Applied Seismology for Engineers

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Week – 10 Lecture - 01

Lecture – 25

Hello everyone, myself Dr. Abhishek Kumar. Today's lecture, that is lecture 25, we will be discussing about another important aspect, the term is called as Paleoliquefaction. Paleoliquefaction is important because when we discussed about seismic hazard analysis, when we are interested to find out the possible level of ground shaking, the expected level of ground shaking, or ground shaking which is an indication of the worst scenario possible because of so many sources in and around your site of interest, so many earthquakes which each of these sources have witnessed in the past, and try to find out the possible level of ground shaking, we will realize that the important information about past earthquakes plays a very important role. That means, if we are having complete information about each and every earthquake which has happened in the past on each and every seismic source or fault and the same with respect to all sources which are likely to cause significant ground shaking at your site of interest, we will understand. We have also discussed, when we were discussing about seismic hazard analysis, that each of this information related to past earthquakes—past earthquake means the earthquake which has happened with respect to today, which has happened, or with respect to the time when we have tried or attempted for seismic hazard analysis. So, each of this earthquake information plays a very important role. Why is it important? Because whenever there is an earthquake, we have discussed earlier also that the earthquake occurrence is primarily related to the building up of strain energy, which is also an indication of what kind of accumulation of strain energy over a period of time is happening. So, depending the rate at which the strain energy is getting accumulated, that will primarily indicate, depending upon the magnitude of the earthquake, how much time it will take to rupture. If the rate of storage of strain energy is smaller, that may prolong a larger magnitude earthquake or greater magnitude earthquake.

That is why we also interpret the occurrence of earthquakes in the manner that larger is the magnitude of the earthquake, more time will be required for the building up of strain energy on that particular fault plane. Once the energy reaches a particular level, which can also be correlated with respect to seismic moment and seismic energy, then the earthquake will happen, the matter will undergo failures in terms of rupture, in terms of melting, in terms of generation of waves. So, if we discuss about earthquake occurrence with respect to the seismicity of a particular region or a particular fault, these two important things are very important when we are interested to find the seismic hazard. So, one is going to give you what a particular source is capable of—that means the magnitude of the earthquake which is known to us. The second information is not only one magnitude which is going to give me a clear indication about different magnitudes of the earthquakes which are possible to occur on a particular source zone or on a particular fault.

So, in order to have more and more accurate information about the seismic activity or how frequently different magnitudes of the earthquakes are possible on each of these faults, subsequently this observation will also be applicable to all the faults which are available in your seismotectonic region. As far as earthquake recording is concerned, we know that the recording of earthquakes primarily in this part of the world has started in the last 45–50 years. However, the occurrence of earthquakes, if we take into account important valleys, important mountains in this particular region, we can say that the dominating mechanism, whether you talk about convergent boundaries present in the Himalayas or in the Indo-Burmese subduction zone, the governing processes which are responsible for these hilly terrains has been happening since millions of years. So, on one side, we are having information about earthquake occurrence in terms of ground motion record for the last 40 years, 50 years, and on the other side, the governing tectonics has been prevailing for more than a few million years. Of course, we cannot have complete information about all the earthquakes which have been happening for several thousands of years, but on the contrary, we also cannot deny the fact that more and more information about different earthquakes which have happened in the past will give you more confidence about how on a particular fault a different magnitude of earthquake is likely to occur because if it has experienced n number of earthquakes in the past, then accordingly we can also try to understand what will be the frequency of different magnitude earthquakes to get repeated in the near future. When we say near future, mostly depending upon the type of structure we are dealing with, we will take into account the design life of the structure, which can be 35 years, 50 years, 100 years. So, we will be interested to know if a fault has produced M magnitude of 5 earthquakes in the last 250 years, then accordingly, what will be the frequency of these magnitude earthquakes, starting with 5 to M value, which is likely to happen in the near future. Primarily, we will be focusing on the design life of the structure.

So, overall, if we look into the topic which we are going to discuss today, paleo-liquefaction, we are interested more in paleo-earthquakes or the earthquakes which have happened in historic and prehistoric times, such that there was no information in terms of intensities because if we discuss about the origin of intensity scales, it will go to the last maybe 100, 150 years. If you talk about recording, it will last for maybe 50 to 80 years, but if you take about earthquake occurrence, that too primarily, we are discussing large to major to great earthquakes where sometimes the occurrence of an earthquake or the return period of an earthquake is in the order of 500 years, 1000 years, 10,000 years. Similarly, the known information in terms of whether intensity map or whether in terms of recordings will not be sufficient. Once it is not sufficient, definitely there will be a lot of uncertainty related to predicted ground shaking or predicted seismic hazard value. So, in order to get more and more confidence, we have to have more and more information about historic earthquakes. When, we are discussing the faults, characteristics of the faults. We also discuss that the identification of faults in a particular region is primarily because of the movement of the sediments, because of unconformities, because of abrupt changes in the sediment layers, because of sudden shifts in the alignment of the river, because of sudden jumps in the course of the river, because of offsets present in the ridges. So, these are indications of faults, but in order to identify a particular fault in a particular region, that is a continuous process. The process never ends. It keeps on happening because the geomorphology of the region, the tectonics of the region, is continuously undergoing evolution. So, the same with respect to paleo-earthquakes. We will never have complete information, but more and more information will give us more and more confidence in terms of whatever predictions we are going to do for seismic hazard analysis.

So, paleo-liquefaction mainly will be focusing on historic earthquakes in terms of some features which were created by these earthquakes when these happened maybe 400, 500, 700 years back, 2000 years back, if those features remain intact.

Many a time, these features were created by these earthquakes, but because of disturbances, maybe for construction activity, because of the laying of roads, or for other activities, if that particular feature undergoes disturbance, certainly we are losing that particular feature which was important as far as understanding a particular earthquake, understanding the seismicity of the region, is concerned. So, searching for these features on the ground surface by means of available seismic atlas maps, then going for detailed investigation at the site, in addition to when we are going for identification of the faults, we can also carry out detailed investigation pertaining to the identification of historic earthquakes, which means you are also looking for features which were created during historic earthquakes or which were possibly created during historic earthquakes. If you can study those features, you can also try finding out when these features were created, what likely was the magnitude of the earthquake, and so on and so forth. So, here are the outlines of today's lecture, that is lecture 25. We will be discussing what paleo-seismology is, then we will also discuss how one can determine the magnitude of paleo-earthquakes, then what is paleo-liquefaction, then the development of liquefaction features because these features have already been developed at a particular site, the majority of the time not at the ground surface but beneath the ground surface. So how you can identify such features, how you can interpret such features, then categorization of liquefaction features, how you can categorize different-different features. Next one is conditions which can influence the formation of liquefaction features. Then identification of such features on the ground surface when we are going for detailed investigation that we will talk about. Possible features which are more common, are sand blows, sand dikes, and deformation structures which are likely to be witnessed within the liquefied layers. Then we will also discuss some of the numerical problems which are related to paleo-earthquakes, which can help in understanding primarily the magnitude of the earthquake, the location of the earthquake, as well as likely the time on which that particular earthquake has happened.

