Near-fault ground motions have special characteristics that affect the response of structures. Their importance in earthquake design of civil structures was not fully realized until several failures occurred during the 1994 Northridge and 1995 Kobe earthquake events. The objective of this study is to investigate the effect of near fault earthquakes on the response of reinforced concrete structures. A new technique based on digital filters is proposed to identify the special characteristics of near-fault ground motion and also to separate the near-fault pulses from the geological noise. The proposed method shows when a smoothed near-fault record with the same pulse duration and PGV can substitute the complete near-fault record. The response of flexible structures when subjected to filtered near-fault records was very close to the response of the complete near-fault record while for stiff structures the response is highly dependant on the high frequency content of the near-fault record. This shows that velocity pulses dominate the inelastic response to near-fault records for flexible structures. For this type of structures, conventional code design methodologies do not satisfy the actual demands of near-fault records. It was found that the response of structures to near-fault ground motion is substantially different from the response to far-field earthquake records. It is concluded that codes should address the near-fault motion explicitly in time history form and not by the implicit form of increasing the coordinates of the design response spectra.

FILTERING NEAR-FAULT RECORDS

Following the 1994 Northridge and the 1995 Kobe earthquakes, near-fault pulse-type ground motion has attracted the interest of earthquake engineers. These events are characterized by the occurrence of the earthquake under a heavily urbanized area or very close to it. The 1992 Cairo earthquake was also close to the urban areas to generate near fault effects. The earthquake ground motion in the region within 15 to 20 km of the fault is characterized by large amplitude pulse with low frequency in both the velocity and displacement time histories. These pulses represent high input energy to the structure and results in different structural response than that due to far-field earthquakes. Ground motions with high velocity pulses were not included in the development of current design methodologies. In earthquake engineering practice, the severity of the ground motion is often measured by the peak ground acceleration (PGA) while for the near-fault records this is not always true. The acceleration record in the near-fault may contain high PGA value that corresponds to a short duration pulse with little or no effect on the structure. On the other hand, a low PGA with long duration pulse may have severe damaging effects on civil engineering.
In the near-fault, the propagation of the fault rupture toward a site at a velocity very close to the shear wave velocity makes most of the seismic energy from the rupturing process arrive in single large pulse of motion. A simplified representation of strong ground motion was proposed with one cycle sine wave whose acceleration amplitude is the PGA of the near fault record and with a period computed by minimizing the differences between the near-fault earthquake response spectra and the response spectra of idealized pulse. This simplified method have used the PGA to express the actual damage to the structure and consequently the pulse duration needs to be adjusted in order to obtain close results for single degree of freedom system, SDOF. This methodology may work only for SDOF. Changing the near-fault pulse duration, which it is a key parameter of near-fault records, will change the way the structure will respond. Alavi studied the elastic and inelastic response of frame structures subjected to near-field motion. The sensitivity of the structural response to the ratio of near-fault pulse to the natural period of the structure was illustrated. This effect was noted on the distribution of the elastic storey shear forces over the height. The traveling wave effect causes highly non-uniform distribution of ductility demands over the height. An attempt was made to characterize the near-field ground motions based on minimizing the differences between the structural response to both idealized pulses and near-fault records. The output of this procedure is the effective peak ground acceleration for each near-fault earthquake record. The effective PGA for the idealized pulses is dependant on the ductility of the structure to be analyzed. The generalization of this procedure is difficult because of the combination of effect of high frequency and low frequency components of the near-fault records.

It is important to incorporate the special effects of near-fault ground motion in building design codes. Simplifying the near-fault effects should be done in a way that preserves the pulse duration and magnitude. Understanding the special frequency characteristics of near-fault ground motion and how it affects different structural configurations is crucial to the development of relevant design guidelines for structures located in the near-fault regions.

CHARACTERISTICS OF NEAR-FAULT RECORDS

Near-fault records are characterized by long duration pulses attributed to the rupture directivity effect, style of faulting and hanging wall effects for thrust faults. The peak acceleration, the peak velocity or the peak displacement of the pulse can be used to describe these near-fault pulses. Usually the peak ground acceleration PGA is the parameter associated with severity of ground motion. Unfortunately, PGA does not correlate well with the damage potential. Near-fault records may contain acceleration spikes or long duration pulses of low frequency. In the first case, the high-recorded peak acceleration is of short duration, which may be out of the range of the natural frequencies of most structures. Therefore, large values of PGA with short duration alone can seldom initiate either resonance or be responsible for damage in the inelastic range. However, in the second case significant deformation of the structure even with lower PGA can occur.

Since the PGA is inappropriate for quantifying near-fault effects, the focus is directed to the velocity and displacement pulses. The peak ground velocity (PGV) corresponds to the integration of relatively large pulses in the acceleration time history. The displacement time history may also contain large pulse, which can be used to quantify near-fault records. However, most recording systems do not adequately record the complete permanent displacements, which are filtered out of the records during processing. This leaves the velocity pulses as the most representative parameter for quantifying the characteristic of near-fault records based on the damage potential of these records.

