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VARIATION OF GROUND MOTION CHARACTERISTICS IN PARALLEL AND NORMAL DIRECTIONS IN NEAR-FAULT REGION: A CASE STUDY ON 1999 CHI-CHI EARTHQUAKE

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Abstract

Structural engineering involves clear understanding of characteristics of ground motion used in the design of structures to identify the critical aspects of their behavior. Peak amplitude of response (a, v, or d), predominant frequency and duration of strong ground motion are the most important parameters of ground motion that are required for this purpose. These parameters are influenced by the source, path and site conditions. However, it is also found that for the same distance these characteristics are highly sensitive to the fault direction and the side on which the site lies i.e., hanging wall or foot wall.

In this paper, a case study is performed to understand the influence of fault direction and location of site on the characteristics of the ground motion. For this purpose, 371 ground motions recorded during 1999 Chi-Chi, Taiwan earthquake are selected. Initially, these ground motions were arranged in terms of fault parallel and fault normal direction and also according to distance from the fault. Later, ground motion characteristics were obtained using standard procedures. From the above, it was found that, in the near-fault region, PGA and PGV on the hanging wall are higher by at-least 20% than that on the footwall. From this observation, the near-fault region can be defined not by using the distance from the fault, but by observing the ratio of PGA values in fault normal and parallel directions. This method of estimating the near-fault region is reliable because the hanging wall effect is caused only due to the inclined dip-angle of the fault which is inevitable in most of the thrust and normal faults.

Keywords: Hanging wall effect; PGA; Thrust faults; Fault Normal; Fault Parallel

1. Introduction

Earthquakes are one of those natural disasters that are sporadic but calamitous. The rupture process associated with the earthquake is translated to the ground in the form of ground motions. It is well known fact that these ground motions are used to understand the rupture process of the earthquake source, the behavior of the path through which the seismic waves, that are emitted from the source, travelled and the response of the location at which the ground motion is measured [1, 2, 3, 4]. Although, understanding of the rupture process of an earthquake is crucial, the critical analysis of the effects of the ground motion on the built environment ensures to adopt specific design and construction practices required for the structures to withstand the resulting ground motions due to earthquakes. Any earthquake as a whole has two major repercussions namely life loss and economic loss. Although, complete economic loss is inevitable, the expected life loss must be avoided which is possible by analyzing the behavior of structures to anticipated ground motions at a location. The seismic behavior of structure can be well appreciated if the ground motions are systematically quantified and characterized [5, 6, 7, 8, 9].

Although, the characterization of ground motions is significant in ensuring a seismic resistant built environment, it is associated with a lot of uncertainty at various levels [3, 4]. These uncertainties can be broadly classified into source effects, path effects and site effects for any ground motion recorded. Among these uncertainties, the most predominant are the near-fault effects that are observed in the region near to the rupture plane of an earthquake. The characteristics of near-fault ground motions are associated with specific parameters of source, path and site. Unlike any other ground motion, the near-fault ground motions represent not only the effects of seismic waves that travel from the rupture plane to the location of measurement but also the fault displacements of earthquake since the location is very near to the fault plane. Such complexity adds to the existing uncertainties and results in particular effects like hanging wall effect, directivity effect and fling-step to the recorded ground motions [10, 11, 12, 13, 14]. Hence the characteristics of near-fault ground motions and their influencing parameters should consider all these effects to ensure proper quantification of ground motions.

The near-fault effects mentioned above such as hanging wall effect, directivity effect and fling-step are all associated with the direction of fault rupture relative to the location of measurement. It is a well-known fact that any earthquake ground motion is recorded in three directions; one parallel to the North-South, second one parallel to the East-West and the third in the vertical direction. However, from the past studies [10, 11, 12, 13], it is identified that some of these near-fault effects are predominantly identified in those directions that are parallel and perpendicular with respect to the fault plane at the recorded location. Therefore, the fault parallel and normal components of the ground motion are the likely critical directions for the structural behavior on the ground. Therefore, it is essential to study the characteristics of near-fault ground motions in the fault normal and parallel directions to ensure the complete consideration of all such effects.

