Teknisia
Vol. 29, No. 2, November 2024, pp.080-093
E-ISSN: 2746-0185

Prediction of ground motion due to the influence of nonlinear soil conditions using a probabilistic approach

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Article Info
***Article history*:**
Received:
September 6, 2024
Revised:
May 15, 2025
Accepted:
May 15, 2025
Available online:
June 12, 2025

***Keywords*:**
Earthquake
Ground motion
Probabilistic
Spectral matching
Site spesific analysis

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Abstract
Ground acceleration data plays a vital role in obtaining accurate dynamic analysis results. This data is difficult to find in Indonesia. There is a need for a comprehensive study on ground motion prediction that considers soil conditions, which can alter acceleration and significantly impact building damage. The latest earthquake events and soil test data need to be collected. Probabilistic analysis was performed to obtain the target spectra. The deaggregation analysis is used as a reference for collecting earthquake recording data. The spectral matching process is carried out according to the target spectra. Earthquake records with minor errors to the target spectra are selected. Only ground motion with the most minor deviations of acceleration, velocity, displacement, directivity, and Arias intensity from the original earthquake recording is used in non-linear site response analysis. Surface ground motion is obtained from the analysis of wave propagation from the bedrock to the surface by considering the influence of nonlinear parameters of the soil. The spectral response analysis at bedrock shows the acceleration value at seconds is 1.326g and at 1 1-second period is 0.447g. Each year, the hazard is dominated by earthquakes with magnitudes from 6.97 to 7.23 Mw, which occur in the 89 to 111 km range, with a 22.20% percentage. Darfield, New Zealand, ground motion from spectral matching results is the best ground motion recording and is most suitable when used in a research area. Surface ground motion tends to amplify by about 1.2 times.

Introduction

The Yogyakarta region has high seismic activity due to its location in the ring of fire, situated between the convergence of the Eurasian and Australian tectonic plates, and its proximity to active faults. On May 27, 2006, a 6.3-magnitude earthquake struck Yogyakarta and its surrounding areas. The disaster claimed 5,048 lives, injured 27,808 people, destroyed 240,396 homes, and caused losses exceeding 29 trillion rupiahs. (USGS, 2024).

Disaster-aware spatial planning and infrastructure development must be implemented to minimize future losses of life and property. The use of both linear and nonlinear dynamic methods in the planning and assessment of building structures, combined with accurate earthquake load calculations, can prevent building damage effectively (Suhendro, 2022).

Ground acceleration data plays a crucial role in obtaining accurate dynamic analysis results. The selection of ground acceleration must be aligned with geological and seismological conditions and target parameters such as acceleration, frequency content, and duration (Irsyam, 2010). Indonesia's earthquake-resistant building design regulations (BSN, 2019) have already recommended time history analysis as part of the calculation procedure, both in linear and nonlinear analysis, to ensure that building structures' strength, stiffness, and ductility can withstand maximum earthquake shocks. In the current 4.0 era, large-scale earthquake records from global seismic events are more easily accessible. However, the subsequent procedure for selecting appropriate ground motions remains a challenging issue that needs to be addressed (Lanzo, 2015).

Indonesia is a country that lacks comprehensive seismic data for nearly all of its regions (PusGEN, 2017). As the solution, ground motion can be developed using artificial time histories based on conditions of geology, seismology, and criteria from probabilistic analysis (Irsyam, 2010). This method involves creating ground motion by modifying earthquake records from other regions so that their acceleration values closely match the target response spectrum through a process of deaggregation and spectral matching. This approach generates ground motion that aligns with the probabilistic analysis results of a specific area while preserving similarities in geological and seismological conditions.

Several studies have previously addressed the development of ground motion, including works by (Sunardi, 2015), (Misriani, M. dkk, 2016), (Makrup, L. dan Jamal, A.U., 2016), (Saputro, 2019), (Prawirodikromo, W. dkk, 2019) and (Abduljaleel, Z.A. dan Taha, B.O., 2020). However, these studies have not explicitly considered the impact of soil conditions on the propagation of seismic waves, known as site specific analysis, and thus have not clearly and thoroughly explained how the process of seismic wave propagation from bedrock to the ground surface can affect the characteristics of ground motion, including frequency, amplitude, and duration. Soil conditions have a complex influence on the characteristics and frequency content of earthquake records (Irsyam, 2010). In large magnitude earthquakes, local soil conditions can alter the acceleration of ground motion, which can significantly affect the state of structures above (Munirwansyah, dkk., 2020).

Moreover, the availability of reliable seismic data for analyzing local soil conditions and building behavior is one of the most significant and most complex challenges in earthquake engineering (Prawirodikromo, W. dkk, 2019). The use of spectral matching methods should involve selecting the most suitable earthquake records from among many similar candidates (Fahjan, Y. Dan Odemir, Z., 2008). It is necessary to choose earthquake records with minimal relative error to the target spectrum, and only the best and most appropriate records should be used for analysis. A well-performed spectral matching should result from a ground motion time history that does not have significant deviations in parameters (acceleration, velocity, displacement, directivity, or Arias intensity) compared to the original earthquake records (Franke, K., 2017).

