.e., since 1905).
53
54 Empirical ground motion prediction equations (GMPEs) have been widely used for
55 probabilistic seismic hazard analysis (PSHA) because they are directly constrained by the
56 observed data (Abrahamson et al., 2008). Boommer and Abrahamson (2006) noted that GMPE
57 controls the shapes of the seismic hazard curves and has a significant impact on PSHA. However,
58 the availability of recorded strong ground motion data is limited, particularly in near-source
regions, even in very active seismic regions. Strasser et al. (2009) illustrated the problem and challenges that arise when we constrain GMPEs for various spectral frequencies with a lack of near-source strong motion recordings.

In Korea, there have been few strong ground motion records produced, and it is difficult to develop GMPEs based on the observed data. Therefore, most of the previous GMPE studies (Park et al., 2001; Jo and Baag, 2003; Yun et al., 2005; Korea Hydro and Nuclear Power Co., Ltd (KHNPRP), 2015) have constrained a few physical parameters, such as stress drop and attenuation (Q) for a small range of earthquake magnitudes, and simulated ground motions for a wide range of earthquake magnitude using the stochastic point-source ground motion model developed by Boore (1996, 2005). Park et al. (2001) used 26 events with local magnitude ranges from 1.4 and 4.3, which occurred from 1997 to 1999. Jo and Baag (2003) used 16 events that occurred from 1999 to 2001. The only empirical GMPE based on observed data in Korea was presented by Emolo et al. (2015). They analyzed data from 222 earthquakes recorded at 132 three-component stations of the South Korea Seismic Network, from 2007 to 2012, with local magnitudes ranging between 2.0 and 4.9. They noted that because of the characteristics of the adopted database, their GMPEs can be confidently applied up to a maximum local magnitude of 5.0. However, there are still many limitations in our understanding of the physical characteristics of near-source ground motions and their attenuation with distance in Korea.---

Physics-based ground motion simulation methods have received much attention as the effect of finite-source processes on near-source ground motion characteristics can be efficiently taken into
account and understood. Dynamic rupture modeling has been successfully used in physics-based modeling for decades (Olsen et al., 1997; Dalguer et al., 2008; Ripperger et al., 2008; Shi and Day, 2013). The finite-faulting process in dynamic modeling is governed by stress and frictional behavior. This approach enables us to generate the physically self-consistent spatio-temporal evolution of a finite-source model. However, dynamic modeling requires high-cost computing resources and time to generate synthetic waveforms of large earthquakes. As an alternative method, pseudo-dynamic source modeling has been introduced to improve computational efficiency. The framework of pseudo-dynamic source modeling is still that of a kinematic source model, while it simultaneously emulated the source physics inferred from rupture dynamics and observations (Guatteri et al., 2004; Song and Somerville, 2010; Mena et al., 2012; Schmedes et al., 2013; Song et al., 2014).

Song et al. (2014) developed a pseudo-dynamic source modeling method based on the 1-point and 2-point statistics of earthquake source parameters. They demonstrated that the effect of earthquake source processes on near-source ground motions could be investigated efficiently in the framework of 1-point and 2-point statistics. Song (2016) developed a generalized pseudo-dynamic source statistics model for $M_w$ 6.5–7.0 earthquakes by analyzing a number of dynamic rupture models, and validated the synthetic broadband ground motions derived from the pseudo-dynamic source models against empirical GMPEs. However, the dynamic rupture models used in Song (2016) have limitations, especially in terms of the uncertainty of their input stress models and friction laws. Given the uncertainty imposed in the developed pseudo-dynamic source models, it is important to understand the sensitivity of near-source ground motions to the

perturbation of the pseudo-dynamic source models.

In recent studies, near-source ground motion characteristics have been studied through finite-source modeling approaches. Vyas et al. (2016) analyzed ground motion datasets simulated from the kinematic source parameters of the $M_w$ 7.3 Landers earthquake of 1992 in terms of the distance and azimuth-dependence of the peak ground velocity. Their simulations revealed that intra-event ground motion variability is higher closer to the fault and decreases with increasing distance. The physical explanation of high near-source ground motion variability is the presence of strong directivity and rupture complexity. Crempien and Archuleta (2017) simulated kinematic rupture scenarios on several vertical strike-slip faults and computed ground motions using a representation theorem. They demonstrated that both intra-event and inter-event ground motion variabilities increase when the slip correlation length on the fault increases. Imíatz et al. (2015) studied the distance dependency of ground motion variability, especially in near-source regions, using ground motions for strike-slip events, which were generated from finite rupture models of past earthquakes. They showed that the standard deviation of ground motions depends significantly on the rupture type. For bilateral ruptures, variability tends to increase with distance. On the contrary, the variability of unilateral events decreases with distance. They also noted that unilateral rupture models would strengthen directivity effects.

This study builds upon previous work by Song et al. (2014), who illustrated the efficiency of pseudo-dynamic source models based on 1-point and 2-point statistics of kinematic source parameters. Here, we extend this previous work by investigating how the input 1-point and 2-

Point statistics affect near-source ground motion characteristics, especially with respect to the specific locations of near-source stations, such as a forward rupture directivity zone. We simulated ground motions for $M_w$ 6.6 and 7.0 vertical strike-slip events using pseudo-dynamic source models derived from multiple sets of input source statistics, and investigated the characteristics of near-source ground motions relative to the input source statistics.

**Source Modeling**

**Pseudo-dynamic source modeling**

To simulate ground motions for a target event, many source parameters are needed to characterize a finite-fault rupture model, such as rupture dimension (length and width) and kinematic rupture parameters (slip, rupture velocity, and peak slip velocity). If we assume that future earthquakes share the finite-source characteristics of past earthquakes, at least in a statistical sense, we may constrain earthquake parameters for future events by studying the characteristics of past earthquakes (Mai and Beroza, 2000; Mai and Beroza, 2002; Song et al., 2009). However, we are often limited to resolving the details of a kinematic rupture model, especially the temporal source parameters such as rupture velocity and peak slip velocity, by inverting geophysical data observed on the ground for past events (Beresnev, 2003; Mai et al., 2016). Researchers often rely on spontaneous, dynamic rupture models to extract physics-based correlation structures between earthquake slips and temporal source parameters, which have been categorized as pseudo-dynamic source modeling (Guatteri et al., 2004; Schmedes et al., 2010; Song et al., 2010; Mena et al., 2012; Song et al., 2014). In other words, pseudo-dynamic source
modeling is still kinematic modeling, but it utilizes the physical correlation structures of
kinematic source parameters derived from spontaneous, dynamic rupture modeling.

Song et al. (2014) proposed characterizing earthquake rupture processes within a framework of
the 1-point and 2-point statistics of key kinematic source parameters. In brief, their approach
involved assigning a set of random spatial fields to a finite-fault plane to model the spatial
distribution of several key kinematic source parameters, such as slip, rupture velocity (Vr), and
peak slip velocity (Vmax). In other words, one random field was assigned to each source
parameter, and one random variable (i.e., one element of the random field was assigned to every
subfault patch on the fault). If there are three source parameters, there are also three random
fields. The number of random variables for each random field is equal to the number of subfault
patches on the finite fault. The 1-point statistics is a marginal probability density function at a
given point on the fault. If a Gaussian distribution is assumed, the mean and standard deviation
are the two main representative parameters that control the possible range of values for each
source parameter. The 2-point statistics is composed of both auto and cross correlation.
Autocorrelation controls the heterogeneity of each source parameter, while cross-correlation
controls the coupling between source parameters. Once the 1-point and 2-point statistics are
modeled for a certain event, finite-source rupture scenarios can be generated by stochastic
modeling.

Song (2016) developed a source statistics model by analyzing a number of spontaneous,
dynamic rupture models ranging in magnitude from $M_w$ 6.5–7.0. He assumed a multivariate
Gaussian distribution for a random field model and developed an input source statistics model for both 1-point (mean and standard deviation of source parameters) and 2-point statistics (correlation length and correlation coefficient). For 2-point statistics, a simple exponential function was adopted, as given in equation (1), for a functional form of correlation:

$$
\rho(h) = \rho_{\text{max}} \cdot \exp(-\sqrt{((h_x - RD_x)/a_x)^2 + ((h_z - RD_z)/a_z)^2}); \quad h = (h_x, h_z),
$$

where $h$ is the separation vector between two locations on the fault. The remaining parameters are as follows: $a_x$ and $a_z$ are correlation lengths in the along-strike and along-dip directions, respectively (six parameters: slip versus slip, slip versus $V_r$, slip versus $V_{\text{max}}$, $V_r$ versus $V_r$, $V_r$ versus $V_{\text{max}}$, $V_{\text{max}}$ versus $V_{\text{max}}$). $V_r$ and $V_{\text{max}}$ represent rupture velocity and peak slip velocity, respectively. The maximum correlation coefficient is denoted as $\rho_{\text{max}}$ (three parameters: slip versus $V_r$, slip versus $V_{\text{max}}$, $V_r$ versus $V_{\text{max}}$); $RD_x$ and $RD_z$ are the response distances in the along-strike and along-dip directions (three parameters: slip versus $V_r$, slip versus $V_{\text{max}}$, $V_r$ versus $V_{\text{max}}$).

