Applied Seismology for Engineers

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Week – 12 Lecture - 01

Lecture – 28

Hello everyone, myself Dr. Abhishek Kumar. Welcome to lecture 28 of the course Applied Seismology for Engineers. In earlier lectures, we have discussed about the different plates available across the globe, and because of the relative motion between the plates, some plates are moving towards each other, some tectonic plates are moving away from each other, and some plates have horizontal movement between them. As a result of this, there will be zones in which there will be accumulation of strain energy when the stored energy exceeds the in-situ strength of the material. When this particular situation arises, the material at the interface will undergo failure in terms of maybe rupture or melting. As a result, different kinds of seismic waves originate from the source, that is, the focus, and start radiating in three-dimensional space away from the focus. When these waves interact with the medium, there are heterogeneities present in the medium. Secondly, because this scattering is happening in three-dimensional space. Thirdly, because when seismic waves are passing through a particular medium, there are oscillations, and there is shearing happening in the material.

Because of scattering, heat, and heterogeneity present in the material, there will be a reduction in the energy the wave was carrying, particularly related to particle oscillation at larger distances. So, if you are talking about a certain recording station that is very close and a recording station that is maybe 100-200 kilometers away from your focus or epicenter, definitely the characteristics of ground motion at the close-by recording station and another recording station located 200 kilometers away will be significantly different though both the ground motions or both the recording stations are generating ground motion corresponding to the same earthquake at the same epicenter location.

Then, later on, we discussed that these waves will also interact with the near-surface soil medium, depending upon the shear strain the vibration is inducing in a particular soil medium. The soil is going to offer resistance in terms of primarily the shear modulus, and secondly, the damping ratio. So, depending upon these two parameters, which are available at a particular value of shear strain, the soil is going to offer resistance, and accordingly, the vibration characteristics will change when the incident wave is passing between the bottom of a particular soil layer to the top of that particular soil layer. Similarly, this revision and change, as well as modification in the soil characteristics and ground motion characteristics, will happen between the bedrock and the surface. Finally, once the ground motions are reaching the surface, which we can also find out using ground response analysis, we have also discussed in earlier lectures about what the different kinds of seismic waves are, starting with body waves, surface waves, and how the information about different kinds of waves can be used in accordance with the one-dimensional equation of motion, applying boundary conditions, and this way we will be able to find out how much the transfer function is, and how much the amplitude of motion changes at different frequency content.

In a nutshell, we discussed ground response analysis, which will help us in identifying how the ground motions are modified by each of the soil layers existing between the surface and the bedrock. So, because of this modification in the ground motion between the bedrock and the surface, subsequent modification in the bedrock motion will happen when it reaches the ground surface. Now, at the ground surface, you might be having a soil medium, so depending upon what shear stress and ground vibration, modified ground motion at the ground surface is inducing, and how much the in-situ shear strength of the soil is, soil again at the ground surface will offer resistance. It may undergo ground subsidence, and it may show some signs of liquefaction. So, in earlier lectures, we discussed what ground response analysis is, what the different kinds of seismic waves are, how the seismic wave information can be used to find out the modification of ground motion characteristics by different soil layers. Finally, at the surface, because of modified ground motion, additional stresses will be generated in the soil medium. If the soil is relatively soft, it may undergo failure.

A critical example is liquefaction, where again, the soil will lose all its shear strength, and it almost flows like a liquid. In such a case, when the soil has lost all its shear strength, which was there during static loading conditions, anything located on the soil, whether it was a simple vehicle or any other kind of superstructure, will not be able to withstand that particular load. The superstructure or the car will start sinking into the ground. So, that is part of the induced effect of an earthquake. Whenever we talk about induced effects, that means whenever earthquake loading, whether it was direct loading or excessive ground shaking because of amplification in the soil medium, occurs. This modification, which is not directly happening because of the earthquake at the source, but subsequent modifications as well as the characteristics of the in-situ soil conditions, are observed. Similarly, in the case of slopes, tunnels, and superstructures, depending upon the characteristics of each of these systems and how much resistance the systems are offering to external loading conditions, induced by earthquake-generated vibrations, that is called the induced effect.

Later on, we discussed primarily related to liquefaction: what parameters help in identifying whether a particular site is prone to liquefaction or not, and how that can be used to find out the safety effect against liquefaction, and subsequently, maps can be developed that identify regions that are prone to liquefaction and those that are not. Later, we discussed seismic microzonation, which will give a combined effect of what locations are relatively safe or relatively have low components of hazard, whether you talk about seismic hazard, ground motion, liquefaction, or landslides or tsunamis. It identifies the potential induced effects at a particular site of interest.

We started with lecture one about the different layers of the Earth, and in the end, till lecture 27, we were discussing seismic microzonation. Later, we also discussed landslides and their classification. So, overall, based on the understanding so far, what we have learned is, keeping in mind that there are different seismic sources in and around your study area, in and around your project site, and each of the seismic sources, which are faults, primarily active faults that have been producing repeated earthquakes of different magnitudes from time to time, keeping that seismicity into account, we now have to design a particular structure that has to be exposed for at least the design life of the structure. You can consider maybe 25, 30, 35 years, whatever is the type of structure and its design life. So, there is a structure being constructed at a particular site, and once it is kept in position, it will be exposed to different kinds of seismic scenarios. Some scenarios may be at 10-kilometer distance, some might be at 100 kilometers, and some might be very active but located at a 300-kilometer epicentral distance. Now, whether it is at 5 kilometers, 10 kilometers, 100 kilometers, or 500 kilometers, whenever there is an earthquake, each of these sources will transfer seismic loading to the structure. If a very small magnitude earthquake happens very close to the site, it can also contribute to significant earthquake loading. Similarly, if a larger magnitude earthquake or great earthquake happens even at 300 kilometers, 400 kilometers radial distance from the site, that can also produce significant vibrations at your site of interest.