Based on the description, there are discrepancies and research gaps from previous studies that this study aims to address and improve. Specifically, the objectives of this research are to determine the 2% probability exceedance response spectrum over 50 years, identify the most dominant earthquake events in terms of magnitude and distance through deaggregation analysis, predict bedrock ground motion, assess the influence of various soil conditions on seismic wave propagation, and predict surface ground motion time histories under different local soil conditions

Research Methodology

The research was conducted in Yogyakarta, Special Region of Yogyakarta, with coordinates at Latitude: -7.796 and Longitude: 110.370.

Figure 1. Map of the special region of Yogyakarta (Source: Kompas.com)

The stages of the research process are briefly outlined as follows:

1. Data Collection
   The data required for the research includes:
   a. Earthquake data
      Collect earthquake data, including magnitude, occurrence time, coordinates, and depth of the earthquake source. The data selected includes earthquakes with a magnitude ≥ 5.0 Richter scale occurring between 1900 and 2023 year within a 500 km radius from the city center of Yogyakarta. This data is obtained from the United States Geological Survey (USGS) catalog and Badan Meteorologi, Klimatologi dan Geofisika (BMKG).
   b. Soil Test Data
      The field test data includes N-SPT values and layer thicknesses, while the laboratory test data includes soil density and shear stress. This information is obtained based on the existing building planning archive.
2. Probabilistic Seismic Hazard Analysis (PSHA)
   PSHA is carried out by collecting and converting earthquake data so that the data obtained is uniform. Declustering is needed to separate aftershocks from the main earthquake. Earthquake identification is carried out to group of earthquake data based on source categories and mechanisms (Franke, K., 2017). Earthquake source characterization is carried out to obtain several parameters, namely a value, b value, lambda, magnitude of completeness, maximum magnitude, type of fault, slip rate, and dip (Makrup, L. dan Jamal, A.U., 2016). Then a probabilistic analysis is calculated using several attenuation equations. There are hundreds to thousands of attenuation functions that have been published throughout the world. The selection of the attenuation function can't be done carelessly rather requires careful consideration and study beforehand (Nurhidayatullah & Kurniati, 2021). Several considerations used in selecting the attenuation function in this research include the level of novelty, suitability of geological conditions, Suitability of the seismic conditions, and the mechanism of earthquake events. So, from these considerations, it was decided to use attenuation functions Eq. (1) & Eq. (2). The attenuation equation for the fault earthquake source (shallow crustal) in this study uses GMPE Boore and Atkinson NGA (2008) - Shallow Crustal.

$$Ln\, y = FM(M) + FD(Rjb, M) + Fs(Vs - 30, Rjb, M) + \varepsilon\sigma T \quad (1)$$

Meanwhile, the equation of megathrust and benioff subduction earthquake sources use GMPE Atkinson-Boore Worldwide Data NGA (2003) Interface and intraslab.

$$Log\, y = fn(M) + c3h + c4h - glogR + c5slSC + c6slSD + c7slSE \quad (2)$$

Spectra response with an earthquake probability of 2% in 50 years is designated as a target spectrum in the spectral matching process can be obtained from probabilistic analysis (Nurhidayatullah & Kurniati , 2020). The dominant and most dangerous earthquake events in magnitude and distance to the earthquake source can be determined through deaggregation analysis (Sunardi, 2015). The results of the deaggregation analysis are used as a reference in selecting accelerograph earthquake recordings so that ground motion similar to the appropriate geological and seismological conditions can be obtained. Deaggregation analysis is used to obtain the most dominant and dangerous earthquake scenarios from the results of probabilistic analysis (Irsyam, 2010) also can be used as reference in selecting ground motion recordings.

3. Spectral Matching
   All earthquake recordings that have been collected are used in the spectral matching process. Ground motion scaling is carried out on each earthquake recording so that the spectral acceleration value approaches the target (Fahjan, Y. Dan Odemir, Z., 2008). Elimination is carried out on ground motion results from spectral matching with significant relative errors so that only a few earthquake recordings closest to the target spectra were selected. Ground motion that has the slightest deviation of parameters such as acceleration, velocity, displacement, directivity, and intensity variations from the original earthquake recording, is the best (Franke, K., 2017). This ground motion can be used in site-specific analysis.
4. Classification and analysis of soil dynamic properties
   The initial condition of soil type is known based on the average value of the N-SPT test results at a distance of 30 meters from the ground surface (N-30). To analyze the influence of soil layers on wave propagation behavior from the bedrock to the ground surface, a detailed analysis of soil condition, namely, shear wave velocity (Vs), unit weight, effective shear stress, layer thickness, and soil properties content, is needed.
5. Ground Motion Propagation Analysis
   Analysis of earthquake wave propagation is carried out by combining selected ground motion with the dynamic properties of each soil layer using non-linear earthquake site response modeling (Munirwansyah, dkk., 2020). From this analysis, the behavior and changes of ground motion parameters including acceleration, frequency and duration can be seen in each soil layer. So that, the earthquake wave propagation mechanism either amplification or attenuation can be identified. Analysis of ground motion propagation in each soil layer from bedrock to the ground surface refers to modeling and simulation (Hashash, 2020).
6. Ground Motion Time History Surface of Various Ground Conditions Ground motion time history of the surface is obtained through analysis of wave propagation from the bedrock to the ground surface by considering the influence of dynamic parameters of each soil layer. Soil conditions can change drastically only at a distance of tens of meters (National Research Council, 1994). Therefore, ground motion analysis needs to be carried out on various soil test results so that the effects can be known in detail, and the actual ground motion time history at the surface can be obtained.

