Seismic Response Validation of Simulated Soil Models to Vertical Array Record During A Strong Earthquake

Rena Misliniyati[1,2], Lindung Zalbuin Mase[2,*], Masyhur Irsyam[1], Hendriyawan[1] & Andhika Sahadewa[1]

[1]Department of Civil Engineering, Faculty of Civil and Environmental Engineering, Institut Teknologi Bandung, Jalan Ganesha No. 10, Bandung 40132, Indonesia
[2]Department of Civil Engineering, Faculty of Engineering, University of Bengkulu, Jalan W.R. Supratman, Bengkulu 38371A, Indonesia
*E-mail: lmase@unib.ac.id

Abstract. Several soil models, such as linear elastic, equivalent linear, and non-linear models, are employed in seismic ground response analysis. The aim of this study was to validate the seismic responses at ground surface of several soil models with the vertical array record of the Kobe earthquake. One-dimensional seismic response analyses were performed at Port Island using several soil models. The responses at ground surface from the simulated soil models were validated with the vertical array record of the Kobe earthquake. The results showed that the extended hyperbolic model yielded the most appropriate response according to the Kobe earthquake's recorded motion. This means that this model can be considered a suitable soil model to predict the response of strong earthquakes. In general, the results support the recommendation to select the most appropriate soil model for seismic ground response analysis.

Keywords: *Kobe earthquake; Port Island; soil models; seismic ground response analyses; vertical array record; strong earthquake.*

1 Introduction

In the past fifty years, many researchers have intensively investigated soil dynamics. The study of soil dynamics is important because earthquakes can result in structural building collapse, ground failure, liquefaction, and other catastrophic damage. The seismic ground response problem has been investigated by Hashash, *et al.* [1]. The basic framework for seismic ground response analysis is the propagation of seismic waves through horizontal soil layers [2]. There are two major methods to analyze the seismic ground response, i.e. the equivalent linear method [3] and non-linear methods [4]. The equivalent linear method uses the frequency domain in the seismic ground response analysis. In non-linear methods, time domain analysis is commonly used for the one-dimensional wave propagation problem [5].

Received August 11th, 2019, Revised October 2nd, 2019, Accepted for publication October 21st, 2019.
 ISSN: 2337-5779, DOI: 10.5614/j.eng.technol.sci.2019.51.6.3

Nowadays, sophisticated computer programs use the above methods for analysis. For instance, the SHAKE program by Schnabel, *et al.* [3] adopted the equivalent linear method while the NERA program by Bardet and Tobita [6], Cyclic 1D by Elgamal, *et al.* [7], FLIP by Iai, *et al.* [8], and DEEPSOILS by Hashash, *et al.* [5] used non-linear methods. These computer programs are helpful in seismic wave propagation analysis for engineering practice as well as for theoretical problems [2]. An engineer must fully understand how these programs work, especially regarding their reliability and the models they use. A deep understanding of these models and programs is necessary to know which one is appropriate for each case [9]. So far, most researches focused on the development of seismic ground response models related to the need to depict soil behavior during an earthquake using various models. Studies to choose the most appropriate seismic ground response model are still limited. Studies with the emphasis on the reliability of soil models in capturing the recorded ground motion have rarely been performed. This study aimed to determine the most suitable soil model for the seismic ground response problem. Several soil models were implemented using a one-dimensional ground response analysis. Furthermore, the responses at ground surface from the implemented soil models were validated with the recorded motion of the Kobe earthquake at Port Island in 1995 [10]. Thus, this study compared the ground motion parameters of simulated soil models with recorded conditions.

2 Theoretical Background

2.1 Soil Models of One-Dimensional Seismic Wave Propagation

Various researchers have proposed soil models of one-dimensional seismic wave propagation during the last fifty years, such as Schnabel, *et al.* [3], Hashash, *et al.* [5], Bardet and Tobita [6], Iai, *et al.* [8], Martin, *et al.* [11], and Elgamal, *et al.* [12]. The undamped linear elastic model is a first-generation soil model. This method of analysis is similar to linear elastic analysis. However, soil behavior is not linear due to cyclic loading, so the model needs to compute the complex soil behavior during cyclic loading [5].

The equivalent linear model is the most commonly used method for seismic response analysis [3]. This model was designed to predict the non-linear behavior of soil through an equivalent linear approach. The maximum shear modulus (G_{max}) of soil is estimated using the secant modulus (G_{sec}). However, this model is limited in seismic ground response analysis on soft soil. Finn, *et al.* [13] reported that the equivalent linear method overestimates the maximum acceleration while it can also underestimate amplification at high frequency [14]. Therefore, a non-linear method is expected to provide better results.

Iwan [15] and Mroz [16] introduced the piecewise element model to estimate the non-linear shear modulus in one-dimensional seismic ground response analysis. The backbone curve of the shear stress-shear strain is reconstructed from a piecewise-shaped modulus reduction curve. The relation between volume shear strain and cyclic shear strain is independent of confining pressure [11]. The NERA program uses this model [6].

Martin, *et al.* [11] proposed the post-liquefaction Finn model (PL Finn model) to simulate non-linear soil behavior. This model can also predict changes in volumetric strain and pore pressure. Itasca's fast Lagrangian analysis of continua (FLAC) uses the Finn model [17]. Iai, *et al.* [8] developed another non-linear model called the multi-spring element model to compute the non-linear cyclic behavior of soil. The model combines two major models, i.e. the multi-spring element model and the effective stress model, and can predict the hysteresis loop in cyclic behavior of anisotropic consolidated sand [18], whereas the effective stress models can estimate the excess pore pressure. The Finite Element Liquefaction Program (FLIP) uses this multi-spring element model.

Elgamal, *et al.* [12] introduced the non-linear effective stress model, which is used in the CYCLIC 1D program. The non-linearity is simulated by incremental plasticity that allows to compute permanent deformation and generate hysteretic damping. Mase, *et al.* [19] found that this model was reliable in estimating the dynamic behavior of liquefied soil in northern Thailand during the 2011 Tarlay earthquake. Hashash, *et al.* [5] introduced a simulation to analyze the one-dimensional seismic ground response and greatly extended the hyperbolic model from the original model proposed by Matasovic [20]. This model focuses on the hysteresis loop during cyclic loading and defines the backbone curve as a hyperbolic function. Hashash, *et al.* performed non-linear analysis by defining discrete time increments in the time domain on a lumped mass system [5].