FILTERING NEAR-FAULT RECORDS

A set of 5 near-fault records from major earthquake events was selected to demonstrate the proposed method for the identification of near-fault characteristics. The selection of the earthquakes was based on major events with moment magnitude larger than 6. The records were made at horizontal distance to the surface projection of the rupture no further 5 km (Table 1).

Digital filters can be used in the process of separating low frequency signals from geological noise in near-fault records. Digital filters are of two main types; non-recursive and recursive filters. Non-recursive filters generate the output signal solely from the current and previous input values. This type is also known as Finite Impulse Response (FIR) filter. A recursive filter uses the input values of signal as well as the previous output values, and it is usually called Infinite Impulse Response (IIR) filter. The order of the FIR filters is the number of previous inputs used to calculate the current output while for IIR it is the largest number of previous input or output values required to compute the current output.

The main advantage of the IIR filter is that it has the same performance with a much lower filter order than a corresponding FIR filter but FIR filters are always stable. In this study the IIR filters were selected because they typically meet a given set of specifications with a much lower filter order than a corresponding FIR filter. While using IIR filters, instabilities may occur at the end of the output record.
**Table 1. Properties of selected near-fault ground motion records**

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>Date</th>
<th>Station</th>
<th>Fault Dist. (km)</th>
<th>Comp. (Deg.)</th>
<th>PGA (g)</th>
<th>PGV (cm/s)</th>
<th>PGD (cm)</th>
<th>ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superstition Hills</td>
<td>11/24/87</td>
<td>5051 Parachute Test Site</td>
<td>0.7</td>
<td>225</td>
<td>0.46</td>
<td>112.00</td>
<td>52.80</td>
<td>SH-PT-1</td>
</tr>
<tr>
<td>Kobe, Japan</td>
<td>1/16/95</td>
<td>Kobe University</td>
<td>0.2</td>
<td>90</td>
<td>0.31</td>
<td>34.20</td>
<td>7.14</td>
<td>KB-KU-2</td>
</tr>
<tr>
<td>Tabas, Iran</td>
<td>9/16/78</td>
<td>9101 Tabas</td>
<td>3.0</td>
<td>TR</td>
<td>0.85</td>
<td>121.40</td>
<td>94.58</td>
<td>TB-TB-2</td>
</tr>
<tr>
<td>Landers, CA</td>
<td>6/28/92</td>
<td>24 Lucerne</td>
<td>1.1</td>
<td>275</td>
<td>0.73</td>
<td>146.50</td>
<td>262.70</td>
<td>LA-LC-2</td>
</tr>
<tr>
<td>Erzincan, Turkey</td>
<td>3/13/92</td>
<td>95 Erzincan</td>
<td>2.0</td>
<td>NS</td>
<td>0.52</td>
<td>83.90</td>
<td>27.35</td>
<td>ER-ER-2</td>
</tr>
</tbody>
</table>

**IDENTIFICATION OF NEAR-FIELD PULSES**

Analysis of near-field ground motion in the frequency domain can be conducted by plotting Fourier amplitude versus frequency to produce what is known as Fourier amplitude spectrum. Fourier amplitude is a measure of the input energy at various frequencies. The amplitude spectra are roughly constant over the range between $f_c$ and $f_{max}$, at lower frequencies the amplitude decreases with decreasing frequencies. The point where this occurs is called the corner frequency $f_c$ and depends primarily on the size of the source. At higher frequencies there is a tendency for the motion to attenuate after $f_{max}$ since the concern is with velocity pulses in the near-fault region, identification of the cut off frequency of the velocity record may be useful in order to separate low frequency pulses from the superimposed high frequencies. Figure 1 shows the velocity amplitude spectrum with an estimation of the cutoff frequency for Kobe record.

The spectrum was smoothed in an approximate manner. More accurate smoothing can be achieved by minimizing the sum of the square error between the jagged spectrum and the smoothed one. The calculation of the cutoff frequency from the logarithmic Fourier amplitude spectra may be inaccurate because of the nature of the logarithmic scale. A practical method to determine the cutoff frequency is that once the duration of the major velocity pulse is identified by inspection, the corresponding frequency can be calculated as $1/T_p$. This frequency can be used as the cut off frequency for the lowpass filter. This simplified method satisfies the objective of preserving the velocity pulse in the filtered record without changing its magnitude or duration.

As a result of filtering the velocity record, the acceleration time history is changed especially if the original record contains high frequency spikes. Figures 2 and 3 show a comparison between recorded and filtered time histories for SH-PT-1 and TB-TB-2 records, respectively. SH-PT-1 record represents near-fault records that contain several peaks in the velocity power spectrum but they all correspond to low frequency pulses. As the filter is applied to SH-PT-1 record no significant change in the PGV and minor changes to the PGA result. TB-TB-2 earthquake record has completely different characteristics than SH-PT-1. High frequencies are superimposed on the near-fault velocity pulse but with low input energy. Comparison between recorded and filtered time histories for TB-TB-2 record shows small variations in the PGV before and after applying the filter but the PGA for filtered signals is significantly smaller than the recorded one. It is believed that the near-fault low frequency pulse is responsible for most of the damage in flexible structures even when it has relatively low PGA.