Results and Discussion

The earthquake data used in the research are earthquake recordings with a radius of 500 km from the location of the building research object (Latitude: -7,796; Longitude: 110,370). This data was acquired through the United States Geological Survey (USGS) catalogs and the Meteorology and Geophysics Agency (BMKG) between 1900 and 2023. The distribution of earthquake data is shown in Figure 2.

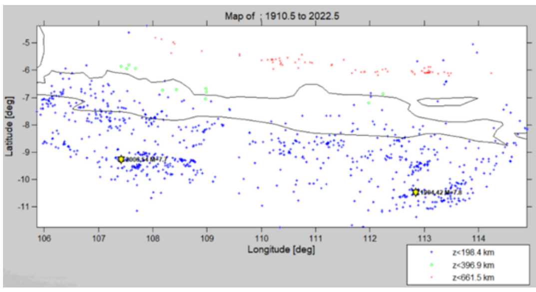


Figure 2. Distribution of earthquake data

The initial earthquake data collected consists of various types and is sourced from many earthquake stations using different measurement methods. It is necessary to convert the size of the earthquake data before processing it, considering that the data collected through USGS has various types of magnitude, including moment magnitude (Mw), surface magnitude (Ms), body magnitude (MB), and local magnitude (ML). This research uses a moment magnitude (Mw) reference with the highest suitability parameter according to (Asrurifak, 2010). All earthquake data that has been gained is converted to the moment magnitude (Mw) scale. The mechanism and location of the earthquake sources are identified so that the converted earthquake data can be grouped into three types of earthquake sources, namely faults (shallow crustal), Benioff subduction and megathrust as shown in Figure (3) .

Declustering was carried out to separate independent earthquakes (main shock) and dependent earthquakes (foreshock and aftershock) for each earthquake source (Saputra, E., Makrup, L., Nugraheni, F., & Pawirodikromo, W., 2020). Declustering is carried out based on the Reasenberg (1985) approach. Figure (4) displays the distribution of earthquake data before and after the declustering process.

The Characteristics of earthquake sources, including a value, b value, lambda, and magnitude threshold, are obtained by taking the distribution of earthquake data in the area of each earthquake source, then carrying out statistical analysis using the maximum likelihood model. The results are shown in Table 1.

Afterward, the earthquake parameters resulting from the maximum likelihood model analysis are converted into the Gutenberg-Richter model as carried out by (Erlangga, W, 2020). The analysis results are shown in Table 2.

Probabilistic Seismic Hazard Analysis (PSHA) is carried out to predict the acceleration of earthquakes that may occur within a specific period. This analysis uses attenuation functions Eq. (1) and Eq. (2). This research examines the earthquake scenario in a return period of 2500 years or a probability of exceeding 2% in 50 years. The PSHA spectral acceleration ordinate (SaT) value is estimated based on 16 structural earthquake periods using 3 seconds as a maximum duration. The result of the probabilistic analysis is a spectrum response graph that represents how dynamic earthquake loads act on building structures when an earthquake occurs, as shown in Figure 5.

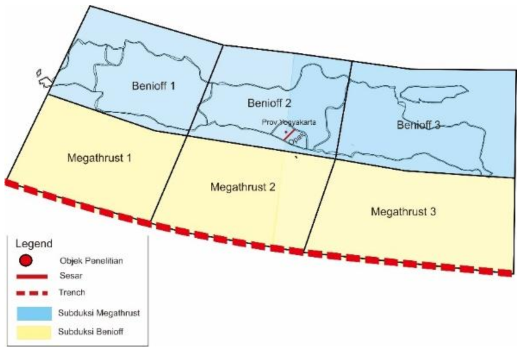


Figure 3. Earthquake source modeling

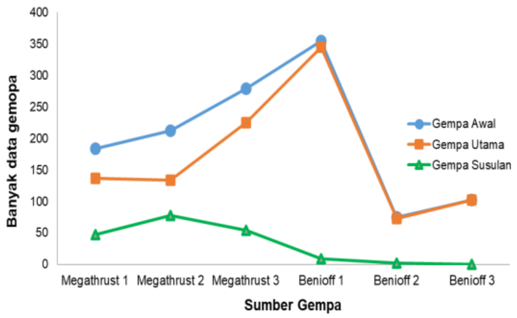


Figure 4. Comparison of earthquakes before and after declustering

Table 1. Results of analysis of the characteristics of each earthquake source

Earthquake source	a value	b value	M thresold	Mmax	Mechanism
Megathrust 1	11.6	1.69	5.7	6.9	Interface
Megathrust 2	9.32	1.30	5.7	7.3	Interface
Megathrust 3	12.3	1.79	5.7	6.9	Interface
Benioff 1	10.5	1.45	5.8	7.3	Intraslab
Benioff 2	10.8	1.62	5.6	6.5	Intraslab
Benioff 3	14	2.16	5.7	6.5	Intraslab
Sesar Opak	7.51	1.46	5.2	6.3	Strike-Slip