2.2 Ground Motion Parameters

Ground motion parameters can describe the characteristics of ground motion. Bommer and Martinez-Pereira [21] have suggested that the estimation of ground motion characteristics is required to identify the destructive potential of the ground motion. Three main parameters can describe the ground motion, i.e. the amplitude parameters of the vertical array, the frequency content, and the duration of the earthquake [22].

Recently, Seismosoft [23] has suggested that ground motion parameters should be investigated to obtain specific ground motion characteristics. The ground motion parameters that Seismosoft suggested to observe are: maximum acceleration (PGA_{max}), maximum velocity (PGV_{max}), maximum acceleration (PGD_{max}), time values of PGA_{max}, PGV_{max}, PGD_{max}, the ratio of V_{max}/A_{max}, root mean square (RMS) values of acceleration, velocity, displacement, Arias intensity, characteristic intensity, specific energy density, intensity of spectrum responses, Housner intensity, effective duration, and energy flux. The National Research Institute for Earth Science and Disaster Resilience (NIED) offers a detailed overview of these parameters [24]. The ground motion parameters for the Kobe earthquake are presented in Table 1.

This study observed the vertical array record of the Kobe earthquake and compared the ground motion at the ground surface of the simulations with the recorded conditions. Figure 1 demonstrates that the maximum surface acceleration (PGA_{max}) recorded at Port Island was about 0.315 g, while PGV_{max} was about 74.921 cm/s and PGD_{max} was about 38.342 cm. Figure 2 presents the spectral responses. The peak spectral acceleration (SA_{max}) was about 1.059 g, which occurred during a period (T) of about 1.24 sec.

The peak spectral velocity (SV_{max}) and the peak spectral displacement (SD_{max}) were about 220.398 cm/s and 74.054 cm, respectively. Both peak values occurred with T at 1.86 sec and 7.12 sec, respectively. Based on the SA_{max} and its T value, Wen, *et al.* [25] and Hashash and Park [26] categorized the recorded ground motion of the Kobe earthquake as low-frequency motion.

Figure 3 presents the interpretation of Arias intensity (AI) and energy flux. Arias [27], proposed the AI parameter to represent the strength of the ground motion per second, which is shown by the relation between intensity in percentage and time. Energy flux represents the build-up of specific energy density, which was proposed by Bommer and Martínez-Pereira [21]. The significant duration of the Kobe earthquake was about 6.51 sec. This value is defined from the time difference between the time at 95% AI and the time at 5% AI. As for energy flux, the maximum accumulated energy of the ground motion was about 9600 cm2/sec.

Campbell [28] stated that peak ground acceleration (PGA) is the most widely used parameter in strong ground motion. Therefore, the results of the seismic ground response analysis should be validated by comparing it to the recorded data, especially the surface ground motion. This study compared the ground motion from the one-dimensional site response analysis and the recorded ground motion using PGA and SA.

Table 1 Ground motion parameters of Kobe earthquake ground motion.

Parameters	Record	Unit	Reference
PGA_{max}	0.315	(g)	[22]
Time of PGA_{max}	5.830	(sec)	[22]
PGV_{max}	74.921	(cm/sec)	[22]
Time of PGV_{max}	7.440	(sec)	[22]
PGD_{max}	38.342	(cm)	[22]
Time of PGD_{max}	6.700	(sec)	[22]
V_{max} / A_{max}	0.243	(sec)	[22]
Acceleration Root Mean Square (ARMS)	0.059	(g)	[22]
Velocity Root Mean Square (VRMS)	17.071	(cm/sec)	[22]
Displacement Root Mean Square (DRMS)	9.204	(cm)	[22]
Arias Intensity (AI)	1.765	(m/sec)	[27]
Characteristic Intensity (Ic)	0.082	(Ic)	[29]
Specific Energy Density (SED)	9611.106	(cm^2/sec)	[22]
Cumulative Absolute Velocity (CAV)	986.527	(cm/sec)	[30]
Acceleration Spectrum Intensity (ASI)	0.200	(g*sec)	[31]
Velocity Spectrum Intensity (VSI)	314.420	(cm)	[31]
Housner Intensity (HI)	335.200	cm	[22]
Sustained Maximum Acceleration (SMA)	0.251	(g)	[32]
Sustained Maximum Velocity (SMV)	56.418	(cm/sec)	[32]
Effective Design Acceleration (EDA)	0.315	(g)	[33]
A95 parameter	0.312	(g)	[34]
Predominant Period (T)	1.240	(sec)	[22]
Mean Period (Tm)	1.477	(sec)	[35]

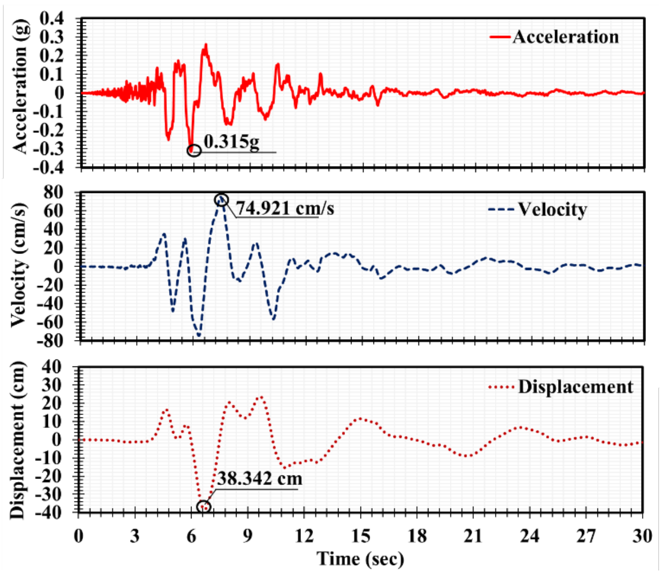

Figure 1 Vertical array of Kobe earthquake at Port Island [24].