The complete form of input parameters for the source statistics model is defined in Table 1 of Song (2016). We set both response distances (i.e., $RD_x$ and $RD_z$) to zero in this study because most models used by Song (2016) exhibited near-zero values for these parameters. However, due to rupture propagation effects, particularly in long strike-slip events, the response distance could be relatively large (Song et al., 2009; Song and Sommerville, 2010). The response distance may play an important role in controlling the directivity effects in future studies. Since we considered 3 kinematic source parameters (i.e., slip, rupture velocity, and peak slip velocity) for pseudo-
dynamic source modeling, there were 6 input parameters for 1-point statistics and 15 input parameters for 2-point statistics.

In this study, we simulated 4 sets of pseudo-dynamic source models for both $M_w$ 6.6 and 7.0 vertical strike-slip target events. The geometry of both target events is summarized in Table 1. Input models were extracted from the source statistics model developed by Song (2016), and are summarized in Tables 2 and 3. For each set of input source statistics model, 30 earthquake scenario models were developed to allow for statistical stability when we investigated near-source ground motion characteristics. Figure 1 shows an example of four different pseudo-dynamic source models for the $M_w$ 7.0 target event, and we present examples of four different pseudo-dynamic source models for the $M_w$ 6.6 in Figure S1.

**Perturbation of 1-point and 2-point statistics**

In this study we aimed to investigate the characteristics of near-source ground motions controlled by the 1-point and 2-point statistics of pseudo-dynamic source models. We adopted the same strategy of perturbing 1-point and 2-point statistics as that used by Song et al. (2014). Thus, we can systematically investigate the effect of input source statistics models on near-source ground motion characteristics. Pseudo-dynamic source models are presented in Figure 2 and Figure S2 after perturbing their 1-point statistics. The 1-point statistics of $V_r$ and $V_{max}$ (i.e., their standard deviations), were reduced by half or expanded by a factor of two, respectively. The effect of temporal source parameters on ground motion has been studied recently (Moschetti et al., 2017; Wirth et al., 2017), however, mostly in the aspect of their mean behavior rather than
standard deviation. There have been several studies to investigate the variability of earthquake slip, but almost no attempts to constrain the variability (standard deviation) of the temporal source parameters such as rupture velocity and peak slip velocity. The perturbation scheme used in our analysis, i.e., by half or by a factor of two, does not have physical and observational basis yet, but we think it is still meaningful to test its effect on near-source ground motions since we are very limited to constraining the variability of temporal source parameters at this point.

For 2-point statistics, the cross-correlations of slip-Vr, slip-Vmax, and Vr-Vmax were sequentially perturbed. Finally, 6 sets of pseudo-dynamic source models were constructed, which were linked to the perturbation of 1-point statistic, and 7 sets of models were constructed that were linked to the perturbation of 2-point statistics. Given an input source statistics model, 420 (= (1 + 6 + 7) × 30) pseudo-dynamically generated source models were produced for each target magnitude, including both the original and perturbed pseudo-dynamic source models. We then compared ground motions generated from all 6 sets of pseudo-dynamic source models for 1-point statistics and 7 sets of pseudo-dynamic source models for 2-point statistics with those generated from the original pseudo-dynamic modeling in a statistical sense. Since we simulated pseudo-dynamic source models using the source statistics model developed by Song (2016), it may not be clear why we focus on the perturbation analysis of the pseudo-dynamic source models. Although Song (2016) developed the source statistics model by analyzing a number of spontaneous dynamic rupture models, dynamic rupture models have its own limitation, especially in terms of the uncertainty of its input models such as stress and friction. If we expect that our pseudo-dynamic source models have a certain level of uncertainty, it is important to
understand how much it affects near-source ground motions. In addition, in the framework of 1-point and 2-point statistics, it would also be important to understand how each component of the source statistics model affect near-source ground motions.

Figures 3 and S3 show how the simulated source parameters were affected by perturbing the input 2-point statistics. The pseudo-dynamic source model in Figure 3(a) includes the full correlation of 2-point statistics, and it can be seen that high slip patches are correlated with high rupture and peak slip velocities. However, in Figure 3(h), no coupling is observed between the source parameters since the correlation coefficients of the off-diagonal components were set to zero. Figure 3(b–g) shows additional sets of perturbed pseudo-dynamic source models for 2-point statistics. Since there were three off-diagonal cross-correlation structures, 7 different sets of perturbation for 2-point statistics, as in Figure 3, were constructed. The corresponding autocorrelation matrices and 1-point statistics were retained while perturbing the cross-correlation matrices. If a finite source model is simulated without a certain component of cross-correlation matrices (Figure 3(b–h)), we may not claim that it is still a pseudo-dynamic source model. However, this type of perturbation is useful when we try to understand the effect of each component of the source statistics model on ground motions.

Characteristics of near-source ground motions

Ground motion modeling

We initially generated 30 scenario earthquakes via stochastic modeling for each input source
statistics model shown in Tables 2 and 3. The slip velocity function (SVF) proposed by Tinti et al. (2005) was adopted to compute the spatio-temporal evolution of earthquake-generated rupture along the fault. The pseudo-dynamically generated finite-source models were combined with Green's functions computed by the FK method (Zhu and Rivera, 2002). The same 1D velocity model used in Song et al. (2014) was adopted for the Green's function calculation. Then, we generated three-component (fault-normal, fault-parallel, and vertical) synthetic seismograms that were effective up to 3 Hz. Figure 4 shows the locations of 168 stations along with the surface trace of the rupture dimension for the Mw 6.6 event. The circle size of each station indicates the mean Peak Ground Velocity (PGV) (normal fault normal) of 30 earthquake scenarios for the first source statistics model (SSM 1) in Table 2. Two colored areas show both the forward and backward directivity regions, which were analyzed with the perturbation of 1-point and 2-point statistics in this study. Synthetic waveforms at a few selected stations shown in Figure 4 are displayed in Figure 5. Figure 6 shows the locations of 400 stations, with the surface trace of the rupture dimension for the Mw 7.0 event, and Figure 7 shows waveforms at the stations selected in Figure 6. We clearly observed the forward directivity effect especially clearly in the normal fault normal component.

**Directivity analysis effects of 1-point and 2-point statistics**

Directivity effects indicate that earthquake ground motions, especially fault normal components, are more severe in the direction of rupture propagation than in other directions. Sommerville et al. (1997) showed that rupture directivity effects cause spatial variations in
ground motion amplitudes and durations around faults, and cause differences between the fault-normal and fault-parallel components of horizontal ground motion amplitudes, which also have spatial variation around the fault. They also found that for strike-slip faulting, the directivity effect on amplitudes is weak at sites close to the epicenter, but grows large at sites located near the fault rupture zone but away from the epicenter. Finally, they have developed the directivity term that accounts for the spatial variations of ground-motion amplitudes and durations, which may be used in GMPEs. Ben-Menahem and Singh (1981) also describes the azimuthal variation of the directivity effects, depending on rupture velocity and source dimension. Bray and Rodriguez-Marek Adrian (2004) developed empirical relationship between the PGV and period of the velocity pulse of forward directivity motions. Spudich et al. (2008) introduced a new and physically-based isochrone directivity predictor and models of directivity effect based on this predictor. The directivity effect is an important element in understanding the near-source ground motion characteristics, in particular in finite-source modeling.

As was discussed in the section "Pseudo-dynamic source modeling" above, 6 sets of pseudo-dynamic source models were constructed that are linked to the perturbation of 1-point statistics and 7 sets of pseudo-dynamic source models that are linked to the perturbation of 2-point statistic. We computed the PGV ratios with the waveforms obtained from the original and perturbed pseudo-dynamic source models in the selected forward and backward directivity zones as well as in the total area in Figure 4 and Figure 6, and compared the maximum difference of the mean and standard deviation of the PGV ratios. Figures 8 and 9 show the changes of the pseudo dynamically generated ground motions after the perturbation of 1-point and 2-point
statistics for both $M_w 6.6$ and $M_w 7.0$ target events, respectively.

