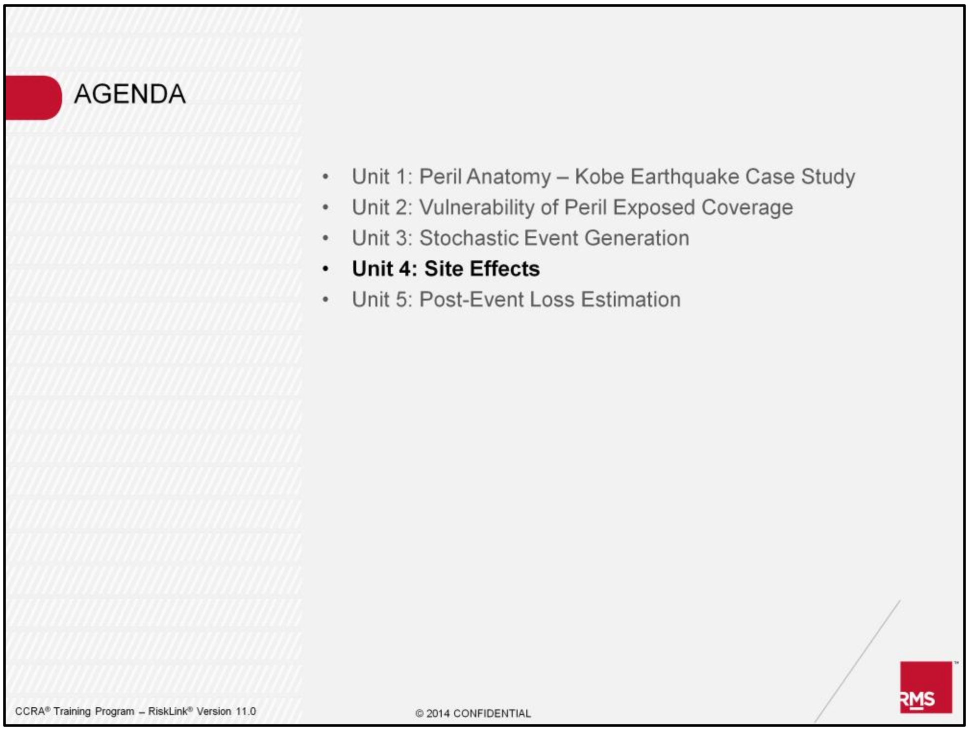
EARTHQUAKE MODELING UNIT 4

RMS® CCRA® Training Program



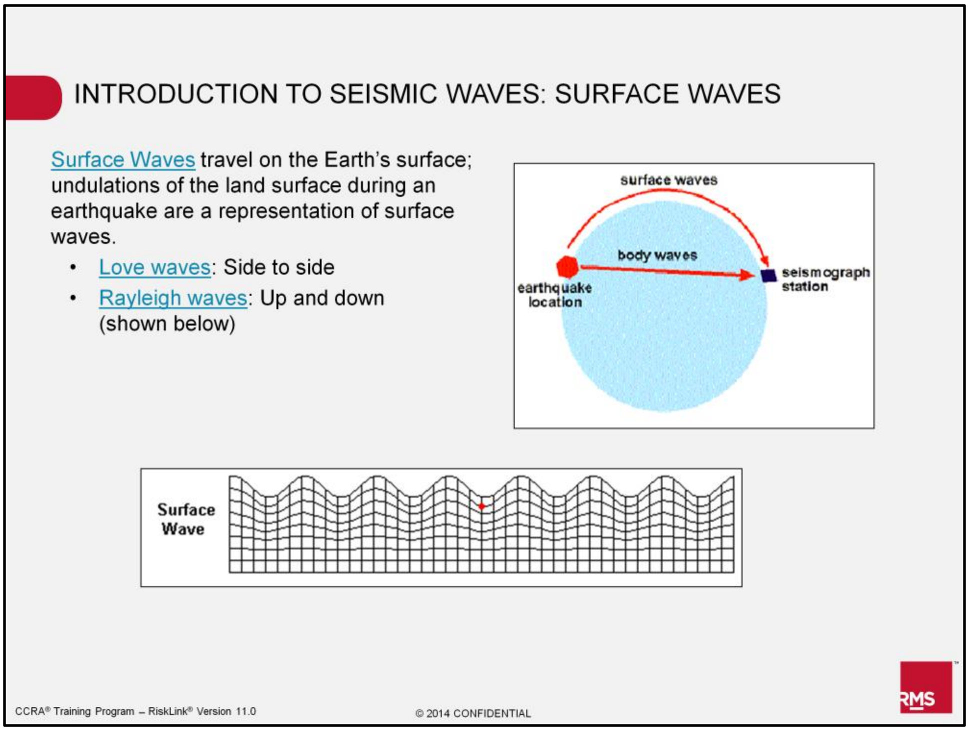
Unit 4 looks at site effects. First we will define the key characteristics of ground motion records and we will walk through the different components of the seismic wave that cause ground motion. We will then explain how site conditions impact ground motions and building damage. Then we will talk about a building's predominant period and how that relates to the acceleration that the structure experiences. We will also talk about liquefaction and landslide and how they contribute to site hazards. Finally, we will examine the sources of uncertainty when looking at losses.

UNIT 4

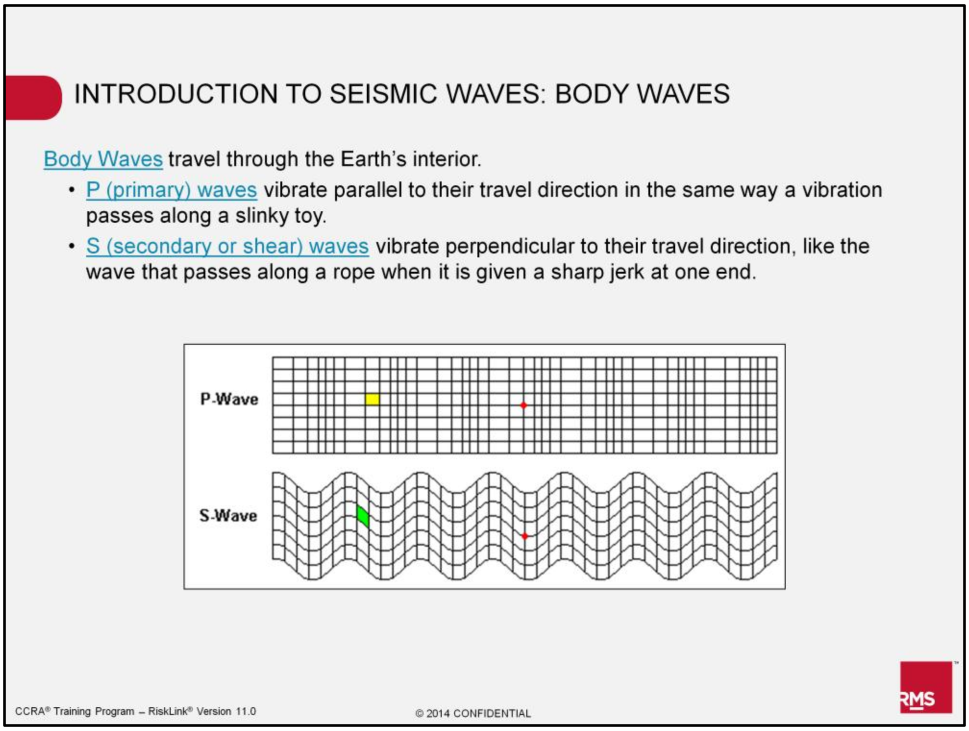
Site Effects – Learning Objectives

- Define the key characteristics of earthquake ground motion records.
- Explain how site conditions impact ground motions and building damage.
- Estimate a structure's predominant period, and relate this to accelerations that a structure would experience in an earthquake.
- Define the processes of liquefaction and landslide and how they contribute to site hazards and losses.
- Explain how uncertainty is quantified using empirical loss data from historical events.

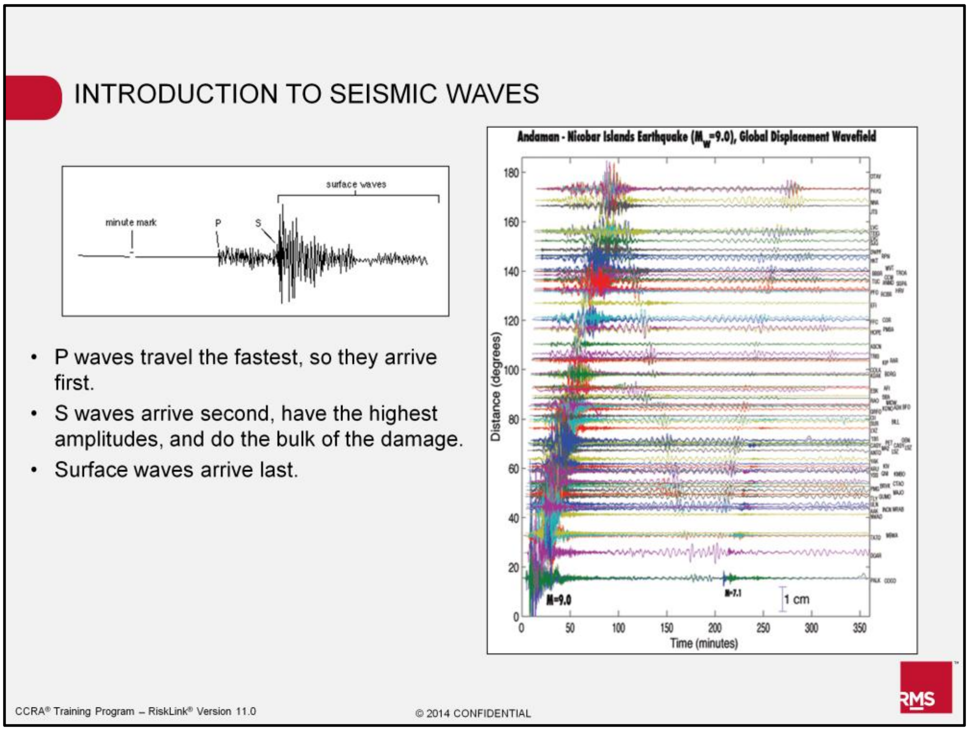
At the end of this unit you should have a good understanding of each of the five learning objectives listed on this slide.



We will begin with an introduction to seismic waves to provide some understanding about how ground motions work. There are essentially two major types of waves that are produced by an earthquake. One type is surface waves, which travel along the surface and simply undulate the land as they travel. The image at the bottom of the slide shows surface waves. The red dot on the image will go up and down as the waves pass by, similar to riding on the ocean and having swells go by. There are two components to these surface waves; the Love waves, which move from side to side, and Rayleigh waves, which move up and down. The image shows Rayleigh waves.