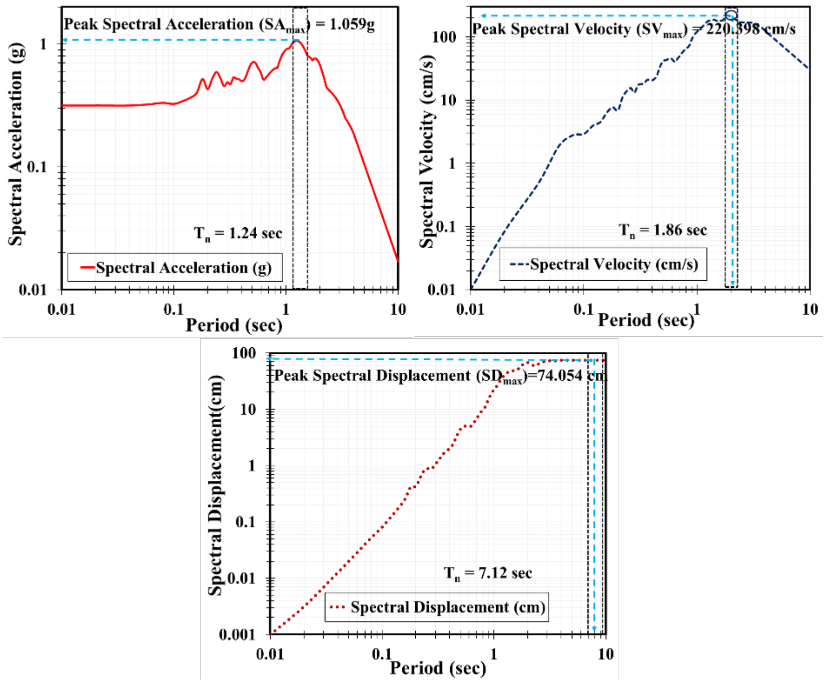

Figure 2 Spectral Responses of Kobe Earthquake recorded by NIED [24].

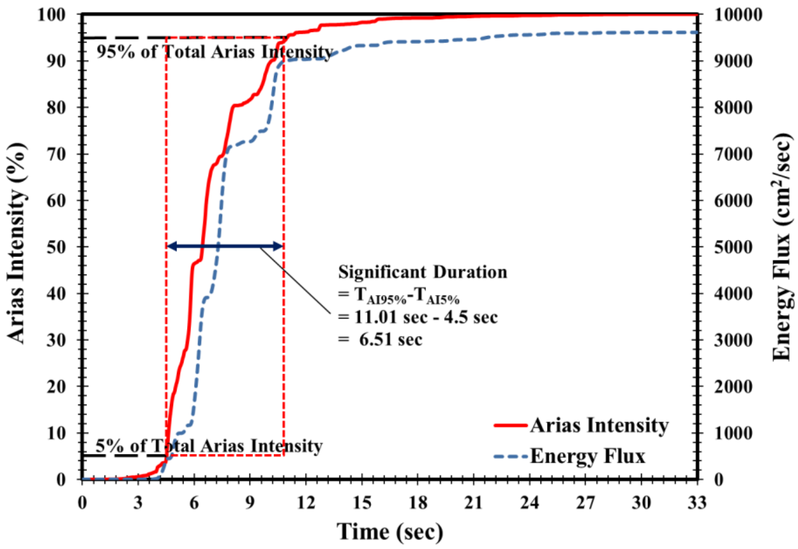

Figure 3 Arias intensity and energy flux from the Kobe earthquake motion record.

3 Research Methods

First, we define the problem of seismic ground response analysis. The soil profile of Port Island in Kobe, Japan was obtained from the study of Cubrinovski, *et al.* [36] (Figure 4(a)). Following Figure 4(a), a one-dimensional horizontal-layered soil model was generated. Four accelerometer sensors recorded the ground motion of the Kobe earthquake at Port Island seismic station in 1995 [36], which were located at depths of 0.0 m, 16 m, 32 m depth, and 83 m. This study used the recorded ground motion at 32 m depth from NIED [24] as the input motion. Then, the surface ground motion generated from the analysis was compared to the recorded ground motion of the Kobe earthquake [37].

The one-dimensional horizontal-layered soil model was adopted from several studies performed by Mase, *et al.* [38], as presented in Figure 4b. In this figure, the wavelength is used to estimate the element thickness (*h*). This is because the thickness (*h*) controls the maximum frequency (f_{max}) propagated through the layer, as stated by Hashash, *et al.* [5]. Therefore, a greater layer thickness means that a lower frequency propagates through the layer [5]. The element thickness is expressed in the following equation:

$$h = \frac{V_s}{4 f_{\max}} \tag{1}$$

In Eq. (1), *h* is dependent on shear wave velocity (V_s) and maximum frequency (f_{max}). Hashash, *et al.* [5] suggested that for engineering practice an f_{max} of 25 Hz can be used in seismic ground response analysis. Several studies have implemented this wavelength analysis, for example Mase, *et al.* [19]. Using Eq. (1), the element thickness was determined at 1.7 m for all simulations.

In Figure 4(b), the model was only drawn up to 32 m depth, since no information for ground motion was collected at 83 m depth. The input motion was performed at the bottom of the soil profile, i.e. at 32 m. Since the recorded ground motion was applied, it could be assumed that at that depth the ground motion began to propagate through the layer. In other words, the bottom of the soil profile could be assumed as a rigid half-space.

The soil column was assumed as a fixed boundary where vertical deformations are allowable and horizontal displacement on both sides is equal. Furthermore, a one-dimensional seismic ground response analysis was performed to observe the soil behavior during the Kobe earthquake. One-dimensional seismic ground response analysis can employ several models, such as the linear elastic model [5], the equivalent linear model [3], the non-linear extended model [5], the non-linear effective stress model [12], the multi-spring element model [8], the Iwan-Mroz model [6], and the post-liquefaction model [11,39,40].

This study compared the ground motion parameters at ground surface obtained from the analysis to the recorded ground motion of the Kobe earthquake. This paper also presents a misfit analysis for both values.

