The Next Generation of Ground Motion Attenuation Models NGA Project was undertaken to develop new attenuation models - ground motion prediction relationships for shallow crustal earthquakes in the western United States and similar active tectonic regions. As already referred previously the attenuation models modify the earthquake waves with distance from the earthquake focus in order to give the characteristics of the earthquake vibrations below a site at bedrock level. Attenuation models are usually coupled with a site response model in order to adjust the earthquake ground shaking at a site for the influence of weathered rock and overlying soils on the propagating waves. These typically amplify the vibrations, thereby causing a greatly accentuated impact upon certain building types.

The presented herein NGA project has been accomplished through a comprehensive research program that has included the following components:

- Developing separate ground motion models by five teams which developed independently their models but interacted extensively with one another throughout the development process
- Developing an updated and expanded Pacific Earthquake Engineering Research Center ground motion database that provided the recorded ground motion data and the supporting information about the recordings that were used in developing the ground motion models

To meet the needs of the earthquake engineering community all NGA models were initially required to be applicable to the following:

- Ground motion parameters of peak ground acceleration PGA, peak ground velocity PGV and 5% damped elastic pseudo response spectral accelerations in the period range of 0 to 10 seconds
- Average horizontal ground motion, as well as ground motion in the fault strike normal and fault strike parallel directions. In the first part of the NGA project there was a concentration on the average horizontal component of the ground motion.
- Shallow crustal earthquakes (strike slip, reverse and normal earthquakes) in the western United States and similar regimes.
- Moment magnitude range of 5 to 8.5 for strike slip earthquakes and 5 to 8 for reverse and normal earthquakes
- Distance range of 0 to 200 km
- Commonly used site classification schemes.

To provide a common database of recorded ground motions and supporting information for the ground motion model developers, the NGA project conducted an extensive update and expansion of the PEER database. The magnitude distance distribution of the new earthquake data that have been added to the PEER is shown superimposed on the preexisting data. The expanded data set includes 173 earthquakes, 1456 recording stations and 3551 multicomponent recordings.

The following effects on ground motions were taken into consideration:

- Moderate to large magnitude scaling at close distances

- Distance scaling at both close and far distances
- Rupture directivity
- Footwall versus hanging wall for dipping faults
- Style of faulting (strike-slip, reverse, normal)
- Depth to faulting (buried versus surface rupture)
- Site amplification relative to reference rock condition
- Basin amplification versus depth to basement rock.

A decision made by all developers was to use as a characteristic of the soil deposit at the examined site the average shear wave velocity in the upper 30 meters of sediments. The parameter V_{S30} was used for characterizing effects of sediment stiffness on ground motions.

Presentation of the distribution map of the 173 earthquakes in the NGA database.

Comparison of distance scaling of PGA for strike slip earthquakes for V_{S30} = 760 m/s

Comparison of distance scaling of T=1 sec for strike slip earthquakes for V_{S30} = 760 m/s

Herein we shall discuss certain effects that are not taken into account in all NGA developed models . Of special interest is the effect of the hanging wall and the footwall in dipping faults. As previously referred the hanging wall is the part of the fault over the faultplane on which the epicenter usually is located. In the presentation both a view as well as a map view and a cross section of the hanging and the foot wall are presented. In what regards the effect of the hanging wall on the ground motion at a site it can be seen that sites situated on the hanging wall are much more affected than sites laying on the footwall, although both kind of sites may be equidistant from the upper edge of the fault rupture. Furthermore it is interesting to observe that in the case of buried rupture where there is not a surfacial indication of the fault rupture the effect at the ground motion at a site are much stronger . The only exception is at the region next to surface eruption of the fault rupture in case the rupture is not buried.

Another interesting case affecting te ground motion is the existence of basin effects. In that case the waves entering from beneath can propagate nearly vertically as the reach the surface and are modified by resonance and impedance contrast effects. The waves entering through the edge can undergo critical body wave reflections that generate surface waves that travel across the basin. If the seismic waves enter a sedimentary layer from below will resonate within the layer but escape if the layer is flat. They become trapped in the layer if it has varying thickness and the wave enters the layer through its edge. In this illustration the basin amplification as a function to depth given as the 1.5km/ second isosurface is presented. The values are presented for three different periods with the mean values and the standard deviations. Another example is presented regarding the same phenomenon where you see that the phenomenon is amplified for larger periods due to surface wave effect.

Another interesting result is the correlation existing between the depth to the bedrock and the V_{S30} velocity. It can be seen that the larger the depth the smaller the velocity can be considered.

