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APPLICATION OF WAVELET THEORY IN THE ANALYSIS OF EARTHQUAKE MOTIONS RECORDED DURING THE KOCAELI EARTHQUAKE, TURKEY 1999

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ABSTRACT

The Marmara region of Turkey was shaken by an earthquake with a magnitude of 7.4 and epicentre in Golcuk on August 17, 1999. Structural damage of various degrees occurred in the region. In this paper the strong motion data acquired from this earthquake at various locations are closely inspected using Fourier transform and a time-frequency technique using harmonic wavelets developed at Cambridge, Newland (1993). The advantage of harmonic wavelet analysis when dealing with non-stationary signals like earthquakes is that one can plot the signal in a time-frequency space enabling the energy distribution in the signal to be observed. An introduction to wavelet theory will be presented along with various methods for applying this theory to earthquake acceleration signals for analysis. Conclusions are drawn based on the application of wavelet method to the Kocaeli Earthquake strong motion data. These data is analyzed for four locations with increasing distance from the epicentre. The energy of a signal can be broken into its constituents at different frequency bands and time locations via wavelet analysis, giving insight into the localised portions of the signal. The magnitude of accelerations decreases as one moves away from the epicentre. Wavelet transform allows us to see the discontinuities within the signal and zoom in for closer inspection. Using the wavelets, it was observed that in the Kocaeli earthquake ground motions, acceleration with same frequency occurred at different time instants. This could not have been observed by traditional DFFT methods.

INTRODUCTION

Kocaeli and the Marmara region were shaken by an earthquake with a moment magnitude of 7.4 on the Richter scale on August 17, 1999 at 3.02am local time. Structural damage occurred in Kocaeli, Adapazari, Istanbul, Eskisehir, Zonguldak and Yalova. The earthquake lasted for 45-50 seconds and was felt as far away as Ankara about 300 km away from the epicentre in Golcuk, a suburb which is 11 km south-east of Izmit and 90 km east of Istanbul. Following the earthquake the north strand of the east-west extension of the North Anatolian Fault Zone (NAFZ) consisting of the Adapazari, Kocaeli, Golcuk segment was seen to have ruptured. Peak lateral ground accelerations of 0.41g were measured in Adapazari. The main shock was followed by many aftershocks with varying magnitudes. The focal depth of the main shock was estimated by the USGS as 17km, classifying it as a shallow earthquake. The Kocaeli earthquake has produced many acceleration time histories recorded at various strong motion stations. The main shock was registered by a total of 38 strong motion stations, ten of them were operated by the Kandilli Earthquake Research Centre of Bosphorus University, four of them by the Istanbul Technical University and the rest by the National Earthquake Research Department. The ten records of the Bosphoros University are digitally available from their website which is *http://www.boun.edu.tr*. Peak lateral acceleration of 0.41g in EW direction was measured in Adapazari, which was the maximum acceleration observed in this earthquake. The peak ground accelerations about 10km away from the epicentre at Yarimca Petrochemical Facility were 0.32g in EW, 0.23g in NS and 0.24g in UD. Unfortunately, strong motion recording instruments were sparse in the area where the damage was particularly severe. No data was available for Golcuk and its vicinity, the epicentral area.

Geology of the Region

A simplified geological map of the key features of the Marmara Region can be seen in Fig.1. The Adapazari city is located on an alluvial plain which overlies Quaternary Age alluvial deposits with alternating layers of gravel, sand, silt and clay. The groundwater level is shallow and is between 0.5m to 3.0m below ground level. Izmit is located on the northern and eastern side of Izmit Bay, on a coastal plain with a gentle slope to the south, towards the sea. It is underlain by Quaternary age deposits with alternating layers of clay, silt, sand, gravel and a dense silty fine sand. Avcilar, which is about 20km west of Istanbul's city centre, is located on a moderate to steeply inclined hillside facing south and east. The geological map shown in Fig.1 indicates that Pliocene age deposits underlie the Avcilar area and that Quaternary age deposits occur near Bakirkoy and Buyuk Cekmece with unconsolidated sand and gravel. (Kocaeli Earhquake, EEFIT,

2000) Overall, these soil conditions are considered to be problematic for building in such a high seismically active region.