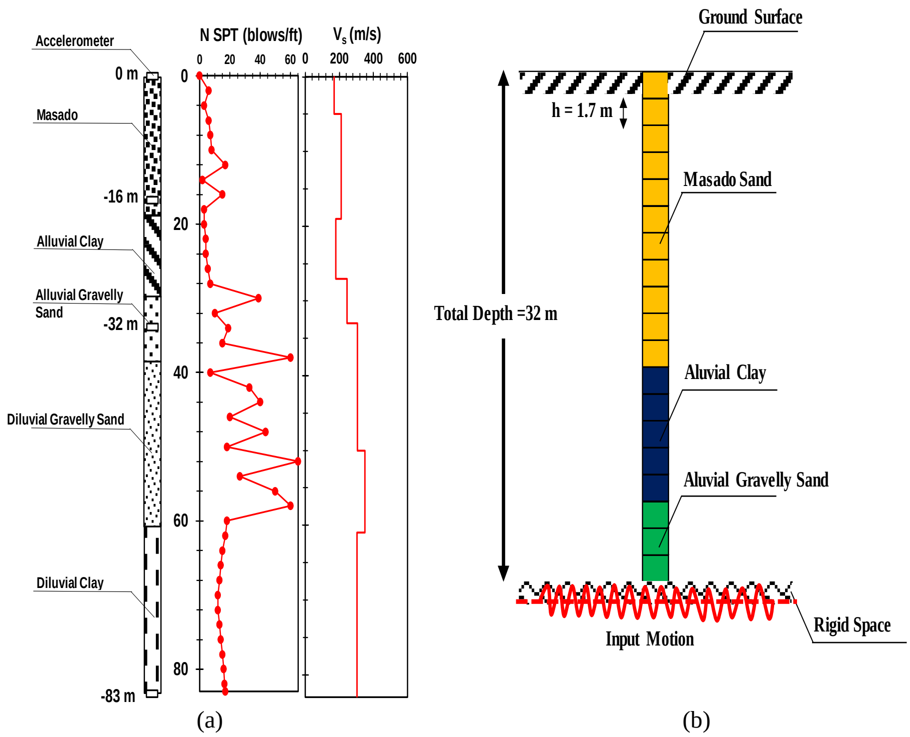

Figure 4 One-dimensional analysis model: (a) soil profile of Port Island, Kobe (redrawn from Cubrinovski *et al.* [36]), (b) soil column model.

4 Results and Discussion

4.1 Time History and Frequency Content

As elaborated in the previous section, peak ground acceleration is an important parameter to observe ground motion characteristics. Therefore, this study compared the PGA obtained from the seismic ground response analysis with that from the recorded ground motion. Figure 5 presents a comparison of ground motion at the ground surface with that resulted from the one-dimensional seismic ground response analysis. All results showed the same tendency as the recorded ground motion. In general, the non-linear models offered better predictions than the linear model and the equivalent linear model. Among the five non-linear models, the extended hyperbolic model provided the best prediction. This is not only shown by the waveform generated from the extended hyperbolic model but also by the values of PGA_{max} and Time of PGA_{max}, which had the minimum misfit among all models (presented in Appendix 1).

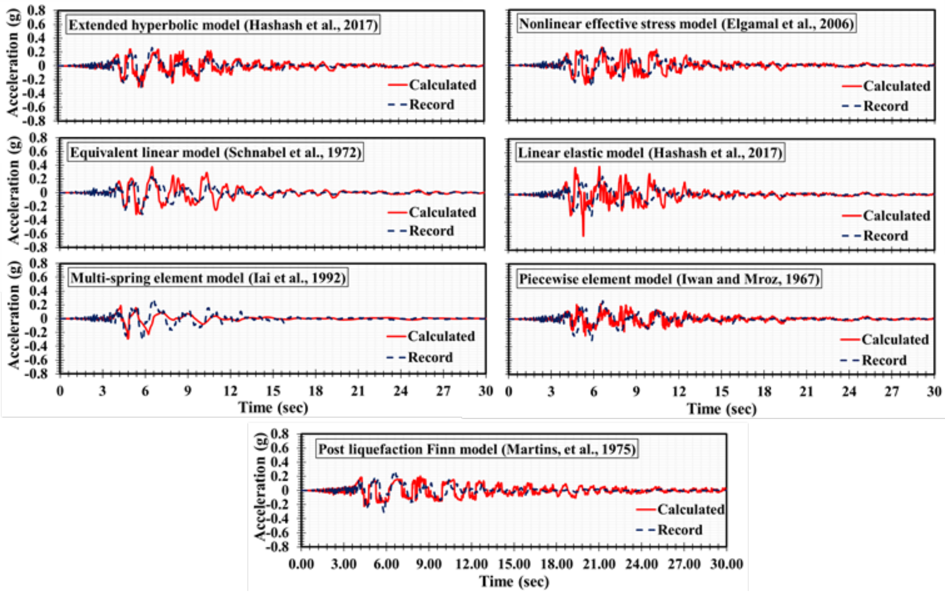

Figure 5 Surface acceleration comparison.

The performance of the other models showed various inaccuracies. Notably, the linear elastic and the equivalent linear model overestimated ground motion. In general, the results were consistent with Mase, *et al.* [2], who reported that the equivalent linear model can overestimate PGA. In addition, the performance of the linear elastic model showed a high overestimation compared to the equivalent linear model. The model overestimated the shear stress that occurs once the shear strain is perfectly plastic [13]. The shear strength of the weakest layer controls the maximum acceleration, which indicates an overestimation of the peak ground acceleration above the layer [41,42]. In conclusion, the seismic ground response analysis showed that the extended hyperbolic model proposed by Hashash, *et al.* [5] is the most appropriate model.

Figure 6 shows a comparison of the spectral accelerations from the one-dimensional seismic ground response analysis and the recorded spectral acceleration. The spectral accelerations resulted from the one-dimensional seismic ground response analysis were similar to the recorded condition.

Meanwhile, the spectral acceleration from the non-linear model generally started at PGA values of about 0.3 g, which is relatively close to the recorded data. For the equivalent linear model and the linear elastic model, the spectral acceleration started at higher values than the recorded conditions. These findings indicate that the linear model and the equivalent linear model tend to be more conservative than the non-linear models. The linear elastic model yielded the most conservative result, as the spectral acceleration was very high compared to the recorded data. This is because the linear elastic model overestimates the peak ground acceleration due to the assumption of linearity, especially for the estimation of shear strain. It yields overestimation of propagated waves occurring in the weakest layer. Mase, *et al.* [38] and Yoshida [41] mention that the weakest layer can control the maximum acceleration at the ground surface. As there is an overestimation of maximum acceleration, the spectral acceleration is also overestimated [38,41].

