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The Effect of the Soil Response to the Change of the Frequency Characteristic of the Earthquake Ground Motions

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Abstract: Generation of an artificial earthquake ground motion for specific purpose mainly to develop a ground motion time-history at the ground surface as a basis to design and assess the structure at a site due to the earthquake load, so the thing should be carried out. To see the effect of the soil response to the earthquake ground motions frequency characteristics change, then two time-histories with different frequency characteristics have been generated. The time-histories is generated in based on the one time-history in base rock result of measurement. The time history then is developed to be two time-histories with the spectral matching method in two mathematical domains namely time and frequency domain. The results of spectral matching are two time-histories with differ frequency characteristic namely time history with narrow and blunt frequency characteristic. The both time history then were utilized as the earthquake ground motion waves in base rock. The waves have been propagated from base rock to the ground surface used a soil response analyses theory. The results of the analyses were acceleration and spectral amplification factor at ground surface caused by the soil response tend to decrease from the time history with narrow to blunt frequency characteristics. Relative velocity and displacement caused by the response of the soil layers tend to increase from the narrow to the blunt frequency characteristics.

Keywords: Ground Motion, Time History, Frequency, Soil Response

1. Introduction

The main cause of shocks, earthquake ground motions on the earth's surface can be developed for a specific location deterministically. Earthquake ground motion waves are performed here as acceleration time history waves or simply called acceleration With regard to structural shocks caused by earthquakes as time history. In order to analyze two or more time histories with different frequency characteristics, for this purpose time histories can be developed based on what is called actual time history (time history is measured at a particular site). A time history basis can be changed its quantity and frequency characteristics by certain methods into two or more new time histories. Experts have done just that. Deterministically, Carlson et al. [1] changes the frequency characteristics of 28 ground motion before it is used as input to a bilinear SDOF system. Ergun and Ates [2] transformed the frequency characteristics of the actual acceleration time histories to generate new time histories and compare the effects of near-fault ground motions on structures with far fault ground motions' effects. Wood and Hutchinson [3] selected ground motion using a probabilistic seismic hazard analysis and altered the frequency characteristics of the ground motion to certain target spectrum. Bayati and Soltani [4] have selected and changed the frequency characteristics of the ground motion deterministically for seismic design of RC frames against collapse. Pavel and Vacareanu [5] were selected actual acceleration time history using a probabilistic seismic hazard analysis and transform its frequency characteristics to appropriate spectrum to generate a new time history. Makrup and Jamal [6] changed the quantity of the earthquake ground motion by time-history analysis (spectral matching procedure) to find new time history without alter its frequency characteristics. Makrup [7] developed design ground motion based on probabilistic seismic hazard analysis and code. Makrup and Muntafi [8] generated the artificial ground motion for the Cities of Semarang and Solo Indonesia as basis to design and evaluate the seismic risk for the multi stories building in the both cities. Irsyam at al. [9] carried out seismic hazard assessment for Liquid Natural Gas storage tank terminal of the National Electrical Company (PLN) at Teluk Banten, Western Java, Indonesia.

In this research was developed two time-histories with different frequency characteristics to notice the effect of the soil response to the earthquake ground motions frequency characteristics change.

2. Site Condition

Sites used as case studies are point 110.377370 East; 7.739370 South (Figure 1). At this point stands the Mataram City Tower with 20 floors. Soil conditions at the site were determined based on ASCE 2013 (ASCE 7-10) [10] and drill results. ACSE 7-10 provides Equation (1) to calculate the average N (Normal Soil Penetration Test/N-SPT) and a table with the correlation between site class versus shear wave velocity (Vs), Normal Soil Penetration Test (N-SPT), and Undrained Shear Strength (S_u), see Table 1.

Figure 1. *Site location in Yogyakarta, Java, Indonesia.*

Drilling results at the point 110.377370 East Longitude; 7.739370 South is the N-SPT parameter (Figure 2). The result is a correlation between N-SPT vs depth. The N–SPT is then converted into the ground shear wave velocity (Vs) (Figure 2) using the Ohta-Goto formula [11], Equation (2) and Imai-Tonouchi [12], Equation (3). Figure 3 is the average value of the two formulas.

$$\bar{N} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \frac{d_i}{N_{Si}}} \tag{1}$$

$$V_s = 85.3\ N^{0.341} \tag{2}$$

$$V_s = 96.9\ N^{0.314} \tag{3}$$

where $\bar{N}$ is mean N-SPT, d is depth of soil layer and N_{Si} is N-SPT of each layer.