To consider all these effects in characterizing the near-fault ground motions, one way is to analyze the influence of each of these effects on the characteristics and the other is to study the recorded ground motions for their influence. The choice of the method of characterization depends on the objective with which the ground motions are characterized. To study the ground motions for understanding the structural behavior, it is required to identify, analyze and compare different features of the ground motion with due consideration to the near-fault effects.

This article is an attempt to study the influence of various near-fault effects on the characteristics of ground motions for a particular source mechanism. The study is carried out with special emphasis on the hanging wall effect and its influence on the ground motions located in the near-fault region of the earthquake. The expected variations of characteristics in the near-fault region due to hanging wall effect are verified on a set of recorded ground motions during 1999 Chi-Chi, Taiwan earthquake. The resulting observations and interpretations are presented with an intention to identify and quantify the hanging wall effect in the near-fault ground motions.

2. Organization of Strong Ground Motion Data

A study of recorded ground motions was carried out to understand the influence of near-fault effects on the characteristics of ground motions with due consideration to the engineering aspects. For this purpose, an earthquake occurred on 21 September 1999 at Chi-Chi in Taiwan was selected due to its large recorded ground motion data set [15, 16]. The epicenter is located at 23.87^0 N 120.75^0 E in the Chi-Chi Township of Nantou County which is located at 12.5km west of Sun Moon Lake and 155km south of Taipei, the capital city of Taiwan. The earthquake occurred as a result of the active tectonics that take place between Philippines sea plate and the Eurasian plate. This earthquake occurred on east dipping fault called Chelungpu fault due to predominant thrust movement that ruptured 80km of fault plane. The fault has a strike angle of 5^0 and dip angle of 30^0. The initiation of rupture took place at a depth of 15km from the surface causing a total energy release of 2.1 x 10^{17} Joules. A small portion of fault towards the north which strikes in the east-west direction was identified to be active only after the earthquake [17].

In view of high seismic hazard due to complex tectonics, Central Weather Bureau (CWB) of Taiwan initiated the installation of closely spaced strong motion seismographs to capture the seismic activity in the island through a program called Taiwan Strong-Motion Instrumentation Program (TSMIP) in the year 1990. This installation completed just before the earthquake occurrence. During Chi-Chi earthquake, the network of instruments recorded strong ground motion throughout the country enabling the availability of large near-fault strong ground motion which was not available till then. A total of 441 strong motion instrumented data located on 5 different soil types, categorized according to Uniform Building code (UBC), are obtained. Out of these, only 376 corrected ground motion data files are available. The details of the categories of soils on which the stations are recorded is indicated in Table 1. The recorded stations are distributed throughout the country with high density on the western side of the fault when compared to the east side. This non-uniform distribution of seismic stations is required as the city is developed on the east side of the fault. Fig. 1 shows the map of Taiwan showing the Chelungpu fault line, location of epicenter, location of seismic stations categorized by the type of soil.

Table 1 – Site Classification of recorded seismic stations

Soil Type	Shear Wave Velocity (m/sec)	No. of Stations
S_B	760 – 1500	48
S_C	360 – 760	53
S_D	180 – 360	180
S_E	< 180	81
Unknown	-	14

Observing the past literature, it reveals that some seismic stations which are near to the fault trace are likely to visualize hanging wall effect. To observe the variation of ground motion characteristics due to hanging wall effect, the seismic stations are categorized into two *viz.*, hanging wall stations and the footwall stations. Those stations that are on the right side of the fault towards east are named as hanging wall stations and those stations that are on the left side of the fault towards west are named as footwall stations. Fig. 2 shows the map of Taiwan and categorized seismic stations according to their location with respect to the surface trace of fault plane. At any seismic station, the strong-ground motion is recorded in three directions; two horizontal and one vertical. To understand the variation of characteristics in fault normal and fault parallel components of ground motion, the coordinate system of recorded ground motion is transformed to new coordinate system with respect to the fault plane. The strike of the fault plane is inclined at 5^0 to the north. Hence, the direction of recorded ground motions is transformed to the strike of the fault. Therefore, the direction of two perpendicular horizontal ground motions are converted into two components; one parallel to fault and the other perpendicular to the fault plane. The transformation is carried out as shown in the Fig. 3.

