Note

Indian & Eurasian Plates Are Active!
Recent and Past Evidence

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Abstract

The recent tsunami caused by an earthquake of magnitude 9.0 at a focal depth of 30km, which occurred on 26 December 2004 (00:58:50 UTC) with the epicentre at 3.298°N, 95.779°E, cost thousands of lives and extensive property damage in south-eastern Asian and East African countries viz., Indonesia, Sri Lanka, India, Thailand, Somalia, Myanmar, Maldives, Malaysia, Tanzania, Seychelles, Bangladesh, Kenya and South Africa (source: USGS). As of 5 January 2005, the confirmed deaths were 1,58,240 in all the aforesaid tsunami affected countries (Blogger™ News Agency, source: Wikipedia, 10:20pm ET, 05 Jan'05). Out of which 94,081 died in Indonesia alone and 48,677 in Sri Lanka. In India nearly 10,000 people lost their lives mostly in the Andaman and Nicobar Islands and the coastal districts of Tamilnadu, Kerala and Andhrapradesh. The epicentre of the earthquake was identified as being located off the coast of Sumatra, Indonesia in the Indian Ocean. Apart from the tsunami generated casualties it is also likely that direct earthquake induced damages also affected the Andaman and Nicobar group of islands. The earthquake took place in a most active seismic region characterised by tectonic features of the north-south trending Indo-Burma ranges in the north, Andaman-Nicobar islands and the Sumatra fault system in the south-east. According to the available fault plane solutions (USGS) the event took place due to thrust type movement.

Introduction

The tsunami on 26 December 2004 cost thousands of lives and caused major destruction in Indonesia, Sri Lanka and India. On the fifth day (i.e. 30 December 2004) after the tsunami originating off Sumatra, an earthquake of intensity 5.5 was observed in the Jammu region. The Hong Kong observatory observed an earthquake of magnitude 5.6 near the site of

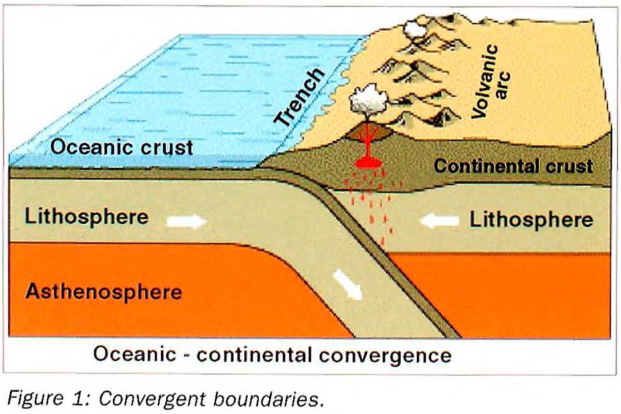

Figure 1: Convergent boundaries.

the last tsunami induced quake on 6 January 2005. Again on 24 July 2005, an earthquake of intensity 7.2 occurred with its epicentre west of the Nicobar Islands (India) in the Indian Ocean. In simple terms a tsunami can be defined as an under water earthquake. In the past decade India has experienced four major earthquakes i.e., Uttarkashi earthquake (1991), Latur earthquake (1993), Chamoli earthquake (1999) and the Bhuj earthquake (2001) of magnitudes 6.6, 6.8, 6.3 and 6.9 respectively. If we look into the recent past, nature has provided a forecast prior to these massive destructions.

The Bhuj earthquake of magnitude 6.9 occurred on the Republic Day of India, 26 January 2001 in one of the most active seismic zones of India. The tectonic causes for the main shock and after shock activities ranging from 10-35km in this region are still not clear. During the past six decades before the onset of the Bhuj earthquake, wide spread occurrence of earthquakes of magnitudes greater than 3.0 have been reported in the Kutch region. The causative factors for the occurrence of the Bhuj earthquake by considering various geophysical and geological parameters for Kutch region, such as stress loading (due to the plate tectonic

Date/Year	State	Magnitude	Casualty	Remarks
26th Jan 2001 08:46 hrs	Gujarat, India (Bhuj)	6.9	> 15000	-
27th Jan 2001 (Midnight)	Meghalaya, India (Near Shillong)	2.5	Nil	-
15th April 2001 08:28hrs.	Japan (South Pacific Ocean)	6.3	Nil	-
28th April 2001 08:25 hrs.	Haryana, India (Near Sonipat)	3.8	Nil	-
14th June 2001	Thivan	—	Nil	-
20th June 2001	Meghalaya, India (Shillong)	3.4	Nil	-
24th June 2001	South Africa	7.9	50	-
16th July 2001 (Late night)	Nepal (Near Bhu, Kathmandu)	5.6	Nil	-
25th Sep'2001	Near Tamilnadu coast, India (Bay of Bengal)	5.5	Nil	-
03rd Jan'2002 (14:00hrs)	Afghanistan and J&K, India	6.3	Nil	Tremors for 40 seconds
26th Jan'2002	Gujarat, India (Bhuj)	3.0	Nil	Tremors Observed
03rd Feb'2002 12:30hrs & 14:00hrs	Turkey	5.6-6.0	45	Focus at SW of Ankara Town
14th Sep'2002 (Evening)	Focus in Bay of Bengal, India	6.3	2	Andaman Is. Affected
18th Sep'2002	Focus near North Andaman Islands, India	4.8	Nil	-
26th Dec'2003 (06:00hrs)	South Eastern Iran	6.3	20,000	Focus at 975km South of Tehran
08th Oct, 2005 (0350 GMT) 0850 hrs. local time	Earthquake centred at 95 km north east of Pakistan capital Islamabad	7.6	> 40, 000	Earthquake centred at 95 km north east of Pakistan capital Islamabad. The quake has severely affected areas of Pakistan administered Kashmir (Muzaffarabad).

Table 1: Series of earthquakes occurred in India and adjacent countries during 2001-03 (Information from the news agencies).

forces), seismicity patterns and the affect of high density underplated material in the middle – lower crust, by considering nearby deep seismic, magneto-telluric studies and zero free Bouguer gravity anomalies revealed that a doughnut pattern of seismicity in the vicinity of Kutch region has been identified (Rao et.al, 2001). It indicates that the main shock and aftershock activities filled the doughnut pattern. The observation of this doughnut pattern indicates ongoing tectonic activities of the region. The dehydration of serpentinite creates embrittlement in the crust and accumulation of structurally bounded fluids, which is responsible for the mid-lower crustal seismicity (Rao et.al, 2001). A few months after the Bhuj earthquake, on 25 September 2001 the southern states of India experienced an earthquake of intensity 5.5-5.6 (News agencies report). Again on 14 September 2002 there was an earthquake of intensity 6.0 recorded off shore of Yangon (Rangoon). The epicentre of the quake was identified in the Bay of Bengal (News agency's report). In the above two events, no casualty or property loss were reported. A series of earthquakes occurred during 2001-05 in India and its adjacent countries and are listed at Table 1. All the above earthquakes might have been a forecast for the 26 December 2005 tsunami disaster and inference of active plate tectonic movements. The recent earthquake of intensity 7.6 centred at 95km north-east of the Pakistan capital, Islamabad, occurred on 8 October 2005 provides strong evidence to the ongoing tectonic movement in this region. The quake has severely affected areas of Pakistan administered Kashmir (Muzaffarabad) and cost more than 40,000 lives.

Plate Tectonics

The detailed theory of continental drift was first described by the German meteorologist and geophysicist Alfred Wegener in 1912. On the basis of geology, biology, climatology, and the alignment of the continental shelf rather than the alignment of the actual coastline, he believed that during the late Paleozoic and early Mesozoic eras, about 275 to 175 million years ago, all the continents were united into a vast super continent, which he called Pangaea. Later, Pangaea broke into two super continental masses; Laurasia to the North, and Gondwanaland to the South. The present continents began to split apart in the latter Mesozoic era about 100 million years ago, drifting to their present positions. Based on these findings in geology, oceanography, and geophysics, plate tectonics theory holds that the lithosphere, the hard outer layer of the earth, is divided into about 7 major plates and perhaps as many as 12 smaller plates of 100km thick, resting upon a lower soft layer called the asthenosphere. The continents include Eurasia (conventionally regarded as two continents, Europe and Asia), Africa, North America, South America, Australia and Antarctica. Asia is the world's largest continent covering 44,390,000km^2, with about 3.3 billion people, nearly three fifth of the world's total population. Africa (30,244,050km^2), North America (24,346,000km^2), South America (17,819,000km^2), Antarctica (14,245,000km^2) and the Australia (7,686,810km^2) stands at second, third, fourth, fifth and sixth positions respectively.

Earthquakes Caused by Tectonic Plate Movement

Scientists now have a fairly good understanding of how the plates move and how such movements relate to earthquake activity. Most movement occurs along narrow zones between plates where the results of plate-tectonic forces are most evident. There are four types of plate boundaries:

- Divergent boundaries: where new crust is gen-

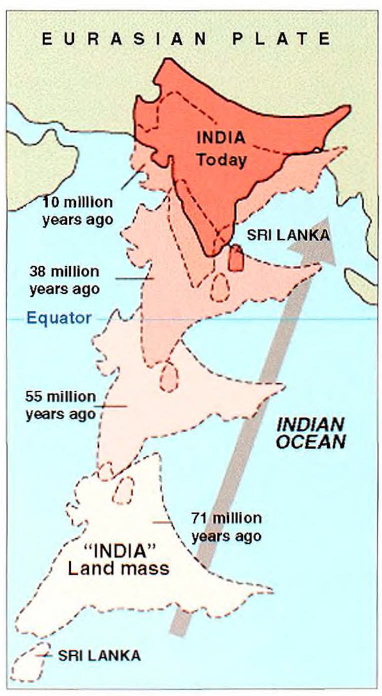

Figure 2: The 6,000km-plus journey of the India landmass (Indian Plate) before its collision with Asia (Eurasian Plate) about 40 to 50 million years ago (see text). India was once situated well south of the Equator, near the continent of Australia.

erated as the plates pull away from each other.

- Convergent boundaries: where crust is destroyed as one plate dives under another.
- Transform boundaries: where crust is neither produced nor destroyed as the plates slide horizontally past each other.
- Plate boundary zones: broad belts in which boundaries are not well defined and the effects of plate interaction are unclear.

The second type of plate motion i.e convergent boundaries probably caused the most recent tsunami.

Convergent boundaries: The type of convergence, called by some a very slow 'collision', that takes place between plates depends on the kind of lithosphere involved. Convergence can occur between an oceanic and a largely continental plate, or between two largely oceanic plates, or between two largely continental plates (Figure 1).

Among the most dramatic and visible creations of plate-tectonic forces are the lofty Himalayas, which stretch 2,900km along the border between India and Tibet. This immense mountain range began to form between 40 and 50 million years ago, when two large landmasses, India and Eurasia, driven by plate movement, collided. Because both these continental landmasses have about the same rock density, one plate could be relieved by thrusting skyward, contorting the collision zone, and forming the jagged Himalayan peaks. About 225 million years ago, India was a large island still situated off the Australian coast, and a vast ocean (called Tethys Sea) separated India from the Asian continent. When Pangaea broke apart about 200 million year ago, India began to move northward (Figure 2). By studying the history – and ultimately the closing – of the Tethys Sea, scientists have reconstructed India's northward journey. About 80 million years ago, India was located roughly 6,400km south of the Asian continent, moving northward at a rate of about 9m a century. When India rammed into Asia about 40 to 50 million years ago, its northward advance slowed by about half. The collision and associated decrease in the rate of plate movement are interpreted to mark the beginning of the rapid uplift of the Himalayas (Figure 3). The Himalayas, towering as high as 8,854m above sea level, form the highest continental mountains in the world. Moreover, the neighbouring Tibetan Plateau, at an average elevation of about 4,600m, is well above the summits of most mountains in the United States. The Himalayas and the Tibetan Plateau to the north have risen very rapidly. In just 50 million years, peaks such as Mt. Everest have risen to heights of more than 9km. The collision of the two landmasses has yet to end. The Himalayas continue to rise more than 1cm a year—a growth

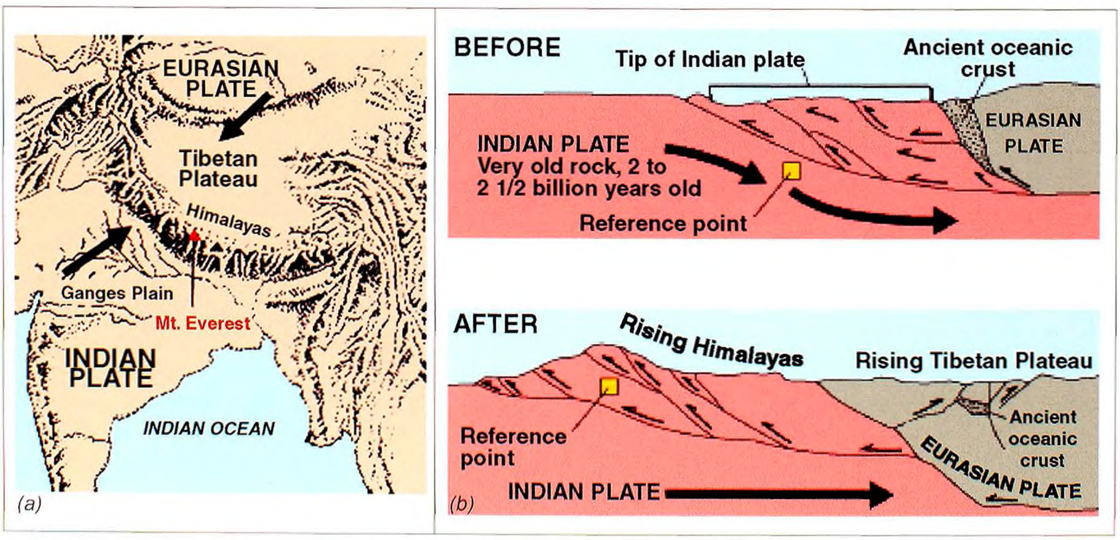

Figure 3: (a)The collision between the Indian and Eurasian plates has pushed up the Himalayas and the Tibetan Plateau. (b) Cartoon cross sections showing the meeting of these two plates before and after their collision. The reference points (small squares) show the amount of uplift of an imaginary point in the Earth's crust during this mountain-building process.

rate of 10km in a million years! If that is so, why are the Himalayas not even higher? Scientists believe that the Eurasian Plate may now be stretching out rather than thrusting up, and such stretching would result in some subsidence due to gravity.

At present, the movement of India continues to put enormous pressure on the Asian continent, and Tibet in turn presses on the landmass to the north that is hemming it in. The net effect of plate-tectonics forces acting on this geologically complicated region is to squeeze parts of Asia eastward toward the Pacific Ocean. One serious consequence of these processes is a deadly 'domino' effect: tremendous stresses build up within the Earth's crust, which are relieved periodically by earthquakes along the numerous faults that scar the landscape. Some of the world's most destructive earthquakes in history are related to continuing tectonic processes that began some 50 million years ago when the Indian and Eurasian continents first met.

Rates of Plate Motion

We can measure how fast tectonic plates are moving today, but how do scientists know what the rates of plate movement have been over geologic time? The oceans hold one of the key pieces to the puzzle. Because the ocean floor magnetic reversal striping records the flip-flops in the Earth's magnetic field, scientists, knowing the approximate duration of the reversal, can calculate the average rate of plate movement during a given time span. These average rates of plate separations can range widely. The Arctic Ridge has the slowest rate (less than 2.5cm/yr), and the East Pacific Rise near Easter Island, in the South Pacific about 3,400km west of Chile, has the fastest rate (more than 15cm/yr).

Role of a Hydrographer

The seafloor movements may be monitored by hydrographers through mapping the sea bottom using the latest marine equipment like 3D side scan sonars and multibeam depth sounders. The continuous monitoring of the sea bottom profiles and texture of the seabed and its extent in what direction can provide the information about the seafloor spreading. Today GPS interfaced underwater survey vehicles are capable enough to provide the accurate positions of the submarine geological and geomorphological features with 3D views. Marine reflection seismic surveys are useful for mapping the subsurface with great precision. Positional changes in the off shore platforms and the effect of subsidence may be assessed by continuous height monitoring using GPS over these structures. Integrating all the above observations could help us to study the tectonic movements and its resultant earthquakes.

National Programme on Global Positioning System (GPS)

Current plate movement can be tracked directly by means of ground-based or space based geodetic measurements. GPS has been the most useful tool for studying the Earth's crustal movements. After the 1993 Latur Earthquake, with the World Bank assisted DST project on seismic instrumentation in the Indian Peninsular Shield, geodetic and geophysical studies including GPS surveys have also been undertaken by the Survey of India and other organisations in the Peninsular Shield. The Department of Science and Technology (DST), Government of India had set up an expert group on Global Positioning System observations and geodetic studies with special reference to the Himalayas during July 1997 to evolve a national programme of GPS and other geodetic studies for monitoring the crustal deformation due to earthquake occurrences and other geodynamic phenomena. The Expert Group recommended that an extensive GPS control network consisting of Permanent Stations (observing continuously), Semi Permanent Stations (to be observed for 3-5 days at least once in a year) and field stations (for local investigations) might be established in a phased manner. In addition to the above, the committee had also recommended for establishment of a GPS data centre at the Survey of India for storage and dissemination of GPS data and organisation of specialised training programmes to train the personnel. As a follow up action of the recommendations of the Expert Group, DST has launched the National GPS Programme. An Expert Group set up by DST is monitoring this programme. The objectives of the programme are:

- To establish the rate of movement of the tectonic plates relative to each other.

- To establish the strain rates in different tectonic domains of India and to constrain strain partitioning in discrete tectonic domains/block and identify the area of higher strain build up/release.

Eighteen permanent GPS Stations have been established all over India, which include stations at Dehradun, Dharmashala, Delhi, Hanle, Leh, Bangalore, Almora, Kodaikanal, Lucknow, Itanagar, Dhanbad, Bhubneswar, Pune, Trivandrum, Tezpur, Gauwahati, Aizawl, Imphal and Kohima. The GPS data for eleven stations is now available at the Sol Data Centre in Dehradun. The establishment of permanent GPS stations in the north western part of the Himalayas, with the help of the Wadia Institute of Himalayan Geology (WIHG) is being taken up and setting up of permanent stations at Jabalpur and Shillong is being done by the Survey of India (SOI), Dehradun. GPS receivers have also been installed at Tirunelvelli, Kolhapur, Nagpur and Allahabad and data are being collected by Indian Institute of Geomagnetism (IIG), Mumbai. DST is also planning to establish permanent stations at Bhopal, Gangtok, Bomdilla, Visakhapatnam, Port Blair and Pondicherry. A number of projects have already been funded to SOI, WIHG (Dehradun), IIG (Mumbai), IIT (Mumbai), Tezpur University, CSIR Centre for Mathematical Modeling and Computer Simulation (C-MMACS, Bangalore), National Geophysical Research Institute (NGRI, Hyderabad), Manipur University, Cochin University, GB Pant Institute (Almora), Centre for Earth Science Studies (CESS, Trivandrum), etc., for studying the crustal deformation process in consortium mode. Some significant results related to the movement of the Indian Plate and velocity vectors have been obtained (Report by Seismology Division, DST, New Delhi). A National GPS Data Centre has been established at the Survey of India, Dehradun, where all the data of permanent stations are being stored and analysed. SOI is also planning to make the data available to all authorised users through ftp/internet, so as to reduce response time for data delivery and eliminate avoidable manpower costs.

Conclusions

Within the Indian subcontinent, while subduction and collision related earthquakes occur along the Indo-Burmese range, where the Indian lithosphere underthrusts obliquely below the Burmese continent, collision earthquakes are located all along the Himalayan front. Oceanic ridge type shallow foci, low magnitude earthquakes occur in the Andaman Sea, which is an active marginal sea spreading ridge, and the intra-plate earthquakes occur within the Indian shield and passive continental rifted margins, as well as in Indian Ocean. The stable continental region earthquakes, like the Killari or the Jabalpur earthquakes, and those in the Indian Ocean are often difficult to explain in terms of simple plate tectonic concepts. It can, however, be explained from the realm of convection tectonics with continental blocks being directly affected by small-scale convection flow in the mantle beneath, which are generated by disturbing the overall large-scale mantle flow, both at their margins and their roots. The continents are affected by frictional coupling that causes compressional, shear and extensional stress, and associated with deformation and displacement along existing fracture system.

In the area of oceanic trenches, lithospheric plates are consumed by subduction. Earthquakes in this part of the world (in the Andaman Arc-Trench gap) are generated by the plate convergence. The Burmese-Andaman Arc System presents nearly a 3,500km long subducting margin in the northeastern part of the Indian Plate where varying degrees of seismic activity, volcanism and active tectonism are evidenced. The region is of particular interest, *inter alia*, for the tectonic significance (a) it serves as important tectonic link between the Eastern Himalayas (a typical collisional margin) with the Sunda arc (which is a part of the western Pacific arc system) (b) The Andaman back arc spreading ridge underlying the Andaman sea relates to the oblique convergence of the Indian plate at the Asian continental margin (c) Further south is the intense seismic zone of the west Sunda arc with its attendant volcanism. At present the Andamans are gradually sinking, but there is ample evidence in the raised beaches that fringe the shores of the Andamans, that in the immediate past elevation has exceeded subsidence (Ref. 'the Geology of Andaman Islands by R.D. Oldham').

According to the DST reports, the Survey of India has obtained some significant deformation results in Khandwa, Bhopal, Jabalpur and Yavatma areas. Two GPS networks have been set up by IIT, Mumbai for carrying out the deformation studies in the

Koyna dam and Bhuj area. The average velocity and strain field in the study area have already been obtained. 50 Campaign mode GPS stations covering the entire Himachal Pradesh, Garhwal region and parts of Ladakh, Punjab and adjoining region have been established by WIHG, Dehradun. Results from repeat measurements of the GPS stations in the north western Himalayas have revealed some important conclusions about the strain accumulation and plate velocities. The CSIR Centre for Mathematical Modeling and Computer Simulation (C-MMACS), Bangalore has also covered several areas through GPS campaigns, which include Southern Peninsula, Garhwal, Kumaon, Ladakh Himalayas and Gujarat. GPS measurements were also carried out in Bidar, Andamans, Shillong and Darjeeling by C-MMACS, Bangalore.

Prediction of near-source ground motion and nature response of man-made structures to major earthquakes is important both from the societal as well scientific viewpoints. It is necessary to estimate seismic hazard, predict behaviour of structural systems during earthquakes and study the socio-economic impact, which would enable adoption of appropriate mitigating measures. Earthquake hazard and risk analysis, based on probabilistic and deterministic approaches, play a major role in identifying the potential consequences of an earthquake, both in relation to existing structures as well as planning and locating of new facilities. In view of frequent earthquakes and flood disasters in India, few specific problems, which need to be attended, are detailed below:

- Preparation of probabilistic seismic hazard map of the critical regions of India.
- Risk analysis in identified earthquake prone areas.
- Microzonation of mega cities.
- Site response studies.
- Strict implementation of building construction norms in the sensitive areas.
- Development of emergency response planning strategy.
- Public awareness and societal response.
- Strict implementation of Coastal Regulatory Zone rules in the coastal states.
- Identification of low lying and frequently affected areas by the floods in the coastal states.
- Construction of three fold sea wave protection barriers along the beaches of major cities.
- Establishment of effective weather forecast and communication systems in the coastal areas.
- Constitution of Beach Protection Force manned with expert divers and boats equipped with life saving apparatus in each Coastal State.

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