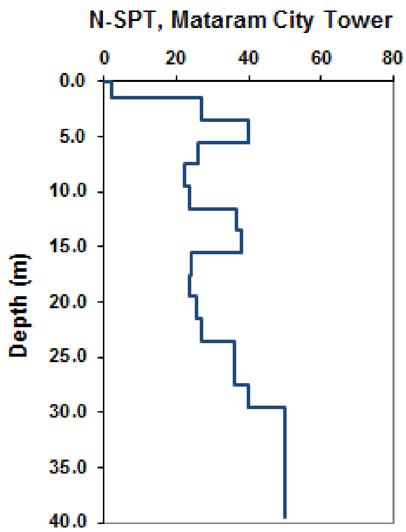

Figure 2. *The drilling result of site.*

With the data from Figure 2 and Equation 1, the mean N-SPT = 15.393 is obtained. Based on the average N-SPT and Table 1, the site class for the site is D (stiff soil). Figure 3 data is used as the basis for conducting a soil response analysis, namely to propagate the earthquake acceleration waves from the bedrock to the ground surface in the next paragraph.

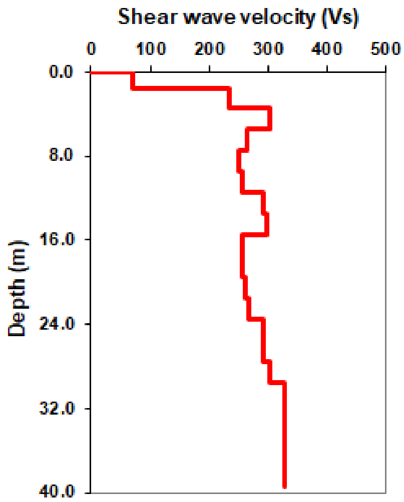

Figure 3. *Relations between the dept of soil layer and average Vs.*

3. Time History Analysis

Time history analysis referred to here is changing the quantity and or frequency characteristics of a time history into a different new time history. The procedure for carrying out this analysis is by the spectral matching method. Spectral matching is an analytical model for changing the quantity and frequency characteristics of the time history. Spectral matching in the time domain changes the time history amplitude and spectral matching in the frequency domain changes the time history amplitude and its frequency characteristics, Nicolaou [13]. The time history that should be used here is the result of the earthquake acceleration wave measurement, which is called the actual acceleration time history or simply the actual time history. The spectral matching in the time domain gives the response spectrum of the acceleration pattern similar to that of the real-time history response spectrum. In other words the spectral matching in the time domain turns the actual time history quantity into a new time history without changing the frequency characteristics The spectral matching in the frequency domain provides a different response spectrum pattern with the response spectrum from the actual time history and converts the actual time history into a new time history with changing quantity and frequency characteristics.

3.1. Target Spectrum

The target spectrum is the acceleration response spectrum which can be found in actual form, seismic code (design), and attenuation response spectrum (Nicolaou) [13]. For this paper, a deterministic response spectrum will be developed based on the prediction equation for ground motion (attenuation equation) for earthquakes that may occur in the crustal fault, namely the Opak fault (Yogyakarta fault). The fault has a maximum magnitude of M = 7.2 (Assrurufak et al.) [14], with a maximum horizontal distance to site of 31.6 km and a minimum of 12.3 km (Figure 1). In the future, it is assumed that an earthquake will occur with a magnitude of M = 6.5 and a rupture distance of R = 15 km from the source to the site with the soil condition is rock (base rock). To develop the response spectrum based on magnitude and distance, the Idriss GMPE [15] is used. The results of the spectrum computation are in Figure 4.

3.2. Actual Time-History

The acceleration time history used as the basis for generating the artificial acceleration time history is the time history measured at the accelerograph station.