The mean and standard deviation of the PGV ratios were computed following the equations (2) and (3), given below.

\[
\text{mean}(PGV_{\text{ratio}}) = \frac{1}{nm} \sum_{i=1}^{n} \sum_{j=1}^{m} \log_2 \left( \frac{PGV_{\text{perturbed}}}{PGV_{\text{original}}} \right)_{ij},
\]

and

\[
\text{sigma}(PGV_{\text{ratio}}) = \sqrt{\frac{1}{nm-1} \sum_{i=1}^{n} \sum_{j=1}^{m} \left( \log_2 \left( \frac{PGV_{\text{perturbed}}}{PGV_{\text{original}}} \right)_{ij} - \text{mean}(PGV_{\text{ratio}}) \right)^2}.\]

where $n$ is the number of selected stations for directivity analysis and $m$ is the number of scenario earthquake models ($m = 30$). We used the base 2 in the log-scale because it is easy to understand the amplitude of the ratio even after taking the logarithm.

As was observed in Figures 8(a), 9(a), S4, and S6, the PGVs increased if the standard deviation of either rupture velocity ($V_r$) or peak slip velocity ($V_{\text{max}}$) increased. These results are consistent with the findings of Song et al. (2014). Regarding the perturbation of 2-point statistics shown in Figures 8(b), 9(b), S5, and S7, the PGVs were reduced once certain components of the off-diagonal elements, shown in Figure 3, were removed. More interestingly, the PGVs are compatible with those of the original pseudo-dynamic source models if the correlations between $V_r$ and $V_{\text{max}}$ are included (e.g., corr_23 in Figure 9). The right panels of Figures 8 and 9 show the standard deviations of the PGV ratios computed by equation (3). We also found that the variations in ground motions, as measured by the standard deviation, were generally greater in
the forward directivity region.

Figures 10 and 11 show the maximum differences of the PGV ratios for the $M_w$ 6.6 and 7.0 target event, respectively, after the perturbation of 1-point and 2-point statistics for all 4 input source statistics models. The results clearly show that the ground motion intensity in the forward directivity region is affected more significantly by the perturbation of source statistics in pseudo-dynamic source modeling. However, we also found that this pattern is not dominant for the perturbation of 2-point statistics for the $M_w$ 6.6 target event, which may imply that there is a magnitude dependency for the forward directivity effect relative to the input source statistics models. In other words, the greater the magnitude of the earthquake, the greater the influence of forward directivity. However, we also admit that it is too early to generalize this statement and it requires additional analyses to understand the magnitude dependency of the forward directivity effect.

Azimuth analysis dependency of 1-point and 2-point statistics

We also analyzed the dependency of the PGV ratios on azimuth. Figure 12 shows the 9 different regions used in this analysis; each region had a 30° range. This analysis should contain all stations for the entire distance range, but may be able to better resolve the azimuthal dependency, compared to the station selection in Figure 6. Figure 13 shows the azimuthal dependency of the PGV ratios after the perturbation of 1-point and 2-point statistics for all 4
input source statistics models for the $M_w$ 7.0 target event. It can be clearly observed that the perturbation effect of 1-point and 2-point statistics is more dominant in the forward directivity regions, such as $A_1$ and $A_2$, and the effect is slightly greater in the backward directivity regions, compared to such as $A_8$ and $A_9$, than in the other regions $A_4$–$A_7$. This pattern may be affected by the near-source forward and backward directivity effects since the difference is relatively low in the direction perpendicular to the fault plane ($A_5$).

Period analysis

PGV in general represents the characteristics of long period ground motions while PGA (Peak Ground Acceleration) represents that of short period. Synthetic ground motions were computed in a deterministic sense by using pseudo-dynamic source models. The effective frequency is roughly up to 3 Hz, which is why we primarily investigated the PGV characteristics rather than PGA in this study. However, it may be also interesting to see the dependency of our sensitivity analysis to period. As shown in Figures 14 and 15, we performed the same sensitivity analysis as we did in Figure 11, but for pseudo-spectral acceleration (PSA) with different periods ($T = 0.5$, 1, 2, and 5 seconds). We observe that near-source ground motions are mostly sensitive to the perturbation of 1-point and 2-point statistics in the forward rupture region, even for the PSAs with various periods. However, the degree of the sensitivity decreases with increasing periods for the
perturbation of both 1-point and 2-point statistics. It may be reasonable to think that the long period ground motion is less sensitive to the details of pseudo-dynamic source models. This pattern is also effective in general for the standard deviation of the ratios, i.e., right panels in Figures 14 and 15.

Discussion

We investigated the sensitivity of near-source ground motions to the input 1-point and 2-point statistics of pseudo-dynamic source models. Although our main goal of this paper is to understand the relative sensitivity of ground motions, it would be also interesting to compare them with empirical GMPEs and to understand the significance of the role of the input pseudo-dynamic source models. Figures 16 and 17 show the comparison plots between our synthetics and several empirical GMPEs for Mw 6.6 and Mw 7.0 target events, respectively. First of all, our synthetics are in general below the median predictions of the GMPEs for Mw 6.6 while they are around the median predictions for Mw 7.0. This indicates that the magnitude scaling of our synthetics is not consistent with that of the empirical GMPEs. This may be an important research item in following studies, but beyond the scope of this paper. However, we also find several interesting features in these comparison plots. The variability of ground motions seem to be
larger at longer distances (~ 50 km), compared to that at shorter distances (~ 10 km), especially for Mw 7.0. The variability of near-source ground motions is mostly generated by the difference between the forward and backward directivity effects as seen between the red and blue symbols. The pseudo-dynamic source models, developed by Song et al. (2014), are composed of 1-point (mean and standard deviation) and 2-point (correlation) statistics of earthquake source parameters. Both the effect of standard deviation and cross-correlation were investigated in this study, but not the mean of source parameters. Figure 18 shows the sensitivity analysis of ground motions to the mean of rupture velocity and peak slip velocity. As expected, higher mean rupture velocity and peak slip velocity produce stronger ground motions.

Our investigation of the sensitivity of near-source ground motions to pseudo-dynamic source models was primarily focused on discerning the maximum difference, which can be observed from the perturbation of 1-point and 2-point statistics, as shown in Figures 10 and 11. However, it would also be interesting to examine the perturbation details between the maximum and minimum PGVs. As shown in Figures 8(a), 9(a), S4, and S6, the greater standard deviations of both rupture velocity ($V_r$) and peak slip velocity ($V_{max}$) produce stronger ground motions, although their means are not perturbed. The standard deviation of temporal source parameters such as $V_r$ and $V_{max}$ was well constrained by neither kinematic source inversion nor pseudo-dynamic source modeling. Song (2016) explicitly constructed probability density functions (PDFs) for these parameters, but they were based on synthetic dynamic rupture models. Therefore, one must be careful when determining the reasonable range of the standard deviations.
of these source parameters for physics-based ground motion modeling. Minimally, it may be desirable to test a wide range of possible values.

Regarding the effect of 2-point perturbation, we also found interesting patterns. For example, if the correlation structure contained a non-zero cross-correlation between $V_r$ and $V_{max}$ (e.g., corr-23), it produced stronger ground motions, which were compatible with the ground motions derived from the original pseudo-dynamic source model, as shown in Figure 9(b). Song et al. (2014) found that the non-zero cross-correlation between slip and $V_r$ (e.g., corr-12) shows the same effect. It seems that it is not yet clear whether or not a certain correlation pair between source parameters plays a dominant role in determining ground motion intensities. However, since the original pseudo-dynamic source models always produce stronger ground motions when compared to the pseudo-dynamic source models with no cross-correlation, it is important to determine an appropriate level of cross-correlation between source parameters for physics-based ground motion simulations.

The greater variation of near-source ground motions in the forward directivity zone may indicate the potential utility of physics-based ground motion modeling for seismic hazards assessment of specific sites. In advanced probabilistic seismic hazard analysis, the directivity effect, which affects both the intensity and variability of ground motions in the directivity zones, may need to be considered carefully, depending upon the direction and characteristics of nearby fault structures. Even in Korea, major industrial facilities, such as nuclear power plants, are located adjacent to fault lines, which need to be considered as line sources. The type of pseudo-
dynamic source modeling performed in this study may help to develop our understanding of a wide range of potential variations in ground motions, which may be expected in the forward directivity zone.

Conclusions

In this study, we investigated the detailed characteristics of near-source ground motions controlled by finite-source processes, utilizing pseudo-dynamic source modeling that were based on the 1-point and 2-point statistics of earthquake source parameters. We simulated a large number of near-source ground motions using vertical strike-slip pseudo-dynamic models of $M_w$ 6.6 and 7.0, derived from multiple sets of input source statistics. We found that near-source ground motions are more significantly affected by input source statistics models in the forward directivity zone, and this effect is also observed in the analysis of PSAs with various periods. It is important to understand the characteristics of near-source ground motions in advanced seismic hazard analysis. The pseudo-dynamic source modeling method, with 1-point and 2-point statistics of kinematic source parameters, seems to be an efficient framework for understanding the effect of earthquake source processes on near-source ground motion characteristics systematically.