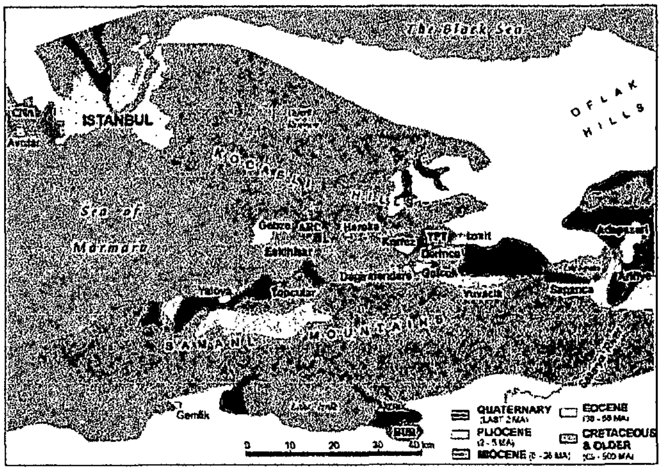


Fig.1 Simplified geological map of earthquake affected area. (After Kocaeli Earthquake, EEFIT, 2000)

The location of the four strong motion stations YPT, ARC, CNA, and BUR chosen for this paper are as shown in Fig.1. The reason these four stations were chosen among ten signals is due to their distance from the epicentre with YPT station being the nearest to the epicentre and BUR station the farthest. Therefore the change in the earthquake accelerations at YPT and BUR stations and the behaviour of earthquake as it progressed away from the epicentre could be investigated. Bursa Tofas Factory (BUR) station is located in the south-west and Cekmece Nuclear Center CNA in the north-west of the epicentre. At the Yarimca Petrochemical facility (YPT) station the instrument was placed on the ground floor of a three story high building in YPT. These signals used do not represent free-field conditions since they are all based within a building usually on the ground floor of a one or two-story building. The records obtained for YPT strong motion station is shown in Fig.2. These acceleration-time histories are only for the first 80 seconds of the earthquake and the sampling rate of the signals was 200Hz.

As can be seen from the records, YPT has recorded the peak acceleration in EW direction as 0.322g. YPT shows two distinctive peaks which might mean two particular earthquakes as seen in Fig.2. The first peak was at 10 seconds, then the second one at 42 seconds yielding the time between the two events of about 30 seconds. Comparing the ratios of the peak accelerations acquired in each direction between YPT signal and the others, the maximum ratio acquired between the NS components of YPT and ARC signals is 0.92. Table 1 shows the attenuation factors with respect to YPT station which is the closest to the epicentre being only 10 km away. All the acceleration traces have shown two significant peaks suggesting two earthquakes which happened with 30 seconds between each event.

Table 1 Normalised accelerations with respect to acceleration at YPT station.

Station	N-S	E-W	U-D	Epicentral Distance(km)
ARC	0.92	0.41	0.35	35
CNA	0.77	0.41	0.24	105
BUR	0.44	0.31	0.2	130