So, let us talk about paleo-seismology. Paleo is derived from the Greek term that is palaios. Palaios, which means old or ancient. So, paleo-seismology is the study of prehistoric earthquakes. When I am referring to prehistoric earthquakes, primarily I am also referring to earthquakes which are before the recording and before MMI values, or where the intensity maps were developed taking into account the kind of shaking which was witnessed by people living in the affected areas. Remember, when we were discussing intensity maps, we also took into account, depending upon the level of intensity, there will be associated ground witness or there will be associated ground experience which will be experienced by a particular person, which can start from minor shaking to throwing off cutlery or falling of objects and then flowing of objects into the air. So, each of these features which had been witnessed during different earthquakes were witnessed by different people. So, now if you go and interview those people, they can tell you what features they had experienced during those particular earthquakes. This method of understanding the damage characteristics of the earthquake is important as far as the damaging characteristics of the earthquake are concerned. Similarly, it also gives you an understanding of the expected level of ground shaking which was experienced during those historic earthquakes in the absence of ground motion recording stations.

So, when we talk about prehistoric earthquakes, primarily I am talking about those earthquakes for which directly the MMI scale or intensity maps are not available, and certainly, actual ground motion records are not available. So, paleo-seismology is the study of prehistoric earthquakes, especially in finding out the location of those earthquakes, where the earthquakes or primarily the epicenter of the earthquake was located. Secondly, about the timing. Of course, when we discuss the timing, there will be some uncertainty with respect to the occurrence of those earthquakes. And the last one is the size of the earthquake. So, if you take into account these three parameters collectively, that is the location, timing, and the size, it is going to tell you when the earthquake has happened, how big was the earthquake, and where it had happened. So, if for each paleo-seismological observation you are able to get one month event, you can understand there will be a significant change in your understanding of the seismicity of the region. If you talk about northeastern India, there are many such studies which have happened in the past, which have identified a lot of prehistoric earthquakes or paleo-earthquakes which have happened maybe 700 years back, 1000 years back, and more than that. So, if you take those earthquakes and compare them with the catalogue of earthquakes which was prepared before this earthquake information was known, you can observe there is a significant change in terms of seismic activity. Or, if you take two catalogues, one is the earthquake catalogue which was without paleo-earthquake information and another one is with recent paleo-earthquake information, and use both the catalogues in seismic hazard analysis, you will see significant change in terms of the expected level of ground shaking at the site of interest, particularly in the northeastern part of India.

So, when we discuss paleo-seismology or paleo-earthquake, the primary objective is to find out the location of those earthquakes and the timing when it has happened. Now, generally, timing means, because we are talking about earthquakes based on some features, so mostly we will be going with some indirect measurements of assessing the relative age of those features. So, there will be some uncertainty with respect to the relative age. The last one is the size of the earthquake based on the features as preserved in the geological record. This improves us in developing our understanding or improving our understanding in terms of long-term behavior—how a particular fault or a series of faults have responded over a long period of time in terms of repetition of different magnitude earthquakes—and of course, this is collectively going to affect the seismicity of the region. If you are going to construct a very important structure, definitely the inputs you are getting from paleo-seismology will be very helpful because these are going to give you more important inputs, primarily about major to great earthquakes. Because if you talk about the return period, the major to great earthquakes will have significantly longer return periods, where, if you take only the recorded earthquake catalogue, many of the important earthquakes would have been missed. So, paleo-earthquakes are going to give really very important inputs in terms of completion of earthquake catalogue, subsequently in determination of accurate seismic activity parameters, and later on, in terms of determination of accurate value of seismic hazard level.

So, the application of paleo-seismology is useful, especially in the regions where strain rates are relatively low. So, that means, when we are talking about repetition of earthquakes, the repetition of major to great earthquakes is taking a really, really long time, such that it is almost impossible to understand the repetition or the return period of major to great earthquakes taking into account the current information about the earthquakes which have happened since the recording has started. So, everything will accumulate in terms of recurrence time—how frequently a particular magnitude earthquake is repeating itself in terms of the occurrence of earthquakes with respect to the fault. So, the recurrence time of larger earthquakes, major great earthquakes, will be significantly high in comparison to minor earthquakes or moderate earthquakes. In such regions where the rate of strain accumulation is relatively low, the seismic catalogue is often insufficient to characterize the expected seismicity and return period of larger earthquakes. So, when you are talking about larger earthquakes and great earthquakes, if you do not take the inputs from paleo-earthquakes, mostly it will end up underestimating the seismic activity of the region.

So, the investigation of paleo-earthquakes—generally, when we talk about investigation, we are basically looking for the evidence which have been created by past earthquakes. These evidence mean something which, by virtue of loading conditions or by virtue of seismic waves created by these earthquakes, when these waves interacted with the medium, this medium can be at the source, between the source and the site—that is, the propagation path medium—or at a particular site. The expected evidences can be in terms of long deformation of ground surface along the crystal fault. These include fault scarps. Fault scarps, you can see, are visible evidence of possible movement happening along a particular fault, or lateral offset which we had discussed earlier also in terms of offset for ridges, in terms of triangulation facets which are also indications of fault movement. Just like these features, because whatever features I have just told, these are surface features. Not every time an earthquake-induced deformation will be visible on the ground surface, so we have to also seek some features which are not available only at the ground surface but at later stages, that means beneath the ground surface.

Similarly, in terms of stratigraphic or geomorphic effects of strong ground shaking which can be witnessed near the site or away from your epicenter, near the site means again you can have some kind of unconformity. Away from the site, many times you will have features like those generated during liquefaction, or features generated during landslides. Once these features have been created at a particular site, over a period of time you will see whatever feature was created, maybe some portion of those features were then overlaid with subsequent layers, and these features will remain intact. So, in paleo-seismology, we will be searching for these features which are primarily available beneath the ground surface. Then, by analyzing these features, we will try to understand what seismic scenario in terms of location, size, and timing of occurrence resulted in these features. Of course, when we get a sample, we have to also analyze the sample in order to mark approximately what is the date in which the sample was preserved at that particular site. Most often, we will be talking about, if there is organic material, radiocarbon dating. If there is inorganic material, we can also talk about optically stimulated luminescence. Another method is cosmogenic nuclides dating. I will not be discussing these methods. This is primarily to give you an indication of what methods can be adopted because going with these methods again, each of these methods' interpretations will take many more terms which are not directly related to this particular course. So, I will restrict myself and my discussion with respect to just naming these methods which can be used in order to find out the exact date of the feature when these features were created and were conserved at that particular location.