Data and Resources
Pseudo-dynamic Source Modeling

Pseudo dynamic rupture models and ground motion simulations produced all data used in this article. The simulations were done in the computer server running CentOS (http://www.centos.org) version 6.2 at seismological laboratory of Seoul national university. And 1-point and 2-point statistics computation of simulated ground motion were performed using the Mathworks MATLAB (www.mathworks.com/products/matlab). The pseudo-dynamic rupture model generator used in the study is available upon request to the corresponding author.

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Sensitivity analysis of near-source ground motions to pseudo-
dynamic source models derived with 1-point and 2-point statistics of
earthquake source parameters

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Abstract

Ground motion prediction is an important element in seismic hazard analysis. However, the availability of recorded strong ground motion data is limited, particularly for large events in near-source regions. Recently, several physics-based ground motion simulation approaches have been developed, which may be useful for understanding the effect of earthquake source on near-source ground motion characteristics. In this study we investigated the sensitivity of near-source ground motions to finite earthquake source processes with pseudo-dynamic source models, based on 1-point and 2-point statistics of earthquake source parameters. We simulated ground motions for $M_w$ 6.6 and 7.0 vertical strike-slip events using pseudo-dynamic source models derived from multiple sets of input source statistics, and investigated the characteristics of near-source ground motions relative to the input source statistics. Our results show that the effect of earthquake source on near-source ground motions can vary depending on the locations of near-source stations. The variability of ground motion intensities derived from multiple sets of input source statistics is greater in the forward directivity region. This pattern is also consistent for pseudo-spectral accelerations with various periods. The pseudo-dynamic source modeling method with 1-point and 2-point statistics seems to be an efficient framework for understanding the effect of earthquake source on near-source ground motion characteristics.
Introduction

It has been noted that the Korean Peninsula belongs to a stable seismic zone in comparison with active seismic zones, such as the western United States and neighboring Japan. However, according to historical earthquake data that covers approximately 2,000 years, it is known that there was a time period in which many large earthquakes (Modified Mercalli Intensity, MMI > VII) occurred in the southeastern region of the Korean Peninsula (Lee and Yang, 2006). As instrumental earthquake data have been accumulated since 1905, it is also known that moderate earthquakes ($M_L=5.0$) took place several times, and caused damages more than 5 times (e.g., the Ssanggyesa earthquake ($M_L=5.0$) on June 4, 1936, the Hongsung earthquake ($M_L=5.0$) on October 7, 1978, the Gyeongju earthquakes ($M_L=5.1$, $M_L=5.8$) on September 12, 2016, and the Pohang earthquake ($M_L=5.4$) on November 15, 2017. Even though an earthquake of $M_L$ 6.0 or greater, which might cause serious damages, have not taken place in the last century, predicting potential seismic hazards has become a more important issue after the occurrence of the Gyeongju earthquake ($M_L=5.8$) on September 12 2016, which is considered to be the largest earthquake in South Korea since the initiation of instrumental recordings (i.e., since 1905).

Empirical ground motion prediction equations (GMPEs) have been widely used for probabilistic seismic hazard analysis (PSHA) because they are directly constrained by the observed data (Abrahamson et al., 2008). Boommer and Abrahamson (2006) noted that GMPE controls the shapes of the seismic hazard curves and has a significant impact on PSHA. However, the availability of recorded strong ground motion data is limited, particularly in near-source
regions, even in very active seismic regions. Strasser et al. (2009) illustrated the problem and challenges that arise when we constrain GMPEs for various spectral frequencies with a lack of near-source strong motion recordings.

In Korea, there have been few strong ground motion records produced, and it is difficult to develop GMPEs based on the observed data. Therefore, most of the previous GMPE studies (Park et al., 2001; Jo and Baag, 2003; Yun et al., 2005; Korea Hydro and Nuclear Power Co., Ltd (KHNP), 2015) have constrained a few physical parameters, such as stress drop and attenuation (Q) for a small range of earthquake magnitudes, and simulated ground motions for a wide range of earthquake magnitude using the stochastic point-source ground motion model developed by Boore (1996, 2005). Park et al. (2001) used 26 events with local magnitude ranges from 1.4 and 4.3, which occurred from 1997 to 1999. Jo and Baag (2003) used 16 events that occurred from 1999 to 2001. The only empirical GMPE based on observed data in Korea was presented by Emolo et al. (2015). They analyzed data from 222 earthquakes recorded at 132 three-component stations of the South Korea Seismic Network, from 2007 to 2012, with local magnitudes ranging between 2.0 and 4.9. They noted that because of the characteristics of the adopted database, their GMPEs can be confidently applied up to a maximum local magnitude of 5.0. However, there are still many limitations in our understanding of the physical characteristics of near-source ground motions and their attenuation with distance in Korea.

Physics-based ground motion simulation methods have received much attention as the effect of finite-source processes on near-source ground motion characteristics can be efficiently taken into
account and understood. Dynamic rupture modeling has been successfully used in physics-based modeling for decades (Olsen et al., 1997; Dalguer et al., 2008; Ripperger et al., 2008; Shi and Day, 2013). The finite-faulting process in dynamic modeling is governed by stress and frictional behavior. This approach enables us to generate the physically self-consistent spatio-temporal evolution of a finite-source model. However, dynamic modeling requires high-cost computing resources and time to generate synthetic waveforms of large earthquakes. As an alternative method, pseudo-dynamic source modeling has been introduced to improve computational efficiency. The framework of pseudo-dynamic source modeling is still that of a kinematic source model, while it simultaneously emulated the source physics inferred from rupture dynamics and observations (Guatteri et al., 2004; Song and Somerville, 2010; Mena et al., 2012; Schmedes et al., 2013; Song et al., 2014).

Song et al. (2014) developed a pseudo-dynamic source modeling method based on the 1-point and 2-point statistics of earthquake source parameters. They demonstrated that the effect of earthquake source processes on near-source ground motions could be investigated efficiently in the framework of 1-point and 2-point statistics. Song (2016) developed a generalized pseudo-dynamic source statistics model for $M_w$ 6.5–7.0 earthquakes by analyzing a number of dynamic rupture models, and validated the synthetic broadband ground motions derived from the pseudo-dynamic source models against empirical GMPEs. However, the dynamic rupture models used in Song (2016) have limitations, especially in terms of the uncertainty of their input stress models and friction laws. Given the uncertainty imposed in the developed pseudo-dynamic source models, it is important to understand the sensitivity of near-source ground motions to the
perturbation of the pseudo-dynamic source models.

In recent studies, near-source ground motion characteristics have been studied through finite-source modeling approaches. Vyas et al. (2016) analyzed ground motion datasets simulated from the kinematic source parameters of the $M_w$ 7.3 Landers earthquake of 1992 in terms of the distance and azimuth-dependence of the peak ground velocity. Their simulations revealed that intra-event ground motion variability is higher closer to the fault and decreases with increasing distance. The physical explanation of high near-source ground motion variability is the presence of strong directivity and rupture complexity. Crempien and Archuleta (2017) simulated kinematic rupture scenarios on several vertical strike-slip faults and computed ground motions using a representation theorem. They demonstrated that both intra-event and inter-event ground motion variabilities increase when the slip correlation length on the fault increases. Imitiaz et al. (2015) studied the distance dependency of ground motion variability, especially in near-source regions, using ground motions for strike-slip events, which were generated from finite rupture models of past earthquakes. They showed that the standard deviation of ground motions depends significantly on the rupture type. For bilateral ruptures, variability tends to increase with distance. On the contrary, the variability of unilateral events decreases with distance. They also noted that unilateral rupture models would strengthen directivity effects.

This study builds upon previous work by Song et al. (2014), who illustrated the efficiency of pseudo-dynamic source models based on 1-point and 2-point statistics of kinematic source parameters. Here, we extend this previous work by investigating how the input 1-point and 2-
point statistics affect near-source ground motion characteristics, especially with respect to the specific locations of near-source stations, such as a forward rupture directivity zone. We simulated ground motions for $M_w$ 6.6 and 7.0 vertical strike-slip events using pseudo-dynamic source models derived from multiple sets of input source statistics, and investigated the characteristics of near-source ground motions relative to the input source statistics.

**Source Modeling**

**Pseudo-dynamic source modeling**

To simulate ground motions for a target event, many source parameters are needed to characterize a finite-fault rupture model, such as rupture dimension (length and width) and kinematic rupture parameters (slip, rupture velocity, and peak slip velocity). If we assume that future earthquakes share the finite-source characteristics of past earthquakes, at least in a statistical sense, we may constrain earthquake parameters for future events by studying the characteristics of past earthquakes (Mai and Beroza, 2000; Mai and Beroza, 2002; Song et al., 2009). However, we are often limited to resolving the details of a kinematic rupture model, especially the temporal source parameters such as rupture velocity and peak slip velocity, by inverting geophysical data observed on the ground for past events (Beresnev, 2003; Mai et al., 2016). Researchers often rely on spontaneous, dynamic rupture models to extract physics-based correlation structures between earthquake slips and temporal source parameters, which have been categorized as pseudo-dynamic source modeling (Guatteri et al., 2004; Schmedes et al., 2010; Mena et al., 2012; Song et al., 2014). In other words, pseudo-dynamic source modeling is still
Pseudo-Dynamic Source Modeling

kinematic modeling, but it utilizes the physical correlation structures of kinematic source parameters derived from spontaneous dynamic rupture modeling.