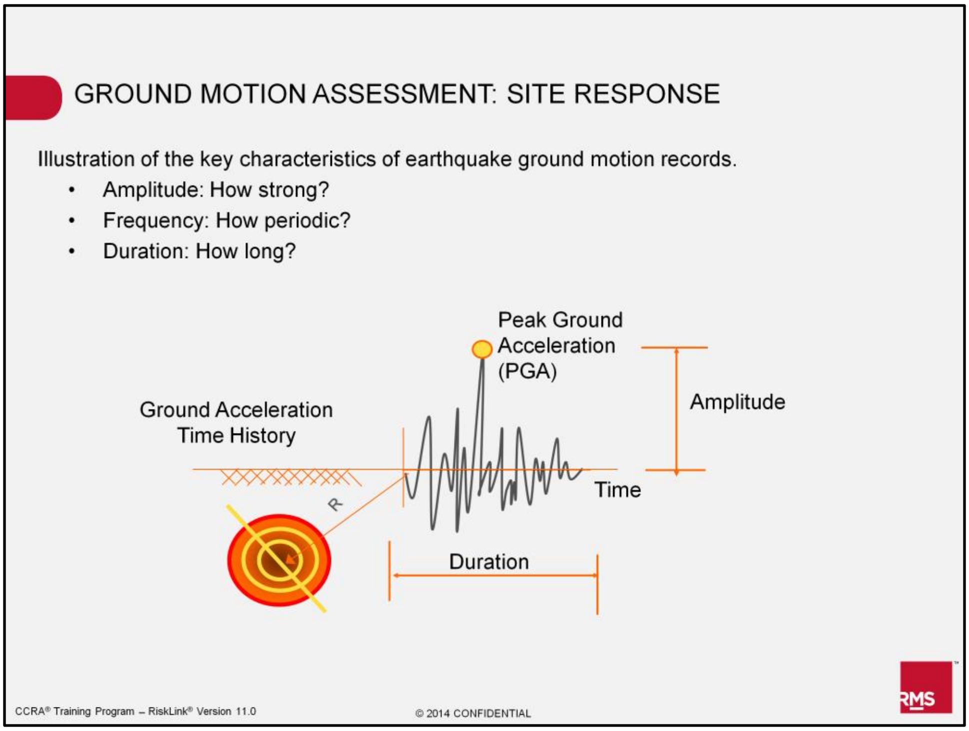


Body waves are waves that travel through the Earth's interior. These are the waves that cause the most damage. P waves, or primary waves, vibrate parallel to their direction. The image on this slide shows that an individual cell will experience a change in volume as a P wave goes by and it will be compressed and expanded as the wave goes by. This is distinguished from the secondary or shear wave, which actually vibrates through a location and causes a change in shape of the volume. The volume stays the same but its shape is changed. These two types of waves travel very differently and because of that, they travel at different speeds. Seismologists use the travel time difference between the P waves and the S waves to determine how far away an earthquake is as well as its location. The P waves travel the fastest; they arrive first, followed by the S waves. The difference between P wave and S wave arrival is very similar to the difference between the arrival of thunder and lightening, giving a sense of time travel between the two.

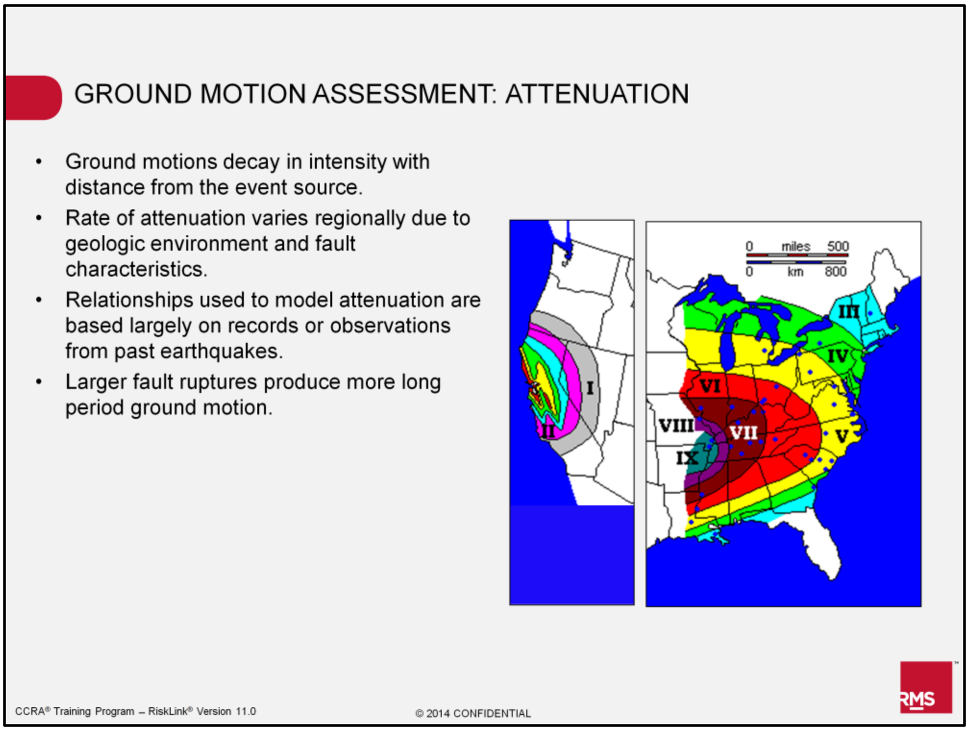


This plot combines the P waves, the S waves, and the surface waves. This is what a time history for an individual event looks like. First the P waves come in, then the S waves come in, and the surface waves are on top of all the other signals. The S waves, though they arrive second, have the highest amplitude and do the bulk of the damage. The surface waves arrive last because they have traveled the farthest. They have come around the Earth's surface to the location.

The plot on the right is from the December 2004 earthquake in Indonesia. You can see that with the increasing distance from the epicenter, the location is getting farther and farther away and actually getting around to the other side of the earth. At the bottom of the plot is the station where the earthquake occurred and we see high ground motions right away. At the top is a station located on the other side of the Earth. You can see that it takes time for the ground motions to travel around the Earth.

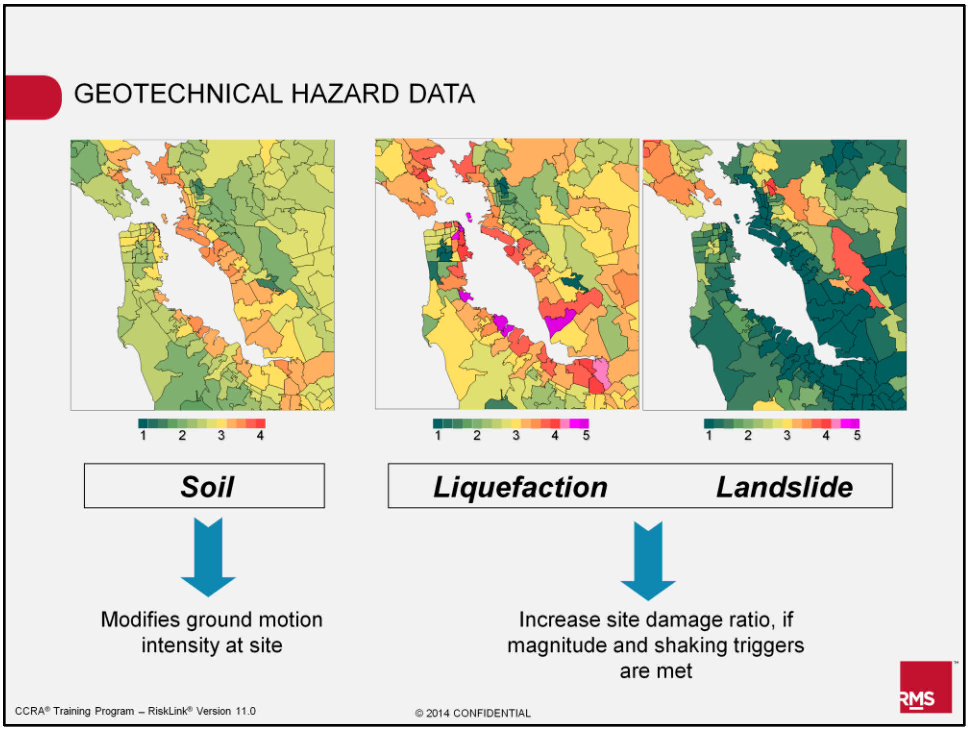


When we combine all these pieces into a ground motion, how does this affect a site? What is most critical to understand about a ground motion is that we need to know the amplitude, or how strong the ground motion is. What is the periodicity, or how is the frequency content distributed? How long did the ground shaking last? The longer the ground shaking lasts, the less likely a building is going to be able to withstand the shaking.

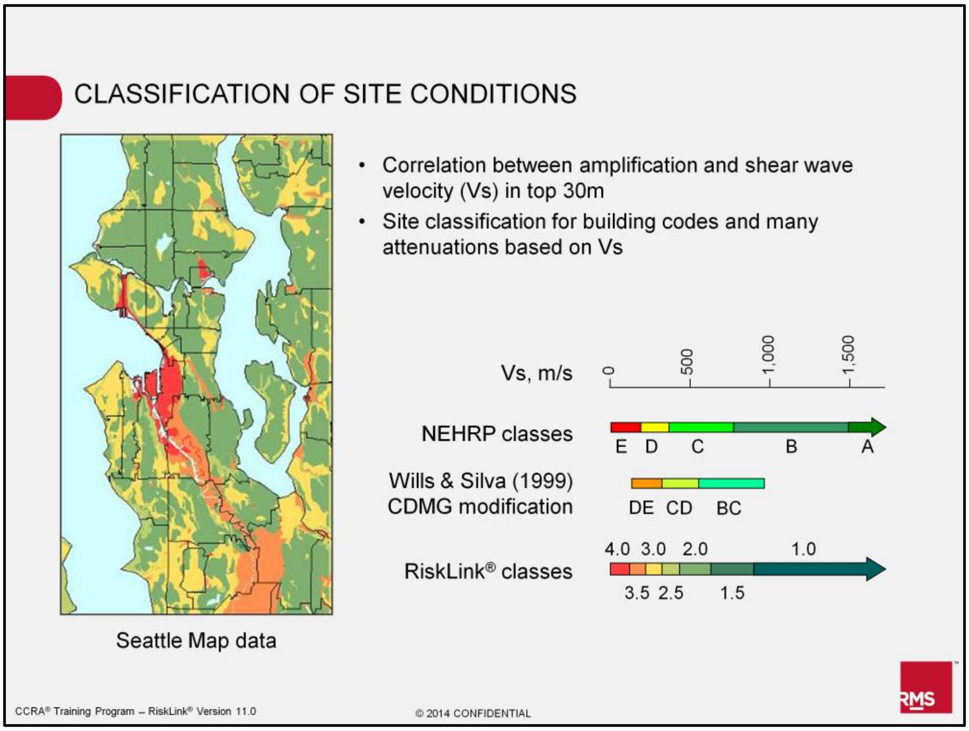


When we look at ground motions we can see that they have all of these components but we need to simplify them into a numerical method of how we model them. In terms of ground motion modeling, one of the important pieces of information we need to look at is how the ground motions attenuate. By attenuate we mean how do the ground motions decrease with distance as they go away from the seismic source? It is important to understand that how ground motions attenuate actually varies dramatically by geologic environment and by the fault characteristics. The image on right side of this slide is the intensity data from the largest of the New Madrid earthquakes that happened in 1812. The blue points are the data that were used to generate the map. You can see there is intensity nine over a very large area but there is intensity three all the way into New England. The ground motions in this case are not attenuating very quickly and there is a very large area that is experiencing intensity six and intensity seven, which could cause damage to unreinforced masonry structures.

