Post-Seismic Effect of Sumatra-Andaman Earthquake on the Western Part of Indian Plate

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The paper gives a broad overview of the work carried out by the Indian Institute of Technology Bombay (IITB) in determining the post-seismic effect of the December 26, 2004 Sumatra-Andaman earthquake on the Indian plate, using space-based technology, the GPS. A GPS network established by the IITB along the western coast of the Indian peninsular was considered for this purpose, observed and analyzed thoroughly, in order to investigate the potential of GPS technology in studying Earth dynamics. To understand the pattern of movement of the Earth's surface to the effect of the large Sumatra-Andaman earthquake, the magnitude and, most importantly, the direction of deformation of the GPS network were estimated. The GPS-estimated deformations were thereby used as indicators to identify any change in the Earth surface movement due to the large external force caused by the 2004 earthquake.

Keywords: GPS, Sumatra-Andaman earthquake, Post-seismic adjustment, Indian plate

Introduction

The Sumatra-Andaman earthquake of Mw 9.0-9.3 was a powerful undersea earthquake that occurred on December 26, 2004 at 00:58:53 UTC, with an epicenter off the west coast of northern Sumatra, Indonesia, and is considered as the largest earthquake of the modern seismological era. This earthquake that originated in the Indian Ocean triggered a series of devastating tsunamis with waves up to 30 mm along the coasts of most landmasses bordering the Indian Ocean, killing a large number of people and inundating coastal communities across south and south-east Asia, including parts of Indonesia, Sri Lanka, India and Thailand. The hypocenter of the main earthquake was at 3°19' N 95°51.24' E, approximately 160 km west of Sumatra, at a depth of 30 km below the mean sea level. The earthquake caused large displacements in the Andaman-Sumatra region and also caused significant coseismic displacement at far field distance of up to 2,000 km from the epicenter (DST, 2006).

This earthquake is the first event that has been well-detected in the era of modern GPS technology. Several existing GPS sites, mostly set up along the maximum damaged Andaman

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and Nicobar Islands, were remeasured after this event by renowned organizations in the field of deformation monitoring, with the main aim of estimating the effect of the Sumatra-Andaman earthquake on the Indian plate. The GPS observations and analysis by various organizations, namely, Survey of India (Dehradun), National Geophysical Research Institute (Hyderabad), Centre for Mathematical Modelling and Computer Simulation (Bangalore) and Centre for Earth Science Studies (CESS) (Trivandrum), revealed extremely valuable information about this earthquake. Some of the contributions from some major projects sponsored by DST are explained below.

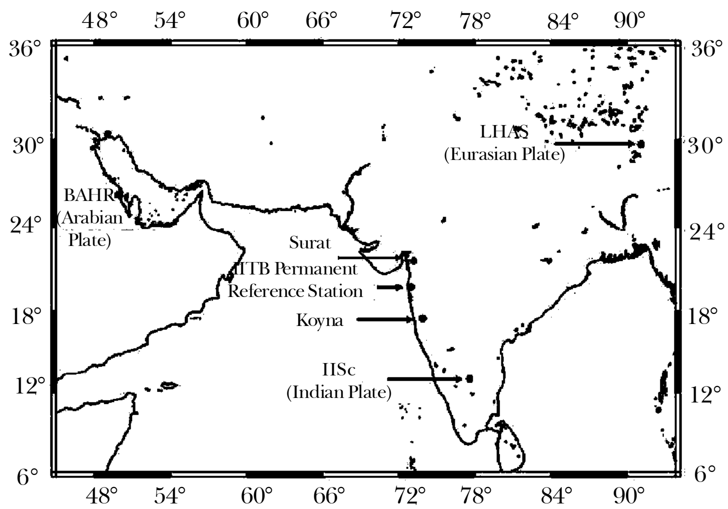
National Geophysical Research Institute (NGRI) used GPS data from nine permanent GPS sites surrounding the epicenter of the Sumatra-Andaman earthquake to infer coseismic displacements at these sites. Their results suggest that GPS site in Sumatra Island, the nearest site from the epicenter, experienced a westward coseismic horizontal displacement of about 14 cm, while sites in southern India, namely, IISc (IGS station) experienced predominantly eastward coseismic horizontal displacement of about 6-11 mm. Centre for Mathematical Modelling and Computer Simulation (C-MMACS) analyzed GPS data of permanent and campaign GPS sites in the Indian subcontinent to study the effect of Sumatra-Andaman earthquake. They estimated coseismic displacements at 11 permanent GPS stations of the National network situated over the Indian subcontinent, five campaign sites in southern India and four campaign sites in Andaman and Nicobar Islands. The results indicated coseismic eastward displacements of 12-20 mm in southern India almost directly west of Andaman, 1.8-6 mm in central India and insignificant displacement in the Himalayas. Four campaign sites in the Andaman and Nicobar Islands showed large horizontal coseismic displacements of 1.5-6.5 mm WSW and SW. Vertical displacement varied from uplift of 0.6 mm in north Andaman to 1.1 m subsidence at Car Nicobar. Based on the GPS observations at five sites in the Andaman-Nicobar region, CESS derived vertical displacement of –1.36 mm (subsidence) to +0.63 mm (uplift). The survey of India (SOI) estimated horizontal displacement of about 4.0-6.5 mm in the Nicobar region and 1.5-5.0 mm in the Andaman region.