So, depending upon whatever is the material involved, you can have different methods which can be used for the dating depending upon whether it is organic, whether it is composed of minerals, whether it is composed of inorganic material, or depending upon the limitation of each of these methods and relative standard error which these methods will give in terms of determining the approximate of the feature which has been created by the earthquakes. So, as far as considering the determination of magnitude of paleo earthquake, we discussed about whenever these features are created on the ground surface that is by virtue of the deformation, which is primarily an indication of earthquake occurrence or possible movement along the fault, which is also subsequently an indication of the occurrence of an earthquake, there will be some feature which will be created on the surface. So, if you know the approximate size of the surface rupture length (SRL), we can determine the magnitude of the earthquake. SRL in this particular slide is given as surface rupture length in kilometers.

Regression Relations by Wells and Coppersmith (1994)

$$M = a + b \ \text{Log(SRL)}$$

SRL – Surface Rupture Length in Kms.

The Table below shows the values of Regression coefficients of Rupture Length, Rupture Width, Rupture Area and Moment Magnitude (M). SS – Strike-Slip; R – Reverse; N – Normal Faulting.

Equation	Slip Type	Coefficients of Standard error		Standard Deviation (S)	Correlation Coefficient	Magnitude Range	Length/ Width
		a	b				
M = a + b*Log(SRL)	SS	5.16	1.12	0.28	0.91	5.60 - 8.1	1.3 - 432
	R	5.00	1.22	0.28	0.88	5.4 - 7.4	3.3 - 85
	N	4.86	1.32	0.34	0.81	5.2 - 7.3	2.5 - 41
	ALL	5.08	1.16	0.28	0.89	5.2 - 8.1	1.3 - 432

So, Wells and Coppersmith correlation, 1994, you can use this correlation to determine the magnitude of the earthquake as far as you know the surface rupture length, which is given as M equals to A plus B times log of SRL, that is surface rupture length in kilometers. So, if you know surface rupture length and also take into account the fault mechanism, that is whether it is a strike-slip fault, whether it is a reverse fault, or whether it is a normal fault, you can pick up each of these features and then pick up the value of correlation coefficient, that is a and b, and the standard error corresponding to that, you can find out how much will be the value of the magnitude of the earthquake which has actually created this kind of surface rupture length. So, that means some features which have occurred in the past resulted in the formation of surface rupture features, or you can say offset which has been created on the ground surface parallel to the ground surface. Just taking that length into account approximated with respect to the surface rupture length that is available to you, some minimum value of magnitude, because if there has been some disturbance with respect to the surface rupture length because of weathering agency or because of manmade activities, so you may have maximum the value of surface rupture length which was created or some value which is lesser than that. So, the minimum value of magnitude of the earthquake which was created by this particular surface rupture length, you can estimate.

Now, one question may arise that I have no idea about what kind of fault mechanism it has created, so we can take the last one that is independent of the fault mechanism, whether it was strike-slip, reverse, or normal faulting. If I do not know, I can take the last correlation that is applicable for all types of fault mechanisms and take the value of a and b, and it is also given the magnitude range as well as length and width range. So, we do not know whether what is available on the surface is surface rupture length or surface rupture width, that you can take into account here and then determine the value of the magnitude of the earthquake. The good part here is you have to only see on the ground surface what are the features which are possibly an indication of surface rupture length, measure those features, and try determining approximately the length of the earthquake magnitude of the earthquake which actually resulted in these kinds of features. So, the last one was if on the ground surface there is some kind of surface rupture which has been elevated or which has been witnessed on the ground surface, or it has been raised along the ground surface. The second one is if you are having the exact value of offset or the deformation by which one part of the fault or one part of the ground has been raised with respect to its original ground, that will be determined as maximum displacement, or average displacement also can be determined if there is too much variation in the displacement values. So, you can see over here, maximum displacement, average displacement, strike-slip fault, and reverse fault, normal fault.

Equation	Slip Type	Coefficients of Standard error		Standard Deviation (S)	Correlation Coefficient
		a	b		
M = a + b*Log(MD)	SS	6.81	0.78	0.29	0.90
	R	6.52	0.44	0.52	0.36
	N	6.61	0.71	0.34	0.80
	ALL	6.69	0.74	0.4	0.78
Log(MD) = a + b*M	SS	-7.03	1.03	0.34	0.90
	R	-1.84	0.29	0.42	0.36
	N	-5.90	0.89	0.38	0.80
	ALL	-5.46	0.82	0.42	0.80
M = a +b*Log(AD)	SS	7.04	0.89	0.28	0.89
	R	6.64	0.13	0.5	0.10
	N	6.78	0.65	0.33	0.64
	ALL	6.93	0.82	0.39	0.50
Log (AD) = a + b*M	SS	-6.32	0.90	0.28	0.89
	R	-0.74	0.08	0.38	0.10
	N	-4.45	0.63	0.33	0.64
	ALL	-4.80	0.69	0.36	0.50

Ref: Wells and Coppersmith (1994)

Then these are the additional equations which are given if you know the value of surface displacement or offset fault offset. If it is known to you, you can pick up the value. So, M value with respect to MD, MD is maximum displacement. If you have the value of maximum displacement which was created on the ground surface, you can use this and corresponding to the likely to be the beach ball solution or likely to be the fault plane solution of your earthquake event, you can pick up the value of a and b and determine the value of the magnitude of the earthquake. So, this is again helping you in understanding what kind of feature was created at the surface in terms of whether in terms of surface rupture length or in terms of fault offset, both these features are going to give you an indication about what is the magnitude of the earthquake which has resulted in these features. Similarly, if you are interested to know the maximum displacement which can be created by a particular magnitude earthquake, you can go with the second equation and try determining what will be the magnitude of the earthquake. So, this is if you are interested to find out the magnitude of the earthquake and the surface rupture offset is known. The second equation is if you know the magnitude of the earthquake, as we know in today's term that the recent earthquake is there, then we can determine what will be the maximum displacement this particular earthquake has created on the fault plane or even at the ground surface. The last one is if there is too much undulation, you can find out average displacement and again correlate with respect to the magnitude of the earthquake and vice versa. So, if the magnitude of the earthquake is there, you can calculate the average displacement. If average displacement is there, you can calculate the magnitude of the earthquake responsible for the displacement values depending upon whether it is strike-slip faulting, reverse faulting, or normal faulting. Each of these correlations has different values of correlation coefficients. So, you can use this correlation back and forth, both. You can use this particular correlation and try finding out whether it is maximum magnitude, maximum displacement, or average displacement.

Now, we are coming to, so it is like based on the feature which has been created at the surface, we can determine the magnitude of the earthquake. These magnitudes can be because of historic earthquakes or recent earthquakes also. Since the fault offset rupture surface length, if it has been safe in the current times also with respect to when the earthquake has happened, like over a period of maybe 700, 800 years, you can take approximately these values and try determining what will be the magnitude of the earthquake. So, this is about the paleo earthquake, meaning you are discussing historic earthquakes in terms of some manifestation, some evidence, some deformation which has actually generated on the ground surface, maybe several hundred or thousand years back. Paleo liquefaction, unlike the previous feature, which were actually surface-generated features, paleo liquefaction. So again, here the objective remains to find out more information about historic earthquakes in terms of magnitude, in terms of time, in terms of size of the earthquake, or location of the earthquake.

