Introduction to Engineering Seismology
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Lecture - 59
SHA Contd - Maximum Magnitude Estimation

Vanakkam. We will continue our lecture on engineering seismology. So we have been discussing about the seismic hazard analysis and the essential component of the hazard analysis. We have talked about the preparation of the seismo-tectonic map, how we can prepare a seismo-tectonic map, how we can consider different seismo-tectonic parameters in the region, followed by we also discussed about the seismic data collection, homogenization and declustering and completeness analysis.

By doing this entire process, you will be knowing what are the seismic sources are active in the region, what are the seismic sources, what is M minimum? M minimum means a minimum magnitude occurred in the region, and complete period. So the complete periods are essential to recurrence relation developed by Gutenberg-Richter relation, because that relation says that you should only develop GR relation for the complete data, not the incomplete data.

But later Kijko and (()) (01:28), they also introduced a method for incomplete data, but we have been only concentrating on the GR relation, that is the most widely used relation. So the complete data period, that is what plays the role. So this data will indicate that what is the seismic city associated in the particular seismic study area. For the future seismic hazard analysis, you have to identify what is the maximum possible earthquake we need to consider or maximum magnitude you need to consider for design of particular structure.

That process, the estimating of the maximum probable earthquake or maximum credible earthquake or any seismic study area is actually process of estimating the maximum magnitude. So today class, we are going to talk about the maximum magnitude method estimation and I also talk about how the seismic study area related with the M max estimation. What are the different methods are there, how these methods will affect your data.

Your data, how it will contribute to the M max value in the region and I also developed a new methodology, which is scaled as a regional ruptured based approach to estimate M max. That methodology also I will discuss in today's class.

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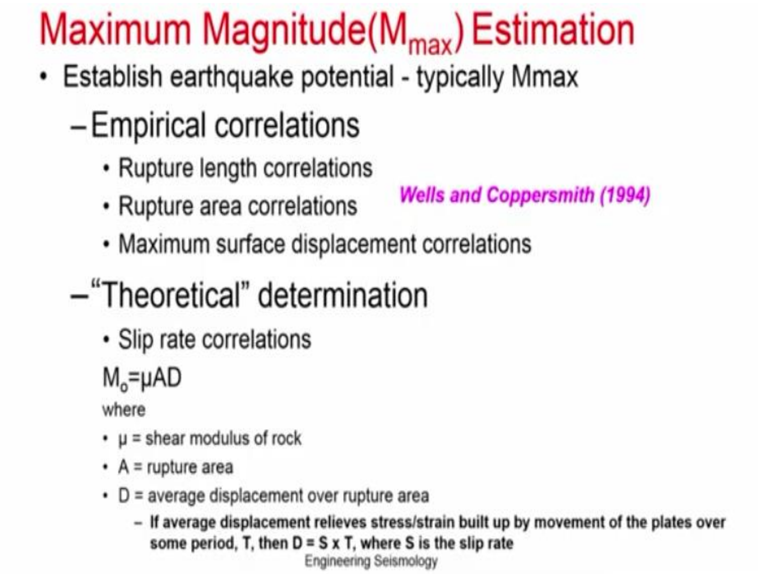

The M max, basically the earthquake potential of the region typically the M max, which can be estimated by knowing the rupture length in the particular region or rupture area in the particular region and maximum surface displacement correlation in the particular area. So these are all some of the empirical formula, one can use. If you know that this is my rupture length or rupture area based on the old seismo-tectonic details, then you can estimate what is the M max using the empirical correlation.

These empirical correlation also we will discuss in detail or you can estimate theoretically, if you know the slip rate, as we know that the slip rate associated with the seismic moment, M is equal to shear modulus of the rock, area of rupture and their average displacement over a rupture area. A slip rate, area of the rupture and their rock properties, if you know, you will estimate M naught. If you estimate M naught, from the M naught, you will get your Mw.

That Mw will be taken as M max. So theoretical based approach and empirical based approach, but it is very difficult to get a rock where the rupture is taking place. You will be knowing only the from old earthquake where the rupture occurred. For the new earthquake, you do not know what depth is going to occur. Even though you have some fair idea, but it may come more or less, you do not know.

If 20 meters is your average depth in the earthquake in the region, if you take 15 meters or 25 meters also, it will occur, we do not know. That you cannot really accurately estimate. So the theoretical based approach has always constraint. Because of that, the empirical based approach are widely used in the M max estimation.

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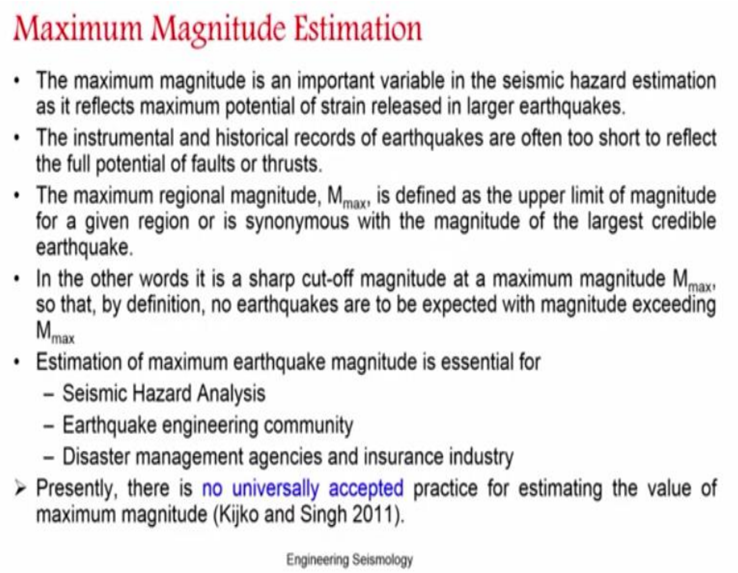

The M max is basically the maximum magnitude is on an important variable of the seismic hazard estimation, it reflects a maximum potential strain released at large earthquakes. So the instrumental and historical record of earthquake are often too short to reflect a full potential of the fault in the thrusts. So if you do not have the proper instrumentation, proper documentation in the historic times, you may not be knowing what was the M max, potential fault rupture has happened in the region.

So that you should always remember when you estimate M max. So maximum regional magnitude M max is defined as upper limit of the magnitude given a region or synonymous with the magnitude of the largest credible earthquake. Beyond that, you cannot expect any earthquake, that is the maximum magnitude of the particular earthquake. In other words, it is a sharp cutoff magnitude at maximum M max, so that by definition, no earthquakes are to be expected with magnitude exceeding M max.

Now you may understand how M max estimations are very important. The estimation of maximum earthquake magnitude is essential for seismic hazard analysis for earthquake engineering community, disaster management agency and insurance industries to decide, how much the seismic energy will be released, how the losses will be there, how many people will die, how many collapse you can expect all that.

But as on 2017 or 2013, I do not know, maybe 2013 so up to that or 2011, Kijko and Singh said that there is no universally accepted practice for estimating the value of M max. Even though it is very important there is no universally accepted procedure to estimate M max. So this issue was actually realized by my research team, myself and we worked on the alternate M max estimation method, which can be adopted irrespective of the seismic study area. That we are going to discuss part of today’s class.

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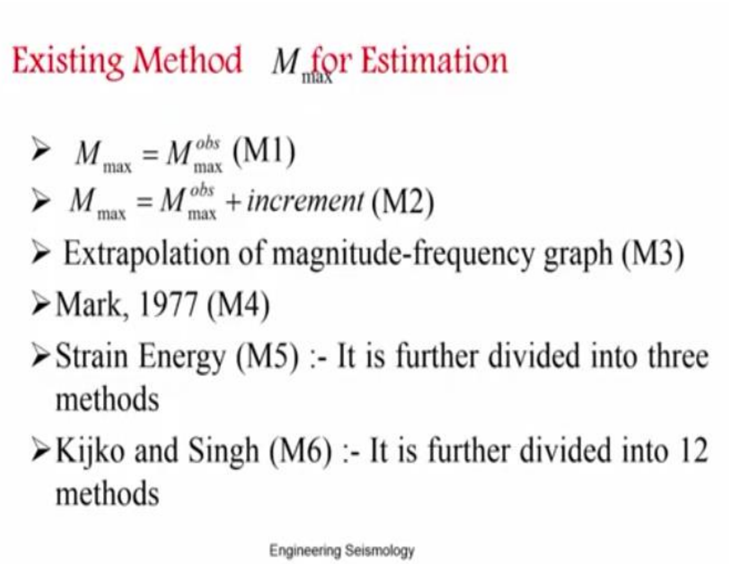

What are the method M max are estimated in general? So generally people will take the M max as maximum observed magnitude in the region. That is called method 1. The observed magnitude has been taken as maximum M max. That is one way you can do, where you know that, but if you have the very short catalogue, this will lead to a very low M max value for the future designing. Then, the another one is the M max observed and add some increment.

So this increment can be added depending upon the interest of the person and then some kind of relation with other parameters. So the other one is extrapolation of the magnitude frequency graph, where you generate a magnitude frequency graph, which we have seen now, extrapolate that and take that. The other one is fault rupture based method, Mark method. What he says is that, if you know the length of the fault, you assume that the entire length of the fault, so much portion will be ruptured.

