**Geotechnical Earthquake Engineering**

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**Module - 7**

**Lecture - 29**

**Seismic Hazard Analysis (Contd…)**

Let us start our today's lecture for this NPTEL video course on geotechnical earthquake engineering. We are going through module seven, which is on seismic hazard analysis. A quick recap, what we have learnt in our previous lecture.

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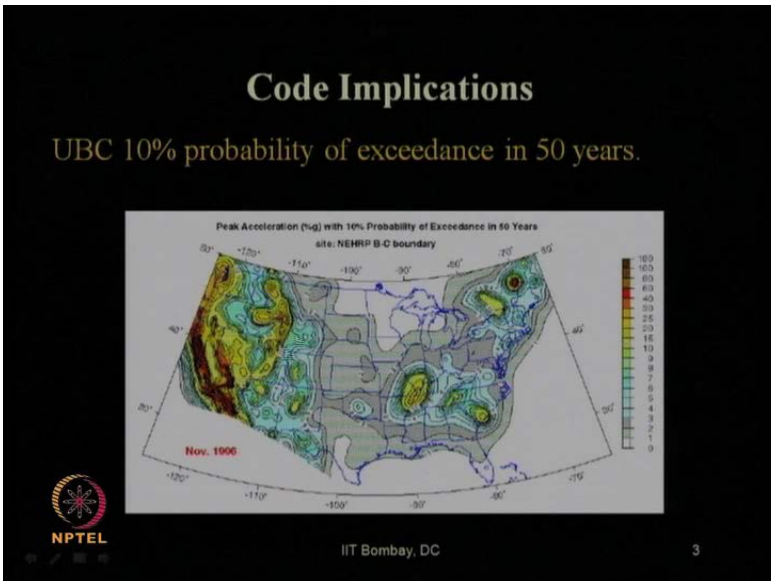


We can see in this slide that what is the application in the design code or seismic design code world wide of this seismic hazard curves; like UBC suggest for 10 percent probability of exceedance in 50 years time. This map shows the peak acceleration values for that 475 years return period. These are the values in percent g for a NEHRP based site category of B and C for US.

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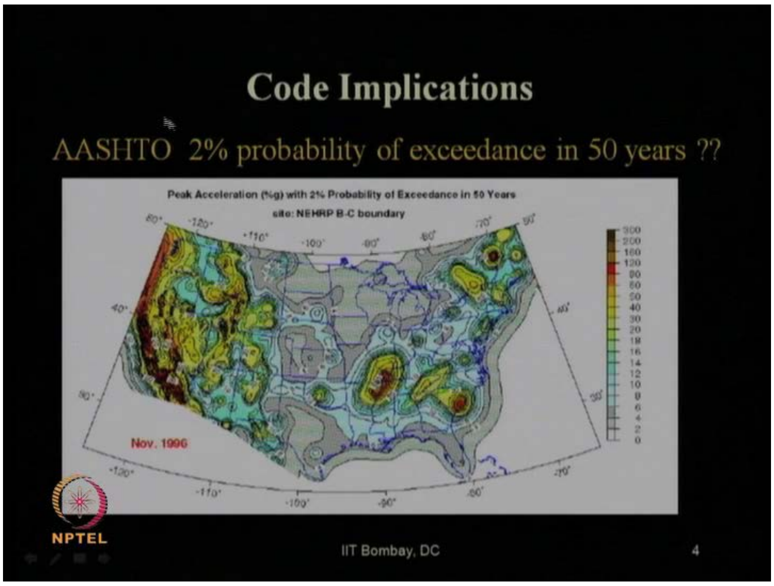


Similarly, for AASHTO code, the proposed map for US is like this with 2 percent of probability of exceedance in 50 years scale. So, that is how the seismic design codes – they implement the seismic hazard analysis results for further application in design. Then, in the previous lecture, we had started with dealing with an example of extensive case study for a particular region, which is the Gujarat state of India. And, we discussed in detail. We have initiated the discussion in detail for the seismic hazard study for Gujarat region of India.

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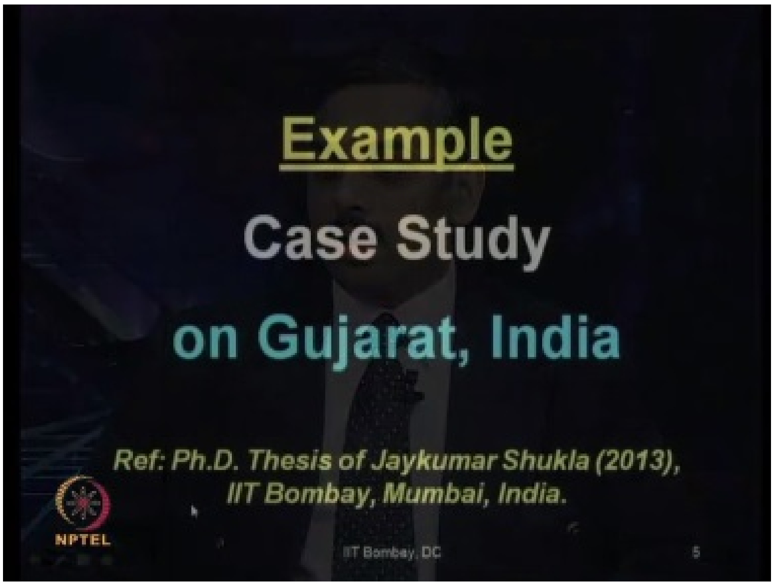

If we look at this slide, as I have already mentioned, this is the work done for the Ph.D. thesis of Doctor Jaykumar Shukla, who completed his Ph.D. in 2013 at IIT Bombay under my supervision.

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This is the map of location of Gujarat. Gujarat is the central western most state of India as shown over here. This is the Gujarat state, which is surrounded by here Arabian sea; here the neighbouring country Pakistan.

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The urban areas of Gujarat region has been subdivided into three major regions: one is Kachchh region; another is Saurashtra region; another is Mainland Gujarat region. And, these are the 25 cities, which are selected for our present case study or present analysis. Further later on, four port sites: Kandla port, Mundra port, Hazira port and Dahej port are also considered for site specific ground estimation analysis, which we will discuss in our next module of this course.

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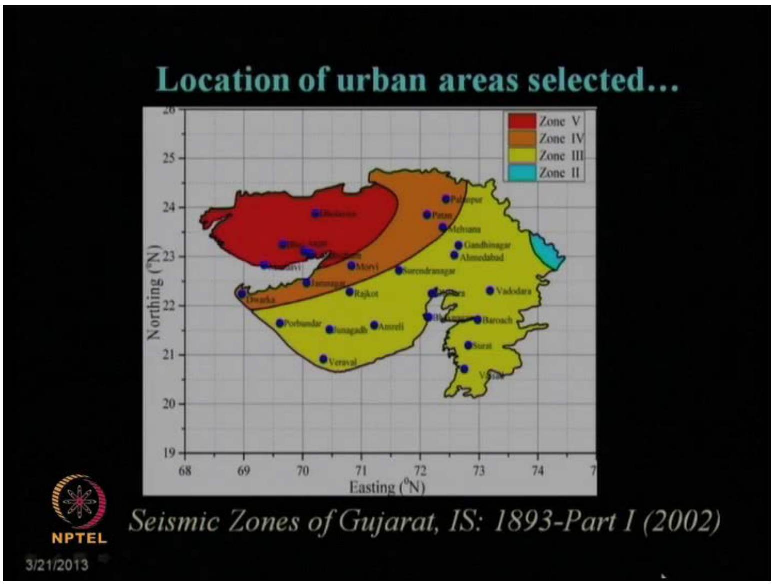


Now, this is the seismic zonation map of Gujarat state of India as per Indian seismic design code, IS: 1893-part 1 of 2002 version. That is the latest version still available. These are the four colour codes like red, orange, yellow and blue. These are showing four different zones: zone 5, zone 4, zone 3 and zone 2. Among these, zone 5 is the most vulnerable one; zone 4 is lesser than that; zone 3 is lesser than that; and, zone 2 is least vulnerable in the Gujarat region. So, you can see, Gujarat is the only state in India, which is having all the four zones as per our IS seismic design code 1893-part 1. That is another reason why the Gujarat state has been chosen. Another reason is 2001 Bhuj earthquake is very well-known, very damaging earthquake, which occurred in Bhuj region of Gujarat. And, it affected several other parts of the Gujarat as well. That is the reason why we want to find out the seismic hazard study, we want to do the seismic hazard study for the Gujarat region.

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Now, for any particular seismic hazard study, these are the various components as shown over here. For our particular case, seismic hazard study for Gujarat region, we need to get first the earthquake catalogue for that region, then regional seismicity parameters, sensitivity analysis. Using them, we can do the deterministic seismic hazard analysis and probabilistic seismic hazard analysis. And finally, we can do the site specific ground motion analysis for particular sites; which I will discuss in the next module of this course.

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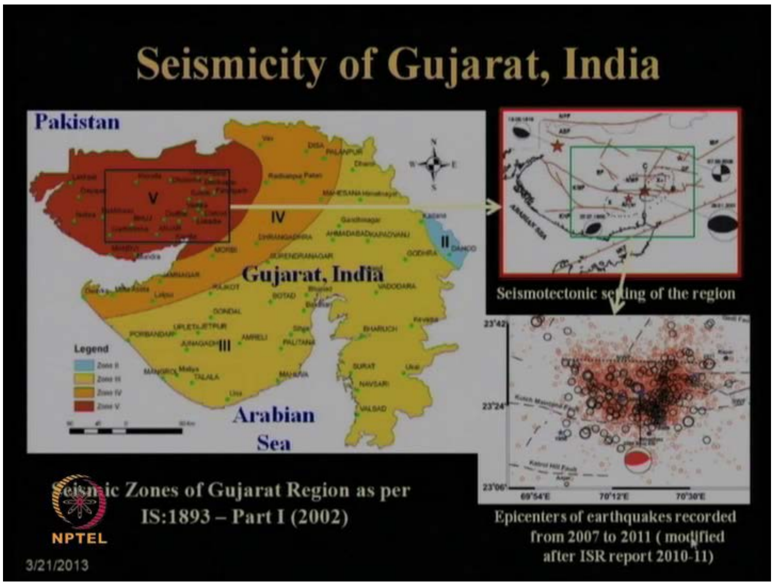

This is the seismic zonation of map of Gujarat as I have already explained. And, if we exaggerate this part – zone 5 of Gujarat region or Kachchh region, this is the seismotectonic setting of that region. And, if we further expand it, we can see, these are the points showing the epicentres of various earthquakes recorded during 2007 to 2011 as given in the ISR report 2010-11.

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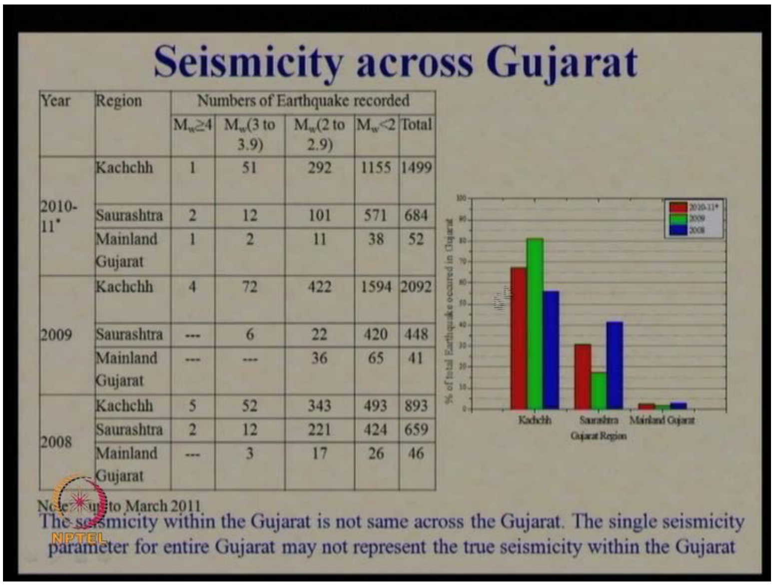


| Year | Region | Numbers of Earthquake recorded | | | | |
|---|---|---|---|---|---|---|
| | | $M_w \geq 4$ | $M_w$(3 to 3.9) | $M_w$(2 to 2.9) | $M_w<2$ | Total |
| 2010-11* | Kachchh | 1 | 51 | 292 | 1155 | 1499 |
| | Saurashtra | 2 | 12 | 101 | 571 | 684 |
| | Mainland Gujarat | 1 | 2 | 11 | 38 | 52 |
| 2009 | Kachchh | 4 | 72 | 422 | 1594 | 2092 |
| | Saurashtra | --- | 6 | 22 | 420 | 448 |
| | Mainland Gujarat | --- | --- | 36 | 65 | 41 |
| 2008 | Kachchh | 5 | 52 | 343 | 493 | 893 |
| | Saurashtra | 2 | 12 | 221 | 424 | 659 |
| | Mainland Gujarat | --- | 3 | 17 | 26 | 46 |

From various reliable data collection units or sources like USGS, IMD, ISR, we can collect year-wise number of occurrence of earthquake in different regions; like we have subdivided in three regions of Gujarat. This is the way. This shows typical values for 2008, so many earthquakes occurred; 2009 – so many earthquakes occurred. And, their magnitude scalings are also mentioned over here, which automatically shows Kachchh region, which is in zone 5, is experiencing more number of earthquakes than other two regions, which are in zone 4 and zone 3. Hence, considering a single seismicity event or single seismicity hazard study or single seismicity parameter for entire Gujarat, is not justifiable. We should do region-specific or area-specific study for Gujarat state. Now, we had also seen in our previous lecture, how the seismicity migrates from one region to another region.

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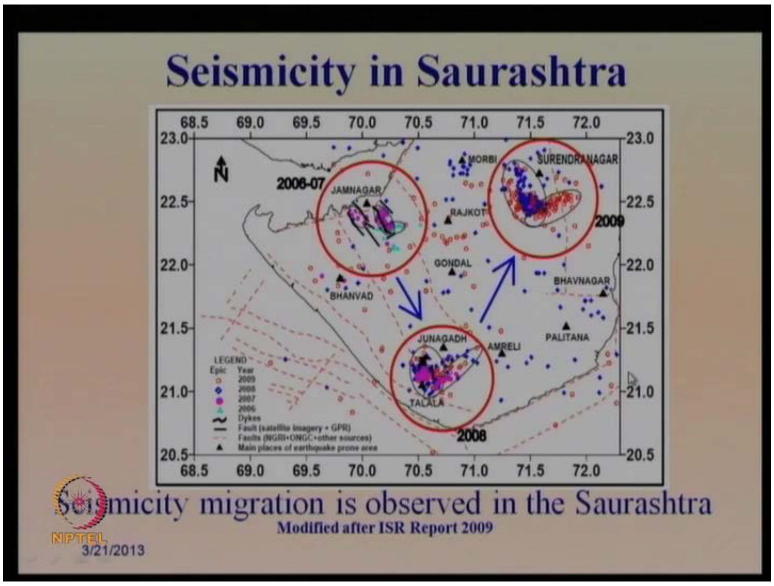


Let us look at here in this slide; let us take the example of seismicity in Saurashtra region of Gujarat. This is 2006 to 7. In Jamnagar area, these are the earthquakes occurred. Then, it shifted to more clustering in the Junagadh area. Then, it again migrated to Surendranagar area over the years 2008 and 2009. There is a way that, seismic events get migrated from one place to another place within a given region. That also needs to be considered when we are doing any seismic study for a particular region.

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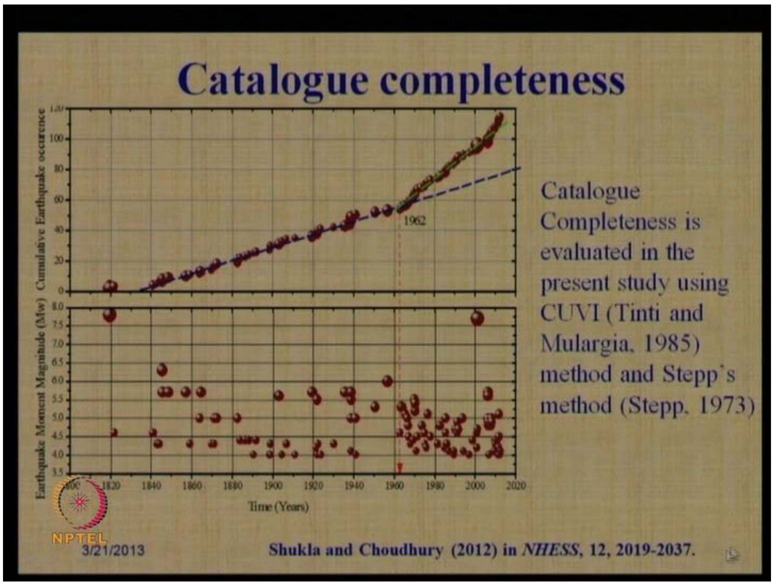

Next, we had also seen in our previous lecture, what is called earthquake catalogue and then catalogue – how to check the catalogue completeness. First earthquake catalogue is this picture, which is shown below over here – the bottom one, that is, earthquake magnitude M W scale. We have taken all magnitudes equal and above 4. So, that is the line you can see over here – magnitude of 4 and above. Recordings are available from 1820 to 2012. So, all data points have been collected. After doing that, we can either use the CUVI method as given by Tinti and Mulargia in 1985 and the Stepp's method 1973 to get this cumulative earthquake occurrence.

We can add these up and get the cumulative scale with respect to time and find out whether there is any change in the slope of that variation of occurrence of number of earthquakes. So, if there is a change in the slope, as we can see here, this is the blue line – slope of this initial portion; and, there is a slope of the green line in the recent past; there is a change in the slope at around this point. So, that point indicates, where this change has occurred; 1962 is the year we obtained for the present analysis; which I said, the details are available in the journal paper Shukla and Choudhury 2012 in Natural Hazards and Earth System Science journal. This is the volume number; this is the page number. One can go through that paper for the detail study on this earthquake catalogue generation and to check the catalogue completeness.

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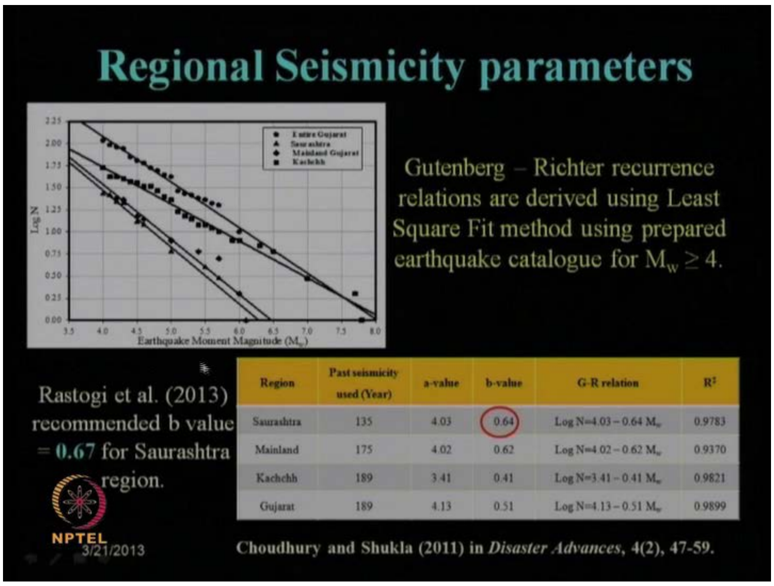

Now, let us continue in our today's lecture further next step – to check the regional seismicity parameters. So, to check that regional seismicity parameters, already we have this earthquake moment magnitude M W and we have already taken M W equals to 4 and above. So, that is why, you can see, all the points are 4 and above. And, what is log of N? In the log scale, N value, that is, the number of occurrence of that magnitude of earthquake. And, that we have subdivided into three regions, that is, Kachchh region, Saurashtra region and Mainland Gujarat. And then, we have found it out for entire Gujarat also by summing them up. By adding them, we have proposed it for entire Gujarat also. That is what we want to see, what is the variation of that Gutenberg-Richter parameter for individual area or individual region compared to entire Gujarat region and which region is having more effect or influence on entire Gujarat states seismicity events or recurrence of earthquake.

See if we look at this figure again, Gutenberg-Richter recurrence relations are derived using the least square fit method. So, least square fit method is used for preparing the earthquake catalogue of M W greater than or equals to 4. Now, if you see over here various regions like Saurashtra, Mainland, Kachchh and entire Gujarat, past seismicity recordings, which are used in terms of years; you can see over here for Saurashtra region, data of last 135 years have been used and that value till 2011 March as I have already mentioned; for Mainland Gujarat, last 175 years; for Kachchh region, 189 years. And hence, automatically, for entire Gujarat also, it is last 189 years of data set have been collected.

And, after plotting it in this fashion, what we can get? The intercept a value and the slope of this line b value. So, Gutenberg-Richter relationship if we propose in this form that, log of N equals to that a minus b M W – that will give us this equation – individual equation for individual region; like for Saurashtra, this region, because you can see, if we look minutely, this is for Kachchh region, that is, square shape, dark dots. So, this is for Kachchh region if we look at here. So, this slope and this a value will give for the Kachchh region. So, for Kachchh region, the equation is this one. Whereas, for Mainland Gujarat, it is this; for Saurashtra, it is this.

And, for entire Gujarat, by summing all these data points, we get this line, which is giving us the Gutenberg-Richter relationship for entire Gujarat like this; and, corresponding R square value when you do the best fit curve as we already know. That is the standard way we find out whether it is a good estimation or not. You can see, it is more than 0.95 in all the three cases like Saurashtra, Kachchh and entire Gujarat. But, it is little less than 0.95 for Mainland Gujarat. So, the detail study about this regional seismicity parameters of Gujarat is available in the journal paper Choudhury and Shukla 2011 in the journal – Disaster Advances, volume 4, issue 2, page number 47 to 59. So, if one wants to know the details about this study, he or she can refer to this journal paper for further details.

Now, let us look at here. Let us highlight this value over here. If somebody wants to compare or validate this value with other researchers result, what we have done, our publication came in the year 2011 as I have already shown over here. Look at the b value. What we have proposed for Saurashtra region, 0.64. And, the latest finding by Rastogi et al. of 2013 publication, that is, after our publication, they recommended, they also did similar analysis for Saurashtra region only; and, they recommended the b value of 0.67, which is pretty close to our value. The difference can be always due to the model, which we have used; like least square fit method we have used. Also, it depends on how many data points they have used; from which year they have considered. All these are the reasons for the change in the value. But, still you can see for a particular region, this value should not vary too much among researchers. If it varies, a particular reason needs to be obtained. So, here you can see a kind of a validation of Rastogi's result with our results of 0.64, which we have proposed in 2011.

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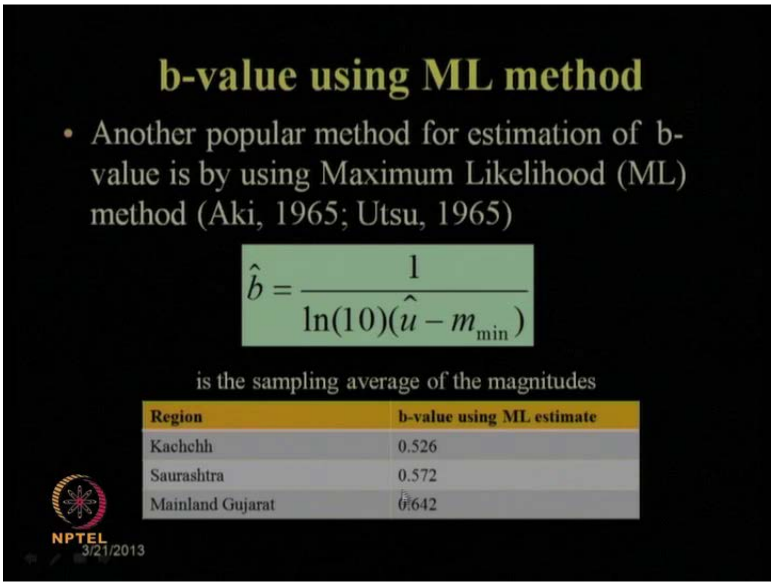

Now, this b value using another method of maximum likelihood; if we want to find out using maximum likelihood method, which is proposed by Aki in 1965 and Utsu again in 1965, it is another popular method to find out or to estimate the beta value. One is least square fit method, which gives us beta value like this; another method, which we are now mentioning is maximum likelihood method. In that case, how we compute this b value? This is the equation – log of u minus m minimum; that is, it depends on what is the minimum threshold value we are using, is the sampling average of the magnitude. And, region-specific b value using this maximum likelihood methods are coming; like for Kachchh region, 0.526; for Saurashtra region, 0.572; and, for Mainland Gujarat, 0.642. You can see, at maximum likelihood, methods are giving the higher values of b compared to this least square method.

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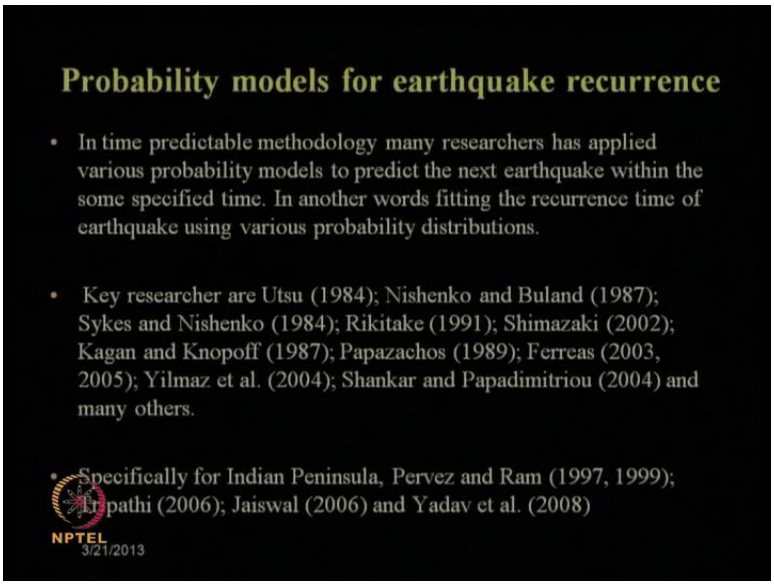


Now, probability models, which can be used for earthquake recurrence, are discussed over here. In time predictable methodology, many researchers have applied various probability models to predict the next earthquake within the specified time; like in the beginning of this course, I have already mentioned, whether we can predict the earthquake; scientifically we said, no, we cannot say exact date, we cannot say exact time; but, yes, in the sense of probability, we can say chances of occurrence of probability of this much percentage within this year band; that kind of estimation we can provide based on the historical or earlier earthquake data points and seismicity events and parameters involved. So, this is how we are now going to use the various probability models, so that we can propose the recurrence time of earthquake using various probability distributions at a particular region; which may be helpful for NGOs, government organizations, designers, practitioners, everybody to understand that, in this region, there is a chance in this year band or in this time scale that, earthquake of this magnitude may occur. So, proper measure may be taken.

The key researchers you can see in this slide, who used various probability models to predict the next earthquake in a specific band of time; it is not an exact time, but band of time like Utsu in 1984, Nishenko and Buland in 1987, Sykes and Nishenko in 1984, Rikitake in 1991, Shimazaki in 2002, Kagan and Knopoff in 1987, and several other researchers as you can see listed over here. And specifically, for Indian Peninsula region, where this Gujarat state also comes from, that is, Peninsula region of India, the central part of India like Pervez and Ram in 1997 and 1999; they also proposed various probability models to predict the occurrence of next earthquake; Tripathi in 2006, Jaiswal in 2006, Yadav et al. 2008. So, these are the researchers, who proposed or used various probability models for earthquake recurrence estimation for Gujarat.

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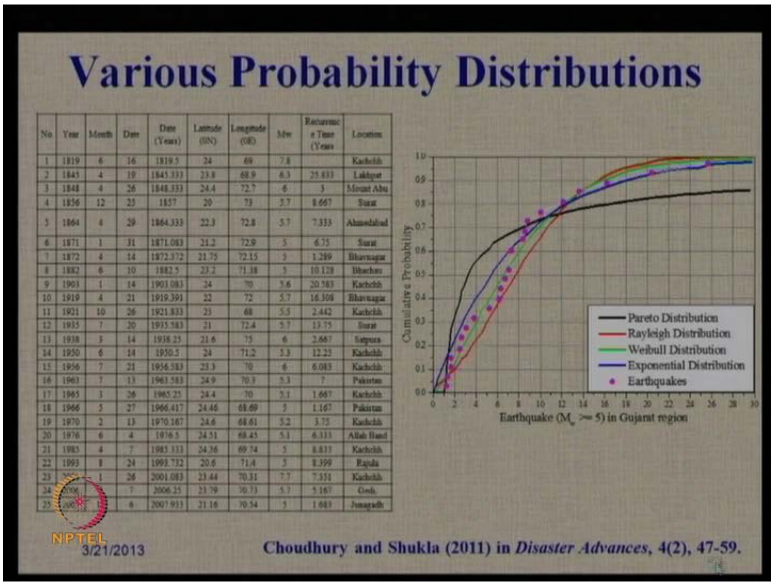


Let us look at the various probability distributions. You can see from this curve, various lines are proposed; you can see, this dots are showing the earthquakes occurred in the Gujarat region with magnitude greater than equals to 5. In this model, we have selected magnitude greater than equals to 5. And, cumulative probability we obtained using four different probability models. If you look at here, what are the various probability models? Pareto probability distribution model, Rayleigh distribution model, Weibull distribution model and exponential distribution model. These are four seismicity model parameters, which are used to estimate the probability of distribution. How it has been done?

Let us look at this table. These are the data points; various numbers; occurrence of these events year wise. Remember, we have taken magnitude more than or equals to 5. So, that is why, you will see M W equals to or greater than 5 listed over here. Their occurrence in terms of year, in terms of their month and date; that is exact occurrence dates when those earthquakes occurred. And, those dates can be expressed in year format like this in decimal considering month and date; where these earthquakes occurred; their latitude and longitude. And, recurrence time in years we can easily find it out using Gutenberg-Richter relationship. And, where this earthquake occurs we have found out in terms of location like Kachchh region or whether a particular name has been given, whether it comes to Saurashtra region; those identifications also we did. So, this study in details you can again find it out in the journal paper by Choudhury and Shukla in 2011 in the same journal – Disaster Advances, issue 4, number 2 – volume 4, number 2, page number 47 to 59.

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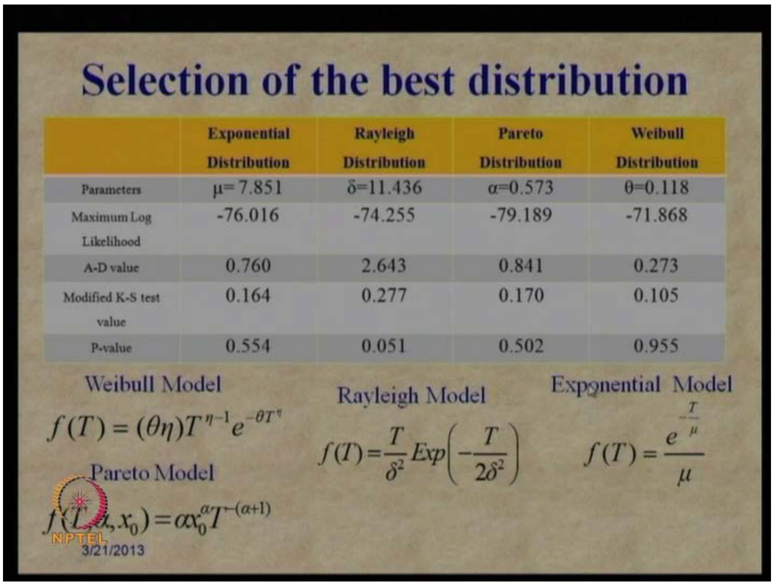

Let us look at the selection of the best distribution – which distribution is the best one and which one we can select out of this four different distributions. So, these are the basic models or basic equations of this probability distribution; like Weibull model is expressed by this function; Rayleigh model is expressed like this function; exponential model is exposed by this function; and, Pareto model is expressed by this function. But, details – you can refer to any probability book for details of this individual probability model; which I am not going to discuss in this course. Now, using these various probability mathematical models, we can automatically find out based on maximum log likelihood values, individual values – their mu, delta, alpha, theta – whatever parameters are involved in individual cases and their p values or probability of occurrences, etcetera. You can see from this graph also, which one is giving a better result. So, like that, we can select a better model from this probability distribution of various seismicity model parameters, which are involved over here.

Now, next we need to see among these four seismicity models, which one is the best for this given set of data of earthquake. Let us go back once again in this data set. When we were calculating the values, you can see over here, the cumulative probability of their occurrence with magnitude scale of more than or equals to 5 – we have plot it over here. These are the earthquake data points as I have already mentioned and 4 seismicity model parameters. Now, among them, which one is the closest one? If we see Weibull model, that is, the green coloured curve is the best average, which is going through this actual dots of this earthquake occurrence. So, Weibull model is one of the best model. Next, another better model is exponential distribution, that is, the blue coloured line. If you look at that, that is the next better one after Weibull distribution. Like that, you have to identify, which seismicity model is acting well for our satisfying well for the given set of data of earthquake catalogue.

Now, in this column; if we relook at this column, this says recurrence time in years; recurrence means starting from this year 1819 data up to the 2007 data, what we are considered in this paper, from the gap between 1819 and 1845 event, is something about 25.833 years; that is, if you deduct this year, month and date from this year, date and month, you will get this value in terms of unit of year. Similarly, for all other things as you can see over here; that means magnitude of 5 earthquake or more than that occurred in the interval of these many years. These are actual data.

Now, based on this actual bit data, we are now using these seismicity model parameters to extrapolate it; that is the point. In this case, what we are planning? To make use of this known data points for further extrapolation, so that this extrapolated data can give us – based on these probability model parameters, what can be the next expected range of occurrence of magnitude more than 5 earthquakes at that location, at that region; that is what we want to find out. So, that is why, this data set is very important. So, last one when it has been recorded and considered in our paper of this 2011 – that is, 2007 earthquake data, which occurred on 6th of November in 2007.

As you can see over here that, magnitude was 5; it occurred at Junagadh area of Gujarat. So, the difference between the previous occurrence of earthquake date and this date is about 1.683 years; you can easily find it out. This in terms of years – 2007 – 0.933 minus 2006 – 0.25; that will give you 1.683. So, now, we want to extrapolate this using these seismicity model parameters, so that when the next earthquake is expected in Gujarat region or the specific region of Gujarat like in Kachchh region or Saurashtra region or Mainland Gujarat after 2007, which will have a magnitude of 5 or more than that. So, that is how we are going to use these seismicity model parameters. And, we have seen which distribution is best for current data set; that also we have mentioned.

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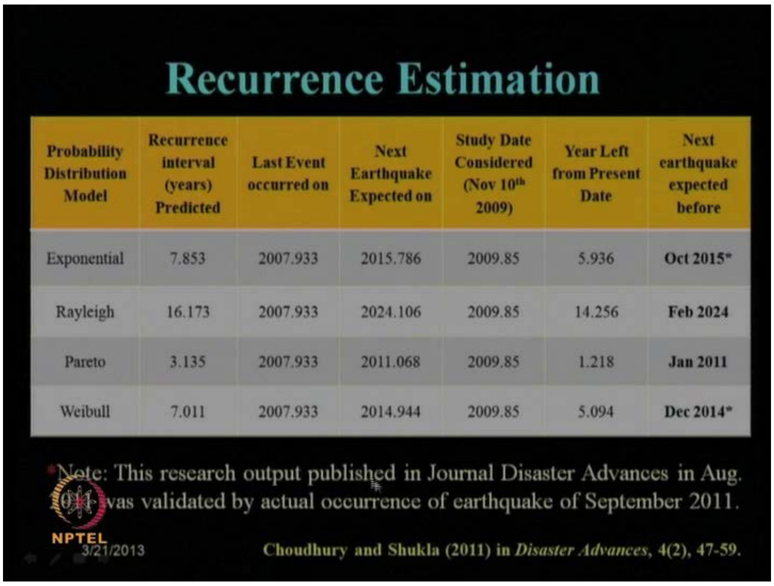


| Probability Distribution Model | Recurrence interval (years) Predicted | Last Event occurred on | Next Earthquake Expected on | Study Date Considered (Nov 10th 2009) | Year Left from Present Date | Next earthquake expected before |
|---|---|---|---|---|---|---|
| Exponential | 7.853 | 2007.933 | 2015.786 | 2009.85 | 5.936 | Oct 2015* |
| Rayleigh | 16.173 | 2007.933 | 2024.106 | 2009.85 | 14.256 | Feb 2024 |
| Pareto | 3.135 | 2007.933 | 2011.068 | 2009.85 | 1.218 | Jan 2011 |
| Weibull | 7.011 | 2007.933 | 2014.944 | 2009.85 | 5.094 | Dec 2014* |



This is the recurrence estimation – how we are doing now the estimation. If you use these four different probability distribution models: exponential model, Rayleigh model

Pareto model and Weibull distribution model, recurrence interval you can predict; that is, after extrapolating, you can calculate from that behaviour from the equations that, these are the next recurrence interval as per exponential model. It says after that 2007 November, next one will occur 7.853 year; whereas, as per Rayleigh model, it says after 16.173 years; as per Pareto model, it says 3.135 years; whereas, as per Weibull model, it gives 7.011 years. Now, what we have mentioned, for the given data set, which models are better or good models – exponential and Weibull model. So, the last event that occurred on – that 6th of November 2007, which comes out to be in the scale of year 2007.933. So, next expected earthquake will be this value plus what is your predicted value – that you can add up; and, you will get in the year unit, what is the next expected earthquake.

Now, the study date considered when this study was considered; that is, on 10 of November 2009, which comes in year scale this one; that is, when we started communicating the paper to this journal. So, year left from the present date. Present date is 10th November 2009 – we considered as our present date when we communicated the paper. So, the difference between this to this is so many years. So, as per exponential model, after 5.936 years, there will an earthquake magnitude 5 or more in the Gujarat region. Whereas, as per Rayleigh model, it is after 14.256 years; whereas, as per Pareto model, after 1.218 years; whereas as per Weibull model, it is after 5.094 years; which if we add up to this value, we will get the next earthquake expected before these many years. So, October 2015 as per exponential model; as per Rayleigh model, before February 2024; as per Pareto model, before 2011 January. Remember, our study date is 2009. So, that time, we got from Pareto model; it is giving before January 2011, there will be an earthquake magnitude of 5 or above. As per Weibull model, the value comes out to be the next earthquake probability of occurrences before 2014 December.

Now, this paper after communicating, this got published in 2011. You can see over here, this research output was published in the journal – Disaster Advances in the month of August 2011 issue. And, it was actually validated by a real earthquake, which occurred more than 5 magnitude in September 2011 in this locality. So, that again proves the actual validity of exponential and Weibull model, which are better model; whereas, Pareto model is very unrealistic or I should say, it is over estimating; that is, it is predicting that, it will occur very soon, but it has not happened. Whereas, a Rayleigh model is towards an unsafe side, because it is predicting that, it will occur far later. So, compared to these two models, for the given set of earthquake catalogue for Gujarat, exponential and Weibull models are much better, which we have validated through mathematical proof in the presentation as well as through actual validation of the earthquake, which occurred. Though people may say, this is not that scientific, but the occurrence of calculation based on probability model is really scientific. So, we can give a band. We can never give this exact date of September 2011; that I want to again highlight here; we are not going to predict the earthquake date; we are only going to say the chances or probability of occurrence of earthquake in a span or band. That is what has been proposed over here, which has been validated.

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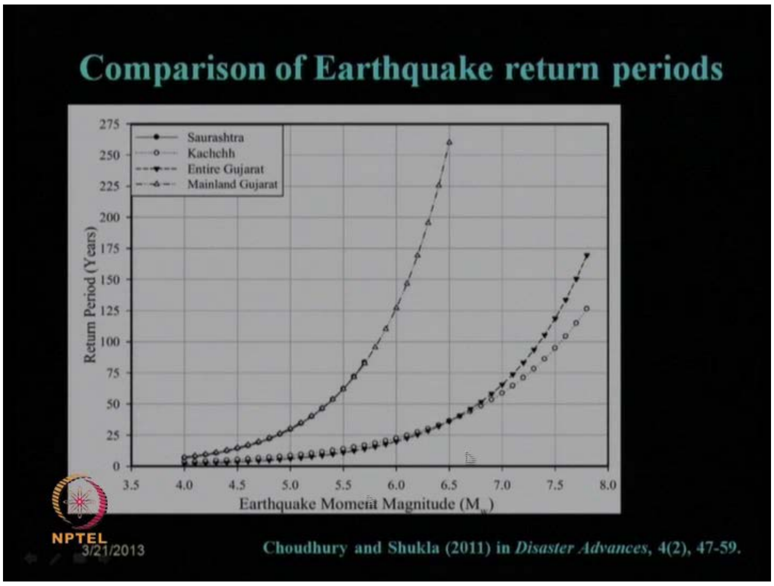


Now, let us compare this various earthquake return periods for different regions of Gujarat; like return period in the year unit; and, this is the earthquake magnitude M W above and equal to 4, but we have taken initially. So, for Saurashtra region, Kachchh region, entire Gujarat and Mainland Gujarat, graphs have been showed over here. The detail about this study can again be obtained in this journal paper.

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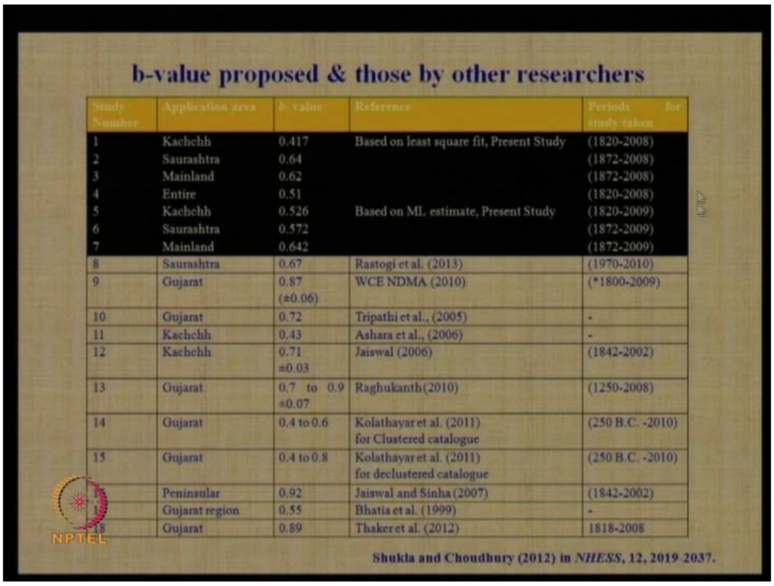


| Study Number | Application area | b- value | Reference | Periods for study taken |
|---|---|---|---|---|
| 1 | Kachchh | 0.417 | Based on least square fit, Present Study | (1820-2008) |
| 2 | Saurashtra | 0.64 | | (1872-2008) |
| 3 | Mainland | 0.62 | | (1872-2008) |
| 4 | Entire | 0.51 | | (1820-2008) |
| 5 | Kachchh | 0.526 | Based on ML estimate, Present Study | (1820-2009) |
| 6 | Saurashtra | 0.572 | | (1872-2009) |
| 7 | Mainland | 0.642 | | (1872-2009) |
| 8 | Saurashtra | 0.67 | Rastogi et al. (2013) | (1970-2010) |
| 9 | Gujarat | 0.87 (±0.06) | WCE NDMA (2010) | (*1800-2009) |
| 10 | Gujarat | 0.72 | Tripathi et al., (2005) | - |
| 11 | Kachchh | 0.43 | Ashara et al., (2006) | - |
| 12 | Kachchh | 0.71 ±0.03 | Jaiswal (2006) | (1842-2002) |
| 13 | Gujarat | 0.7 to 0.9 ±0.07 | Raghukanth(2010) | (1250-2008) |
| 14 | Gujarat | 0.4 to 0.6 | Kolathayar et al. (2011) for Clustered catalogue | (250 B.C. -2010) |
| 15 | Gujarat | 0.4 to 0.8 | Kolathayar et al. (2011) for declustered catalogue | (250 B.C. -2010) |
| [illegible] | Peninsular | 0.92 | Jaiswal and Sinha (2007) | (1842-2002) |
| [illegible] | Gujarat region | 0.55 | Bhatia et al. (1999) | - |
| 18 | Gujarat | 0.89 | Thaker et al. (2012) | 1818-2008 |

Now, let us come to the b value, what is proposed by the present method and similar b values proposed by other researchers for the same region. Let us compare that, how our b values proposed differ or validate or matches with other researchers findings for this Gujarat region; and, what is the study period or earthquake recurrence or earthquake data points have been taken for which area. So, this portion, which is black shaded – that is the present results, that is, present study we obtain this beta values. As already I have discussed, there are two methods we have used to obtain this b value: one is least square fit method – LSF method; and, another one is maximum likelihood method. So, as per least square fit method, for Kachchh region, we have seen b value we obtain – 0.417; for Saurashtra, we got it as 0.64; that we have already compared in that slide with respect to Rastogi et al., 2013; latest finding, which is 0.67 for Saurashtra. So, you can compare these two values, which compares pretty well. For Mainland Gujarat, 0.62; and, for entire Gujarat, 0.51. So, these four are obtained using least square fit method. And, the study period taken, that is, the earthquake data points taken between 1820 to 2008. For these regions for Saurashtra and Mainland, it is 1872 to 2008. Whereas, for maximum likelihood method, the same study; the Kachchh region, we got b value as 0.526; for Saurashtra region, 0.572; and, for mainland Gujarat, it is 0.642. For the same set of data set, only one extra year we have taken, because this analysis was done after this least square fit method. That is why one more year of earthquake data points have been taken.

Now, if we compare our results of b values with respect to the other researchers results, who have calculated for the same region, Gujarat region; like as I have already mentioned, Rastogi et al., 2013 value for Saurashtra region matches very close or very well with our study; whereas, WCE NDMA report of 2010 – that gives for entire Gujarat. Remember, this value is given for entire Gujarat; they have not subdivided Gujarat into different seismic zones, what it should have been, as I have already given the explanation. So, they have suggested 0.87 as the b value, which is pretty on the higher side as you can see with a plus minus of 0.06. And, they mention that, they used the earthquake data from 1800 to 2009 for the analysis; whereas, Tripathi et al. in 2005 proposed again for entire Gujarat, the value of b as 0.72; whereas, for Kachchh region, Ashara et al. in 2006 proposed the b value as 0.43, which is again very close to our observation of 0.417.

Now, Jaiswal in 2006 proposed for Kachchh region, the value of b value – 0.71 with plus minus error of 0.03; and, taken range of data between 1842 to 2002. So, obviously, as you can see, as the data set point or this year increasing or changing, there is always a chance that, the b value will keep on changing as we have already explained it earlier. Raghukanth in 2010 for entire Gujarat – once again, it is for entire Gujarat, the value has proposed between a range 0.7 to 0.9 with an error factor of 0.07 when they considered the earthquake between 1250 to 2008. And, Kolathayar et al. in 2011 – they proposed for entire Gujarat once again, two ranges of values: one for the clustered catalogue – I have already mentioned, what is clustering; and, another is de-clustered catalogue. Without doing the clustering of the earthquake data points considered, they are ranges they have mentioned for b values 0.4 to 0.6 or 0.4 to 0.8. And, they mentioned in their paper that, they considered between 250 before Christ to 2010 earthquake data; whereas, Jaiswal and Sinha in 2007 for entire peninsular India. Remember, this is not only for Gujarat region; this is for entire peninsular. So, obviously, Madhya Pradesh, Maharashtra – all these comes under this peninsular region. So, their value is again very high – 0.92. And, when they considered the earthquake? Between 1842 to 2002.

Bhatia et al. in 1999 for entire Gujarat region proposed the b value of 0.55, which is again close to our proposed value of b as you can see over here. And recently, Thaker et al., 2012 proposed for entire Gujarat again b value, which is very much on the higher side – 0.89. And, they considered the data set between 1818 to 2008. So, all these details one can find it out in this journal paper of Natural Hazards and Earth System Sciences.

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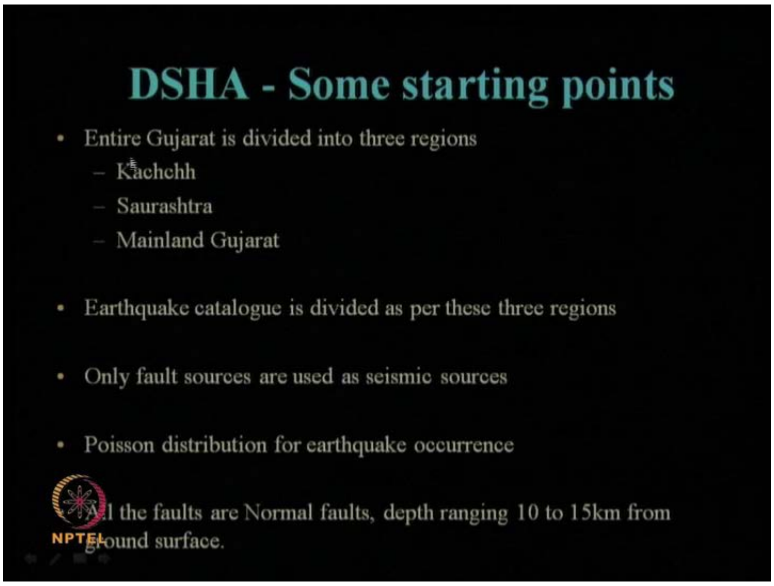


Now, let us do – once this earthquake data clustering and recurrence period everything we obtained, next step is to carry out the hazard analysis. So, to do the seismic hazard analysis, as we know, first, we will do the deterministic seismic hazard analysis and then we will take care of probabilistic seismic hazard analysis. So, for DSHA, let us start with few salient points to carry out the deterministic seismic hazard analysis for entire Gujarat. So, already we mentioned, entire Gujarat has been subdivided into three regions like Kachchh, Saurashtra and Mainland Gujarat. Earthquake catalogue is also divided as per these three regions, so that we can get different regions, different DSHA values.

And, only fault sources are used as seismic sources; that is, no other plane boundaries were been considered; only the fault information has been considered for calculating this DSHA. Poisson distribution for earthquake occurrence is considered. And, all the faults are assumed as normal faults. This is an assumption in the present study; that is, when it is not known, one can grossly assume like this; but, if the fault characteristics for all the faults – it is known, accordingly, the fault whether it is a normal fault, reverse fault, strike slip fault – all these things should be considered. So, in the present study, it has been considered all as normal faults and their depth are ranging between 10 to 15 kilometers from the ground surface; which essentially means these are shallow earthquake sources.

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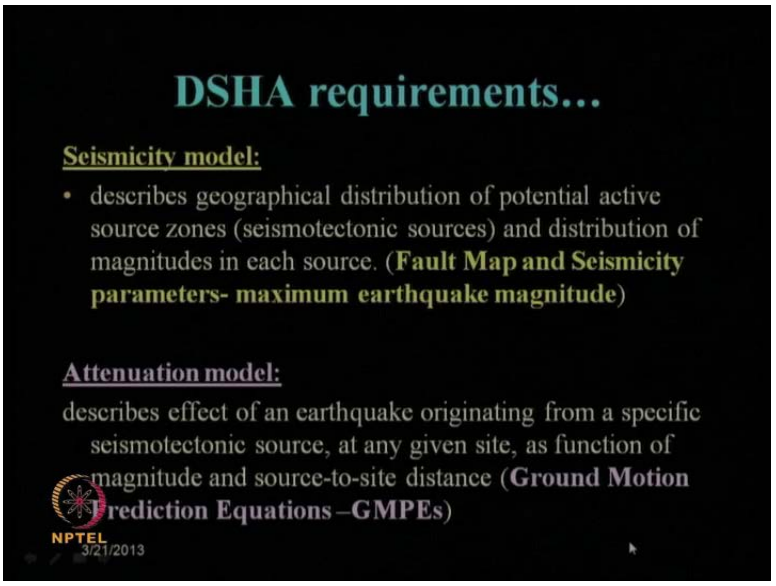


Now, what are the requirements for carrying out this DSHA? First one is seismicity model. We have to first select which seismicity model we are going to use. So, it describes the geographical distribution of potential active source zones like seismotectonic sources and distribution of magnitude in each of the sources. So, that takes care of the fault map and seismicity parameters like maximum earthquake magnitude by using proper seismicity model. Whereas, which attenuation model has to be used? As I have already mentioned, there can be several attenuation relationships. So, attenuation relation model, which describes effect of an earthquake originating from a specific seismotectonic source at any given site as function of the magnitude and source to site distance. So, it has to be function of both these two, not only function of magnitude or only function of distance. So, that automatically means we have to take care of ground motion prediction equations. As I have already mentioned, GMPEs in short we call. These have to be identified.

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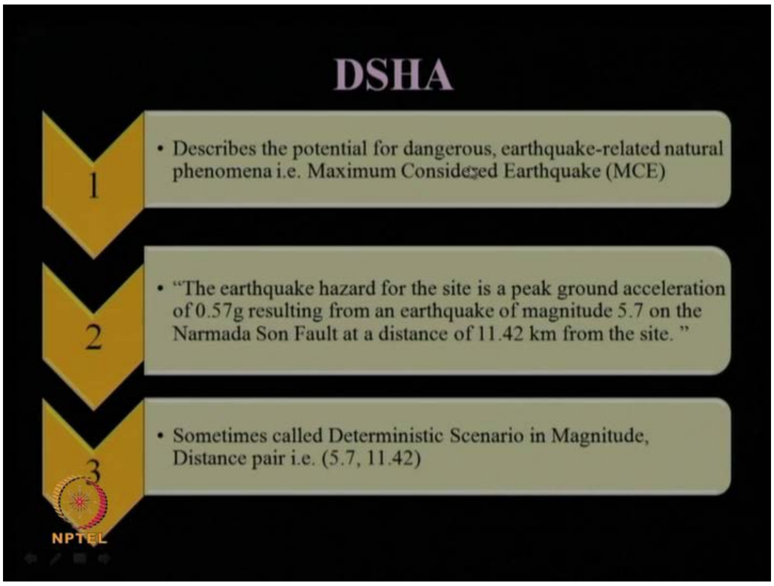


For DSHA – if we carry out the DSHA, it describes the potential for dangerous earthquake related natural phenomenon, that is, the maximum credible earthquake or maximum considered earthquake; maximum credible earthquake we call as MCE – that is the earthquake, which we consider for our DSHA or deterministic seismic hazard analysis. Already I have mentioned this in the beginning of DSHA. So, the earthquake hazard for the site is a peak ground acceleration of let us say 0.57 g, which is resulting from an earthquake magnitude of say 5.7 on a particular fault, which has been obtained say Narmada Son fault at a distance of 11.42 kilometer from the site. So, in other words, as we mention the final result, sometimes, the deterministic scenario we call it as magnitude and distance pair in this form; that is, 5.7 and 11.42. That shows that this is the magnitude – maximum magnitude is going to occur at a site, which is located 11.42 kilometer from the Narmada Son fault. This is just for one particular site, remember. So, this way, we can mention the DSHA result for any other site in the entire Gujarat region.

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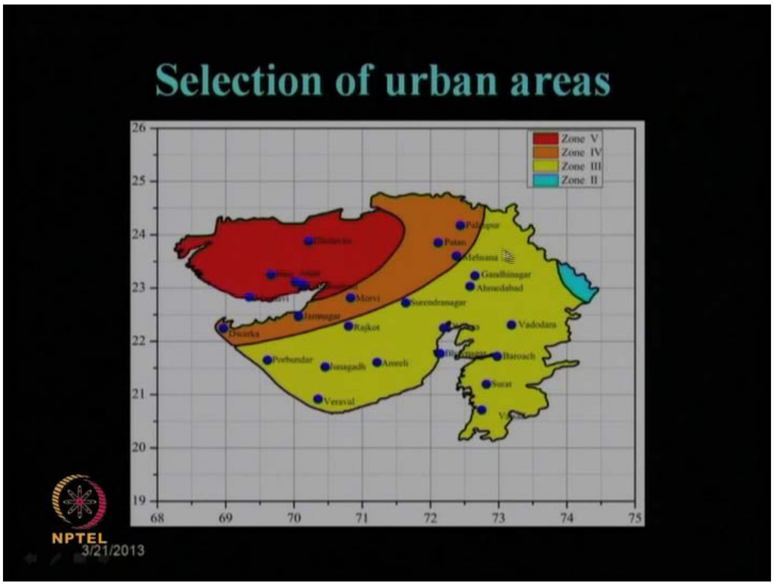


Now, let us see, how we apply this for all the selected 25 urban areas or urban cities distributed in these three major seismic zones of Gujarat. Next is to study the fault map of the entire region, because unless we have the complete picture of the fault map, we cannot start our seismic hazard calculation.

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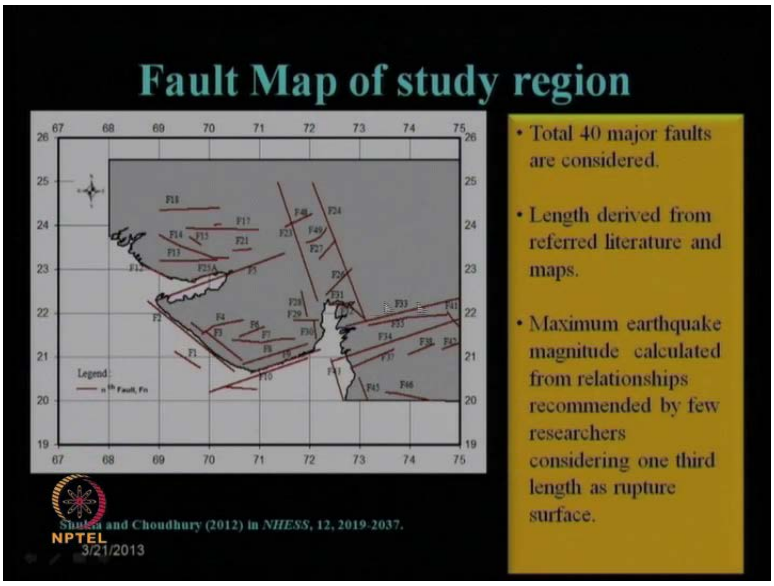


This slide shows us, how the faults have been mapped in the entire Gujarat region. You can see, there are total about more than 40 faults; you can see the numbers over here – fault numbers – this F 18, F 48, F 49, F 23, F 5 – these indicate the fault numbers. This n-th fault is F n. So, among all these faults, only total 40 major faults are considered in the analysis. And, length derived from referred literature and maps; that is, from the available literature, this length of each fault has been obtained; or, from the seismologist or geologist, you need to collect this fault data when you are starting your seismic hazard analysis. Now, maximum earthquake magnitude, which is calculated from relationships recommended by previous researchers, consider that, one-third length of the rupture surface needs to be taken care of when we are doing the calculation; that means suppose for F 24, this is the actual length; one-third of its length will be actually taken when we are doing the hazard calculation.

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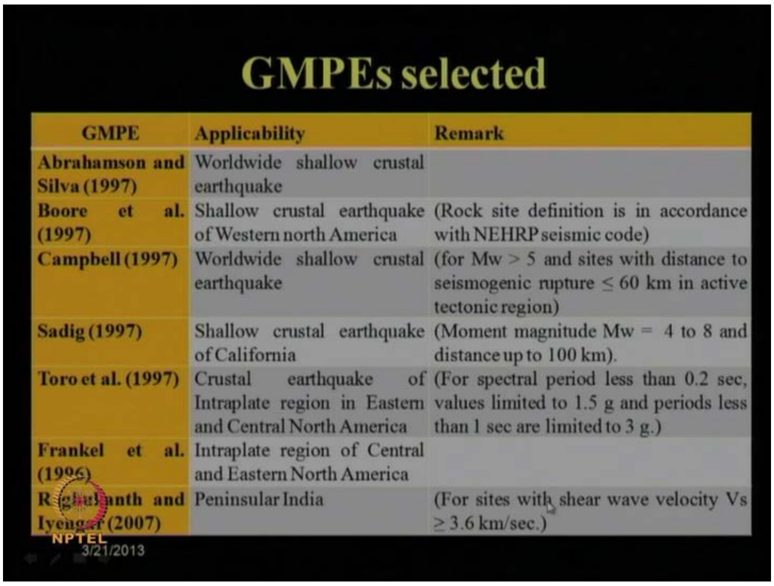


| GMPE | Applicability | Remark |
|---|---|---|
| Abrahamson and Silva (1997) | Worldwide shallow crustal earthquake | |
| Boore et al. (1997) | Shallow crustal earthquake of Western north America | (Rock site definition is in accordance with NEHRP seismic code) |
| Campbell (1997) | Worldwide shallow crustal earthquake | (for Mw > 5 and sites with distance to seismogenic rupture ≤ 60 km in active tectonic region) |
| Sadig (1997) | Shallow crustal earthquake of California | (Moment magnitude Mw = 4 to 8 and distance up to 100 km). |
| Toro et al. (1997) | Crustal earthquake of Intraplate region in Eastern and Central North America | (For spectral period less than 0.2 sec, values limited to 1.5 g and periods less than 1 sec are limited to 3 g.) |
| Frankel et al. (1996) | Intraplate region of Central and Eastern North America | |
| Raghukanth and Iyengar (2007) | Peninsular India | (For sites with shear wave velocity Vs ≥ 3.6 km/sec.) |

Now, let us see, which GMPEs we need to select to do the seismic hazard analysis. So, these are the various GMPEs. There are seven ground motion prediction equations, are mentioned over here – Abrahamson and Silva, 1997; Boore et al., 1997; Campbell, 1997; Sadig, 1997; Toro et al., 1997; Frankel et al., 1996; and, Raghukanth and Iyengar, 2007. So, among these seven ground motion prediction equations or attenuation relationships, which we are now planning to use for our seismic hazard analysis, only the last one is for peninsular India; remaining all other from worldwide data, not from Indian data; like from the Abrahamson and Silva's data, it is worldwide shallow crustal earthquake; whereas, for Boore et al.'s attenuation relationship is valid for shallow crustal earthquake of western north America region; for Campbell, it is worldwide shallow earthquake data.

And, this is valid; it is also mentioned for M W greater than 5 and sites with distance to seismogenic rupture within the 60 kilometer in the active tectonic region.

Whereas, Sadig data is valid for shallow crustal earthquake of California region, where moment magnitude between 4 to 8 are considered and distance within 100 kilometers, because we have already seen, when we discussed in detail, various attenuation relationships about their validity or limit. So, these are the limits. Toro et al. mentioned their attenuation relationship or GMPEs are for crustal earthquake of intraplate region in eastern and central North America; and, for spectral period less than 0.2 second values limited to 1.5 g and periods less than 1 seconds are limited to 3 g. Whereas, Frankel et al. data is valid for intraplate region of central and eastern North America; whereas, Raghukanth and Iyengar's attenuation relationship of 2007 or GMPEs of 2007 is valid for peninsular India, which is logically should be more correct to use for doing the seismic hazard analysis for Gujarat region, which is also in the peninsular India region. But, the validation or the limit for that GMPE is for sites, which shear wave velocity of V s greater than or equals to 3.6 kilo meter per second. So, that is the crustal velocity.

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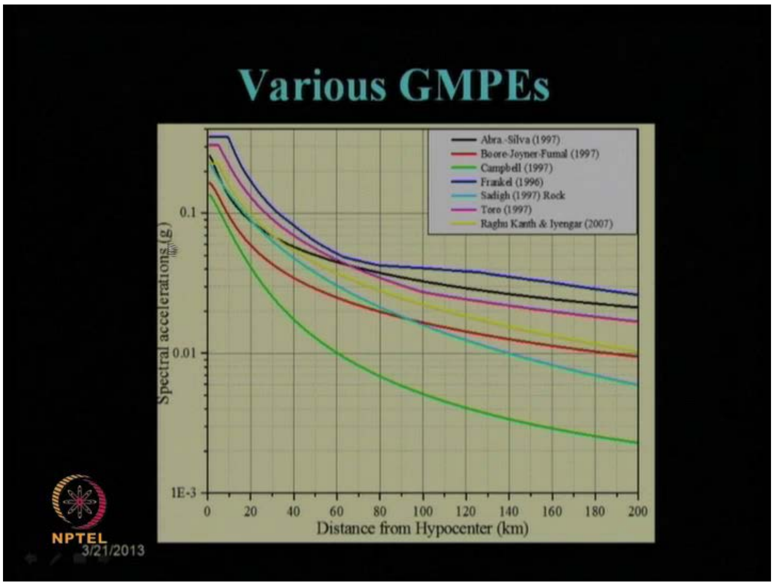


Let us now look at these various GMPEs, what we have already mentioned, these seven GMPEs – they are now represented in the form of spectral acceleration in y-axis in terms of g. So, this is 0.1 g like that. And, x axis is distance from the hypocenter in kilometer unit. So, these are various attenuation relationships – seven attenuation relationships as proposed by these seven attenuation equations or ground motion prediction equations. Now, these results we will be going to use for our deterministic seismic hazard analysis. We will continue further in the next lecture on this DSHA for Gujarat region.