Song et al. (2014) proposed characterizing earthquake rupture processes within a framework of the 1-point and 2-point statistics of key kinematic source parameters. In brief, their approach involved assigning a set of random spatial fields to a finite-fault plane to model the spatial distribution of several key kinematic source parameters, such as slip, rupture velocity (Vr), and peak slip velocity (Vmax). In other words, one random field was assigned to each source parameter, and one random variable (i.e., one element of the random field was assigned to every subfault patch on the fault). If there are three source parameters, there are also three random fields. The number of random variables for each random field is equal to the number of subfault patches on the finite fault. The 1-point statistics is a marginal probability density function at a given point on the fault. If a Gaussian distribution is assumed, the mean and standard deviation are the two main representative parameters that control the possible range of values for each source parameter. The 2-point statistics is composed of both auto and cross correlation. Autocorrelation controls the heterogeneity of each source parameter, while cross-correlation controls the coupling between source parameters. Once the 1-point and 2-point statistics are modeled for a certain event, finite-source rupture scenarios can be generated by stochastic modeling.

Song (2016) developed a source statistics model by analyzing a number of spontaneous, dynamic rupture models ranging in magnitude from Mw 6.5–7.0. He assumed a multivariate
Gaussian distribution for a random field model and developed an input source statistics model for both 1-point (mean and standard deviation of source parameters) and 2-point statistics (correlation length and correlation coefficient). For 2-point statistics, a simple exponential function was adopted, as given in equation (1), for a functional form of correlation:

\[ \rho(h) = \rho_{\text{max}} \cdot \exp\left(-\sqrt{\left(\frac{h_x - RD_x}{a_x}\right)^2 + \left(\frac{h_z - RD_z}{a_z}\right)^2}\right); \quad h = (h_x, h_z), \quad (1) \]

where \( h \) is the separation vector between two locations on the fault. The remaining parameters are as follows: \( a_x \) and \( a_z \) are correlation lengths in the along-strike and along-dip directions, respectively (six parameters: slip versus slip, slip versus \( V_r \), slip versus \( V_{\text{max}} \), \( V_r \) versus \( V_r \), \( V_r \) versus \( V_{\text{max}} \), \( V_{\text{max}} \) versus \( V_{\text{max}} \)). \( V_r \) and \( V_{\text{max}} \) represent rupture velocity and peak slip velocity respectively. The maximum correlation coefficient is denoted as \( \rho_{\text{max}} \) (three parameters: slip versus \( V_r \), slip versus \( V_{\text{max}} \), \( V_r \) versus \( V_{\text{max}} \)); \( RD_x \) and \( RD_z \) are the response distances in the along-strike and along-dip directions (three parameters: slip versus \( V_r \), slip versus \( V_{\text{max}} \), \( V_r \) versus \( V_{\text{max}} \)).

The complete form of input parameters for the source statistics model is defined in Table 1 of Song (2016). We set both response distances (i.e., \( RD_x \) and \( RD_z \)) to zero in this study because most models used by Song (2016) exhibited near-zero values for these parameters. However, due to rupture propagation effects, particularly in long strike-slip events, the response distance could be relatively large (Song et al., 2009; Song and Sommerville, 2010). The response distance may play an important role in controlling the directivity effects in future studies. Since we considered 3 kinematic source parameters (i.e., slip, rupture velocity, and peak slip velocity) for pseudo-
dynamic source modeling, there were 6 input parameters for 1-point statistics and 15 input parameters for 2-point statistics.

In this study, we simulated 4 sets of pseudo-dynamic source models for both $M_w$ 6.6 and 7.0 vertical strike-slip target events. The geometry of both target events is summarized in Table 1. Input models were extracted from the source statistics model developed by Song (2016), and are summarized in Tables 2 and 3. For each set of input source statistics model, 30 earthquake scenario models were developed to allow for statistical stability when we investigated near-source ground motion characteristics. Figure 1 shows an example of four different pseudo-dynamic source models for the $M_w$ 7.0 target event, and we present examples of four different pseudo-dynamic source models for the $M_w$ 6.6 in Figure S1.

Perturbation of 1-point and 2-point statistics

In this study we aimed to investigate the characteristics of near-source ground motions controlled by the 1-point and 2-point statistics of pseudo-dynamic source models. We adopted the same strategy of perturbing 1-point and 2-point statistics as that used by Song et al. (2014). Thus, we can systematically investigate the effect of input source statistics models on near-source ground motion characteristics. Pseudo-dynamic source models are presented in Figure 2 and Figure S2 after perturbing their 1-point statistics. The 1-point statistics of $V_r$ and $V_{max}$ (i.e., their standard deviations), were reduced by half or expanded by a factor of two, respectively. The effect of temporal source parameters on ground motion has been studied recently (Moschetti et al., 2017; Wirth et al., 2017), however, mostly in the aspect of their mean behavior rather than
standard deviation. There have been several studies to investigate the variability of earthquake slip, but almost no attempts to constrain the variability (standard deviation) of the temporal source parameters such as rupture velocity and peak slip velocity. The perturbation scheme used in our analysis, i.e., by half or by a factor of two, does not have physical and observational basis yet, but we think it is still meaningful to test its effect on near-source ground motions since we are very limited to constraining the variability of temporal source parameters at this point.

For 2-point statistics, the cross-correlations of slip-Vr, slip-Vmax, and Vr-Vmax were sequentially perturbed. Finally, 6 sets of pseudo-dynamic source models were constructed, which were linked to the perturbation of 1-point statistic, and 7 sets of models were constructed that were linked to the perturbation of 2-point statistics. Given an input source statistics model, 420 (= (1 + 6 + 7) × 30) pseudo-dynamically generated source models were produced for each target magnitude, including both the original and perturbed pseudo-dynamic source models. We then compared ground motions generated from all 6 sets of pseudo-dynamic source models for 1-point statistics and 7 sets of pseudo-dynamic source models for 2-point statistics with those generated from the original pseudo-dynamic modeling in a statistical sense. Since we simulated pseudo-dynamic source models using the source statistics model developed by Song (2016), it may not be clear why we focus on the perturbation analysis of the pseudo-dynamic source models. Although Song (2016) developed the source statistics model by analyzing a number of spontaneous dynamic rupture models, dynamic rupture models have its own limitation, especially in terms of the uncertainty of its input models such as stress and friction. If we expect that our pseudo-dynamic source models have a certain level of uncertainty, it is important to
understand how much it affects near-source ground motions. In addition, in the framework of 1-point and 2-point statistics, it would also be important to understand how each component of the source statistics model affect near-source ground motions.

Figures 3 and S3 show how the simulated source parameters were affected by perturbing the input 2-point statistics. The pseudo-dynamic source model in Figure 3(a) includes the full correlation of 2-point statistics, and it can be seen that high slip patches are correlated with high rupture and peak slip velocities. However, in Figure 3(h), no coupling is observed between the source parameters since the correlation coefficients of the off-diagonal components were set to zero. Figure 3(b–g) shows additional sets of perturbed pseudo-dynamic source models for 2-point statistics. Since there were three off-diagonal cross-correlation structures, 7 different sets of perturbation for 2-point statistics, as in Figure 3, were constructed. The corresponding autocorrelation matrices and 1-point statistics were retained while perturbing the cross-correlation matrices. If a finite source model is simulated without a certain component of cross-correlation matrices (Figure 3(b-h)), we may not claim that it is still a pseudo-dynamic source model. However, this type of perturbation is useful when we try to understand the effect of each component of the source statistics model on ground motions.

Characteristics of near-source ground motions

Ground motion modeling

We initially generated 30 scenario earthquakes via stochastic modeling for each input source
statistics model shown in Tables 2 and 3. The slip velocity function (SVF) proposed by Tinti et al. (2005) was adopted to compute the spatio-temporal evolution of earthquake rupture along the fault. The pseudo-dynamically generated finite-source models were combined with Green's functions computed by the FK method (Zhu and Rivera, 2002). The same 1D velocity model used in Song et al. (2014) was adopted for the Green’s function calculation. Then, we generated three-component (fault-normal, fault-parallel, and vertical) synthetic seismograms that were effective up to 3 Hz. Figure 4 shows the locations of 168 stations along with the surface trace of the rupture dimension for the $M_w$ 6.6 event. The circle size of each station indicates the mean Peak Ground Velocity (PGV) (fault normal) of 30 earthquake scenarios for the first source statistics model (SSM 1) in Table 2. Two colored areas show both the forward and backward directivity regions, which were analyzed with the perturbation of 1-point and 2-point statistics in this study. Synthetic waveforms at a few selected stations shown in Figure 4 are displayed in Figure 5. Figure 6 shows the locations of 400 stations, with the surface trace of the rupture dimension for the $M_w$ 7.0 event, and Figure 7 shows waveforms at the stations selected in Figure 6. We clearly observed the forward directivity effect especially in the fault normal component.