Then, if you know the rupture length, you can convert that into your M naught or moment magnitude based on the empirical relation followed. So that is the Mark method, which is called as M4. So the strain energy method, it is actually taking into account of how much earthquake occurred in the region, how much energy is released. Then by cumulating that, you can get a future earthquake. That is called the strain energy method, M5.

The Kijko and Singh method M6, it is further divided into 12 methods. This method is basically a statistical method, which account seismic data in the region. It does not do anything, only statistically look at a data and try to arrive the M max by this one. So we are going to discuss all these method in detail plus the new method what I have developed.

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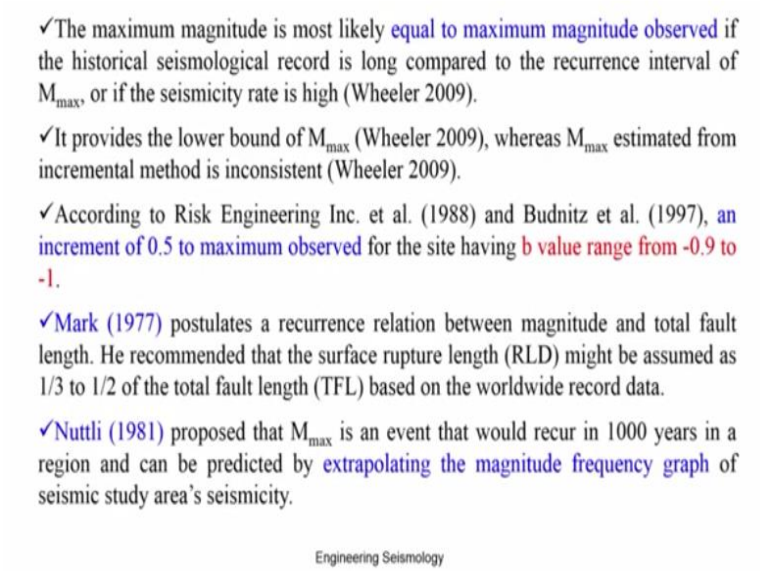

So the maximum magnitude is most likely equal to the maximum magnitude observed, like M1 method. If the historical seismology record is long compared to the recurrence of the interval of the M max. So the seismicity rate is high, so basically I have the 200 years written period of earthquake, but I have 1000 years' data. So then, I can go for this M observed as a magnitude where it will be close to the M max.

But this was most of the region in the world, these kind scenario does not exist. So using of that is always one has to be very cautious. Second, it provides lower bound of M max whereas M max estimation from incremental method is inconsistent. So you can also estimate an incremental method, where you can add some value to the M observed value. That is method 2. So according to risk engineering limited, 1988, Budnitz et al 1994 on increment of 0.5 to the observed magnitude for site having the B value of so much.

This 0.5 number is actually random. So some people even take 0.3, some people take 1, 0.7, depends upon that. There is no consistency among this one and there is no reason, because if you see this -0.1 to this one, is mostly most of the region you will get, that depends upon your minor and major earthquakes when you are talking about the recurrence relation, I will explain how the B values varies there.

Mark, he said that if you know the length of the fault, then you assume that in the length one-third to two-third is going to rupture. So if I have 100 km fault length, I will assume that 30 km to 50 km it is going to rupture, since I know the subsurface rupture length, I can get an empirical equation, which I discussed in the first slide, then I can get M max. So that kind of method was suggested by Mark, that method is called Mark method.

Nuttli, he proposed M max event that would recur 1000 years' region can be predicted by extrapolating the magnitude frequency graph of the study region. So you can prepare a magnitude frequency graph, then you extrapolate to the x-axis. The magnitude frequency graph is basically this is your M, this is your frequency, so you will be like this. So they extrapolate this, like this and take this value as your M max. That is the magnitude frequency. It is proposed by Nuttli in 1981.

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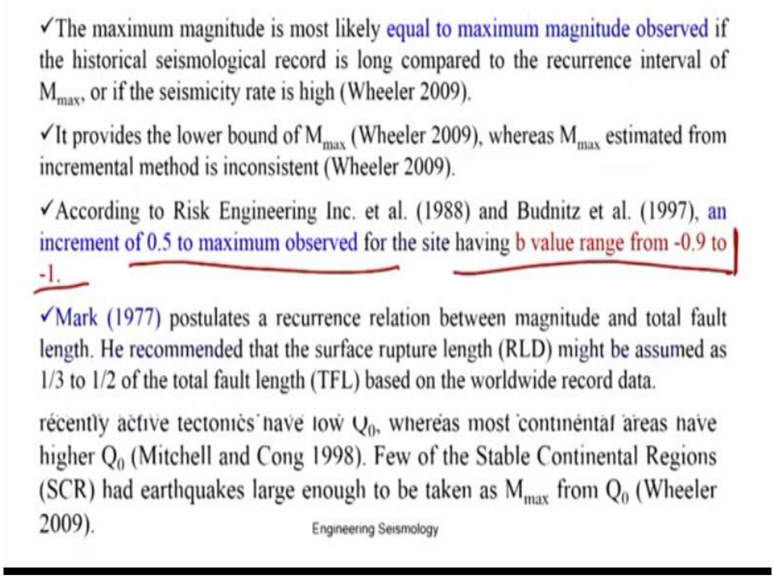

So the M max value computed extrapolation method is actually consistent with the size of the study area, whereas inconsistent with the recurrence interval of the large earthquake. So the Wheeler in 2009, the studied detailed different M max approach for the nuclear power plant design in US and they have taken a different approach and commented by doing the analysis. That is what we are discussing right now, whatever points he has commented.

The maximum magnitude can be also evaluated from the historic data by taking arithmetic mean of the large earthquakes having the magnitude 7 and above reported in the seismic study area. So Wheeler also suggested extrapolation can be done like this, arithmetic mean kind. The estimated seismic rate could be considered as a valid indicator of M max, but paleoseismic and instrumental seismicity suggest that validity of seismic rate is restricted approximately to the magnitude of 7 and above.

Beyond that, there is issue with estimating that, so the extrapolation method on estimating should be used with caution. That is what Wheeler says. So you can browse in the Google, Wheeler 2009, what are all he talks about the different M max extrapolation and methods and all, if you want to do research on this area. So Jin and Aki proposed an inverse relation between the Coda wave. So the Coda wave means basically after S wave, you get surface waves.

Those waves are called as Coda wave. So it will be helpful to hazard assessment in the region, active region, the relative activity of the tectonic have the low Q naught, whereas the most continental area higher Q naught further stable continent region, the earthquake is large enough to be taken as M max of the Q naught. This was actually suggested by Jin and Aki. So this was having the different Q value. It depends on that; you can take this one.

But there is an issue with what type of seismic tectonic region, like active region, continental region and stable continent region, you will have the different Q naught. So Q naught based approach may not be again universally adapted.

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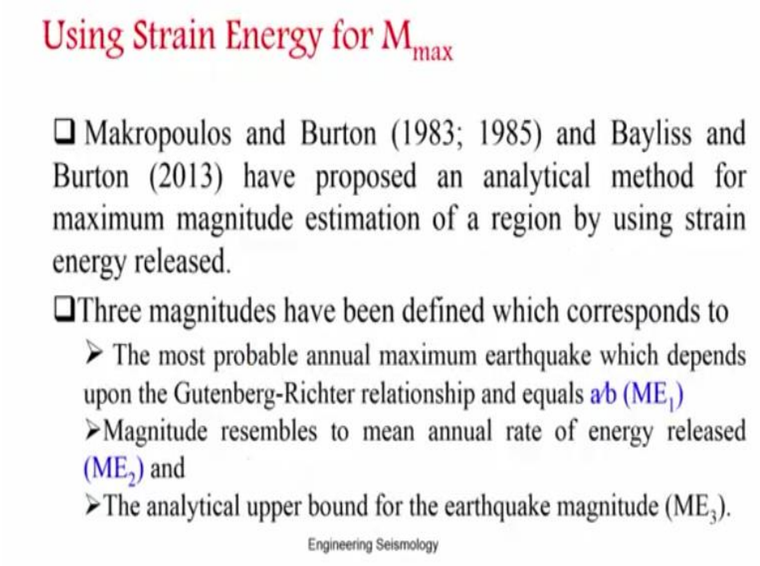

Then another approach where using the strain energy approach, what they did actually Makropoulos and Burton, then Bayliss and Buron have proposed an analytical method for maximum magnitude estimation of the region by using the strain energy released in the region. So the three magnitude have been defined, which corresponds to the most probable annual maximum earthquake, which depends upon the Gutenberg-Richter relation equal to ab, that is called as ME1 and magnitude resembles the mean annual rate of energy released that ME2, the analytical upper bound of the earthquake magnitude, which is called as ME3.