Till now, only the estimation of coseismic displacement and the immediate post-seismic displacement of the Earth's surface to an earthquake has been reported. However, the adjustment of the Earth's surface takes time, and no work has been reported that estimates the post-seismic adjustment of the Earth after 2 or 6 months or a year from the date of earthquake. The theoretical models determining the adjustment of the Earth are, however, available, but the practical application has not been documented. Thus, in the wake of this issue, Indian Institute of Technology Bombay (IITB) undertook the task of studying the post-seismic effect of the Sumatra-Andaman earthquake phenomenon on the Indian plate. The results and the analysis of this study are thus the subject of this paper.

Role of IITB in GPS Deformation Measurements and Analysis

IITB has been actively involved in extensive GPS studies, including crustal, structural deformation monitoring under research projects funded by the Department of Science and Technology (DST), Government of India, and Land Subsidence monitoring research project funded by Research and Development (R&D) Cell of IITB. The many projects include monitoring and analyzing crustal and structural deformation in the seismically active Koyna region in western Maharashtra (Figure 1). A rubble concrete dam structure located in this region is being subjected to the effect of crustal movements, seasonal changes in water load in the reservoir and the effect of seismicity in the region for over four decades. Therefore, for monitoring the deformation of the structure and the surrounding areas in response to various external loads, an extensive GPS network of 31 stations, with 12 stations on the dam body and the rest in the area surrounding the dam, was established and monitored periodically for 13 campaigns for over a period of six years from December 2000-May 2006, with the main aim of investigating the potential of GPS technology in deformation measurements and analysis. The details of the work are given in Manake and Kulkarni (2002) and Kulkarni *et al.* (2004 and 2006).

Figure 1: Distribution of IGS Stations and Location of Koyna, Surat and IITB Stations



The Olpad province situated in the Surat district of Gujarat, situated along the west coast of the Indian peninsular (Figure 1), is identified as a rich source of oil/gas in the energy map of Gujarat, and this is the best site for gas extraction by many companies. However, the extraction of gas poses to be the major cause of land subsidence over this area, and hence the area is under high surveillance. To monitor and understand the degree of land subsidence (vertical deformation) as well as horizontal deformation in response to gas extraction, the IITB GPS team established a precise GPS network of 37 stations (4 references and 33 deformation stations) covering an area of 19 km^2 and was periodically monitoring at intervals of 3-4 months every year from February 2004-May 2006. The results of the detailed analysis undertaken by the IITB are explained in detail in Kulkarni and Patel (2007 and 2008).

Under another DST sponsored research project, a GPS permanent reference station has been set up on the terrace of the Civil Engineering Department at IITB and has been continuously operating since January 1, 2002. This permanent station is located about

10-15 km from the ocean coast, as shown in Figure 1. The GPS data collected at this station has been used for crustal, structural deformation and subsidence studies at Koyna and Surat regions as well as the region on which IITB station is set up. The data has been made available to other organizations and institutes, and also been submitted to the National GPS Data Centre at Survey of India, Dehradun, for archival (DST, 2005).