**Directivity analysis**

Directivity effects indicate that earthquake ground motions, especially fault normal components, are more severe in the direction of rupture propagation than in other directions. Sommerville et al. (1997) showed that rupture directivity effects cause spatial variations in ground motion amplitudes and durations around faults, and cause differences between the fault-
normal and fault-parallel components of horizontal ground motion amplitudes. They also found that for strike-slip faulting, the directivity effect on amplitudes is weak at sites close to the epicenter, but grows large at sites located near the fault rupture zone but away from the epicenter. Finally, they have developed the directivity term that accounts for the spatial variations of ground-motion amplitudes and durations, which may be used in GMPEs. Ben-Menahem and Singh (1981) also describes the azimuthal variation of the directivity effects, depending on rupture velocity and source dimension. Bray and Rodriguez-Marek (2004) developed empirical relationship between the PGV and period of the velocity pulse of forward directivity motions. Spudich et al. (2008) introduced a new and physically-based isochrone directivity predictor and models of directivity effect based on this predictor. The directivity effect is an important element in understanding the near-source ground motion characteristics, in particular in finite-source modeling.

As was discussed in the section "Pseudo-dynamic source modeling" above, 6 sets of pseudo-dynamic source models were constructed that are linked to the perturbation of 1-point statistics and 7 sets of pseudo-dynamic source models that are linked to the perturbation of 2-point statistic. We computed the PGV ratios with the waveforms obtained from the original and perturbed pseudo-dynamic source models in the selected forward and backward directivity zones as well as in the total area in Figure 4 and Figure 6, and compared the maximum difference of the mean and standard deviation of the PGV ratios. Figures 8 and 9 show the changes of the pseudo dynamically generated ground motions after the perturbation of 1-point and 2-point statistics for both $M_w$ 6.6 and $M_w$ 7.0 target events, respectively.
The mean and standard deviation of the PGV ratios were computed following the equations (2) and (3), given below.

\[
\text{mean}(PGV_{\text{ratio}}) = \frac{1}{nm} \sum_{i=1}^{n} \sum_{j=1}^{m} \log_2 \left( \frac{(PGV_{\text{pertubated}})_{ij}}{(PGV_{\text{original}})_{ij}} \right), \quad (2)
\]

\[
\sigma(PGV_{\text{ratio}}) = \sqrt{\frac{1}{nm-1} \sum_{i=1}^{n} \sum_{j=1}^{m} \left( \log_2 \left( \frac{(PGV_{\text{pertubated}})_{ij}}{(PGV_{\text{original}})_{ij}} \right) - \text{mean}(PGV_{\text{ratio}}) \right)^2}. \quad (3)
\]

where \( n \) is the number of selected stations for directivity analysis and \( m \) is the number of scenario earthquake models (\( m = 30 \)). We used the base 2 in the log-scale because it is easy to understand the amplitude of the ratio even after taking the logarithm.

As was observed in Figures 8(a), 9(a), S4, and S6, the PGVs increased if the standard deviation of either rupture velocity (\( V_r \)) or peak slip velocity (\( V_{\text{max}} \)) increased. These results are consistent with the findings of Song et al. (2014). Regarding the perturbation of 2-point statistics shown in Figures 8(b), 9(b), S5, and S7, the PGVs were reduced once certain components of the off-diagonal elements, shown in Figure 3, were removed. More interestingly, the PGVs are compatible with those of the original pseudo-dynamic source models if the correlations between \( V_r \) and \( V_{\text{max}} \) are included (e.g., corr_23 in Figure 9). The right panels of Figures 8 and 9 show the standard deviations of the PGV ratios computed by equation (3). We also found that the variations in ground motions, as measured by the standard deviation, were generally greater in the forward directivity region.
Figures 10 and 11 show the maximum differences of the PGV ratios for the $M_w$ 6.6 and 7.0 target event, respectively, after the perturbation of 1-point and 2-point statistics for all 4 input source statistics models. The results clearly show that the ground motion intensity in the forward directivity region is affected more significantly by the perturbation of source statistics in pseudo-dynamic source modeling. However, we also found that this pattern is not dominant for the perturbation of 2-point statistics for the $M_w$ 6.6 target event, which may imply that there is a magnitude dependency for the forward directivity effect relative to the input source statistics models. In other words, the greater the magnitude of the earthquake, the greater the influence of forward directivity. However, we also admit that it is too early to generalize this statement and it requires additional analyses to understand the magnitude dependency of the forward directivity effect.

**Azimuth analysis**

We also analyzed the dependency of the PGV ratios on azimuth. Figure 12 shows the 9 different regions used in this analysis; each region had a 30° range. This analysis should contain all stations for the entire distance range, but may be able to better resolve the azimuthal dependency, compared to the station selection in Figure 6. Figure 13 shows the azimuthal dependency of the PGV ratios after the perturbation of 1-point and 2-point statistics for all 4 input source statistics models for the $M_w$ 7.0 target event. It can be clearly observed that the perturbation effect of 1-point and 2-point statistics is more dominant in the forward directivity regions, and the effect is slightly greater in the backward directivity regions, compared to the
other regions.

**Period analysis**

PGV in general represents the characteristics of long period ground motions while PGA (Peak Ground Acceleration) represents that of short period. Synthetic ground motions were computed in a deterministic sense by using pseudo-dynamic source models. The effective frequency is roughly up to 3 Hz, which is why we primarily investigated the PGV characteristics rather than PGA in this study. However, it may be also interesting to see the dependency of our sensitivity analysis to period. As shown in Figures 14 and 15, we performed the same sensitivity analysis as we did in Figure 11, but for pseudo-spectral acceleration (PSA) with different periods (T = 0.5, 1, 2, and 5 seconds). We observe that near-source ground motions are mostly sensitive to the perturbation of 1-point and 2-point statistics in the forward rupture region, even for the PSAs with various periods. However, the degree of the sensitivity decreases with increasing periods for the perturbation of both 1-point and 2-point statistics. It may be reasonable to think that the long period ground motion is less sensitive to the details of pseudo-dynamic source models. This pattern is also effective in general for the standard deviation of the ratios, i.e., right panels in Figures 14 and 15.

**Discussion**
Pseudo-Dynamic Source Modeling

We investigated the sensitivity of near-source ground motions to the input 1-point and 2-point statistics of pseudo-dynamic source models. Although our main goal of this paper is to understand the relative sensitivity of ground motions, it would be also interesting to compare them with empirical GMPEs and to understand the significance of the role of the input pseudo-dynamic source models. Figures 16 and 17 show the comparison plots between our synthetics and several empirical GMPEs for Mw 6.6 and Mw 7.0 target events, respectively. First of all, our synthetics are in general below the median predictions of the GMPEs for Mw 6.6 while they are around the median predictions for Mw 7.0. This indicates that the magnitude scaling of our synthetics is not consistent with that of the empirical GMPEs. This may be an important research item in following studies, but beyond the scope of this paper. However, we also find several interesting features in these comparison plots. The variability of ground motions seem to be larger at longer distances (~ 50 km), compared to that at shorter distances (~ 10 km), especially for Mw 7.0. The variability of near-source ground motions is mostly generated by the difference between the forward and backward directivity effects as seen between the red and blue symbols.

The pseudo-dynamic source models, developed by Song et al. (2014), are composed of 1-point (mean and standard deviation) and 2-point (correlation) statistics of earthquake source parameters. Both the effect of standard deviation and cross-correlation were investigated in this study, but not the mean of source parameters. Figure 18 shows the sensitivity analysis of ground motions to the mean of rupture velocity and peak slip velocity. As expected, higher mean rupture velocity and peak slip velocity produce stronger ground motions.
Our investigation of the sensitivity of near-source ground motions to pseudo-dynamic source models was primarily focused on discerning the maximum difference, which can be observed from the perturbation of 1-point and 2-point statistics, as shown in Figures 10 and 11. However, it would also be interesting to examine the perturbation details between the maximum and minimum PGVs. As shown in Figures 8(a), 9(a), S4, and S6, the greater standard deviations of both rupture velocity ($V_r$) and peak slip velocity ($V_{max}$) produce stronger ground motions, although their means are not perturbed. The standard deviation of temporal source parameters such as $V_r$ and $V_{max}$ was well constrained by neither kinematic source inversion nor pseudo-dynamic source modeling. Song (2016) explicitly constructed probability density functions (PDFs) for these parameters, but they were based on synthetic dynamic rupture models. Therefore, one must be careful when determining the reasonable range of the standard deviations of these source parameters for physics-based ground motion modeling. Minimally, it may be desirable to test a wide range of possible values.