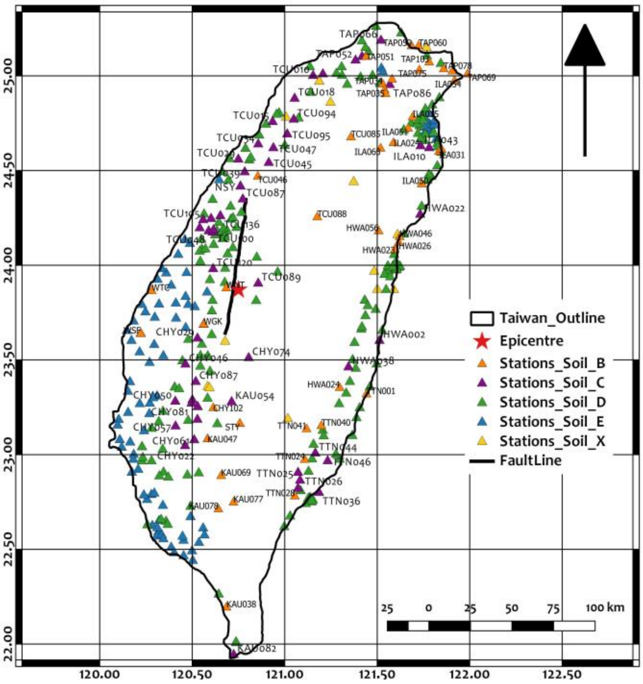

Fig.1 – Map of Taiwan country with Chelungpu fault line, location of epicenter, location of seismic stations categorized by the type of soil

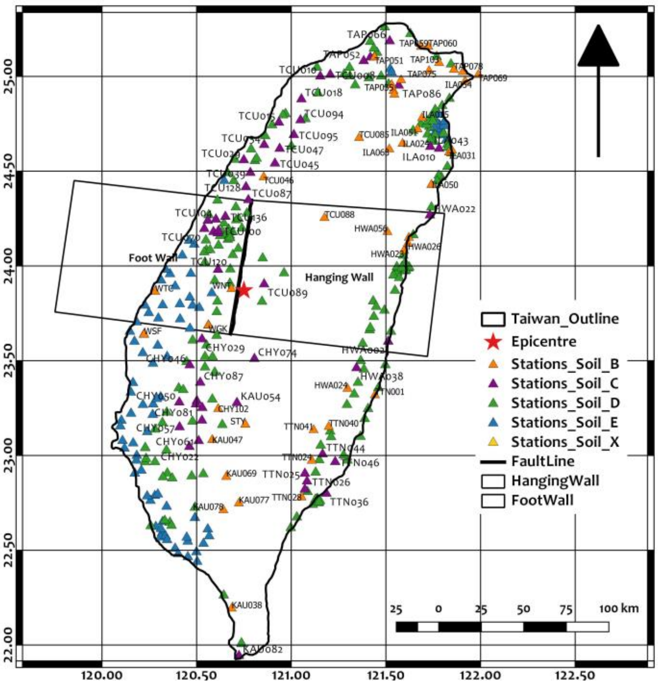

Fig.2 – Map of Taiwan showing the fault line, recorded stations categorized according to hanging wall (to the right of fault plane) and foot wall (to the left of fault plane)

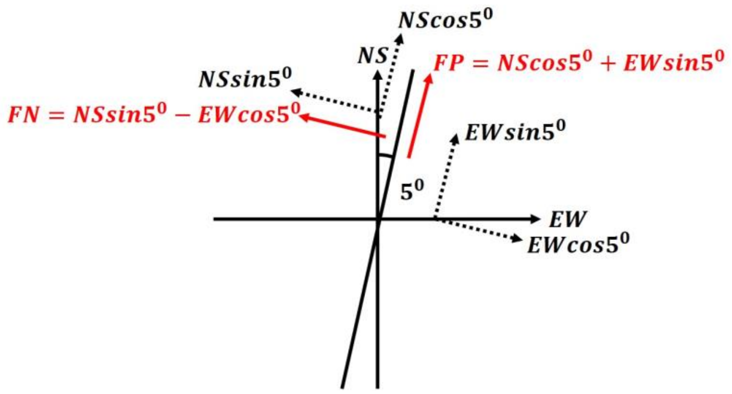

Fig. 3 – Axes transformation of North-South and East-West components of recorded ground motions