Table 2. Earthquake parameters based on Gutenberg Richter

No.	Source	Mo	λo	β	CV(β)	Mu
1	Megathrust 1	5.7	1.967	3.891	0.2	6.9
2	Megathrust 2	5.7	1.910	2.993	0.2	7.3
3	Megathrust 3	5.7	2.097	4.122	0.2	6.9
4	Benioff 1	5.8	2.090	3.339	0.1	7.3
5	Benioff 2	5.6	1.728	3.339	0.1	6.5
6	Benioff 3	5.7	1.688	4.974	0.3	6.5
7	Sesar Opak	5.2	0.828	1.460	0.5	6.3

From the response spectrum, the acceleration at the base rock at short period (0.2 seconds) is 1.326g and 1 second is 0.447g. The spectrum response graph above is the target spectrum response used as a reference in matching ground motion time history. Hazard deaggregation analysis is used to determine the contribution of hazards (earthquakes) that have the most influence on the research object (Makrup, L. dan Jamal, A.U., 2016). Deaggregation hazard calculations are carried out according to the coordinates of the research location. The results of the deaggregation analysis are shown in Figure 6.

Based on the diagram, it can be seen that each year, the hazard is dominated by earthquakes with a magnitude of 6.97 to 7.23, which occur at a distance of 89 to 111 km from the research location, accounting for up to 22.20% of the total. These results are used as a guide in selecting original ground motion data.

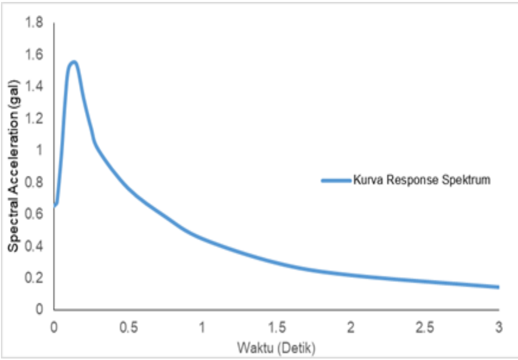


Figure 5. Response spectrum graph of 2% probability in 50 years

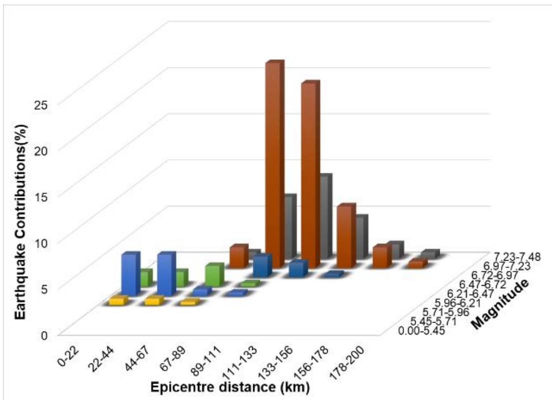


Figure 6. Earthquake deaggregation results

There are tens of thousands of earthquake ground motion data points that have been recorded using accelerometers or seismometers worldwide. Without clear parameters and measurements, choosing the proper ground motion is undoubtedly too difficult. The selection of original ground motion data refers to the results of the hazard deaggregation. Furthermore, in this research, earthquake records were selected referring to historical earthquakes in Yogyakarta. A destructive earthquake occurred on May 26, 2006, in Yogyakarta, measuring 6.3 SR, at approximately 20 km with a depth of approximately 12.5 km from the center of the research location (USGS, 2024). Based on these two references, appropriate earthquake data can be obtained, as shown in Tables 3 and 4. Figure 7 shows an example of an original earthquake recording.

Table 3. Results of selecting earthquake records based on hazard deaggregation analysis

No.	Event	Magnitude (M)	Jarak, Rjb (km)	Mechanism
1	El Mayor-Cucapah, Mexico 1	7.2	80.59	Strike slip
2	El Mayor-Cucapah, Mexico 2	7.2	82.26	Strike slip
3	Darfield, New Zealand	7.0	72.5	Strike slip
4	Hector Mine	7.13	72.88	Strike slip
5	Montenegro, Yugoslavia	7.1	85.31	Reverse

Table 4. Results of selecting earthquake records based on the May 2006 Mw 6.3 Jogja earthquake scenario

