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IIC

Addressing Earthquake Risk in India

Proceedings of the Workshop on 'Addressing Earthquake Risk in India', held on 12 April 2023 at India International Centre

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The views expressed in this publication are solely those of the author and not of the India International Centre.

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Addressing Earthquake Risk in India

CONCEPT

Earthquakes are among the major hazards in India. The areas vulnerable to earthquakes are the plate boundary regions, e.g., Himalaya, Andaman & Nicobar Islands, northeast India and some of the regions in plate interior, e.g., Kachchh. Unlike other hazards such as cyclones, tsunamis or floods, where forecasts for their likely arrival are made, earthquakes strike without any warning. The current scientific knowledge is not sufficient to predict earthquakes. Hence it is necessary to assess our vulnerability to impacts of earthquakes and ensure preparedness to mitigate their effects on society. The development of such resilience can certainly help to avoid disasters. This issue has to be addressed at three levels:

a) earth system level or status of knowledge about earthquake generation processes and it's hazard potential;

b) social system level or response mechanism, role of government, private sector and non-government organisations, and infrastructure development; and

c) human system level or consciousness, awareness and readiness of people towards an earthquake hazard.

Today, in our country, monitoring of earthquakes, estimating earthquake parameters, and disseminating this information has become very efficient. All the earthquake monitoring systems have been networked to provide data in the shortest possible time. It is well known that earthquakes do not kill people; poorly designed and built buildings do. The building codes designed to minimise the impact of earthquakes depend on potential risks from hazards. Microzonation maps, useful in assessing seismic hazards and risk potential, seismic response of engineering structures and land-use planning maps, have been prepared for many cities.

During the last two decades, the response mechanism has been made very efficient. The National Disaster Management Authority (NDMA) and National Disaster Response Force (NDRF) along with the central and state governments have been provided necessary relief and rescue.

Still, there are certain gaps and many questions to be addressed.

a) Is there is a possibility of a large earthquake in Himalaya, especially in Uttarakhand and Himachal Pradesh, in the near future? If so, what actions do we need to take?

b) How do we use our current understanding acquired through research in objective hazard assessment? What are the shortcomings, what should, can and needs to be done?

c) How can microzonation maps be integrated in urban planning? What are the impediments?

d) Are there any precursors to earthquakes? What is the status of precursor research in the country?

e) Is early warning of earthquakes possible and can it be safely implemented? What is the current status of our knowledge about earthquake warning systems and their effectiveness?

f) What are triggered earthquakes? What is the state of knowledge and can they be avoided?

g) What is the status of the response mechanism (organisational strength) at the central, state and local levels? How effective is communication with people?

h) What is the status for providing relief and rescue in an earthquake event? What are the preparations for providing medical care, shelter and food?

i) What kind of public outreach programmes are required? How can we sensitise people, especially children?

To discuss these issues and to provide possible solutions, a Workshop was organiaed on 12 April 2023 at the India International Centre, New Delhi. What follows are the presentations made by experts in the field.

INTRODUCTION

Shyam Saran, President, IIC, Delhi

This workshop on addressing earthquake risk in India is extremely important as it is perhaps one of the most underrated risks in this country. We do have today much better institutional as well as scientific capabilities to assess earthquake risk to understand what are some of the seismically sensitive regions in this country, and also a very efficient response mechanism in the event of an earthquake and other disasters. Today it would be fair to say that India has the capability of responding very quickly and efficiently to these kinds of events. These have now reached a point where we are also able to assist other countries when they are struck by these kinds of disasters. India was one of the first respondents when the recent earthquake in Turkey occurred. We were able to send relief teams and equipment which the Turkish government said was a great contribution in dealing with the effects of a very, very severe earthquake.

I am not a scientist, but I can certainly testify to the fact that geological history shows that the Indian plate has been pushing against the Eurasian plate and that is the reason why we have the wonderful multiple range of the Himalaya. Not many people know perhaps that this shift is still taking place. There is still an Indian plate which is pushing against the Eurasian plate and the Himalayan mountains are also still rising by a small fraction every year. So that itself is a very sensitive seismic zone. I happen to have a home in Dehradun which is in the Shivalik and the foothills of the Himalaya. It is perhaps one of the seismically more sensitive zones in the country. But I despair at the amount of construction being done around Dehradun. It is not an area for multi-storied buildings. But if necessary, we need to make sure that there is earthquake proofing. A large number of the buildings in Dehradun are now geared to withstand a very major earthquake. I suspect that is the case despite our capabilities, despite the fact that we have perhaps a much higher level of knowledge today than we have ever had before. This is not translating into practical action. What do I mean by that? For example, our urban bylaws, which are the first line of defence, in a sense, define adequate earthquake proofing technologies and techniques which should be utilised, but are perhaps not being utilised. We always wait for a disaster to happen before we try to learn from it; why should that be the case, especially in a country which has such a formidable range of scientific and technological capabilities.

One of the weaknesses that I have found during my work in government is that while we have very important and globally acclaimed institutions of excellence, we need these institutions to be able to talk to each other as well. There is always a tendency to work in silos and therefore each provides a very fine picture of a problem from one angle, but we do not always get a complete picture. Having some kind of a cross domain, cross disciplinary approach is something we should consider. This workshop is a great opportunity because some of the finest institutions are represented here. Perhaps this can also trigger a conversation amongst yourselves, and that can be a great learning from this. The second aspect is public outreach. Conversations which take place among scientists and engineers need to be framed in a language easy for the general public. This document which summarises the discussions at the workshop will be beneficial for the public at large.

There is also the need to involve students and young people. I have served in Japan, where earthquakes are a daily phenomenon. Knowledge about earthquakes and how to respond to them is now part of the daily routine in all the schools and there are regular drills. These were incorporated as part and parcel of general education. I don't suppose this is required everywhere in India, but at least in the more sensitive zones.

Let me give you a sense of why we decided to have this workshop. We were very fortunate to have Dr Shailesh Nayak, a very eminent scientist and a former secretary of the Ministry of Earth Sciences to lead this. I was privileged to have been associated with him for a number of years, especially when I was Prime Minister's special envoy on climate change. Perhaps not many people realise that there is also a very strong link between climate change and today's subject. In the recent earthquake in Joshimath there was a very major subsidence leading to several houses and buildings being affected. As I mentioned, if there is a terrain which is still shifting, if it is a terrain which is very fragile and young, we should be extra careful in terms of the construction in these areas and the kind of population load which we put on them. I was not surprised at what was happening at Joshimath because I have been trekking in the Himalaya for the last 40 years and I have seen over the period of time the kind of ecological degradation that has been taking place. We need to really look at this very seriously.

M. Ravichandran, Secretary, MoED, Government of India, Delhi

I am thankful for this gathering to discuss this particular subject. We know that one-third of casualties are due to earthquake risk, but we are not aware of the embedded risks and what needs to be done in all sectors, either in terms of science or policy or strategy.

First and foremost is a monitoring mechanism. We have an adequate monitoring mechanism for where the earthquake will occur and when to make this information available. But what do we do beyond this? Even if we can predict the timing a few seconds before, it will have a huge impact on the number of causalities.

I am addressing what we need to know more than what we know presently. Can we get signals only from the earth or maybe even the ionospheric level and other tools? We have to enhance our mechanism for monitoring signals just before the earthquake occurs. Will we be able to do that? Second, much information is available from time series observation. Can we use various tools or modelling from this? Maybe we should consider new tools like AIML and deep tech to see if there is any precursor available. Third, can we identify any one among the latest technologies we can incorporate for our understanding? Understanding is the first thing and second, on the basis of that understanding, can we provide some products and services? In terms of services we will not be able to give 100 per cent correct forecast, but there is a small distinction—can we predict? There is a subtle difference between prediction and forecast. In forecast we have to see the past rhythm and present rhythm and try and quantify that. That is very difficult in terms of signs for the earthquake. Predictability, or potential predictability, say in the Himalayan region, is what we are building on.

Again in terms of services, we have to provide policy guidelines to the government about the existing buildings or new buildings, microzonation, etc. At the city level, especially in earthquake zones 4 and 5, what are the things to do and what should we not do and how to protect what is there. Only seismology can provide that information.

Shailesh Nayak, Director, National Institute of Advanced Study (NIAS) Bengaluru

Unlike other hazards, our existing knowledge about earthquakes is not sufficient to allow us to make any reasonable prediction. In that scenario we need to assess our vulnerability to earthquakes, how well we are prepared to face such an event, and whether we can develop some resilience in the community to address this issue.

There are three aspects to consider. One is knowledge about the earth system. How does the earthquake generate? What is its hazard potential? The second is, how well can we respond with our existing knowledge? What is the government mechanism at the state and central level to respond to such an event? What is the infrastructure required to respond to such an event? And the third is, how conscious or aware about this hazard are the people, especially children? In the global scenario these aspects—the knowledge, the response and the awareness—come together, let's say in Japan, and casualties are less. With the same knowledge in Turkey, we saw that the response mechanism was not adequate and there were large casualties. So all three aspects must come together. Dr Ravichandran mentioned ocean and atmospheric observing systems; in the case of earthquakes, unfortunately, we cannot observe where the earthquake is happening. This is the fundamental difference between these two. We try to understand what is happening 5 to 100 kilometres below the ground from observations at the surface; but the signal gets modified when it comes to the surface, so we are not in a position to see what happens. In that scenario, how do we know the structure and composition of the entire lithosphere? We need to have the monitoring stations, but whether the density is sufficient or not needs to be assessed. We may need different densities in the Himalaya or in Kachchh or near Jabalpur, etc. We may need an additional 500 to 600 seismic stations to do that. We also need to have various transacts or temporary stations at certain specific areas.

We should not ignore the ocean bottom from where we need information through ocean bottom seismometers. These have been deployed in a few places for some time, but we need a much more dense programme. Once we have this, we also need information which can come from the various satellites like GRACE or Altimetry, which can also provide knowledge of the structure of the lithosphere. We now have satellite CHAMP which can provide magnetic data which is also very critical. By using GPS we are trying to measure the stress at the plate boundaries which is very important. We need a much more dense network of GPS to measure the stress. But more important is to measure the strain everywhere because how this moment is affecting the entire subcontinent is not very well understood. This strain measurement can be done with the SAR interferometry. We are going to launch satellite Nisar hopefully this year or maybe next year, which will provide information on the strain everywhere. This should be further validated by putting deep boreholes. The Ministry of Earth Science already has one in the geophysics lab, essentially to understand triggered earthquakes, but I think the scope has to be enhanced to have various deep boreholes, let's say north and south of Palghat Gap, which is one of the major structures, or the Narmada Swicher in the Shivalik in the north east. There may be challenges, but India has their own capability to drill at very deep lengths.

This kind of a programme will be able to provide us some of the answers on the many questions which we have raised. Whether an earthquake will occur in Himalaya, Uttarakhand, Himachal or Kashmir, or what the precursors are, how can microzonation help? What is the difficulty which we are facing to integrate the micro solution with the urban master plans?

The other issue which is now gaining ground is a triggered earthquake. Large engineering structures can also cause earthquakes. There are some places where heavy monsoon rains are triggering earthquakes. We still don't know what is happening in Palghar and why the earthquakes are occurring. Maybe not in very large dimension, but it creates panic. At the same time, with this knowledge we need good response and the setting up of NDMA and NDRF has dramatically changed our response mechanism. The public outreach programme we started at the school level must spread all over India. Education about the environment imparted in schools has proved beneficial and the same can be done to sensitise them about earthquakes and disasters.

K. N. Shrivastava, Director, IIC, Delhi

I had the good fortune of working more than three decades ago in the Ministry of Earth Sciences as Deputy Secretary and much later as a member of NDMA. From those two assignments I had the opportunity of associating myself with everything relating to disaster management and particularly earthquakes.

As Shailesh Nayak mentioned, disaster management has three important aspects. One of course is response and we have developed the capability of responding to any disaster situation. The second one is capacity building which also includes training, and third, the most important one, is risk reduction measures including mitigation measures. This is the aspect that requires a lot of work. So far as other kinds of disasters are concerned we have good capability to forecast them or to predict them, but earthquakes is one disaster where our existing scientific research is not adequate to predict the event.

After what happened in Turkey and Joshimath, IIC felt the need to bring together experts and scientists associated with this subject to deliberate and ultimately bring out specific recommendations which can be given to policymakers as well as disseminated to the public at large.

I would also like to mention that I had the good fortune of visiting Chile, which, like Japan, experiences frequent earthquakes. I was taken to meet with an architect who has been credited with devising various new techniques for the construction of earthquake proof high rise buildings. I am sure our planners and architects will also be looking at such techniques.

Another area I would like to particularly mention is microzonation. It has no doubt been taken note of by all the state governments and municipal authorities, and they have also been included in the building codes. What needs to be seen is how strictly it is being enforced because if not, we are only inviting a disaster.

1. SEISMOGENESIS

By **Vineet K. Gahalaut**, Chief Scientist, CSIR-National Geophysical Research Institute, Hyderabad

I do not want to talk about what I know but to tell you where the gaps are, what I do not know. As was rightly pointed out, bridging the gap between engineers and different stakeholders should be the purpose here. The way to do it is to accept that there is much we do not know and what is the natural variability in the entire process of earthquakes. If you look at the variability in their occurrence processes, then we keep getting surprises in terms of the extent and type of damage, and in terms of the process/mechanism involved in its occurrence. That only shows our lack of understanding and that's where all of us need to work.

We can visualise the earthquake process thus: there are two end-members of the earthquake processes. The top one is a caterpillar moving in a very funny manner; this is the stick and slip motion which we witness in earthquakes. The strain accumulates (the stick motion in which the front part of the caterpillar is fixed to the ground and the back part curls up to accumulate motion) and then it gets released (the curled up part pushes the front part of the caterpillar to move forward, releasing the motion accumulated so far). The lower one is a snail, which glides on any surface without any kind of hindrance, without any jerk, as if there is no friction. This represents the case of no earthquake. This is what we are trying to understand. If you change the surface on which this caterpillar is moving, or if you put a glass sheet and some oil (making it frictionless), it will not be able to move and hence will not be able to accumulate motion (or strain). You change the properties and the caterpillar size and it results in a change in the behaviour of movement. In a way, these are the physical properties which are involved in earthquake processes.

Although my topic is quite wide, 'Seismogenesis', which deals with the earthquake occurrence process, I will confine my discussion only on the Himalayan arc. One of the important questions is about the next big earthquake, or the monster earthquake. Of course we know that we cannot predict an earthquake, we do not know when it is going to happen, but let me try to rephrase it. Let me try to not simplify it, but to complicate it. If I say that the Garhwal–Kumaun region is due for a big earthquake, am I asking if the Garhwal–Kumaun is more prone to a big earthquake, or am I asking if the big earthquake will occur here first then elsewhere in other segments. Can I answer this question? Probably not. Where is it going to be? Will it be Garhwal–Kumaon first, or if it is going to be in Garhwal–Kumaun, then which part of Garhwal–Kumaun are we talking about? The important question here is, how big is it going to be? Is it going to be of magnitude 9? To me all these questions are perfectly valid but we probably cannot answer them. That is one of the biggest challenges. These are questions to start a debate, but when it comes to actual science it is difficult. I will not use the word complex but the entire earthquake process has so much nonlinearity and there are so many parameters involved in it that as of now it's not easy to answer all these questions. Of course, at some point of time I also debated on whether the Himalayan region can host a magnitude 9 earthquake?. Let's debate on what we know, what is the variability in the earthquake occurrence process here in the Himalayan region. Forget about magnitude 9; even if a magnitude 8 earthquake occurs anywhere in the Himalayan region, except probably in the sparsely populated region of Arunachal, it will be disastrous. I only pray to God that at least in my lifetime I don't see a magnitude 8 earthquake in the Himalayan region.

Let’s move from when, where and how big it is going to be. Which are the faults, which are the regions, which are the tectonic units that can host these big earthquakes? How well do we know that surface which we call Main Himalayan Thrust and several similar other faults? How well do we know about modes of strain accumulation? What is a strain budget in all these segments? Which are the regions that are perfect to produce earthquakes or where the strain accumulation process is more heterogeneous than other regions?

What are the lessons learned from past earthquakes? This is a problematic question, and while it is not a criticism, but the way our simulations have been done for all bigger earthquakes has been problematic—whether it is the 1905 earthquake, the 1897 earthquake or the simulation which is going on for the 1934 earthquake. We are not learning from what we have understood so far. We are either stuck with the conventional way of Himalayan tectonics or we are using outdated results from those earthquakes. If we are trying to build our simulations on them then we have serious problems.

Paleoseismology is what is required. We need to know the history of earthquakes in each region, how big it was, where it was, etc. And for our simulations, we need to understand how these waves attenuate, and which are the regions that can amplify these waves.

How does the Indian plate move and what is the configuration of the faults? The Indian plate is moving towards the north east and then it collides with the Eurasian plate and the earthquake occurs. This is the conventional way of putting it. Let us take a cross section across the Himalaya and cut through it vertically. You see that the Indian plate is subducting, is going down, underthrusting below the Eurasian plate. That is a fault of a width of almost 100 kilometres where these big earthquakes occur. The fault farther in the north, i.e., in the Tethys Himalaya or below the Tibetan plateau, slips aseismically, that means it does not produce earthquakes. But then by slipping aseismically it is loading strain on the frontal part, which is to be released in the next big earthquake, whether strong or mild.

What we need to know is how much loading is taking place and which are the faults which can host these big earthquakes. These are two essential ingredients of the earthquake process in the Himalayan region. Once we know this then we can look at ground motion, attenuation, fluids and the role of water in all these processes. But broadly speaking there are two important things: (i) what is the structure on which these big earthquakes occur? What is the configuration of those faults? (ii) What are the dynamics? What is the source of strain? How much is it accumulating?

This is the conventional way of looking at it. This is the variability in earthquake occurrence in the Himalayan region. There are different cases in which different parts of the Main Himalayan Thrust (MHT) have ruptured with time. There is a huge variability in earthquake occurrence and unfortunately all our simulations are based on simple assumption. In our conventional simulations, all these earthquakes are assumed to occur on the MHT. That's not correct. We need to consider all these scenarios. We need to consider all these sources. We need to consider all the variability in the earthquake processes.

Geophysics also poses constraints. The geophysical methods which have been used to image the MHT, which is the host of all these big earthquakes, provide varying configuration and that is problematic. We are not able to map it in full detail. Our understanding is primarily based on geological cross sections, but from our geophysical imaging we are not able to map it in a very precise manner.

Now the subject of dynamics. We know about the convergence of the Indian and Eurasian plates. What has been done is a mapping of the regions which are strongly coupled where the friction between the Indian and Eurasian plates is very large so it is not able to move. It is accumulating strain at a very large rate; and a mapping of which regions could not be perfectly locked. That has been done well and we are able to understand the dynamics and the rate of strain accumulation and its variability along the fault. We are able to refine these maps using GPS observations, using InSAR. For example, look at the scenario in Garhwal–Kumaun and the fault below Dehradun or right up to Joshimat–Gangotri, an area so strongly coupled that there is hardly any movement between the overlying wedge and the Indian plate. They are all moving together. There can be a time when suddenly it all slips to cause an earthquake. We are able to map all this. But why are we doing it? The strongly coupled regions are the regions which will define the strain release in the next bigger quake. These are the regions which are going to experience maximum damage in the next big earthquake. That is the importance of doing this. But the problem is with the geometry of the fault, the MHT, which can host all these earthquakes but is is not precisely known. That is where we need to work.

We are able to delineate that this is a zone where a big earthquake can occur. We are precisely able to know it's northern limit also. As far as its extent along the arc is concerned, we have some idea that there are some inherited structures which can delimit the rupture of these big earthquakes. We are essentially close to defining the regions through which the earthquake rupture cannot propagate, which will act as a barrier for the next big earthquake. We are able to identify the future earthquake ruptures all along the Himalayan arc.

All our simulations are very primitive. We need to learn from our current standing and whatever is happening around the world. There is a project known as M9 in Cascadia subduction zone. There are two scenarios here. First, the rupture initiates in one place and then moves towards the north towards Seattle. In the other scenario the rupture is initiated near Seattle and then is propagated towards the south. There is a variation in the damage at Seattle. Everything is the same, the earthquake is the same, the only thing different is the nucleation point of the earthquake and it is making such a huge difference in the damage scenario. That's what we need to understand. What will happen if the earthquake nucleates somewhere close to the India–Nepal border and the same earthquake rather than nucleating at the India–Nepal border nucleates somewhere near Ponta Sahab or further north. Is the damage scenario going to be the same at Dehradun? No. The characteristic of the earthquake is not changing, the wave propagation is, and its interference is changing the damage area. This is what we need to work on. We also need to delineate the subsurface structure which can host these big earthquakes. We need to do a lot of active and passive seismic surveys. It is time that we take up some active seismic surveys in the Himalayan region. I know that people do not support it from the environmental point of view, but that's probably the only way to go forward to precisely delineate those subsurface faults which can host large earthquakes.

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2. PLATE INTERIOR EARTHQUAKES

By **Sumer Chopra**, Director, Institute of Seismological Research, Gandhinagar

The Institute of Seismological Research (ISR) is located in Gujarat, which is considered a plate interior region and the most active interior plate region in the world. We have a dense network of seismic stations spread all over Gujarat, and have carried out lots of geological, geophysical and seismological surveys across the length and breadth of Gujarat in the last decade. We have done microzonation at many places and that has helped us to characterise the sites. We have recorded more than 30,000 earthquakes in the last 15 years of network operation. I will give you a glimpse of what we have done so far and what is the outcome of our research.

We know that earth consists of a number of plates. The major plates are Eurasian plate, Indian plate, Australian plate and North American plate, and these plates are moving at different velocities. Due to this movement relative to each other, converging plate boundaries, diverging plate boundaries and transformed plate boundaries are formed. The rates of movements are also different at different places. We will concentrate more on the Eurasian and Indian Australian plates. It has been observed that most of the earthquake activity around the world is along the plate boundaries but there are a few regions in the interior of the plates where earthquakes are also occurring. Though their recurrence rate and magnitude are less as compared to the plate boundary earthquakes, they are still destructive. The frequency of occurrence of large earthquakes in the plate interior is very low. In the last 200 years, only 20 earthquakes of magnitude greater than 6 have occurred.

The plate interior earthquakes are commonly known as intraplate earthquakes. These are very rare and infrequent and generally occur in regions where the present day strain rates are low and the deformation is of the order of 1 to 2 mm per year. Along the Himalayan plate boundary, the deformation is more than 10 mm per year and it varies along the plate boundary. The low deformation rates are due to the fact that in the interior of the plates, the rocks are more competent and attenuation is very low. Many researchers of plate interiors have found that more than half of these earthquakes occurred along the failed rifts and some occur in regions devoid of seismicity. Some regions appear to have ruptured only once in recent times, while others show evidence of multiple events, sometimes clustered in time, separated by quiescent intervals of 10,000 to more than 100,000 years. In some regions, like northern China, it has been found that large earthquakes roam between widespread faults. There faults are interconnected, and earthquakes seems to roam across different faults. With regard to damage potential, the intraplate earthquakes are deadly. The 6.2 Latur earthquake in 1993 killed around 10,000 people and the total economic loss was around USD 300 million. During the 2001 Bhuj earthquake, around 20,000 people lost their lives and economic loss was around USD 4 billion. According to some researchers, if there is a repeat of the same New Madrid sequence that happened in 1811–12, the total economic loss will be USD 300 billion.

The main challenge is quantifying the seismic hazard in the plate interior region and zeroing in on the region where the next earthquake will occur. All the hazard calculations are generally based on concepts and methods which are developed for plate boundary regions due to lack of proper understanding. The process of earthquake occurrence in plate boundary and in stable regions—in plate interior regions—is different. Plate boundary earthquakes occur because of tectonic loading at the plate margins and due to which the strain energy is accumulated and then it is released in the form of earthquakes once the applied stress surpasses the frictional strength of the underlying rocks. The plate boundary faults are loaded by plate motions and earthquakes mostly repeat at the same fault.

On the other hand, the deformation is very low in intraplate regions and is almost flat. But here too, the earthquake occurs because of the change in the fault strength, that may be due to the tectonic loading or hydrological loading in some local pockets, where pore pressure changes play an important role. It has been observed that in intraplate regions, the earthquakes are distributed among different faults at different times. In addition to occurrence, there is a lot of difference between the aftershock activity from a large earthquake at a plate boundary, diffused plate boundary and the plate interior regions. In a plate boundary region, generally, the aftershock activity may die down in one or two decades whereas in an intraplate region it continues for hundreds of years.

It has been found that during the 1964 Alaska earthquake the aftershock activity continued for more than 10 years. During the 1923 Kanto earthquake, it continued for around 20 years. But in the New Madrid region, a plate interior region, the aftershock activity is still continuing after almost 200 years. In intraplate regions, the seismicity rate returns to the background level after around 500 to 800 years. It is found that two orders of stresses occur on the continental lithosphere. The first order stress, extending to thousands of kilometres, is generally associated with plate tectonics forces. And the second order stress is superposed on the regional stresses with wavelength of hundreds of kilometres. The probable mechanism involves localised stress build up in pre-existing zones of weakness, like failed rift regions and reduction of strength by mechanical and chemical processes that may be due to the increase in pore pressure or due to the hydrological loading.

We can observe some common features in intraplate regions that have experienced large earthquakes in the past. In the Saurashtra region of Gujarat, an intraplate region, we have found that the activity is mostly periodic in nature and mostly due to the hydrological loading during the monsoon in the pre-existing zones of weaknesses. In this case, it is found that the earthquake affected pockets are highly fractured and have inter-connecting faults. The New Madrid seismic zone that experienced a sequence of earthquakes during 1811 and 1812 has a number of intersecting faults and a buried pluton, which may have acted as local stress concentrators. The

North China region has experienced at least five magnitude 8 earthquakes in the historical past. The region has lots of intersecting faults and a failed rift. The same is the case with Brazil, where the earthquake affected region is a failed rift with a buried pluton.

As far as India is concerned, in the last 200 years, around 10 large earthquakes have occurred in the stable peninsular shield region. The major one is the 1819 Kachchh earthquake of magnitude 7.8 and the latest one is the 2001 Bhuj earthquake of 7.7. In addition, the 1956 Anjar earthquake of 6.0, 1967 Koyna earthquake of 6.3, 1993 Latur earthquake of 6.2, and 1997 Jabalpur earthquake of magnitude 5.8 are significant and caused damages. Among all regions, the 200 x 300 kilometre Kachchh rift is seismically one of the most active regions. In the last 200 years, the region has experienced three deadly earthquakes, in 1819, 1956 and 2001. The Harappan site, Dholavira, has also experienced an earthquake of magnitude 6 or more in 2700 BCE. The Kachchh region has many active faults. In the last 15 years, the ISR has mapped many active faults and found that most of the faults are segmented and all segments are not active. We have dug a number of trenches and carried out paleo-seismological studies and found that the region was active during Quaternary and many earthquakes have happened in the historical past.

For the Kachchh intraplate region a conceptual model of the fault system is available, deduced after numerous field investigations in this region. The seismological, geophysical and geological investigations by various researchers have interpreted a mafic intrusive body beneath the epicentre zone of the 2001 Bhuj earthquake. After this earthquake, the Government of Gujarat took an initiative and established ISR. ISR has a dense network of almost 60 online and around 65 offline permanent seismic stations. In addition, ISR has a strong motion network of 50 seismic stations. Using the data generated from this dense network, ISR has carried out several studies in the last 15 years with a database of around 30,000 earthquakes. A seismicity map of Gujarat for the past 15 years shows that earthquakes are happening everywhere in Gujarat (Figure 1). Almost 60 per cent of the earthquakes are located in the Kachchh region alone. In the Saurashtra region, most of the earthquake activity is of the swarm type, that is seen only after the monsoon.

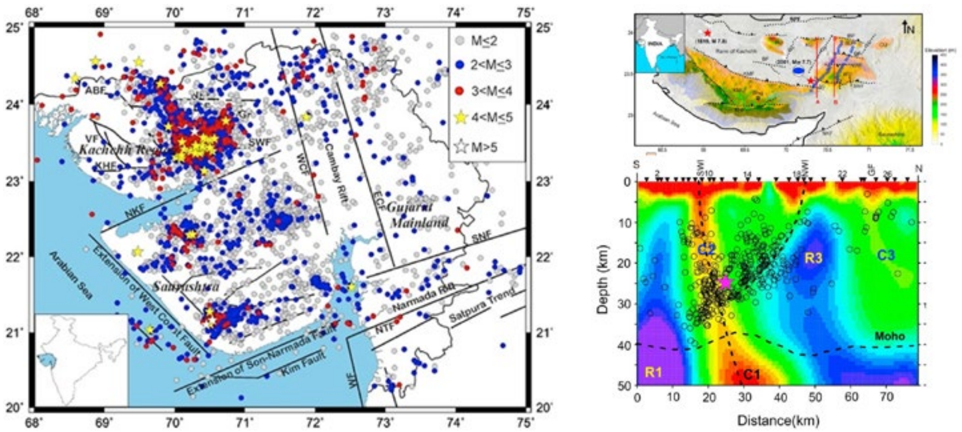

Figure 1: Seismicity in Gujarat (left panel) and seismotectonic model from MT studies (right panel)

ISR carried out magnetotelluric (MT) surveys to map deeper layers in the Kachchh rift to understand the physics of earthquakes in this region. Around 150 sites are occupied for MT surveys. A few MT transacts were carried out across the 2001 Bhuj epicentre zone. It was found that the South Wagad fault (SWF) is a high angle deep fault and almost connected to the upper mantle. It is postulated that mantle fluids are channelised towards upper crust, thereby putting some additional strain in this region. Most of the earthquake activity is concentrated in the region. This channel is feeding the mantle fluids to different fault systems as most of the faults are interconnected with each other. These fluids under high pressure are distributed among different faults and put additional strain, and that might be the reason for continued earthquake activity in the Kachchh rift. In the Saurashtra region, a horst, we found that the basement is fractured and hydrological loading due to intense monsoon activity in this region is putting additional strain, which results in the periodic swarm type activity.

All these studies in the past 15 years show that the crust in this Kachchh region is very rigid and brittle with a lot of heterogeneity. The rock matrix is fluid filled and the lower crust is highly altered. There are some locales where partial melts have been found and injecting volatiles containing CO_2 into the lower crust adds strain in this region.

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3. TRIGGERED EARTHQUAKES

By **Sukanta Roy**, Project Director, Borehole Geophysics Research Laboratory, Ministry of Earth Sciences, Karad

The previous papers have set the stage to talk now about a special kind of earthquake, namely, ‘Triggered Earthquakes’, which is a societally important area of earthquake science. I would rather generalise the term to anthropogenic earthquakes, i.e., earthquakes that are caused by human induced changes. What are those kinds of changes? Anthropogenic seismicity is the result of human induced changes, and these changes are brought about by various human activities that are often absolutely essential for the development of the economy of any country. For example, activities such as conventional or unconventional energy production, oil and gas, renewable energies (geothermal, for example), and potentially environment friendly methods related to climate change like geological sequestration of CO_2 that involves burying of the industrial carbon dioxide into the earth and minimising its impact on global warming. The need to understand anthropogenic seismicity, therefore, has become extremely important in view of the socio-economic impacts that they bring about, and they are relevant not only in India but all over the world.

In Figure 1 you see the stress building up slowly and then it reaches a critical value. Then it drops and then again it rises and drops. This is a very simplistic picture. More realistic is the other picture. What happens if you induce changes into the stress regime in the subsurface, for example by all of those processes mentioned previously? The stress levels do not recover up to the red line, but the failure is effected before that because of other changes. Thus, if you leave it as business as usual, an earthquake may happen at recurrence intervals of hundreds of years, but in this case, when you induce changes by man-made interventions, it can actually lead to failure quite frequently and that is what we have seen at a number of places in the world, but most importantly in India in the Koyna region of Maharashtra where a huge reservoir was built and impounded in 1962. It is very important to have the reservoir but it also led to enhancement of seismic activity there.

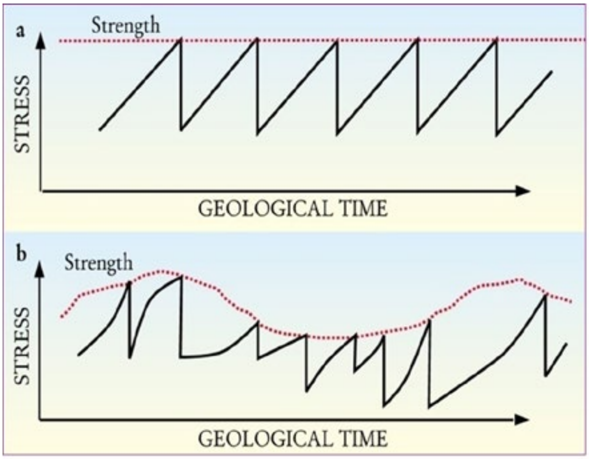

Figure 1: Stress change and earthquake sequence (after Kanamori and Brodsky, 2004).

What do we mean by triggered versus induced earthquakes? There is a slight difference. Basically, both comprise anthropogenic seismicity. I will first briefly show the global distribution and the underlying mechanisms and what we are doing in Koyna. I will then dwell upon how we use our current understanding acquired through research in objective hazard assessment.

What are the different kinds of human activities that cause induced or triggered seismicity? Many industrial activities alter the stress distribution in the subsurface by the changes that happen at the surface. In principle they can induce earthquakes, although most do not. There are geologically favourable conditions where the earthquakes are induced and in not so favourable conditions we will not expect earthquakes to occur.

Industrial operations such as water reservoir impoundment, or dams, are needed not only for hydropower production but also for flood control and irrigation. A lot of excavation that takes place for mining can lead to induced earthquakes. When oil and gas are extracted from the subsurface it can lead to some kind of a subsidence and the resulting impacts. Hydrofracturing for shale gas exploitation, for example, is widely prevalent in North America but also slowly catching up in our country. In this process we inject fluids at high pressure to create artificial fractures in the subsurface, in the crystallite basement hard rocks, and that often leads to seismic activity. Although they are not of a very high level, they do create panic.

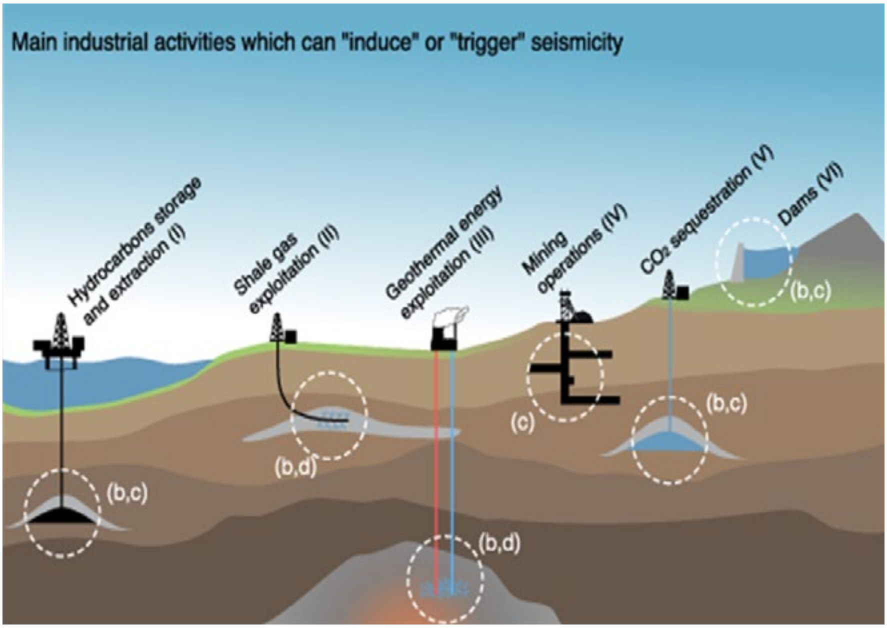

Figure 2: Main industrial activities that can cause induced or triggered earthquakes (Grogoli et al., 2017)

Wastewater disposal is an important issue. In the oil and gas industry there is a lot of brine that comes up along with the oil. Where do you dispose of this? You have to inject it in the subsurface; this is the best scenario that is available today but again involves injection of the fluids into the subsurface that can cause stress levels to change. As a general rule the deeper the activities, the larger the stress alteration and the closer the seismogenic faults, the more likely the earthquakes. It is just not one but a number of conditions that need to be favourable. Also, we have seen that the largest number of induced seismic events at a global scale have been related to mining operations, but the largest induced events in terms of magnitude are related to water impoundment, i.e., reservoirs and dams.

Briefly, by induced seismicity we mean that these events are entirely controlled by the stress changes caused by human operations. Humans are totally responsible for induced events, whereas in triggered events there is an underlying reason, for example the tectonic stress that plays a primary role, whereas human activity adds a trigger and so contributes for a small fraction of the stress change. That is very important to understand. For example, if you have a geological fault or a plane or weakness, that might lead to earthquakes in the natural sense, possibly in several hundred years. But if you add the reservoir load there, then the trigger from that might lead to very frequent seismic activity. That is the case in triggered events. If you inject water into the subsurface even in an aseismic area you can actually cause induced earthquakes irrespective of whether you expected it there or not. There are many who have worked in this area in India. Dr Harsh Gupta prescribed the criteria for distinguishing between reservoir triggered earthquakes and natural earthquakes. Essentially one major common criterion is the spatio-temporal correlation between seismicity and industrial activities. If you see an area where there was no past seismicity, but after the introduction of a particular kind of industrial activity the seismicity level dramatically changes, that is a very clear indication of an anthropogenic or triggered earthquakes scenario.

There are other ways to distinguish between these earthquakes. If you look at the global distribution of induced and triggered earthquakes you can see they can occur anywhere. They occur in all continents, they can occur from dams, oil and gas, geothermal, wastewater, mining activity. The Koyna region in western India experienced a big earthquake of magnitude 6.3 in the intraplate region primarily after the impoundment of the Koyna reservoir, or the Shivaji Sagar reservoir, in Maharashtra, which today contributes about 2,000 megawatts of electricity to the National Grid.

If you look at the distribution of anthropogenic activities by source, you can see almost half or just about less than half is caused by mining activities, about a third by water injection and less than a third by water reservoir impoundment. Maximum observed magnitudes of the different anthropogenic activities are plotted and we can again see that the water reservoir improvement causes the maximum observed magnitude among all the anthropogenic activities.

The largest earthquake induced by fluid injection currently is in Oklahoma in the US where the wastewater being injected in the subsurface is causing big earthquakes of 5.8 magnitude, which is really large when one considers that the area did not have any prior seismicity. Koyna is the largest earthquake triggered by water reservoir impoundment anywhere in the world, and Gazli in Uzbekistan is the largest triggered earthquake by mass removal. It is important to realise that the stress released in an induced earthquake is the anthropogenic stress that we add by human activity, acting on pre-existing stress, and the minimum amount of stress that is required to modulate such activity is only a few hundreds of a mega Pascal. It is really small and therefore these can occur anywhere. The largest magnitude induced by industrial activities is proportional to the scale of the activity, the scale of the fluid injection pressure and rate, etc.

If you look at the mechanisms, the alteration of the subsurface stress field that can reach certain critical thresholds can trigger these earthquakes. There are different settings but essentially stress is a key parameter when we talk about earthquakes and we need to understand the stress inside the earth; that gives us a clue to distinguish between the different kinds of triggered earthquakes. Reservoir triggered earthquakes are the result of the load of a very large lake, the pore pressure, the water percolation from the reservoir, etc., all of which play different roles and interact with the stress field and cause failures in the rock mass.

How can human induced earthquakes be controlled or reduced? It requires the modelling of triggered seismicity using near field information and that is the key to understanding the various controls. One must realise that induced earthquakes are inherently a multidisciplinary arena that involves geology, geophysics, seismology, rock mechanics, modelling of complex systems, etc. Seismology is a multidisciplinary area where all fields of earth sciences are extremely important to understand and to model the system. And many of these parameters come only through deep drilling. You have to measure deep inside the earth where the faults are or by doing advanced laboratory experiments on the rock samples that are recovered from default zones at depth.

I will summarise a result that we have obtained from our own studies in Koyna region. The Koyna dam has a height of 103 meter. The reservoir volume is approximately 2,800 million cubic metres. It is a huge dam and the seismic activity that this has caused is visible. Figure 3 shows the Koyna reservoir in the north and the Warna reservoir in the south, along with the distribution of seismic activity. The seismic activity is related to the changing water level, the annual loading and unloading cycle of the reservoir—loading cycle because of the monsoons, unloading cycle post-monsoons.

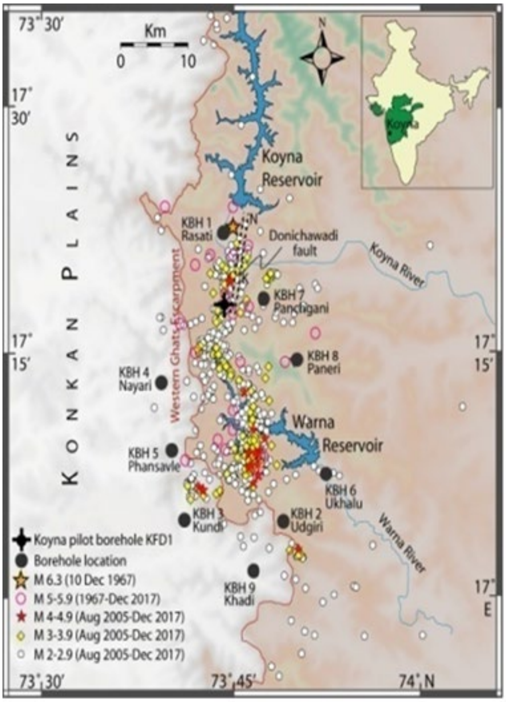

Figure 3: Map of the Koyna–Warna region in western Maharashtra, showing the distribution of seismicity since 1967 and locations of the boreholes drilled in recent years by the Ministry of Earth Sciences (Source: MoES-BGRL, CSIR-NGRI)

Therefore, the Ministry of Earth Sciences took up the programme of scientific deep drilling, where we have now drilled up to 3 km in the region to acquire various kinds of data sets that are extremely important to understand this process. We have already got a lot of data on geology, geochemistry, rock mechanics, thermal structure, stress, etc., which we are now able to analyse. The main conclusion that we are able to draw about Koyna from such studies is that the area has geologically favourable conditions for earthquakes due to the presence of optimally oriented, critically stressed, hydraulically conductive fractures. Small changes in fluid pressure and/or frictional strength could provide the necessary trigger for failure. And for further constraints, we have to go for further deep in-situ measurements that have been planned, and also laboratory experiments. In the next phase, a deep borehole observatory has been planned and this may become a reality in the next few years.

How do we use our current understanding acquired through research in objective hazard assessment? The main thing is that in our understanding of the relevant processes and the site-specific conditions that matter, the location of faults and their stressing state is yet incomplete. This is the central area where we need to improve, but there are also other things that we can do, because a comprehensive risk governance strategy must also include a suitable monitoring infrastructure wherever such industrial activities are found. A sophisticated data analysis technique for real time seismic characterisation, quantitative risk analysis and transparent decision protocols is needed. Many of these are yet to be implemented but they will allow us to evaluate the system response before the occurrence of critical events. We need some additional data and modelling efforts.

The final take home messages: human activities can have a real impact on earthquake occurrences with various mechanisms that impact stress conditions. Triggered earthquakes are becoming more and more frequent, as seen from the rise in the number of publications in the last 40 years or so. Induced seismicity is inherently a multidisciplinary process, and we have to treat it as such. We still have incomplete understanding of all the relevant processes, but the programmes, such as the scientific deep drilling in Koyna, are crucial to develop a comprehensive understanding of the mechanisms and assessment of the associated seismic hazards.

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4. EARTHQUAKE PRECURSORS

By **Kalachand Sain,** Director, Wadia Institute of Himalayan Geology, Dehradun

Based on some examples in the Kumaon–Garhwal Himalaya of the Uttarakhand state, I will be demonstrating how the earthquake precursors could be useful in forewarning earthquakes. But before we discuss precursory events, we need to have some sort of background knowledge on the genesis of earthquakes. All of us know that the collision between the Indian plate with the Eurasian plate, which was initiated 55 million years back, has formed the mighty Himalaya. The interface between the Indian plate and the Himalayan wedge has been defined as the Main Himalayan Thrust or MHT. The geometry and subsurface disposition of the MHT govern the earthquakes in the Himalayan region, and the landscape and geomorphology control the damage pattern during the calamity. Several crustal scale faults such as the Main Boundary Thrust (MBT), Northern Almora Thrust (NAT), Main Central Thrust (MCT), South Tibetan Detachment (STD) are soled into the MHT at depth, and these have divided the entire Himalaya into the Sub-Himalaya, Lesser Himalaya, Higher Himalaya, Tethyan Himalaya and the Tibetan Himalaya. Numerous subsurface processes have led to the youngest and most rugged mountain chain of the Himalaya in the northern part of India.

If you look at the earthquake scenario in the entire Himalayan arc, we had a few major/great earthquakes such as the Assam earthquake (8.7 m) in 1950, the Shillong earthquake (8.4 m) in 1897, the Bihar–Nepal earthquake (8.1 m) in 1934, and the Kangra earthquake (7.8 m) in 1905. Besides these, we had the 2005 Kashmir earthquake (7.6 m) and the 2015 Nepal earthquake (7.8 m) in April; 7.3 m in May), 1833 Nepal Bihar earthquake (7.6 m), etc. There are some paleo-evidences of the 1803 Chamoli earthquake (7.8 m). However, the central part of the Himalaya bracketed by the epicentres of the 1905 Kangra and 1934 Bihar–Nepal earthquakes has not experienced earthquakes of magnitude more than 7.5 during the last two centuries. From the subsurface seismic image, we see that the MHT plays a crucial role in the occurrences of earthquakes. One profile in the Garhwal Himalaya and another profile in the Kumaun Himalaya demonstrate that the earthquakes are associated with the ramp structure of the MHT and associated fluid into the subsurface, and hence these features are important in comprehending the genesis of earthquakes.

The seismicity study, undertaken by the Dehradun-based Wadia Institute of Himalayan Geology (WIHG) from 2007 to 2022, shows that more than 4,500 earthquakes with magnitude greater than 1.8 have taken place in the Kumaun–Garhwal Himalaya (Figure 1). However, only a few earthquakes have occurred of magnitude 6.8 for the Uttarkashi earthquake in 1991, 6.6 for the Chamoli earthquake in 1999, and 5.7 for the Rudrprayag earthquake in 2017. In the eastern part of the Pithoragarh district, which falls in the western boundary of the Nepal Himalaya, we experienced the 6.3 magnitude Doti earthquake at the end of 2022 and the Jumla–Nepal

Earthquake (5.6) at the beginning of 2023. Though the Nepal Himalaya experienced major earthquakes in 2015, the central part of the Indian Himalaya did not have any major or great earthquake(s) during the last two centuries or more.

It is well known that the convergence of the Indian plate beneath the Eurasian plate in the Himalaya has been responsible for several subsurface processes like convergence and deformation, which have led to stress accumulation. It has been observed from several studies that subsurface physical properties such as seismic velocity, resistivity, magnetic susceptibility, density, compressibility, and phenomena like emanation of inert gas (helium, radon), carbon dioxide and water level fluctuations behave abnormally before a seismic event takes place. These anomalous behaviours of the subsurface properties and phenomena are defined as the precursors. If we have the precursory study or monitoring of such spatio-temporal behaviour and comprehend them based on certain physics, we shall be able to translate the anomalous behaviour in terms of pre-warning for an earthquake. For this, we need to establish a net of relevant stations at locations where we expect earthquakes, particularly in the central Himalaya. The WIHG has been continuing such a precursory study at Guttu in the Tehri district of Garhwal Himalaya in Uttarakhand by setting up numerous sophisticated stations and monitoring the physical, chemical and geotechnical properties, and water level fluctuations. The real time transmission of data from the field to the processing centre, analysis and processing of such data sets using artificial intelligence and machine learning algorithms, identifying a threshold for alert, is the need of the hour. Since human analysts cannot do this job continually, we are dependent on the machine for real time analysis, monitoring and decision taking. The success depends on understanding the processes, sensitisation of the locals, and effective implementation of such a system as a measure of mitigation of disasters due to earthquakes.

To know the location to set up the observatory, we need to identify the seismically potential zone. This is generally done based on seismicity, delineation of ramp structure of MHT, identification of locked zones, finding out the fluid/partial melt-rich zone, mapping and characterisation of active faults, rheology, rupture propagation, plate motion, deformation, ground acceleration, etc. The study has brought out two low strain rate corridors along (i) Ramganga–Baijro and (ii) Nainital–Almora in the outer lesser Himalaya, which have not experienced any strong earthquakes and surface ruptures during the last few centuries. The strong coupling of the

MHT over 90 km beneath the Garhwal–Kumaun Himalaya with convergence rate of ~18 mm/year equivalent to accumulated slip deficit of 9 m in the last few centuries is enough for the generation of a major or a great earthquake. But we do not know how much of that energy would be released and when it would be released. This is the main concern with regard to the envisaged major/great earthquake in the Garhwal–Kumaun Himalaya. The high strain rate zone in the higher Himalaya has experienced the 1991 Uttarkashi and 1999 Chamoli earthquakes. The Guttu observatory also lies in the higher Himalaya.

Monitoring the spatio-temporal b-values is also important, and reduced b-value implies occurrences of larger magnitude earthquake in the region. This example shows a drop in Vp/Vs, fluctuation of water level, co-seismic changes on gravity measurement, radon anomaly, etc., before the main event took place. These are the precursor events, and we need to constantly monitor as many precursory events that will lead us to understand an earthquake going to take place in a region. The anomalous behaviour of a set of parameters such as the seismic velocity, resistivity, density, ground acceleration, emanation of inert gas, water level fluctuations, etc., are very important with regard to the precursory study of an earthquake.

We have been studying the temporal behaviour of multi parameters by setting multiple sensors into Guttu with the BBS, GPS, magnetic observatories, accelerographs, superconducting Gravimeter, emission of radon as well as monitoring of groundwater level. Figure 2 is an example from the Guttu observatory. It shows the anomalous behaviour of water level, radon-gamma, radon-alpha before the 2015 Nepal earthquake. Even on the gravity observation, we notice co-seismic changes for the 5.0 magnitude Kharshali earthquake in 2007 and 5.7 magnitude Nepal earthquake in 2011 at epicentral distances of 60 and 222 km, respectively, from the Guttu observatory. If we can understand how these physical and chemical parameters behave and other phenomena take place before the main event, we will be able to comprehend the earthquake process or seismogenesis in a region.

Towards the mitigation of disaster related to an earthquake, it is essential to develop a warning system and a prototype has been developed by IIT Roorkee. An earthquake can be located by a local network of seismic stations, and the magnitude can be estimated within seconds using the earthquake generated P-waves. The destructive shear wave arrives later depending on the epicentral distance. Depending on the time difference between the P-onset and destructive S-arrival, which again depends on the epicentral distance, a warning can be issued. Preventive measures can be taken by automatic stopping of lifts, traffic, metro, and switching off electric and gas supply and power stations. There have been some success stories in Japan, China, USA and Mexico. Of course, this has been accomplished by strict implementation of earthquake-resilient structures and building codes, sensitisation of people, mock drill practices, etc.

While looking into earthquake risk in India, we know that the population has been growing with time. In 1905 during the Kangra earthquake, 20,000 people lost their lives. If such an earthquake takes place now when the population has exploded six times, and if it happens in the early morning, the devastation would be much more; maybe two lakh people would be affected and many buildings would be damaged. If we look into the Quetta earthquake in 1935 and the Muzaffarabad earthquake in 2005, a large number of lives were lost, mainly due to poor structures in the region. Hence, we need to comprehend the damage and loss by keeping the present population increase and nature of buildings in mind.

Results from theoretical consideration, field experiments and laboratory modelling, as claimed by Russian scientists (Zeigarnik et al., 2022) over the past 25 years in Pamir and Tien Shan, demonstrate a new type of triggering impact on the deformation processes in the Earth's crust: EM triggering of weak seismicity. This means if a region is capable of producing a 6 magnitude earthquake, injection of electromagnetic wave into the field can increase the seismicity or produce many weak magnitude earthquakes that may not cause any damage. If we want to conduct that type of experiment, we need to understand the theory behind it and pursue some sort of laboratory experiments to conceive how to defuse the accumulated energy in the form of non-destructive, low-magnitude earthquakes. Again, I don't know if we can think of such experiments in the convergence zone of the Himalaya. I would like to disseminate another hypothetical issue of changing the physical-mechanical characteristics of a seismogenic fault by transferring the deformation mode from stick-slip (dynamic event; sharp release of accumulated energy) to non-hazardous low-frequency aseismic-slip (creep event/slow earthquake), as proposed by Kocharyan and Novikov (2015). The laboratory experiments can be pursued by simulating conditions of an earthquake source zone for conceiving and testing.

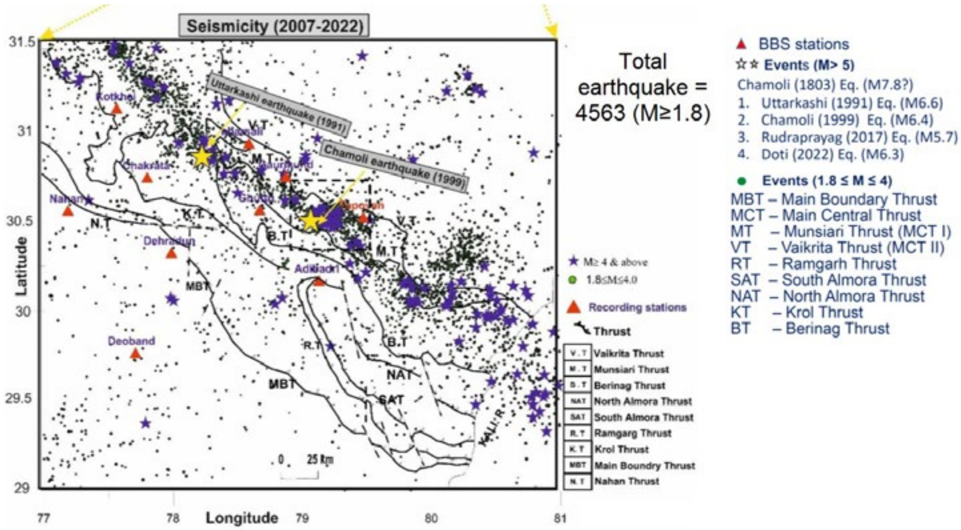

Figure 1: Seismicity in the Uttarakhand Himalaya between 2007 to 2022
(Tiwari et al, 2021, Natural Hazard)

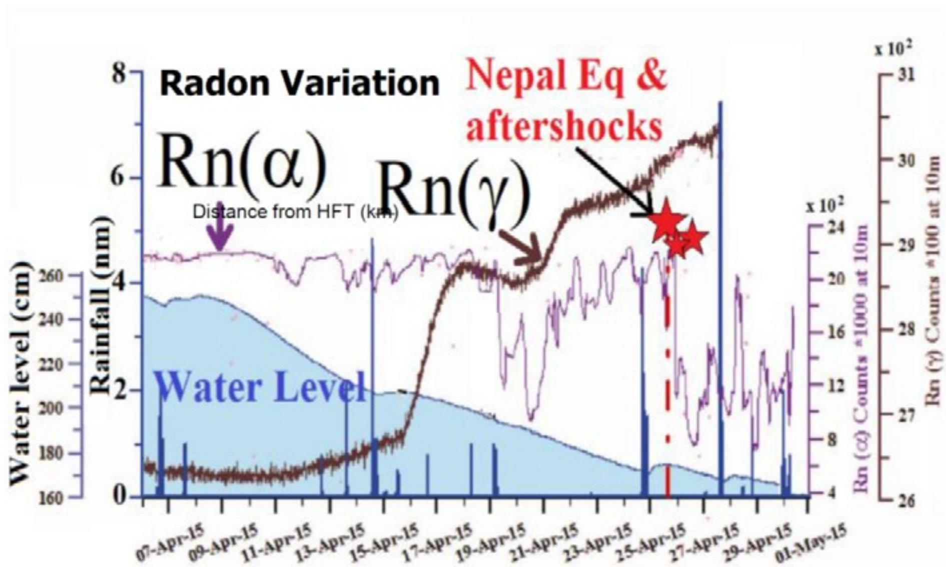

Figure 2: Precursory Events observed at Guttu MPGO, Garhwal Himalaya
(Kumar et al. 2017, Current Science)

In conclusion, I would like to point out that we have dense coverage of sensors, and human resources or expertise. Hence, it is highly possible to grasp the earthquake processes through precursory studies by establishing multi-parametric earthquake observatory at suitable places like Guttu in the central Himalaya. This may lead to developing an alert system against the tragic event caused by earthquakes based on real time transmission of data of multiple data sets, processing/analysis of data using fast computing machines, advanced modelling, and application of AI/ML. The second important aspect is the development of a warning system consisting of detection of an earthquake with its location and magnitude by a net of seismic sensors and alerting before the damaging S-wave arrives.

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5. MICROZONATION

By **O.P. Mishra, Director**, National Centre for Seismology, New Delhi

It is very important for us as scientists, technocrats, bureaucrats, researchers, media and policy planners to come together to discuss the most challenging topic of earthquakes. Today we are not able to predict earthquakes, but tomorrow we might, and research is continuing to understand earthquake mechanisms. It is not possible to predict an earthquake with respect to time, space and size (authentication). We have already done a prediction of the three stages (anticipation, expectation, justification), but the last stage (authentication) of earthquake prediction has not yet been achieved.

We are aware of seismogenesis in the Himalaya, in the Bhuj area, Latur area, Koyna area— these are all demarcated seismic zones. In earthquake prediction, we have already anticipated where the earthquake can occur. In an earthquake-prone area, if the earthquake has not happened for the last 50 or 60 or 70 years, then one can expect a rupture, irrespective of its size. Scientific justification for earthquakes includes presence of locked zones, non-locking zones, fluids, anthropogenic activities, etc. We still are in search of the last stage of 'prediction' of earthquakes which is authentication with respect to its time, space and size. Earthquake risk can be mitigated by only three aspects. One is to predict the earthquake, second is to develop an early warning system, and the third, if these two are not possible, then build structures in such a way that earthquake shakes have no impact on them.

The National Centre for Seismology is dealing with earthquake research, starting from the monitoring of earthquakes 24x7 to its processing and dissemination of information to the various stakeholders and public. To understand the earthquake processes, we set up a national network equipped with the distribution of digital broadband seismographs and strong motion accelerographs that detect and record earthquake tremors of varying strengths from the different subsurface source depths that help identify potential zones of the earthquake, along with the estimates of the propensity of earthquake hazards. Based on these data sets, seismogenically active and less active zones having different earthquake potential and strength have been demarcated. We can take precautions based on this information and make our houses earthquake risk resilient.

India has 59 per cent of land vulnerable to earthquakes; of this, 12 per cent is vulnerable to severe earthquakes (zone 5). Contrary to that, 68 per cent of the land is vulnerable to drought, 12 per cent is vulnerable to floods, and 8 per cent is vulnerable to cyclones. We are now able to forecast and predict these hydrometeorological disaster events because of the observation system and robust computational system with skills and acumen. The crux is that we cannot predict the earthquake because we don't know the exact physics involved in the earthquake generating processes. Hence, we depend on hazard zonation maps. These maps actually depict the impact of the amplification of earthquake shaking and the extent of damage to people and property in the affected areas. Zones 4 and 5 of the Himalayas, of course, represent both the earthquake source zonation and seismic hazard zonation maps. Thus Delhi, falling in the seismic hazard zone 4, is justifiable, but it does not represent an earthquake source zone 4 as that of the Himalayas.

Almost all earthquakes of different magnitudes are concentrated in the same zone and that is the puzzle. Why does the same source zone sometimes generate a bigger earthquake, sometimes a smaller earthquake, and sometimes at a deeper depth? A bigger earthquake at a deeper depth is not damaging but even a small earthquake at a shallow depth is. This gives us an idea of how to cope with the menace of earthquake impacts. The seismic hazard zonation map is given in Figure 1.

The seismic hazard zonation map is not going to solve the problem engineers face. The zones with peak ground accelerations (PGA) vary from 0.18 g to 0.22 g, 0.22 g to 0.24 g, 0.24 g to 0.36 g, and greater than 0.36 g for seismic hazard in zones 2, 3, 4, and 5, respectively. But such a crude estimate of the peak ground acceleration for a particular hazard zone is not going to resolve the issue of building safer and earthquake risk-resilient structures, which can only be done through seismic microzonation of the area. If the earthquake occurs close to the vicinity of four trees, the impact of the earthquake is different for all four trees. One tree does not move, the other three move and one falls down. That means it was the material property heterogeneity that is dictated by the mode of earthquake shaking. Some trees were diffracted by shaking, some absorbed the shaking, some dissipated by shaking, and some scattered by shaking that impacted the structures in a similar way. There are engineering needs to generate the foundational design parameters. Microzonation study is the physics behind this: that if the earthquake occurs in the harder rock, then the seismic wave propagates and there is no change in the foundation. But if it passes through sediments that are loose material then the seismic wave amplifies and when the frequency of the earthquake shaking matches that of the structural frequency then the damage

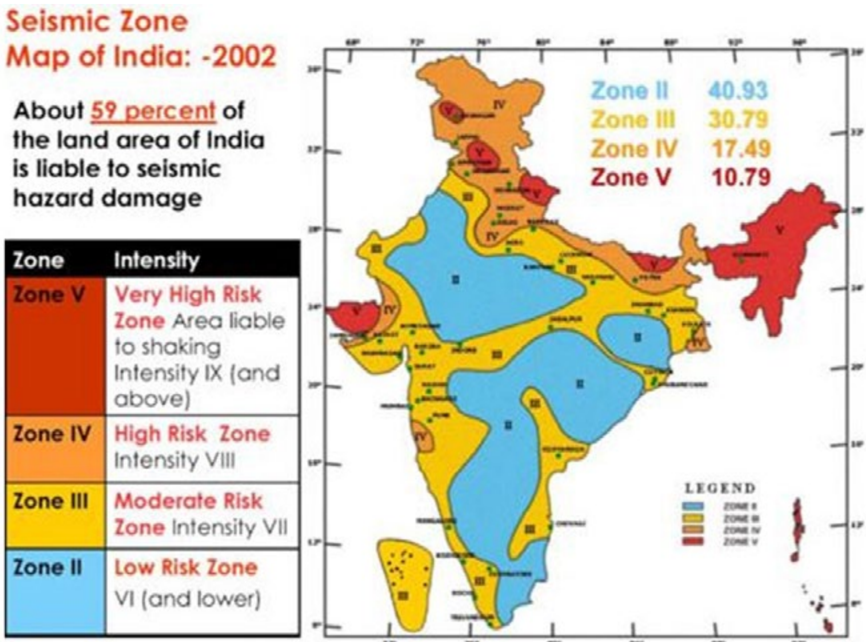

Figure 1: Seismic macro hazard zonation map of India (BIS, 2002)

takes place—this is the philosophy of employing seismic microzonation. It is worthwhile to invest resources into detailed investigations on seismic microzonation for constructing earthquake risk-resilient structures.

Buildings can be constructed as earthquake resistant and this is the most authentic engineering solution. Japan is proof of this where no building was razed to the ground during a tsunamigenic earthquake of magnitude 9. It proves that engineering and scientific solutions are capable of designing structures that can withstand earthquake shaking of magnitude 8 or 9. That is why India is trying to make vital installations in all dwelling structures and critical infrastructures based on the concept of seismic microzonation. In the Ministry of Earth Sciences, Dr Shailesh Nayak initiated this project as a flagship project of seismic microzonation in 2012 and we are doing it in 30 Indian cities in the first phase and have completed some of strategic cities with a population of at least half a million or more (Figure 2).

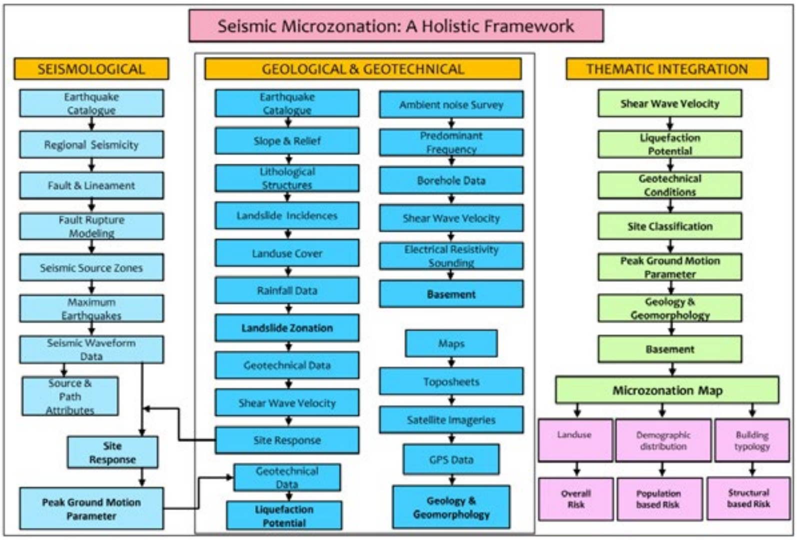

Figure 2: A flow-diagram of conducting seismic microzonation study by involving several estimates of diverse geoscientific and geotechnical parameters

Seismic microzonation is nothing but zonation of the zone. Many detailed studies are carried out by applying all available technologies of a geophysical, seismological, geotechnical and geological nature, and all others as part of the computational mechanism (Figure 2) inputs for the seismic risk resilient buildings design. A seismic tomography for the Devang multipurpose hydroelectric project in zone 5 of Arunachal Pradesh was carried out to suggest a plausible seismic risk resilient design for the 300 m high concrete structure.

The zonation map has only seismic path characterisation based on empirical law whilst in seismic microzonation we do the source characterisation, site characterisation and also a detailed path characterisation. All three physical laws will be used to generate the model. How will we do that? Many institutions are doing seismic microzonation. That is why the Ministry of Earth Sciences developed a Standard Operating Procedure (SOP) to do all the studies systematically. Geological parameters, seismological parameters and geotechnical parameters are considered. These parameters are integrated through GIS microzonation of the four cities (Bhubaneshwar, Chennai, Coimbatore, Mangalore). The other eight cities (Agra, Amritsar,

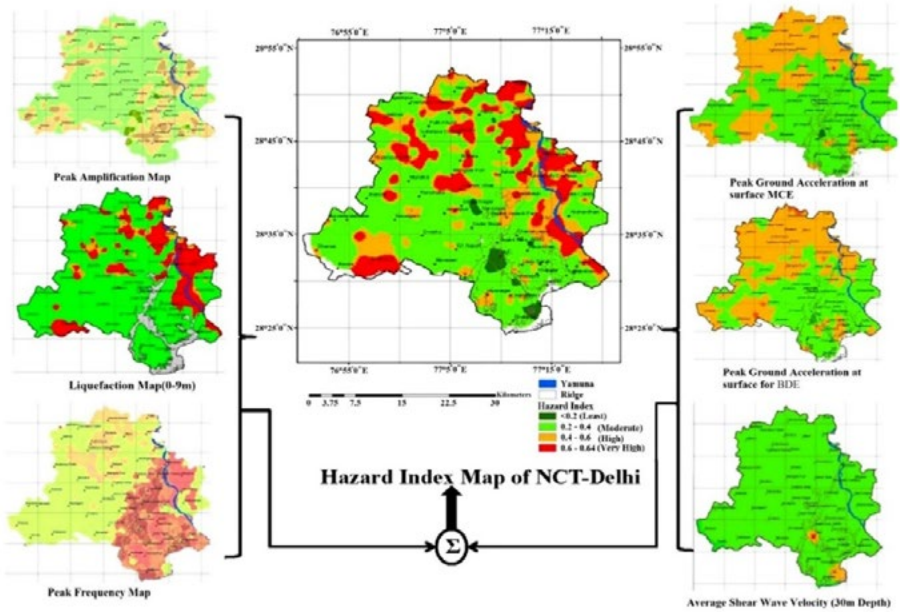

Figure 3: Seismic Hazard Index map (based on peak amplification, peak frequency, PGA at MCE and DBE, liquefaction and shear wave velocity) for the city of Delhi–NCR (after NCS-MoES (2016)

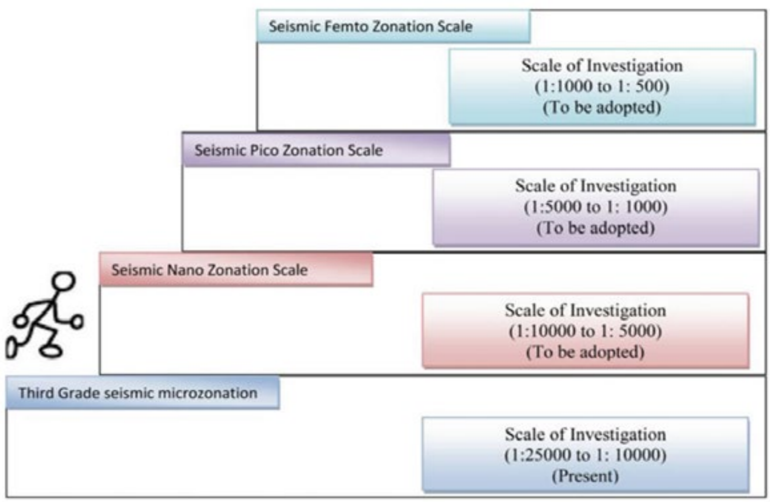

Figure 4: Advanced grades of seismic zonation for safer and earthquake risk resilient urban agglomerates proposed in this study (modified after SAARC [2011] & adapted from Mishra [2020])

Dhanbad, Kanpur, Lucknow, Meerut, Patna, Varanasi) have been taken up in collaboration with the ISR-Gandhinagar, Government of Gujarat. We are doing it in public-private partnership and also in government-to-government partnerships.

Many geotechnical parameters are determined in situ and laboratory. Microtremors study, Down-hole test, and MASW wave for shear velocity are conducted. Analyses of core samples from the boreholes to estimate the stiffness coefficient, its bulk density, all tests, SPT, SCPT, DCPT, Cyclic Triaxial test, Resonant column test, Attenberg test, are undertaken and integrated into a composite map which helps to introduce the factor of safety in their design. This is a very fine grid. The grids are 100 metres, 500 metres or one kilometre to get all values of every parameter.

The microzonation map for Delhi–NCR has been released (Figure 3). We have also found the liquefaction potential zone and the entire city hazard index map has been prepared by taking all parameters of the entire city. The Yamuna river flood plain is the most hazardous area and classified as zone 4. The crux today is microzonation and tomorrow nano zonation. The day after tomorrow it could be pico seismic zonation and femto seismic zonation, etc.

All policy planners need to know how to implement it. This is only possible if it is made legally binding to build a risk-resilient structure. It should be applied to schools, hospitals, prisons and many vital installations.

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6. USE OF SPACE BASED REMOTE SENSING FOR CRUSTAL DEFORMATION AND ACTIVE TECTONICS

By **Prakash Chauhan,** National Remote Sensing Centre, (ISRO), Hyderabad

Since earth is a living planet, core-mantle dynamics leads to plate tectonics which have surface manifestation in terms of surface deformations. Surface deformation can be caused either by earthquakes, landslides or anthropogenic activities like ground water extraction, mining, coal fires, etc. I will deal with how space based earth observation systems have evolved over a period and techniques like radar interferometry, image object tracking and digital elevation differencing are being used to quantify these very subtle deformations, which are happening at the scale of millimetres to centimetres both in temporal and spatial scales.

The Himalayan range in the northern part of our country is dominated by active tectonics, where a large amount of thrust and strain accumulation occurs. Elsewhere in the region, the Indo–Sumatra arc zone and intraplate tectonic activities all across India do produce crustal strain, which needs to be monitored on a regular basis. India has been divided into various seismic hazard zones and many of regions of zones 4 and 5 are heavily populated with high building density. Efforts by various organisations are being made for micro-seismic zonation to arrive at the appropriate building design codes to address these seismic risks. In order to address the future potential seismic hazards across a large region like the Himalaya, it is also important to understand the historic seismicity of the region and seismic gaps. Historically, several earthquakes have taken place in this region which have periodically released the built-up strain, but the question to be addressed is how can we measure the strain. For this it is necessary to integrate various technologies such as remote sensing based eformation and GNSS based ground measurements. We can combine observations from space as well as the GNSS and seismological networks to generate high resolution strain maps.

Today, by using techniques like synthetic aperture radar (SAR) interferometry, subtle crustal deformations measurements are being used to generate time series of continental strain rates. Very high resolution (VHR) satellite data is also being operationally used for post-earthquake damage assessment and post-disaster need assessment (PDNA). There is also wide scope for earth observation data in terms of understanding the tectonics and strain kinematics in pre-, inter- and post-seismic stages.

Satellite based digital elevation models (DEM) are derived using optical satellite image with photo grammetry techniques. Geoscientists have used DEM difference of pre- and post-event situations to assess the surface deformation level. This technique was used during the rockslide event in Rishi–Ganga region of Chamoli during February 2021. To assess the quantum of rockslide volume, the entire rockslide zone was imaged before and after the event and digital elevation models were created. Subsequent digital elevation difference told us how much mass had slipped and what kind of deformations had taken place. Figure 1 shows the DEM difference image and assessment of volume of mass wasting during the event.

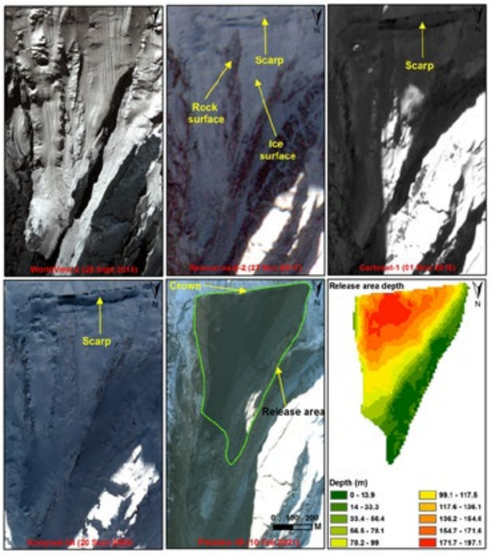

Figure 1: Multi-temporal high-resolution image showing gradual emergence of the joint plane in the crown area. Landslide release area depth estimated from DEM differencing analysis is shown in a colour scale

Another interesting technology is synthetic aperture radar (SAR) technology. It makes use of the larger wavelength of energy which can penetrate through clouds; not only the backscattered energy but the phase differences over the same area at different times of observation are used to quantify the surface deformations. This type of data processing technique is called the interferometric SAR technology (InSAR). There are different methods of doing interferometry, i.e., permanent scatter (PS) interferometric technique or small baseline subset (SBAS) interferometry technique or differential InSAR. A study has been carried out around Chandigarh for quantifying subsidence mainly due to ground water extraction. A significant amount of water extraction is taking place in Indian cities. Chandigarh residents are complaining that houses have developed cracks. This is basically subsidence in various parts of Chandigarh of the order of a few millimetres to centimetres which we can quantify and precisely make maps at a spatial resolution of around 30 metre x 30 metre grid.

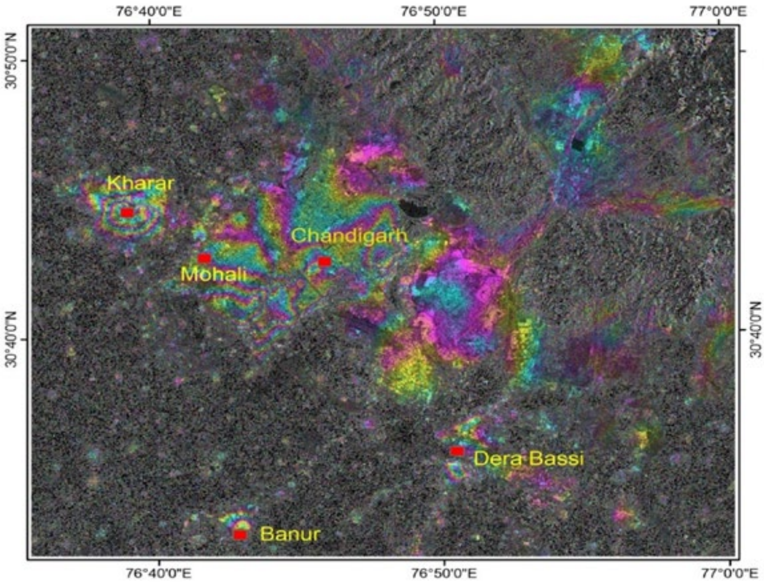

Figure 2: Deformation around Chandigarh and Dera Bassi area as observed using radar interferometric technique

In a recently published work, we have analysed time series data of PS-InSAR over a large landslide in Sirmaur, Himachal Pradesh. We analysed time series data from a satellite called Sentinel-1A and generated the permanent scatter landslide deformation analysis in different phases of the landslides and calculated the velocity of the moment. Figure 3 shows the ascending and descending mean velocity and different components of velocity vectors around the study area.

In another case study around Joshimath area, we have used the PS InSAR technique to estimate the long term deformation rate over Joshimath town. This study deals with time series assessment of land instability/movement around the town. In January 2023, land movement increased many fold and resulted in huge cracks in buildings. An advanced multi-temporal radar remote sensing technique, i.e., SBAS-InSAR, is used to detect, measure and undertake continuous spatio-temporal monitoring of land movement. A network of 424 small baseline interferograms was generated using a stack of 111 Sentinel-1 descending images acquired during May 2019–April 2023. Figure 4 shows the cumulative line of sight deformation (LOSD) rate

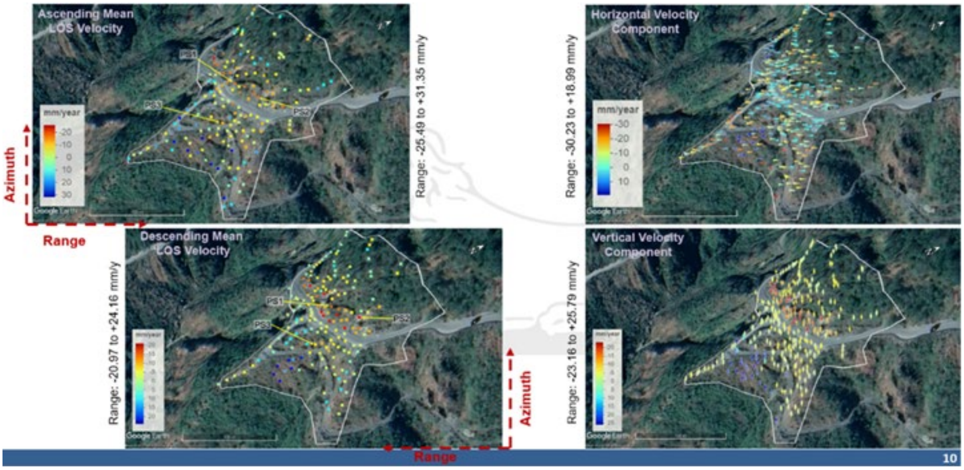

Figure 3: Ascending and descending mean line of sight deformation (LOSD) rate along with horizontal and vertical velocity components around Sirmaur landslide zone using PS InSAR method

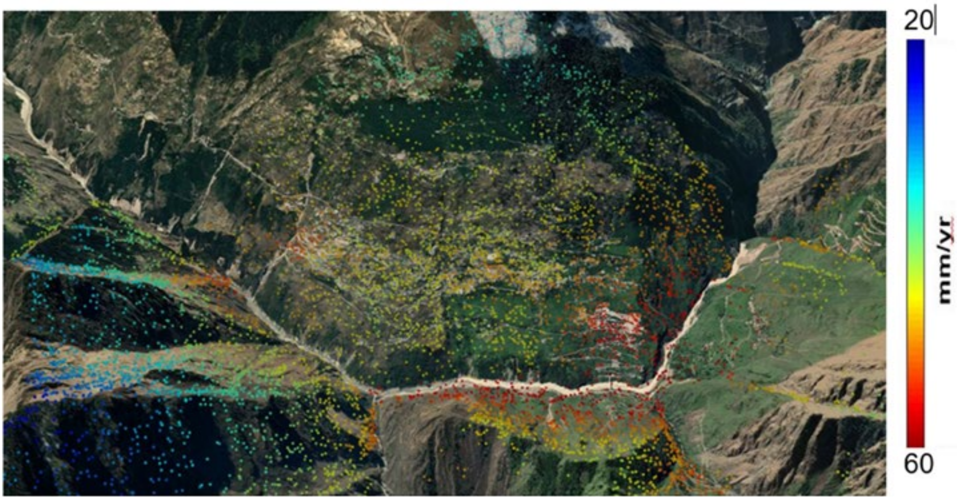

Figure 4: Cumulative line of sight (LOS) deformation over Joshimath using InSAR data during March 2019–April 2013

over the study area. The deformation time series trends show the slow increase in LOSD from January–November 2022, rapid increase from November 2022 ending about mid-January 2023, and thereafter becomes almost constant till the end of March 2023.

Another important use of earth observation data is for post-earthquake rupture assessment and damage detection. Figure 5 shows an example of very high resolution data over Turkey after the devastating earthquake of 6 February 2023. One can clearly see around the airport region how the zone ruptured after the earthquake. Combining multiple such optical and microwave InSAR images, surface and sub-surface manifestation of post-earthquake ruptures can be estimated.

Space based global navigation satellite system (GNSS) signals received by ground receivers have also been very effectively used by various researches to estimate crustal deformation patterns across large seismogenic belts. It is recommended that GNSS based deformation be combined with InSAR based data to get much more precision and high-resolution mapping of deformation leading to strain mapping. Often ground based GNSS networks are not very dense but the accuracy is high, so combining it with InSAR observation is a good strategy, which is currently not being done. Such products will be very useful for assessing potential seismic hazards in future.

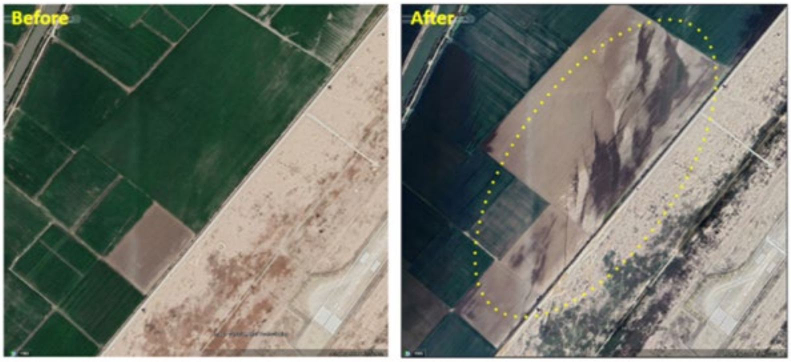

Figure 5: Surface rupture of turkey earthquake of February 2023 around Hatay Airport, Turkey

The Indian Space Research Organisation (ISRO) and NASA of the USA are jointly working on the NISAR satellite mission and the satellite will be launched in early 2024. NISAR is a dual frequency, L and S band SAR system. S band system is being developed by India, while L band SAR is being done by NASA. This will be a game changer for the earth science community as far as the space observations for surface deformations are concerned. Every 12 days there will be systematic observation and a 12-day time series of deformations all across the Himalaya can be generated. It is being planned to generate deformation products as a service and the geoscience community will be immensely benefitted by these observations to quantify the strain rates all across the Himalayan arc system.

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7. EARTHQUAKE INDUCED LANDSLIDES

By **D. P Kanungo**, Chief Scientist & Coordinator, Geotechnical Engineering & Geo-Hazards Group of CSIR-CBRI, Roorkee

Earthquakes can trigger a landslide; landslides can trigger a tsunami or can dam a water body leading to a flash flood—we are talking about a multi-hazard scenario. It is known that the Himalaya is fragile and being a young mountain chain it has immature geology and variability in the litho-tectonic set up with rock strata or soil or debris. The topography is also varying across the area. With such variations in the litho-tectonic set up of the Himalaya, we face earthquakes, landslides, landslide dams, flash floods, etc.

We generally classify landslide disasters into three categories: rainfall induced landslides, earthquake induced landslides and anthropogenic induced landslides. More than 95 per cent of landslides are rainfall induced, are more frequent and earthquakes are less frequent. Earthquake induced landslides are triggered with the ground shaking in the existing litho-tectonic set up of the ground resulting in deformation or the failure of the earth mass. Anthropogenic induced landslides are man-made and the debate is whether all the landslides in the Indian scenario are man-made landslides. Can we call landslides a natural disaster or man-made disaster? Everywhere on hilly terrain we have interfered with the bearing capacity of the ground and ignored building bylaws or regulations. We have engineering knowledge, but we have casually planned our infrastructures on the ground. That is why we are facing such consequences.

Earthquake induced landslides are mostly distributed in the western and north-eastern Himalaya. The 184 landslides including rock slides, rock avalanche, rock fall, debris avalanche, debris slides, etc., were triggered due to the 1991 Uttarkashi earthquake. Similarly, there were 56 landslides of different types due to the 1999 Chamoli earthquake. In any earthquake there is a distribution in different types of landslides. Landslide science and research has four quadrants encompassing hazard-vulnerability-risk assessment: landslide investigation; identification of precursor signatures; instrumentation and monitoring system; leading to early warning and landslide conservation and mitigation measures. But most of the time we talk about hazard zonation only. We should look beyond hazard zonation. We should assess our infrastructure, how vulnerable they are when exposed to landslides, whether it is rainfall, earthquake or human induced. There is a need to understand precursors for landslides also. There is no point waiting for the pore pressure or the stress condition to cross the threshold, causing devastation.

Rainfall induced landslides are predictable in space and time. Landslide hazard/susceptibility zonation mapping predicts the potential landslide areas in space. For rainfall induced landslides, ground based IoT enabled real time monitoring and AI/ML enabled early warning systems are developed and deployed for validation. Research on SAR interferometry based and drone based landslide monitoring and early warning is still going on. Earthquake induced landslides are predictable in space and we are still struggling with its prediction in time scale. As yet we cannot predict the time of an earthquake, and therefore cannot predict the time of earthquake induced landslides. But if at all we are able to predict the time of an earthquake, the lead time prior to the disaster will remain a concern to us in the future scenario. Anthropogenic landslides are especially predictable in space and time scale as we are responsible and accountable for these.

As early warnings systems are not in place we should focus on the issue of resilience. Our vision or focus should be to build a landslide disaster resilient society or built environment. We need to focus on how we can make our environment or society more resilient towards landslides, be they earthquake, rainfall or human induced. The aim is to develop and implement mitigation strategies for reducing the risk of landslides with institutional mechanisms, disaster prevention strategy, early warning system, disaster mitigation schemes, existing infrastructure strengthening system, preparedness, and human resource development and capacity building. The prime objective is to provide a mechanism to enhance landslide resilience through local level interventions to address landslide vulnerability and risk effectively. Several scientific interventions are going on, but if we don't do disruptive science or translational science, it will not help our communities. The last mile reached should be the community who are affected by such disasters.

Why is it relevant? The whole northern, north-western, north-eastern Himalaya and the Western Ghats are prone to landslides of varying nature. We should look beyond landslide hazard in assessing the vulnerability and risk of a hill habitat. This has two aspects. One is the intensity of the landslide and the other is the resilient capacity of our built environment or infrastructure. We have to reduce the intensity of the landslide and we have to increase the resiliency of the infrastructure. Only then can we have a better balance for protecting our infrastructure and thereby protecting our lives. For reducing the intensity of the landslide, we need to focus more on the non-invasive investigation techniques such as geophysical tools to ascertain the failure mechanism, and subsequently on cost-effective sustainable optimised mitigation measures, including bio-engineering and drainage measures, specifically. To increase the resilience capacity, we have to opt for a repair-retrofitting and strengthening strategy for infrastructures to improve their resiliency towards such disasters. In each such phase, the participation and involvement of the local community is essential in the present scenario. The local public or the common man who has built a house in his lifetime should be educated in the process to understand the safety of his life through such interventions on the ground and on the infrastructure. We have to work with them to develop the strengthening system and they will come forward to invest in retrofitting their own buildings. Obviously, the early warning systems or awareness or capacity building need to be integrated in every component of the development process; only then can the system to make a resilient built environment work. We have to interact, we have to integrate the public, and we have to understand their emotions and their level of understanding.

The methodology for hazard-vulnerability-risk assessment is already developed. This is not only applicable to landslide hazards, but also to multi-hazard scenarios including both earthquakes and landslides. This exercise has been done for Gopeshwar township, the district headquarters of Chamoli, Uttarakhand, and is being carried out for Uttarkashi township. The buildings can be stone masonry, two-storey drystone masonry with wooden pitched roof, single-storey dry stone masonry with flat roof, RCC building, mixed typology of buildings, etc. There is variability in the construction practices and we have to understand each typology of buildings in the hills and what sort of intervention is required in each to make it resilient.

The other most important aspect is the mitigation of landslides to reduce intensity. We lay more stress on structural measures and making the whole hill slope a concrete one. Structural measures should be kept to a bare minimum and precisely optimal. We should focus more on the drainage management system on hill slopes and the bio-engineering measures.

Building bylaws and regulations should be different for different hill regions or states as their topography, litho-tectonic set up, hydrology, etc., are different. Community level participation and involvement in formulating building bylaws and regulations should be explored so that these can be adopted and not imposed.

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8. IMPACT OF EARTHQUAKES ON MORAINES DAMMED LAKES

By **Ashim Sattar,** Inspire Faculty, Divecha Centre for Climate Change, Indian Institute of Science, Bengaluru

I will cover the glacial lake outburst flood (GLOF) triggers and processes, earthquake and glacial lake outburst trigger mechanisms, and GLOF hazard exposure in the Himalaya. I will also examine two specific regions. One is Uttarakhand and the other Himachal Pradesh for the distribution of glacial lakes in high seismic source zones, and GLOF implication of Gorkha earthquakes. I will also look at GLOF risk reduction in Himachal Pradesh.

We all are fascinated by satellite images or glacier terrains. Water bodies in high altitudes attract tourists. Some of these lakes can be of glacier origin. Glacial lakes are formed when glaciers melt and recede with time. The meltwater is dammed by frontal moraine (glacier deposits) and with time the glacier meltwater is accumulated in the form of liquid water in depressions. Figure 1 shows a glacier body. With time, as the glacier recedes, the bedrock is exposed. We can use remote sensing data which is very useful to monitor the growth of these lakes. This is Landsat Optical imagery which allows us to go back in time and see how the lake has grown. The first image is from 1994. The lake was 0.09 square kilometres and with time it almost doubled in size.

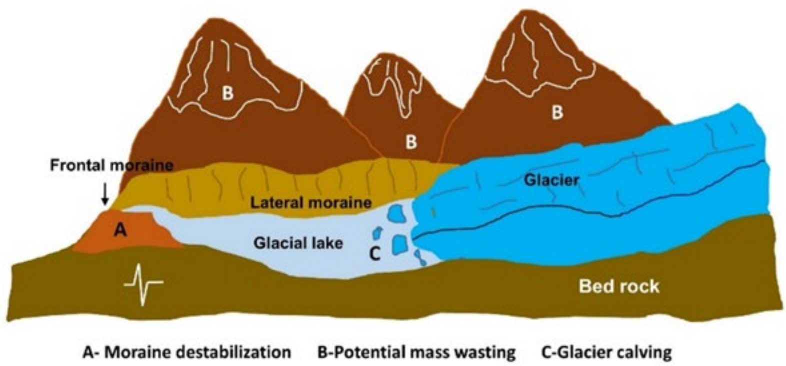

Figure 1: Schematic showing a glacial lake and its surroundings including the glacier, the damming moraine, mountain cliffs and glacier calving

What are the trigger mechanisms of GLOF? 80 per cent of GLOF events occur because there is an impulse wave which is like a tsunami on a smaller scale. There is a mass movement into the lake which basically generates a tsunami-type wave which overtops the frontal dam and finally causes a flood downstream. One of the major triggers can be earthquakes. To be specific, when the ground shakes, there can be failure or rupture of the frontal dam. Other causes can be glacier mass coming down from the hanging valleys or debris flows into the lake (Figure 2). This shows an avalanche which struck the lake and caused impulse wave which will finally led to overtopping and moraine erosion.

Earthquakes and GLOF: How are the mechanisms connected? There are many causes, but the primary cause of GLOF can be earthquakes. Earthquakes can directly lead to the rupture of

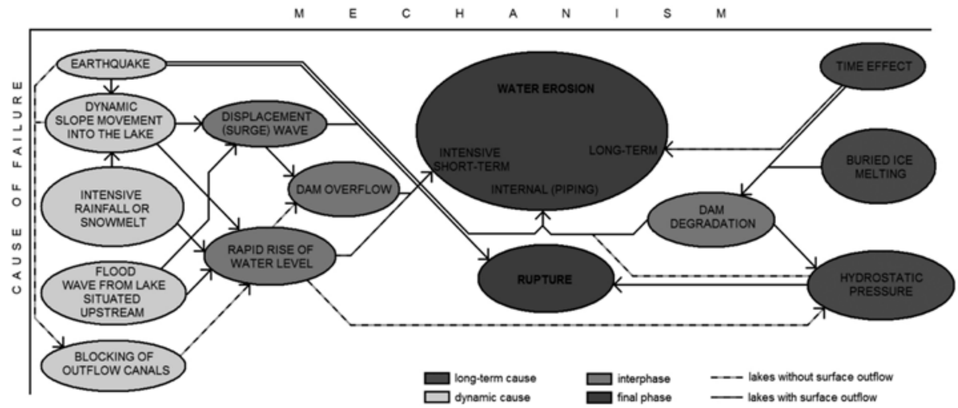

Figure 2: Mechanisms of GLOF (Emmer and Cochachin, 2013); Earthquakes can be a dynamic cause of GLOF that can lead to direct rupture of the frontal moraine or trigger mass movement that can potentially impact a glacial lake

the moraine and to slow internal piping failures. But again, earthquakes can trigger secondary hazards. For example, it can trigger dynamic slope failures which are basically landslides or avalanches which are triggered by the earthquake. Then there are displacement waves which are created. There can be rapid rise in the water level, eventually leading to the rupture where hydrostatic pressure at the dam increases.

How have the glaciers been behaving over the years? One paper (see Bolch et al., 2012) tells us that most of the benchmark glaciers in eastern, central and western Himalaya have been showing glacial recession. There's been cumulative length reduction of these benchmark glaciers. What does this mean? Glaciers are losing mass and because of that the hazard situation is changing. Another paper (see Shugar et al., 2020) shows rapid worldwide growth of glacial lakes. The numbers are shocking: 50 per cent increase in the glacial lake area and volume from 1990 to 2018—doubled in its area and volume. Of course, the hazard situation is increasing, there are more lakes, there is more hazard potential, and of course potential risk downstream.

In another interesting study (see Taylor et al., 2023) of population exposure to glacier lake outburst floods, we see the population exposure is highest in high mountain Asia. Out of that, 32 per cent of the exposed population is in India. If we look into the numbers, three million people are potentially exposed to glacial lake outburst floods. But how great is the risk from the glacial lakes if we look at the average distance? Within 5 kilometres there is already exposure of population. It shows that over time, the population is migrating towards higher elevations. But in other mountain ranges we can see that it is not that high.

Glacier inventory is what we have been doing. If we look into the earthquake source zone (zones 4 and 5) and if you see temporal growth of the lakes, in the year 1968 there were 60 moderately sized glacial lakes which are above 0.5 kilometres. By 1994, 27 new lakes formed. By 2001 we had 102 lakes and by 2016 we had 130. We matched our estimates with the inventory which is published by ISRO, and we found similar results. The numbers have gone from 61 to 130, but in terms of area it has gone up from 1.9 square kilometres to 4.6 square kilometres.

Where are these new lakes located? They are located in the Alaknanda and Bhagirathi basins mostly. Both these basins are in zone 5 of earthquakes. We can see that most of the lakes are formed in the altitudinal range of 4,500 to 5,500 metres above sea level. These are some of the data sets which have recently been made available for the glacial lake inventory, one from ISRO and one from Wadia Institute of Himalayan Geology. We know that Uttarakhand has a lot of lakes in zone 5.

Let's look into the impact of earthquakes on moraines with the example from the Gorkha earthquake. The Gorkha earthquake impacted Rolpa lake in Nepal, which, before the earthquake in 2000, was lowered by 3 metres by engineering interventions. After the Gorkha earthquake, slumping and cracking developed on top of the frontal moraine and boulders also got displaced from the moraine which is disturbing to the integrity of that particular damming structure. We also have cracking right at the frontal moraine which is very crucial when it comes to potential GLOF events.

Imja is one of the most hazardous lakes in Nepal. What was the impact of the Gorkha earthquake on this particular moraine? Huge amounts of boulders were displaced from the frontal moraine and lateral cracks developed; and most importantly, there was seepage after the event. But can such earthquakes lead to problems in the near future? Take the example of the 2016 transboundary event that occurred in China and had an impact in Nepal. This was intensified because of the Gorkha earthquake. How? The GLOF started in China and impacted Nepal. There is a history of GLOF events in this transboundary basin, which is called the Poiqu basin. This particular valley had previous GLOF events in 1964, 1981, 1983, 2002 and 2016. All these GLOF events have occurred from the large lake called Cirenmaco. But the 2016 event occurred from a tiny lake next to it which is unbelievable; it is 100 times smaller. But the impact of this particular event was equally similar to what this bigger lake has created. What is the reason? The reason is that the Gorkha earthquake was one year before this event and there was a lot of landslide deposit which was available for the GLOF to transport.

One study (see Sattar et al., 2022) showed very high landslide density which destructed the Bhote Khoshi Hydropower Station in Nepal. This GLOF actually led to reactivation of the landslides triggered by the Gorkha earthquake. The debris flow that went into the lake caused it to overflow and finally led to GLOF.

The cross-section before the Gorkha shows that almost 80 metres of sediments were deposited during the Gorkha landslides at places. A lot of loose sediment is available for the little water that has come to transform into hyper-concentrated or debris flow. Interestingly, there was an early warning system which failed, but we have a new early warning system in this valley constructed after the 2016 flood event in 2020. Now it is functional, and we have a monitoring system at the dam site itself.

India is equally exposed to transboundary GLOF hazards. India shares its borders with China, Nepal, Pakistan and Bhutan where several glacial lakes are present. All of them are hazardous and it is most important to examine how hazardous they are.

Finally, how can we use modelling techniques to look into glacial lakes hazard reduction before it is actually implemented on the ground? In a recent paper (see Sattar et al., 2023) we looked at the Gepang Gath lake, the largest lake in Himachal Pradesh and potentially hazardous. A village called Sissu which is 10 kilometres downstream is a tourist attraction. It started as a tiny little lake and is now 2.3 kilometres long. We tried to examine different ways in which we can mitigate and reduce the hazard. We tried to model different avalanches that can hit this particular lake and what would happen if we tried to lower the water level in the lake by

10 metres; what effect would it have in terms of hazard potential and downstream risk. If we reduce the water level of the lake by 10 metres or 30 metres, there is no overtopping of the moraine in case of low and moderate events (Figure 3). The wave is not overtopping the frontal dam. The risk has come down at the source itself. When we consider large magnitude events, there is overtopping of the water but the risk in Sissu village is significantly reduced. This is the place where, for the first time, hydropower was generated from a glacial lake. They lowered the lake and generated electricity out of it to support the villagers; around 120 households are getting electricity from this lake.

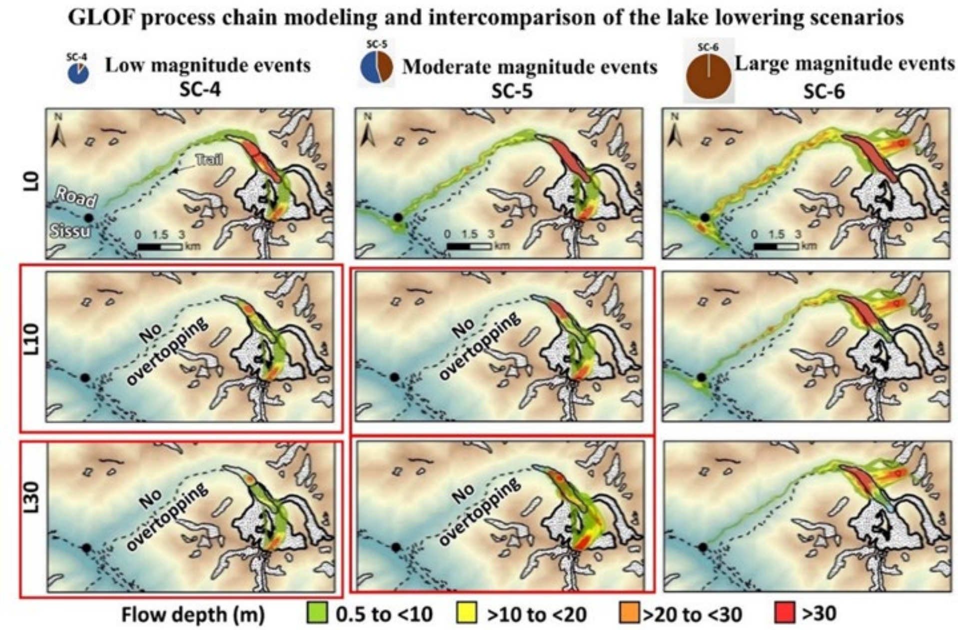

Figure 3: The effect of lake lowering in GLOF risk reduction; GLOF flow in different lake lowering scenarios; L0, L10 and L30 refers to no lowering, 10 m lowering, and 30 m lowering respectively

In the new NDMA guidelines for GLOF, this statement is important: 'The frequency and magnitude of moraine dam failures and GLOF will continue to increase with the current and continued scenario of global warming and present one of the greatest threats to people.'

To conclude, earthquakes can be primary triggers of glacial lake outburst floods. Earthquakes can be the cause of secondary triggers like landslides and avalanches and evaluating earthquake hazards must be an integral part of glacial lake outburst flood hazard assessment. Of course, disaster risk reduction measures significantly reduce the potential exposure. Finally, we must bring awareness about potential risks to the community.

The last statement I make is, Is the vulnerability decreasing at the rate to offset the increasing potential hazard and risk?

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9. EARTHQUAKE RESPONSE

By **Kamal Kishor**, Member Secretary, National Disaster Management Authority, New Delhi

The seismic zone action map which we have seen is likely to be updated soon. The area in zones 2, 3 and 4 is 58 per cent, but within that, a population of 75 per cent resides. Therefore, we have disproportionately high earthquake exposure. The urban population is increasing at 4 per cent per year, there is a housing shortage in the country—more in urban areas than in rural areas—we are adding to the built environment at breakneck speed, nearly 80 per cent of the houses are in zones 3, 4 and 5, and most of our built environment is in areas that have moderate to high earthquake risk.

The population density of India and seismic zonation needs to be reflected upon. In north and north west India, there are zones of high population density that almost match one to one with areas of moderate to high earthquake risk. It's not just that we have a high risk of earthquakes; it is also that disproportionately more people live there. Those areas are experiencing high growth as well. We cannot do much about reducing our exposure. But what we have to do is that in view of that increasing exposure, we have to reduce our vulnerability and have much better building stock.

If you go by the building typology given by the Census of India, in urban areas, 78 per cent of the houses are burnt brick. These are masonry buildings which are not reinforced and every year we add 10 lakh buildings to this stock and these are all going to collapse in an earthquake. While reinforced concrete frame buildings are seen, their proportion is still very low in the country.

In order to address earthquake risk, we have to identify different kinds of risk context. Let us consider four different contexts: the National Capital Region (NCR); hill towns; other urban areas; and rural areas. We require different strategies for each of them. Needless to say, NCR is important because it is the Capital Region and 7 per cent of India's GDP comes from here, even though the population is only 3.8 per cent—7.6 per cent of India's urban population and 2.1 per cent of the rural population lives here. Some of the major issues are increased demand for housing resulting in unsafe high rise buildings. Every building demands parking space. For this, buildings are made on stilts. As a result, we create a building stock which is vulnerable to damage. But there are ways to address this and it need not be a choice between parking space and earthquake safe buildings. But it is not being done and it is needed on scale. Several unauthorised colonies with poor building conditions, poor accessibility and of course lack of enforcement of codes are coming up. We need a focused effort in the NCR region.

Hill towns are always in the news. Unplanned construction, shortage of land which results in construction in unsafe areas, and that too, mostly non-engineered construction. There are secondary hazards as a result of an earthquake. One of the problems in hill towns is that apart from the stable population, there is a huge influx of tourists. They may be coming from areas where there are no earthquakes and they have no awareness of what to do. They don't know about drop, cover and hold, for instance. Also, a lot of our building codes are not specific to hills. How do we upgrade that? Many of these urban centres are located on river banks that are susceptible to liquefaction which requires a different kind of land zonation. Many of them are now seeing high rise buildings to meet the demand for housing and much of this building stock is unsafe.

Unplanned development and no application of building codes are characteristic of rural areas, mostly non-engineered, unsafe construction built by masons. In many areas what is happening is that a place is actually neither urban nor rural, it is peri-urban, hence unplanned construction and no codes. The area is basically subsumed in municipality boundaries. Some penalties are paid and those get regularised. How do we make sure that we have a futuristic vision for these areas as well?

We need to do three things. We have to reduce future risk. That is not to say that we will reduce the risk of earthquakes themselves, but we will reduce the losses from earthquakes which means constructing all the new buildings such that they can withstand earthquakes. It is entirely possible. The big opportunity for our country is that a lot of the buildings are yet to be built. We should make sure that the 3 to 4 per cent growth is only of good construction. If we do this, in 10 years we can turn the building stock from earthquake vulnerable to earthquake safe and mitigate existing risks by mechanisms such as retrofitting. There will still be risks so we should have a strong response capacity when earthquakes do occur.

There is a lot of work on seismic microzonation that the Ministry of Earth Sciences has done. We need to look at the vulnerability of buildings, infrastructure, multiple techniques, retrofitting, etc. We just need to scale it up.

Hoe do we reduce future risk? This has policy issues, and one is serious capacity gaps. We need to update the regulations in line with some of the new knowledge and new understanding of earthquakes, and we must have a way of financing risk reduction. Till a few years ago, we did not have a mitigation fund. Now India has the largest sum of money for disaster risk reduction in the world—roughly 6 billion dollars. It might not look like much for 1.3 billion people, of whom about a billion live in moderate to high earthquake risk areas. At $6 per person, it is still a lot of money. The kind of resources we have for disaster reduction other countries can just dream of. If we come up with imaginative projects we can actually implement risk reduction. There is also need for more multidisciplinary research.

There is the issue of dealing with residual risk as well, that is, having a good response and recovery system. We did a wonderful job in Nepal a few years ago and now in Turkey. We were amongst the first teams to land there. Despite the fact that our people are working in very difficult and cold conditions which they were not trained for, and despite the fact that they had language constraints, they were the most appreciated. The NDRF teams and the Army's medical corps were involved, and the latter treated more than 4,000 people for injuries and performed 100 surgeries on the spot. We erected field hospitals within a matter of 48 hours. We had our own operation theatre, our own generator sets, we flew in fuel from India. And the case load of injuries was such that there were a lot of repeat patients and follow-up cases. We have collected data on the kinds of injuries. Have people been injured inside the house, outside the house, in what kind of building? Who else survived in that building? What are the kinds of injuries? This will help develop a very good epidemiological model of earthquakes so that we can predict for a similar built environment. How many anaesthesiologists are needed? How many orthopaedic specialists are needed? What is the kind of medical response required? We should be able to predict the number of deaths as well as the case load in terms of minor and major injuries. There is a lot we have learnt from these two earthquake responses and we must use that not only for future response outside the country, but also to strengthen our own systems.

We know about public awareness messaging of drop, cover and hold. There is the issue of risk financing. How can we ensure some of our assets? How do we finance many of the risk reduction measures, particularly safety of schools and hospitals? Do we need response funds? There are many dimensions of awareness generation. Capacity building also has many dimensions, many stakeholders in constituencies that we need to target through our capacity development efforts.

If we don't act soon, the level of earthquake risk will continue to rise. When I say earthquake risk, I don't mean hazard, I mean the risk of losses. But if today we begin to enforce building codes and bylaws without even touching the existing vulnerable buildings, in 2065 we will be in a different position with a very small proportion of building stock which will be vulnerable. Adding retrofitting of existing structures during their life cycle will make losses even lower.

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10. DISASTER RESPONSE

By **Abujam Bijoy Kumar Singh,** Commandant, National Disaster Response Force (NDRF), New Delhi

I would like to start with a brief history about the NDRF. The NDRF was set up in 2006 as per the Disaster Management Act 2005, specialised in response to natural and manmade disasters. Presently, we have 16 battalions, each battalion a strength of 1,149. A battalion consists of 18 teams and there are 47 personnel in each team. We are well trained in medical first responder (MFR), collapse structure, search and rescue (CSSR), and chemical, biological, radiological and nuclear (CBRN).

Most of the members in the search and rescue team are from the executive cadre, but we have specialised members like structural engineers. For search and location of victims there is a canine team (dog squad) and a medical support team which have the necessary paramedical staff and medicines to give first aid and to stabilise the patient before transporting them to hospitals.

NDRF has a pan India presence and the 16 battalions are deployed at different locations. There is more deployment in the Himalaya because of its vulnerability. Each battalion has regional response centres (RRC) which are spread across India.

What is our response mechanism?

Information about an incident is received, after which we try to find out the type of hazard, the extent of damage and when the incident occurred. Accordingly, we mobilise and activate our teams. One team might be is sufficient for one building or if it is a cluster of buildings we may need more teams accordingly. After arrival at the site, we again confirm from the incident commander what the access route is and the expected number of victims. Whether the building is GO or No GO, and if it is No GO and the victim is inside then we have to do the strengthening of the building (shoring) or mitigate the hazard if any. The incident command post is most important. It will be connected through to the higher commands and our information can be sent to the Headquarters and also to NDRF. After completion of ops, we check our men and material and after obtaining clearance from the district authorities, we fall back to our locations.

The Turkey earthquake was a pancake type collapse. In such a case it is very difficult to locate and rescue victims. Locating the victim is very difficult because there is no void space (where the possible live victims will be found), and if it is there it may be in the basement or on higher floors from where it is a herculean task to gain access to the victim.

Mobilization. At this stage our team commander briefs troops under his command to save time. As per protocol, the team has to leave within 20 minutes of the information being received. We specifically brief the teams about the nature of the disaster, hazards present if any, and further divide the task and brief them about it.

Let us take the example of Chintel Paradiso, the building that partially collapsed in Gurugram last year. The officer is inspecting and making his initial assessment. Five floors have fallen on the first floor, and we are entering the ground floor at great risk. I am trained only for rescue. But the amount of confidence we gain from training makes us brave enough to enter. We are then placing sand bags as only shoring will make the structure stable.

Securing the scene is very important. There is no point if the rescuer becomes a victim. So we want to stabilise the building and the work site before trying to reach the victim and we also ensure that the victim is not injured while evacuation. In the Chintel Paradiso case the rubble of five floors made it difficult. We couldn't use the big machines and cutters for fear of more rubble falling. We used chipping hammers manually and that took 18 hours. When asked about this time gap, I say life is more important so we should not take risks.

Our team leaves no stone unturned to physically search the place, be it with canines or technical search equipments.

When we locate a victim, we start the breaching process. First, we make an inspection hole. From the inspection hole we try to find out where the victim is, because if the wall or floor is cut, it may injure the victim more, so we have to shift our location again. From the inspection hole I use the victim locating camera to find the victim. If I need to shift the cutting part then I shift to another area so that the trapped victim is not injured in breaching.

Lifting the load. Sometimes we find the rubble on top of the victim, and after lifting it, only the rescuer can approach the victims. There are two types of approaches. One is vertical. In a pancake type structural collapse we generally enter from above. This is the vertical approach. If the walls are not damaged, the walls are cut through a V shape and the rescuers enter and rescue. This is the horizontal approach.

Victim stabilization is done by our medical first responder. First, a cervical collar is placed on the victim because in earthquake situations the spine may be injured. After that we take the victim on a stretcher (if possible) and then pull them out gradually. After rescuing the victims we don’t leave the work site in case all the people are not accounted for. We will search again and this time heavy machineries can be used because dead bodies do not emit heat and it is very difficult to detect with the help of canine/thermal imager.

Equipment. There are some standard equipments used by NDRF while doing search and rescue operations: life detector type 1—it is also done through seismic and acoustic sensors; victim location camera—it has a telescopic camera which can be inserted through small gaps; cutting equipment like chipping hammers; bolt cutters for iron rods; diamond tip chain saw for cutting wood; and rotary rescue saw—this is the hallowed equipment for rescuers as it has three types of blades with which concrete, steel and wood can be cut; breaching and lifting equipment; airlifting bag; Ramset, etc.

We learnt a few lessons from Turkey. If such massive disaster happens in our thickly populated cities, what will we do? During such high intensity earthquakes roads are damaged, flyovers topple, and the most important part will be the heavy machineries for clearing the roads. Turkey had many vehicles on the roads, many lorries which were helping the people, volunteering on their own for rescue work. The same is required in India. Communication was a problem for us as the teams couldn't be contacted because our quick deployment antenna (QDA) was not working there.

Physical fitness is more important for us than for the common person and training has to be vigourous. Team members need to work almost 24 hours a day in stressed conditions and in confined spaces. If they are not physically fit they will not be able to perform their duty. The difference between state disaster and NDRF is the training and quality equipments.

The NDRF has so far conducted 9,808 programmes for community awareness. In 2023 within three months the NDRF conducted almost 500 programmes with more than 2.5 lakh beneficiaries. We have also started school safety programmes and mock exercises. Spreading awareness to the communities is most important. People ask what does NDRF do when there is no disaster? We conduct community awareness programmes and school safety programmes. I train my team and I train the community because I feel that this is my primary duty. When the community is trained, I may not be required because the community will be saving the victims first. It is the community which brings out live bodies as they reach the incident site before us. We, the think tank, have so many promises to keep. And miles to go before we sleep.

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11. AWARENESS ABOUT EARTHQUAKES

By **Vikrant Mahajan,** CEO, Sphere India, Noida

We need to have awareness among different stakeholder groups. First of all it begins with knowing the risks, wherein the earthquake zonation map of India helps. We have seen that a large population is exposed to various earthquake zones, but along with that we have a very mobile population. As far as awareness is concerned, our general experience is that people look at weather patterns, but we need to simultaneously look into how we are moving into different earthquake zones.

India's population has been increasing, and the demographics are also shifting. From the lens of disaster analysis, every year due to various other disasters, around 25 lakh people move to urban centres and most move to places which are more vulnerable with semi urban construction. This is where the earthquake risks and other hazard risks are increasing. The risk vulnerability is probably increasing and of course the Himalayan belt and some of the other areas are highly vulnerable for earthquakes in India.

Some of the critical areas of earthquake management in India are:

- Awareness among the various stakeholders and structural mitigation measures.

- Monitoring and enforcement of earthquake resistant building codes and appropriate town planning: India is a largely rural country that is rapidly transitioning to an urban country. The level of risk is increasing, especially with the poor enforcement of building codes.

- Trained manpower is needed for all manner of disasters.

Why do we need awareness about earthquakes?

As mentioned, there is a lack of awareness among people about earthquakes and associated risks, especially in the highly mobile population living in densely populated urban centres and new infrastructure. While there is planned infrastructure within building bylaws, we are often not convinced. I live in a high rise society in Noida. After the Chintel building collapse in Gurugram there were a lot of concerns taken up with RWAs and other agencies but they could not collate the technical resources to get the assessments of buildings. This is where the issues of compliance come in.

The consequences of earthquakes can be severe. The recent one in Turkey was devastating even though the country is less populated. But in India we have areas which are very highly populated, and even in the NCR there are clusters where large equipment cannot enter. The same goes for old Delhi clusters. Even fire brigade trucks cannot enter these areas and it raises concerns about the kind of construction that has been allowed. The people living in these clusters are among the most vulnerable because they come from the poorest segments of society.

We cannot look at earthquakes singularly as they are linked with other hazards. Earthquake triggers landslides, earthquakes are linked with the glacial lake outburst flood, etc. Even the community is not homogeneous so planning has to account for that. There are children in school and colleges, elderly people, and among the latter some could have mobility issues. There are people residing in informal settlements, a working population that commutes to and from work over great distances, and those who have limited access to information and other critical infrastructure.

Who are the stakeholders?

Important stakeholders are those who are involved in awareness building. They include the government, non-government organisations, educational institutions, the private sector, and the community of course. The media also can play a very important role but there is a need to sensitise the media more.

Awareness is at different levels. Firstly, awareness is required at the individual and household levels. Beyond the drop, hold and cover there is the pre-prepared earthquake emergency kit to evacuate safely.

Then there is awareness at the community level. They develop a community based earthquake organisation and preparedness plan. Every community must have safe areas where people can reach after evacuation. Evacuated victims can't be left to move around in areas that are still vulnerable. Further, business organisations and offices must have evacuation plans.

Of course, the emergency responder: the NDRF, SDRF, etc. But beyond, it is the community that becomes the first responder reaching the site even before. The level of effort that is being put into training the communities must be highlighted. Approximately 50 lakh people have been trained by NDRF as community responders. Even if 1 per cent of the population at risk is minimally trained it will result in 1.25 crore trained community volunteers. We are still very far behind that level. We should aim for at least one trained person for every 100 people in the most vulnerable areas. We need to have collaborative forces for them.

When we look at awareness, there is a before-during-after earthquake paradigm that needs to be kept in mind. Attention is primarily towards 'drop, hold and cover', which is a 'during earthquake' phenomenon and a drill for moving out of the affected area. I think it's the preparedness time, before the earthquake, when we need 'more awareness' as to which area we are in, the vulnerability associated, what are the earthquake risks, etc.

I am assured that the building I live in is resilient to earthquake risk and is under compliance of the building codes and bylaws. If I am aware about this I can work with the authority, RWA or other agencies as necessary liaison points within the community. If these liaisons are maintained it will amount to a significant level of awareness and preparedness against disasters/earthquakes.

How can we increase awareness about earthquakes?

1. Education about them should be an essential part of the curriculum of schools and colleges. There should be a paper on disaster management that builds the minimum level of understanding about the hazards and risks where we live and in the vulnerable parts of the country.

2. There are early warning systems and processes for early dissemination of information. Emergency preparedness trainings which the NDRF organises, along with the community level training organised by NGOs and other civil society actors play a crucial role in generating awareness on earthquakes.

3. Building codes are updated regularly, but we must ensure they are being enforced properly.

4. Public campaigns are a very important component of awareness building. NDMA has a national earthquake description project, and the government also has some mobile apps like weather apps, the 'India Quake' and 'Sagar vani', etc.

5. Japan makes for an important case study. In comparison to earthquake risk in Japan, India is very different. Every year there are high frequency earthquakes and the intensity of earthquakes over years has grown. Earthquake preparedness in Japan is part of their culture. Every child in school is taught earthquake safety and drills are carried out regularly. It becomes part of their growing up. We should develop a similar culture in our youth also. If we ensure new buildings are earthquake resilient, simultaneously investing in the education of the new generation, a turnaround can happen.

Sphere India is a collaboration of multiple entities, including NGOs, the UN, corporates, academic institutions, etc. We have a network of 805 organisations spread all across India. We regularly organise such awareness programmes and our target is to train at least 1 per cent of the population. They can also get trained on a digital platform. We are working on such a learning module and working towards collaborating with various authorities and agencies to take that forward. By 2030 we should have trained at least 10 per cent of the population.

Way forward

What is required is a coordinated collaborative approach, regular training and drills, community involvement, continuous monitoring and evaluation of training and capacity, building awareness programmes, revision of our building codes and bylaws and enforcing them properly. Rapid developments in science and technology should be used towards an early warning systems.

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The India International Centre was founded with a vision for India, and its place in the world: to initiate dialogue in a new climate of amity, understanding and the sharing of human values. It is a non-government institute, designed, in the words of its founder president, Dr. C.D. Deshmukh, to be a place where various currents of intellectual, political and economic thought could meet freely. In its objectives, the Centre declares its purpose as being that of society to 'promote understanding and amity between the different communities of the world by undertaking or supporting the study of their past and present cultures, by disseminating or exchanging knowledge thereof, and by providing such other facilities as would lead to their universal appreciation.'

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