Table 1. *Soil site classification.*

Site Class	Vs	N	Su
A	>5000 ft/s	Not	Not
Hard rock	>1500 m/s	Applicable	Applicable
B	2500 to 5000 ft/s	Not	Not
Rock	760 to 1500 m/s	Applicable	Applicable
C	1200 to 2500 ft/s	>50	>2000 psf
Very dense soil and soft rock	370 to 760		>100 kPa
D	600 to 1200 ft/s	15 to 50	1000 to 2000 psf
Stiff soil	180 to 370 m/s		50 to 100 kPa
E	<600 ft/s	<15	<1000 psf
Soft soil	<180 m/s		<50 kPa
	Any profile with more than 10 ft (3 m) of soil having character		
	* Plasticiy index PI > 20		
	*Moisture content, w > 40%		
	*Undrained shear strength, Su < 500 psf		
F	a. Soil vurnerable to potential failure or collapce		
Soil requiring the	b. Peats and/or highly organic clays		
site-specific	c. Very high plasticity clays		
Evaluation	d. Very thick soft/medium clays		

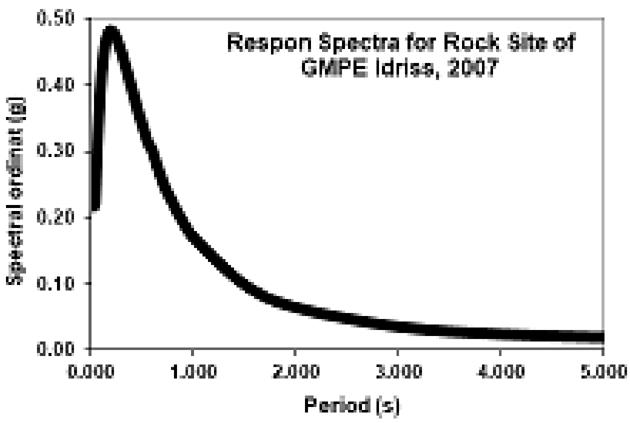

Figure 4. *Target spectrum developed based on Idriss (2007) GMPE.*

Associated with the target spectrum (Figure 4) developed at the rock site, it will also produce a time history of the rock site conditions. Therefore, the time history that will be used as the basis for time history must also be found in the rock site conditions. Furthermore, time history will be selected with the site of the rocks associated with Table 1, namely the shear wave velocity of the soil (Vs) for rocks is 760-1500 m/s. From the PEER catalog the time history with rock sites is the 2000 Titori earthquake Japan (Figure 5) with magnitude M = 6.61, rupture distance R_{rup} = 15.23 km and V_s = 940.2 m/s.

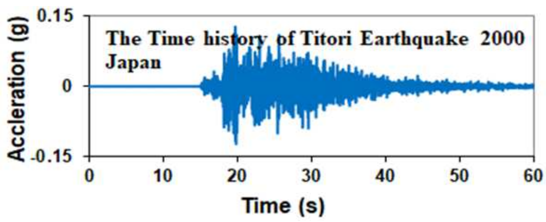

Figure 5. *The acceleration time history of Titori earthquake 2000 measured at sta. OKYH07-EW.*

3.3. Results of the Time History Analysis

The results of the time history analysis are also the results of spectral matching in the time domain (Figure 6(a)) and in the frequency domain (Figure 6(b)). Spectral matching was performed under the computer program namely SPECMATCH developed by Makrup [16] as described by Nicolaou [13]. The results of the time history of the matching process are shown in Figure 7. Matching in the time domain gives the calculation result, namely the scaling factor. In this case, a scaling factor of 1.3946 is obtained. Figure 7(a) time history is the product of Figure 5 time-history with a scaling factor of 1.3946. Matches in the frequency domain provide immediate results in the form of a time history. Figure 7(b) is the time history generated from the Fourier inverse of the discrete Fourier series coefficients from the time history of Figure 5.

The frequency characteristic of the acceleration time history is characterized by its response spectrum. The time history can have a narrow frequency characteristic or a blunt frequency characteristic. From the time history analysis, it was found that there were two acceleration time histories with different frequency characteristics. i) Time history Figure 7(a) has a narrow frequency characteristic corresponding to its response spectrum Figure 6(a)-3, developed based on time domain matching, ii) Time history of Figure 7(b) with jagged frequency characteristics corresponding to its response spectrum Figures 6(b)-3, developed based on frequency domain matching. The two time-histories will be used as the basis for conducting the soil response analysis.

