The increased density of recording stations in the near to fault areas has permitted the collection of near field ground motion recordings which present characteristics quite different from those of the usual far field ground motions. These near field characteristics are mainly present in the form of large pulses in the ground velocity time history in sites towards which the fault ruptures. These pulses are due to a phenomenon called directivity. In the present lesson the directivity phenomenon is to be explained and its characteristics and effects presented.

Rupture generally progresses across a fault as a series of individual cracks or subevents. Each crack produces a dislocation or slip which has a duration called the rise time and a slip velocity or slip rate amounting to 50-150 cm/sec. Each crack creates a velocity pulse with duration equal to the rise time and amplitude equal to the slip rate. These pulses travel along the fault with the velocity of shear waves. At the same time the rupture spreads towards a certain direction with a rupture velocity similar to that of the shear waves. In the rupture direction rupture cracks and crack velocity pulses travel with the same velocity. Accordingly, in the rupture direction, a phenomenon similar to the Doppler phenomenon takes place. The generated pulses overlap and the waves arrive at an examined site in the rupture direction as a large pulse of motion- a shock wave effect- that occurs at the beginning of the record. The phenomenon is called forward directivity and the pulse of motion is typically characterized by large amplitude and short duration. At a site located near the epicenter, where rupture propagates away from the site, the arrival of the pulses is distributed in time. This condition, referred to as backward directivity, is characterized by motions with relatively long duration and low amplitude.

Rupture directivity effects can be present both for strike slip and dip slip events. As it can be seen from the plan view of a strike slip fault the radiation pattern of the crack dislocations, because of its polarization, causes the pulse of motion to be predominant in a orientation perpendicular to the fault plane and the fault trace. The same phenomenon happens with a dip slip fault where forward directivity conditions occur for sites located near the up-dip projection of the fault plane. As seen from the cross section of a dip slip fault, in that case also the pulse of motion is oriented perpendicular to the dip fault’s plane on a plane vertical to the fault trace. In reality, directivity velocity pulses occur in a bigger or smaller degree for different angles around the vertical component of the ground motion in such a way that the orientation of the velocity pulse is usually ambivalent.

In order to evaluate the possibility of directivity effects at a site in the near field region, Baker and Shahi have recently presented a model taking into account the azimuth of the examined site regarding the fault as well as the distance of the site from the fault plane. These authors present a method based on the well-known concept that the forward directivity, which is considered to be the cause of the pulselike ground velocity time history, depends on the source-to-site geometry according to Somerville et al (1997). Iervolino and Cornell (2008) showed that the parameters r, s and θ, for strike slip faults, as r, d and φ, for non-strike slip faults, permit a better prediction for the probability of pulse occurrence according to a logistic regression. The model, although it presents a 70% correlation for strike slip faults, where the direction of fault rupture can be considered coaxial with that of the fault strike, in the case of non strike slip faults has a correlation of only 30%. This is due to the fact that in non strike slip faults the dip of the fault is not necessarily coaxial with the fault rupture direction as the Shahi-Baker model presumes based on the Somerville (1997) parameters. In the case of the Athens event, the fault rupture appears to have a west-east direction where the dip direction is north-south. Since rupture directivity effects occur when the rupture front propagates towards the site and the direction of the fault is aligned with the site, a more sophisticated model, taking into account the configuration of the position of the examined site, the hypocenter location and the distribution of the asperities and the slip on the fault plane, has been proposed by Rowshandel. This model takes into account heterogeneous slip distribution, the existence of high slip asperities as well as the presence of geometrical complexities which can be called local directivity effects instead of the global effects associated with the Somerville model. It appears that such a model would be much more appropriate for the case of the Athens event since the most affected area is distributed along an axis normal to the vector of the fault rupture and not the dip of the fault. According to the above referred it is probable that in the case of non strike slip the simplified global model based on the Somerville parameters is not adequate. For the purpose of analyzing pulses, the model according to Somerville assumptions categorizes earthquakes in pure strike slip and dip slip events. This simplification does not allow a consideration of the complexity of the fault rupture, especially in the case of dip slip fault events. Rowshandel (2006) developed his more generalized model that does not need to take into account the fault characterization. The model takes into account the effects of any rupture type and can approximate segmented faults having complex fault geometry. According to the model, the geometrical directivity parameter ξ is given as:

$$\xi_j = \frac{\sum_{i=1}^{N} \Delta A_i \vec{r}_1 \cdot \vec{r}_2}{\sum_{j=1}^{N} \Delta A_i} = \frac{\sum_{i=1}^{N} \Delta A_i \cos\theta_{ij}}{A} \qquad \cos\theta_{ij} = \vec{r}_1 \cdot \vec{r}_2$$