This is compared or contrasted against what happened in the 1906 San Francisco earthquake in the left image. These earthquakes are relatively similar in size; in fact the California earthquake is slightly larger. The scale of these two images is the same. What we see is that in California the ground motions attenuate much more quickly. Intensity three barely leaves the state of California. Reno would have experienced intensity three but the zone of intensity three is very small. The ground motions drop off much more dramatically than the New Madrid event. This is a combination of the types of events and the geologic structures. In the western U.S. there are many mountain ranges and fault zones. The geology is very broken up so ground motions cannot be transmitted very consistently. In the eastern U.S., there is a large area that has not been actively deformed in a long time. Essentially the ground motions are not hitting these variations in geology; they are able to be transmitted over very large areas. It is important to take these into account when ground motion models are developed. It is also important to understand that the large rupture zones produce a longer period of ground motion.

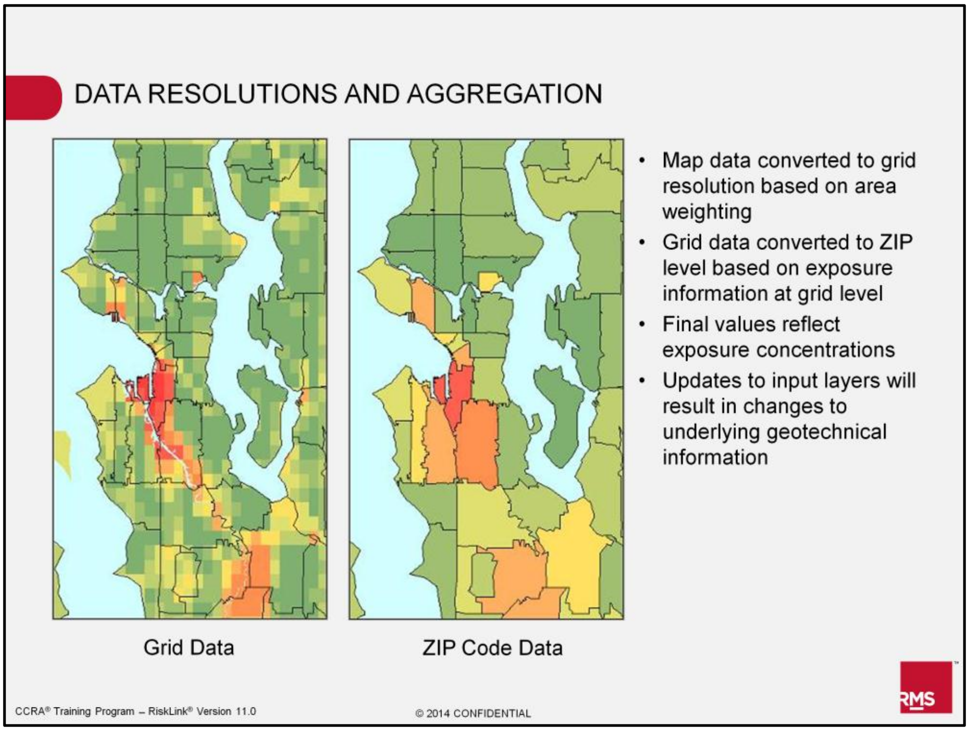


We have talked about how ground motions attenuate and the content of ground motions. We also need to talk about the site conditions. When the ground motions arrive at a site, they are modified by the geology at that site. For example, if they have traveled through the Earth and arrive at a basin of soft material, the ground motions will be amplified. We will look at how we quantify that. There are other components to site conditions that are important. We will talk more about the importance of liquefaction and landslide shortly but they do not necessarily affect the ground motions that would affect a structure. Rather, they cause ground deformation. Earlier we talked about the difference between ground motion and ground deformation. Ground deformation causes damage due to changes in the surface underneath the structure.

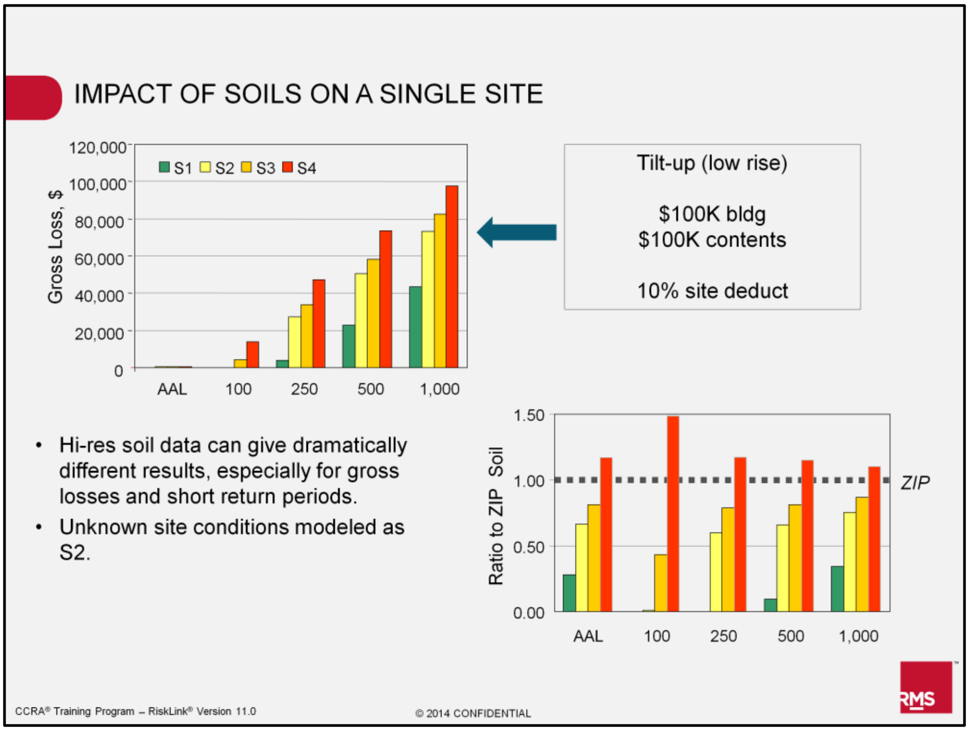


One question that is often raised is how we go from a geologic map to incorporating site conditions into a hazard or risk model. The first thing we do is to digitize a geologic map to incorporate it in a GIS environment. We then examine the characteristics of those structures unit by unit to get a sense of how likely they are to amplify ground motion. The best measure of this, and what is essentially the standard in the industry currently, is to look at how shear wave velocities actually move through those structures. That gives a sense of exactly how ground motions are amplified.

When we look at a particular unit, we have a pretty good understanding of how the shear wave velocities move through that structure. Typically we think of the shear wave velocity in terms of what is happening in the top 30 meters of the geology at a site. There are a number of different classification schemes including the NEHRP classification scheme and the recently developed Wills and Silva scheme by the California Divisions of Mines and Geology (CDMG), which has now changed its name to the California Geological Survey. These essentially set the standard in California. They look at all units in California and determine their shear wave velocities and then we map the shear wave velocity to our classification scheme.

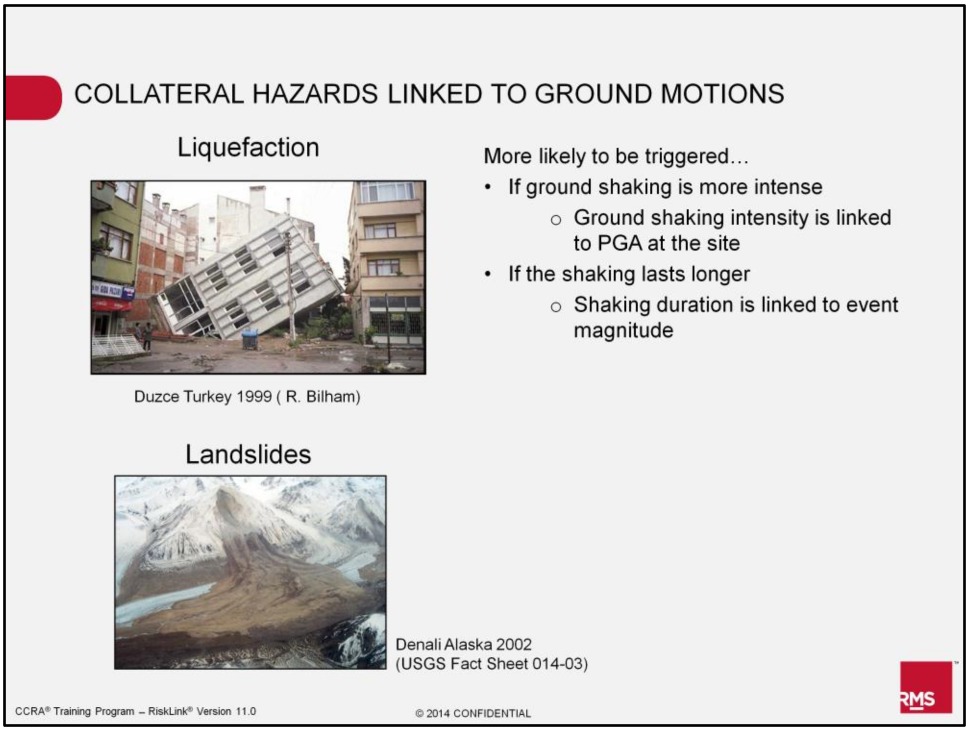


For non-coordinate level geocoded locations, we need a way to access site conditions. This is where the application of the VRG or variable resolution grid (see Geocoding and Hazard Retrieval course material) is useful. We take the detailed geology map and review it through a set of variable resolution grid cells. We can then weight those individual grid cells by exposure in those locations. The information about the exposure might come from census data or it might come from some other type of GIS layer, potentially based on LandSat images or land use information so it helps us to know the location of the exposure. We can then weight the geotech within each grid cell with its population or its exposure concentration.