Regarding the effect of 2-point perturbation, we also found interesting patterns. For example, if the correlation structure contained a non-zero cross-correlation between $V_r$ and $V_{max}$ (e.g., corr-23), it produced stronger ground motions, which were compatible with the ground motions derived from the original pseudo-dynamic source model, as shown in Figure 9(b). Song et al. (2014) found that the non-zero cross-correlation between slip and $V_r$ (e.g., corr-12) shows the same effect. It seems that it is not yet clear whether or not a certain correlation pair between source parameters plays a dominant role in determining ground motion intensities. However, since the original pseudo-dynamic source models always produce stronger ground motions when
compared to the pseudo-dynamic source models with no cross-correlation, it is important to
determine an appropriate level of cross-correlation between source parameters for physics-based
ground motion simulations.

The greater variation of near-source ground motions in the forward directivity zone may
indicate the potential utility of physics-based ground motion modeling for seismic hazards
assessment of specific sites. In advanced probabilistic seismic hazard analysis, the directivity
effect, which affects both the intensity and variability of ground motions in the directivity zones,
may need to be considered carefully, depending upon the direction and characteristics of nearby
fault structures. Even in Korea, major industrial facilities, such as nuclear power plants, are
located adjacent to fault lines, which need to be considered as line sources. The type of pseudo-
dynamic source modeling performed in this study may help to develop our understanding of a
wide range of potential variations in ground motions, which may be expected in the forward
directivity zone.

Conclusions

In this study, we investigated the detailed characteristics of near-source ground motions
controlled by finite-source processes, utilizing pseudo-dynamic source modeling that were based
on the 1-point and 2-point statistics of earthquake source parameters. We simulated a large
number of near-source ground motions using vertical strike-slip pseudo-dynamic models of \( M_w \)
6.6 and 7.0, derived from multiple sets of input source statistics. We found that near-source
ground motions are more significantly affected by input source statistics models in the forward
directivity zone, and this effect is also observed in the analysis of PSAs with various periods. It is important to understand the characteristics of near-source ground motions in advanced seismic hazard analysis. The pseudo-dynamic source modeling method, with 1-point and 2-point statistics of kinematic source parameters, seems to be an efficient framework for understanding the effect of earthquake source processes on near-source ground motion characteristics systematically.

**Data and Resources**

Pseudo dynamic rupture models and ground motion simulations produced all data used in this article. The simulations were done in the computer sever running CentOS (http://www.centos.org) version 6.2 at seismological laboratory of Seoul national university. And 1-point and 2-point statistics computation of simulated ground motion were performed using the Mathworks MATLAB (www.mathworks.com/products/matlab). The pseudo-dynamic rupture model generator used in the study is available upon request to the corresponding author.

**Acknowledgments**

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Science and ICT).
References


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(J. Rhie)
### Tables

**Table 1.** Source geometry of the simulated events.

<table>
<thead>
<tr>
<th></th>
<th>$M_w$ 6.6</th>
<th>$M_w$ 7.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rupture dimension* (length / width)</td>
<td>30 km /12 km</td>
<td>54 km /14 km</td>
</tr>
<tr>
<td>Depth to top of fault</td>
<td>2 km</td>
<td>0 km</td>
</tr>
<tr>
<td>Dip angle</td>
<td>90 degree (strike-slip)</td>
<td></td>
</tr>
<tr>
<td>Source statistics model</td>
<td>1, 2-1, 2-2, 3</td>
<td>1, 2-1, 2-2, 3</td>
</tr>
<tr>
<td>Source statistics model</td>
<td>(3 different input source statistics models for $M_w$ 6.6)</td>
<td>(3 different input source statistics models for $M_w$ 7.0)</td>
</tr>
</tbody>
</table>

*Rupture dimension was determined, based on Wells and Coppersmith (1994).
### Table 2. Input 1-point and 2-point statistics models for $M_w$ 6.6.

<table>
<thead>
<tr>
<th>Model &amp; parameter</th>
<th>Description</th>
<th>Source statistics model 1 (SSM 1)</th>
<th>Source statistics model 2-1, 2-2* (SSM 2-1, SSM 2-2)</th>
<th>Source statistics model 3 (SSM 3)</th>
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</thead>
<tbody>
<tr>
<td>$\mu_{slip}$</td>
<td>Mean slip (cm)</td>
<td>75.02</td>
<td>75.02</td>
<td>75.02</td>
</tr>
<tr>
<td>$\mu_{V_r}$</td>
<td>Mean rupture velocity (km/s)</td>
<td>2.18</td>
<td>1.61</td>
<td>1.79</td>
</tr>
<tr>
<td>$\mu_{V_{max}}$</td>
<td>Mean peak slip velocity (cm/s)</td>
<td>113.14</td>
<td>98.66</td>
<td>99.77</td>
</tr>
<tr>
<td>$\sigma_{slip}$</td>
<td>Standard deviation of slip (cm)</td>
<td>43.25</td>
<td>32.41</td>
<td>33.77</td>
</tr>
<tr>
<td>$\sigma_{V_r}$</td>
<td>Standard deviation of rupture velocity (km/s)</td>
<td>0.71</td>
<td>0.56</td>
<td>0.58</td>
</tr>
<tr>
<td>$\sigma_{V_{max}}$</td>
<td>Standard deviation of peak slip velocity (cm/s)</td>
<td>87.48</td>
<td>69.14</td>
<td>72.98</td>
</tr>
<tr>
<td>$a_x$</td>
<td>Correlation length in the along-strike direction (km)</td>
<td>(3.9 2.6 2.4)</td>
<td>(5.1 5.7 12.1)</td>
<td>(6.2 7.9 7.5)</td>
</tr>
<tr>
<td></td>
<td>(slip vs. slip, slip vs. $V_r$, slip vs. $V_{max}$, $V_r$ vs. $V_r$, $V_r$ vs. $V_{max}$, and $V_{max}$ vs. $V_{max}$)</td>
<td>(1.3 5.6)</td>
<td>(3.6 12.8)</td>
<td>(4.6 15.9)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(6.3)</td>
<td>(9.5)</td>
<td>(16.4)</td>
</tr>
<tr>
<td>$a_z$</td>
<td>Correlation length in the along-dip direction (km)</td>
<td>(5.4 1.9 1.5)</td>
<td>(1.4 1.5 0.8)</td>
<td>(0.9 0.3 1.0)</td>
</tr>
<tr>
<td></td>
<td>(slip vs. slip, slip vs. $V_r$, slip vs. $V_{max}$, $V_r$ vs. $V_r$, $V_r$ vs. $V_{max}$, and $V_{max}$ vs. $V_{max}$)</td>
<td>(3.6 1.4)</td>
<td>(1.3 1.8)</td>
<td>(2.7 1.2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1.9)</td>
<td>(2.1)</td>
<td>(1.6)</td>
</tr>
<tr>
<td>$\rho_{max}$</td>
<td>Maximum correlation coefficient</td>
<td>(1 0.71 0.94)</td>
<td>(1 0.62 0.71)</td>
<td>(1 0.43 0.65)</td>
</tr>
<tr>
<td></td>
<td>(slip vs. $V_r$, slip vs. $V_{max}$ and $V_r$ vs. $V_{max}$)</td>
<td>(1 0.64)</td>
<td>(1 0.77)</td>
<td>(1 0.70)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1.00)</td>
<td>(1.00)</td>
<td>(1)</td>
</tr>
</tbody>
</table>

* Two source statistics models (SSM 2-1 and SSM 2-2) share the same input values, but used different seed numbers in stochastic modeling.
Table 3. Input 1-point and 2-point statistics models for $M_w$ 7.0.