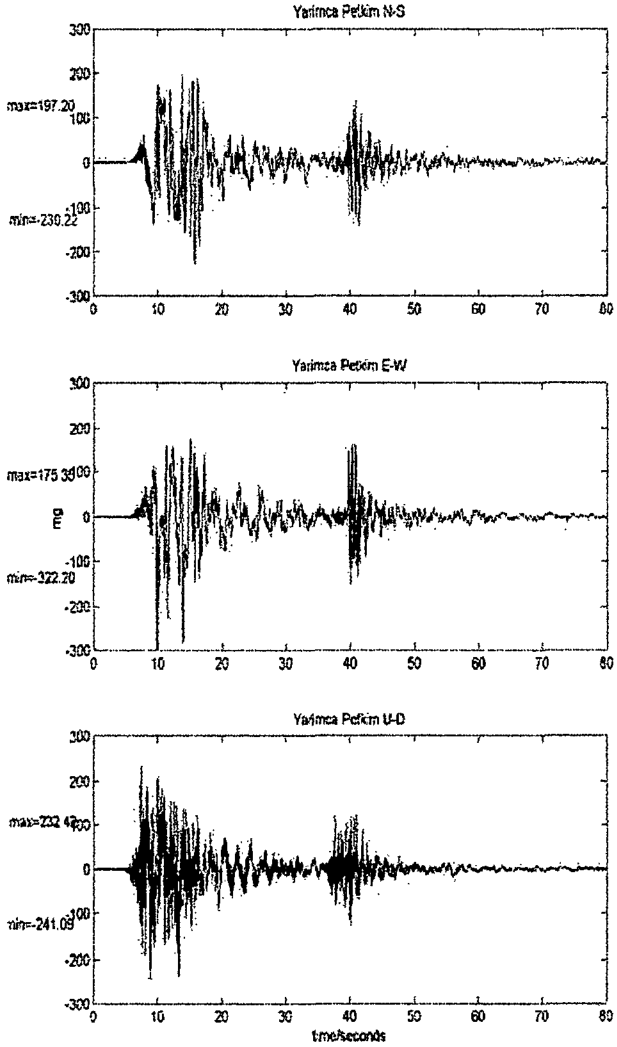


Fig.2. The acceleration time history of YPT station.

When analysing the strong motion data acquired from this earthquake, Fourier transform and a time-frequency technique using harmonic wavelets developed by Newland (1993) were applied, and spectral density graphs and wavelet maps were used. In the following sections an introduction to wavelet theory will be presented along with various methods for applying this theory to earthquake acceleration signals for analysis. Finally, conclusions will be drawn with the application of this methodology to the Kocaeli Earthquake, 1999.

METHODS OF ANALYSIS

The majority of signal analysis techniques include signal magnitude, as well as time domain, frequency domain and a combined time-frequency domain analysis. The last two provide detailed information about the signal. Time-domain and frequency-domain constitute two alternative ways of looking at a signal. In the time domain, signals can be analyzed in the form of the time histories and identifying signal peaks or any significant property of the signal. In the frequency domain analysis of continuous signals, the time history of a digital signal has to be converted into frequency domain using a Discrete Fast Fourier Transform (DFFT). Fourier transform allows us to switch from one domain to the other; however it does not combine the two domains. (Hlawatsch and Boudreaux-Bartesl, 1992). In the frequency domain, time information is not accessible and it does not provide time localization of spectral components; it only shows the overall frequency distribution. Using the frequency-time domain a Wavelet transform can be used to spot small details of a signal, which would not be recognized by any other method. For example, if a time signal had the same frequency of vibrations at two distinct times, such information will show up as a single peak in the DFFT plots. However, in the 3D time-frequency plots using the wavelet method, the frequency peaks would show up as two peaks at two different times. In other words, the localization of earthquake energy at different frequencies and time instants can be fully represented in one 3-D map.

Wavelet Analysis

Wavelet analysis provides an alternative way of breaking down a signal into its constituent parts. This is done through a system of combining the temporal and spectral domains. In wavelet analysis the signal is broken into a series of local basis functions called wavelets. A signal can be further decomposed into its wavelet components called levels, which are numbered from -1 upwards. When the separate wavelet levels are added together, the original signal is retrieved. A wavelet is described by its wavelet function, W(x), which is derived from the corresponding scaling function, $\phi(x)$, by taking differences. The dilation wavelet function is:

$$W(x)= \sum_{k=0}^{N-1}(-1)^k c_k \phi(2x+k-N+1) \qquad (1)$$

where c_k is the numerical constants. The same coefficients are used as for the definition of $\phi(x)$, but in reverse order and with alternate terms having their signs changed from plus to minus. For generation of appropriate wavelets, their coefficients have to be chosen carefully with particular attention to several conditions that these coefficients must satisfy (Newland, 1993). The main aim of the wavelet transform is to decompose any arbitrary signal f(x) into an infinite summation of wavelets at different scales according to the expansion:

$$f(x)= \sum_{j=-\infty}^{\infty} \sum_{k=-\infty}^{\infty} c_{j,k} W(2^j x-k) \quad . \qquad (2)$$

Harmonic Wavelets.