Next we will look at the impact of site conditions, which is significant. The plot on the upper left shows gross losses versus average annual loss and certain return period loss levels for soils 1, 2, 3, and 4. This is a low rise tilt-up building with $100,000 of building and $100,000 of contents and a site deductible of 10%. You can see that for soils 3 and 4, the gross losses are significantly higher, on the order of 10% for soil 4. There is definitely a dramatic difference in gross losses, particularly at the shorter return periods.

The plot on the lower right assumes all we know about the structure is a ZIP Code level soil. You can see in this case the ZIP Code level soils appear to be very poor because they are matching somewhere between a soil level 3 and a soil level 4. It is important to understand that having details about site conditions gives a much better representation of the risk. Having a high-resolution geocode that can pull up the detailed geotech at the site is a much better representation of the risk for an individual structure.



This slide looks at liquefaction and landslide. These are linked to the ground motion but are not treated as amplifications to ground motion because they need to be triggered. Not every event is going to cause liquefaction and/or a landslide. There needs to be a certain level of shaking to cause a landslide or liquefaction. Admittedly, the conditions can be such that a small ground shaking will produce a landslide but, in general, when we consider landslide associated with earthquakes, we assume that they need to be triggered at a relatively moderate ground motion; at least something comparable to intensity six or seven. Additionally, it is the length of the shaking that is particularly problematic when we look at landslide and liquefaction. A sudden shake is not going to cause materials to liquefy. It may cause a landslide to initiate but for the most part, the longer the shaking the more likely liquefaction or landslide are to be triggered. Longer shaking is always going to be attributed to larger magnitude events.

LIQUEFACTION SUSCEPTIBILITY

1964 Niigata Earthquake Japan (NOAA/NGDC)

- Saturated, sandy soils may temporarily transform into a semi-liquid state when vibrated.
- The ground loses its bearing capacity, causing extensive damage to structures.
- Increases site damage ratio, if magnitude and shaking triggers are met.

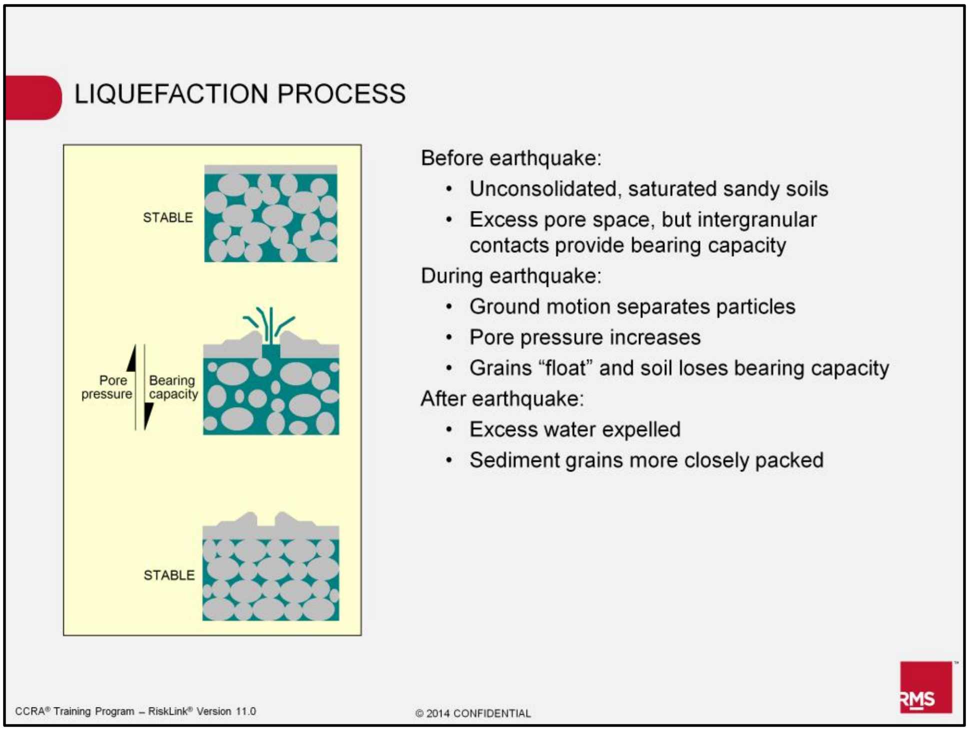
Sand Blow 1979 El Centro Earthquake

CCRA® Training Program – RiskLink® Version 11.0

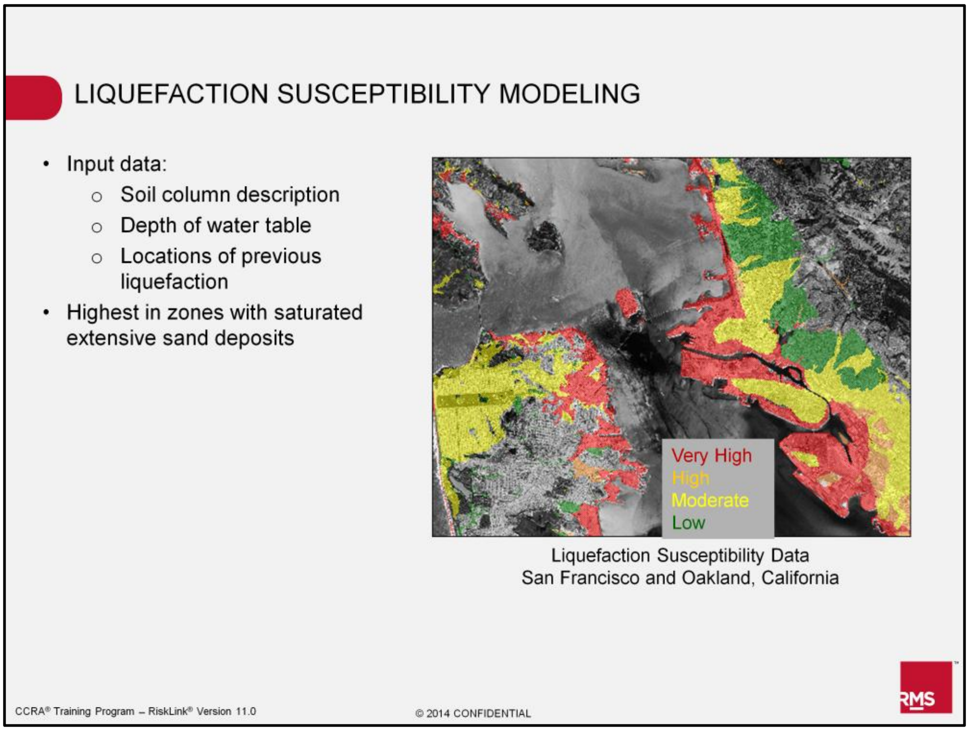
RMS

Let’s talk about liquefaction in more detail. The photo in the upper left is a classic example of extreme liquefaction. These are multi-family residential structures in Niigata, Japan. This event happened in 1964. These buildings were built on saturated, sandy soil which did not support the structures. These structures were essentially floating on the sands that were liquefied and so could not be supported.

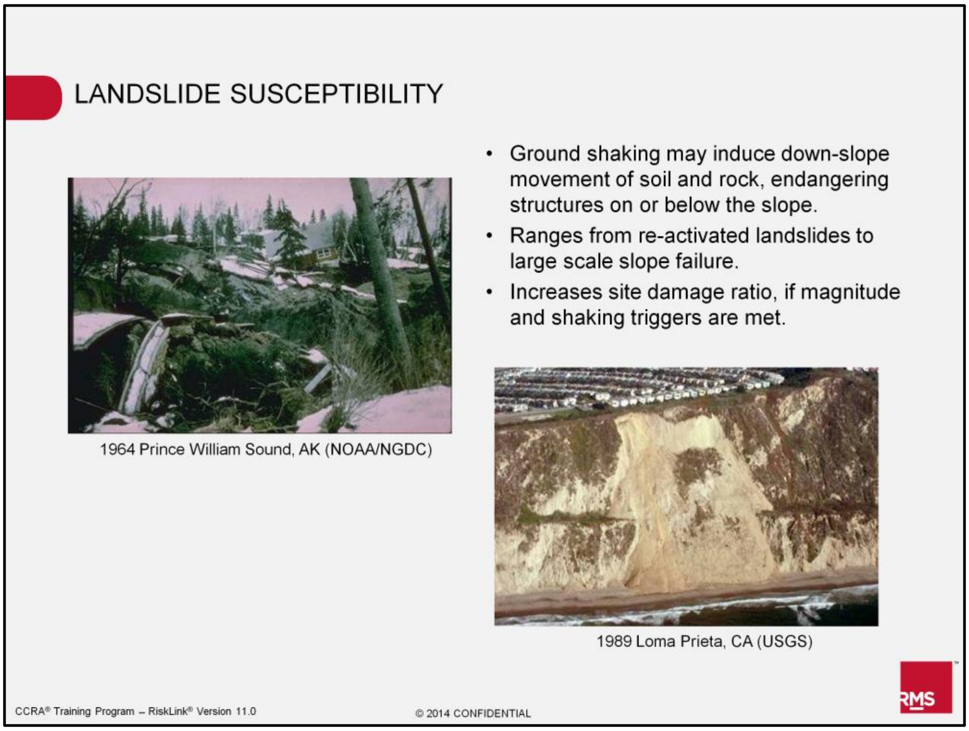
The bottom photo is a sand blow. In these situations, not only does water come pouring out of the ground, but also significant quantities of sand resulting in large sand deposits. Fortunately we can look at these sand deposits, called sand blows or boils, to get a sense of how these liquefactions happened in the past. There is currently a lot of research in the New Madrid area to understand the extent of intense ground shaking by looking at these liquefaction deposits. Liquefaction is not really amplifying ground motion but rather undermining the bearing capacity of the site. The way we implement this within a catastrophe model is to directly impact the damage ratio if the triggering conditions of a large enough event magnitude and large enough site shaking are met.