So, depending upon your building construction material, the vertical similarity in the building, the similarity in the plan, the frame structure, and the health of load-bearing members, one can have a rough idea about whether, when this particular building is subjected to earthquake loading, it will undergo minor cracks, will show no distress, or will undergo complete collapse. So, it is like we are discussing earthquake loading conditions; this is seismic hazard analysis. We are basically trying to identify what the potential ground motion is likely to occur. So, we are talking about probabilistic hazard analysis, which we have also discussed in earlier lectures. The objective was to find out what the potential ground motion is that my building is expected to witness during its design life, which will govern the design of the building. So, I have to ensure, as a designer, that whatever components I am designing, each of these components and my overall structure should be able to withstand the most likely ground vibration that will occur at my site of interest.

So, this is about the earthquake loading condition. Now, many a time we discussed that whenever there is an earthquake, there are a lot of building damages because earthquake loading will transfer vibration to buildings. Depending upon the building characteristics, these vibrations, some of them will be able to withstand, some of them will undergo minor damage, and some of them may undergo complete collapse. Recently, during the 2023 Turkey earthquake, we also saw a lot of devastation, a lot of building damages, a lot of uneven settlement, a lot of cracks, and foundation failure. So, many things were witnessed during different locations, during maybe the main earthquake or aftershocks. So, that means whenever we are interested in finding out earthquake loading, we are not only restricting ourselves to finding out what is the potential ground motion. Definitely, this information has to be utilized somewhere in order to mitigate the scenario that happened during the 2023 Turkey earthquake in terms of devastation. It is basically the response of your system, whether you are talking about a parking lot, a bridge, a building, a tower, cable suspension supports, or bridge abutments. All of these are basically the systems that will be exposed to earthquake-induced loading. If these are not designed properly, they will undergo failure.

So, one is about the vulnerability, which we will be talking about in today's class, about what is vulnerability. That means whenever an earthquake has happened, we have to basically correlate with respect to what is the most likely ground motion and how this ground motion is going to define the stability of a particular building and the safety of its intended users. So, that will come under seismic vulnerability and risk. Once you go to risk, we can even find out what is the potential exposure of a particular building and its intended users whenever there is an earthquake involved, or there is an earthquake scenario likely to occur during maybe a definite exposure period.

So, Lecture 28 is basically the understanding of seismic vulnerability and risk. It has been divided, in general, into three lectures. So, today we will be discussing and giving an overview about what vulnerability is, how it is correlated with respect to hazard, and how vulnerability and hazard can be correlated with respect to the risk. So, this is part one, and subsequently, Lectures 29 and 30 will be part two and part three for seismic vulnerability as well as risk.

Year	Earthquake Name	Magnitude	Fatalities
1255	Kathmandu Valley	-	1,00,000
1555	Srinagar	-	60,000
1737	Kolkata	-	1,00,000
1819	Kutch	7.8	1543
1833	Bihar-Nepal	-	500
1897	Shillong	8.1	1500
1905	Kangra	7.8	19,500
1934	Bihar-Nepal	8.1	10,500
1950	Assam	8.5	1526
1991	Uttarkashi	6.5	2000
1999	Chamoli	6.8	150
2005	Kashmir	7.6	80,000

So, we know different earthquakes have happened across the globe. In this particular table, we are discussing some of the important earthquakes that have happened from time to time in different sections of the Himalayas and definitely in other locations, primarily in the Indian subcontinent. So, carefully looking at these earthquakes, we will get an idea that it is not only the seismic activity of a particular source in terms of producing maybe major earthquakes, great earthquakes, and moderate earthquakes, but also, every time there is an earthquake, there are a lot of lives lost, a lot of people injured, and a lot of buildings undergoing collapse or damages that are beyond repair.

At the same time, because now there has been some earthquake, as a result of which there have been fatalities and building damages, the government and the local agencies will put a lot of money into restoring the buildings that were involved. In case there is a complete collapse, then people have to undergo rehabilitation. So again, there, in order to bring the condition back to normal or at least close to normal, to remove debris, to continue transportation, to supply food, to supply essential medicines, and to communicate with hit areas during a particular earthquake, a lot of finance also has to be pumped into the system. So, not only the fatalities—definitely, when people lose their lives, that is the most important concern related to earthquake occurrence—but at the same time, in addition to this, a lot of money that should have been used for the development of infrastructure and securing health, as well as basic infrastructure facilities, could have been arranged. Now, this money has gone into rehabilitation work. So, definitely, it is going to affect the overall development of society.

So, whenever we are discussing seismic vulnerability and risk, the overall target is to find out what are the potential locations that are more prone to earthquake effects. When we talk about effects, that means building collapse as well as the life of its intended users. Earlier, I also mentioned that many a time it has been seen that fatalities are directly a function of at what time of the day the earthquake has happened. If the earthquake has happened during late night, that means where the majority of the residents were inside their houses, and the building has undergone complete collapse, definitely, in this particular case, the fatalities will be significantly higher in comparison to if the same earthquake had happened during the daytime, when most of the people were outside. Maybe they were in the market, traveling, or in their offices, or some of them were in open areas. So, in comparison to the people who were sleeping and suddenly hit by an earthquake, the building undergoes damage. Definitely, the chances for these people to go to an open area will be relatively less in comparison to other people where the earthquake has happened during broad daylight. And whenever any earthquake shaking occurs, or when people are told that some warning has been issued that an earthquake is going to hit, people can go to a safer location. So, if it is happening during the day, there are definitely more chances that relatively fewer fatalities will be there. Building damage is independent of what time of the day your earthquake is hitting your site of interest, but definitely, fatalities are directly related to what time of the day the earthquake has happened.

So, looking at this particular figure, we can get an idea that in 1255, there was an earthquake in Kathmandu, Nepal, and the fatalities were close to 1 lakh. Similarly, in 1555, there was an earthquake in Srinagar, and fatalities were close to 60,000. Subsequently, we can see more earthquakes that have happened in different parts of the Indian subcontinent. Starting with the 1255 Kathmandu earthquake, similarly in 1897, there was an earthquake in Shillong with a magnitude of 8.1, but considering the population density, it was relatively less. So, we can see close to 1,500 people lost their lives. In 1950, again, there was an earthquake in Assam with a magnitude of 8.5, and 1,526 people lost their lives. In 2005, there was an earthquake in Kashmir with a magnitude of 7.6, and close to 80,000 people lost their lives. 2005 is quite recent in comparison to 1255, when 1 lakh fatalities were there, even in 2005, the number of fatalities was significantly high. So primarily, it is related to construction practices, how sound the construction is at a particular site, and secondly, the population density. Many times, locations that are in close proximity to very active seismic sources and also have very high population density are more vulnerable. Those are the reasons that one must be more careful, if similar earthquakes are going to happen in the near future, definitely, the population size that will be affected by the occurrence of these earthquakes will be significantly larger. So, if you talk about the population density in terms of what was there during 1255, when close to 1 lakh people lost their lives, the current population density will be much more. It will be many more, manifold increased in comparison to the 1255 population density. So, if the same earthquake is going to hit today, or even the 1905 earthquake is going to hit today, then depending upon again where this particular earthquake is happening, the fatalities will be significantly higher because the population density is very high. Many times, the equal contribution comes from the type of construction—how proper is the construction material chosen, how effective is the design and reinforcement, and all those things.

So, this particular table gives an idea that not every time there has been an earthquake happening across different centuries, but at the same time, whenever there is an earthquake, lives are involved. There are lives that have been lost during these particular earthquakes. So, every time there is an earthquake, it’s not only the vibration. So far, we were discussing vibration, but there is life, which is also getting lost at the same time. Life should be given the top priority. Now, this is about the fatalities.

Earthquake	Damage
2010 Haiti Earthquake	Death toll was in the range of 46,000 to 3,16,000
2011 Tohoku Earthquake	The death toll was 20,475. Around 1.108 million people became homeless. The economic loss was 140 million USD.
2011 Turkey Earthquake	Economic loss was 2.2 billion USD.
2011 Sikkim Earthquake	Economic loss was 1.7 billion USD.
2015 Nepal Earthquake	Fatalities close to 10, 000 with an economic loss of 290 million USD.
2023 Turkey-Syria Earthquake	Fatalities close to 56, 000 with an economic loss of 80 billion USD.

Again, we have another table on the right. Again, we can see over here, in 2010, there was an earthquake, the Haiti earthquake, where the death toll was in the range of 46,000 to 316,000. Again, so many people—very recent, 2010 Haiti earthquake. In 2011, there was an earthquake in Japan, the Tohoku earthquake. So, again, we can see the death toll was close to 21,000 people, and close to 1.108 million people became homeless. So, it's like not only people are losing their lives, but because of building collapse, people are also losing their homes, so they are becoming homeless. Close to 140 million US dollars of economic loss happened just because of the 2011 Tohoku earthquake. Again, in 2011, there was an earthquake in Turkey, leading to an economic loss of 2.2 billion US dollars. So, keeping the fatalities as the most important, but keeping fatalities also aside, at the same time, there is a lot of finance getting lost because of rehabilitation, food supply, essential items, and many more things. In 2011, again, there was an earthquake in Sikkim of magnitude 6.8.

So, again, in Sikkim, we see the fatalities were also there, but at the same time, close to 1.7 billion US dollars of economic loss was triggered or had happened during the 2011 Sikkim earthquake. In 2015, there was an earthquake in Pokhara, Nepal. Close to 10,000 people lost their lives, and again, the number of people lost their lives can be slightly varying, and the economic loss was close to 290 million US dollars. So, again, we can see every time there is an earthquake, we have fatalities, as given in the table on the left, and in addition to those fatalities, a lot of economic loss is also involved, primarily because of building damages and other infrastructural damage. It's kind of complete devastation, so not only human lives, but all types of infrastructure are also getting badly affected and, when near time, getting complete collapse.

Similarly, in 2023, there was an earthquake in February 2023 in Turkey-Syria, that particular location. So, again, the fatality was close to 56,000, and close to 80 billion US dollars. Again, this figure has been taken from the existing literature. So, there is significant variation in terms of the economic losses. So, every time—why I am insisting on this particular part is that understanding past earthquakes, understanding the activity of a particular fault, or maximum potential earthquake or seismic activity or hazard analysis, that certainly is the objective to know about the seismicity of a particular region or how active a particular region is in terms of earthquake occurrence. But at the same time, this understanding or outcome from seismic hazard also has to be looked into from fatalities or building collapse point of view, which is primarily the objective for vulnerability and risk assessment.

Now, risk—when we are talking about risk, particularly about seismic risk, it is basically how much is the potential disaster loss which is going to occur. If you are talking about seismic risk, what is the potential disaster which is going to occur primarily because of a particular earthquake? If you are talking about one particular scenario, if you are talking about a particular region, we have to take into account the potential scenarios and then try to determine the risk. So, definitely, this is in terms of property loss, as well as in terms of health loss, livelihood loss. People are losing their entire building, their offices, their setup—that is gone. So, again, livelihood also, their markets, shops, are there. Livelihood is also getting completely lost—asset, infrastructure, property. People are losing services: telecommunication services, health services, maybe if gas pipelines are also there, those are also getting badly affected. So, all these kinds of disasters, which are primarily related to lives, related to livelihood, assets, or services, resulting in the form of a disaster, are happening during a particular community or a particular society. It's not like happening at present or happened in the past. Primarily, when we are talking about risk, that means what is the potential risk involved for a particular scenario? I am talking about earthquake here, or I am talking about tsunami. I can talk in terms of fire, I can talk about drought, ground subsidence. So, all these different kinds of natural phenomena or anthropogenic activities—every time when there is any activity involved, how this particular activity, how this particular phenomenon, whether it is man-made or whether it is natural, how it is going to affect in terms of all these things during a fixed exposure period.

So, I am interested to find out how much the risk is involved for the next 20 years, next 25 years, next 30 years. If you are talking about hazard, that means in terms of earthquake occurrence, how much is the risk involved which can result in loss of lives? It can result in health status degrading, loss in livelihood, services, assets during maybe the next 25 years, 30 years, 35 years. So, that is going to definitely give us an idea about how much is the risk involved. And definitely, if you are talking about the mitigation plan, if you are talking about how to deal with the disaster which is likely to occur in the next 25 years, next 10 years, next 30 years, it's not only that only at the end of 25 years you are going to experience an earthquake. Because the site is located, or the region is located in such a way that once every six months, or once every two years, you are expecting one moderate to great earthquake, moderate earthquakes, or maybe large earthquakes. And once in maybe 15 years, 20 years, 100 years, you are expecting to experience one great earthquake.

So certainly, down the line, if you are starting from today, maybe in the next five years, how much is the risk involved in terms of all these parameters because of the seismic scenario, which might be generated because of one or maybe different seismic sources? That will come under risk, and accordingly, we can come up with the policies like how one can deal with it—whether in terms of developing shelters, whether in terms of issuing warnings, whether in terms of training people, like how one has to respond during a particular earthquake. Definitely, the seismic scenario, which was actually resulting in disaster or loss of lives, can be reduced significantly if we are having a proper mitigation plan and, of course, followed by regular training to its intended user on what they are supposed to do when they are exposed to a particular seismic scenario, or whenever they are supposed to expose to any other kind of natural disaster.

So, this is, of course, whenever we are talking about risk, there will always be some exposure period. How much is our exposure period? I cannot determine the risk for infinite time because every seismic scenario or every natural phenomenon will be corresponding to some probability of occurrence. When we are talking about tsunami, it will be happening at different frequency in comparison to an earthquake. Similarly, in terms of fire incidents, in terms of drought, in terms of maybe landslide. If a landslide is there, what if a particular slide, which is more prone to failure, undergoes failure in the next 20 years, 30 years? What are the areas which will undergo complete collapse, or what are the lives will be lost? So, all those things we can discuss in terms of risk. Definitely, three things will come into picture. One is what is the loading you are getting? If you are talking about slope failure, definitely, because of the failure of the material, how much is the load involved? What is the triggering mechanism? That will also be there. What is the exposure? If I am designing or assessing the risk today, then considering what is the chance that the slope, or maybe a number of slopes, will undergo failure in the next 20 years, next 30 years, next 40 years? Accordingly, taking into account the probability of failure in the next 20 years, I will determine what is the risk my site is exposed to for the next 20 years. So, hazard has also come into the picture, exposure period has also come into the picture.

The next part will be vulnerability. What are the characteristics of the system which is actually undergoing failure? If you are talking about maybe a building, what are the characteristics of the building that actually differentiate or help us find out what is the suitability of a building to withstand maybe a slope failure scenario or maybe an earthquake scenario? So, vulnerability will come into the picture, exposure will come into the picture, and definitely the loading condition. So, if you are talking about the seismic part, seismic hazard will also come into the picture. So, risk, is a measure of how much is the expected loss. If you are talking about hazard, how much is the expected loss which is likely to occur during a particular seismic scenario? And we are talking about a seismic scenario, definitely during a particular magnitude earthquake, if you are talking about a deterministic one. If you are talking about a probabilistic one, then again, depending upon what is the frequency of occurrence you are targeting, you can find out what is the seismic scenario. More precisely, if you are going with the probabilistic one, you can go with deaggregation and find out what is the worst scenario of magnitude and distance combination. So, that can also be used over here.

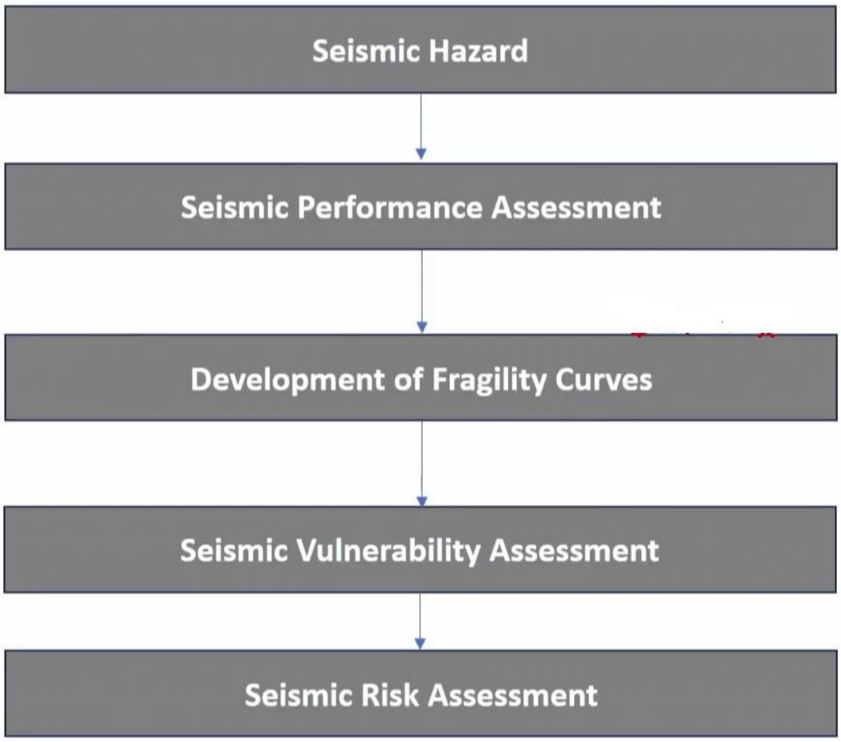
Risk, it is a function of hazard, as I mentioned, because it's directly related to how many lives are at stake. Definitely, we have to have an understanding of how much is the loading which is going to come, what is the duration in which I am expected to know the potential loading. Thirdly, when this loading is being applied, where this particular loading is being exposed to—whether it will be applied to a particular building, whether it will be applied to a particular tower, whether it will be applied to a particular parking area or any other thing—such that there should be a component of risk. So, vulnerability means I am interested to find out where actually you are going to apply, and then, depending upon the characteristics of that particular superstructure, that particular, maybe, tower, that particular building, that particular parking area, I can find out the vulnerability. And, of course, I can also take into account the subsoil medium characteristics while assessing the vulnerability.

Risk = f(hazard, vulnerability, exposure)

So, risk, is a collective function of hazard, that means the loading condition for what duration I am expecting a particular loading condition. If you remember probabilistic hazard analysis, there also we were telling that this is a particular seismic scenario like 0.1 g, 0.15 g, 0.2 g, 0.23 g. So, that was the spectral acceleration which my site was expected to experience. How much, maybe, the chances that this particular ground motion of spectral acceleration will not expose? Like 90% or 98% probability was there that it's not going to expose during the next 50 years. So, if you recall, you are having primarily two definitions. That means a 2% probability that my ground motion, which I am going to give based on probabilistic hazard analysis, is not going to exceed during maybe the next 50 years, next 60 years, depending upon what is the exposure period I am defining in my calculation.

So, in probabilistic hazard analysis, we were giving the seismic scenario corresponding to seismic hazard, corresponding to some particular exposure period. So, depending upon your design life of the structure, or if you are targeting for some scenario, accordingly, we can define—the user can define—how much is the exposure one is expecting to use corresponding to risk assessment. Remember, more exposure, the longer duration one is interested in terms of assessing the risk, that particular hazard value again will increase. Because you are interested, basically, if I am increasing the exposure. That means suppose I am considering exposure for 20 years, and another way, I am considering exposure of 80 years, whenever I am going with mitigation, I am interested to find out, like, how much seismic scenario my building will be exposed to in the next 20 years and how much seismic scenario my building will be exposed to in the next 80 years. So, certainly, in the next 80 years, the ground motion expected will be relatively more because now your building is exposed for a longer duration on the site. So, certainly, there will be a lot of uncertainty in terms of ground motion which will be available. That will definitely increase the magnitude of hazard value which my building will be exposed to if the exposure period I am considering is 80 years.

Similarly, if I am going with the probability of accidents, if I am taking a 2% probability of accidents, that means I am ensuring that 98% chances are there that my ground motion in the next 50 years, next 30 years, next 40 years is not going to exceed the ground motion which I am giving based on my hazard analysis. Similarly, if I reduce this probability from 98% to 90%, that means I am interested in finding out the spectral acceleration corresponding to 10% probability in 50 years. That means I am ensuring whatever ground motion I am going to give, 90% chances are there that this ground motion is not going to exceed. Your site is never going to experience ground motion beyond or above the spectral acceleration which I am giving based on probabilistic hazard analysis. And this probability that it is not going to exceed is 90%. It may exceed, that chance is 10%. So, all those things will come under hazard as well as exposure period. In addition to this, when we are going with risk, we have to also take into account what is the vulnerability, what are the system characteristics on which hazard will be applied for a definite exposure period. So, when these three components are there, definitely, I will be having all the important information related to risk assessment.



So, seismic hazard, we have discussed. We take into account all the seismic scenarios or the seismic activity of all the adjoining faults which are available in your seismotectonic region, determine the value of seismic hazard, take that into account. You can go with seismic performance because not only one set of ground motion characteristics will be potentially occurring at your site, but your site will be exposed to a lot of ground motion characteristics, which we have a chance to undergo variation. These may change whenever a seismic scenario is going to hit your site of interest. So, definitely, one has to go with seismic performance-based design. So, corresponding to different sets of ground motions, what is the performance your building or your structure is going to show whenever we go for stability analysis of a particular building? Or when we are trying to find out the analysis of a particular building or a particular structure to above seismic hazard. Based on this, the user can define—the damage characteristics. So, fragility analysis is going to tell us what is the correlation between the ground motion and the damages which are going to happen at a particular structure. Because now the structure is exposed to particular ground vibration, definitely, there might be some critical joints. If you are going with a building, you can develop the damage characteristics of the building in terms of fragility curves. If you are going with, maybe, small connections, maybe an operating machine, or maybe pipe connections, you can go with the development of fragility curves for different, different important components. So, this fragility curve is going to give us an understanding of how, with the change in ground motion properties, my damage characteristics of the critical component will vary. I can define the damage—whether the damage at this particular threshold value should be considered as minor damage, beyond that, it should be considered as more damage. And then, depending upon the critical values, I can also define, like, corresponding to what level of damage I can say it has complete collapse. So, all those characteristics will come under fragility curves. It is basically going to give you an understanding of the correlation between your ground motion, which will be exposed to your building, and, correspondingly, if your ground motion is very low, what is the percentage damage? If the ground motion is moderate, what is again the damage? If the ground motion is very high, what is the damage? Definitely, it will not be the seismic hazard value alone, but it will be the complete picture of the ground motion characteristics which will help us in finding out the damage characteristics.

So, I am interested in finding out, based on that, based on the design of the building, based on the literature, also, we can find out what are the critical components. If those undergo failure, the entire structure—whether the building, whether the beam, whether the column—remains stable, but it's going to compromise the safety of a particular structure. So, that means we have to find out what are the critical components which are ensuring the safety of a particular structure. A critical example is, if you are going with nuclear power plants, the critical component is maybe some pipe connections, maybe some machine operation, some movements of some mechanical components, whose movements are also critical. Primarily, it may be related to during the time when the power plant is undergoing in its running condition or when there's any kind of radiation leak. Then, again, there are a lot of safety measures. So, suppose there was some seismic scenario because of which there are chances that radiation may undergo leakage, then a lot of safety measures will come into the picture. The objective of those safety measures is to prevent any kind of movement, whether it is in terms of mechanical components or in terms of some pipelines which are providing essentials in order to arrest the reaction. So, these are basically the important components whenever we are going with fragility analysis. In addition to finding out the probabilistic hazard analysis, which a particular reactor building will be exposed to, we can also try determining what is the potential of damage in terms of ground motion characteristics which your site is exposed to. Such that, now I know the fragility curve of my critical component, I can define accordingly, like if my structure is exposed to this particular level of ground motion, then the critical component will be able to withstand that ground motion. If the structure is exposed to higher ground motion, this component may undergo partial failure, or it may undergo total failure. So, those kinds of understandings we can develop for critical components for a particular structure. These critical components can be defined by the intended user, or if you are talking about specific buildings, maybe well-defined codal provisions are there in order to find out what are the critical components for which one can go with the development of fragility curves.

So, we started with seismic hazard, then taken into consideration, corresponding to the potential ground motion scenario, we perform the seismic performance design, how the system is going to respond, and corresponding to that response, one can determine the fragility curves, which is going to give me an understanding about the potential damage. Taking that into account, we can perform the vulnerability assessment. That means you are having the building characteristics, you are having some understanding about the plan of the building, the aerial view of the building, and the construction material used in the building. Then, you can continue with the seismic assessment because you will be having the characteristics of the building as well as some characteristics of seismic hazard. Collectively, you can take into account, for a known exposure period, what will be the risk involved. Because from seismic hazard, you know it is corresponding to some exposure period. Based on fragility, you will be able to determine the vulnerability, and then, taking all those components, we can determine the value of seismic risk.

Now, again, going back to the hazard, we have discussed in earlier lectures also about hazard, both the deterministic hazard analysis, which is going to give us an understanding about the worst-case scenario, which is generally corresponding to the maximum magnitude of earthquake happening or most likely to happen on the most earthquake-causing fault or the fault which is very close to your site of interest. And again, on that particular fault, the earthquake of maximum magnitude is happening at a location closest to your site of interest. So, that was the definition of deterministic, and then dealing with the uncertainty with respect to earthquake size in terms of earthquake magnitude, in terms of location, and ground motion accidents, we have another approach that is called probabilistic hazard analysis. So, we have discussed probabilistic hazard analysis or deterministic hazard analysis. It is basically going to give us, corresponding to a particular earthquake, an understanding of seismic hazard. It's going to give us what is the magnitude of loading which is expected at your site of interest.

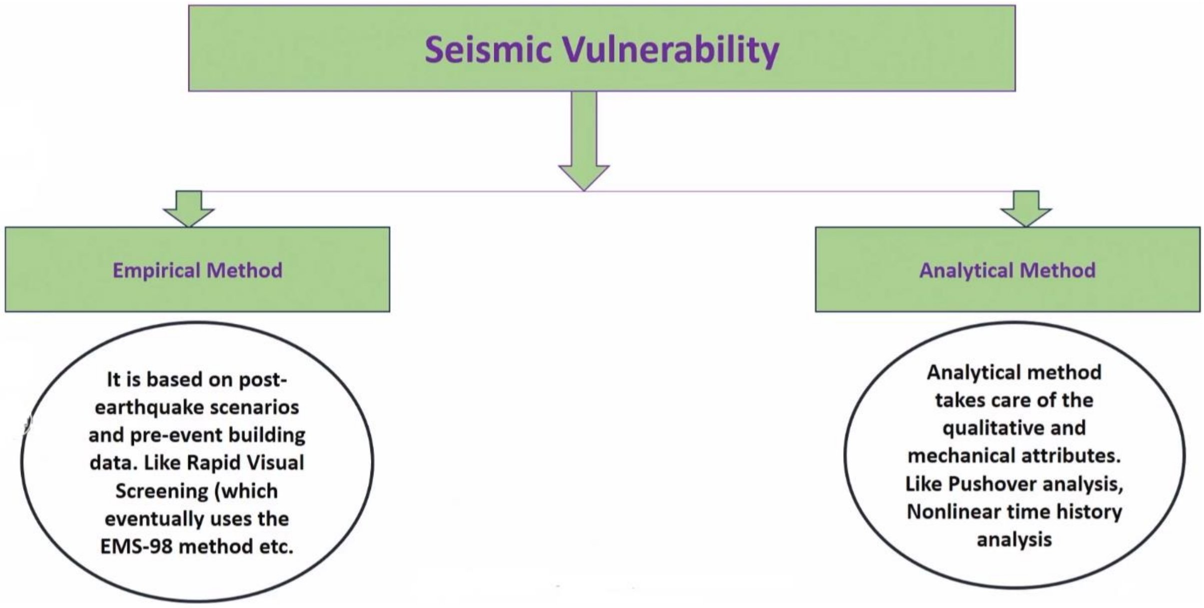
So, if you are talking about seismic hazard, it's going to tell us how much earthquake loading you are likely to be exposed to at your site of interest. That actually can cause building damage and later on lead to loss of lives, injury, and other health impacts. Similarly, property damages can be there, asset damages can be there. So, all these things, which are basically triggered losses, have been triggered primarily because of the occurrence of a particular hazard. It can be seismic hazard, it can be other kinds of natural hazards or anthropogenic hazards. But primarily, the purpose here is to find out how much loading you are going to get because of a particular earthquake, or because of maybe a tsunami, or any other natural phenomena. If you are talking about blast anthropogenic activities, then corresponding to blasting, if you are going to design some bunkers, then you can take into account the characteristics of that particular loading and then try determining the blast-related hazard values. So, that can also come into the picture in terms of hazard assessment. Depending upon what kind of hazard you are dealing with, the corresponding value of loading on a particular infrastructure, where you are interested to find out, like if I am in a particular region, I am interested to find out the hazard value. That means I am going to find out how much loading my infrastructure is exposed to. If seismic hazard is there, then building; if you are talking about blasting, then maybe bunkers or any other airfields/strips. So, there also you can take into account directly the measure of how much the magnitude of a particular loading condition.

It need not be the current hazard, but considering the past scenarios which we have in terms of literature, whether you are talking about earthquake hazard, landslide, or any other tsunami hazard, take into account what has happened in the past. Based on that, in light of that particular information and existing models, try to forecast what should be the scenario for the future. Considering latent conditions, considering the existing conditions, what should be the scenario likely to emerge in the next 10 years, 15 years? And as I mentioned earlier also, the scenario keeps on changing. If you are talking about a prediction for the next 5 years, it may be different. A 10-year prediction definitely involves more uncertainty because not only earthquakes but many other activities are also changing in and around a particular site, which may not be changing significantly in the next 5 years but can change in the next 15–20 years. Moreover, the longer the duration of exposure, the more chances that some earthquakes happening at longer distances over a longer duration may also be exposed to your building, which perhaps you are not anticipating in the next 10 years but will occur in the next 50 years.

So, hazard includes latent conditions. They may represent future threats, maybe anthropogenic or natural. Both will give us an understanding of what the future threat or loading scenario is. Threat, again, we can replace with respect to the loading scenario, which is actually going to compromise the safety of a particular infrastructure. If you are considering human activities, it's again going to directly impact the risk values. So, this can be natural or anthropogenic/man-made. Each hazard is characterized primarily by means of location—where it is, more or less intensity, how much, more or less frequency—how frequently these hazards are going to be experienced, and the probability of occurrence. So, this we have already discussed in probabilistic hazard analysis.

Then, hazard analysis is related to the identification and monitoring of any kind of hazard. So, when we are talking about seismic hazard, we also go with early warning systems. When we are talking about tsunami hazards, a lot of information can be used in terms of developing useful tsunami warnings that will give us primarily an alarm before the actual loading hits your site of interest. Certainly, buildings cannot be saved, but at least the people living can be moved to safer locations. So, seismic hazard accounts for damage to property. If not directly damaged, it will be related to loading, and then loading, in addition to building characteristics, will lead to damage characteristics of the earthquake for a particular seismic scenario. Definitely, when the building undergoes damage, lives are also involved. So, injury and fatalities will also come into the picture. Seismic hazard analysis requires a quantitative assessment of how much ground motion is exposed at a particular site during a particular exposure period. The knowledge of seismic hazard analysis—if you know well in advance what the seismic loading is going to be experienced in the next 20 years—then definitely you can use it in terms of retrofitting the existing infrastructure, in terms of assessing the damage characteristics of the infrastructure which you cannot repair, maybe because of a number of reasons. Thirdly, whenever you are going for new infrastructure development, definitely this knowledge is going to give you a lot of important information in terms of the mitigation of future damages.

Vulnerability is basically the characteristics and circumstances of a particular system or community when it is exposed to the damaging characteristics of a particular hazard. As I mentioned, if you are talking about the vulnerability of a particular system, that means how vulnerable or what the characteristics of the system are when it is subjected to a particular hazard—that will come under vulnerability. That means that will make it susceptible. Susceptible means whenever earthquake loading is there, how the characteristics of the building are going to change whenever it is subjected to an earthquake loading condition. So, it is a concept that describes factors or constraints—economic, social, physical, and geographic—that can reduce the ability of the community to prepare for or to cope with the impact of the hazard. That means vulnerability is going to directly tell us when this particular hazard is being exposed to a particular community, whether the community is going to withstand it or whether it is going to cope with it or undergo a kind of failure. A disaster happens when a hazard interacts with vulnerability. That means when vulnerability is more, and subsequently loading is also applied to the system, that will result in disaster. It can be man-made, or it can be natural. Disasters affect the population primarily if there are buildings involved—whether it is because of bombing, whether it is because of a tsunami, or whether it is because of seismic activity. Finally, the building, which was vulnerable, or which was declared as vulnerable because of these loading conditions, will undergo failure if your building is exposed to any of these loading conditions. There will be a loss of lives because there are people living there, so where there is physical infrastructure, environmental, and socio-economic consequences related to vulnerability as well as exposure to a particular hazard. Seismic vulnerability is defined as the tendency of the structure to undergo structural or non-structural failure or damages in case of a seismic event. So, if we are talking about seismic vulnerability, that means we are talking about what the chances are that the building will be able to withstand that seismic loading or not. Accordingly, that will define whether the building is vulnerable or not.



Seismic vulnerability, again, can be assessed using an empirical method, where you can actually identify, based on visual screening, the characteristics of the building—what type of soil the building is located on, what type of construction material has been used in constructing this particular building. All those things will come under that. Then, you have an analytical method where you can go with modeling and find out the response of the building to a large set of ground motion characteristics. You can go with pushover analysis; you can go with non-linear analysis in order to find out what the vulnerability of at least the critical components of the building or any other infrastructure is. Whenever you go with the empirical method, it is based on a post-earthquake scenario. If you are going after an earthquake has happened and are interested in finding out vulnerability studies or damage studies, you can refer to standard charts and correlate them with the kind of damage you see in a particular site affected during a particular earthquake. Similarly, you can use pre-event buildings to find out whether those were vulnerable or not. The same concept can be extended to existing buildings, where we try to understand what the vulnerability of those buildings will be. The characteristics of the building can be taken into account to find out whether the building will be vulnerable or not. Again, we can refer to the EMS-98 method to conduct a vulnerability assessment based on the empirical method.

The analytical method will take more quantitative assessments of vulnerability or damage characteristics of the building, primarily related to pushover analysis, where you can correlate the seismic demand of a particular structure and how much loading the structure is exposed to.

You can also go with non-linear time history analysis in order to find out the degradation in the components over the period of seismic loading conditions.

Classification of damage to masonry buildings	Classification of damage to reinforced concrete buildings
Grade 1: Negligible to slight damage (No structural damage, slight non-structural damage) Hair-line cracks in very few walls. Fall of small pieces of plaster only. Fall of loose stones from upper parts of buildings in very few cases.	Grade 1: Negligible to slight damage (No structural damage, slight non-structural damage) Hair-line cracks in very few walls. Fall of small pieces of plaster only. Fall of loose stones from upper parts of buildings in very few cases.
Grade 2: Moderate damage (Slight structural damage, moderate nonstructural damage) Cracks in many walls. Fall of fairly large pieces of plaster. Partial collapse of chimney and Mumpty.	Grade 2: Moderate damage (Slight structural damage, moderate nonstructural damage) Cracks in columns and beams of frames and in structural walls. Cracks in partition and infill walls; fall of brittle cladding and plaster. Falling of mortar from the joints of wall panels.

The EMS method, an empirical method, provides damage classification based on the European Macroseismic Scale. Based on the damage characteristics, you can define whether it is about a masonry building or a concrete building. You can define it by observing the damages that happened during a particular earthquake with respect to the pre-event building. So, grade one is related to negligible to slight damages of non-structural members—hairline cracks in very few walls and the fall-off of small pieces of plaster only. This is the characteristic based on which you can say grade one kind of damage has happened to a particular building. Similarly, with respect to grade two—moderate damage—slight structural components undergo damage, cracks in many walls, the fall-off of very large pieces of plaster, and partial collapse of chimneys as well as mantis. Again, if these scenarios have been experienced during a particular earthquake to a building, keeping in account the information about the building before the earthquake happened, that collectively helps in understanding the damage. It should not happen that before a particular earthquake, some of these characteristics were already experienced by the building. In such a case, that will not be considered damage to the building during the earthquake. Similar classification details can be obtained for damages to reinforced concrete buildings.

Classification of damage to masonry buildings	Classification of damage to reinforced concrete buildings
Grade 3: Substantial to heavy damage (moderate structural damage, heavy nonstructural damage) Large and extensive cracks in most walls. Roof tiles detached. Chimneys fractured at the roof line; failure of individual non-structural elements (partitions, gable walls etc.).	Grade 3: Substantial to heavy damage (moderate structural damage, heavy nonstructural damage) Cracks in columns and beam-column joints of frames at the base and at joints of coupled walls. Spalling of concrete cover, buckling of reinforced bars. Large cracks in partition and infill walls, failure of individual infill panels.
Grade 4: Very heavy damage (heavy structural damage, very heavy non-structural damage) Serious failure of walls (gaps in walls); partial structural failure of roofs and floors.	Grade 4: Very heavy damage (heavy structural damage, very heavy non-structural damage) Large cracks in structural elements with compression failure of concrete and fracture of rebars; bond failure of beam reinforcing bars; tilting of columns. Collapse of a few columns or of a single upper floor
Grade 5: Destruction (very heavy structural damage) Total or near to total collapse of the building	Grade 5: Destruction (very heavy structural damage) Collapse of ground floor parts (e.g. wings) of the building.

Similarly, classifications for grades three, four, and five are also there. Grade four indicates very heavy damage, particularly to structural members, with very heavy damage to non-structural members. Structural members, meaning load-bearing members that directly offer resistance to external loading conditions, also experience heavy damage. Non-structural members experience very heavy damage. Grade five indicates complete destruction or collapse of the building. If you are going with grade five for reinforced concrete buildings, then it is called the destruction of primarily the structural members, followed by the collapse of ground floor parts. This could include the loss of wings or shear reinforcement or confinement of structural members during a particular earthquake. Based on that, you can determine if grade five kinds of damages have occurred in reinforced concrete structures.

Based on rapid visual screening (RVS), the most popular method for vulnerability assessment or determining how vulnerable a particular building is, it was developed by the Federal Emergency Management Agency (FEMA) in 1998. The second edition was given in 2002, and recently, in 2015, the third edition was published. It is a cost-effective method. Visual screening means just by walking on the sidewalk for 15 to 30 days, observing each and every building, you go around the building and find out the characteristics mentioned. Based on these characteristics, you can classify the RVS (rapid visual screening value) value of a particular building will also help in understanding what the grade of potential damage is likely to be during a particular earthquake. So, a surveyor does not necessarily need to be an expert or a structural engineer, but certain points are given, and one can be trained for those points. You go to a particular site, observe that particular site with respect to those points. If the interior can be accessed—because many times buildings are not accessible for various reasons—then that gives additional confidence in the RVS value. If it is not accessible, then we can restrict ourselves to whatever is observed based on sidewalks.

Okay, so I will stop here, and we will further continue this particular discussion in lecture number 29 and subsequently in lecture number 30. Thank you.