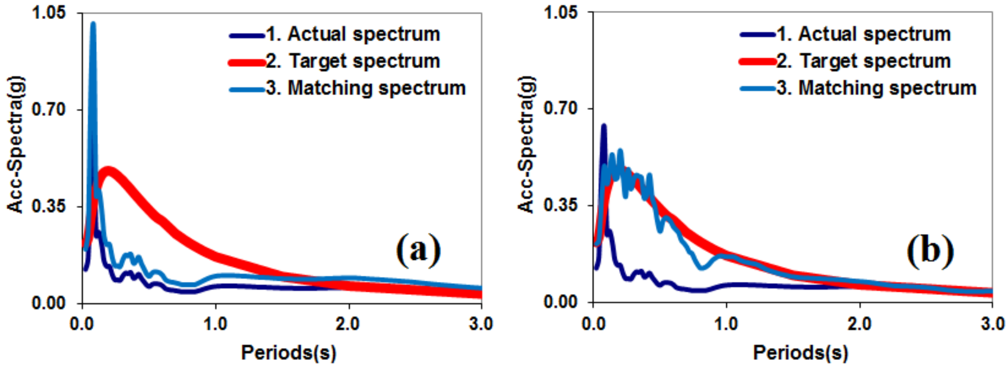

Figure 6. *Result of spectral matching in time domain (a) and frequency domain (b).*

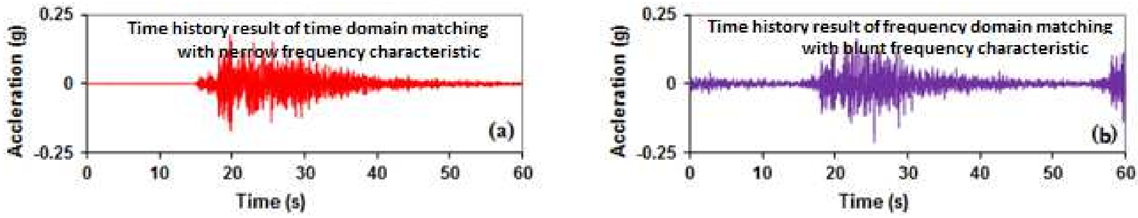

Figure 7. *The time-history with different frequency characteristics (a) and (b) that was obtained from spectral matching in time and frequency domain respectively (see Figure 5).*

4. Soil Response Analysis

To see the effect of soil response on changes in the frequency characteristics of earthquake ground motion, the following is a one-dimensional analysis of the soil response. The analysis was used by Bardet and Tobita [17]. Analysis related to vertically propagating shear waves from bedrock to soil surface in a one-dimensional layered system. This theory was used by Bardet and Tobita to develop a computer program for the analysis of the non-linear site response of layered soil deposits. The equation for making calculations for analysis is:

$$\rho\frac{\partial^2 d}{\partial t^2}+\eta\frac{\partial d}{\partial t}=\frac{\partial \tau}{\partial z} \tag{4}$$

where ρ is the soil unit mass, d is the horizontal displacement, z is the depth, t is the time, τ is the shear stress, and η is a mass-proportional dumping coefficient.

Bardet and Tobita's computer programs have been used to calculate time history at the soil surface based on soil layers (Figure 2) and time history in bedrock. Two time-histories (acceleration waves) in bedrock, namely the time history of Figure 7 with different frequency characteristics will be used as the basis for conducting soil response analysis. The two time-history were derived from one time-history namely Titori earthquake Japan 2000 (Figure 5). The two time-histories will propagate from the bedrock to the soil surface, and the influence of the soil layer on the two accelerating waves can be seen after the waves propagate up and arrive at the ground surface. It is assumed that the site conditions under the soil layer in Figure 2 are rock with soil shear wave velocity (Vs) = 940.2 m/s. This condition is in accordance with the target spectrum developed for the rock site conditions and the actual time history measured in the rock with Vs = 940.2 m/s. The result of the soil response analysis is the ground motion on the ground surface in the form of time history which can be seen in Figure 8.