No.	Event	Magnitude (M)	Jarak, Rjb (km)	Mechanism
1	Parkfield-02, CA	6.0	9.12	Strike slip
2	Northridge-02	6.05	17.51	Reverse
3	L'Aquila, Italy	6.3	15.51	Normal
4	Kozani, Greece-01	6.4	14.13	Normal
5	Joshua Tree, CA	6.1	17.15	Strike slip
6	Irpinia, Italy-02	6.2	14.73	Normal
7	Chi-Chi, Taiwan-06	6.3	5.72	Reverse
8	Chi-Chi, Taiwan-06	6.3	1.04	Reverse
9	Christchurch, New Zealand	6.2	18.47	Reverse Oblique
10	Chalfant Valley-02	6.19	14.38	Strike slip

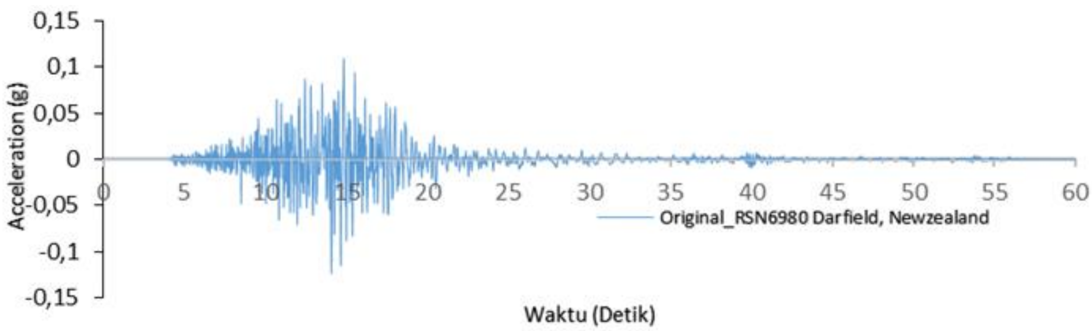


Figure 7. Time history of Darfield, New Zealand ground motion

All earthquake recordings that have been selected are original ground motion from developed countries such as New Zealand, America, Taiwan, Japan, Italy, and so on, while the research is located at Yogyakarta, Indonesia, so the earthquake recordings cannot be used due to geology and seismology differences (Irsyam, 2010). It is necessary to adjust these conditions, specifically by carrying out spectral matching, which involves modifying the original earthquake spectrum response to match the target spectrum response. The ground motion is adjusted to the target response spectrum as discussed previously (Figure 5). Figure 8 illustrates an example of the spectral matching process for one of the ground motions.

The original spectrum response shows a tiny earthquake acceleration when compared to the target spectrum. This indicates that the original earthquake acceleration will only produce small internal forces on the building structure. The nonlinear behavior of both structures and building materials cannot be accurately represented if earthquake recordings are used in structural analysis. The spectral matching process increases the ground acceleration to match the target response spectrum.

A comparison of the original earthquake recording and the spectral matching results reveals significant differences in acceleration. Significant differences also occur in other ground motion parameters such as velocity and displacement, except the Arias intensity.

Figures 9 to 12 illustrate that the four ground motion parameters, namely, the relationships between acceleration, velocity, displacement, and Arias intensity versus time, can be powerful variables in assessing the suitability of ground motion selection. Not all ground motions that have been collected and through the spectral matching process can be used in structural analysis, but only the best ground motion. To select the best ground motion, it can be done using the elimination method by considering the following things:

1. The difference between the spectral response and the target spectrum response.
2. The deviation of the original ground motion Arias intensity from the matching results.
3. The similarity of amplitude and direction of waves between the original ground motion and the matching results.
4. The similarity of frequency content between the original ground motion and the matching results.

To find out how much the difference in spectral response results of each ground motion with the target spectrum, the curve of all matching results needs to be plotted on one graph, as seen in Figure 10. From this graph, it is known that the ground motions that are close to the target spectrum deviate too far. Ground motions that have a deviation of response spectrum too large from the target can be eliminated, resulting in some ground motions whose differences are relatively small. The differences between the spectral response of each ground motion and the target spectral response are shown in Figure 14.