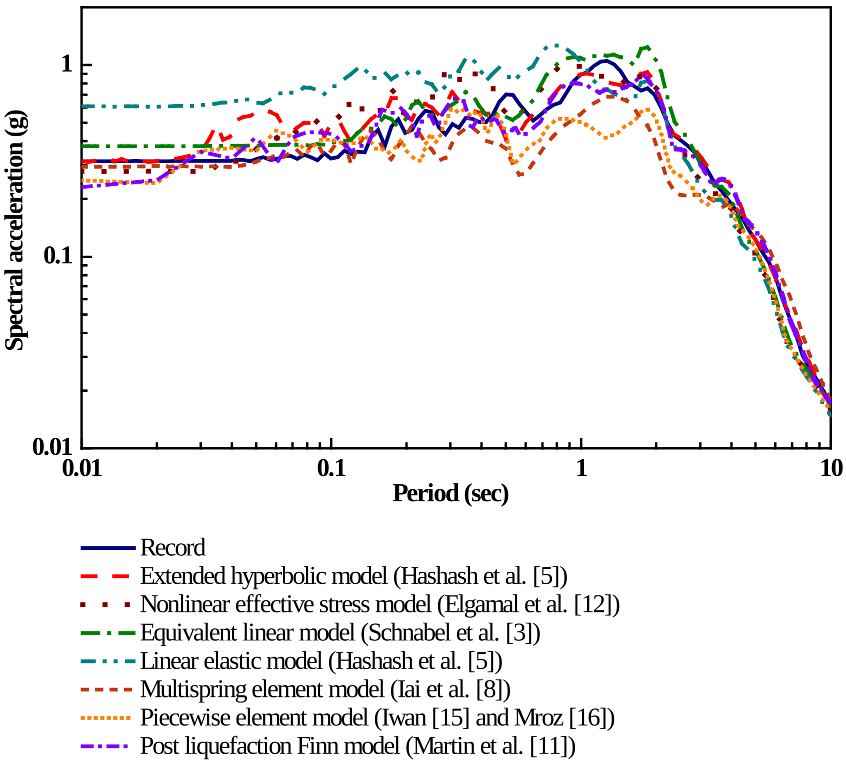

Figure 6 Surface spectral acceleration comparison.

4.2 Energy Flux and Significant Duration

Figure 7 presents the interpretation of the energy flux from the simulations and the recorded ground motion. The equivalent linear model resulted in a maximum energy flux of about 15000 cm^2/sec, while the piecewise element model by Iwan [15] and Mroz [16] generated the lowest energy flux, i.e. about 5500 cm^2/sec. The recorded energy flux of the Kobe earthquake ground motion was about 9500 cm^2/sec. Several non-linear models, such as the extended hyperbolic model by Hashash, *et al.* [5], the PL Finn model by Martin, *et al.* [11], and the non-linear effective stress model by Elgamal, *et al.* [12], generated a more accurate energy flux prediction. The predictions of the linear elastic model by Hashash, *et al.* [5] and the multi-spring element model by Iai, *et al.* [8] were lower than the recorded ground motion. In general, energy flux has a correlation with the specific energy density (SED). This is due to the fact that both the extended hyperbolic and the non-linear effective stress model yielded the closest prediction of recorded ground motion, as shown in Figure 5. A suitable prediction of acceleration means a suitable prediction of velocity. Velocity of ground motion itself is used to calculate specific energy density (SED), which is used to estimate energy flux [22 and 23].

Figure 8 presents the interpretation of the Arias intensity and the significant duration. All models reached 100% Arias intensity after 30 seconds of wave propagation. The significant duration was estimated based on the time difference between the time at 95% of total Arias intensity and the time at 5% Arias intensity. The multi-spring element model [8] predicted a lower significant duration, i.e. about 6.19 seconds. Meanwhile, the equivalent linear [3], the linear elastic [5], and the non-linear effective stress [12] model predicted a significant duration of about 8.263 sec. Moreover, the PL Finn [11], the piecewise element [15,16] and the extended hyperbolic [5] model predicted a significant duration of about 11.77 sec. Overall, the multi-spring element [8] model produced the best prediction for significant duration. Arias intensity [27] has a correlation with significant duration. Significant duration [23] is the interval of time over which a proportion (percentage) of the total Arias intensity is accumulated. Therefore, when the 5% and 95% Arias intensity from the models are consistent with the records, the significant duration is consistent with them as well.

4.3 Comparison of Ground Motion Parameters

The ground motion parameters are summarized in Appendix 1. Analysis of the ground motion parameters showed that the predictions of some models were inaccurate. For instance, the predictions of the linear elastic model by Hashash, *et al.* [5], which is due to the fact that the model is not reliable in observing non-linear soil behavior, especially the behavior of saturated sandy soils during liquefaction. Moreover, the equivalent linear model by Schnabel, *et al.* [5] and the piecewise element model by Iwan [15] and Mroz [16] resulted in a misfit for most ground motion parameters. Nevertheless, these models predicted four parameters best. The piecewise element model had the best model performance as indicated by the smallest misfit of the acceleration root mean square (ARMS) and cumulative absolute velocity (CAV). Meanwhile, the equivalent linear model by Schnabel, *et al.* [3] had the best prediction of the ratio of PGV_{max}/PGA_{max} (V_{max}/A_{max}) and mean period (T_m). Thus, this model is quite appropriate for predicting the maximum value of ground motion peaks, even though it overestimates acceleration.

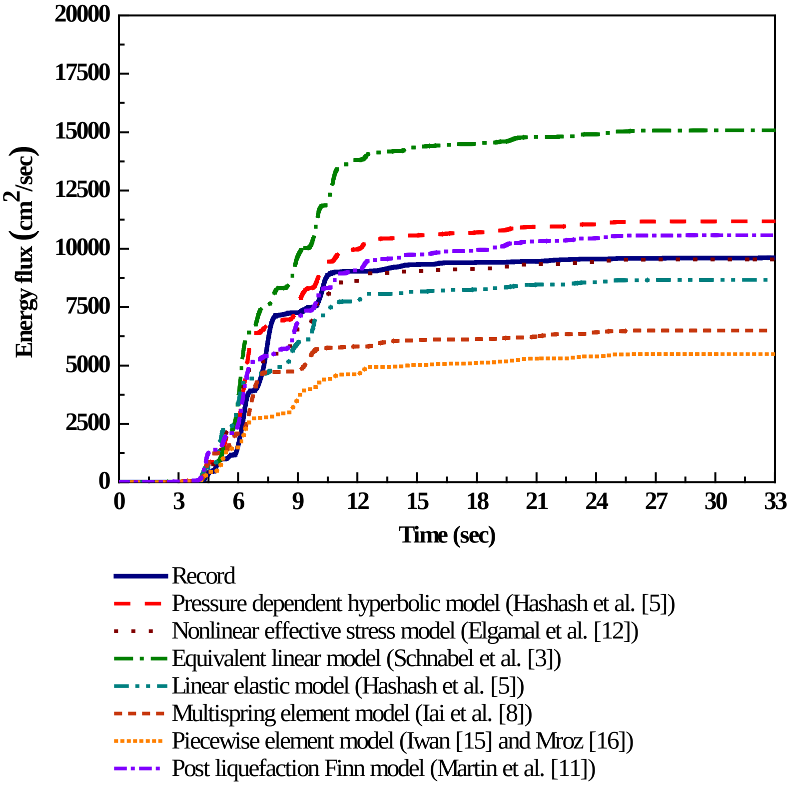

Figure 7 Energy flux corresponding to wave propagation time.