Effect of Sumatra-Andaman Earthquake on the Indian Plate

The main objective of this paper is to emphasize on the analysis of the post-seismic effect of Sumatra-Andaman earthquake on the Indian plate. It is observed that the period of study for Koyna (2000-2006), IITB (2002-2006) and Surat (2004-2006) also include the period of occurrence of this earthquake of 2004. Therefore, attention was now aimed at analyzing the GPS data collected at the following three regions, to study the effect of this large earthquake on the western coast of the Indian peninsular.

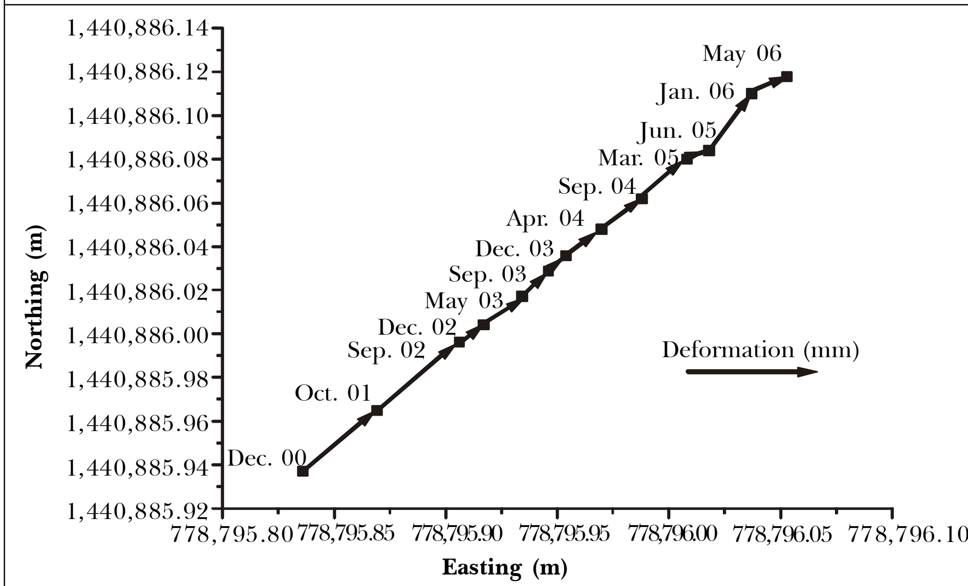
The observations at the selected stations at Koyna, IITB and Surat were taken using dual frequency geodetic GPS receivers: Trimble 4000 SSi with Choke Ring antenna and Trimble 5700 with Zephyr Geodetic antenna. The data was collected for a period of 6-8 h with a sampling rate of 15 s for the rover stations, and 24 h with a sampling rate of 30 s for the reference and permanent stations, and satellite elevation mask of 15°. The data collected at respective stations at Koyna, IITB and Surat were processed using Bernese v4.2 software (Hugentobler *et al.*, 2001) to yield single baseline solutions and coordinates in both Cartesian rectangular and Geodetic coordinate systems. Apart from the data files for the station points, three reference stations of International GNSS Service (IGS) belonging to different continental plates were considered for the purpose of tightly constraining the coordinates of the GPS station points from these reference sites in ITRF2000 reference frame. The reference sites selected were BAHR (Bahrain) on the Arabian plate, LHAS (China) on the Eurasian plate and IISc (a permanent station set up at Indian Institute of Science, Bangalore) on the Indian plate. The locations of the following IGS stations are shown in Figure 1. The geodetic coordinates obtained for the stations (latitude, longitude and height) were projected onto a UTM grid to give results in Northing (m), Easting (m) and Height (m).

Deformation Analysis of IGS Station IISc

GPS data can be used to determine plate motion. To determine the motion of the Indian plate, the change in coordinates of IGS station set up at IISc was estimated between successive campaigns from December 2000-May 2006 (period of study for Koyna region was considered). The precise coordinates of IISc station per campaign was obtained by Bernese processing. The change in IISc station coordinates between successive campaigns in the north and east directions were thereby estimated, as shown in Table 1, and pictorially represented in Figure 2. Here, ΔN and ΔE represent the deformation vectors in the north and east direction respectively; and $\sqrt{(\Delta N^2 + \Delta E^2)}$ represents the residual deformation in the horizontal plane or plate motion. The resultant deformation in mm/yr was also calculated and given in Table 1.