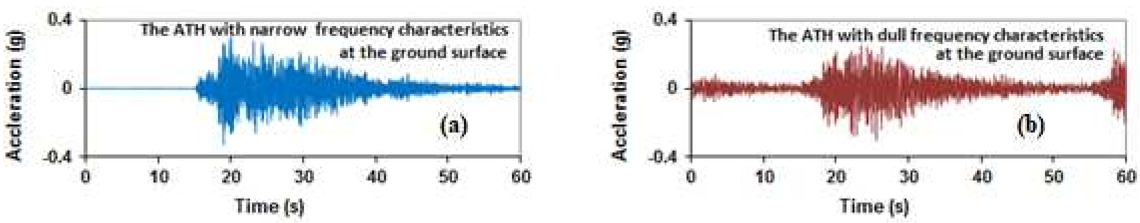

Figure 8. *The time history at the ground surface (result of soil response analysis).*

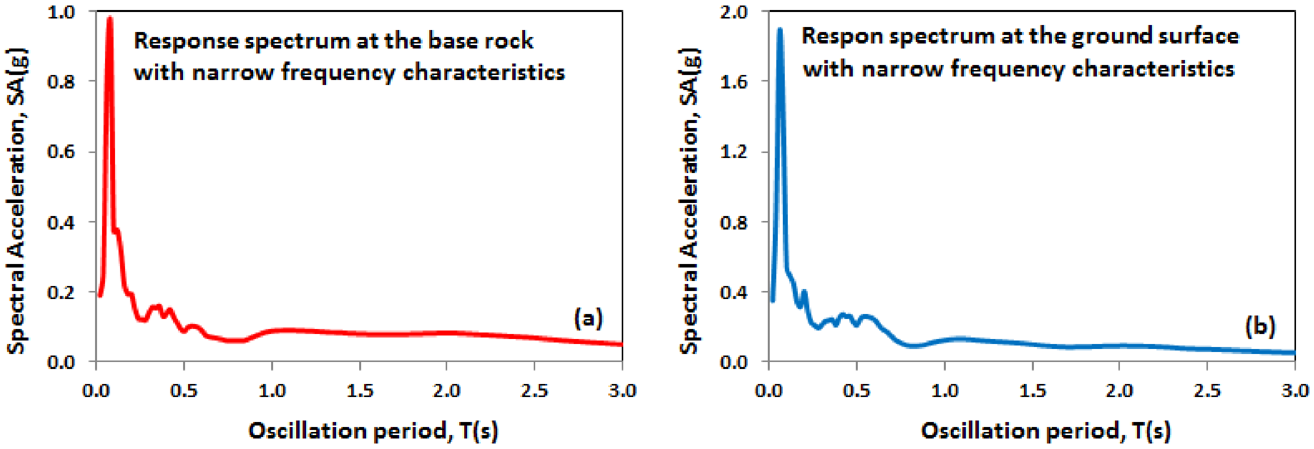

Figure 9. *Response spectrum of the time-history Figures 9(a) and 9(b) are in Figures 10(a) and 10 (b) respectively.*