The best prediction of maximum velocity (PGV_{max}) was from the non-linear effective stress model by Elgamal, *et al.* [12]. Jafarian, *et al.* [43] mention that ground motion velocity plays an important role in determining the excess pore pressure during an earthquake. In addition, Mase [44] recommends the ground motion velocity parameters to estimate the kinematic energy density for excess pore pressure build-up in liquefaction problems. Therefore, this model is highly reliable in estimating PGV_{max}. Consequently, the velocity room mean square (VRMS) and specific energy density (SED) parameters were also estimated well.

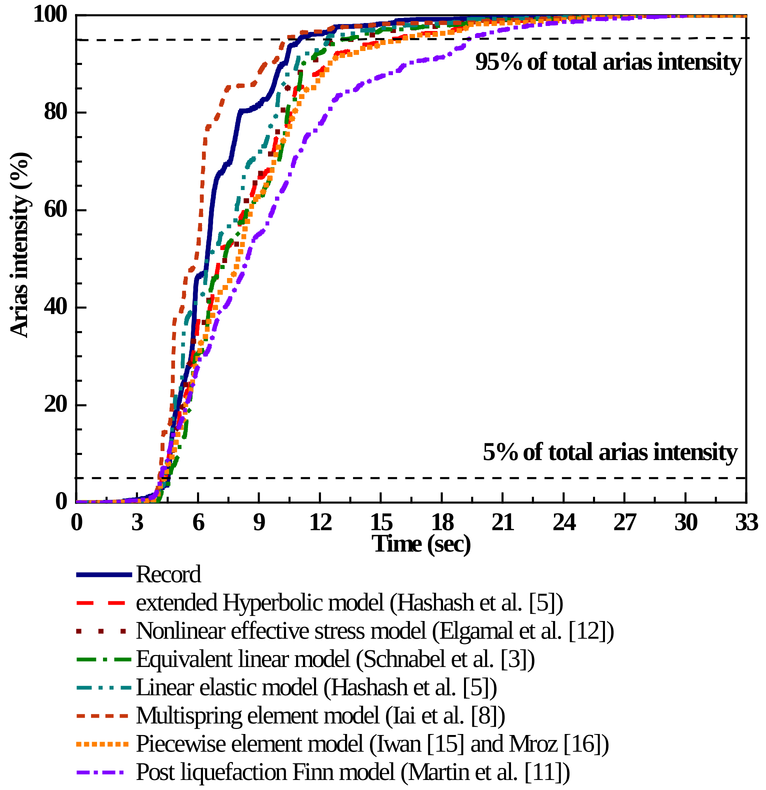

Figure 8 Arias intensity and significant duration of the simulated models.

The multi-spring element model by Iai, *et al.* [8] produced the best predictions of time of PGV_{max}, time of PGD_{max} and predominant period (T). This indicates that the multi-spring element model is quite good in predicting the time of the maximum peak of ground motion but is less effective in predicting the maximum values of ground motion. The multi-spring element model accurately predicted the spectral acceleration of ground motion and predominant period (*T*). The PL Finn model by Martin, *et al.* [11] resulted in misfit parameters of PGD_{max}, displacement root mean square (DRMS), acceleration spectrum intensity (AIS), velocity spectrum intensity (VSI), and sustained maximum velocity (SMV).

The extended hyperbolic model proposed by Hashash, *et al.* [5] predicted several parameters best, among others PGA_{max}, time of PGA_{max}, AI, Ic, VSI, SMA, EDA, and A95. This indicates that this model is relatively consistent in predicting the parameters of ground motion. As stated by Hashash, *et al.* [5], the model emphasizes the hysteresis loop during cyclic loading, which plays an important role in determining soil behavior during an earthquake. The hyperbolic function is meant to capture a more appropriate hysteresis loop to approach the real soil conditions during cyclic loading. Therefore, the model yielded the best prediction for most ground motion parameters among all models. Overall, the extended hyperbolic model is the most appropriate model for predicting the vertical array of strong motion during an earthquake based on its performance in this study.

5 Conclusion

The linear elastic and equivalent linear models are generally used in one-dimensional seismic ground response analysis. The predictions of these models overestimate the ground motion parameters of the vertical array for strong earthquakes. During a strong earthquake with large acceleration, normally, a non-linear response exists. Under this condition, linear elastic and equivalent linear models are not suitable to depict non-linear behavior. The overestimation of ground motion parameters from linear elastic and equivalent linear models would lead to overestimation of peak ground acceleration and spectral acceleration. Thus, these models cannot accurately capture non-linear soil response during an earthquake. In general, non-linear models are relatively reliable in predicting the ground motion parameters of strong motion. The accuracy of the predictions highly depends on the purpose of the model. For example, the non-linear effective stress model was designed to capture excess pore pressure, which makes it more accurate in predicting the soil behavior during cyclic loading.

It is essential to understand the purpose of one-dimensional analysis and the observed parameters before performing an analysis. The performance of models in estimating the Kobe earthquake ground motion was quantified, as summarized in Appendix 1. The misfit values summarized in Appendix 1 can be a consideration in determining the most suitable model. Generally, sophisticated approaches for capturing the shear modulus and damping ratio are very important in non-linear models since those parameters are likely to significantly influence the ground motion parameters during an earthquake. Correctly predicting the soil response depends on using the appropriate model. Therefore, selecting the right attenuation model should be carefully done, especially related to the ground motion parameters. For frequency content prediction, the multi-spring element model, the PL Finn model, and the extended hyperbolic model are reasonably accurate in predicting the ground motion parameters. Meanwhile, the extended hyperbolic model, the non-linear effective stress model, and the multi-spring element model can reasonably accurately predict energy flux and significant duration. Overall, the extended hyperbolic model and the PL Finn model are the most appropriate models to predict the ground motion parameters. This study further recommends engineers to use the equivalent linear and non-linear models in one-dimensional seismic ground response analysis to obtain a better description of ground motion parameters.

Acknowledgements

This research was supported by research grant no. 2357/UN30.15/LT/2018 and 2183/UN30.15/LT/2019 from the University of Bengkulu, Indonesia. The authors would like to thank the National Research Institute for Earth Science and Disaster Resilience (NIED), Japan for the vertical array of the 1995 Kobe earthquake. The first author would also like to thank the Directorate of Indonesian Higher Education of Ministry of Education (DIKTI) for his doctoral scholarship.

References

[1] Hashash, Y.M.A., Phillips, C. & Groholski, D.R., *Recent Advances in Non-linear Site Response Analysis,* Proceeding of the 5th International Conference in Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, San Diego, California, May 24-29, USA, 2010.