So, paleo liquefaction features basically result in searching for liquefaction features which were not created recently but during paleo earthquakes. So, some features which were created during historic earthquakes, and these historic earthquakes not only created surface manifestations or need not create surface manifestations but certainly created or triggered liquefaction at certain layers within the soil. So, if you are talking about surface layers and n number of layers are there beneath the ground surface in some soil layer provided the favorable conditions for liquefaction were there, that means groundwater table was higher, the soil is potentially liquefiable, and the situation was created such that during earthquake loading conditions, there was development of pore water pressure which subsequently tried to dissipate by creation of channels through which the pore pressure generated was trying to dissipate. So, when we talk about paleo liquefaction features, we are basically interested in finding out the features indicating possible liquefaction which were created during historic earthquakes. As the name suggests, because these are paleo liquefaction features, many a time you will see like some earthquake has happened even in recent times. When there is an earthquake and some liquefaction feature is created by that particular earthquake, you will see some kind of sand blows available on the ground surface which suggest possible locations through which the water is oozing out and then getting spread on the ground surface.

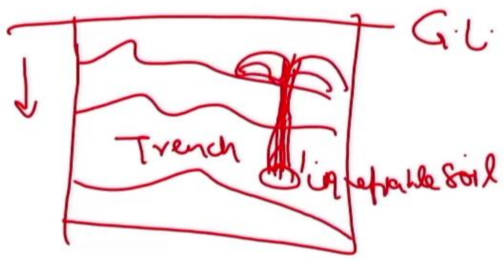
But if such features, like sand blows, have been created 100 years back, 500, 700, or 1000 years back, certainly, most of the time these features will be disturbed by means of weathering agency. They will be disturbed by means of man-made activities. So, we have to search for these features not only at the ground surface but beneath the ground surface as well. So, we will try to search for locations which are possible indications of deformation, triangular facets, and offsets which are giving, even based on the surface manifestation, an indication that the geomorphology, the tectonic setting, is not as stable. It is quite active, and then we will try searching for surface features like sand blows or any other feature which is also an indication that there have been earthquakes in the past. Then we will try to find out these features. So, certainly, along some rivers, along some water bodies where you can actually see a lot of stratifications along the bank of these rivers or streams, actually visible there, sometimes you will be able to track these features which have been created during historic earthquakes. So, you will see some features which are primarily an indication of the movement of soil mixed with water, moved because of excessive pore pressure development from some particular layer beneath the ground surface towards the ground surface as a result of dissipation of pore water pressure.

So, paleo-liquefaction deformation features, when we talk about paleo-liquefaction deformation, it is an approach focused primarily on soft sediment deformation structures and related ground failures. As I mentioned, many times it may be visible on the ground surface even at present, but at the same time, many times it will not be visible because of a lot of disturbances created because of so many activities. But still, if some exposed feature is there on the ground surface, maybe for the construction of bricks, if they are going for some kind of excavation, you will see some larger stratifications now exposed on the ground surface. So, if such features have been created along those particular stratifications, certainly you can see those. Same ways walking along the coastline, walking along the shore of rivers or the bank of the rivers, you will again see these kinds of features that will directly give you a hint about some earthquake, which had actually created these features, had happened in the past, and at present, there is no information about these features. So, that means you have to go for a detailed investigation about these features.

So, these are primarily the resultants of liquefaction features which were created by historic earthquakes. Even at present, whenever you say liquefaction, there will be development of pore water pressure. In order to dissipate that pore water pressure, the water along with soil particles will start moving towards the free surface. As a result, if the potentially liquefiable soil is located at a certain depth, it will start forming some channels through which this slurry can come onto the surface and start undergoing large movement spread. So, when we talk about paleo-liquefaction features, we are actually looking for the features which are the channels that have been created within other layers, which are primarily fine soils or the layers through which relatively softer sediment, through which the pore pressure dissipation, had happened during those earthquakes. The systematic study of paleo-liquefaction is a young discipline. So, we are seeing, for the last 40-50 years, there is a lot of information related to or more emphasis on historic earthquakes, and in terms of understanding the true seismicity and seismic hazard of a particular region, the understanding about historic earthquakes more and more accurately is giving more and more confidence to the expected level of ground shaking. So, it provides important information about the timing of the earthquake, the source area. If you are able to locate the fault which is triggering the earthquake, that means you are trying to find out the efficient of the earthquake. And then nearby, if there are faults, depending upon the fault plane solution of that particular fault, you can even locate any historic earthquake to the associated fault, magnitude of the earthquake, a recurrence time. If you are finding, in the last 50 years, some earthquake is there, and then that earthquake in the last 700 years, how many times it has occurred, that certainly gives you an indication about what is the recurrence time or what is the minimum return period of that particular earthquake likely to occur on that particular fault.

So, paleo-liquefaction studies are especially useful in intraplate and interplate regions where the seismogenic faults may not rupture the surface. As I mentioned earlier also, many times these features will be visible on the ground surface. However, the majority of the time, these features will not be available on the ground surface. Primarily, we are discussing interplate and intraplate earthquakes. We have already discussed interplate and intraplate earthquakes in previous slides in previous lectures. So, it has been observed that whenever we are talking primarily about interplate and intraplate earthquakes, surface features are not that common. So, we have to search for paleo-liquefaction features or features of liquefaction which were generated during historic earthquakes. So, finding paleo-liquefaction features can be difficult because, later, deposition, some features have happened because of some feature was created by an earthquake 700 years back. After that, because some feature was created on the ground surface, there can be a lot of disturbance because of the construction of the road, railway alignment, because of the excavation of the material for construction purposes, because of weathering, because of deposition, and many more things which have happened last several hundred years to thousand years which will create a lot of disturbance.

So, many times these features will be disturbed on the ground surface. Over that, there will be deposition of subsequent sediments if the feature you are talking about is several hundred to thousand years. So, there will be deposition of additional material on these features. So, the feature was there; one is the features can be removed by means of surface disturbance or otherwise these features can be buried by additional layers which are coming over that. That can be because of natural activity or man-made activity. You are removing soil from one particular side and start dumping over here. Again, these features can be found at a deeper depth. So, finding these features, many times, will be difficult because they are not visible on the ground surface. You have to find out some indirect indication of seismic activity of that particular region such that this indicates you have to go for detailed investigation. So, you have to go many times with respect to trenching, but then, you dig out a trench within the ground surface and try finding out the stratification. Once you start digging the trench, you will see a lot of stratifications are there because layers are not perfectly horizontal, and within these features, you will also find out some features which are possibly an indication of some movement which has happened in the past.



So, that means this was potentially liquefiable soil. These are potentially liquefiable soils which had undergone liquefaction during a historic earthquake as a result of which, whatever pore pressure dissipation has happened, that particular dissipation resulted in the formation of these channels and then started creating a deposition, whether in this particular layer or even at the ground surface if you are talking about current times. So, we will be searching for these kinds of features when we are discussing paleo-liquefaction features. This trenching will help in understanding generally what the characteristic of this particular stratification is, this particular location of the trench, these features you are finding, so that you can interpret this feature and take it for record at a later stage.