Table 1: Plate Motion Vectors of IGS Station IISc Estimated Using Bernese Processed GPS Data					
Campaign	**ΔN (mm)**	**ΔE (mm)**	**Resultant Deformation (mm)**	**Rate of Deformation (mm/yr)**	**Direction of Movement from North**
Dec. 00-Oct. 01	28.0	33.0	43.3	53.6	NE
Oct. 01-Sep. 02	31.0	37.0	48.3	54.2	NE
Sep. 02-Dec. 02	10.0	11.0	14.9	52.6	NE
Dec. 02-May 03	13.0	17.0	21.4	51.4	NE
May 03-Sep. 03	12.0	12.0	17.0	51.0	NE
Sep. 03-Dec. 03	7.0	8.0	10.6	50.9	NE
Dec. 03-Apr. 04	12.0	16.0	20.0	53.3	NE
Apr. 04-Sep. 04	14.0	18.0	22.8	54.7	NE
Sep. 04-Mar. 05	18.0	20.0	26.9	53.8	NE
Mar. 05-Jun. 05	4.0	10.0	10.8	48.0	NE
Jun. 05-Jan. 06	26.0	19.0	32.2	53.7	NE
Jan. 06-May 06	8.0	16.0	17.9	53.7	NE

Figure 2: Direction of Movement of IISc from 2000-2006



From Table 1 and Figure 2, it is observed that the Indian plate is moving in the north-east direction. One of the major applications of GPS in the field of crustal deformation studies in India has been in the Himalayas. Based on the analysis of observations collected from 8-10 permanent GPS stations established along the Himalayas, Wadia Institute of Himalayan Geology (WIHG) Dehradun and DST have been able to establish that the

Himalayas came into existence as a result of India-Eurasia plate collision, and the Indian plate is moving towards the Eurasian plate situated in the north-east at a speed of nearly 51-55 mm/yr (Banerjee and Burgmann, 2002). Therefore, the computed plate motions with respect to IISc station, as in Table 1 and Figure 2 during most of the campaigns, are found to be in agreement with the actual plate motion of 51-55 mm/yr in the NE direction, except for March 2005-June 2005 campaigns, which shows a lesser movement of 48 mm/yr in the NEE direction.

Deformation Analysis of Koyna Deformation Station

In order to study the deformation of the Koyna dam due to continuously fluctuating water table, dam body temperature, seismicity, etc., a GPS station, i.e., Dam Deformation Station (DDS), set up at the topmost and center of the dam was analyzed. Continuous observational (24 h) data was collected for DDS throughout the 13 campaigns of GPS measurement from December 2000-May 2006, and its coordinates per campaign were estimated by processing the data using Bernese software. The changes in the coordinates between subsequent repeat observations (campaigns) were thereby estimated to define the degree of deformation between the campaigns in the horizontal plane. Table 2 and Figure 3 show the magnitude of deformation of the Koyna dam estimated between periodically monitored thirteen campaigns from 2000-2006.