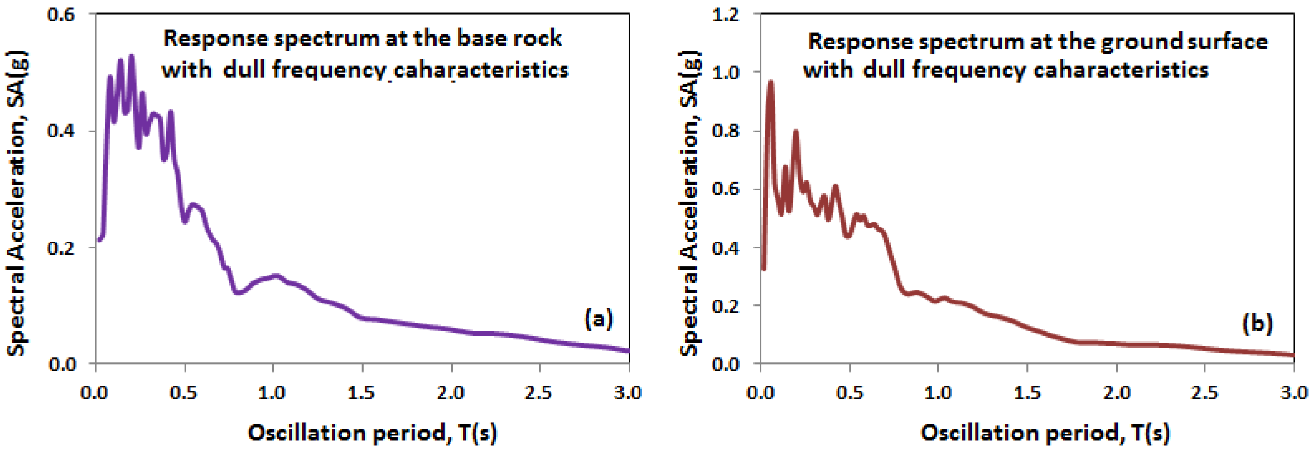

Figure 10. *Response spectrum of the time-history Figure 6(b) and 7(b) in Figure 11(a) and 11(b) respectively.*

The response spectrum of the time history in Figures 8(a) and 8(b) can be seen in Figures 9(b) and 10(b), respectively. The time history in Figures 8(a) and 8(b) is the result of the propagation of the accelerating waves in Figure 7(a) with a narrow frequency characteristic and Figure 7(b) with a blunt frequency characteristic, respectively, from bad rock to the ground surface.

5. Discussion

The effect of soil response on changes in the frequency characteristics of earthquake ground motion can be seen and discussed, starting with generating two artificial time histories with different frequency characteristics in the bedrock. An artificial time history can be generated by spectral matching based on the measured time history. The frequency characteristics of the time history are indicated by the response spectrum. The time history used is the time history in Figures 7(a) and 7(b). The time history in Figure 7(a) was developed by time domain matching, so that the frequency characteristics of the time history are the same as the actual time history of Figure 5. The similarity of the frequency characteristics of the two time-histories of Figures 5 and 7(a) is shown by their response spectra of Figures 9(a) and 9(b).

The time history in Figure 7(b) was developed with frequency domain matching, so that the frequency characteristics of the time history is different from the actual time history of Figure 5. The difference in frequency characteristics of two time-histories of Figures 5 and 7(b) is shown by their response spectra of Figures 10(a) and 10(b). Visually the time history in Figure 7(a) has a different pattern from the others in Figure 7(b). Initially about 0.0 to 15 seconds and finally about 45 to 60 seconds the amplitude of the time history of Figure 7(a) is smaller than that of the time history of Figure 7(b). Amid, the patterns and amplitudes of the two time-histories are slightly different. Based on the shape of the response spectrum (Figure 10) of the two time-histories, the time history of Figure 7(a) has a narrow frequency characteristic and the time history of Figure 7(b) has a blunt frequency characteristic, therefore the two time-histories in Figure 7 have different frequency characteristics. Therefore, both time histories are appropriate to be used to see the effect of soil response on changes in the frequency characteristics of earthquake ground motion.