So, understanding the paleo liquefaction features, development of liquefaction features, as discussed earlier, during strong ground shaking, these can induce liquefaction and fluidization of water-saturated loose sandy sediments. So, sandy sediments, which are in a loose state, which have a chance to undergo liquefaction, and also because of water which is available over there, when these are exposed to significant ground shaking, there will be the development of excess pore pressure. This excess pore pressure will dissipate by means of movement towards the drainage path, and it can lead to the formation of liquefaction features. As far as the dissipation of pore pressure is concerned, once it is done, subsequent flow of material that is loose and mixed with water, that movement will stop because the dissipation of pore pressure is completed. But during this particular flow, there will be the formation of liquefaction features. So, these form, from a geological perspective, these kinds of features indicate deformation of unconsolidated sand, or that means relatively softer medium which triggered a wave kind of action during seismic loading. So, seismic shaking triggers regionally, leading to extensive liquefaction, and these can also result in the formation of sand dikes and sand blows. Sand blows often you will see on the ground surface, but if it was created during a historic earthquake, followed by a subsequent layer or deposition, you will again see sand blows also as a subsurface feature.

Additionally, dish structure, load cast, pseudonodules, ball and pillow structures—these can also be formed in muddy and sandy sediments, which are also indications that some earthquake loading has been subjected to the stratification beneath the ground surface. Earthquake-induced liquefaction features can be divided primarily into two categories. That means the first one is the feature which is related to deformation extending beyond the layers that liquefied. So, there were some layers which had undergone liquefaction, but these features have been extended beyond these particular layers, including intrusive dikes, sills, diapirs, extrusive sand blows and volcanoes. So, these are indications of some feature which has actually been extended beyond the layers which have undergone liquefaction. The second one is the features which are related to deformation within the sedimentary layers. So, these are the features which have been created within the sedimentary layer and are getting intact or are indications of some kind of possible movement. These are disturbed bedding; because of some movement from these particular layers, you will have some disturbed bedding, dish structure, ball and pillow structure, load cast-related faults, pseudonodules, convoluted bedding, and deformation faults related to slumping.

So, conditions influencing the formation of liquefaction features: earthquake-induced liquefaction features are commonly found in alluvial deposits, coastal, deltaic, and lacustrine deposits of Holocene age. In this particular feature, you will see sand embedded within clay and silt, primarily when we are talking about alluvial and lacustrine deposits. So, there will be sand which is interbedded or sandwiched between silt and clay layers, and there is also the formation or presence of a shallow groundwater table. So, when these are subjected to earthquake-induced loading, and this has happened primarily during Holocene deposits or the deposits which have happened during 0.1 million years before present, largely due to aging effects, primarily due to pleistocene sediment, which is between 2.58 to 0.01 million years ago. These deposits tend to be less susceptible to liquefaction than Holocene deposits. So, that means, again, whenever liquefaction or earthquake-related loading is triggered, Holocene sediment will undergo liquefaction. So, well-rounded, well-sorted, loose to moderately dense, fine sand with a high groundwater table, as well as low relative density and very high void ratio, are susceptible to undergoing liquefaction. These liquefaction susceptibilities decrease with an increase in fine content, as we have discussed in the liquefaction lectures. Layering in the sediment also plays an important role in the formation of liquefaction features. So, when there are layers of clay, sand, or silt, these form impermeable layers that result in the formation of building up of pore water pressure in the underlying soil layer. As a result, this will lead to the formation of sand diapirs or dikes, which are indications of dissipation of pore water pressure towards a shallower layer, even many a time punching through the clay layers.

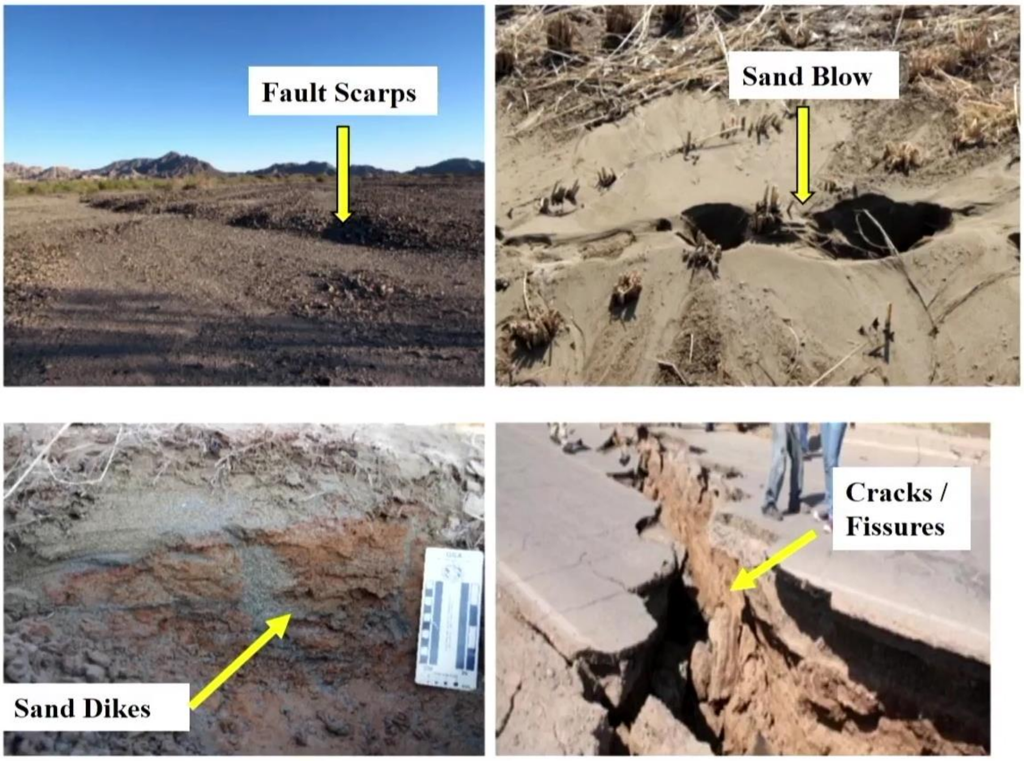


Fig: Paleoseismic Features (Ref; Kumar et al., 2018)

So, identification of liquefaction features, you can see over here potential photos of fault scars, which are available or are indications of movement that has triggered the ground surface. Sand blows in the second figure you can see. So, that means these are particularly indicating a kind of hole through which the liquefied soil, that means the loose sand mixed with water, actually came onto the surface and started spreading. So, this is sand blows which have been witnessed during many of the recent earthquakes. Sand dikes you can see over here. So, these are possible indications of some movement of soil layers, which have actually been moved from the deeper layer to the shallower layer and getting deposited over here. So, these are sand dikes which are indications of possible movement or liquefaction features that were created because of earthquake loading conditions. Then, many a time these features land; you will see this particular soil has undergone liquefaction, and fissures have also been created. You can see there is no material that is supporting the material from beneath. You will see some kind of cracks, even differential settlement on the ground surface. The sand blows result when water mixed with sediment went out at the ground surface at the time of an earthquake. A mixture of water, sand, and silt can continue to flow to the surface for hours after the earthquake till the shaking stops or till the excess pore pressure development has completely dissipated. These are also called sand volcanoes since these resemble simple small volcanic cones with craters at the surface that align with the ground fissure. So, you will see, similar to a volcano, these are sand volcanoes where, rather than lava, the sand is coming onto the ground surface and getting created in the forms of cones on the ground surface, and craters have also been created. The opening at the ground surface that makes the path for slurry to come out is called a vent. So, it is the vent through which the material has come onto the ground surface and then gotten deposited. The formation of a crater can also be seen over there.