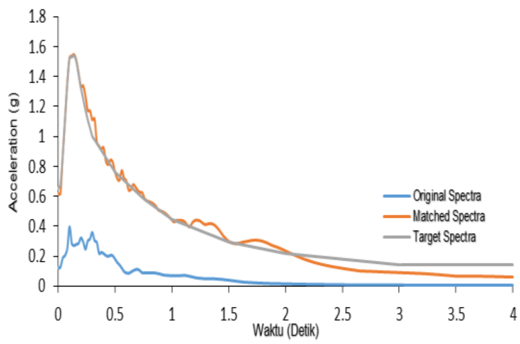


Figure 8. Spectral matching process

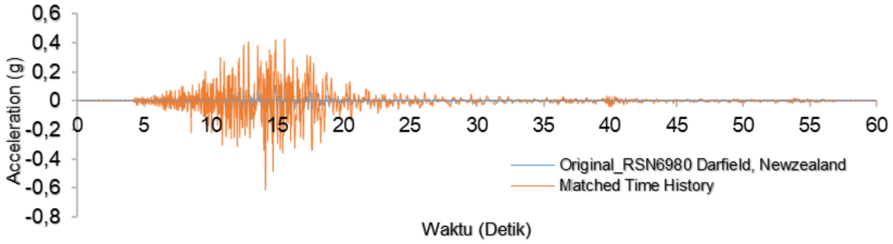


Figure 9. Original ground motion time history and spectral matching results

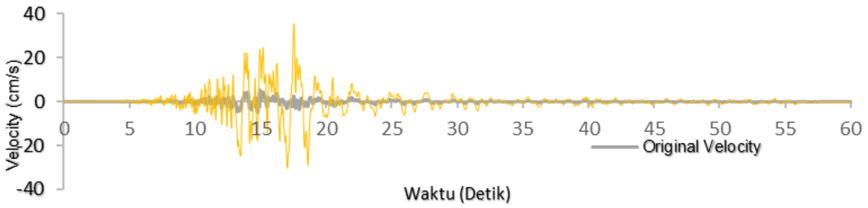


Figure 10. Original ground motion velocity and spectral matching results

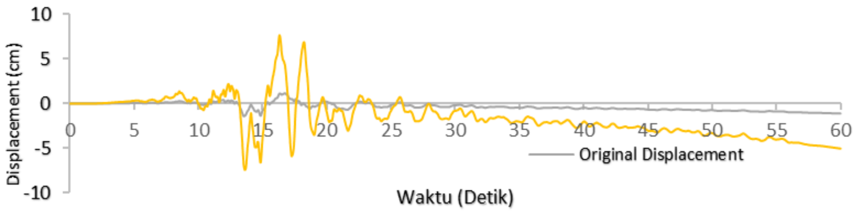


Figure 11. Original ground motion displacement and spectral matching results

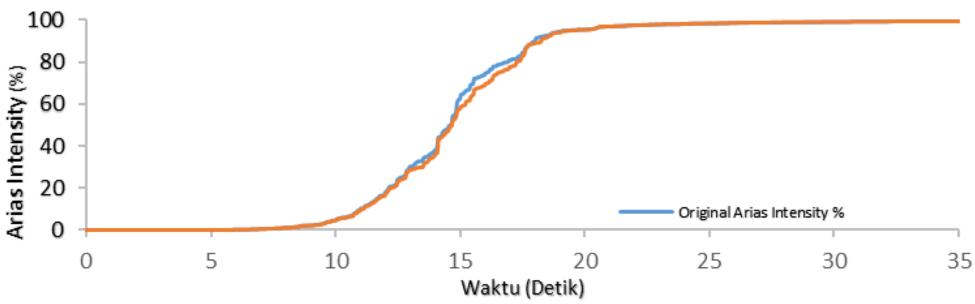


Figure 12. Original ground motion intensity arias and spectral matching results

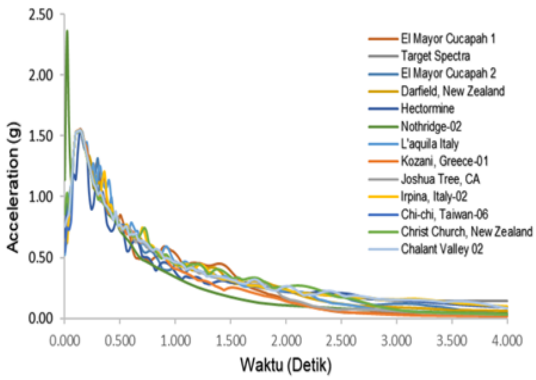


Figure 13. Response spectrum of all ground motion vs target response spectrum

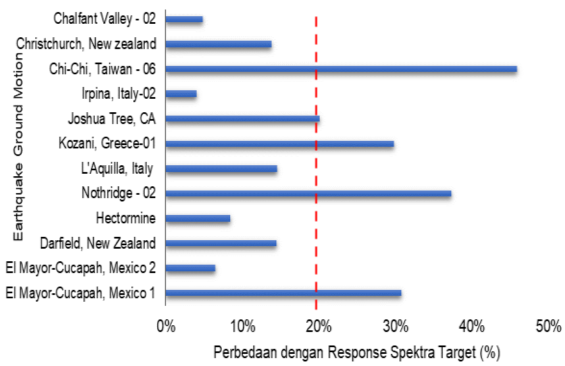


Figure 14. The differences of response spectrum

It can be seen from the diagram that several ground motions exhibit significant differences in spectral response, ranging from more than 20% to the target response, specifically Chi-chi, Taiwan 06, Joshua Tree, CA, Kozani, Greece-01, Northridge-02, and El Mayor, Cucapah, Mexico 1. These ground motions can be eliminated while still leaving some that require further evaluation. The next consideration in selecting ground motion is the Arias intensity parameter. Arias intensity is a representation of the accumulated strength, energy, and shocks of ground motion during the duration of an earthquake, which is obtained from the cumulative sum of the areas of ground motion waves in acceleration mode. The difference in the percentage of arias intensity shows the amount of ground motion deviation from the curve shape, amplitude, peak, and direction of the wave as well as its frequency content. Arias' intensity analysis is carried out on each selected ground motion. Here are examples of the comparison of the results of Arias intensity analysis for each ground motion that has undergone selection for suitability of the response spectra.