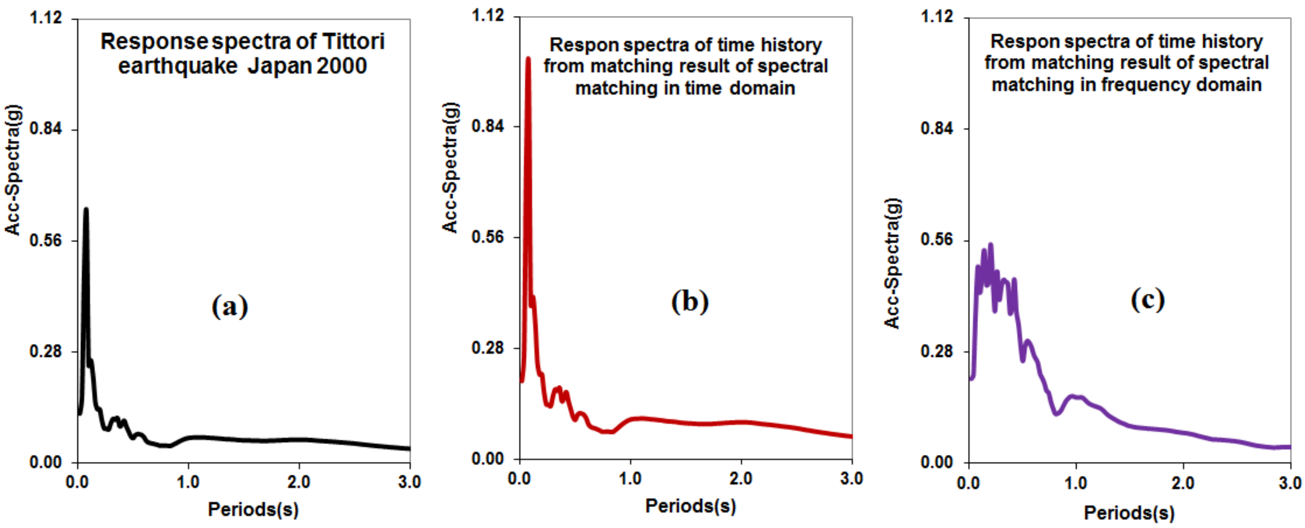

Figure 11. *Actual, time domain matching, and frequency domain matching spectrum time history (b) and (d) are the results of soil response analysis.*

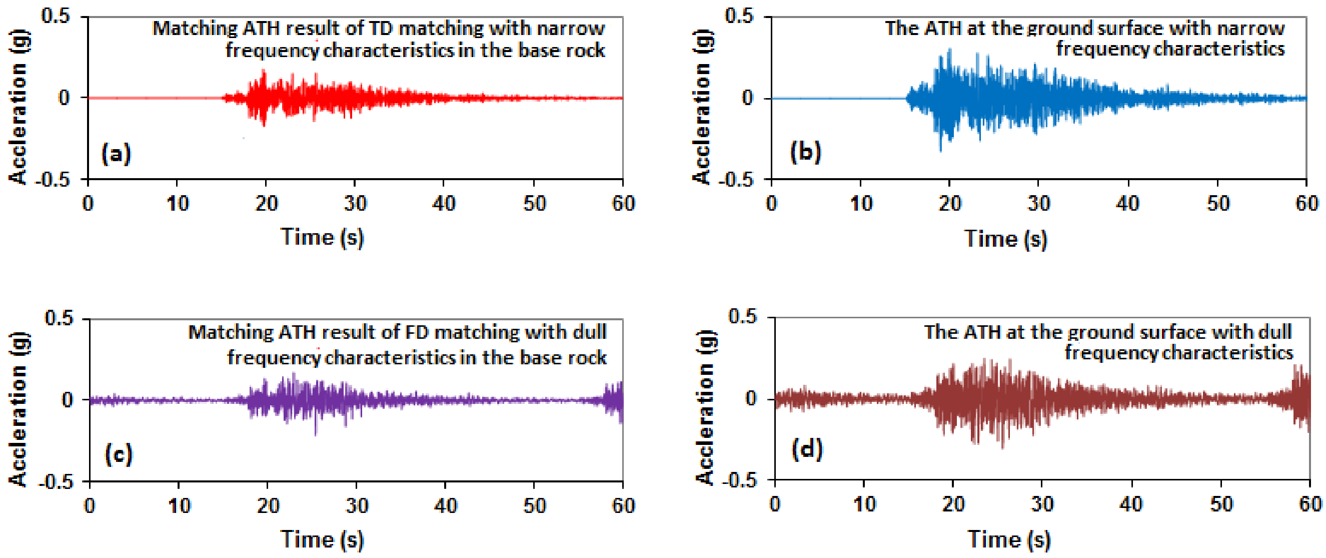

Figure 12. *The time histories (a) and (c) are the result of spectral matching and (b) and (d) are soil response analysis.*

5.1. Amplificatio Factor for Acceleration

From the time history Figure 12(a) on bedrock to 12b on the soil surface with the same narrow frequency characteristics visually shows the amplification acceleration caused by the soil response. The maximum acceleration in Figure 12(a) in bedrock is 0.1785g at 19.69 seconds and in Figure 12(b) at ground level is 0.324g at 18.97 seconds, then the amplification factor caused by the response of the soil layer is 1.82. The peak acceleration moved closer from 19.69 seconds to 18.97 seconds to the original time of 0.0 seconds.