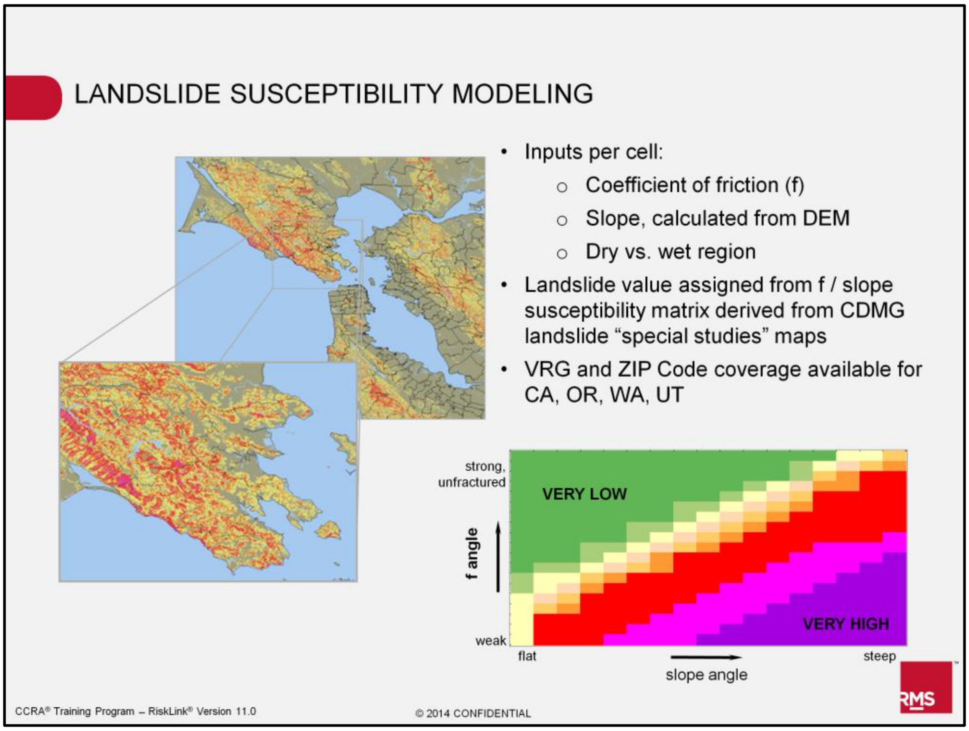
The soils that are vulnerable to liquefaction in the event of an earthquake are saturated sandy soils where all of the particles are in contact with each other. They are not necessarily fitted together as well as they could be but they are supporting each other and they can support a structure. During an earthquake, the ground motion moves the particles and increases the pore pressure. Essentially, the water pushes the particles apart, the grains start to float, and the soils lose what is called bearing capacity. In other words, the soil can no longer support a structure. The image shows water being forced out and the sandy soil being developed. After the earthquake all this extra water has been pushed out and now the grains of sand are in much closer contact with each other. They have gone back to being firm enough to support a building. There must be extensive sand deposits for conditions to be just right for liquefaction to occur during an earthquake. The bottom image gives the impression that the problem with the soil that allowed liquefaction to occur has been corrected. Typically there are multiple sand layers in these environments and not every layer will be activated during an event. So even though there has been liquefaction at a location, it is still possible for liquefaction to occur again in the same location.



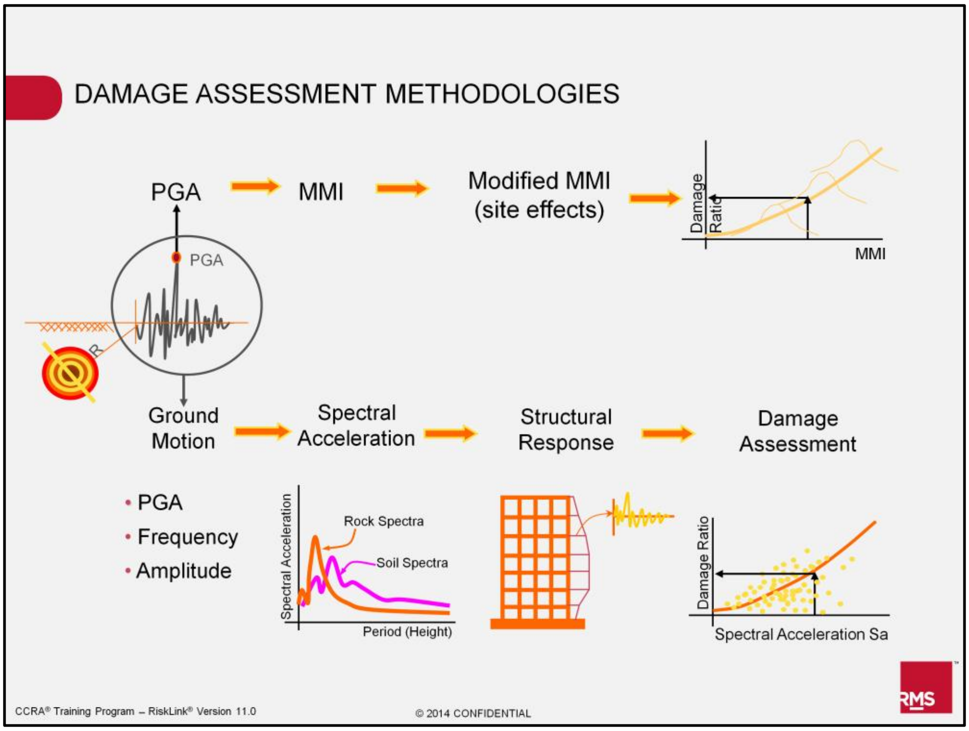
How do we model liquefaction susceptibility? It is important that we know what is in the soil column at that site. We are looking for sandy deposits. The sandy deposits also must be wet so the water table depth must be relatively shallow. Then we look for locations where there have been previous liquefactions. The zones of high liquefaction susceptibility are definitely going to be associated with extensive sand deposits. The image on this slide shows the liquefaction susceptibility data for the San Francisco and Oakland areas in California. You can see there are large areas of very high susceptibility. This is quite common in populated areas, particularly where there has been expansion into marshland. This was the situation in Kobe, Japan. The extensive liquefaction that impacted the port in Kobe was an expansion of artificially developed islands located in the bay.



Landslides are a little more intuitive. Ground shaking induces some sort of slope failure, either soil or rocks. Landslides range across a large group of gravity induced failures. They can be simple free flows of material down a slope, such as what happened in the Loma Prieta earthquake shown in the bottom photo, or they can be very extensive areas of ground deformation, such as what occurred in Alaska in 1964, shown in the upper photo. A lot of the structures that failed in 1964 were not very steep, they were only shallowly dipping, but because the ground motions were so strong and lasted for so long, large areas were moved and there was extensive deformation. It is hard to tell from the photo but this was a residential community. We are looking at houses. One has been destroyed, it is completely buckled and broken apart with large crevasses. There was extensive damage in this residential community.



How do we model landslide susceptibility? Identifying pre-existing landslides has been done, particularly in California. The Geological Survey of California has identified large pre-existing landslides but not necessarily all the similar structures that are likely to fail. To get a sense of this, we have looked at what the slope is at a site. The steeper the slope is at a site, the more likely it is to fail. Then we look at the materials at a site, which is called the coefficient of friction. A material is less likely to fail based on how strong it is. In other words, stronger material can hold together and not fail in ground shaking. We end up with hazard from very low to very high based on the steepness of the slope and the strength of the rocks. Another consideration is the wetness of the site. A wetter environment is more likely to have landslides. Often the surface on which the landslide occurs is lubricated by water, which can initiate large landslides.



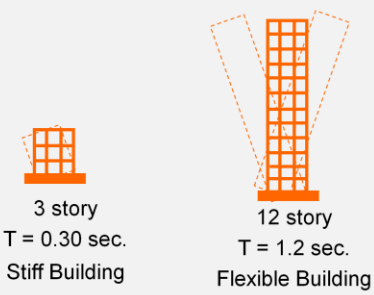
Now we need to look at how to get from the ground motion to damage. This plot shows two of the primary methodologies used for damage assessment. On the top you can see we take the peak ground acceleration. So there is an event, there is a distance to the site, and at that site there is this time history for this ground motion that has occurred. One approach is to take the peak ground acceleration, the PGA, and convert it into a Modified Mercalli Intensity. So take the PGA, assume some intensity based on historic data relating PGA to intensity, take into account some site effect to modify intensity, and then have some relationship between a damage ratio and the intensity, taking into account uncertainty. This is a relatively basic approach and we do use it in a number of places. But now look at more of the ground motions than just the PGA. We are looking at the frequency content and the amplitude as well. We are taking the ground motion, the full content, and using a spectral acceleration approach. We will walk through all the pieces of the spectral acceleration approach in the next few slides. Essentially, by looking at the full component of ground motion, you get a much better understanding of how the different components of the building respond. Each story of the building will see a different ground motion. Then we have a much better way to relate that spectral acceleration to damage through detailed analysis of how structures perform.

GROUND MOTIONS: STRUCTURAL PERIOD

Reflects the primary characteristics of buildings

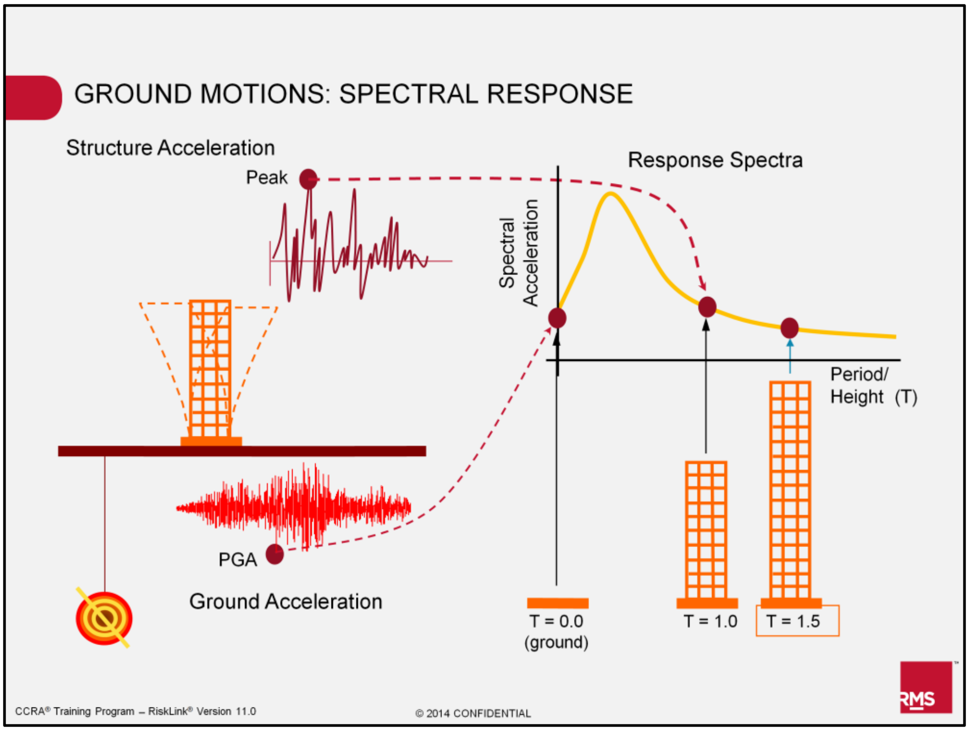
- Building height (e.g., number of stories)
- Structure system (e.g., shear wall, moment frame)
- Building material (e.g., steel, wood, masonry)