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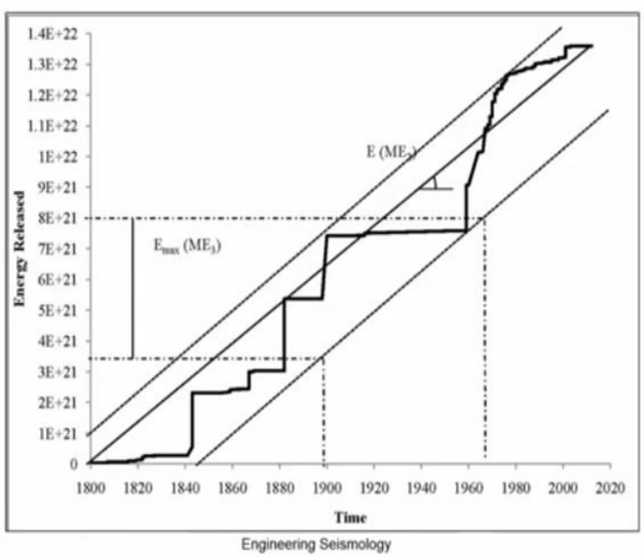

So in this what they do, they estimate a strain from different earthquake in the region, then they do cumulation of the strain. So this is the strain. When you are talking about the magnitude, size, we also discussed about the strain energy versus the magnitude empirical correlation. Those kind of correlation, which is reliable and applicable to your region, you should take and estimate each year, whatever magnitude happen, how much strain it happens.

Then, you try to plot year wise the data. Then, you will find a trend like this. This is the cumulative strain energy released in the particular region, which you obtained from the seismic study area data. You already collected a data know, from there you will get all the independent events after declustering the data and estimate a strain energy and plot like this. So after plotting this, you plot a lower, upper and then the medium portion of the graph.

The slope, for example, you can see the E2. So E2 is actually the median slope is the E2 energy, that is corresponding this. Then the E1 is actually where you can see, where it is hitting, here know. Then, where it is hitting in the upper bound, you can see that this point and then this point and project what is the E max. So this E max you can convert it into the magnitude, because you can estimate energy from the magnitude, again from magnitude to energy.

Earlier, you have estimated the magnitude to energy and used to cumulatively and now you are estimating the energy to magnitude, that magnitude will be unique for different seismic study area. That value will be taken as M max. This is the typical plot, which shows how it has been done. Another method is actually the Kijko and Singh method. Kijko and Singh 2011 proposed several procedures for statistical estimation M max based on the seismic data of particular region.

These methods can be applied when no information about the nature of earthquake magnitude distribution is available, when earthquake catalogue is incomplete. This is basically a statistical based approach, even incomplete data can be used here. Kijki and Singh proposed 12 procedure for the determination of M max. So this estimation of M max magnitude has divided in 3 categories, parametric, non-parametric, and fit to the cumulative density function of the earthquake magnitude.

These are the 3 categories they have done and each category there is a sub-estimation depending upon the different composition and statistical model what they use. So these methods depends upon the time interval, number of earthquake occurred having the magnitude greater than or equal to the threshold complete of the specific study area. So these methodology assume that magnitudes are independent, identical distribution, random values with probability density function, the cumulative distribution of the function.

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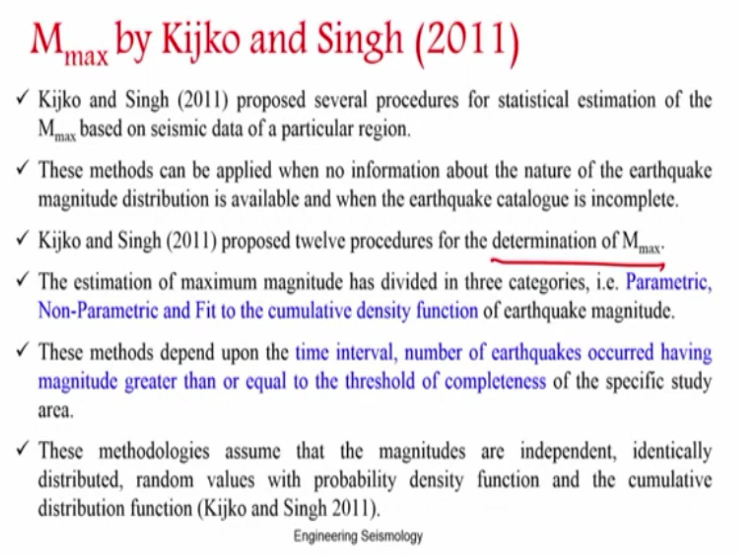

So this method basically you can see here. We have given this method. You can see the serial number. So the parametric approach, each method has observation on that. You can see it is very straight forward method, does not require extensive calculation, but fails to provide estimate having the smaller mean square error. If you visit my paper on M max estimation, you can find more discussion about all these methods.

Kijko released the computer program, where it can be run in the Matlab or any computer exe file, where you can get all the statistical method coded, where you can feed your data and get M max. The mathematical explanation is also given in the computer program. If you are going to do research on M max estimation, you need to go through on that, otherwise this is a statistical method, depends upon the different statistical approach and data, you will get different M max. That message taken from here will be sufficient.

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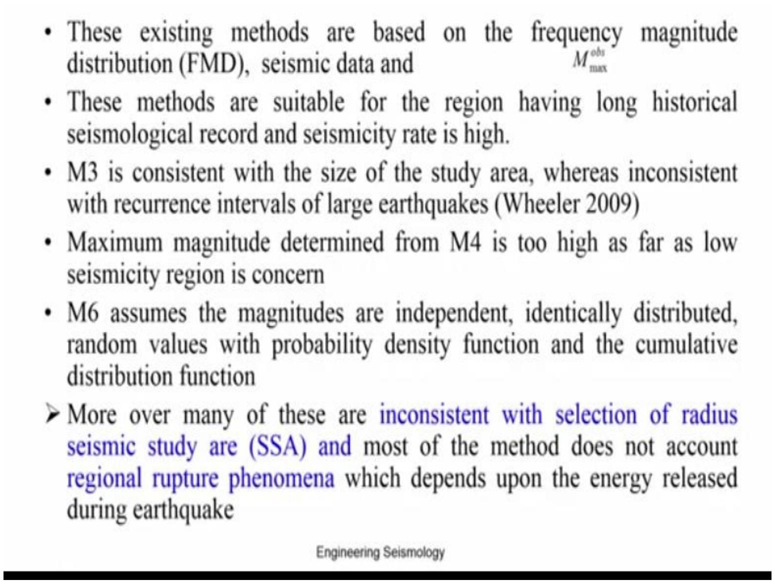

This existing method, whatever we discussed so far, have to be based on the frequency magnitude distribution and seismic data and observed magnitude. So all these method, whatever we discussed 7 methods, you can see that it is a function of existing data or frequency magnitude or observed magnitude, even statistical method or any other method. These methods are suitable for the regions in the long historical and seismological record.

Seismicity rate is very high; these methods can be used. So M3 is consistent with the size of study area, whereas inconsistent with the recurrence interval of the large earthquake. The M3 method, what we quoted there, the maximum magnitude determined from the M4 is too high as far as low as the seismicity region is concerned assuming the 50% and one-third of the data will be by Mark M4 method is more unrealistic.

M6 assumed that magnitude are independent, identically distributed random values with probability density function and cumulative distributive function. Moreover, many of these areas are inconsistent with the selection of the seismic study area. Most of these methods does not account the regional rupture taking place in the particular region. In order to account that, we come up with the new idea called regional rupture character.

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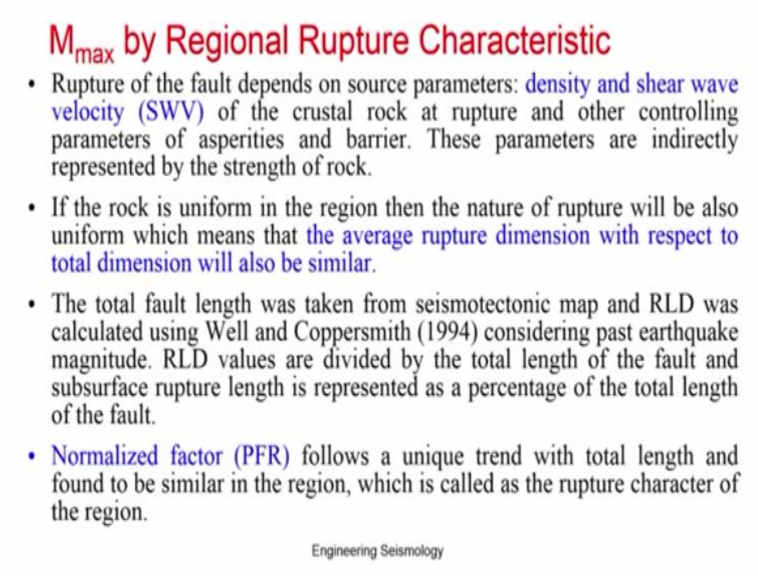

What is the regional rupture character? As we have seen that, the rupture occurring at a particular location is the function of your shear wave velocity or stiffness of the particular rock. That is what we modeled, shear models or shear wave velocity and then the density and type of the rock of the particular location. So crust lock at rupture place is controlling, these are all the parameters, which controls.