So, sand blows are generally of two types: linear, elliptical, and circular, depending upon the feature which has been created on the ground surface. Generally, sand blows are thicker and coarser above the vent and thinner and finer away from the vent. So, as you are close to the vent, you will see sand blows are relatively thicker, but as you move away, depending upon what is the pore pressure which was undergoing dissipation and what was the magnitude of the earthquake which triggered this kind of sand blows, you can see large spreads. Generally, you will see the vent is thicker very close to the sand blows, and as you move away, it will be thinner. So, single-event sand blows have more than one sand layer and are not capped by silt or clay. This is a common occurrence in the case of multiple earthquake sequences that form compound sand blows. When venting of sediment slurry becomes weaker with time, fine particles are deposited on the sand units due to low flow velocity. The sand cones can be as much as in meters in height and tons of matrix in width. The sediment that is left behind is called clastic dikes.

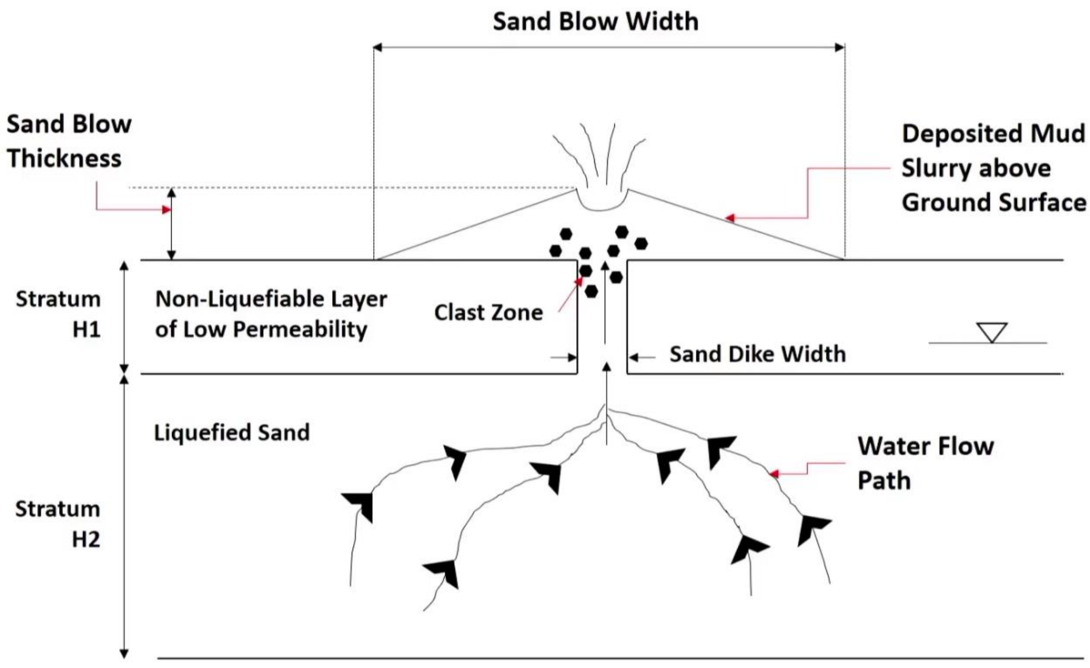


Fig: Cross Sectional Schematic Diagram of a Sand-Blow and Sand Dikes

You can see over here. So, there was a layer in which the groundwater table is also present, and the soil was relatively loose sand, which is a possible indication that if this particular soil is available on the ground surface, it will undergo liquefaction. But by virtue of its position, it is not able to dissipate pore water pressure unless there is the formation of sand dikes which are facilitating the dissipation of pore water pressure by movement of this particular material through clastic zones onto the ground surface. Once it reaches the ground surface, you will see the deposition of these materials through vents near the ground surface. Depending upon the strength of the earthquake and the duration, you can see it will be deposited very close to the clastic zone, or it will be deposited at a larger distance. So, remember, if you see this, we are seeing in terms of sectional elevation. So, if you see in plan, you will actually see this particular sand blow will look like this. It can be elliptical, or it can be circular also in the plan. So, taking that particular part also into account, try finding out the average diameter of the sand blows. Again, you can find out the magnitude of the earthquake as we will see in near slides. So, some of the examples in which the sand blows have been experienced during past earthquakes include earthquakes in New Zealand, the United States, Italy, Japan, and China, many of the earthquakes which actually triggered sand blows during different earthquakes. Again, there are some empirical correlations. If you know the epicentral distance, as we know, as you are moving away from the source, the duration and amplitude of ground shaking will reduce, depending upon the soil which is available at a particular site and the loading which is sustained at that particular site. So, one is going to give you the loading, the other one is going to give you how much resistance the soil is able to offer; that will define whether the soil at a particular site will undergo liquefaction or not. So, this particular feature, which was proposed by Castilla and Audemard in 2007, gives you a correlation between the magnitude of the earthquake and the epicentral distance in kilometers.