<table>
<thead>
<tr>
<th>Model &amp; parameter</th>
<th>Description</th>
<th>Source Statistics Model 1 (SSM 1)</th>
<th>Source Statistics Model 2-1, 2-2* (SSM 2-1, SSM 2-2)</th>
<th>Source Statistics Model 3 (SSM 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_{\text{slip}}$</td>
<td>Mean slip (cm)</td>
<td>142.22</td>
<td>142.22</td>
<td>142.22</td>
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<tr>
<td>$\mu_{V_r}$</td>
<td>Mean rupture velocity (km/s)</td>
<td>2.19</td>
<td>1.63</td>
<td>1.81</td>
</tr>
<tr>
<td>$\mu_{V_{\text{max}}}$</td>
<td>Mean peak slip velocity (cm/s)</td>
<td>149.19</td>
<td>134.71</td>
<td>135.81</td>
</tr>
<tr>
<td>$\sigma_{\text{slip}}$</td>
<td>Standard deviation of slip (cm)</td>
<td>81.29</td>
<td>70.44</td>
<td>71.81</td>
</tr>
<tr>
<td>$\sigma_{V_r}$</td>
<td>Standard deviation of rupture velocity (km/s)</td>
<td>0.76</td>
<td>0.62</td>
<td>0.63</td>
</tr>
<tr>
<td>$\sigma_{V_{\text{max}}}$</td>
<td>Standard deviation of peak slip velocity (cm/s)</td>
<td>117.98</td>
<td>99.64</td>
<td>103.48</td>
</tr>
<tr>
<td>$\alpha_x$</td>
<td>Correlation length in the along-strike direction (km)</td>
<td>(3.5 2.6 1.8)</td>
<td>(4.7 5.6 9.1)</td>
<td>(5.6 7.8 5.7)</td>
</tr>
<tr>
<td></td>
<td>(slip vs. slip, slip vs. $V_r$, slip vs. $V_{\text{max}}$, $V_r$ vs. $V_r$, $V_r$ vs. $V_{\text{max}}$, and $V_{\text{max}}$ vs. $V_{\text{max}}$)</td>
<td>(1.2 5.1 4.9)</td>
<td>(5.1 11.5 7.5)</td>
<td>(4.6 14.2 12.8)</td>
</tr>
<tr>
<td>$\alpha_z$</td>
<td>Correlation length in the along-dip direction (km)</td>
<td>(11.1 3.5 3.2)</td>
<td>(3.1 2.8 1.8)</td>
<td>(1.8 0.6 2.1)</td>
</tr>
<tr>
<td></td>
<td>(slip vs. slip, slip vs. $V_r$, slip vs. $V_{\text{max}}$, $V_r$ vs. $V_r$, $V_r$ vs. $V_{\text{max}}$, and $V_{\text{max}}$ vs. $V_{\text{max}}$)</td>
<td>(4.4 1.8 2.2)</td>
<td>(1.4 2.4 2.5)</td>
<td>(3.1 1.5 1.9)</td>
</tr>
<tr>
<td>$\rho_{\text{max}}$</td>
<td>Maximum correlation coefficient</td>
<td>(1 0.78 0.90)</td>
<td>(1 0.70 0.67)</td>
<td>(1 0.51 0.61)</td>
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<tr>
<td></td>
<td>(slip vs. $V_r$, slip vs. $V_{\text{max}}$ and $V_r$ vs. $V_{\text{max}}$)</td>
<td>(1 0.68 1)</td>
<td>(1 0.82 1)</td>
<td>(1 0.74 1)</td>
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</table>

* Two source statistics models (SSM 2-1 and SSM 2-2) share the same input values, but used different seed numbers in stochastic modeling.
Pseudo-Dynamic Source Modeling
Table 4. Input 1-point statistics models for the sensitivity test of mean rupture velocity ($V_r$)

<table>
<thead>
<tr>
<th>$M_w$</th>
<th>Description</th>
<th>Source Statistics Model (SSM)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>SSM 2-1</td>
</tr>
<tr>
<td>6.6</td>
<td>Mean slip (cm)</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>Mean rupture velocity (km/s)</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>Mean peak slip velocity (cm/s)</td>
<td>98</td>
</tr>
<tr>
<td>7.0</td>
<td>Mean slip (cm)</td>
<td>142</td>
</tr>
<tr>
<td></td>
<td>Mean rupture velocity (km/s)</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>Mean peak slip velocity (cm/s)</td>
<td>134</td>
</tr>
</tbody>
</table>
Table 5. Input 1-point statistics models for the sensitivity test of mean peak slip velocity ($V_{max}$)

<table>
<thead>
<tr>
<th>$M_w$</th>
<th>Description</th>
<th>Source Statistics Model (SSM)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>SSM 1</td>
</tr>
<tr>
<td>6.6</td>
<td>Mean slip (cm)</td>
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<td></td>
<td>Mean rupture velocity (km/s)</td>
<td>2.2</td>
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<td>Mean peak slip velocity (cm/s)</td>
<td>113</td>
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<tr>
<td>7.0</td>
<td>Mean slip (cm)</td>
<td>142</td>
</tr>
<tr>
<td></td>
<td>Mean rupture velocity (km/s)</td>
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</tr>
<tr>
<td></td>
<td>Mean peak slip velocity (cm/s)</td>
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</tr>
</tbody>
</table>
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**Figure 1.** Source modeling examples for the $M_w$ 7.0 target event. One example of pseudo-dynamic source model from each source statistics models in Table 3 is presented although 30 scenario earthquakes were simulated by stochastic modeling for each input source statistics model.

**Figure 2.** Pseudo-dynamic source models after the perturbation of 1-point statistics for $M_w$ 7.0 target event using source statistics model 1 (SSM 1) in Table 3. The standard deviation of the rupture velocity ($V_r$) and peak slip velocity ($V_{max}$) was reduced by half, or increased by a factor of two.

**Figure 3.** Pseudo-dynamic source models after the perturbation of 2-point statistics for Mw 7.0 target event using source statistics model 1 (SSM 1) in Table 3. Three off-diagonal blocks were perturbed sequentially. The perturbed correlation structures are also given on the right-hand side.

**Figure 4.** The locations of 168 stations with the surface trace of the rupture dimension of the target $M_w$ 6.6 event. The circle size of each station indicates the mean PGV (Peak Ground Velocity) of the fault normal component of 30 scenario earthquakes using source statistics model 1 in Table 2. The initial nucleation point is marked with a yellow star. The red numbers in the
black box indicate 7 selected stations, whose waveforms are shown in Figure 5. Both forward and backward directivity zones used in the analysis are also colored.

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**Figure 10.** Comparison of the maximum difference of the mean and standard deviation of the PGV ratios for the $M_w$ 6.6 target event in Figure 8, but for all 4 models.

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**Figure 12.** The 9 different azimuthal zones used for the analysis of the azimuthal dependency for
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**Figure 16.** Comparison of the pseudo dynamically generated PGVs with empirical GMPEs for Mw 6.6. PGV is determined using the GMRotD50 (Boore *et al.*, 2006). PGV values in the forward and backward directivity areas are indicated in red and blue, respectively while PGV values in other regions are indicated in green. The colored lines represent three GMPEs, i.e., 2CVSP (Darragh *et al.*, 2015), B14 (Bindi *et al.*, 2014), and AB10 (Akkar and Bommer, 2010).
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**Figure 18.** Sensitivity analysis of PGV to the mean rupture velocity ($V_r$) (a,c) and mean peak slip velocity ($V_{max}$) (b, d) of the PGV (see Tables 4 and 5 for the details of input models). The PGV was determined using GMRotD50 (Boore et al., 2006). The colored lines represent three empirical GMPEs, i.e., 2CVSP (Darragh et al., 2015), B14 (Bindi et al., 2014), and AB10 (Akkar and Bommer, 2010), respectively.
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Figure 3. (continued)
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Electronic Supplement to

Sensitivity analysis of near-source ground motions to pseudo-dynamic source models derived with 1-point and 2-point statistics of earthquake source parameters

by D. Park, S.G. Song and J, Rhie

The results of source modeling example for $M_w$ 6.6 target event and pseudo-dynamic source models after the perturbation of 1-point and 2-point statistics for the $M_w$ 6.6 are shown in Figure 1, 2, and 3.

For comparison of the pseudo dynamically generated ground motions after the perturbation of 1-point and 2-point statistics for the $M_w$ 6.6 and $M_w$ 7.0, only the results of source statistics model 1 of Table 1, 2, and 3 are included in the main manuscript, therefore, supplementary results for statistics model 2-1, 2-2, and 3 are shown in Figure 4, 5, 6, and 7.
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**Figure S1.** Source modeling examples for $M_w$ 6.6 target event. One example of pseudo-dynamic source model from each source statistics models in Table 2 is presented although 30 scenario earthquakes were simulated by stochastic modeling for each input source statistics model.

**Figure S2.** Pseudo-dynamic source models after the perturbation of 1-point statistics for $M_w$ 6.6 target event using source statistics model 1 in Table 2. The standard deviation of the rupture velocity ($V_r$) and peak slip velocity ($V_{max}$) was reduced by half, or increased by a factor of two.

**Figure S3.** Pseudo-dynamic source models after the perturbation of 2-point statistics for $M_w$ 6.6 target event using source statistics model 1 in Table 2. Three off-diagonal blocks were perturbed sequentially.

**Figure S4.** Comparison of the pseudo dynamically generated ground motions after the perturbation of 1-point statistics for the $M_w$ 6.6 target event using source statistics models 2-1, 2-2, and 3. The y-axes of the left and right panels indicate the mean and standard deviation of the log-scale of the PGV ratios, respectively. The PGV ratios were computed with the waveforms obtained from the original and perturbed pseudo-dynamic source models in the selected forward and backward directivity zones as well as in the total area.
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