Harmonic wavelets have their Fourier transform defined by

$$\begin{aligned} W_{m,n}(\omega) &= 1/(n-m)(2\pi) && \text{for } m(2\pi)\leq \omega < n(2\pi) \\ &= 0 && \text{elsewhere} \end{aligned} \qquad (3)$$

where m and n are real and positive numbers. Inside the band $m(2\pi)$ to $n(2\pi)$ the function has constant magnitude which is normalised to ensure the enclosed area to be unity and outside this band it is zero. The corresponding wavelet function can be defined as follows;

$$w_{m,n}(x)= \{\exp(in2\pi x)-\exp(im2\pi x)\}/\, i2\pi(n-m)x \qquad (4)$$

Level m, n indicate a wavelet in the frequency band $m(2\pi)$ to $n(2\pi)$ where n>m. In order to form a complete set of wavelets, adjacent wavelet levels must have Fourier transforms with frequency bands touching each other, so that all values of ω along the axis 0 to ∞ are included. (Newland, 1995). Figure 3 and 4 show the real and imaginary parts of w(x) defined by equation (4) for the case when m=1 and n=2.

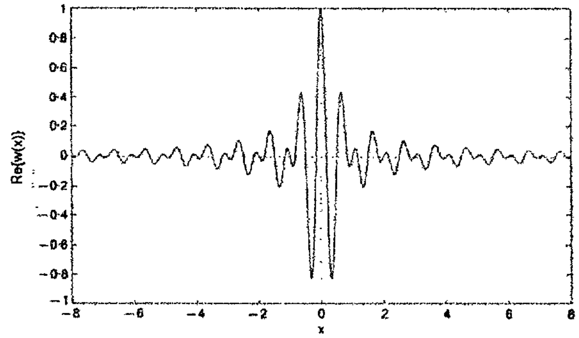


Fig.3 Real part of w(x).

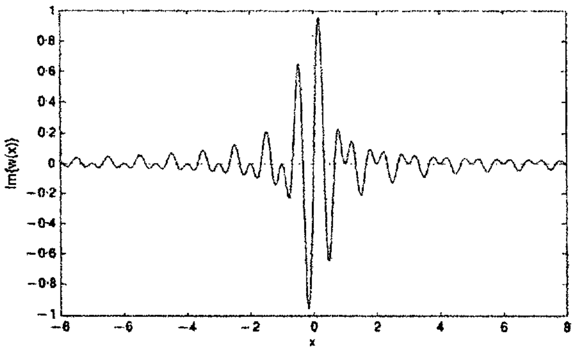


Fig.4. Imaginary part of w(x).

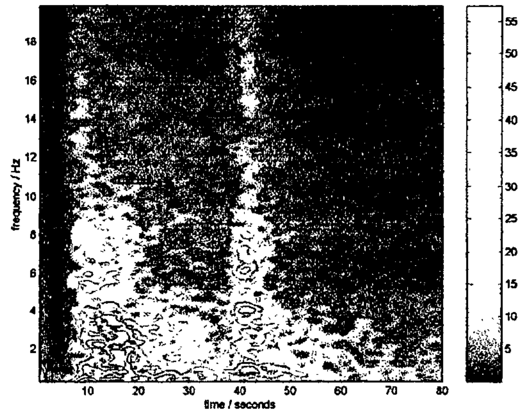
In Fourier analysis, frequency information can only be extracted for the complete duration of a signal f(t). The integral in the Fourier transform equation extends from -∞ to +∞ causing the information it provides in the frequency domain to arise from an average over the whole length of the signal. If there is a local oscillation in f(t), it will contribute to the Fourier transform F(ω), but its location on the time axis will be lost. The cause of the value of F(ω) at a particular ω is not known and it cannot be determined whether it is driven from frequencies present throughout the life of f(t) or during just one or a few selected periods. However in wavelet analysis, this disadvantage is overcomed. Through using wavelets, variations in frequency components with time can be observed.