The changes in these parameters will also result in the changes in your rupture phenomena, some places where the rock is very weak. It may rupture larger for the same magnitude, some places where rock is very strong, it will rupture less for the same magnitude. The rock is uniform in the region, then the nature of rupture will be also uniform throughout the seismic study area, which means that the average rupture dimension with respect to the total dimension will be also similar.

So if you have the seismic study area, which has an uniform rock deposit from the crustal rock deposit or any geological formation, that means your rupture phenomena also similar in that region. By taking this as a consideration, one can establish what is the regional rupture character. How to establish that? You take a length of the fault and take a damaging earthquake. Damaging earthquake means earthquake which can rupture a fault, 4.5 and above magnitude.

And try to estimate what is the subsurface rupture length, using the well known correlation between the subsurface length and magnitude. That RLD you can take at different fault and different earthquake occurred in the seismic study area, if your geology of the study area is same. If the geology of the study area has 2, 3 division, then only adopt to the similar geology of this. Once you take that, then try to normalize that value with the length of the fault. Then we plotted that with again the ruptured length ratio versus length of the fault, we got a unique trend. That trend we call it as a regional rupture character.

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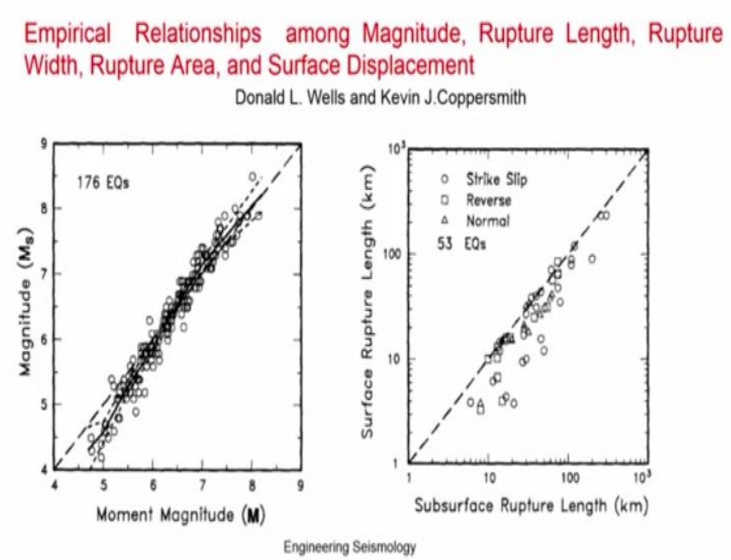

Let us see. Before going into estimation of that, let us see what are the empirical equations available for RLD versus magnitude. This was actually published by Wells and Coppersmith in 1991, even it was also recently updated, but the update was not so much, actually more or less it is same. You can see that the moment magnitude and any other magnitude well related with the fault rupture length and fault rupture area, again is the function of different fault type, different tectonic settings.

Here you can see that subsurface rupture length, the surface rupture length. Subsurface rupture length means the ratio between the ruptured below ground and surface, that also follow an unique trend with differentiable with a different fault type.

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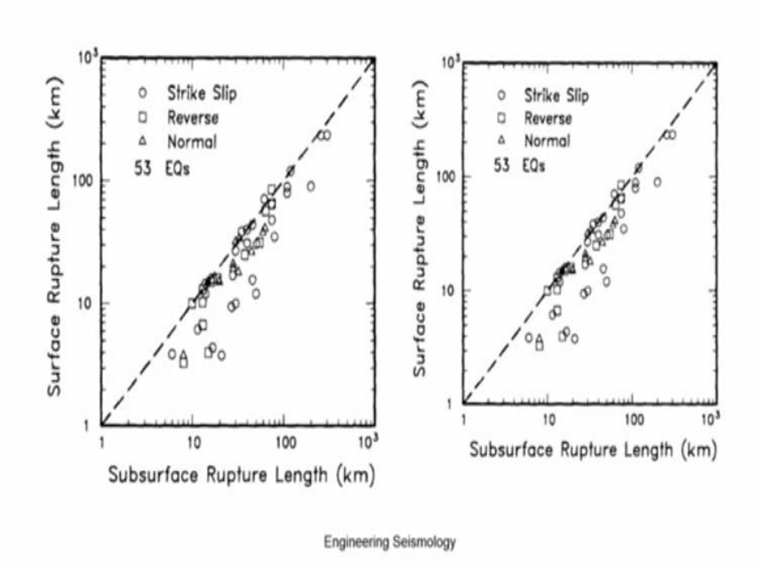

Again, this is for another region, where you can see the subsurface rupture length and rupture length.

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Table 2A

Regressions of Rupture Length, Rupture Width, Rupture Area, and Moment Magnitude (M)

Equation*	Slip Type†	Number of Events	Coefficients and Standard Errors $a(s_a)$	$b(s_b)$	Standard Deviation s	Correlation Coefficient r	Magnitude Range	Length/Width Range (km)
M = a + b * log (SRL)	SS	43	5.16(0.13)	1.12(0.08)	0.28	0.91	5.6 to 8.1	1.3 to 432
	R	19	5.00(0.22)	1.22(0.16)	0.28	0.88	5.4 to 7.4	3.3 to 85
	N	15	4.86(0.34)	1.32(0.26)	0.34	0.81	5.2 to 7.3	2.5 to 41
	All	77	5.08(0.10)	1.16(0.07)	0.28	0.89	5.2 to 8.1	1.3 to 432
log (SRL) = a + b * **M**	SS	43	−3.55(0.37)	0.74(0.05)	0.23	0.91	5.6 to 8.1	1.3 to 432
	R	19	−2.86(0.55)	0.63(0.08)	0.20	0.88	5.4 to 7.4	3.3 to 85
	N	15	−2.01(0.65)	0.50(0.10)	0.21	0.81	5.2 to 7.3	2.5 to 41
	All	77	−3.22(0.27)	0.69(0.04)	0.22	0.89	5.2 to 8.1	1.3 to 432
M = a + b * log (RLD)	SS	93	4.33(0.06)	1.49(0.05)	0.24	0.96	4.8 to 8.1	1.5 to 350
	R	50	4.49(0.11)	1.49(0.09)	0.26	0.93	4.8 to 7.6	1.1 to 80
	N	24	4.34(0.23)	1.54(0.18)	0.31	0.88	5.2 to 7.3	3.8 to 63
	All	167	4.38(0.06)	1.49(0.04)	0.26	0.94	4.8 to 8.1	1.1 to 350
log (RLD) = a + b * **M**	SS	93	−2.57(0.12)	0.62(0.02)	0.15	0.96	4.8 to 8.1	1.5 to 350
	R	50	−2.42(0.21)	0.58(0.03)	0.16	0.93	4.8 to 7.6	1.1 to 80
	N	24	−1.88(0.37)	0.50(0.06)	0.17	0.88	5.2 to 7.3	3.8 to 63
	All	167	−2.44(0.11)	0.59(0.02)	0.16	0.94	4.8 to 8.1	1.1 to 350
M = a + b * log (RW)	SS	87	3.80(0.17)	2.59(0.18)	0.45	0.84	4.8 to 8.1	1.5 to 350
	R	43	4.37(0.16)	1.95(0.15)	0.32	0.90	4.8 to 7.6	1.1 to 80
	N	23	4.04(0.29)	2.11(0.28)	0.31	0.86	5.2 to 7.3	3.8 to 63
	All	153	4.06(0.11)	2.25(0.12)	0.41	0.84	4.8 to 8.1	1.1 to 350
log (RW) = a + b * **M**	SS	87	−0.76(0.12)	0.27(0.02)	0.14	0.84	4.8 to 8.1	1.5 to 350
	R	43	−1.61(0.20)	0.41(0.03)	0.15	0.90	4.8 to 7.6	1.1 to 80
	N	23	−1.14(0.28)	0.35(0.05)	0.12	0.86	5.2 to 7.3	3.8 to 63
	All	153	−1.01(0.10)	0.32(0.02)	0.15	0.84	4.8 to 8.1	1.1 to 350
M = a + b * log (RA)	SS	83	3.98(0.07)	1.02(0.03)	0.23	0.96	4.8 to 7.9	3 to 5,184
	R	43	4.33(0.12)	0.90(0.05)	0.25	0.94	4.8 to 7.6	2.2 to 2,400
	N	22	3.93(0.23)	1.02(0.10)	0.25	0.92	5.2 to 7.3	19 to 900
	All	148	4.07(0.06)	0.98(0.03)	0.24	0.95	4.8 to 7.9	2.2 to 5,184
log (RA) = a + b * **M**	SS	83	−3.42(0.18)	0.90(0.03)	0.22	0.96	4.8 to 7.9	3 to 5,184
	R	43	−3.99(0.36)	0.98(0.06)	0.26	0.94	4.8 to 7.6	2.2 to 2,400
	N	22	−2.87(0.50)	0.82(0.08)	0.22	0.92	5.2 to 7.3	19 to 900
	All	148	−3.49(0.16)	0.91(0.03)	0.24	0.95	4.8 to 7.9	2.2 to 5,184

*SRL—surface rupture length (km); RLD—subsurface rupture length (km); RW—downdip rupture width (km), RA—rupture area (km^2).
†SS—strike slip; R—reverse; N—normal.

Based on this kind of systematic analysis of the entire global data, he has given a relation between M versus subsurface rupture length and surface rupture length. So the subsurface rupture length is the one, which is controlled by a fault and rock in the region. So we take that as a basis. So the equation given for the magnitude versus subsurface relation, a particular fault type depends upon your fault orientation or fault type in the region, or applicable to all the fault you can take.

Those equations you can take it as this one, like subsurface rupture length, moment magnitude, different fault type, and this is the relation you can take. So after taking that relation, you can estimate for the damaging earthquake, like earthquake which has a magnitude of above 4.5 and above, you can estimate the subsurface rupture length using this kind of empirical relation. So this is the typical relation, but you can use the recent updated equation also, no issue.

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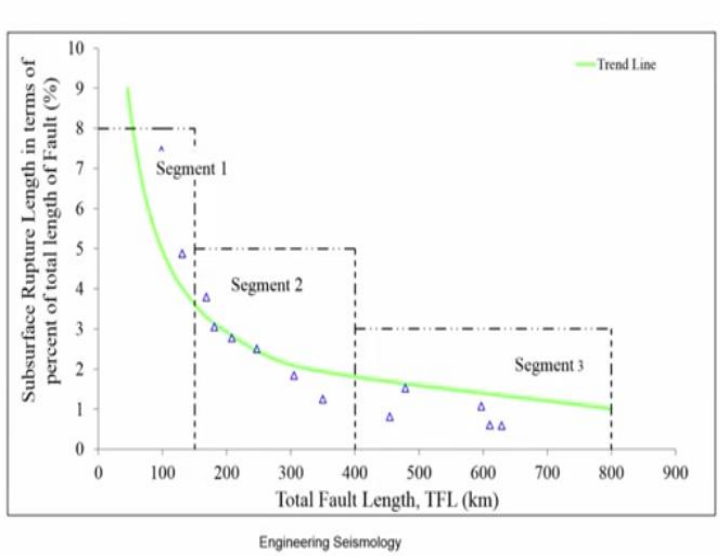

So you can get that. As I told you that you estimate first RLD. RLD is the subsurface rupture length divided by the total length of the fault and then plot again a total length, then we notice that these are all the data what we got from this one. When you fit a trend, it follows an unique trend. This trend is called as regional rupture character. So this trend is same for a particular region, as long as there is no rock changes are occurring.

So this concept once you establish that, now you know that what is the trend. You can decide what is the rupture length percentage you can take. Then, that you can again convert into the magnitude, that magnitude will be taken as maximum magnitude. So that procedure and explanation about that, I am going to discuss further in the class.

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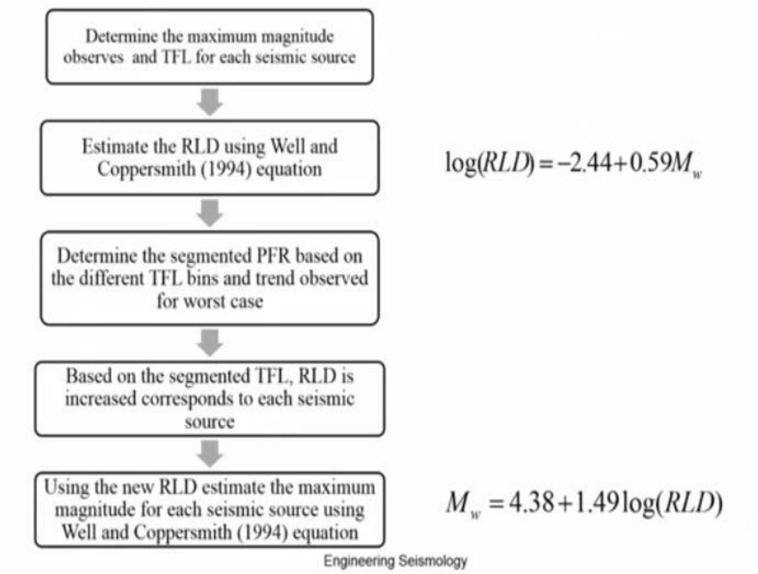

So this procedure is streamlined like that. It has 5 major steps. Determine the maximum magnitude observed on each fault, which is damaging earthquake and then the total length of the fault. You can take from the map. So estimate RLD using the Wells and Coppersmith relation, like this is the inverse of the relation what is given in the table and determine the segment of PFR based on the different TFL basin observed in the worst case.

Here, you can mark, based on this, you can mark that up to 100, this is this one, up to 100, this is one, this segmenting you should do carefully by looking at this line and the maximum and minimum. That you can do, so after that based on the segment, you can fix what is the ratio. This ratio, you can take it for your analysis, percentage of the fault rupture you can take. Then use that again and convert into the magnitude using the same equation here.

Here the plus or minus has been taken as upper side, so the equation comes as only this one. There is no standard deviation. So this process involves 5 step, which is very simple. Let us see how this concept is applicable for different part of India, how it overcome a limitation in the previous method. That is what we are going to discuss further.

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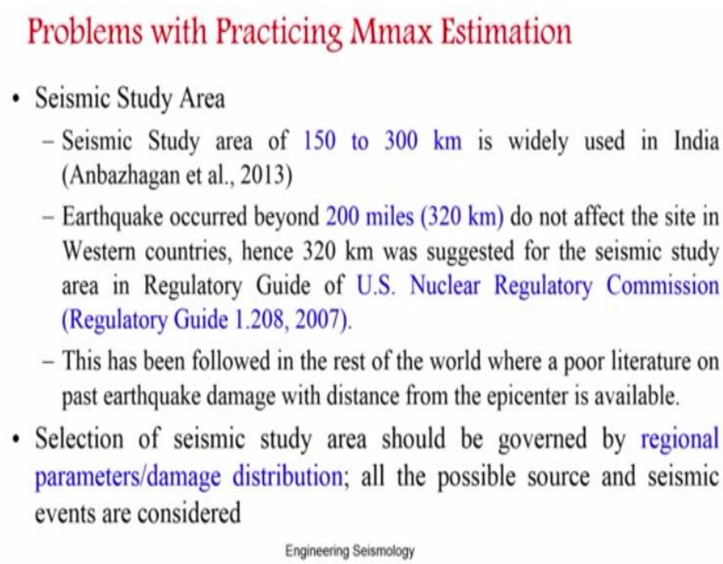

As I told you that the present practicing whatever the 7 method we discussed, it has a problem whenever, there is a change in the data, you M max will be changing. Change in the M max occurs because of the change in the seismic study area, which changes a data, that also result in the change in the M max. So we need a method, which is not affected by these kind of seismic study area change and then the data change.

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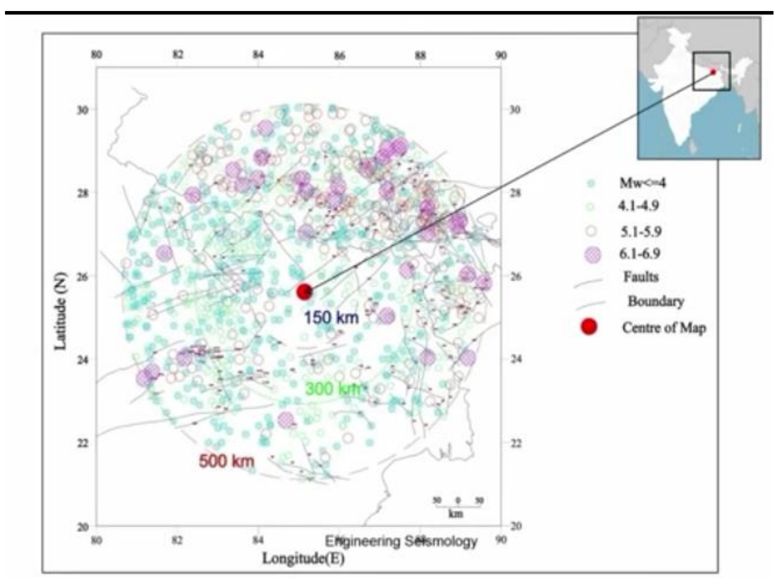

The ruptured based method will actually work like that. In order to demonstrate that, we have taken two region, one is that Patna, another one is basically Kalpakkam, where the Southern India and Northern India stable continent, interslab and intraslab. Both are taken. So we have taken this, a study area. This is the seismic study area. So we have taken 3 radius of seismic study area, 150 km, 300 k and 500 km radius.

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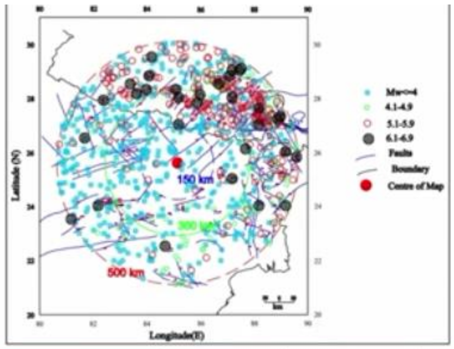

Study Area Radii		150 km	300 km	500 km
Total Number of Events		72	377	1257
Minimum Observed Magnitude		2.4	1.7	1.7
Maximum Observed Magnitude		5.8	6.5	7.0
Number of events <3		9	11	25
Number of Events ≥ 3		63	366	1232
Number of Seismic Source		12	71	176
Gutenberg-Ritcher	"a"	4.524	5.417	5.689
Parameter	"b"	1.42	1.09	0.98

So let us see the data in the file. The 150 km, number of events is actually 72 and 300 you see how much increased and 500 see how much increased. Minimum observed magnitude is 2.4, 1.7, 1.7; maximum observed magnitude is 5.8, 6.5 and 7. Why you need this? Because as I said that M max method, one of them is maximum observed plus maximum observed by increment. There are 2 methods depending on that. That is why you have to take.

The number of events less than 3, so you can note down, number of events more than 3 you can say. These are all will tally actually, when you do that. So the number of seismic sources fault associated with the earthquake and the ab parameters, which we will be discussing in the next, how to estimate the ab parameter. So that also we have taken, because the statistical method, basically looks at the ab parameter of your data.

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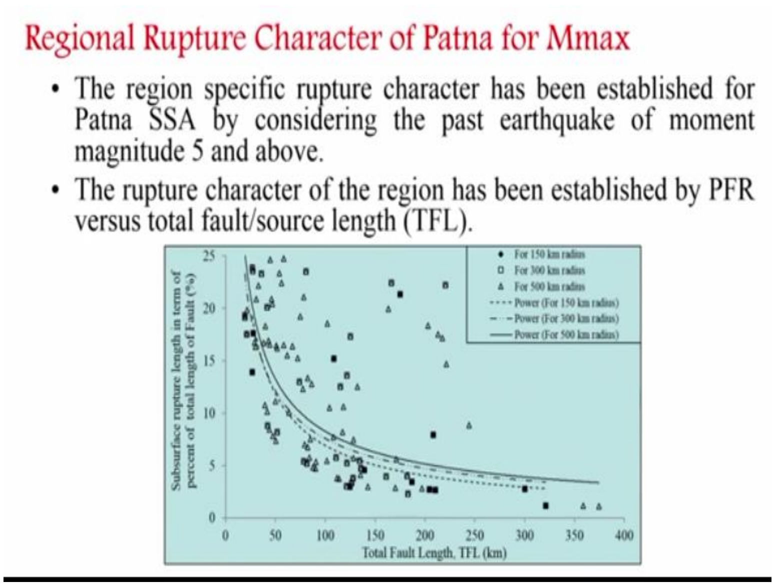

So the regional rupture character, we have to establish for the same study area by dividing data into that and estimating the RLD percentage and plotted. You can see that irrespective of the radius, you get all the lines similar. The trend is similar, irrespective of the area, which will help you to basically arrive your segment also similar. So I can arrive up to this, then maybe this, so then maybe this like this.

You can also see the unusual earthquakes, which you can also consider away from the trend, but it has to be noted when you are assuming your RLD percentage. So that flexibility also gives you this method.

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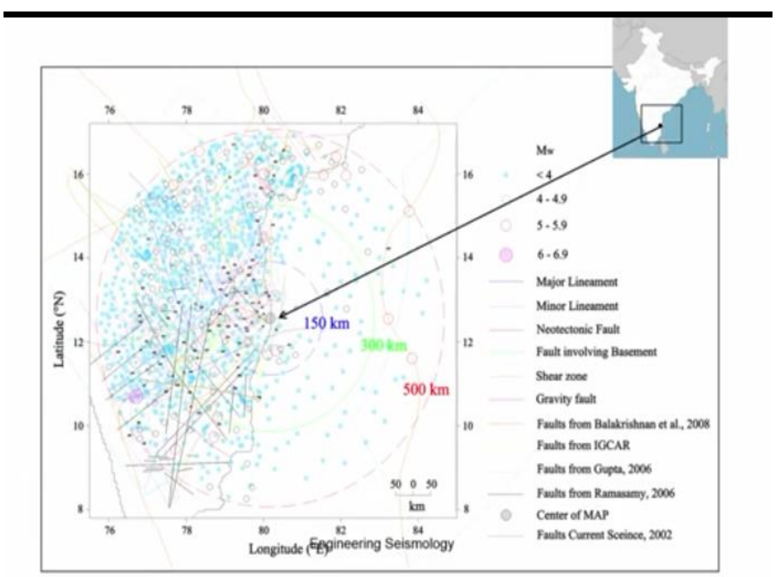

Similar map has been done for again Kalpakkam, so again 150 radius, 300 and 500 radius, similarly all map seismo-tectonic map has been prepared and then try to establish a segment, you can see here.

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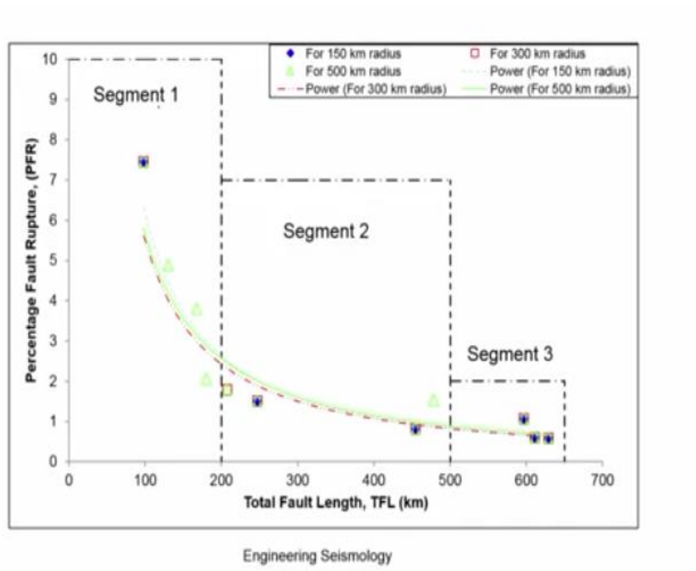

Segment 1, segment 2, segment 3, you can see the rupture character. Here, you can see that there actually Patna has geologically different region, because if you see the Himalayan side and South and West, since we consider all of them, the gap between these are slightly larger, when you go higher radius, the geology composition come into picture, which result in different this one. That means, we have to divide that as a different geological formation and establish this one. But in Chennai, it is the same geology, because it is a Southern Granulite terrain. You can see that; they are very closer lines.

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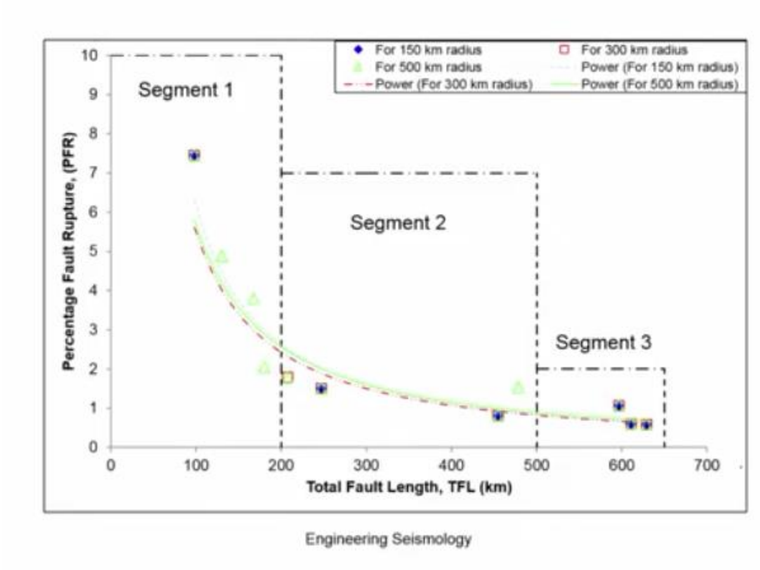

There is no even a small deviation in this. You can see the 150 in blue colour, 300 in the red and then the green is actually 500 radius and the trend. You can get 3 segments.

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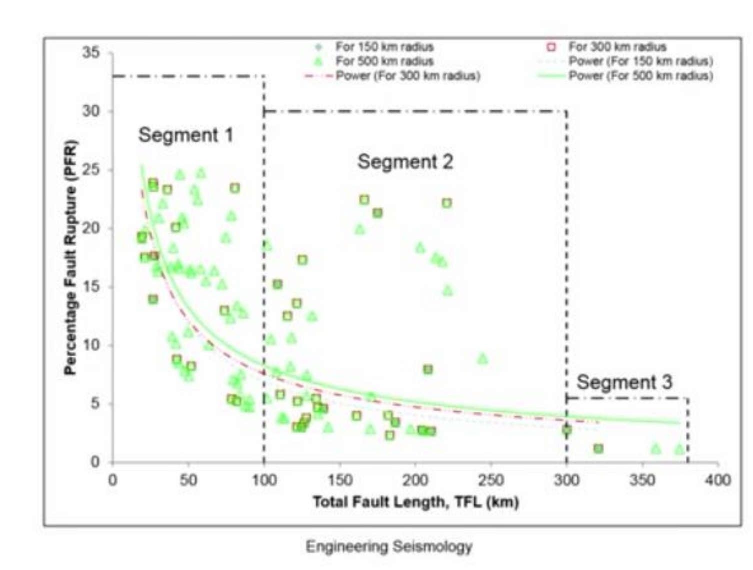

Once you arrive this segment, this is basically for again Patna. So you can decide what is the average value, maximum value, then you can decide depending upon the structures, what value you want to take for the safer side and convert to the M max. That value, we are going to discuss further.

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- It can be observed that the percentage of the total fault ruptured for shorter faults are more when compared to that of longer faults, showing a decreasing trend with an increase in the fault length.
- This indicates that most of the damaging earthquakes in the region follow some trend.
- The trend of the PFR does not vary with SSA radius and also fitness become better due to increase in the SSA radius.

Length bins	PFR (%TFL)			PFR (% TFL) for Worst scenario (WS)	Ratio of PFR for WS to maximum PFR
	Maximum	Minimum	Average		
< 100	25	4.71	15.06	33	1.32
100-300	22.2	2.32	8.74	32	1.44
> 300	3	1.13	1.56	5.5	1.83

Engineering Seismology

It can be observed from the percentage of the total fault ruptured, short fault length having the more rupture than compared to the long fault length, showing decrease in the trend with increase in the fault length. The RLD is actually the function of length of the fault, which is again controlled by geology rock properties in the region. It indicates that most of the damaging earthquake in the region somewhat follows some trend, which is unique.

The trend of PFR, fault rupture ratio does not vary with the seismic study area, also fits better due to increase in the seismic study area radius. You can see the maximum, minimum, average. S this value, you can decide what is the proposed rupture length you want to take or percentage of the rupture length you want to take. So as I know that the maximum is 25. So I want to go for the worst scenario, where I will be taking larger. Say then 22 larger and 3 this one.

If I want to go for the little like the worst scenario for the nuclear power plant, dams like kind of things, where the worst earthquake should not even affect those structures. If you want to go for the regular building, you can go close to the maximum, no need to have so much variation with the maximum value. For example, here the factor, which varies with the maximum. So this also, you can take. This factor you can decide depending upon the importance of the structures. The more important, the more factors will be given, less important, factors should be reduced. That is what you can do.

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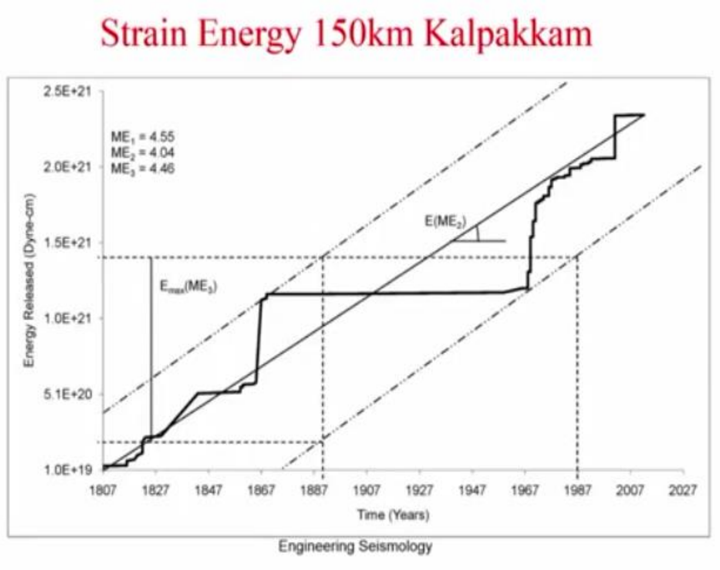

So this is the way we can estimate. Let us see how the M max from different approaches are required. Since all other method only analytical method, this is the graphical method, so the energy based graph has been prepared for both the region. So this is the energy based graph for 50 radius. You can see the ME1, ME2, ME3 for 150 radius, again you see for 300. So these values are changing now, again for 500, you can see how it changes.

So even energy based method also reflect a seismic study area, this one, but RLD does not do that. Let us see how the calculations are done. So this is done similarly for Patna, where we have shown only one graph.

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Seismic Source	Observed magnitude	Regional Rupture characteristics		
		TFL (km)	RLD (% TFL)*	Maximum Magnitude
0-150 km				
S04	5.1	321.03	102.73	7.5
S161	6.2	208.22	66.63	7.2
S19	5.5	186.75	59.76	7.1
S58	5.4	204.19	65.34	7.2
S59	6.8	174.9	55.97	7.1
S60	5.4	210.41	67.33	7.2
S61	5.7	300.18	96.056	7.5
150-300 km				
S03	5.2	183.13	58.6	7.1
S105	6.8	166.32	53.22	7.1
S11	5.6	181.92	58.22	7.1
S62	7	220.63	70.6	7.3
300-500 km				
S02	5.4	206.58	66.1	7.2
S106	6.8	213.24	68.24	7.2
S128	6.4	244.38	78.2	7.3
S130	6.8	203.22	65.03	7.2
S34	5.4	197.04	63.05	7.2
S44	5.3	170.39	54.52	7.1
S45	6.8	217.61	69.63	7.3
S57	6.7	221.6	70.91	7.3
S83	5.8	171.1	54.75	7.1

So after doing this, this is the different source, then the total fault length, RLD rupture estimated and then the converted that RLD assumed value as a maximum magnitude with individual fault. Here you also have the advantage that each fault, you can get M max. You can see that this M max are completely different from your observed M max. You can see. These M max are consistent with respect to the length of the fault. This is nowhere related to the length of the fault, that way also you can get and again the radius, when you consider lower radius, you will get only few sources in to the band.

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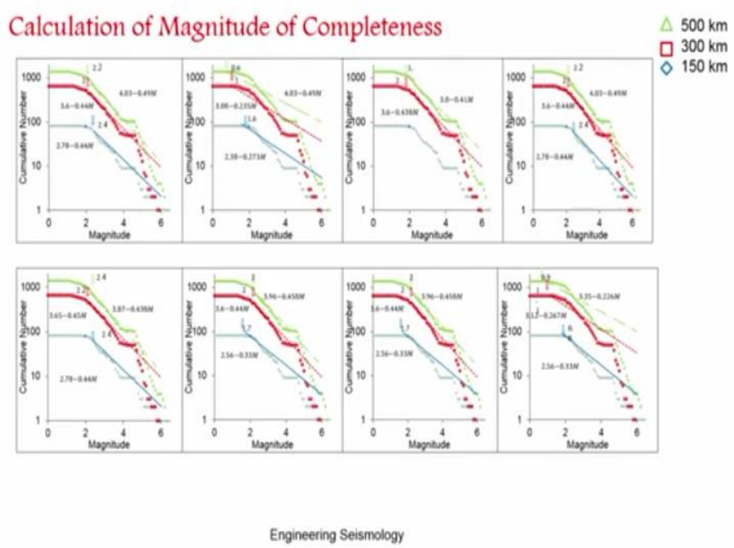

This we will see in detail how it affects this one. So the similar kind of like the Kijko and (()) (34:58) method we have used to get M minimum and then these ab parameters and thereby 12 M max estimation method. So that method also given here, you can see.

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Calculation of Maximum Magnitude

S. No.	Methods		Maximum Magnitude (Calculated) — Radius of Study: 150 km					300 km				500 km				
MM1			5.9					5.9				6.3				
MM2		.5	6.4					6.4				6.8				
		1	6.9					6.9				7.3				
MM3	Extrapolation of magnitude-frequency graph		6.42					6.66				7.29				
MM4	Coda Method		6.4					6.4				6.4				
MM5	Mark, 1977		8.10					8.10				8.10				
MM6	Strain Energy	ME_1	4.55					4.27				4.41				
		ME_2	4.04					4.74				6.11				
		ME_3	4.46					5.25				6.5				
MM7	Kijko's Method*		M1, M5, M6	M2	M3	M7, M8	M9	M1,M3,M5 ,M7,M8	M2	M6	M9	M3, M5	M7, M8	M2, M9	M1	M6
	K1		6.43	6.13	NA	6.15	6.22	6.00	5.93	6.00	5.94	6.36	6.39	6.32	6.4	6.37
	K2		6.24	6.10	NA	6.11	6.15	5.99	5.93	5.99	5.94	6.36	6.38	6.32	6.39	6.37
	K3		6.24	6.10	NA	6.11	6.15	6.00	5.93	6.00	5.94	6.36	6.38	6.32	6.4	6.37
	K4		6.31	6.12	NA	6.13	6.18	5.98	5.93	5.98	5.94	6.35	6.36	6.32	6.37	6.36
	K5		6.20	6.09	NA	6.10	6.13	5.97	5.93	5.98	5.94	6.34	6.36	6.32	6.37	6.36
	K6		6.01	6.14	NA	6.14	6.12	6.12	6.13	6.10	6.13	6.42	6.41	6.43	6.4	6.41
	K7		6.08	6.08	NA	6.08	6.08	6.00	6.00	6.00	6.00	6.32	6.32	6.32	6.32	6.32
	K8		6.04	6.04	NA	6.04	6.04	5.99	5.99	5.99	5.99	6.32	6.32	6.32	6.32	6.32
	K9		6.10	6.10	NA	6.10	6.10	6.10	6.10	6.10	6.10	6.3	6.3	6.3	6.3	6.3
	K10		6.00	6.00	NA	6.00	6.00	6.00	6.00	6.00	6.00	6.3	6.3	6.3	6.3	6.3
	K11		6.06	5.98	NA	6.00	6.16	5.88	5.42	5.9	5.42	6.36	6.41	5.8	6.28	6.28
	K12		6.20	5.82	NA	5.94	6.32	6.00	5.4	6.14	5.4	6.56	6.4	5.8	7.06	6.38
MM8	Regional Rupture Characteristic		varies from 5.8 to 6.7 for TFL diverges from 97.35 km to 454.52 km					varies from 5.8 to 6.7 for TFL diverges from 97.35 km to 493.23 km				varies from 5.3 to 6.7 for TFL diverges from 50.18 km to 493.23 km				

This table gives a very detailed analysis of your M max estimation. So this side basically gives M max estimated method like MM1 means method 1, M max by method 1, M max by method 2, so M max by method 3, like eighth method is proposed by myself and all other methods were existing one. So MM1 where the observed magnitude 5.9, when I consider the 150 km, and 5.9 again 300 km and 6.3 when I go for the larger seismic study area.

You can see 6.3 and 5.9, you know this is 6.3 is 4 times larger than the 5.9. Even though the variation is 0.4, but it is 4 times larger than the 5.9, as it is in the large scale. So M2 method, increment method, it depends upon the ab value, even though recommended. I have taken 2 case, where I added 0.5 and I added 0.1, you can see the M max, so much difference. Here you can see this one similar, but here you can see.

As the observed magnitude changes, your M max by increment method also changes. So the extrapolation method, graph this is 1, this is 1, and this is 1. You can see that there is a consistent increasing in the M max with increase in the seismic study area. So the Coda wave method, this gives almost the same value, because the Coda wave portion remains similar. The Mark method, 8.1, 8.1, and 8.1 because the length this was actually we have given the highest magnitude on each method.

Strain energy method, you can see here. It is around 4. Here 4 to 5.25, here 4.4 to 6.5. This 6.5 can be taken as M3 that was suggested. Kijko method, you can see a different method, M1, M5, M6 give the similar value in 12 method, so that the M2 and M3 are not applicable; M7 and M8, M9. So within the Kijko method, I said there are different methods, 12 methods. You can see the difference. How each region the values are taken, 6.2, 6, and 6.49.

Like that, 6.73, so the M6, so here again M6 is 6.4, we have to do a careful analysis and try to compare these values. Let us see what the regional rupture character gives. The proposed method, you can see that the M max varies from 5.8 to 6.9 for the total derived from so much rupture length. It varies from 5.8 to 6.7 with so much; it varies from so much to so much. You can see that here, the upper magnitude remains same.

Each fault, you will get M max. The rest of the method you will take each fault means, sometimes if there is no earthquake recorded in the fault, only the one magnitude, 2 magnitude are reported, you consider that that fault does not have M max at all. That risk is there in the existing method, but new method it considers all the fault.

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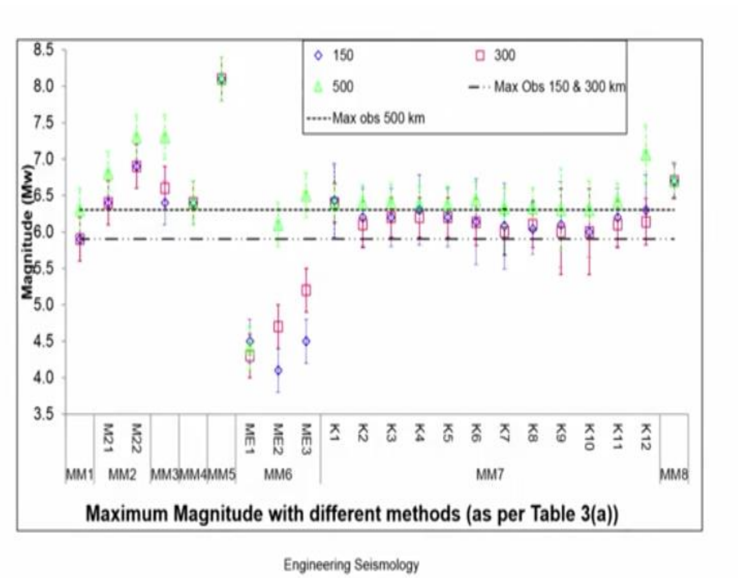

So you can see here, the graphical representation of the M max variation. This is basically a different method in the y axis, in the x axis, you can see M1, M2, M3, M4, M5, M7 and M8 method. This is the magnitude, which is estimated. This line indicates a reported maximum magnitude in the particular seismic study area. So here the line upper and lower bound gives a variation within the particular method.

So you can see that most of the method up to M7 method, there is a huge difference, upper and lower bound you can see here. As your seismic study area changes, your M max also fluctuating. You can see here. Your M max also fluctuating and that is also on all the methods, you can see here. Some of the methods even give a very different value, when you change a seismic study area. If the same thing comes back the newly proposed rupture based method, you can say irrespective of the seismic study area, you get same M max.

The variation also is similar, not like other methods. This is the beauty of the regional rupture character approach on M max estimation. This particular work was already published in the Journal of Seismology, now people started using this kind of approach for estimating the M max of a particular region. I suggest that instead of adding 0.5 or random value, it is always better to take this kind of universally acceptable method, because it does not depends upon the seismic study area at all.

This only depends upon your geology classification at a particular place. How geology is complex in that particular place. Recently also we have validated this method with different papers in the KRS dam. Those who are interested to know more about this, you please visit those papers and read those papers and try to understand. This is basically a particular study area.

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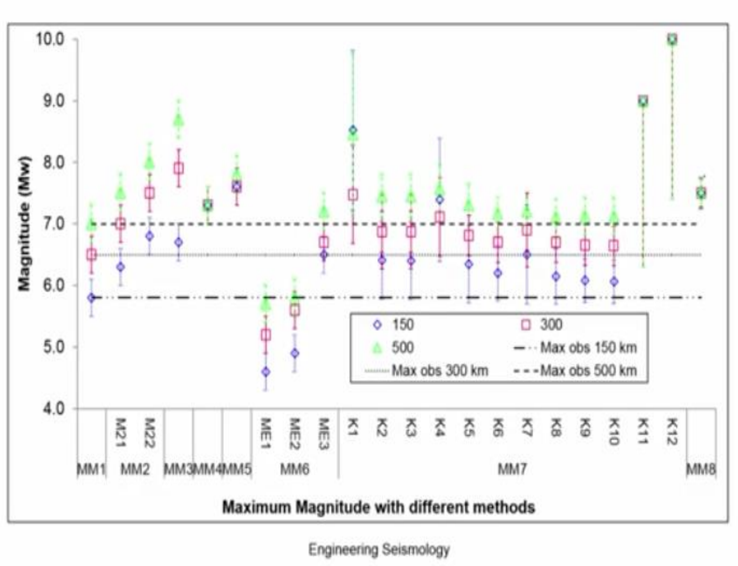

Then, we further went to other this one, there also you can see. This is I think for Patna, earlier one for Kalpakkam. You can see how much difference. These differences are negligible in this newly proposed method, which needs to be considered as one of the best way to estimate M max. This has been published in Journal of Seismology, as I said you that. So I believe that this kind of approach will give you the unique M max at a particular region.

If you want to consider entire seismic study as a single region and you also get individual fault length based M max, which is also possible. That also does not change, irrespective, but other approaches when you change a seismic study area, your M max value keep changing. That is not the issue with the newly proposed method. By looking at what is the importance of the M max and how the different ways you can estimate, and I also discussed the method, which is unbiased.

Because all other methods are biased, depends upon the seismic study area. So M max method proposed by regional rupture character, if you use, you no need to worry about the seismic study area and all, but still you have to consider the seismic study area as very important, because your recurrence relation is the function of how many earthquake data you have, like magnitude and frequency plot.

So magnitude recurrence relation is the function of how much data you have in the particular region. That way, the seismic study area plays a very important role, contributes to the M max as well as contribute to the recurrence relation. So we will discuss about the recurrence relation further in the next class; how to estimate, how it is controlled by this one. Right now, we have seen that the selection of seismic study area and associated effect on the M max and I suggest that the regional based M max estimation will be the more reliable based on my research.

If you want to do other approaches also, you are welcome, you can take both the method and compositely you can mix and estimate the hazard, which we will discuss when we are talking about the hazard analysis of a particular place. This is about the M max estimation, which is also one of the important step in the seismic hazard analysis. With this, we will close this class. Thank you very much for watching this video. Next class, we will be talking about the recurrence relation development for a particular place. Thank you very much for watching this video. We will meet you in the next class.