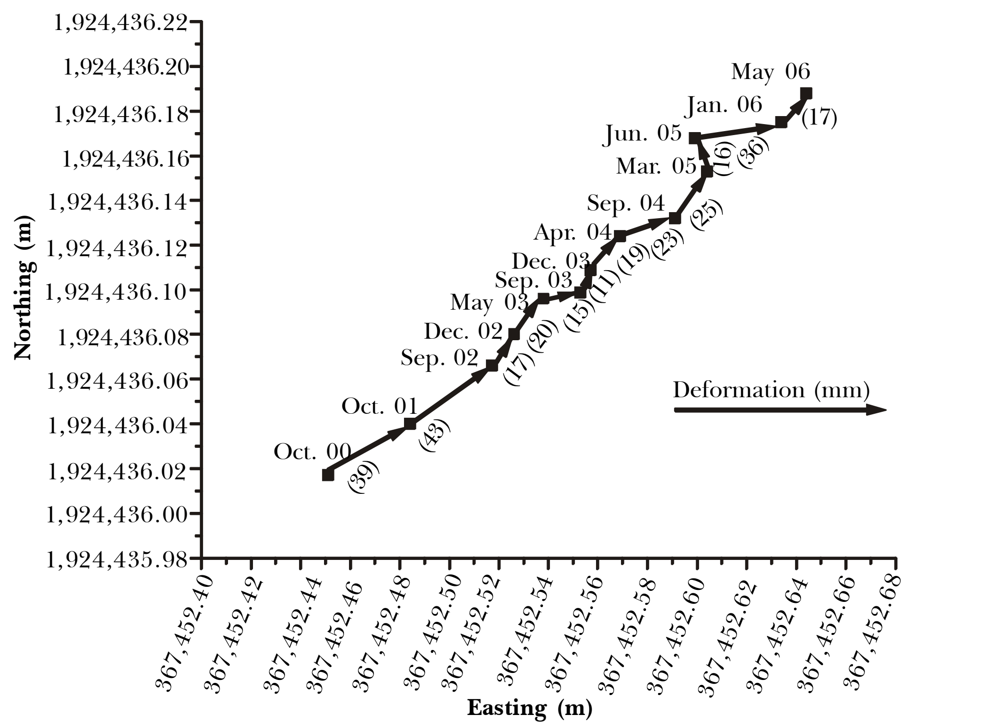
From Table 2 and Figure 3, it is observed that the plate including the Koyna station moves in the NE direction during all the campaigns, with the exception of March 2005-June 2005, which shows a movement of 5 mm (ΔE) towards the west direction. The movement in the NE therefore complies with the GPS studies done at the Himalayas that show the Indian plate moving towards the Eurasian plate. The accuracy of the results estimated for DDS is clearly evident from the submillimeter standard deviation (RMS) of 0.2 mm obtained for northing and easting during all the campaigns.

Table 2: Deformation of Dam Deformation Station

Campaign	ΔN (mm)	RMS (mm)	ΔE (mm)	RMS (mm)	Resultant Deformation (mm)	Direction of Movement from North
Dec. 00-Oct. 01	21.0	0.2	33.0	0.2	39.1	NE
Oct. 01-Sep. 02	28.0	0.2	33.0	0.2	43.3	NE
Sep. 02-Dec. 02	14.0	0.2	9.0	0.2	16.6	NE
Dec. 02-May 03	16.0	0.2	12.0	0.2	20.0	NE
May 03-Sep. 03	3.0	0.2	15.0	0.2	15.3	NE
Sep. 03-Dec. 03	10.0	0.2	4.0	0.2	10.8	NE
Dec. 03-Apr. 04	15.0	0.2	12.0	0.2	19.2	NE
Apr. 04-Sep. 04	8.0	0.2	22.0	0.2	23.4	NE
Sep. 04-Mar. 05	21.0	0.2	13.0	0.2	24.7	NE
Mar. 05-Jun. 05	15.0	0.2	–5.0	0.2	15.8	NNW
Jun. 05-Jan. 06	6.0	0.2	35.0	0.2	35.5	NE
Jan. 06-May 06	14.0	0.2	10.0	0.2	17.2	NE

Note: NE: North-East; NNW: North-North-West; and RMS: Root mean square.

Figure 3: Deformation Vectors for Dam Deformation Station for Thirteen Epochs



Deformation Analysis of IITB Permanent Station

Similar to the Koyna station, the continuous data collected at the permanent station set up at IITB (Mumbai) was also processed using Bernese software to yield precise coordinates of the station point per campaign during the period of study from 2002-2006. The change in coordinates was thus computed to estimate its velocity of movement (or deformation) (Table 3). September 2002 and 2003 and December 2003 could not be included in the analysis due to non-availability of GPS data.

Table 3: Velocity of Movement of IITB Reference Station

Campaign	ΔN (mm)	RMS (mm)	ΔE (mm)	RMS (mm)	Resultant Deformation (mm)	Direction of Movement
Dec. 02-May 03	14.0	0.2	14.0	0.2	19.8	NE
Apr. 04-Sep. 04	14.0	0.2	15.0	0.3	20.5	NE
Sep. 04-Mar. 05	16.0	0.2	17.0	0.2	23.4	NE
Mar. 05-Jun. 05	10.0	0.2	–5.0	0.2	11.2	NNW
Jun. 05-Jan. 06	14.0	0.2	28.0	0.2	31.3	NE
Jan. 06-May 06	9.0	0.3	16.0	0.3	18.4	NE

Note: NE: North-East; NNW: North-North-West; and RMS: Root mean square.