WAVELETS

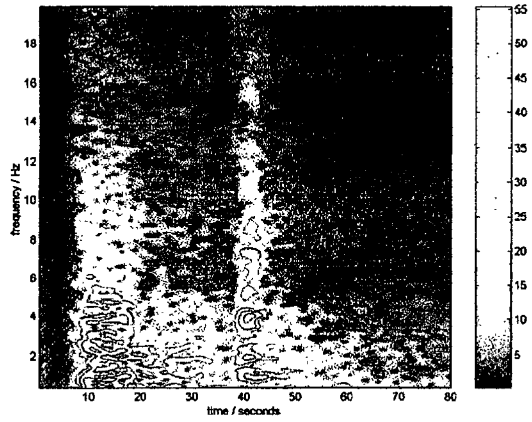
The wavelet program used, computes the harmonic wavelet transform of the record and plots the result as the time-frequency map covering the whole frequency range from 0 to Nyquist frequency. Time-frequency maps are the two-dimensional contour diagrams of the three-dimensional surface plots created from the harmonic wavelet transform calculations. The axes of the map are time plotted horizontally and frequency plotted vertically. Different color shadings represent the various contour levels.

Fig. 5 show the results of harmonic wavelet analysis for the signals from YPT station. It must be pointed out that the color scale is different for different plots, to maximize the resolution for each plot. In Fig.5 the first acceleration of YPT signal has a peak frequency of 0.3 Hz, and the second event a peak frequency content of 1Hz for NS observed at 10 and 42 seconds respectively can be seen. In the EW direction the first peak had a peak frequency of 0.125Hz and 1Hz at 10 and 42 seconds. These two events have different frequency contents at different times which can not be detected with Fourier analysis. Same frequency present at different times and, secondly, the presence of various frequencies at the same time can also be observed which cannot be distinguished by FFT. When one looks at the NS, EW, and UD components of YPT signal, two significant time bands involving various frequencies can be seen. The first one is between 8-20 seconds and then between 38-48 seconds. The 0-5 Hz frequency band is significant over 8 to 60 seconds of the NS and EW signal where this band extends to 8Hz for 5-50 seconds. These were not visible with the FFT graphs seen in Fig.6.

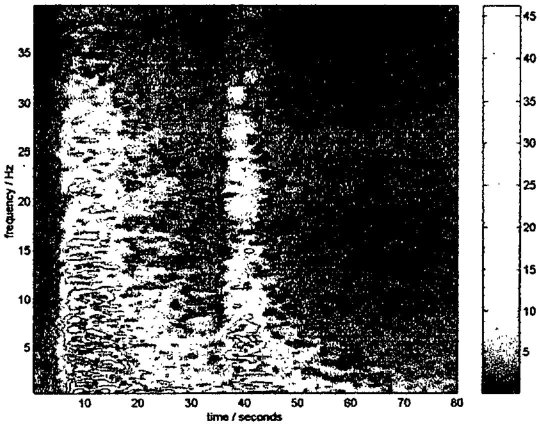
Frequency analysis using DFFT method was carried out on NS, EW and the UD components of YPT signal showing various frequencies between 0-10 Hz. Fig.6 shows the results of the frequency analysis of the signals from YPT station. The frequency contents of the YPT signals seen in Fig.6 shows the first peak at 0.3Hz, 0.125Hz and 0.4Hz for NS, EW and UD components respectively. These graphs show that there are various frequencies present for the duration of the earthquake. There is no one dominant single frequency in the signals. All the signals have different time-frequency patterns which can be seen by wavelets and not seen with the FFT analysis.



(NS component)



(EW component)



(UD component)

Fig.5. Wavelet analysis of YPT signal NS, EW and UD components.