[2] Mase, L.Z., Likitlersuang, S., Tobita, T., Chaiprakaikeow, S. & Soralump, S., *Local Site Investigation of Liquefied Soils Caused by Earthquake in Northern Thailand*, Journal of Earthquake Engineering, pp. 1-24, 2018. DOI: 10.1080/13632469.2018.1469441.

[3] Schnabel, P.B., Lysmer, J. & Seed, H.B., *SHAKE: A Computer Program for Earthquake Response Analysis of Horizontally Layered Sites*, Rep. No. EERC 72-12, College of Engineering, University of Berkeley, California, 1972.

[4] Finn, W.D.L., Lee K.W. & Martin G.R., *An Effective Stress Model for Liquefaction,* Journal of Geotechnical Engineering Division ASCE, **103**(1), pp. 517-531, 1977.

[5] Hashash, Y.M.A., Musgrove, M.I., Harmon, J.A., Groholski, D.R., Phillips, C.A. & Park, D., *DEEPSOIL 7.1, User Manual*, University of Illinois at Urbana-Campaign, 2017.

[6] Bardet, J. P., & Tobita, T., *NERA: A Computer Program for Non-linear Earthquake Site Response Analyses of Layered Soil Deposits,* University of Southern California, United States, 2001.

[7] Elgamal, A., Yang, Z. & Lu, J., *Cyclic1D: Seismic Ground Response User Manuals for Version 1.4,* Department of Structural Engineering, University of California, United States, 2015.

[8] Iai, S., Matsunaga, Y. & Kameoka, T., *Strain Space Plasticity Model for Cyclic Mobility, Soils and Foundations,* **32**(2), pp. 1-15, 1992.

[9] Mase, L.Z., Likitlersuang, S. & Tobita, T., *Non-linear Site Response Analysis of Soil Sites in Northern Thailand during the Mw 6.8 Tarlay Earthquake*, Engineering Journal, **22**(3), pp. 291-303, 2018.

[10] Mase, L.Z., *Reliability Study of Spectral Acceleration Designs Against Earthquakes in Bengkulu City, Indonesia*, International Journal of Technology, **9**(5), pp. 910-924, 2018.

[11] Martin, G.R., Finn L.W.D. & Seed H.B., *Fundamentals of Liquefaction under Cyclic Loading,* Journal of Geotechnical Engineering, ASCE, **101**(GT5), pp. 423-428, 1975.

[12] Elgamal, A., Yang, Z. & Lu, J., *Cyclic1D: A Computer Program for Seismic Ground Response*, Report No. SSRP-06/05, University of California, San Diego, 2006.

[13] Finn, W.D.L., Martin, G.R., & Lee, M.K.W., *Comparison of Dynamic Analyses for Saturated Sands,* Earthquake Engineering and Soil Dynamics, ASCE, GT Special Conference, **1**(1), pp. 472-491, 1978.

[14] Masuda, T., *Study on Damage to Electric Facilities due to Earthquake and Remedial Measures Against It,* Doctoral Thesis, University of Tokyo, Tokyo, Japan, 2001.

[15] Iwan, W.D., *On a Class of Models for the Yielding Behaviour of Continuous and Composite Systems,* Journal of Applied Mechanics, ASME, **34**(1), pp. 612-617, 1967.

[16] Mróz, Z., *On the Description of Anisotropic Work Hardening,* Journal of Mechanics and Physics of Solids, **15**(1), pp.163-175, 1967.

[17] Itaca Consulting Group, *Fast Langrangian Analysis of Continua-User Manual*, Minnesota, USA, 2018.

[18] Mase, L.Z., *Liquefaction Potential Analysis along Coastal Area of Bengkulu Province due to the 2007 Mw 8.6 Bengkulu Earthquake,* Journal of Engineering and Technological Sciences, **4**(6), pp. 721-736, 2017.

[19] Mase, L.Z., Tobita, T. & Likitlersuang, S., *One-dimensional Analysis of Liquefaction Potential: A Case Study in Chiang Rai Province, Northern Thailand,* Journal of Japanese Society of Civil Engineers, Ser A1 (Structural Engineering/Earthquake Engineering), **73**(4), pp. I_135-I_147, 2017.

[20] Matasovic, N., *Seismic Response of Composite Horizontally-Layered Soil Deposits,* Ph.D. Thesis, University of California, Los Angeles, 1993.

[21] Bommer, J.J. & Martínez-Pereira, A., *Strong Motion Parameters: Definition, Usefulness and Predictability,* Proceedings of the 12th World

Conference on Earthquake Engineering, Auckland, 30 January-4 February, New Zealand, 2000.
[22] Kramer, S.L., *Geotechnical Earthquake Engineering*, ed. 1, Prentice Hall, 1996.
[23] Seismosoft, *SeismoSignal Program*, Seismosoft, http://www.seismosoft.com, (April 2018).
[24] National Research Institute for Earth Science and Disaster Resilience (NIED), *The Kobe Earthquake Vertical Array Data, National Research Institute for Earth Science and Disaster Resilience*, http://www.bosai.go.jp/e/, (April 2018).
[25] Wen, K.L., Chang, C.W. & Lin, C.M., *Identification of Non-linear Site Response from Time Variations of the Predominant Frequency*, Proceeding of the 14^{th} World Conference on Earthquake Engineering, Beijing, October 12-17, China, 2008.
[26] Hashash, Y.M.A. & Park, D., *Non-linear One-Dimensional Seismic Ground Motion Propagation in the Mississippi Embayment*, Engineering Geology, **62**(1), pp. 185-206, 2001.
[27] Arias, A., *A Measure of Earthquake Intensity*, in Seismic Design for Nuclear Power Plants, R.J. Hansen R.J. (ed.), pp. 438-483, Massachusetts Institute of Technology Press, 1970.
[28] Campbell, K.W., *Strong Motion Attenuation Relations: A Ten-year Perspective*, Earthquake Spectra, **1**(4), pp. 759-804, 1985.
[29] Park, Y.J., Ang, A.H.S. & Wen, Y.K., *Seismic Damage Analysis of Reinforced Concrete Buildings*, Journal of Structural Engineering, **111**(4), pp. 740-757, 1985.
[30] Cabañas, L., Benito, B. & Herráiz, M., *An Approach to the Measurement of the Potential Structural Damage of Earthquake Ground Motions*, Earthquake Engineering and Structural Dynamics, **26**(1), pp.79-92, 1997.
[31] Von Thun, J.L., Rochim, L.H., Scott, G.A. & Wilson, J.A., *Earthquake Ground Motions for Design and Analysis of Dams*, Earthquake Engineering and Soil Dynamics II - Recent Advances in Ground-Motion Evaluation, Geotechnical Special Publication, **20**(1), pp. 463-481, 1988.
[32] Nuttli, O.W., *The Relation of Sustained Maximum Ground Acceleration and Velocity to Earthquake Intensity and Magnitude*, Miscellaneous Paper S-71-1, Report 16, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi, USA, 1979.
[33] Benjamin, J.R. & Associates, *A Criterion for Determining Exceedance of the Operating Basis Earthquake*, EPRI Report NP-5930, Electric Power Research Institute, Palo Alto, California, USA, 1988.
[34] Sarma, S.K. & Yang K.S., *An Evaluation of Strong Motion Records and a New Parameter A95*, Earthquake Engineering and Structural Dynamics, **15**(1), pp. 119-132, 1987.