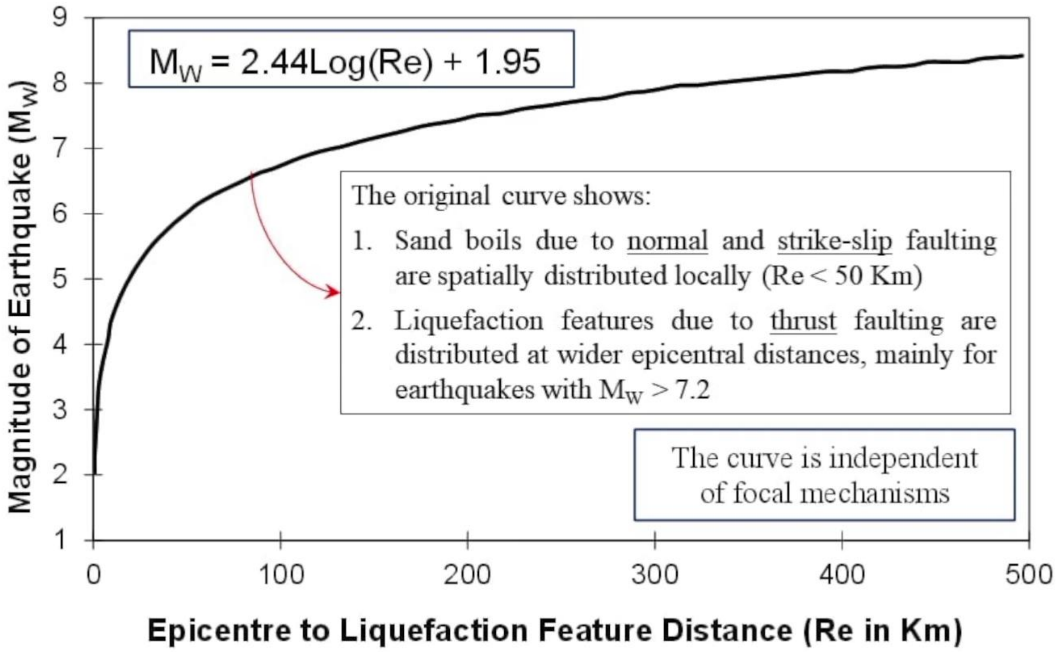
$$M_W = 2.44\text{Log}(Re) + 1.95$$

This correlation was developed primarily for liquefied sites. So, if you know the magnitude of the earthquake, you can find out up to what epicentral distance liquefaction is possible. Or, if you know the epicentral distance of a particular liquefied site, based on this particular correlation, you can develop how much is the magnitude of the earthquake.

$$D = 238\ (Re - 37)^{-0.9}$$

Similarly, if you know the diameter of the sand blows, as I have shown earlier also, if you see in plan, sand blows might be circular; they can be of other dimensions also. So, you can find out approximately or equivalent diameter of the sand blows. Once you know that diameter, you can also find out using this particular equation what is the epicentral distance of this particular sand blow with respect to the focus of the earthquake or with respect to the epicentral of the earthquake. So, you can find out basically the epicentral distance; that means surface distance between the epicentral of the earthquake and where this particular sand blow of diameter D in meters has been created by an earthquake. So, if I am standing at one particular site having diameter D, based on this equation, I can find out this particular diameter sand blow has been created by an earthquake which was created at Re epicentral distance. So, if I am able to find out more than one feature, minimum three features of sand blows in a particular region, and take this Re value corresponding to each feature, we can also locate the epicentre of that particular historic earthquake. So, that is how you can find out more than one, more than three features you have to find out, which are indications of sand blows, sand dikes, and corresponding to those features, if you are able to find out the epicentral distance, keeping those features as centers, draw the circles. Wherever the circles from multiple features are coinciding with respect to each other, that is a possible indication of the epicentral of the earthquake.

So, again, you can see from this correlation, the nature of sand blow diameter and epicentral distance follows a particular pattern, which was by Castilla and Audemard in 2007. Similarly, with respect to magnitude and epicentral distance, as far as the earthquake led to liquefaction occurrence, this is the photo which was also proposed by Castilla and Audemard in 2007.



You can see over here, there are features which are indications of liquefaction that have been created by different earthquakes at different epicentral distances. So, overall, if you know any particular magnitude of the earthquake, we can have an idea about what epicentral distance, like suppose you take an 8-magnitude earthquake, up to what epicentral distance this 8-magnitude earthquake can cause liquefaction. So, that means this is likely to cause liquefaction, again depending upon what is the relative density of the soil available there, what is the position of the groundwater table. That will decide whether liquefaction will occur or not, or which had occurred or not. If you are able to find out the sand blow, that will also confirm whether liquefaction has occurred during that particular loading condition or not.

So, sand dikes are sheet-like structures or tabular-shaped intrusive bodies that intersect the bedding in the host. These have well-defined margins and can be distinguished from the host by means of differences in grain size and weathering characteristics. So, you can easily distinguish between which is the sand dike and which is the other medium or the host medium. These are typically originated in sandy layers and are composed of sediment derived from the source layer. These may contain clasts, which are little chunks of rock that form in the sedimentary rock, often becoming narrower and more fine-grained in sections and sometimes branching upward.

So, sand diapers, these are also additional features which are generally formed by means of piercing mobile material into more brittle surrounding rocks. So, it will be some material which has been pushed forcefully into the brittle rocks by means of the development of excessive pore pressure. So, these are basically indications of small intrusions of sediments into the rock medium, which is primarily an indication of a liquefied soil layer. So, these are formed due to liquefaction, often resulting in mixing of different sand layers and sediment layers. The rising liquefied sand can incorporate and mobilize material from different depths, bringing it together, leading to mixing and intermingling of different kinds of sediments.

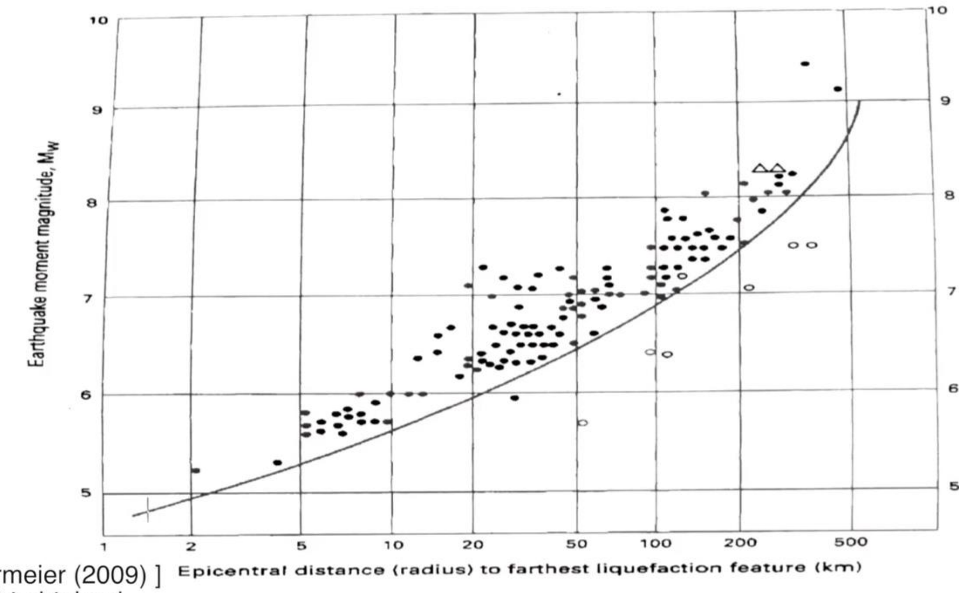
Let us see some numerical problems so that we will have more idea about how to solve a particular equation. Based on our understanding so far, we have understood that we will try to find out, based on available maps, atlas maps, even based on photos from remote sensing or aerial photographs, we will try to find out the features which are showing abrupt changes in the geomorphology where there is the presence of a cliff, then a sudden offset in the ridge, which is a possible indication of faults. Then, we will also go for additional features, which are primarily indications of fault offset and rupture surface values. Thirdly, we will try to find out features that are actually stratified within the soil layer; that is, sand dikes, diapers, sand blows. Correcting those features, try analyzing those features, indicating potentially when these features were formed or when these features were intact in that particular soil layer. That is going to give you primarily the timeline as far as the location as well as size is concerned. We will see some numerical problems.