Building Height	Typical Natural Period
2 story	0.2 seconds
5 story	0.5 seconds
10 story	1.0 seconds
20 story	2.0 seconds
30 story	3.0 seconds

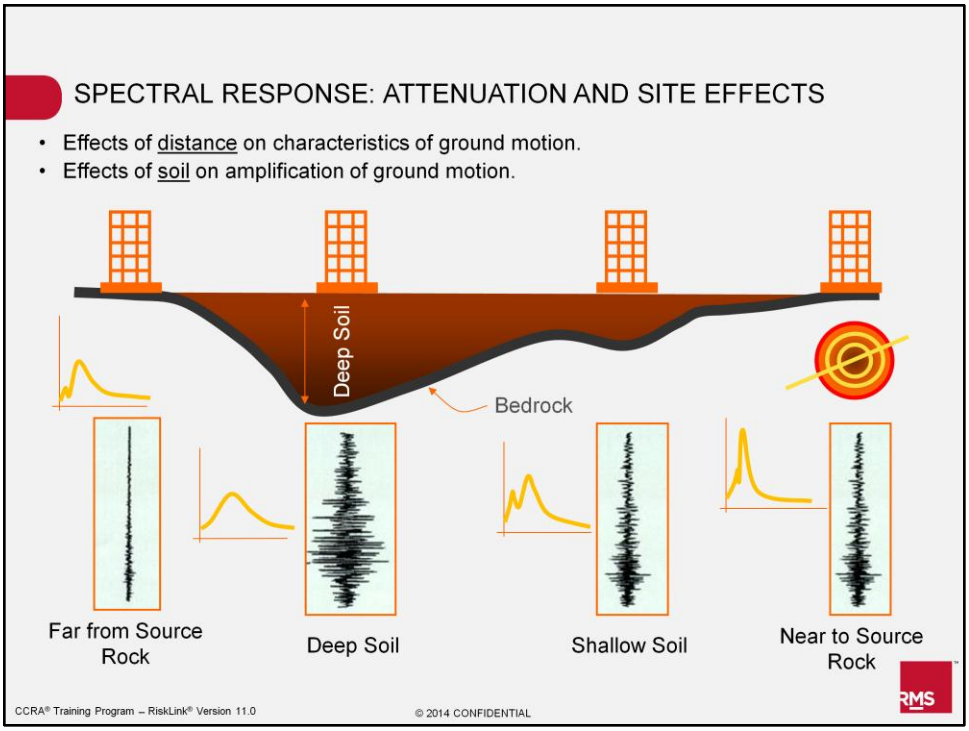


Buildings have a structural period. What exactly does that mean? A building will respond to specific ground motions depending on its primary building period. We define a period based on a number of characteristics, but primarily building height. Knowing the height of a building is a good way of understanding what ground motions will impact it. The structural systems and materials involved are also important.

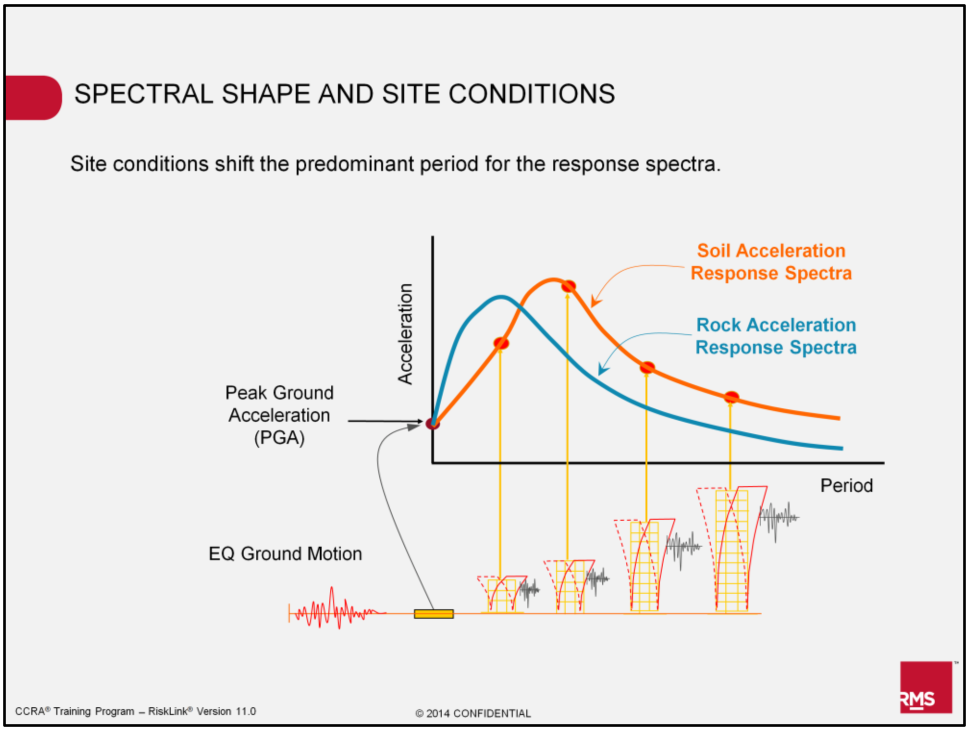
The table on this slide gives some examples. For a two story building, its period is typically only 0.2 seconds, which is a very short period. A building this height is likely to be impacted by very high frequency ground motions. Much taller buildings, such as 20 or 30 story buildings, have a two or three second structural period. These buildings are going to be affected by very long ground period motions. These are the ground motions generated by very large earthquakes. When we look at ground motions and how they attenuate, we see that the long period waves associated with large earthquakes are not attenuated as much as the short frequency ground motions. So distant buildings that are very tall will feel these long period waves from large earthquakes.



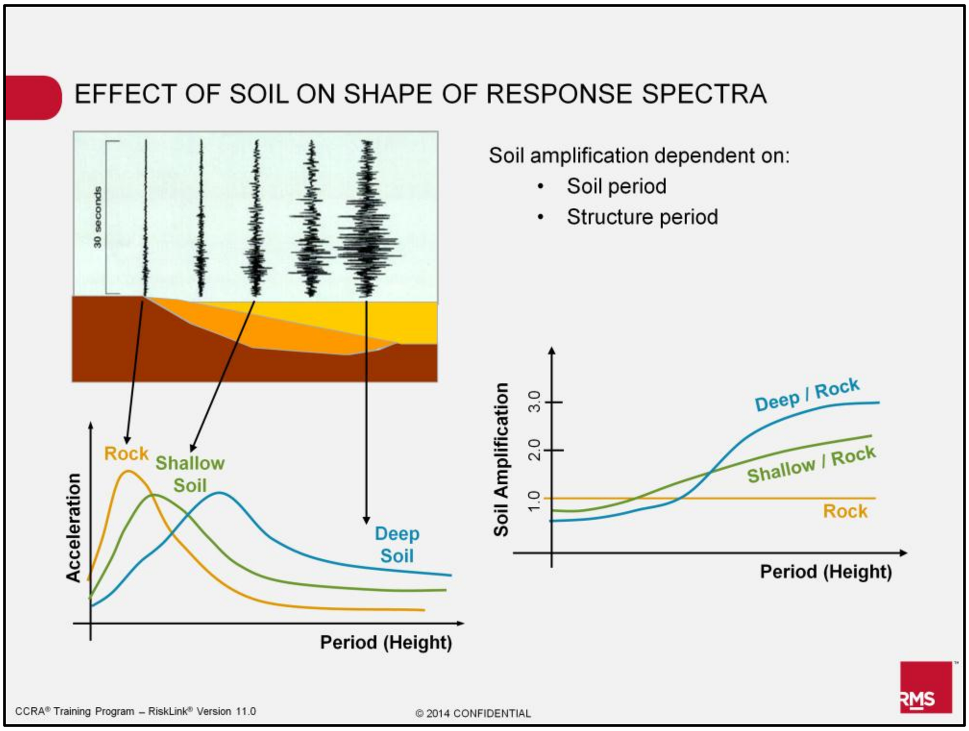
Next we will talk about building a response spectra. An earthquake happens and the ground motion comes in at the base of the structure. The ground motions are transmitted through the building to the top. The top of the building sees a very different ground motion. This resulting building response has filtered the input ground motion through the structure to come up with a peak acceleration at the top of that structure known as the spectral acceleration. We can then plot that spectral acceleration versus a set of buildings of different heights or structural periods to determine the spectral response curve for that particular event at that particular site.



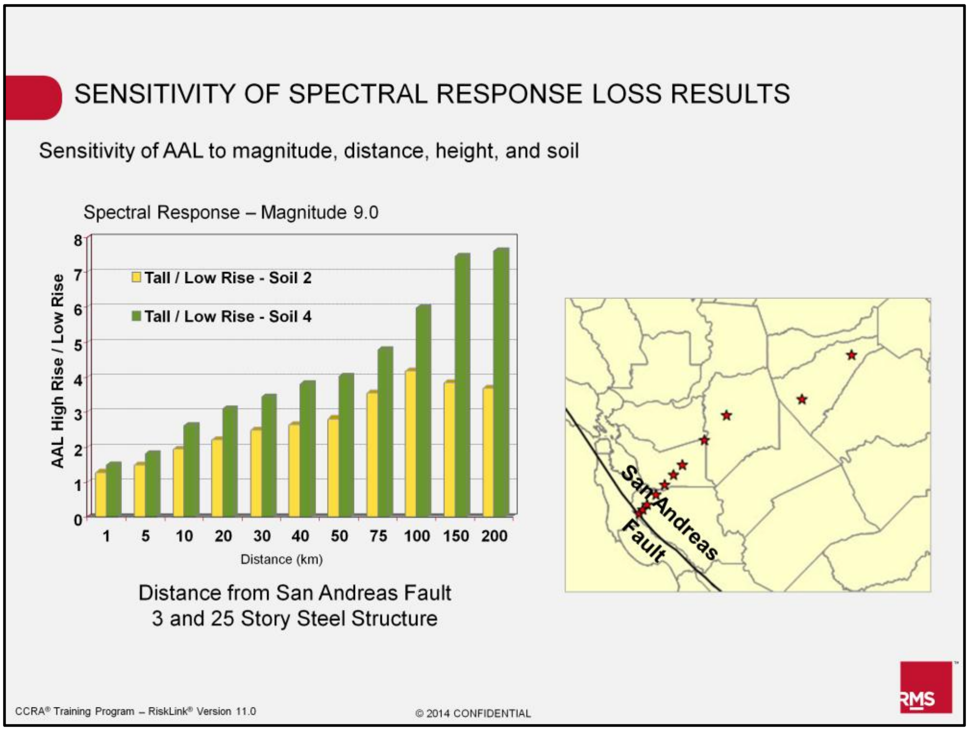
It does get more complicated. The effect of distance is that the farther away you are from an earthquake, the more likely that there is only going to be long-period effects. This slide shows four buildings all the same height and how they are impacted. The five story building near the source sees a very high peak at a very low frequency or very low period. The amplitudes increase and there is a shift in the predominant period slightly to the right for the building on deeper sediment farther away from the source. Looking at the building on even deeper soil, we see the periods within the ground motions are getting longer, the amplitudes are getting much higher, and there is a shift in the point on the curve where we get the highest ground motions pull toward a higher or longer period building. The building that is off the basin shows the predominant period has shifted back, the amplitudes are relatively low because the building is far away and the soil is firmer. So when understanding the response of an individual site, we need to take into account the height of the building, the distance from the source, and the site conditions to understand how spectral acceleration will impact that site.