**RESPONSE SPECTRUM**

The acceleration, velocity and displacement response spectra for 5% damping are plotted for both unfiltered and filtered time histories for SH-PT-1 and TB-TB-2 records in Figures 4 and 5, respectively. For the SH-PT-1 record, the response spectra of the unfiltered and filtered records agree reasonably well for building with natural period more than 1 second. However, for TB-TB-2 the difference between the response spectra of unfiltered and filtered records is significant. Close results can only be achieved for long period structures with fundamental period more than 3 seconds. This means that the high frequencies in near-fault records do not influence the damage potential of flexible structures. If the record contains only low frequency pulses both filtered and unfiltered records will result in...
the same response as in the case of SH-PT-1 record. If the record contains high frequencies superimposed on the low frequency pulse with the high frequencies near a natural frequency of the structure, the filtered record cannot represent the actual earthquake record. In this case, the response of the structure is similar to their response to far-field earthquake records but with higher PGA. For flexible structures the first mode response to the unfiltered and filtered records are almost equal for all near-fault records as the structure natural period is long. However, for higher mode effects there may exist significant differences between the response to the unfiltered and filtered records as in the case of TB-TB-2 record. Considering that the modal participation factor for the first mode is normally much higher than that from higher modes, the total error in the response to filtered records may be small.

RESPONSE OF MDOF SYSTEMS
Two reinforced concrete frame structures of six and twenty storeys were designed according to current codes6, 7. These buildings represent two classes of stiff and flexible structures with natural periods of 1.48 and 3.28 seconds. To determine the nonlinear dynamic response of these reinforced concrete frames a three-dimensional nonlinear static and dynamic structural analysis program was used8. CANNY cross-peak trilinear pinching model was used to model the inelastic behavior of beam elements. Multi-spring hysteresis model was used to model the columns.

Figure 6 compares the roof displacement time histories for both frames due to unfiltered and filtered records of the SH-PT-1 earthquake. In the frequency domain, several peaks with frequencies equal to or less than 0.55 Hz are observed. The roof displacements have a similar response under both the unfiltered and filtered records for both structures. The maximum response occurs at 10 to 12 seconds from the start of the record corresponding to the large velocity pulse in the velocity time history. This illustrates how the near-fault characteristic of the velocity pulse is dominating this record and consequently the response of different structures.

Figure 2. Acceleration, velocity and displacement time histories for filtered and unfiltered SH-PT-1 record.
Figure 3. Acceleration, velocity and displacement time histories for filtered and unfiltered TB-TB-2 record.

Figure 4. Elastic response spectra of unfiltered and filtered TB-TB-2 record.
Figure 5. Elastic response spectra of unfiltered and filtered SH-PT-1 record.

Figure 6. Roof displacements due to recorded and filtered SH-PT-1 record.

Figure 7. Roof displacements due to recorded and filtered TB-TB-2 record.
Figure 7 shows the roof displacement due to TB-TB-2. This time history has high frequencies with large amplitudes superimposed on the near-fault pulses. This results in significant differences between the peak ground acceleration for unfiltered and filtered records. While the PGA for actual TB-TB-2 record is 0.88 g, the filtered record has a PGA of 0.11g. This makes the ratio of PGA filtered/unfiltered very low (0.13). The response due the filtered record does not represent the response of 6-storey frame, which is a stiff frame. In this case, the near fault characteristic may only be represented by how severe is the record in terms of PGA and the effect of velocity pulse is minimum.

The response of the 20-storey frame due to unfiltered and filtered records is close. For such a flexible structure, the near-fault effects are more significant and the higher frequencies are filtered out by the structure itself. The maximum roof displacements due to the unfiltered and filtered records are 1.63 m and 1.78 m, respectively. It is not surprising that the response due to the filtered records even exceed the unfiltered record because of the phase difference between the high frequency and low frequency content of the record. This out of phase effects may reduce the total displacement at some locations and may increase it at others.

**CONCLUSIONS**

1. The separation of the low frequency component of near-fault record from the high frequency content by applying digital signals filters seems to be a realistic method for obtaining the near-fault pulse parameters. This procedure provides some basis to justify and clarify when idealized pulses can substitute the complete near-fault record. The high frequency content of near-fault records affects the response of stiff structures. As the stiffness of the structure decreases the high frequencies only affect the top part of the building.

2. For near-fault records, PGA is a misleading indicator of the damage potential. This study shows how a low level of PGA may be responsible for most of deformation demands in the structure. Alternatively, PGV is an independent parameter, which when combined with the pulse duration can give a complete description of the near-fault characteristic of the record.

3. It is observed that structures designed to meet the minimum code requirements will suffer damage due the high displacement demands of near-fault earthquake records.

**REFERENCES**