The farthest liquefaction feature is found at 150 Km distance from the epicentre of an earthquake. Find the minimum possible magnitude of the Earthquake.

So, the first problem is the farthest liquefaction feature during a particular earthquake is found 150 kilometers away from the epicenter. So, it is like we know the epicenter of the earthquake, and we saw some features which have been triggered during a particular earthquake, which are potentially liquefiable features. In order to find out the maximum magnitude of the earthquake and the minimum magnitude of the earthquake, how do we find out?

Sol: After using the graph between M_W and epicentral distance of the farthest liquefaction features. Approx. $M_W = 7.2$

So, based on the graph we have seen a couple of slides back, where you can see on one side magnitude is there, on the other side epicenter distance is there. So, corresponding to 150 kilometers, you draw a vertical line. Wherever it is touching the graph, you can find out the magnitude of the earthquake. In this particular case, it is 7.2.



[Ref : Obermeier (2009)]
Copyright obtained

So, this is another photo that gives you a correlation between the magnitude of the earthquake and the epicenter distance to the farthest point of a liquefied feature. So, corresponding to 150 kilometers, you can find out how much the magnitude of the earthquake, which actually triggered this liquefaction feature, was.

Surface Rupture Lengths of Two earthquake events are found to be 450m and 600m. Determine the Magnitude of each event.

Second example: surface rupture land during two earthquakes is found to be 450 meters and 600 meters. So, these are the surface ruptures that have been generated or triggered during different earthquakes. In order to find out the magnitude of the earthquake, again correlations have been discussed in earlier slides. Using this correlation and surface rupture land, you can find out the magnitude of each of these earthquakes.

Sol:

Using Wells and Coppersmith (1994) Equation.

$M = 5.08 + 1.16 * Log(SRL)$

Now, SRL1 = 450m = 0.45 Km; SRL2 = 600m = 0.6 Km;

Magnitude of 1st Earthquake (M1) = **4.67** M_W

Magnitude of 2nd Earthquake (M2) = **4.82** M_W

So, Wells and Coppersmith had given, if you know the fault plane mechanism of these events, you can pick up particular correlation, otherwise, if it is not known, you can pick up the generalized equation, use the value of A and B, and try determining the magnitude of the earthquake. So, this is already given. If one magnitude of the earthquake is 4.67 meters, the other magnitude of the earthquake is 4.82. So, in the correlation given for moment magnitude, I am also adding up here Mw value.

Surface Rupture Lengths of Two earthquake events are found to be 550m and 575m. The events have been further found to have been produced by a Normal Fault and a Strike-Slip fault, respectively. Determine the Magnitude of each event.

Third numerical: the surface rupture lengths of two earthquake events are 550 meters and 575 meters. You can solve it yourself to gain more understanding of how to determine the magnitude of the earthquake using these graphs that are available to you. Remember, I am not going into determining the time of these earthquakes, which is still an important part of dealing with value earthquakes. I am only locating the epicenter and magnitude of the earthquake. If, for one earthquake, based on timing, you find multiple features at different locations created during relatively the same time, using this approach, you can find the epicentral distance. Take those features as the center and draw circles corresponding to the epicentral distances. Where these multiple circles, a minimum of three, overlap with respect to each other, that will indicate the possible epicenter of that particular earthquake.

Sol:

From the Table given by Wells and Coppersmith (1994), We get:

1. Normal Fault

M = 4.86 + 1.32 * Log(SRL) = **4.52** M_W

2. Strike Slip Fault

M = 5.16 + 1.12 * Log(SRL) = **4.89** M_W

Here, two surface feature lengths are given. The event has been further found to be produced by a normal fault and a strike-slip fault. So, the first one corresponds to a normal fault, and the second one corresponds to a strike-slip fault. Then, again, the magnitude is asked. So, because the fault plane solution is given, you can pick up the specific equation and try determining the magnitude of the earthquake, as has been given over here. This is provided over here. You can again determine the magnitude of the earthquake. Here, we have taken different equations because one is for a normal fault and the other is for a strike-slip fault.

Average surface displacement of one Earthquake event is found to be 30 cm. Find the Magnitude of the earthquake if the fault producing the earthquake is a Normal Fault.

Sol:

From the Table given by Wells and Coppersmith (1994), taking into account the equation and regression coefficients for Normal Fault, We get:

M = 6.78 + 0.65 * Log(ASD)

ASD = 30cm = 0.3 m

So, M = 6.78 + 0.65 * Log(0.3) = **6.4** M_W

Another numerical: the average surface displacement AD value is given as 30 centimeters, and we have to find out the magnitude of the earthquake. It is also given that the particular earthquake was subjected to or triggered by normal faulting. So, you can pick up the corresponding equation for a normal fault and the corresponding average displacement. Remember, this is not giving you the maximum displacement. So, corresponding to the average displacement, whatever the values of a and b coefficients are, pick those values and try determining how much the magnitude of that particular earthquake is. Be careful with the units you have to use because not every time will you be using kilometers, and not every time will you be using centimeters. Each of these equations has corresponding associated units which you must use. Otherwise, you will end up overestimating or underestimating the magnitude of the triggering earthquake.

A Sand Boil diameter is measured to be 20m. Find out the minimum possible magnitude Earthquake event influencing the sand boil considering the maximum possible epicentral distance.

Sol:

From Castilla and Audemard (2007) curves, We get:

Minimum Epicentral Distance = **50Km**

From the second curve, we get M = **6 M_W**

The last one: if you found at a particular site what the sand blow is, measure the diameter of the sand blow. So, here it is given that the diameter of the sand blow is 20 meters. You have to find out the maximum and minimum magnitudes triggering that particular sand blow. Based on Castilla and Audemard, 2007, we can find out, corresponding to the diameter of the sand blow, how much is the epicentral distance. Corresponding to this epicentral distance, we have another plot that gives you, corresponding to liquefaction features, what the magnitude of the earthquake and the corresponding epicentral distance will be. So, from here, you can find out the epicentral distance, go to the other slide, and find out the magnitude of the earthquake corresponding to this particular epicentral distance. So, corresponding to 50 kilometers, whatever you are able to find out, that is going to give you, at 50 kilometers, this particular magnitude earthquake that has happened, which triggered a sand blow of 20-meter diameter.

So, I hope the discussion we have done so far has given you an insight into what the objective of paleo-liquefaction features is, what paleo-liquefaction features are, and how these features, if you are able to locate them at a particular site, can be taken into account to understand more about the historical seismicity of a particular region.

Thank you, everyone.