3. Discussions

From the categorized recorded stations according to hanging wall and footwall, the Peak Ground Acceleration (PGA) values recorded in the FN and FP directions are plotted against the shortest distance from the fault plane. Fig. 4 shows the plot of PGA values recorded at stations on the footwall with respect to the shortest distance from the fault plane. Similarly, Fig. 5 shows the plot of PGA values recorded at stations on the hanging wall with respect to the shortest distance from the fault plane. At each recording station, there are two PGA values corresponding to FN and FP components. Although from the points plotted, it is evident that the PGA values decrease with increasing distance from the fault in both the cases, a suitable trendline (exponential) is plotted to understand the variation of PGA in both the directions of components. The trendlines in both the plots indicate that the attenuation of the PGA in the near-fault region is rapid and becomes nearly constant at larger distances from the fault plane. Generally, attenuation of energy accounts to damping of vibration energy. There are two types of damping; material and radiation damping. Depending on the local soil conditions and the type of causative fault, results pertaining to popular attenuation trendline may also occur.

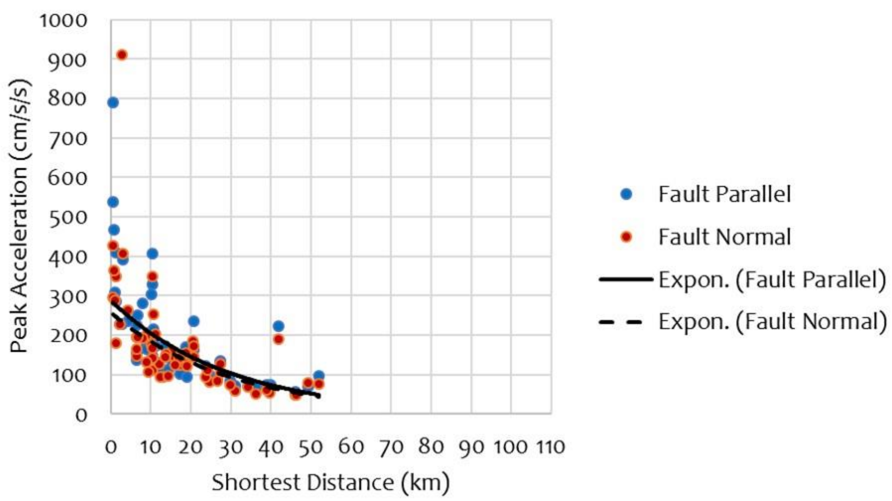

Fig.4 – Plot of PGA values recorded in fault normal and parallel directions at stations located on footwall side of the fault plane with respect to the shortest distance of the station to the fault plane

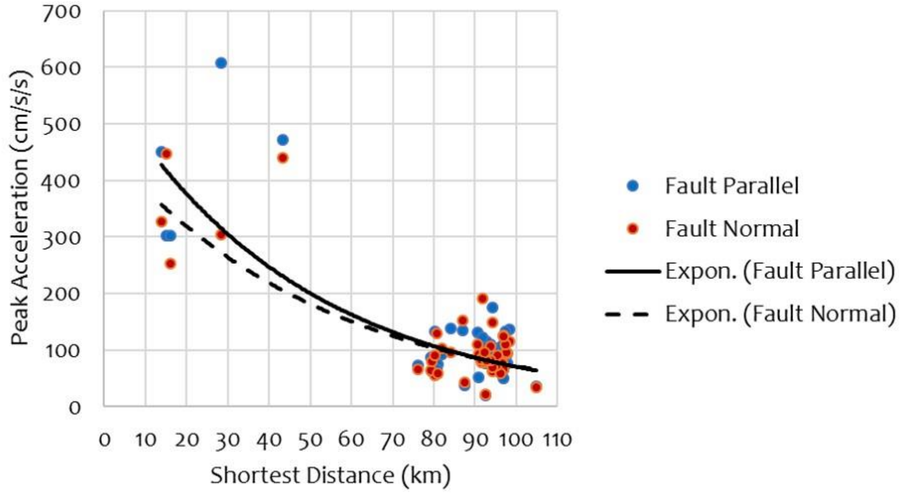

Fig.5 – Plot of PGA values recorded in fault normal and parallel directions at stations located on hanging wall side of the fault plane with respect to the shortest distance of the station to the fault plane

By observing both the plots in fig. 4 and fig. 5, it is evident that the average PGA values recorded on the hanging wall stations are higher compared to those on the footwall stations. Although this observation is reinforcing the existing literature [19, 20, 21, 22, 23], there are also exceptions for this trend at some stations. Apart from the comparison of PGA values on hanging wall and footwall stations, another explicit comparison that can be made is that the PGA values in the FP direction are higher than those in the FN direction at both the sets of stations. Reason for the above is the directivity. However, the difference between the values is very small at stations on footwall compared to the stations on hanging wall.