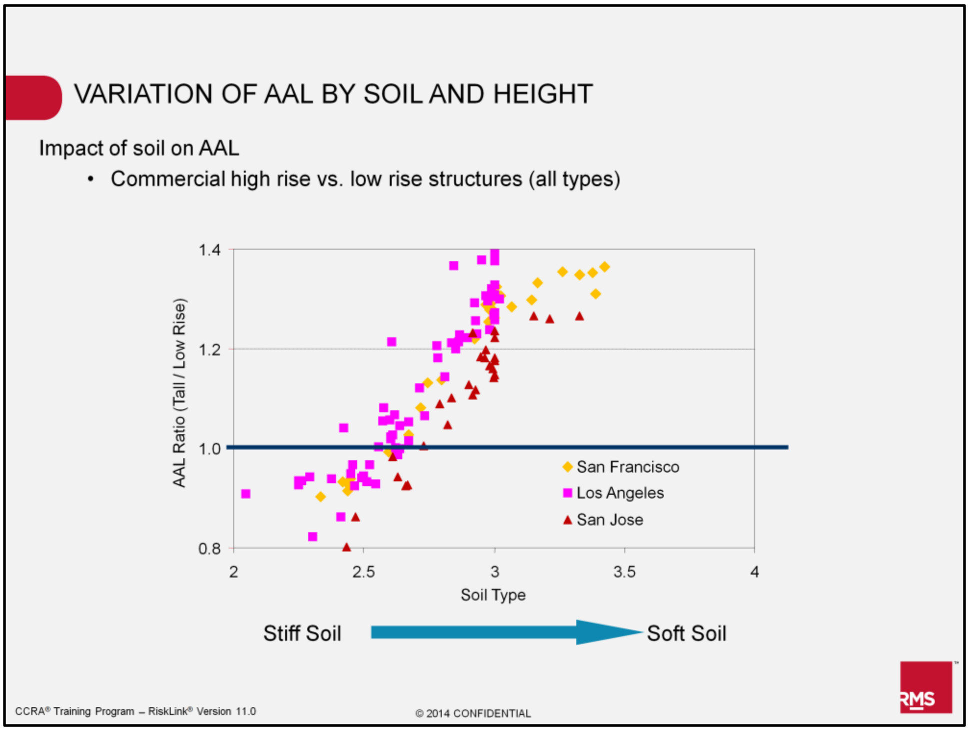
To clarify, we have put two plots on top of each other so we can see the shift in the period of the response spectra. The orange curve represents how a building would respond if it was on a soil condition. The blue curve represents how the same building would respond if it was on rock. The blue curve shows a shift to the left of what we term the predominant period of spectral acceleration. This means that on soft soil, the second building from the left will see the highest damage because it plots to the highest point on the curve. On rock, it is actually the shorter building that will see the highest damage. This is because on rock, the ground motions are not being filtered and there is a lot more high frequency content.



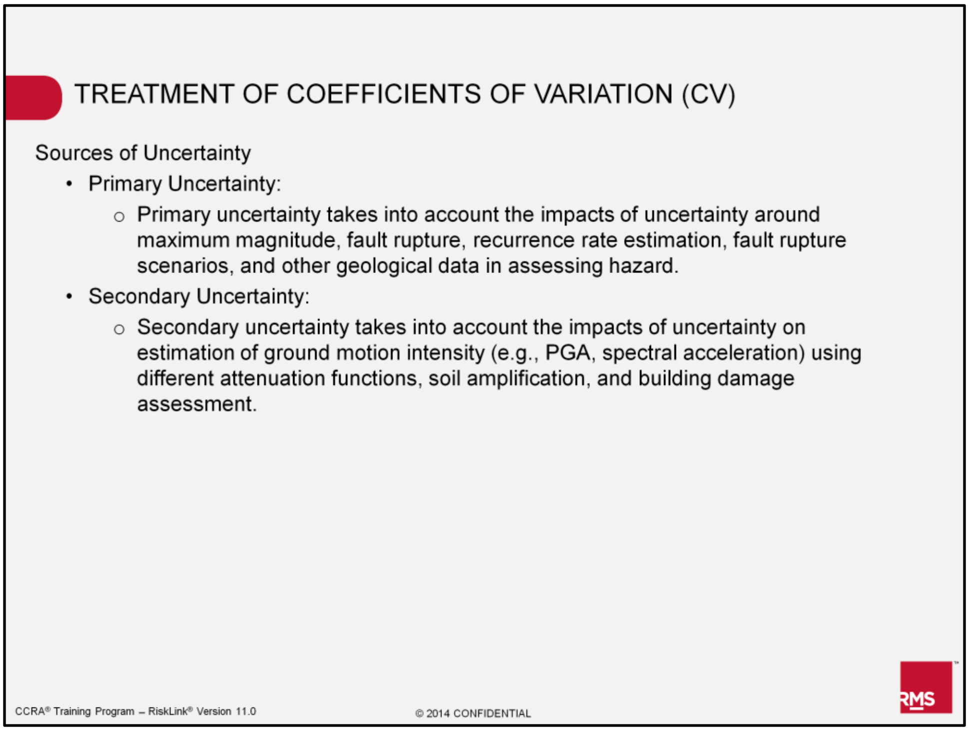
This slide shows another way of looking at it by comparing rock to soft soil to really deep soil, such as in Mexico City. The Mexico City earthquake of 1985 is a very good example of why spectral acceleration is important and why this needs to be included within seismic hazard modeling. Many of the commercial buildings that were impacted by the Mexico City earthquake were in the 20 to 30 story range. They correlated very well with the peak acceleration on the spectral acceleration curve for the deep soil. While the shorter buildings, including unreinforced masonry structures that would be expected to fail in a large earthquake, were unscathed because they had very short periods. It was the taller, newer commercial buildings in the 20 to 30 story range that saw most of the damage.



Soil conditions become more important as we move farther away from the fault. This plot shows average annual loss comparing a high-rise building to a low-rise building, and comparing soil 2 (stiff soil) to soil 4 (soft soil). We are comparing a ratio of the average annual losses of a tall building to a low-rise structure looking at how this ratio changes as we look at the soil type and we get farther away from the fault. What we see is that on soft soil, there are much higher damage ratios than for stiff soil at more distance from the fault. This has to do with the filtering of the ground motions of the longer period information so the taller building is being excited by the long period ground motions that are traveling farther away from the event. Those ground motions are being amplified more by soft soil than they were on stiff soil. So a tall building a long distance away on soft soil is seeing much higher ground motions and, therefore, seeing more damage than the shorter building on stiff soil.

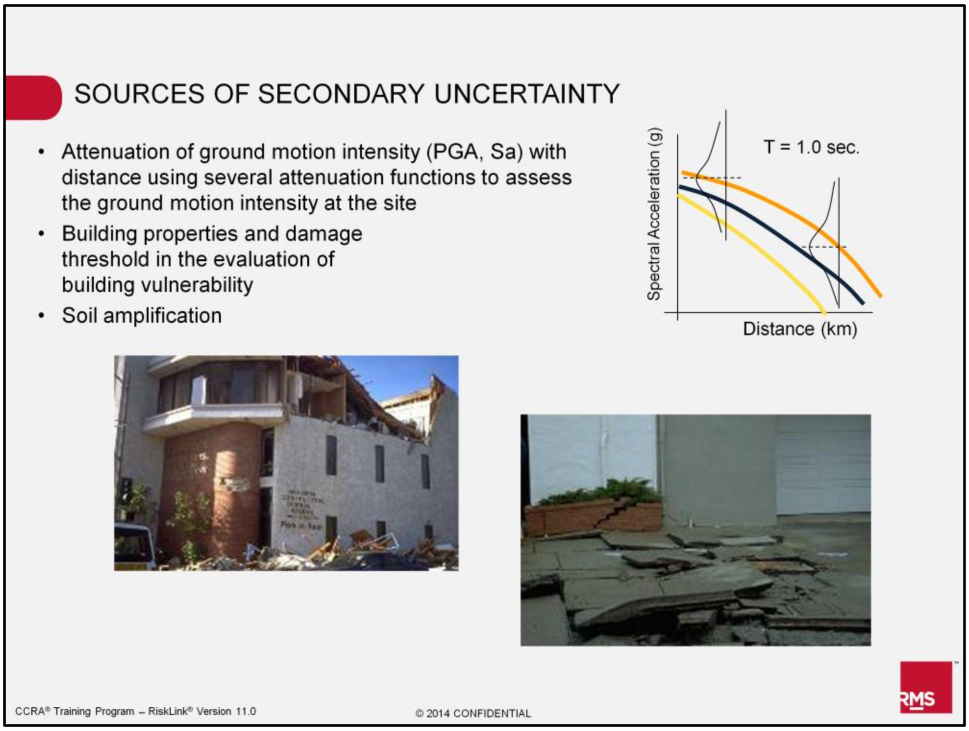


This plot is again the average annual loss ratio of tall buildings to short buildings looking at soil type. The bottom axis goes from stiff soil (soil 2), to soft soil (soil 4). We have plotted locations within San Francisco, Los Angeles, and San Jose in California. The events that are impacting these areas are at different distances to these exposures. You can see fairly consistently that on soil 2.5 and lower the shorter buildings are being impacted; on soils greater than 2.5, it is the taller buildings that are being impacted by the soil. This clearly shows the importance of examining the full frequency content to best assess building damage.