The three graphics from Figure 15 to Figure 17 illustrate the differences in the intensity of the arias of each ground motion after spectral matching with the original version. The Darfield, New Zealand, is the closest and most identical. The other two ground motions, Irpina-Italy and Elmayor-Cucapah, Mexico 2, have large intensity deviations. These differences are displayed in Figure 18. Apart from that, a factor that needs to be considered in choosing ground motion is the directivity parameter.

Based on Figures 19 to 21, it is known that of the three ground motions, the Darfield, New Zealand, has the most identical directivity. The spectral matching process does not significantly alter the amplitude, peak, direction, or frequency content of the original ground motion wave, making it appear very similar to the original version. The research concluded that the ground motion from Darfield, New Zealand, is the most suitable for both nonlinear site response analysis and nonlinear time history analysis of building structural models.

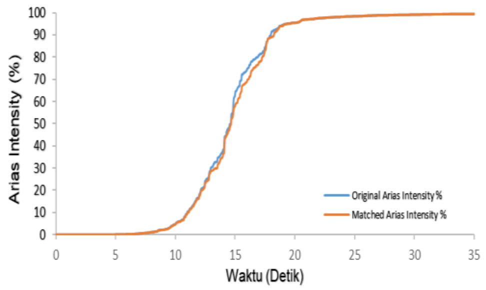


Figure 15. The arias intensity of the Darfield, New Zealand earthquake

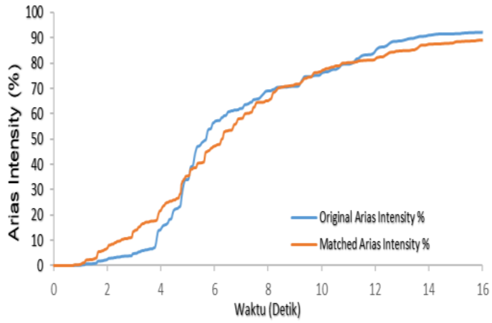


Figure 16. The arias intensity of the Irpina, Italy earthquake

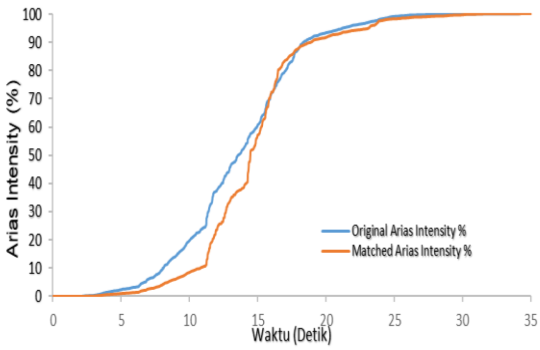


Figure 17. The intensity of the Elmayor Cucapah, Mexico, 2 earthquake

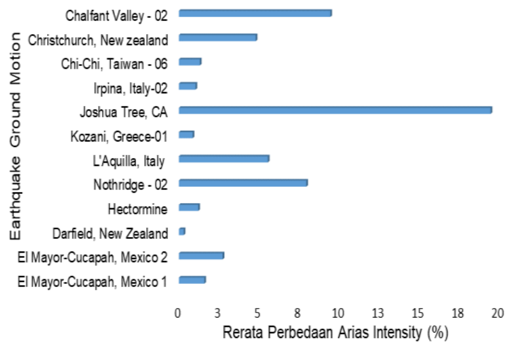


Figure 18. The Arias intensity differences of ground motions

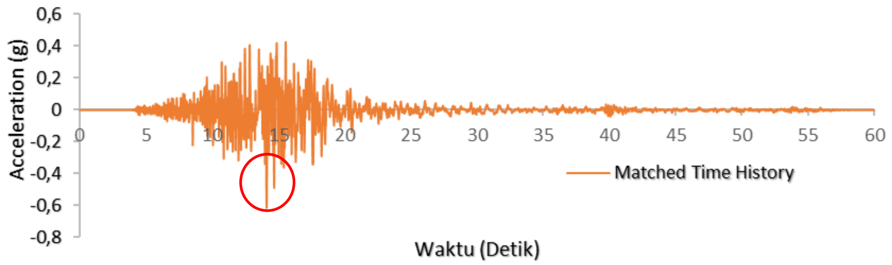


Figure 19. Darfield, New Zealand, ground motion resulting from spectral matching

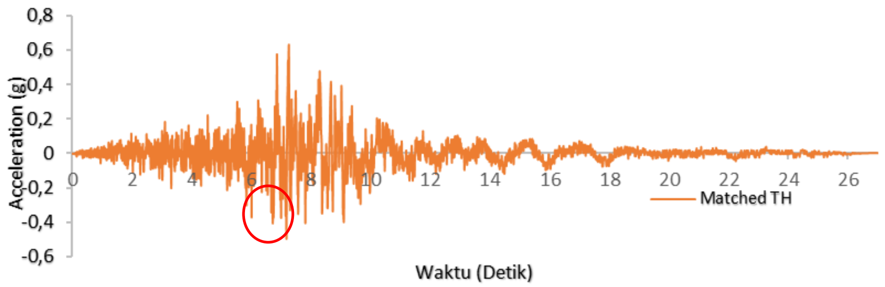
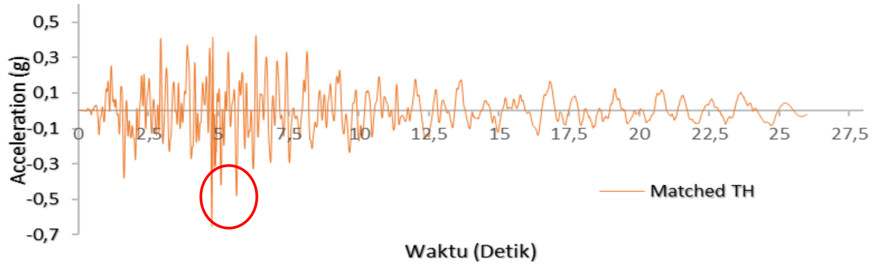


Figure 20. Hectormine ground motion resulting from spectral matching



Gambar 21. Ground motion Irpinia, Italy -02 hasil spectral matching

The ground motion in Darfield, New Zealand, resulting from spectral matching processes is the base rock ground motion, while the building is located on the ground surface. Therefore, earthquake waves must be propagated through the layers of soil until surface ground motion is achieved. Strong earthquake waves trigger high propagation acceleration at the ground media. The accelerated propagation of the wave is transformed into a force that is capable of causing permanent deformation or nonlinear behavior in each layer of soil. Therefore, analysis using a nonlinear model will be more appropriate for predicting ground movements on the surface.

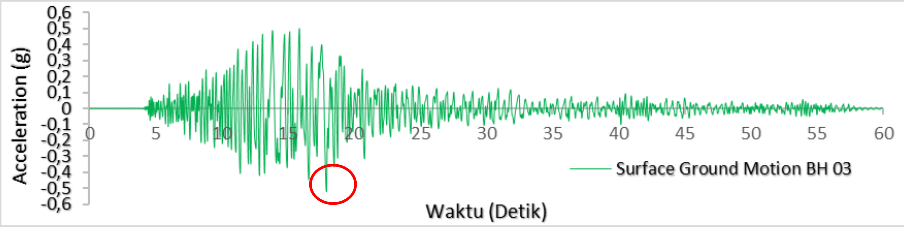


Figure 22. The Surface ground motion of BH 03 soil layer

To analyze the propagation of earthquake waves by considering the nonlinear behavior of soil layers, soil test data are needed. The soil test data obtained is Standard Penetration Test (N-SPT) so it is necessary to convert into shear wave velocity (Vs). The conversion is carried out according to the equation proposed by (Munirwansyah, dkk., 2020).