From the time history Figures 12(c) to 12(d) with the same blunted frequency characteristics also visually show the amplification acceleration caused by the ground response. The maximum acceleration in Figure 12(c) is 0.2145g at 25.41 seconds and in Figure 12(d) it is 0.302g at 25.56 seconds. Then the amplification acceleration factor caused by the response of the soil layer is 1.41.

5.2. Amplification Factor for Spectral Acceleration

Response spectrum from the time history of Figure 12(a) is in Figure 10(a) with bedrock sites. The maximum spectral acceleration for the response spectra is 0.9703g at a spectral period of 0.08 seconds. The response spectra of the time history Figure 12(b) is in Figure 10(b) with soil site. The maximum spectral acceleration for the response spectra is 1.8856g at spectral period 0.06 second. The spectral acceleration amplification factor for the acceleration time history with a narrow frequency characteristic is 1.94.

The response spectrum of the time history Figure 12(c) is in Figure 11(b) with base rock site. The maximum spectral bacceleration for the response spectrum is 0.5281g at a spectral period of 0.2 seconds. The response spectrum from the time-history of Figure 12(d) is in Figure 11(c) with ground surface sites. The maximum spectral acceleration for the response spectrum is 0.9643g at a spectral period of 0.06 seconds. The spectral acceleration amplification factor for the acceleration time history with blunt frequency characteristics is 1.83. The peak spectral acceleration moved closer from a time of 0.08 to 0.06 s and from 0.2 to 0.06 s to a starting point of time of 0.0 s for the narrow and obtuse frequency characteristics, respectively.

5.3. Maximum Relative Velocity and Displacement of Soil Layers

The effect of soil response on changes in the frequency characteristics of earthquake ground motion from a narrow time history to a time history with blunt frequency characteristics to the velocity and displacement of the soil layer can be seen in Figure 13.

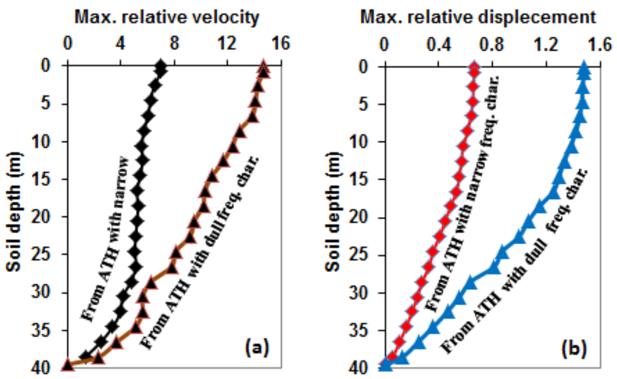

Figure 13. *Maximum relative velocity and displacement of the soil layers.*

From Figure 13 it can be seen that the maximum relative velocity and displacement of the soil layers tend to be greater than the bedrock to the soil surface. Time history with blunt frequency characteristics resulted in maximum relative velocity (Figure 13(a)) and displacement (Figure 13(b)) of the soil layers tended to be larger than time history with narrow frequency characteristics. At ground level the maximum relative velocity and displacement for time history with narrow and blunt frequency characteristics are 7.0068 cm/s and 14.6858 cm/s for velocity and 0.6656 cm and 1.4811 for displacement, respectively. Therefore, the difference in maximum relative velocity and displacement at ground level for the two time histories is 7.6791 cm/s for velocity and 0.8155 cm for displacement, respectively.

6. Conclution

This research has produced two earthquake ground motions (earthquake acceleration time history) with narrow and blunt frequency characteristics in bedrock with spectral matching in the respective time and frequency domains. The ground motion is then propagated from the bedrock to the soil surface through the soil layer with the theory of soil response analysis.

The effect of the response of the soil layer to changes in the frequency characteristics of earthquake ground motion from narrow to blunt frequency characteristics is for acceleration and spectral amplification, changes with decrease. For the velocity and displacement of the soil layer, there is an increase in changes.

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