Now that we have looked at how ground motions affect buildings and cause loss we will look at the uncertainties that go into the calculations within a probabilistic hazard model. There are two components to uncertainty; primary uncertainty and secondary uncertainty. Primary uncertainty centers around the definition of the stochastic event set and includes maximum magnitude, the fault rupture, the recurrence rate, and the fault scenarios and how we have built the model, looking at the individual pieces for which we know there is uncertainty. Maximum magnitude, for example, incorporates events larger than the characteristic magnitude and takes into account the fact that we know there is uncertainty in the maximum magnitude. Some of the others, such as fault rupture and recurrent rate estimation, are taken into account when we are doing rate calculations. In many cases, if it is unclear exactly how to model the recurrence for a structure we may use a logic tree approach. We look at some possible alternatives to how recurrence should be defined or how fault length should be defined and use that within the model to incorporate primary uncertainty.

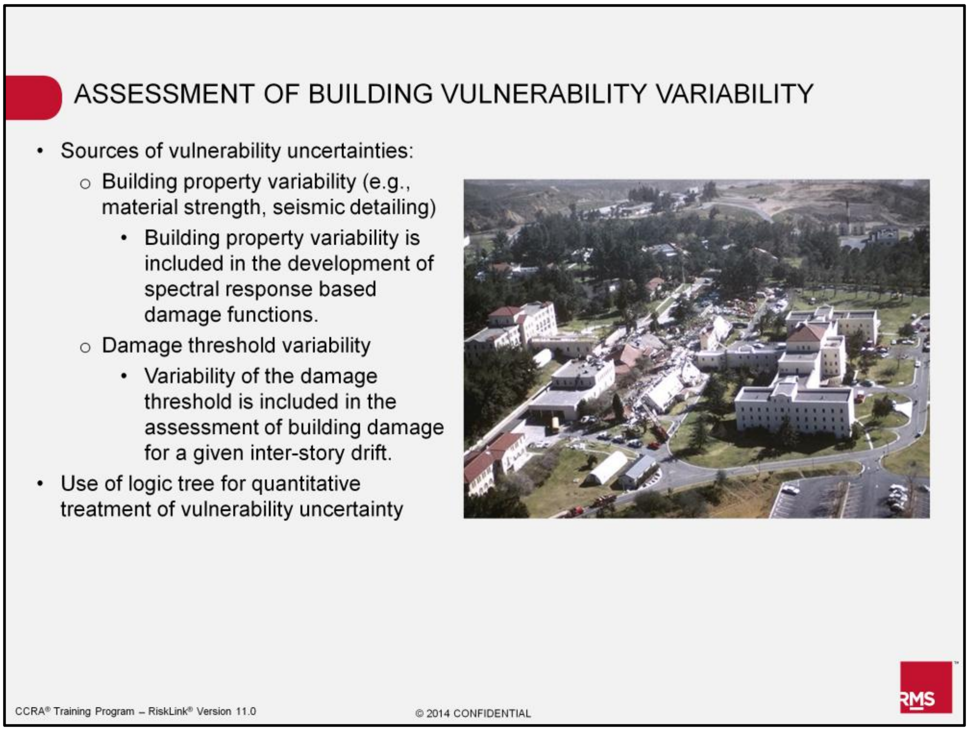
Secondary uncertainty takes into account the uncertainty associated with the impact of each of the stochastic events including ground motion intensity, use of the attenuation functions, how site amplifications are done, and how damage estimations are undertaken.



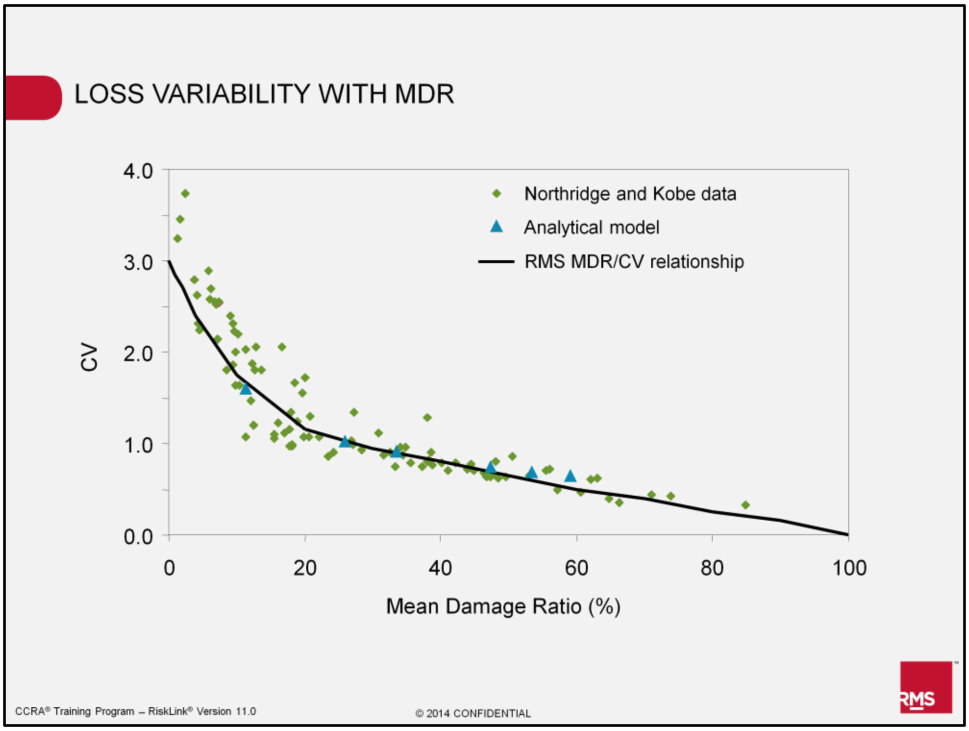
The secondary uncertainties in catastrophe models can be thought of in three parts. There is uncertainty as to the best way to model ground motions for each individual event. The plot in the upper right of this slide shows spectral acceleration versus distance. It shows a series of different relationships have been developed. There is uncertainty around those relationships so that is incorporated in the secondary uncertainty.

There is also uncertainty in exactly how a structure responds to strong ground shaking. We take an attenuation relationship, we come up with a ground motion, and then we apply that ground motion to a structure. There could be two buildings right next to each other that would respond differently when a ground motion is applied. Even when structures are identical they could respond differently based on how the building is oriented to the ground motion or how the structure was put together; for example, were the nails perfectly spaced or was there a problem with the welding? We incorporate this uncertainty as to how a building responds to a particular ground motion within the vulnerability model, looking at all the different possible damage rates that a structure could experience. This also goes into the secondary uncertainty calculation.

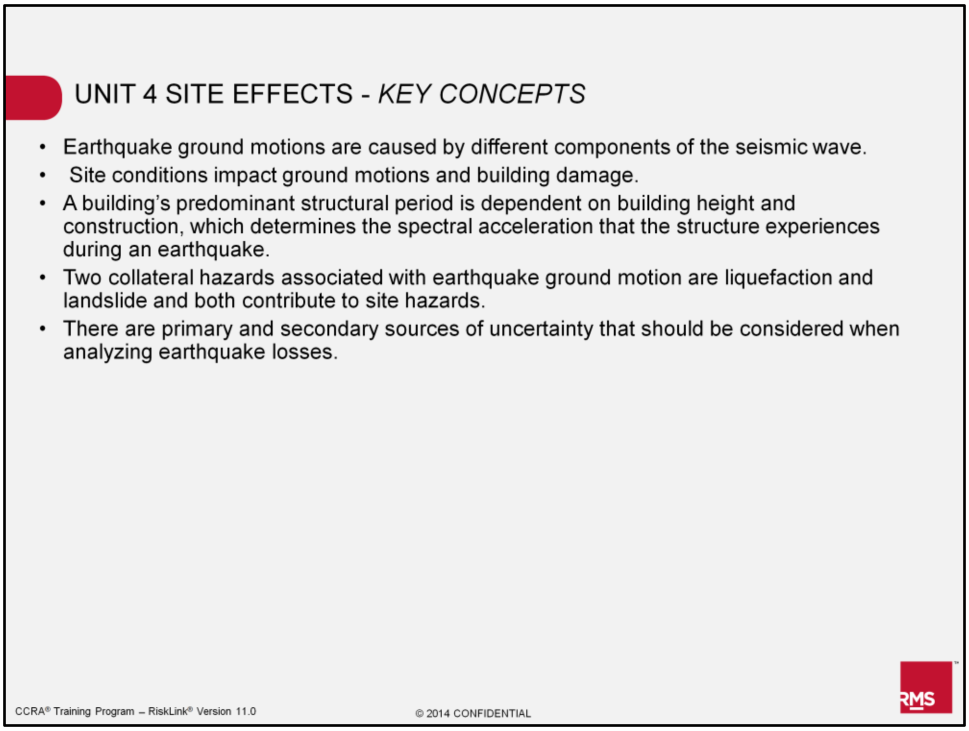
There is also uncertainty in how site conditions amplify ground motions. We have a lot of data but it is a very complicated process. Because soil amplification is dependent on the characteristics of all of the ground motion waves that come into a site, we can have a general idea about how a site should respond but the observed response to an individual event may be very different than the mean response. For this reason, it is important to include the site response uncertainties with the loss calculations.



Perhaps most important is to understand the variation in how structures respond. This is an important piece of the whole picture. When we look at how reinforced concrete buildings respond to an earthquake, for example, there are many different ways to build reinforced concrete structures so there will be uncertainty around how they are going to respond to ground motions. This is included in the development and there is a logic tree approach to quantifying this vulnerability uncertainty.



This is data from the Northridge and Kobe earthquakes, looking at what the CVs by mean damage ratio. The data is plotted in green points. You can see that with lower damage ratios there is more uncertainty as to how much damage has occurred. This is essentially because exactly what ground motions will initiate damage is hard to define. At very high intensity, it is fairly clear that all structures of a particular type are likely to be heavily damaged. But at the low intensity levels or low ground motion levels, it is harder to quantify exactly when damage will be initiated. That is why the CVs are higher at that end. The blue triangles represent detailed analytical studies of how structures respond. These points on the curve show how the understanding between mean damage ratio and CVs can be obtained through an analytical approach. The black curve is how CVs and mean damage ratio are incorporated into the RiskLink model.



This slide highlights the key points from Unit 4 of this course. We encourage you to review these topics to ensure that you have a good understanding of each bulleted item before proceeding to Unit 5.