The analysis results of several soil test data show the values of average shear wave velocity (vs): BH 01 = 240.59 m/s, BH 02 = 240.59 m/s, and BH 03 = 245.09 m/s. According to SNI 1726:2019, all data are included in the classification of medium soil sites (SD). Analysis of ground motion propagation in each soil layer from bedrock to the ground surface refers to modeling and simulation (Munirwansyah, dkk., 2020). Analysis of earthquake waves in multiple soil layers reveals distinct surface ground motions. Differences in soil characteristics trigger these. Upon observation, it can be seen that the most significant magnification of earthquake waves occurs in the soil test data at point BH 03. The peak wave acceleration at the base rock, which was previously around 0.436 g (Figure 19), has changed to 0.518 g at the ground surface (Figure 22). This means that the characteristics of the BH 03 soil layer cause an amplification of earthquake acceleration of up to 1.2. Meanwhile, the other soils tend to be smaller in size.

There is an anomaly in which the soil layer with the highest average shear wave velocity (Vs) tends to experience the most significant amplification among the others. This is slightly contradictory to SNI 1726:2019, which states that a better or harder soil layer tends to produce a smaller amplification factor. Meanwhile, the value of the amplification factor (fv) in Regulation SNI 1726:2019 is in the range of 1.7–2.4 for the medium soil site class (SD), which is greater than the research results. The SNI 1726: 1726 amplification factor value tends to be more conservative, offering a higher level of security.

Conclusion

The spectral response analysis at bedrock reveals that the acceleration value at a short period (0.2 seconds) is 1.326 g, and at 1 second, it is 0.447 g. Each year, the hazard is dominated by earthquakes with a magnitude of 6.97 to 7.23 Mw, which occur at a distance of 89 to 111 km from the research location, accounting for 22.20% of the total. Ground motion recordings from Darfield, New Zealand, resulting from spectral matching, are the best ground motion recordings for use in the research location area. Non-linear wave propagation results in greater ground motion at the surface, with an amplification factor of approximately 1.2 compared to bedrock.

Expression of Gratitude

The author expresses his gratitude to the Directorate of Research and Community Service, Directorate General of Strengthening Research and Development, Ministry of Education and Culture, for funding this research.

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