where $\vec{r}_1$ is the unit vector defining the rupture direction from the hypocenter to each subfault on the rupturing area, $\vec{r}_2$ is the unit vector defining the direction from each subfault on the rupturing area to the recording site, ΔA_i is the increment of the fault area that ruptures in the direction $\vec{r}_1$, A is the total rupture area and θ is the angle between the $\vec{r}_1$ and $\vec{r}_2$ vectors . The values of ξ range from +1 to –1, indicating in the first case strong forward directivity and in the second case backward directivity effects. In the case under examination, it appears that the angles θ_{ij} dominating the ξ values are quite small in the case of the mostly affected sites. Accordingly, the Rowshandel model gives ξ values close to unity which indicate the existence of strong forward directivity effects at the sites under consideration.

Somerville parameterized the conditions that lead to forward and backward directivity. As shown the spatial variation of directivity effects depends on the angle between the direction of rupture propagation and the direction of waves traveling from the fault to the site (θ for strike slip faults and φ for dip slip faults) and on the fraction of the fault rupture surface that lies between the hypocenter and the site (X for strike slip faults and Y for dip slip faults). The greater the fraction of the fault rupture between the epicenter for strike slip faults and the hypocenter for dip slip faults, the largest the number of individual cracks of subevents are considered to exist between the hypocenter and the examined site and, accordingly a larger number of individual pulses are expected to accumulate at the examined site. When the angles θ or φ are larger the distance between the site and the fault plane is larger and consequently the pulse amplitude is attenuated. Since the pulses present characteristic periods that are usually over 1 sec, the directivity pulse effect is more pronounced in the spectral region of large periods. Accordingly, for large values of X and cosθ it is observed that the large period spectral values are amplified. As it can be seen from the relevant slide there exists an amplification for the spectral region larger than 1 sec. This amplification gets larger with the moment magnitude of the event and attenuates with the distance from the site to the fault plane.

Research has shown that simplified representations of the velocity pulse can capture the salient characteristics of the response of structures to near field ground motions. The simplified pulse representations of velocity time histories are defined by the number of the equivalent half cycles, the period of each half cycle and the corresponding amplitudes.

In what regards the period and the amplitude of the velocity pulses it appears that both items scale logarithmically with the moment magnitude of the earthquake. Strong motion recordings of recent large earthquakes confirm that the period of the near fault rupture directivity pulse increases with magnitude. The period of the near fault pulse is related to source parameters as the rise time which generally increases exponentially with magnitude. Characteristically, for a moment magnitude of 6 the pulse period can be less that 1 sec where for large magnitudes of about 8 such a period can be over 5 sec. As a rule it can be proved that the rise time during an earthquake can be considered as 50% of the pulse period.

In what regards the amplitude of the velocity pulse, this is considered to be significantly affected by magnitude, distance and site conditions. Generally, a linear relationship calculates the logarithm of the velocity amplitude from the magnitude and the logarithm of distance from the fault plane. From the presented graph the range of velocity amplitudes can according to magnitude and distance from 20 up to 300 cm/sec. Finally, the number of half-cycles range from 1 up to 3, with a usual number of 2 half cycles. The number of half cycles affect the spectral amplification. As the number of cycles increase the spectral amplification increases also. Since there is a major effect of the number of cycles on the response spectra expected for near field directivity effects, this parameter must be taken into effect when a model for the simulation of the directivity pulses is taken into account. Such case is the wavelet proposed by Mavroeides and Papageorgiou which will be referred as the M&P wavelet.

The M&P wavelet is derived by the coupling of a harmonic oscillation signal and a bell-shaped envelope. Four parameters are used to define the pulse:

- The period T_p of the harmonic oscillation of the wavelet.
- The amplitude A of the bell-shaped envelope, which is associated with the amplitude of the time history of the velocity.
- The duration γ of the wavelet, which measures the number of the oscillations and is defined as $\gamma = t_{tot} / T_p$ with $\gamma > 1$, t_{tot} being the time duration of the wavelet.
- The phase shift ν.