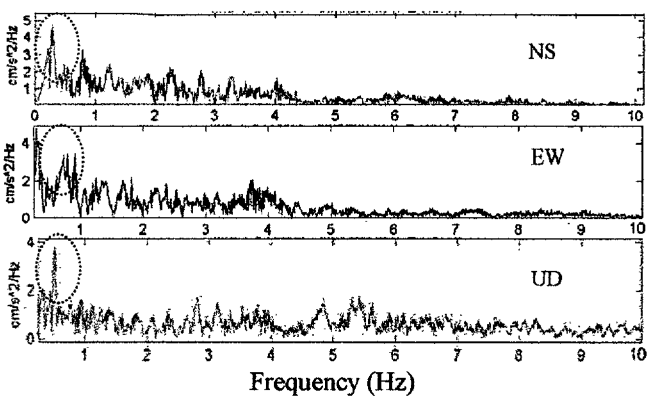


Fig.6 Fourier analysis of YPT signal.

ENERGY CAUSED BY THE EARTHQUAKE

The energy released during an earthquake is often estimated by the following relationship (Clough and Penzien, 1993):

$$\log E= 4.8+1.5M_s \qquad (5)$$

where: E is the energy in Joules and M_s: Surface wave magnitude. For a moment magnitude M=7.5 earthquake, the estimated energy released is 10^{16} joules. For the Kocaeli earthquake, a moment magnitude was calculated of 7.4 and surface wave magnitude of 7.8 by the USGS. Fig.7 shows the relative cumulative significant shaking, that is a representation of energy, calculated by summing the square of acceleration over time. The mesh plots which are 3-D visualization of time-frequency plane from wavelet analysis is presented in Figures 8-11. It must be pointed out that the color scale is different for different plots to maximize the resolution for each plot. Using both of the figures a comparison of energy distribution can be made. With the summation of the acceleration method for the YPT and ARC signals the significant shaking lasts for 15 seconds as seen in Fig.7. The energy in the signal, YPT can be seen by the mesh plot, Fig.8 where the build-up of energy can be seen between 5-20 seconds, indicating the duration of strong shaking to be approximately 15 seconds. This energy build-up can be seen in Fig.7, which were constructed by summing the square of the acceleration over time. In this graph two energy jumps can be seen, indicating the two consecutive energy releases from the source. 80% of the energy was reached after the first event and the rest from the second event.

Conversely, using the wavelet transform, it can be seen that the two peak points for Arcelik EW are located at 15 and 45 seconds. It should be noted that these peaks cannot be seen in the Summation of the Acceleration Traces technique. This occurs as a result of the fact that for the Summation of the Acceleration Traces technique, one is summing over the whole period with the energy of the second peak added onto that of the first peak.
EW component of YPT signal seen in Fig.8 has two significant mountainous areas representing a continuos band of energy at 20 and 50 seconds running along the whole frequency axis. This character was lost in FFT analysis due to the lack of the ability in representing the signal in a time-frequency plane. The ARC signal seen in Fig.9 shows one significant mountain at 20 seconds in EW direction. CNA signal has one peak at 30 seconds, but this time the mountainous area is between 0 to 8 Hz. EW has significant peaks and the acceleration between 0-8Hz as seen in Fig.10. In BUR signal shown in Fig.11, EW has peaks along 0-5Hz over the whole duration of the signal. Height and colour defines the amplitude of the energy in 3D mesh plots. The color bar shown on the right of the figures signifies the energy in the signals. The energy of a signal can be broken into its contributions from different frequency bands and time locations via wavelet analysis, giving insight into the localized portions of the signal. It should be pointed out that EW component has a lower value than the NS component in the summation of the acceleration traces even though peak acceleration in EW direction was more.