[35] Rathje, E.M., Abrahamson, N.A., & Bray, J.D., *Simplified Frequency Content Estimates of Earthquake Ground Motions,* Journal of Geotechnical and Geoenvironmental Engineering, **124**(2), pp. 150-159, 1998.

[36] Cubrinovski, M., Ishihara, K., & Tanizawa, F., *Numerical Simulation of the Kobe Port Island Liquefaction,* Proceeding of the 11th World Conference on Earthquake Engineering, Acapulco, 23-28 June, Mexico, 1996.

[37] Haddadi, H., Shakal, A., Stephens, C., Savage, W., Huang, M., Leith, W. & Parrish, J., *Centre for Engineering Strong-Motion Data (CESMD),* Proceedings of the 14th World Conference on Earthquake Engineering, Beijing, October 12-17, China, 2008.

[38] Mase, L.Z., Likitlersuang, S. & Tobita, T., *Analysis of Seismic Ground Response Caused during Strong Earthquake in Northern Thailand,* Soil Dynamics and Earthquake Engineering, **114**(1), pp. 113-126, 2018.

[39] Finn, W.D.L., Emery, J.J. & Gupta Y.P., *Liquefaction of Large Samples of Saturated Sand on a Shaking Table,* Proceedings of the lst Canadian Conf. on Earthquake Engineering, Vancouver, British Columbia, May 25-26, Canada, 1971.

[40] Byrne, P.M., *A Cyclic Shear Volume Coupling and Pore Pressure Model for Sand,* Proceeding of the 2nd International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, St. Louis, Missouri, March 11-15, USA, 1991.

[41] Yoshida, N., *Seismic Ground Response Analysis*, Springer Netherlands 2015.

[42] Misliniyati, R., Sahadewa, A. & Hendriyawan, Irsyam, M., *Parametric Study of One-dimensional Seismic Site Response Analyses Based on Local Soil Condition of Jakarta*, Journal of Engineering and Technological Sciences, **51**(3), pp. 392-410, 2019.

[43] Jafarian, Y., Vakili, R, Sadeghi, A.R, Sharafi, H. & Baziar, M.H., *A New Simplified Criterion for the Assessment of Field Liquefaction Potential Based on Dissipated Energy,* Proceedings of the 14th World Conference on Earthquake Engineering, Beijing, October 12-17, China, 2008.

[44] Mase, L.Z., *Excess Pore Water Pressure and Liquefaction Potential due to Seismic Propagation and Simplified Energy Concept,* Proceeding of the 2nd South East Asian Geoscience Student Conference, Yogyakarta, 22-27 August, Indonesia, 2016.

Appendix 1. Misfit of ground motion parameters for all simulated soil models in percentage.

Parameters	Misfit of Ground Motion Parameters for all simulated models (%)						
	Linear Elastic by Hashash, *et al.* in [5]	**Equivalent Linear Model Schnabel, *et al.* in [3]**	**Extended hyperbolic by Hashash, *et al.* in [5]**	**Non-linear effective stress model by Elgamal, *et al.* in [12]**	**Multi-spring Element by Iai, *et al.* in [8]**	**Piecewise Element Model by Iwan in [15] and Mróz in [16]**	**Post-liquefaction Finn Model by Martin, *et al.* in [11]**
PGA_{max}	90.496	19.541	**3.605**	11.765	6.778	23.105	5.343
Time of PGA_{max}	9.605	11.835	**2.573**	7.547	18.010	7.376	24.528
PGV_{max}	6.929	25.926	6.085	**0.391**	14.089	29.256	3.825
Time of PGV_{max}	31.452	17.742	14.651	18.817	**11.694**	15.995	18.548
PGD_{max}	18.424	4.569	**1.038**	5.753	9.599	14.146	728.947
Time of PGD_{max}	19.254	16.269	14.627	17.015	**8.955**	13.881	347.463
V_{max} / A_{max}	51.144	**5.342**	10.050	12.890	7.840	8.001	9.687
Acceleration Root Mean Square (ARMS)	37.774	46.123	19.650	23.027	29.493	**15.798**	35.364
Velocity Root Mean Square (VRMS)	0.710	30.937	12.736	**0.332**	14.005	20.945	44.704
Displacement Root Mean Square (DRMS)	20.598	5.524	**5.016**	16.783	26.491	8.192	1667.809
Arias Intensity (AI)	73.628	95.333	**30.978**	51.349	54.510	35.142	66.555
Characteristic Intensity (Ic)	54.668	68.947	**25.198**	36.458	43.360	26.099	50.152
Specific Energy Density (SED)	9.814	56.838	16.265	**0.663**	32.349	42.827	90.344
Cumulative Absolute Velocity (CAV)	33.142	52.896	32.082	36.131	37.468	**4.567**	57.677
Acceleration Spectrum Intensity (ASI)	80.243	13.310	13.589	47.780	20.032	**7.267**	10.003
Velocity Spectrum Intensity (VSI)	8.942	40.157	**4.460**	10.140	36.316	33.984	16.615
Housner Intensity (HI)	2.989	32.881	**0.878**	4.354	36.615	36.635	8.961
Sustained Maximum Acceleration (SMA)	55.645	22.990	**1.351**	3.599	24.561	18.133	8.389
Sustained Maximum Velocity (SMV)	**8.076**	19.603	11.395	10.494	23.777	25.080	9.571
Effective Design Acceleration (EDA)	89.457	19.139	**3.256**	12.376	5.869	33.686	7.727
A95 parameter	90.498	18.323	**5.582**	13.119	6.779	25.082	9.269
Predominant Period (T)	37.097	45.161	45.161	27.419	**6.452**	72.581	40.323
Mean Period (Tm)	29.638	**1.421**	4.610	17.555	4.783	14.297	13.000