These discussed observations indicate that the ground motions exhibit hanging wall effect which is characterized by higher PGA values at stations on the hanging wall side. Although, the hanging wall effect requires all the stations on the hanging wall side to have higher PGA values. However, the studied ground motions indicate some exceptions at certain locations with higher values at footwall stations. This uncertainty can be attributed to the fault mechanism of the earthquake which is predominantly thrust with considerable amount of strike-slipping action at the north of the fault plane and sometimes also to the local site conditions at recorded stations. In general, the hanging wall effect is predominant in low dip-angle thrust faults that ensures required criteria of wedge formation between the fault plane and the surface of the earth. On the other hand, literature [23, 24, 25] suggests that hanging wall effect is very less predominant in strike-slip faults due to lack of such geometric conditions. Although, the ground motions recorded during Chi-Chi earthquake indicate hanging wall effect on an average scale, certain exceptions are inevitable due to combined faulting action of thrust faulting and strike-slip faulting.

Another characteristic of hanging wall effect that is noticed from this study is the difference in PGA values of FP and FN in the near-fault region. As mentioned earlier, the hanging wall stations indicate considerable difference in PGA values in FN and FP components with FP component higher than the FN. Although there may be several other reasons for this behavior, it may also be largely attributed to faulting mechanism of the earthquake. In a pure thrust faulting mechanism, it is intuitive to observe higher PGA values in the FN direction at a near-fault station since the resultant direction of slip is upwards and in the direction of FN. However, since this earthquake is caused due to mixed faulting mechanism with considerable strike-slip, majority of the stations near the end of the fault plane indicate higher FP components. Therefore, although the faulting mechanism consists of thrusting action, the higher average PGA on FP indicate predominant strike-slip faulting mechanism.

Apart from these observations, in general, the near-fault region of any earthquake is considered to be less than 20km – 30km as prescribed by different agencies. However, the present study indicates a highly sensitive characteristics of ground motion with hanging wall effect in the near-fault region that requires a particular definition of near-fault region apart from the distance parameter. Combining all the observations and interpretations of the characteristics of near-fault ground motions that exhibit hanging wall effect, the procedure to identify the near-fault region of the earthquake can be established. It is understood that the hanging wall effect is highly sensitive to the faulting mechanism of the earthquake. For a pure thrust faulting mechanism, it may be derived that the PGA ratio of FN to FP component is greater than one can be termed as a condition to define the near-fault region. On the other hand, if a complex faulting mechanism exists, the PGA ratio should be dependent on the predominant slip direction. For the present case study, the PGA ratio of FP to FN is observed to be greater than one in the near-fault region. Therefore, it can be said that the PGA ratio of FP and FN can be reliably utilized in defining the near-fault region in addition to the distance of the station from the fault plane.

4. Conclusions

The present study is carried out to observe and interpret the variation of characteristics of near-fault ground motions that exhibit the hanging wall effect. The discussions are made by observing the trends in the PGA values of the recorded ground motions during 1999 Chi-Chi, Taiwan earthquake. In addition to establishing the influence of hanging wall effect on certain characteristics of near-fault ground motions, a preferred method to identify the near-fault region of a particular earthquake is elaborated. It is identified that the hanging wall effect is highly sensitive to faulting mechanism of the earthquake. From the ground motions obtained at the recorded stations of the earthquake, the ratio of PGA of FP to FN is greater than one for the near-fault ground motions. Therefore, it can be established that the near-fault region distinctly exhibits PGA ratios greater than one. However, this is specific to the considered earthquake since intuition suggests higher PGA in the FN direction for a pure thrust fault. Although, the method still has uncertainty associated, the procedure that can be adopted for any earthquake of a particular faulting mechanism to identify the near-fault region from the recorded ground motions in addition to the distance of the recording station from the fault plane.

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