The duration of an earthquake was defined by Novikova and Trifunac (1994) as the time interval between the first and the last time when the acceleration exceeds the level of 0.05g or the time interval during which 95 percent of the total energy is recorded at the station. Using this definition and the summation of square of accelerations over time graphs, this earthquake can be established to have lasted about 35 seconds. The energy distribution was observed and the percentage of energy reached after the first event was observed as 80% of the total energy. The energy of a signal was broken into its contributions from different frequency bands and time locations via wavelet analysis and two significant mountainous areas representing a continuos band of energy was observed. The energy distribution as one moves away from the epicentre can be observed in Figures 8-11 along with the high frequency attenuation.

CONCLUSIONS

Even though the acceleration values were not high, the effective duration of the earthquake was about 35 seconds causing the damage to be intensified. The magnitude of accelerations decreases as one moves away from the epicentre. Wavelet transform allows us to see the discontinuities within the signal or the system and zoom in for closer inspection. Using the wavelets, it was observed that in the Kocaeli earthquake ground motions, acceleration with same frequency occurred at different time instants. This could not have been observed by traditional DFFT methods.

In this paper, four strong motion recording stations were looked at with increasing distances to the epicentre. Acceleration traces showed two significant peaks suggesting two distinct rupture events occurred. Methods of analysis used in this report included the traditional FFT method and the new wavelet method. The results of the FFT analysis are that as one moves away from the epicentre, frequency content of the signals changes. The change of frequencies with epicentral distance could not be correlated as it is suspected that the local geology and the super-structure play an important part in the amplification of attenuation of different frequency components. With the wavelet analysis, the different time-frequency patterns which could not be seen with the traditional FFT analysis were observed. Most frequencies concentrated between 10-20 seconds of the earthquake for YPT and ARC and for CNA and BUR signals between 20-30 seconds. Energy of the signals were looked at by 3-D wavelet maps and summation of the acceleration traces to see the total energy and spread of energy with time. Total energy and spreading of the energy was observed with summation of acceleration traces and wavelet mesh maps respectively. The energy of the earthquake decreases, as it travels away from the epicentre. The contribution from different frequencies and times to the energy of the signal was achieved with wavelet analysis. The contour maps aided in the observation of the variation of the earthquake characteristics with time and frequency.

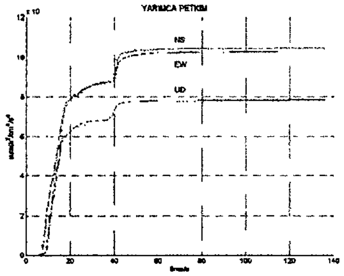


Fig. 7 The relative cumulative significant shaking calculated by summing the square of acceleration over time for YPT signal.

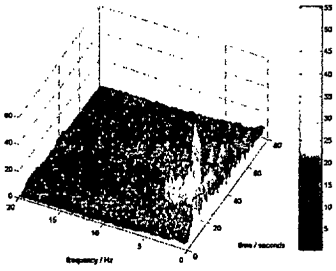


Fig.8. Mesh plot of YPT EW component.

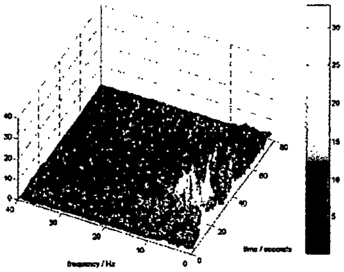


Fig.9. Mesh plot of ARC EW component.

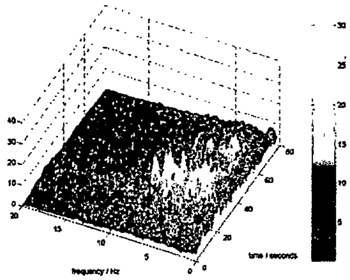


Fig.10 Mesh plot of CNA EW component.

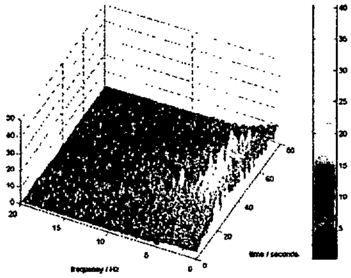


Fig.11 Mesh plot of BUR EW component.

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