Using these parameters, the acceleration $a_p(t)$ and the velocity $v_p(t)$ of the wavelet can be defined by the following equations (Mavroeides and Papageorgiou 2003):

$$a_p(t)=\begin{cases} -\frac{A\pi}{\gamma T_p}\left[\begin{array}{l}\sin\left(\frac{2\pi}{\gamma T_p}(t-t_0)\right)\cdot\cos\left(\frac{2\pi}{T_p}(t-t_0)+v\right)\\ +\gamma\cdot\sin\left(\frac{2\pi}{T_p}(t-t_0)+v\right)\cdot\left[1+\cos\left(\frac{2\pi}{\gamma T_p}(t-t_0)\right)\right]\end{array}\right], & t_0-\frac{\gamma}{2}T_p\le t\le t_0+\frac{\gamma}{2}T_p \\ 0, \quad \text{otherwise} & \end{cases}$$

$$v_p(t)=\begin{cases}\frac{A}{2}\left[1+\cos\left(\frac{2\pi}{\gamma T_p}(t-t_0)\right)\right]\cdot\cos\left(\frac{2\pi}{T_p}(t-t_0)+v\right), & t_0-\frac{\gamma}{2}T_p\le t\le t_0+\frac{\gamma}{2}T_p \\ 0, \quad \text{otherwise} & \end{cases}$$

where t_0 is the time defining the epoch of the envelope's peak.

The ratio between the response spectra of the original ground motions and those of the residuals were estimated as proposed by Shahi and Baker. This ratio is a measure of the spectral amplification in the medium to long period range between pulse-like and non pulse-like records, indicated by Somerville. According to Shahi and Baker, the amplification presents a bell-shaped form around the pulse period. From the functional forms that were tested the best among them, for the minimization of the regression squared error, gave the following mean amplification function:

$$\mu_{ln\,Af} = \mathbf{1.131}\cdot exp(-\mathbf{3.11}\cdot(ln(T/T_p)+\mathbf{0.127})^2)+\mathbf{0.058} \quad if \quad T\le \mathbf{0.88}\cdot T_p$$

or

$$\mu_{ln\,Af} = \mathbf{0.896}\cdot exp(-\mathbf{2.11}\cdot(ln(T/T_p)+\mathbf{0.127})^2)+\mathbf{0.255} \quad if \quad T> \mathbf{0.88}\cdot T_p$$

where Tp is the evaluated pulse period.

The mean curve produced from the ratios between the spectra of the original records and those of the residual time-histories, has a definitely bell shaped form and values that are closely associated with the mean values presented by Shahi and Baker, in example an amplification value of about 3 at a period close to the T_p characteristic pulse period.

In what regards the estimation of the directivity pulse period a useful method has been in use. Generally, it is considered that the pulse period is equal with the predominant period of the 5% damping velocity response spectrum. In the present example, as it can be seen from the record a pulse period of about 4.3 sec can be estimated. A similar period appears as the predominant period of the 5% velocity response spectrum. The same can be seen in the case of the Tabas Iran, 1978 earthquake.

After the presentation of the main characteristics of the velocity pulses it is interesting to see the effects these pulses produce on the elastic and the inelastic response spectra. First in what regards the elastic response spectra we can observe that the acceleration spectra present and amplification at the period range near the period of the directivity pulses. Taking the ratio between the fault normal and the fault parallel components of the ground motion, it appears that this amplification is bell shaped with a central period close to that of the directivity pulse. The mean amplification present a value of 3 regarding the corresponding values of the fault parallel component. Generally the fault parallel component is considered to represent the shape of the type of records not presenting directivity pulses. Accordingly, the fault parallel component is close to the shape of the usual spectra given by aseismic regulations. The same bell shaped amplification is present in the displacement spectra where it can be seen that the fault normal spectra present a serious amplification of values greater than the regulation spectra. The fault parallel spectra are in most cases compatible with the spectra as given by the aseismic regulations.

In what regards the inelastic spectra it appears that in the case of periods smaller that characteristic pulse period, the ductility is quite large than the corresponding reduction factor. As the period gets smaller the ductility- reduction factor ratio gets larger. For periods equal or larger than the pulse period the ratio is close to unity, with ductilities equal to the reduction factors. Usually this increase for large periods is up to the half of the pulse period.

Cases of Aquila and Athens

In the case of the Aquila earthquake ther referred effect on the elastic and inelastic spectra is obvious.

In what regards the records obtained during the Athens earthquake they were at sites at a distance from the mostly affected area, concentrated at the metropolitan subway stations near the center of the Athens conglomeration. From these records two observations can be made which enhance the probability of forward directivity effects during the Athens earthquake. First, the existing records present a strong ground motion duration of a few, three to five, seconds that, according to Elenas, indicate a compression of the seismic waves duration associated with near field effects. A further indication obtained from the existing records is that the predominant periods of the velocity response spectra are between the limits expected for the pulse periods for events of such magnitude as calculated by established regression relationships. The existing records were analyzed in order to evaluate the possibility of inherent velocity pulses. The records were rotated and most of them, at angles from 135 up to 160 degrees, present distinct velocity pulses with periods from 1.4 to 1.7 seconds. In the case of the Sepolia station where the soil is very soft the pulse period is about 2.0 sec.