In this lecture the simplest but quite efficient model given by Boore-Atkinson will be presented. The model takes into account of course the magnitude and the distance scaling. The effect of the hanging wall is taken into account by the use of the Joyner-Boore distance which is the shortest distance from the site to the horizontal projection of the fault rupture. If the site lies in the horizontal projection the Joyner-Boore distance is considered as zero it appears that this distance is quite efficient in taking into account the hanging wall phenomenon. Finally, of special interest is the fact that the model takes into account in its site response approximation the effect of the inelastic response of the site deposit. We know that as a result of the inelastic response both the shear modulus and the damping of the soil deposit change. So, in order that the model takes into account the inelastic response it calculates a value pga4nl which represents the peak ground acceleration for a soil with V_{S30} velocity equal to 760 m/sec. the larger this acceleration the smaller the peak ground acceleration of softer soil deposits because of inelastic response of the soft soil deposit. It is of interest to see that for quite large pga4nl values the ground acceleration can be smaller than pga4nl. This means that the S values given by the EC8 are in favour of security.

The distance and magnitude functions are given

Phenomenon of saturation of pga for large magnitudes.

THE DISTANCE AND MAGNITUDE FUNCTIONS

The distance function is given by:

$$F_D(R_{JB},\mathbf{M}) = [c_1 + c_2(\mathbf{M} - \mathbf{M}_{ref})]\ln(R/R_{ref}) + c_3(R - R_{ref}), \tag{3}$$

where

$$R = \sqrt{R_{JB}^2 + h^2} \tag{4}$$

and c_1, c_2, c_3, $\mathbf{M}_{ref}$, R_{ref}, and h are the coefficients to be determined in the analysis.

The magnitude scaling is given by:

a) $\mathbf{M} \leq \mathbf{M}_h$

$$F_M(\mathbf{M}) = e_1 U + e_2 SS + e_3 NS + e_4 RS + e_5(\mathbf{M} - \mathbf{M}_h) + e_6(\mathbf{M} - \mathbf{M}_h)^2, \tag{5a}$$

b) $\mathbf{M} > \mathbf{M}_h$

$$F_M(\mathbf{M}) = e_1 U + e_2 SS + e_3 NS + e_4 RS + e_7(\mathbf{M} - \mathbf{M}_h), \tag{5b}$$

where U, SS, NS, and RS are dummy variables used to denote unspecified, strike-slip,

SITE AMPLIFICATION FUNCTION

The site amplification equation is given by:

$$F_S = F_{LIN} + F_{NL}, \tag{6}$$

where F_{LIN} and F_{NL} are the linear and nonlinear terms, respectively.

The linear term is given by:

$$F_{LIN} = b_{lin} \ln(V_{S30}/V_{ref}), \tag{7}$$

where b_{lin} is a period-dependent coefficient, and V_{ref} is the specified reference velocity (=760 m/s), corresponding to NEHRP B/C boundary site conditions; these coefficients were prescribed based on the work of Choi and Stewart (2005; hereafter "CS05"); they are empirically based but were not determined by the regression analysis in our study.

The nonlinear term is given by:

a) $pga4nl \leq a_1$:

$$F_{NL} = b_{nl} \ln(pga\_low/0.1) \tag{8a}$$

b) $a_1 < pga4nl \leq a_2$:

$$F_{NL} = b_{nl} \ln(pga\_low/0.1) + c[\ln(pga4nl/a_1)]^2 + d[\ln(pga4nl/a_1)]^3 \tag{8b}$$

c) $a_2 < pga4nl$:

$$F_{NL} = b_{nl} \ln(pga4nl/0.1) \tag{8c}$$

where a_1 (=0.03 g) and a_2 (=0.09 g) are assigned threshold levels for linear and nonlinear amplification, respectively, pga_low (=0.06 g) is a variable assigned to transition between linear and nonlinear behaviors, and $pga4nl$ is the predicted PGA in g for V_{ref} =760 m/s, as given by Equation 1 with F_S=0 and ε=0. The three equations for the nonlinear portion of the soil response (Equation 8a–8c) are required for two reasons: 1) to prevent the nonlinear amplification from increasing indefinitely as $pga4nl$ decreases and

2) to smooth the transition from linear to non-linear behavior. The coefficients c and d in Equation 8b are given by

$$c = (3\Delta y - b_{nl}\Delta x)/\Delta x^2 \tag{9}$$

and

$$d = -(2\Delta y - b_{nl}\Delta x)/\Delta x^3, \tag{10}$$

where

$$\Delta x = \ln(a_2/a_1) \tag{11}$$

and

$$\Delta y = b_{nl} \ln(a_2/pga\_low). \tag{12}$$

The nonlinear slope b_{nl} is a function of both period and V_{S30} as given by:

a) $V_{S30} \leq V_1$: