Applied Seismology for Engineers

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Lecture – 26

Hello everyone, welcome to lecture 26 of the course Applied Seismology for Engineers. In earlier discussions, starting with lecture 1 onward, we primarily focused on how the earthquakes are coming into the picture, primarily related to the movement which is happening along the plate boundaries. Following that, there will be development of stresses along the plate boundary, and subsequently, there will be development of stresses in intraplate regions also. As a result, there has been an occurrence of earthquakes not only confined to the plate boundaries but even to the intraplate regions, as can be evidenced from micro-zonation as well as seismic zonation maps of the country. Then, later on, we discussed how to quantify a particular fault plane, primarily in terms of its strike value, its dip value, and its rake angle, which is basically an indication of, during a particular earthquake, what are the directions in which the hanging wall and footwall are undergoing movement. So, to describe that particular movement, the rake angle is important; to describe the orientation of the fault plane, the strike and dip values are important.

Then, later on, we discussed that whenever there is a release of energy during a particular earthquake, this energy, in terms of seismic waves, will propagate primarily through the crustal medium. As it is moving from the source, which we have also discussed more precisely in terms of synthetic ground motion development as well as modeling of ground motion prediction equations. So, there we discussed how a particular source, whether you are talking about a point source or a finite source, can be modeled using precisely the shear modulus of the soil, then taken into account how much is the stress drop before and after a particular earthquake. Now, when the seismic waves are generated at a particular source and are getting propagated through a propagating medium, these are interacting with different layers of the Earth, primarily the heterogeneity which is present in a particular medium. As a result, whatever the frequency content of the wave generated at the source, these will undergo a lot of attenuation and amplification. As a result, the ground motion characteristics, primarily the duration, the frequency content, and the amplitude of ground motion, which was generated at the source, will keep on changing throughout its propagation medium.

So, that means if there is a source located at a particular location, then this particular source will be interacting with the medium. So, that particular source will be basically interacting with the medium if this is your epicenter of the earthquake. Once the wave is propagating at deeper and deeper locations and away from your epicenter or away from the focus more specifically—these waves or disturbances are basically interacting with the medium properties in the crustal medium, which is located maybe 15-20 kilometers beneath the ground surface. Depending upon the heterogeneity present in the medium, there will be a change in the frequency content, amplitude, as well as the duration of the motion. Depending upon the type of wave generated at the source, primarily we will have body waves, which consist of primary waves as well as secondary waves. When these waves interact with surficial and near-surface mediums, there will be development of surface waves which are coming into existence. So, depending upon the type of wave and its interaction with the medium, there will always be some change in the characteristics of motions. All these parameters—the amplitude, the frequency content, and the duration—are basically the ground motion characteristics which we have already discussed in earlier lectures.

So, ground motion characteristics generated at the source subsequently are getting modified as you are moving away from your focus, depending upon the heterogeneity, again depending upon the geometric spreading, heat, or particle oscillation which is happening all across the propagation medium. Finally, the modified wave which has been altered significantly between the source and beneath a particular site of interest, will again get amplified or de-amplified by different layers of soil available between the bedrock medium and the surface medium. Remember, the surface medium is the same medium on which any kind of construction of a building or any other utilities are generally constructed. So, finally, the further modified ground motions at the ground surface are basically responsible for whether the building will undergo minor damage, the building will not undergo any kind of damage, or the building will undergo complete collapse. That will be governed by how much ground motion is available at the ground surface.

But if we look into a particular site of interest, more or less the damage or the level of expected ground motion at a particular location will be a collective effort of how much the bedrock motion is because bedrock motion is significantly affected by what faults are available in and around that particular region. Or we can say how much the seismic activity of the seismotectonic province of a particular site is. Then, depending upon that seismic activity of the province and taking into account how much the magnitude of the earthquakes happening at different faults within your seismotectonic province, one can determine the seismic hazard values. Primarily, it is determined at the bedrock level, and many a time even at site class A or site class B conditions. So, site class A and site class B are basically referring to the conditions of seismic site classes, which are based primarily on the 30-meter average site classification, which is also discussed in earlier lectures. So, one is the level of motion which has been transferred from the source to the bedrock medium. Secondly, how much modification further is happening because of local soil.

So, collectively, because of these two things, there will be many parameters coming into the picture, each of these components controlling the expected level of ground shaking at a particular site of interest. When I say expected level, that means there is not just one scenario that is going to get generated, but there will be a number of combinations related to maybe higher amplification, maybe lower amplification, higher value of hazard, or lower value of hazard. Similarly, when the ground motion has reached a particular site of interest, depending upon the in-situ properties of the soil, the soil may undergo amplification, or it may not undergo amplification. So, if you recollect whatever we discussed in terms of assessing the liquefaction potential of a particular site, again, the site may be prone to liquefaction depending upon how much the in-situ strength is and how much it is exposed to a particular ground motion during a particular scenario earthquake. So, we had hazard values at the bedrock level.

Secondly, what is the classification at a particular site? Thirdly, depending upon the classification, whether there will be more amplification or there will be less amplification for a particular ground motion. Thirdly, once the modified ground motion reaches a particular site of interest, how much is the potential of a particular site to undergo liquefaction? Similarly, we are talking about some sites that are very close to coastal regions. Then, because of earthquake occurrence, there can be the generation of tsunamis also. So again, we have to find out how much the potential of the region is in terms of the occurrence of tsunamis or exposure to tsunamis.

The same way, if we are talking about some hilly terrain, because of this modified ground motion, what are the chances that the area, which is hilly terrain, can experience maybe landslides? So again, susceptible to landslides, one has to take into account. Subsequently, it is like depending upon where your site is actually located, there might be some chances of induced effects depending upon the terrain type one is dealing with. So, to start with seismic micro-zonation, which we will be discussing in today's class, it is basically a term which will help in microzoning or identifying smaller zones in a particular region. It may happen to a larger area or it may happen to one particular construction site also. So, basically, the objective of doing micro-zonation studies, which are primarily limited to urban centers, is to identify the locations within an urban center or within a particular city that are more prone to earthquake hazards and their induced effects. So, it is like when we are discussing hazards, we will be characterizing a particular region based on the contour of hazard values.

Similarly, on the other hand, when we are talking about soil amplification because of the presence of local soil, again independently, we were talking about how much is amplification, which is going to be experienced by a particular site during a particular earthquake. So, the hazard value was independent; the local site effect was independent. Similarly, if we are discussing liquefaction potential, then again, liquefaction potential of a site, considering different values of scenario earthquakes. But if you take a particular site, whether it is because of high amplification at the bedrock level or because of high surface motion or primarily because of a very low value of the factor of safety, the site may undergo damage which may be related to earthquake-induced effects. So, collectively, in micro-zonation, what we try to do, we try to understand collectively based on all the scenarios, that means based on bedrock values, based on induced effect, based on local site effect, based on landslide, based on any other induced effect which is prone to happen at a particular site of interest, and taking all those effects in a rational manner, like whether bedrock will be more contributing to surface hazard, whether amplification will be contributing more to hazard, or whether the factor of safety against liquefaction or landslide is corresponding more to hazard at a particular site of interest, that means how much is the hazard expected at a particular site of interest. So, collectively, using all those parameters in a rational manner and clubbing the contribution which is coming from each of these components, we can get an idea about what are the locations which are relatively safer, what are the locations which are relatively vulnerable. If you bring again into the exposure period and building classification and the risk involved, we can continue with this for vulnerability and risk studies also.

So, micro-zonation, in the end, will give you some map of a particular study area where you can have an understanding of what are the regions which are more prone to hazards during a particular earthquake in general, not actually related to one seismic scenario but related to all the seismic scenarios, which are primarily taken in bedrock hazard level, soil amplification and liquefaction potential assessment, and many more induced effects. So, it will help basically in identifying what are the regions in a particular study area which are more prone to more hazards and what are the regions which are relatively less prone to hazards. This will also help in maybe city planning, maybe laying of important roads, important transmission towers, maybe for site selection for rehabilitation camps, hospitals because in case there is an earthquake or there are casualties or calamity which have been spread all across your study area, then seismic micro-zonation study-based maps can be referred to in selecting the sites which are relatively safer as far as rehabilitation works are required or maybe some relief works are required to settle the affected area. Similarly, as far as transmission is concerned, so again, the location of transmission towers should be relatively on safer locations such that even though the surrounding area is subjected to large casualties, still the transmission tower is at a relatively safer position so that you can pass on the information in case of any distress or anyone requires medical emergency or so on and so forth. So again, for such locations, whether you are talking about the location of important buildings such as schools which can be used even as relief camps in case of any distress, maybe transmission towers, maybe for laying of important roads, the entire area has undergone damage, that means even the connection of road networks has also been affected.

So, what are the important roads which will suffer relatively lesser damage during a particular earthquake or during a particular seismic scenario such that these can be used, I mean these are the alignments along which important roads can be laid so that in case of any distress, these can be used for medical situations, supply of essential items. So, all this information, similarly, relatively safer areas within a study area. Of course, this is when we say about relatively safer areas, so it is basically in terms of hazard values. We have not taken, particularly in the micro-zonation study, we have not taken the quality of construction based on which the building has been constructed. So, there might be a possibility of an area which is very much prone to high hazard, but depending upon the quality of construction, which is very good, the building may not experience any kind of damage or even minor cracks. So, this, when we say about safety, we are mainly focused on in terms of hazard values or hazard index, more precisely, because hazard index means collectively it will be taken into account what is the effect which is coming from bedrock, what is the effect which is coming from the local site effect, what is the effect which is coming from induced effects also. So, collectively, the hazard index is going to give you a relative representation of potential hazards, which might be because of one or more than one component of surface scenario earthquake. So, a micro-zonation study can help you in identifying locations for important buildings, for important transmission towers, even for laying important roads, which can be used for the supply of medicals, supply of essential items in case of any distress, any casualties, and then identification of relatively safer areas within a particular study area, so you can identify these are the locations which are relatively safe if there is an earthquake going to hit in and around your study area or within your seaport tectonic province.

So, why actually micro-zonation is required, if we take into account the understanding of earthquakes, as I mentioned earlier, also in India, primarily, if we are focusing on plate boundaries, that is Indian Eurasian plate boundaries towards the north and Indo-Burmese plate boundary towards the east, the recording of earthquakes roughly around the 1980s has actually started. But if we look into the damages which have been available in various forms in existing literature, in terms of casualties, we can see in this particular figure.

LIST OF SIGNIFICANT EARTHQUAKES IN THE HIMALAYAN

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

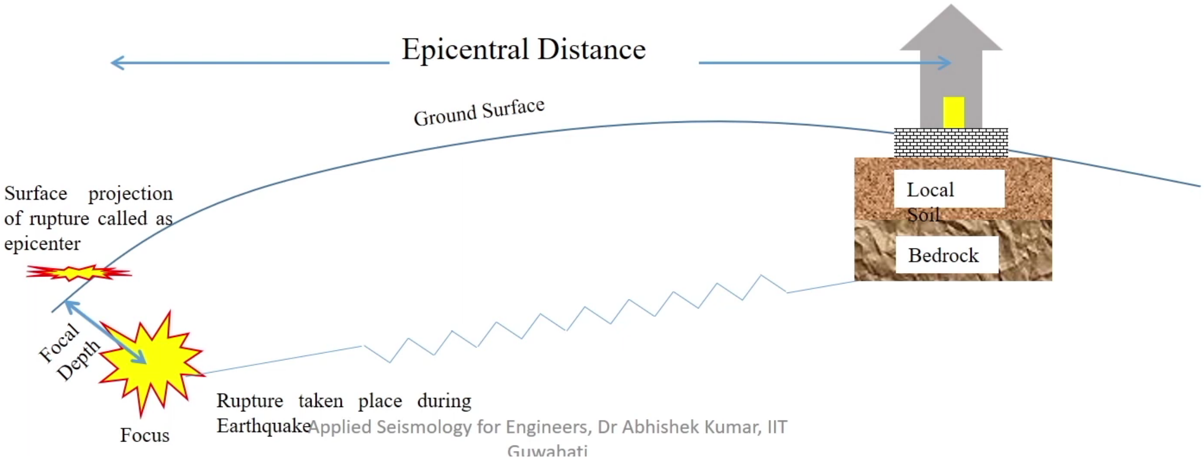
So in 1255, there was an earthquake in the Kathmandu valley. The magnitude of the earthquake, not very closer figure, is known, but if we talk in terms of fatalities, it led to almost one lakh fatalities in 1255. So, we can think of, like, what was the population density in 1255. So, that means relatively, even though the population density was relatively less, but whatever houses people were using had undergone maybe minor, major cracks, or maybe complete collapse. As a result, almost close to one lakh fatalities were reported during the 1255 earthquake. Similarly, so, on one side, we are talking about how much we know about ground motion characteristics. That means in the Indian scenario, after the 1980 Dharmsala earthquake. But if we talk in terms of damage characteristics or how prone is the study area in terms of damages which are generated during different earthquakes. So, here is a list of earthquakes, the year in which these earthquakes have happened, and the relative fatalities. So, 1255 earthquake in Kathmandu, and then 1555, again, there was an earthquake in Srinagar which caused almost sixty thousand fatalities. In 1737, there was an earthquake close to Kolkata, again, the fatalities were close to one lakh. In 1819, there was an earthquake in Kutch, also referred to as Allah Bund earthquake. So, the magnitude of that earthquake, which later was determined, was close to 7.8. So still, if we think in terms of ground motion, the great earthquakes, we have very limited information, and most of the information, particularly in the Indian scenario, is related to the isoseismal map which is available when we are talking about the 1897 Shillong earthquake, we are talking about the 1905 Kangra earthquake, 1950 Assam earthquake, and 1934 Bihar-Nepal earthquake. So, most of the earthquakes which are above eight magnitudes, which we call as great earthquakes, have happened, but as such, we do not have ground motion records for these great earthquakes, particularly in the Indian scenario. However, this understanding, in terms of how much were the casualties, at least gives an idea about what if these earthquakes are going to get repeated, what will be the amount of damages in the region. We know that in comparison to 1819, in comparison to 1833, the population density, if you are talking about seismic zone five, is significantly high, again, taking into account the construction practice which ranges from very poor to poor to very good construction.

So, there are regions which are actually prone to very large magnitude earthquakes, maybe major to great earthquakes also, and the system which is going to offer resistance to the ground motion actually ranges from very poor to very good construction. So, depending upon how much is the loading which is induced by the earthquake and how much is the resistance being offered by the infrastructure, definitely will decide what will be the fate of the infrastructure, whether it will undergo complete collapse, whether it will be minor damages, or whether it will be major damages. And depending upon the damage of the structure, that will define what will happen to the intended user of that particular structure. If the structure undergoes complete collapse and people are actually using it during a particular earthquake, definitely that will lead to larger casualties.

It has also been observed that depending upon the time when the earthquake has happened will also play a significant role in terms of casualties. That means, if the earthquake is happening during daytime, when the majority of the people are not actually staying inside the house but are in open areas or maybe doing different activities that are not related to staying inside a particular building, even if the building undergoes major damage or complete collapse, in such a scenario, the casualties will be relatively less in comparison to the times when the earthquakes are hitting and the majority of the population is inside their house.

Again, in 1819, there was an earthquake in Kutch leading to almost 1,543 casualties; in 1833, again there was an earthquake in Bhan, Nepal, causing close to 500 casualties. So, these are the rough figures which are taken from the literature. In 1897, there was an earthquake in Shillong, close to 1,500 casualties. And again, when we are discussing about casualties, we should also take into account what is the population density, how closely people are staying, how closely the houses are. So, even if one house undergoes collapse, there will be the effect of that particular collapse to the nearby building, so that will also be accounted. In 1905, there was an earthquake in Kangra of magnitude 7.8 and the casualties were close to 19,500. In 1934, again there was an earthquake after 1918, and in 1833, the magnitude of the earthquake was close to 8.1, leading to almost 10,500 casualties. In 1950, again there was an earthquake in Assam of magnitude 8.5 leading to 1,526 casualties, and subsequently, in 2005, there was an earthquake in Kashmir where the casualties were primarily close to 80,000. Though the magnitude of the earthquake was again 7.6. So, we can have an understanding like if we directly correlate the casualties with respect to magnitude, there is significant variation. Many times, major earthquakes cause more damage in comparison to great earthquakes, primarily because the population was available in that particular region, buildings were available in that particular region or not. So, collectively, and thirdly, as I mentioned, the time, the time of the day when the earthquake has hit, where the majority of the population was. So, all these collectively will decide, and of course, most important is the quality of the construction. So, the quality of construction, time of occurrence in terms of the day, and intended user—if there are buildings which are very large but intended users are very few, then certainly the building damage will be more, but fatalities will be very less.

Now, if you focus on the year in which these have happened, starting from 1255, and this is not the complete picture. So, we have yet many more information that can be added up here. For example, in 2015, there was an earthquake in Nepal, close to 11,000 casualties. And again, the economic damages, economic loss was in billions of dollars. So, it's not only about the casualties but also the financial loss which the country has to suffer when a lot of infrastructure failure occurs during a particular earthquake scenario because one has to spend again the same amount of money to develop the infrastructure to the level where it was before the earthquake hit. So, here is the scenario: there is an area that has a long history of earthquake occurrence and subsequently fatalities. Now, we are talking about smart buildings; we are talking about smart cities. So, the primary objective is how one can identify the locations that are more prone to earthquakes and their induced damages, and the locations which are less prone to earthquake hazards and induced damages, so that accordingly we can take this information in city planning. As I mentioned, in terms of locating important buildings, in terms of laying important roads, in terms of laying transmission towers, and many more information. Again, if you talk about earthquakes which we have discussed, basically, it is related to the release of energy which has primarily been released at the focus or the source of the earthquake in terms of seismic waves.



So, we see here, just now in the previous slide, we discussed about the building damages. But if we see the entire problem here, there is a ground surface on which you have a building. Somewhere, maybe hundreds of kilometers away from your site of interest, there was the release of energy at the focus. When the energy was released, there were developments of seismic waves. These are all important terminologies we have already discussed in earlier lectures. Now, again, if you go to a particular building, there will be local soil available beneath that particular soil. You can have bad rock, you can have even bad weathered rock, and then crustal medium is there. So, seismic waves, which are generated at the source, will propagate to the crustal medium, reaching again to the crustal medium, and subsequently to the bedrock. Once it reaches the bedrock, these come in contact with the surface layer or near-surface layer.

So, depending upon the dynamic properties of these surface layers and how much shear strain is getting induced by a particular ground motion in each of these subsurface layers, a number of layers are possible between bedrock and the ground surface. So, depending upon the dynamic properties of each of these layers, dynamic properties of each of these layers of soil, and even the bedrock medium, the medium has actually been exposed to change in the motion characteristics or, more precisely, ground motion characteristics. Remember, we are discussing now in terms of what are the locations which can be declared as relatively safe for further construction. So, waves started from the focus, reached a particular site. Depending upon the dynamic properties, as well as induced shear strain, we remember dynamic soil properties.

So, finally, what properties of the soil, what property of shear modulus, what property of damping ratio, will govern the response of the soil will depend upon how much shear strain is getting induced in a particular soil layer. So, if the shear strain is relatively high, then, corresponding to that level of shear strain, the subsequent value of the damping ratio and shear modulus will take part in controlling or offering resistance to the ground shaking. Subsequently, this phenomenon will keep on getting repeated to different layers. Finally, there will be ground motion which is reaching the ground surface.

Now, when this ground motion reaches the surface, it is basically giving how much earthquake loading is being transferred to the foundation of the building, subsequently to the superstructure also. But at the same time, if the ground available at the particular site, like we are talking about this particular ground on which the foundation is located, is soft, cohesionless, saturated, it can also cause the loss of shear strength. That means there will be development of excess pore pressure; it will lead to liquefaction in the medium. So, even though the building, the superstructure, is designed corresponding to the potential input motion which has been obtained based on the surface scenario of the earthquake or after local side effect as estimation, the building remains intact. But what will happen if the foundation soil has undergone liquefaction? The building will undergo either too much of total settlement or it may undergo too much of differential settlement.

Finally, liquefaction leading to excessive total or differential settlement. So, the building remains intact. But, again, when we were talking about earthquake loading on a particular building, it was the combined effect of bedrock motion and amplification by the local soil. The building remains intact, but at the same time, the foundation medium, which was offering resistance to the bearing capacity of the foundation, has actually lost all the strength. It is almost like a liquid. The building remains intact but has actually started sinking into the ground. It may undergo uniform settlement or it may undergo differential settlement. In such a case, even though the building was intact, it is now not making its sole purpose. I mean, the sole purpose, so it will be considered as failed as far as serviceability is concerned. So, again, one was bedrock motion. Bedrock motion— we are trying to highlight what are the characteristics which are basically defining the safety of this particular building independent of the quality of the construction, because we have not taken the building classification and its intended use. So, we are not right now focusing on the vulnerability and risk; we are only focusing on the hazard part. So, bedrock motion was there, then soil amplification was there. This, independently, we have discussed. But at a particular site, bedrock motion that is obtained from seismic hazard analysis— so we are having some value of hazard. Now, depending upon different values of hazard, what is the amplification? As we discussed earlier also, a low value of PGA or low value of bedrock motion can give you higher amplification. But as the amplitude of bedrock motion keeps on increasing, the soil amplification will keep on reducing because the soil is dynamic in nature in terms of offering resistance to external loading.

Soil amplification came into the picture; this collectively defined the design of the superstructure. Of course, we will take into account the soil-structure interaction also here. Now, soil exposed to loading— exposed to which loading? The modified ground motion at the surface. Because, if you remember, when we were discussing about liquefaction potential of a site, the amax value was surface motion corresponding to peak ground acceleration values. Soil exposed to loading— this will define whether liquefaction or no liquefaction. So, even though the building remains safe, if the soil has undergone liquefaction, it will start excessive settlement. So, this is the third part. This is basically local site effects also leading to excessive ground shaking. Again, the surface motion or the occurrence of liquefaction is also called an induced effect. So, whenever we are discussing about micro-zonation or hazard index (which will be the basis for micro-zonation), we will be taking into account the direct loading as well as the induced effects. In this particular case, it is liquefaction. Again, we are talking about hilly terrain, so there will be chances that the slope may undergo failure because of induced loading by ground motions during a particular earthquake. So, again, this can destabilize the slope; the slope can undergo failure.

Similar to assessing the effect of safety against liquefaction, one can also look into the landslide zonation map of a particular region. There, the slopes which are on the brink of failure, the slopes which are relatively safe, and the slopes which are marginally safe are actually well identified. At times, the factor of safety against failure for scenario earthquakes is also defined. So, taking that into account, when we are talking about hilly terrain, we can also take into account the landslide susceptibility. That means, what is the susceptibility that the site can undergo landslide failure? Because, again, though the building is intact, corresponding to a surface loading or modified ground motion at the surface, if the land on which the building is located, or the land adjacent to the building, undergoes any kind of landslide, definitely it is going to compromise the very existence of the building. So, again, this is an induced effect. So far, we have taken the seismic hazard value, local site effects, and induced effects individually in earlier lectures. But in seismic micro-zonation, we are actually interested in finding out what are the regions which can be declared as relatively safer in terms of hazard values or hazard index. So, again, in hilly terrain, this is there. Again, you are talking about coastal regions, you can bring tsunami into account. If you are talking about maybe any other kind of terrain, what are the potential induced effects which may come into picture whenever we are talking about earthquake scenarios, or how the system in the local region is going to respond to earthquake loading? Very much similar to liquefaction, landslide, tsunami, or even there is a chance that fire can break out during a particular earthquake. We can bring that component into account and try finding out what will be the relatively lower hazard index locations or relatively higher hazard index locations in micro-generation map development.

So, this was the modified ground motion at the surface, which is basically controlling the shaking of the building. But, in addition, this is also controlling the chances that the soil can undergo liquefaction at this particular foundation level. So, modified ground motion leading to failure— again, if we see, there is significant change in the ground motion characteristics between bedrock, within the soil, as well as on the ground surface. We have discussed all these things individually also earlier. So, what is happening at the source will be called as source characteristics. What is happening between the source and the site is called propagation path characteristics. And what is happening at the site can be called as path characteristics. Now, this is a background. At the actual site, what we see: some building is there, and after a particular earthquake, if the building has undergone damage, we can make a comparison between what was the building before, how was the building before the earthquake, and how is the building after the earthquake. So, collectively, this is the combined effect of source propagation path and site characteristics, which is basically defining the level of ground shaking or the amplitude of ground shaking to which the building is exposed or the probable level of ground shaking to which the building is exposed, primarily during its design life.

Again, we have already discussed ground motion and attenuation. We can bring it collectively into ground motion prediction equations, which can be used in determining hazard analysis. Then, based on field investigation, one can go for liquefaction and site classification maps. We cannot avoid the information that earthquake directly is not causing any kind of damage. Whether it's the response, whether you are talking about liquefaction, it is the response of the ground to earthquake loading. And when you are talking about building damage or landslide, again, it is the response of the system to the loading which is being induced by earthquake occurrence. Now, if we are able to find out maybe regional hazard values at the bedrock level, surface level, definitely it will help in giving updated information about earthquake loading for which a building or system has to be designed. Again, if you are talking about landslide, it is going to give you how much earthquake loading a particular slope can be exposed to, to determine the factor of safety of that particular slope and appropriately take a decision on whether there is a need to strengthen the slope or provide some secondary measures so that, even if it undergoes failure, there will not be subsequent effects in terms of the intended user on the slope or adjacent to the slope.

The main reason is the fast-growing population, which has started settling in regions that are moderate to very high seismic hazard zones. If the earthquakes, which triggered almost close to 180,000 fatalities in 1200-1500, are talking about buildings or regions that are now having maybe close to 100,000-200,000 people living in very close areas and are exposed to moderate to major earthquakes. And, of course, in 1200-1300, mostly it was like single-storey buildings, where people were living. We are also talking about poor construction practices, and buildings are becoming higher and higher. So, taking that effect also into account— poor construction practices, high population density— that means one thing is clear. If a similar seismic scenario is going to get repeated, the casualties, the fatalities, the amount of damages, and the economic loss will be manyfold in comparison to what has been witnessed in the past.

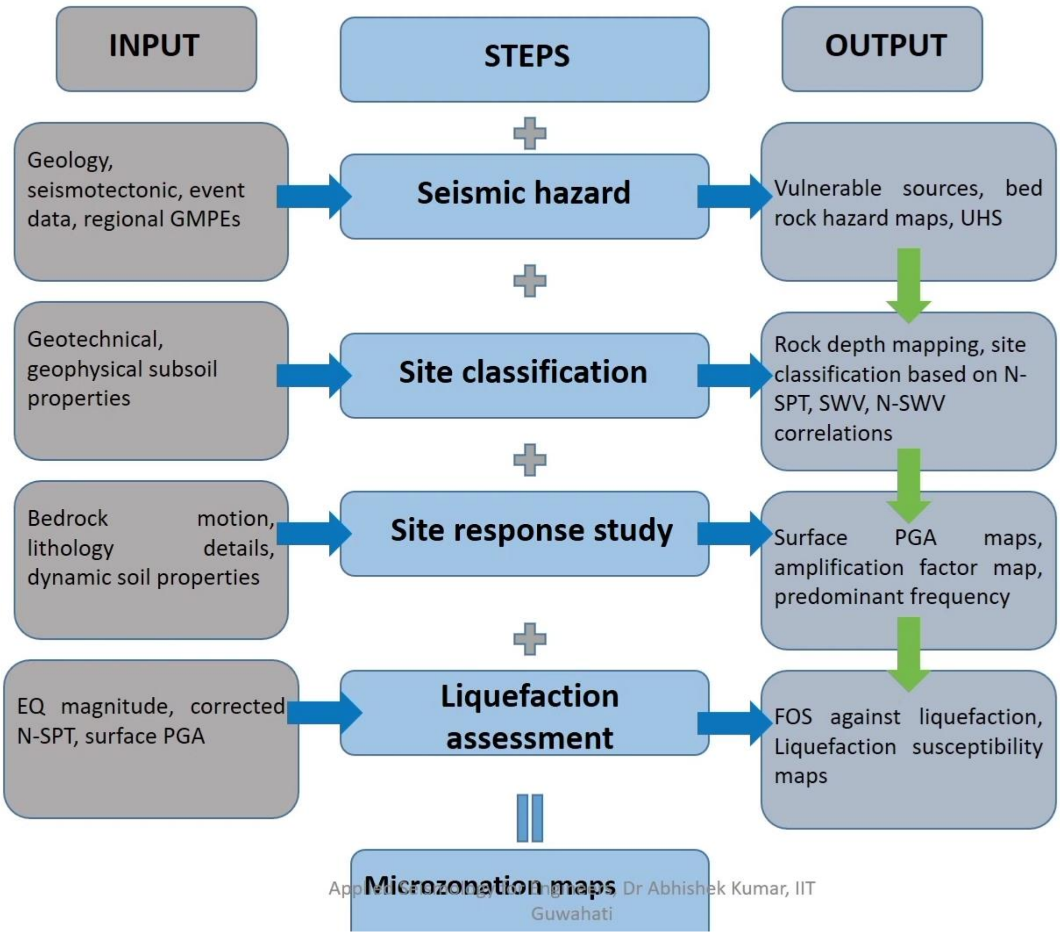
So, this highlights that a more comprehensive study should be done, particularly in seismically active regions which are there in seismic zone 3, seismic zone 4, and 5, as far as the seismic zone map of India is concerned. Because based on these comprehensive studies, firstly, the district authorities will be able to identify the regions which are relatively safe. Secondly, once the maps are available for micro-zonation studies, this is also going to give guidelines to intended users who are thinking of maybe some construction projects, or maybe laying a runway for an airport, or maybe laying important railway lines. So, certainly, additional information is now being given based on micro-zonation maps. Like these are the locations, if your railway track, your runway, or your road is passing through, one has to take extra precautions, and please see if there is any kind of ground improvement needed—please do it, because this is a location that is basically prone to earthquake effects. So, not only the hazard value but also taking into account the induced effects. If that can be considered, will definitely help in mitigation and can significantly reduce seismic hazard values and the corresponding casualties.

Some facts: this is basically related to the Indian scenario. We can see that 4,000 natural calamities have happened in the last decade, killing more than close to 8 lakh people and affecting close to 2 billion people by natural calamities. We are talking about tsunamis, earthquakes, fire outbreaks, avalanches, landslides, and many more things. However, if we are talking about all these, a major portion comes from earthquakes. That means, in terms of building damage and casualties, earthquakes have been playing a dominating role. And if you are talking about tsunamis, the casualties will be more confined to coastal regions. We are talking about landslides again; they will be more confined to hilly terrain. But as far as earthquakes are concerned, they are more or less causing damage to each type of terrain. That means, independent of whether you are talking about the coastal region, hilly terrain, or plain areas, earthquake and induced effects are possible in all types of terrain. That is the reason the majority of the damages which have happened in earlier earthquakes have significantly contributed to earthquakes in comparison to other natural calamities.

Again, if we are talking about economic losses, more than 1,000 dollars in economic losses primarily because of these casualties have occurred. So, we are not only talking about fatalities but also the finances which are getting lost while dealing with these casualties, whether in terms of rehabilitation, medical supplies, or constructing infrastructure so that one can access these affected areas. So, economic loss is also involved. Threats by 2050, because of these particular natural calamities, particularly in India, will be manifold, as per the World Bank report. It will be three times higher. This gives an indication that, if we are talking about casualties at present, which are in terms of tens of thousands or one lakh during even single earthquakes collectively, and in terms of economic loss, sometimes it reaches close to billions of dollars, by 2050, it is going to get significantly higher. So, that means there is a requirement for a more comprehensive study, primarily in terms of micro-zonation, which takes collectively into account all the parameters that are basically governing the surface scenario of hazard values in terms of induced effects and other effects, so that we can minimize these casualties and catastrophes. So, if we are able to take into account the chances that the site can undergo landslides, liquefaction, excessive ground shaking, or soil amplification, all these potential probabilities, if we take them into account well in advance, we can strengthen the slope, strengthen the site, and appropriately determine the earthquake loading on a building, such that the casualties or the catastrophes which are likely to come can be minimized significantly. This will significantly improve economic losses, so we can strengthen our infrastructure rather than waiting for some seismic scenario to hit the infrastructure and lead to damage. Similarly, we can also reduce significantly the casualties which are likely to occur because we cannot ignore what has been learned during previous earthquakes, which we saw in the beginning of this particular lecture.

So, micro-zonation is defined as zonation with respect to ground motion characteristics. So, we will take ground motion characteristics into account, taking source and site conditions also into account. So, we will be taking into account what the site conditions are and how the site conditions are going to get affected when the site is being exposed to earthquake loading conditions. Also taken into account is what has been generated at the source and is getting propagated to the site, and primarily in terms of seismic micro-zonation. We can say zonation with respect to ground motion characteristics is more like seismic micro-zonation. It has been defined as per the International Society for Soil Mechanics and Geotechnical Engineering Technical Committee 4 in the year 1999. The purpose of why we should go for micro-zonation is that it’s going to give you an overall understanding of a particular site in order to go for mitigation. What mitigation measures can be done in order to plan for rehabilitation? At least if a particular site or a particular town has not been developed in a very planned manner, but if micro-zonation maps are available, we can still be better prepared for any kind of rehabilitation work which might be required, maybe in the next five, ten, or twenty years from now. Such that, if we are ready with those rehabilitation plans, we can deal with such calamities and distressful conditions in a more effective manner during a particular earthquake and also after a particular earthquake, in terms of rehabilitation.

Of course, if we are designing a particular region, micro-zonation maps play a very important role in terms of city planning. Again, to assess vulnerability studies and even for risk assessment, primarily because micro-zonation is giving a bigger picture of how a particular site is going to behave during a particular earthquake. Now, it can be collectively because of bedrock motion, amplification, landslides, local soil, overburden, or even the predominant frequency of the site itself. So, all these features, which are directly contributing to the scenario that can be created at a particular site during a particular earthquake, everything is included in a particular micro-zonation map. Some of the cities which I have mentioned here for which micro-zonation studies have been completed, or some are also undergoing, it's not the first time. I mean, the study for micro-zonation maps has been happening for a number of cities. For some cities, more than one attempt has been made to understand the micro-zonation of the study area. This can further be used primarily in vulnerability and risk assessment.



Now, components of micro-zonation: here, we are discussing micro-zonation maps and how they can be developed. There are different inputs required, and corresponding to these inputs, there will be some output, which may act as input for the next level. So, whenever we are discussing seismic hazard, whether you are going with deterministic or probabilistic, one has to take into account the geology of a particular region, then develop the seismotectonic map of the region, taking the past earthquake as well as information about the seismic sources into account. Also, take regional ground motion prediction equations. You will have information about the geology, and you will have information about the tectonic setting of the region, which will definitely help in seismic source characterization of a particular region. Taking that into account, one can determine the seismic activity of the region. Again, bringing the source information and past earthquake information, we can go with the development of a seismotectonic map. So, one, we have the seismotectonic map. Other, we have the source characterization map. Taking this information, primarily the maximum and minimum magnitude potential in a particular region, these we have already discussed in an earlier lecture.

So here, those inputs which we have discussed earlier are also components of micro-zonation maps. Again, taking regional ground motion prediction equations, probabilistic models, or deterministic models, one can develop a hazard map, the seismic hazard map of a particular study area. This can be used to identify what regions are more vulnerable as far as seismic hazard is concerned. It can also be helpful in determining the bedrock-level hazard maps and even for the determination of uniform hazard spectra if you are going with the probabilistic model. Now, this hazard value is definitely at the bedrock level, so at some level, this hazard value will come in contact with the local soil. So, one can go with seismic site classification to find out, on average, what the characteristics of a medium are, whether the medium is very soft, whether the medium is soft, relatively soft, stiff, or hard. One can go with geotechnical methods like standard penetration tests, cone penetration tests, cross-hole tests, or geophysical methods like multi-channel analysis of surface waves, spectral analysis of surface waves, which will also give an understanding about the strength properties of the subsurface medium. It will also help in identifying, overall, what classification a particular site belongs to. This will give you, if the depth of the bedrock is relatively shallower, even geophysical methods can help in identifying the depth of the bedrock. If it is located at a relatively deeper depth, we can go with more precise methods. So, based on the explanations done using geotechnical or geophysical methods, one can develop seismic site classification maps. That means identification of regions which are classified as relatively safe, which are classified as relatively stiff, or which are identified as relatively hard in a particular study area.

So, you go to a particular site, do these tests, and depending upon the output, you can classify. There are classification systems one can refer to, and based on that, based on the SPTN value, based on shear wave velocity, one can classify a particular site. Bedrock motion has given you an understanding of what the amplitude of motion will develop at bedrock across your study area. Site classification has given you overburden characteristics, whether it is soft, hard, or stiff. Now, considering the subsoil characteristics and the input motion, one can perform ground response analysis or site response analysis, taking bedrock into account, taking bedrock motion into account, depth of bedrock into account, dynamic properties of the soil into account, as well as the stratification details into account. So, all this information will go into the site response analysis. You can do maybe linear analysis, equivalent linear or nonlinear analysis, which has already been discussed in earlier lectures. This will help in developing surface hazard maps. The deterministic and probabilistic maps, which are developed over here, were at bedrock level, but after ground response analysis, you are getting surface hazard maps. This will also help in determining amplification maps corresponding to different scenarios—what sites are undergoing more amplification; what sites are undergoing less amplification. Subsequently, because these are the sites having different stiffness across the depths, one can also develop the predominant frequency maps.

So, based on the geotechnical and geophysical methods, whatever stiffness value we are getting, that can be used to determine the predominant frequency of a particular site. Using the same observation for a number of sites, one can develop the predominant frequency maps for the study area. So now we are having surface seismic hazard maps—which are basically going to give you the expected level of ground motion at the surface, based on geophysical and geotechnical methods. We are also having strength characteristics of in-situ soil. So, strength characteristics we are getting from here, stress characteristics we are getting from here. Comparing these two, using standard terminologies, one can also find out, using scenario earthquake into account, using corrected SPT into account (which has also been discussed when we were discussing the liquefaction potential of a site), and taking the surface PGA (peak ground acceleration) into account, one can determine the factor of safety of a particular site or susceptibility of a site—whether it will undergo liquefaction or not. So, collectively, we will get factor of safety against liquefaction maps of a particular area. Once this map is available, we will be able to find out what locations, under favorable loading conditions (which are behind those maps), are potential to undergo liquefaction, considering the current in-situ condition. If someone is going for construction, one can refer to those maps and maybe go for suitable ground improvement measures before constructing any particular sites.

So, a particular site, whether it is exposed to very high bedrock motion, whether the site belongs to soft soil, whether the soil amplification is relatively high, or the soil has a very low value of the factor of safety against liquefaction—any of these parameters can collectively define what will be the effect of the earthquake or its induced effects on the particular site. So, collectively, taking the components which we are getting from each of these thematic layers, we can add up more layers depending on the potential induced effects which are likely to occur at a particular site of interest for which one is developing the micro-zonation map. Collectively, taking all those into account in a rational manner (because all are not given equal importance), some will be given relatively higher weightage, some will be given relatively lower weightage, and one can club all those thematic layers to develop micro-zonation maps. Now, we will refer here to some studies that have been done.

Seismotectonic map of Lucknow

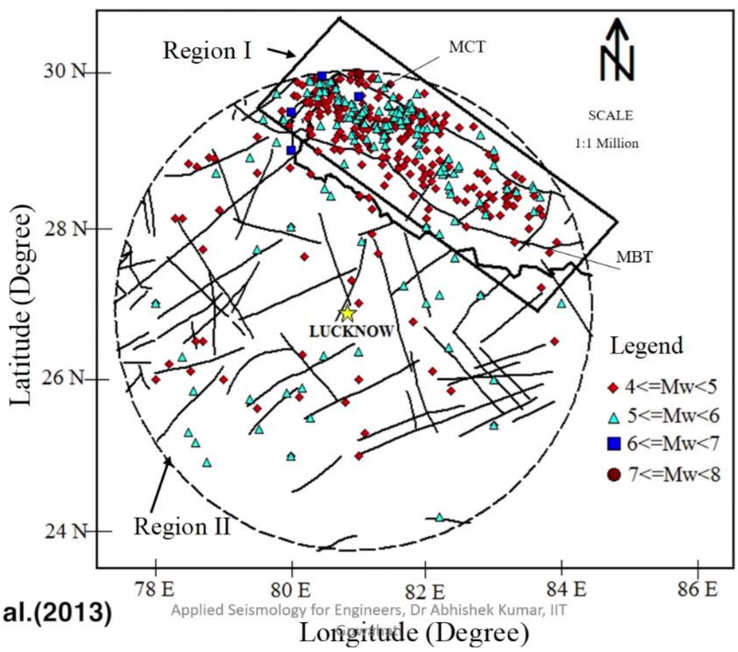
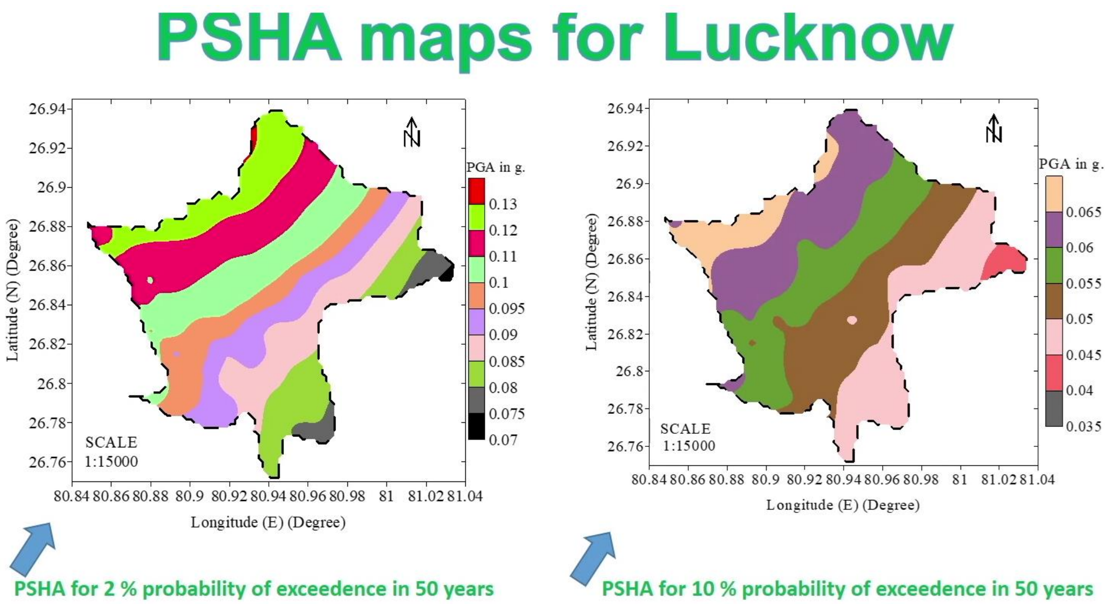


Fig source : Kumar et al.(2013)

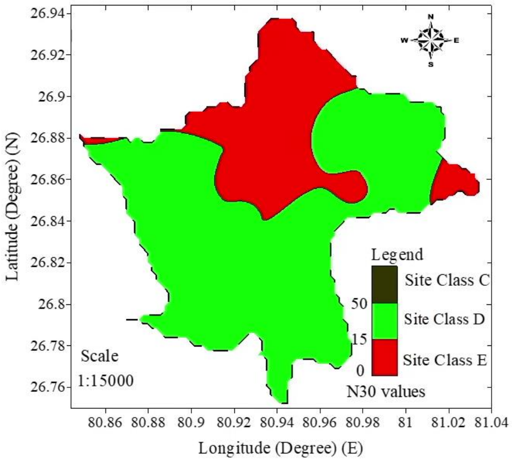
This is particularly related to one published paper. Here, we can see the seismotectonic map developed for Lucknow. We can see that Lucknow is located, and the important faults in and around Lucknow, within a radial distance of 350 kilometers, are shown. These are the regions which show dense past earthquake information or past epicenters are densely located over there. Based on this, one can develop a seismotectonic map. Using this seismotectonic map, taking the duration of completeness, magnitude of completeness, and seismic activity, which have been discussed in earlier lectures, one can develop a probabilistic map.



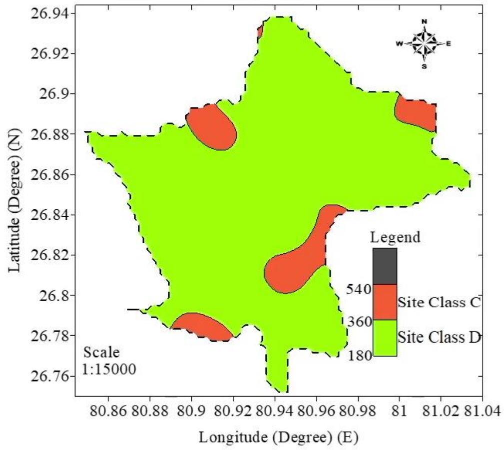
Here are two typical maps related to the probabilistic seismic hazard analysis of Lucknow. Again, the first one corresponds to a two percent probability in 50 years. We can see in this particular location, 0.07g is the seismic hazard, which has a 98 percent probability that it's not going to exceed in the next 50 years. Similarly, if you go with the second map, which is again the probabilistic hazard map of Lucknow, considering 10 percent probability in 50 years, we can see the same site, which was exposed and giving 0.07g, is now giving a relatively lower value of 0.045g. This is going to give you an understanding of the bedrock-level hazard values.

Again, one can go with geotechnical and geophysical measurements. One can refer to the TC4-ISSMGE guidelines, which are to be referred to, or even NDMA (National Disaster Management Authority) has also given guidelines related to the selection of grid size when going for seismic site classification for micro-zonation studies. So, depending on the area in which your site is located, if your site is located in a seismic zone, Zone 3, 4, or 5, as per the seismic zonation map of India, and the site belongs to a heterogeneous or homogeneous medium, we can select a suitable grid size to perform at least one geotechnical and geophysical test. Using those, one can develop micro-zonation site classification maps.

Site classification of Lucknow



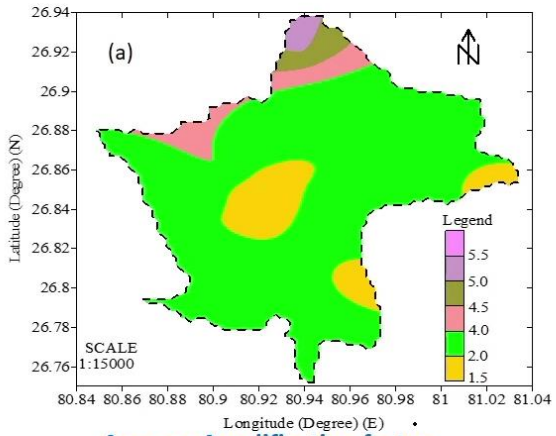
Site classification based on 30 m average N-SPT value



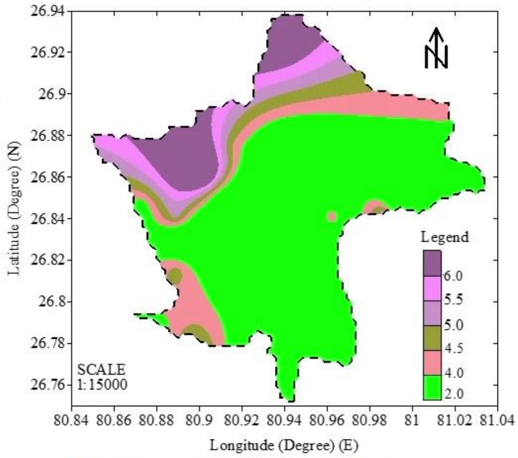
Site classification based on 30 m average SWV values

Again, here, we can see, referring to site classes, these are the locations which belong to site class E. If you are going with shear wave velocity, these are the locations belonging to site class C, and these are the locations belonging to site class D. Some locations belonging to site class E and D are identified based on in-situ site investigation.

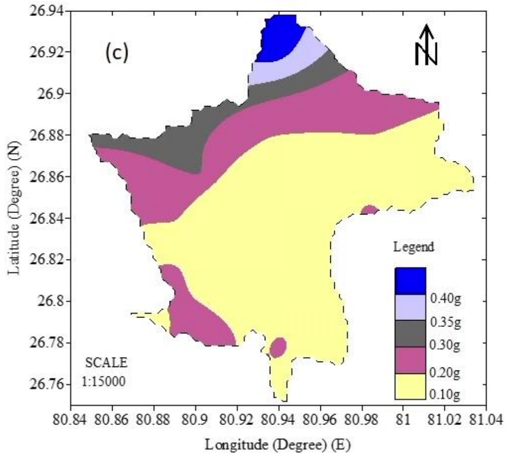
Again, using the bedrock motion and local site effects, one can do ground response analysis and find out the surface scenario. One can also find out how much the average amplification is because soil remains the same at a particular site, but input motion can vary from very low PGA to very large PGA.



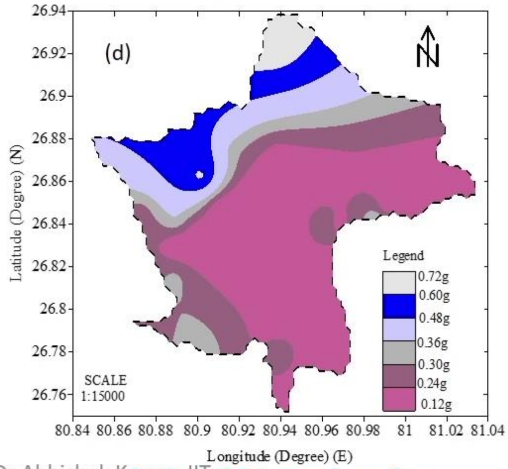
Average Amplification factor



Maximum Amplification factor



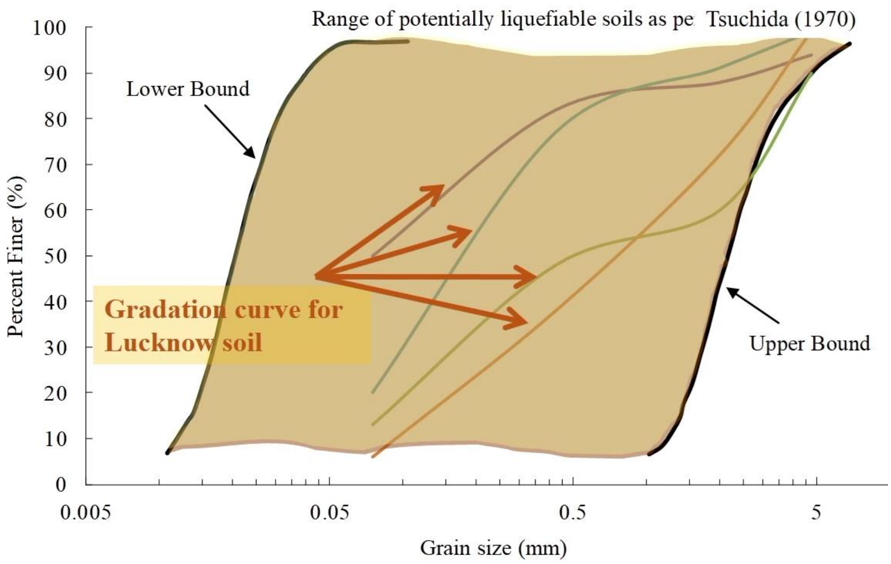
Surface PGA map based on average amplification factor



Surface PGA map based on maximum amplification factor

So, average amplification, maximum amplification, and then corresponding to average amplification, what is the surface scenario or surface seismic hazard scenario, and based on maximum amplification, what is the surface scenario, which basically will be given as an input for liquefaction understanding? Again, liquefaction, we know, liquefaction states like the development of excess pore pressure, where the soil will lose all of its strength and almost flow like a liquid.

- Clay fraction of 0.005mm less than 20%
- Liquid Limit (LL): 21-35%
- Plasticity Index (PI): 4-14 %
- Moisture Content: 90 % of LL
- Liquidity Index: ≤ 0.75



The characteristics for identifying potentially liquefied sites have already been discussed earlier. So, using this, one can develop using in-situ properties and applying different correlations with respect to SPT values.

- As per **Simplified approach by Seed and Idriss, (1971),** the Cyclic Stress Ratio (CSR) which is a measured of earthquake loading can be estimated as

$$CSR = 0.65\left(\frac{a_{max}}{g}\right)\left(\frac{\sigma_{vo}}{\sigma'_{vo}}\right)r_d$$

Cyclic Resistance Ratio (CRR), which is a measured of the resistance of soil against liquefaction can be estimated using following equation as per Idriss and Boulanger (2004)

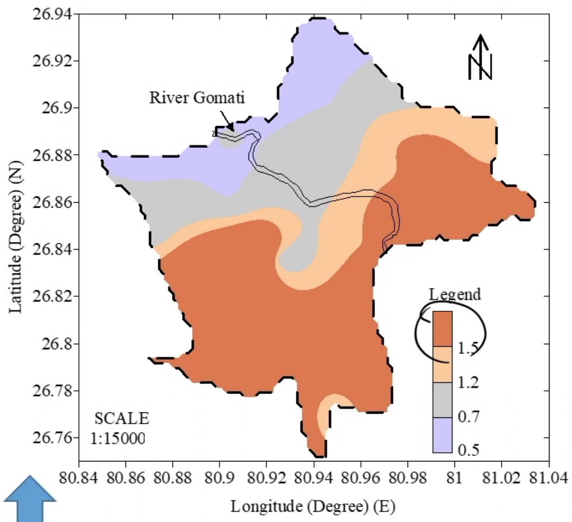
$$CRR_{7.5} = \exp\left\{\left(\frac{(N_1)_{60CS}}{14.1}\right)+\left(\frac{(N_1)_{60CS}}{126}\right)^2-\left(\frac{(N_1)_{60CS}}{23.6}\right)^3+\left(\frac{(N_1)_{60CS}}{25.4}\right)^4-2.8\right\}$$

Thus, FOS can be estimated as;

$$FOS = \left[\frac{CRR_{7.5}}{CSR}\right]MSF$$

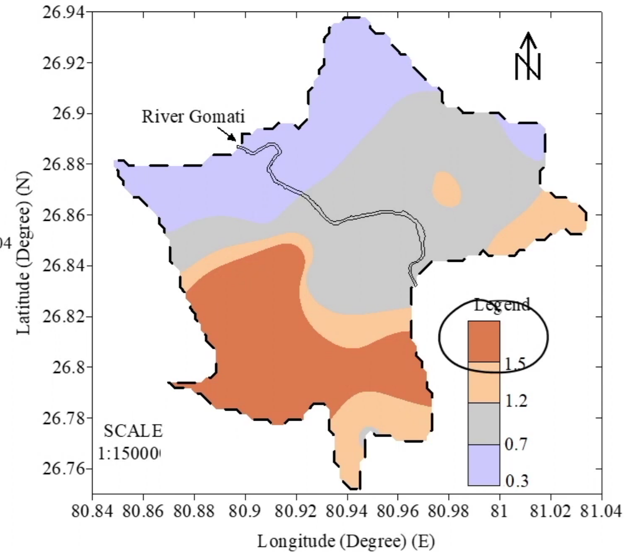
One can find out the cyclic stress ratio, cyclic resistance ratio, and finally, the effect of safety against liquefaction can be determined.

FOS against Liquefaction



FOS for surface PGA from average amplification

Group	Factor of Safety (FOS)	Severity Index
1	0.0-0.7	Very Critical
2	0.7-1.2	Critical
3	1.2-1.5	Low critical
4	>1.5	Non-liquefiable



FOS for surface PGA from maximum amplification

So, using this, one can develop maps which are showing what are the regions which are potential to undergo liquefaction, what are the regions which are having relatively higher value of effect of safety against liquefaction. So, these are again based on average surface PGA value and based on maximum amplification for the same city. Again, this is a case study. So, these findings, if we have more, because these findings are as far as liquefaction is concerned but based on limited information about subsoil exploration. So, if more information related to subsoil or overall information is available, this information can be updated.

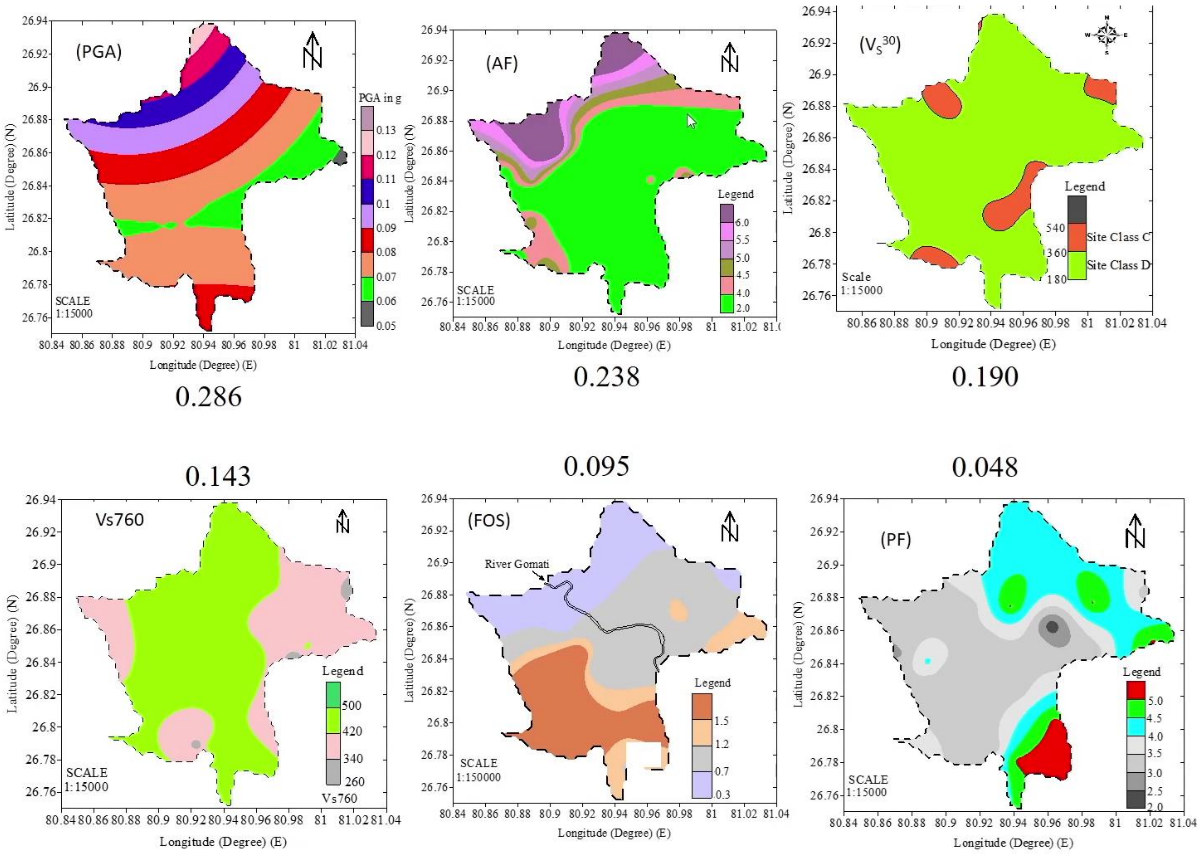
1. **PGA from DSHA and PSHA**
2. **Amplification factor**
3. **V_S^{30}**
4. **V_S till 760 m/s**
5. **FOS against liquefaction**
6. **Predominant Frequency**

Now, hazard index. So, hazard index means basically you are trying to finalize in terms of some index value, which will give you a collective effect of PGA value, amplification, average 30 meters soil classification. An additional parameter which we took into account here is based on 760 meters per second. We identify the regions which are belonging to relatively stiffer medium. Then factor of safety against liquefaction, predominant frequency. So basically, six parameters have been identified which can affect the surface scenario during a particular earthquake. Taking all these six parameters, one can assign ranks.

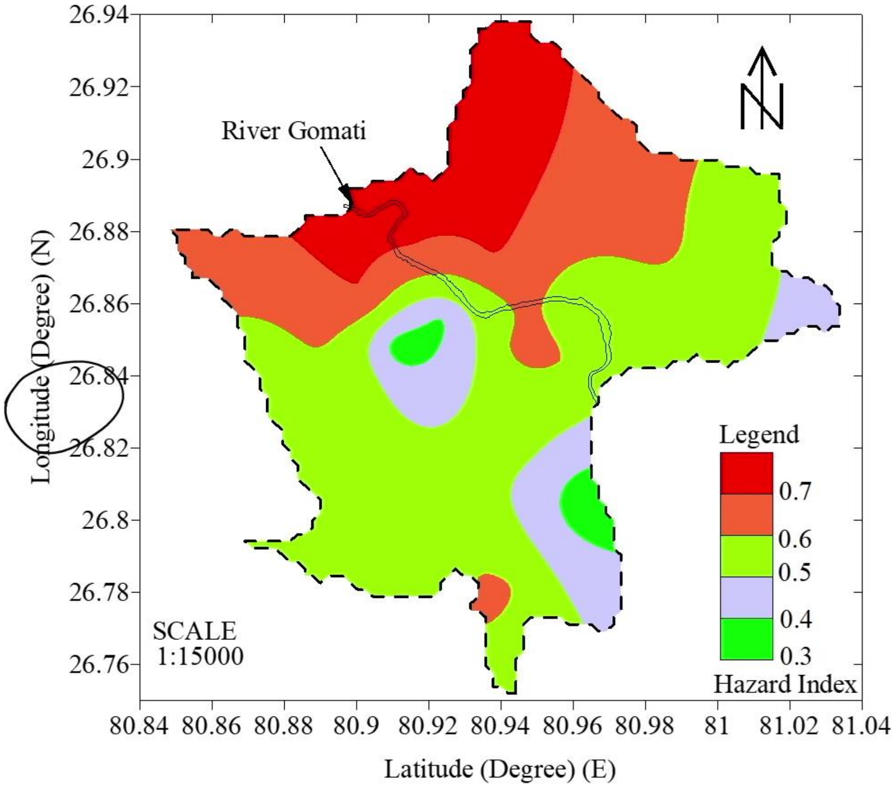
Normalized Ranks of each parameter

Parameters	Ranks	Normalized Weights	Values	Ranks	Weights
PGA	6	0.286	≤ 0.05	1	0
			0.05-0.09	2	0.333
			0.09-0.12	3	0.667
			0.12<	4	1
Amplification Factor (AF)	5	0.238	1.0-2.0	1	0
			2.0-3.0	2	0.5
			3≤	3	1.0
V_S^{30}	4	0.190	<100	6	1
			100-200	5	0.8
			200-300	4	0.6
			300-400	3	0.4
			400-500	2	0.2
			>500	1	0
V_S till 760 m/s (V_S760)	3	0.143	180-260	5	1
			260-340	4	0.75
			340-420	3	0.5
			420-500	2	0.25
			>500	1	0
FOS against Liquefaction (FOS)	2	0.095	<1	1	1
			1.0-2.0	2	0.5
			2<	3	0
Predominant Frequency (PF)	1	0.048	< 2	1	0
			2.0-5.0	2	0.333
			5.0 -8.0	3	0.666
			8.0<	4	1

That means here we can see PGA; it is going to, it should be given higher importance because higher PGA is going to affect more, and it is basically directly the effect of earthquake to the particular site of interest. Second is amplification, so that is next, which is giving higher factor or rank, then stiffness of the medium, then depth to 760 meters per second medium, then factor of safety, then predominant frequency. Again, these are the actual weights. So normalized weight, you can say, like taking all other parameters, what is the normalized weight corresponding to PGA? There are different methodologies. I am not highlighting any methodology here. So again, over here also normalized weights corresponding to all six parameters, these are the normalized weights. Again, very much similar to the ranks which are given over here, we can have like PGA value for Lucknow varying from 0.05 to any value, maybe 0.12. So, this value of PGA again divided into different ranges. Higher is the PGA, that is given higher rank. Again, if you see over here, the entire range of PGA is divided into four categories. So again, we can find out what is the relative corresponding to each of these categories. So normalized weights, and this collectively will help in finding out how much the hazard index for the particular site of interest.

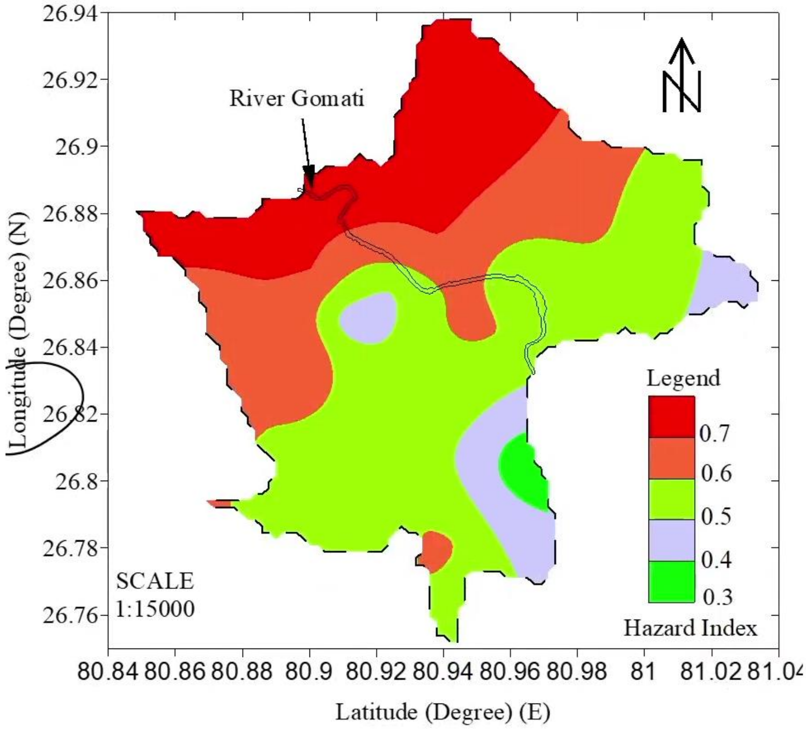


You can see over here, this is the weight, multiply this particular weight, which is corresponding to this thematic layer of bedrock PGA, then there will be a weight corresponding to how much is PGA over here. So, this 0.286 multiplied by that particular weight of PGA, depending upon the value of PGA which is mentioned over here, plus 0.238 multiplied by the amplification value at that particular site of interest. There will be a weight, so 0.238 multiplied by the weights of site amplification which has been defined in the previous slide, plus 0.190 into weights of site class which is defined previously, plus 0.143 into how much is the Vs 760 corresponding value, which is defined over here, and subsequently to other sites. So, if we add up all those contributions: 0.286, 0.238, 0.190, 0.143, 0.095, and 0.048, it sums up to 1. That means we have taken the contribution from each of these thematic layers, and the total contribution is coming as 100%. Out of that 100%, 0.286 or 28.6% is coming from bedrock PGA, 23.86% is coming from amplification, and subsequently like this. Add up those, we will get the micro-zonation map.



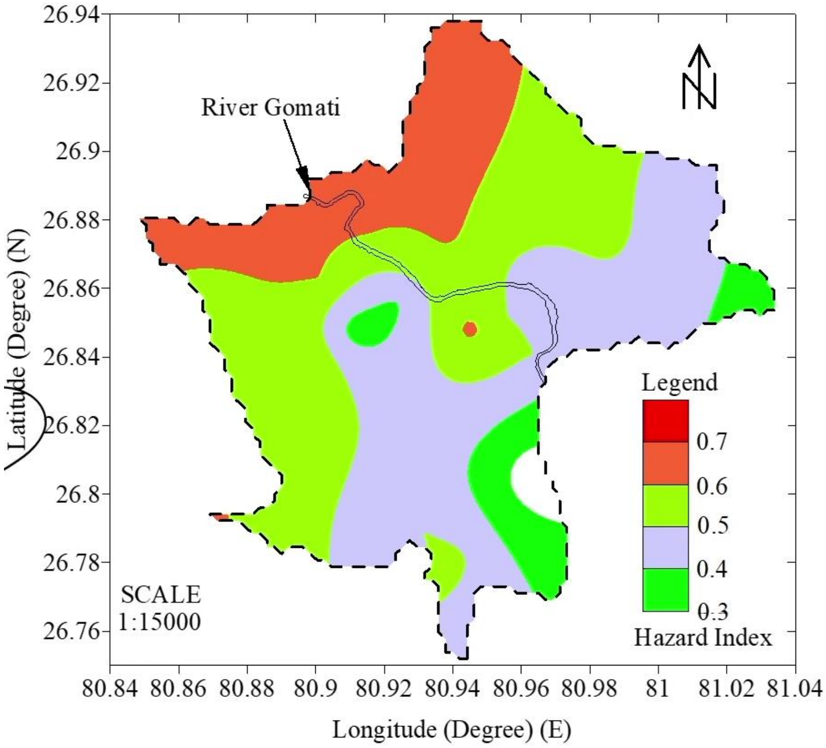
DSHA based Microzonation

So, this is basically in terms of hazard values. So, you can see higher hazard, that means those are the regions which are showing you that relatively those are the locations which are showing more effects of earthquakes, whether it is bedrock or because of induced effects. So, this is based on deterministic hazard values.



PSHA based Microzonation considering 2 % probability of exceedence in 50 years

This is based on 2% probability bedrock motion and the corresponding hazard values.



PSHA based Microzonation considering 10 % probability of exceedence in 50 years

And this is corresponding to 10% probability. So, we can see these are the regions which are relatively showing higher hazards, these are the regions which are showing relatively lower hazards and these are the regions which are showing relatively medium hazards in a particular study area. So, if this kind of map is there, that is going to definitely give you more inputs about how one can proceed as far as city planning is concerned and laying of important roads, hospitals is concerned. So, this is about the micro-zonation. As I mentioned, I have given an overview about one case study, depending upon the area, depending upon additional information available, like geology is there, maybe tectonic setting is there, maybe path attenuation is there. Those can be given more additional thematic layers as far as the micro-zonation map development is concerned.

So, thank you, everyone. This is all related to the micro-zonation studies for a particular study area. Thank you.