The NE movement of the station for almost all the campaigns is observed from Table 3. A different direction of movement in the NNW direction is also observed for IITB reference station during March 2005-June 2005 (similar to DDS at Koyna, as in Table 2 and Figure 3) that fails to agree with the actual motion in the NE direction.

Deformation Analysis of Surat Reference Station

Though the extensive GPS network at Surat has been established to study the land subsidence (vertical deformation) in the area due to gas extraction, horizontal deformation of the Earth's surface due to gas extraction, seasonal ground water level changes as well as pressure depletion and temperature fluctuations were also analyzed during the period of study. Therefore, for the present analysis, a single reference station was considered and the GPS observations taken for seven campaigns from February 2004-May 2006 were thereby processed. The change in coordinates between successive campaigns (or deformations) was estimated, as given in Table 4 and Figure 4. It can be noted that the campaigns of GPS measurement for the station in Surat was different from those of Koyna, but were, however, taken during the same respective seasons to avoid any kind of anomalies.

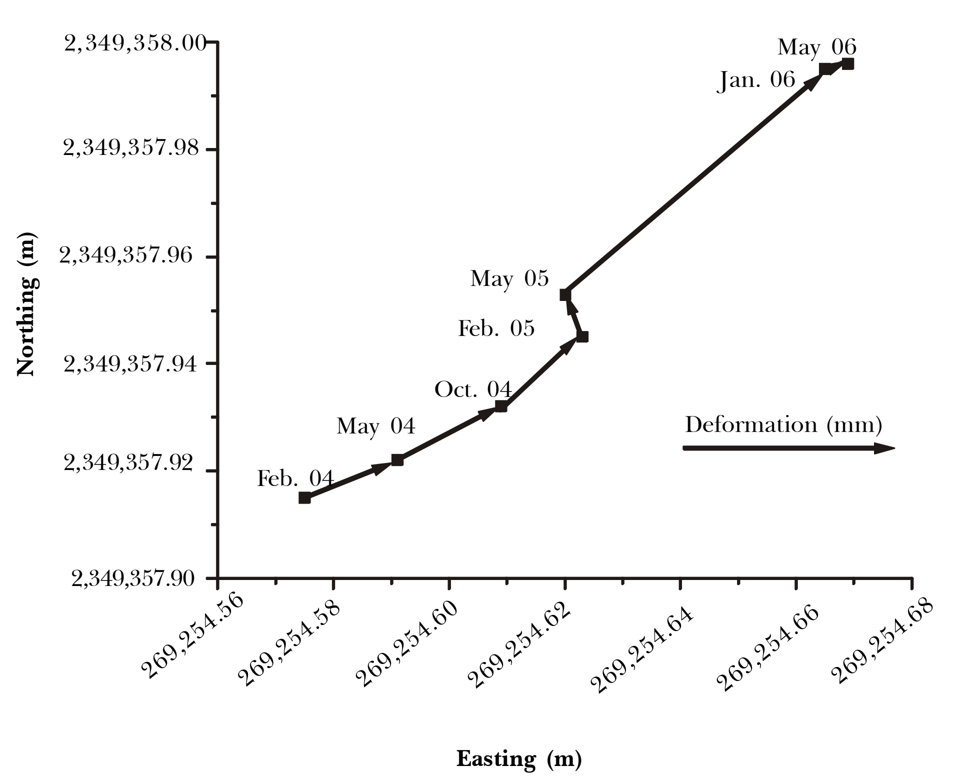
Table 4 and Figure 4 show that in general, the station point was also moving in the NE direction during the period of study from February 2004 to May 2006. A surprising NNW movement was observed during February 2005 to May 2005 campaigns, which is similar to what was observed for Koyna dam deformation station and IITB reference station.

Table 4: Deformation of Surat Reference Station

Campaign	ΔN (mm)	RMS (mm)	ΔE (mm)	RMS (mm)	Resultant Deformation (mm)	Direction of Movement from North
Feb. 04-May. 04	7.0	0.3	16.0	0.3	17.5	NE
May 04-Oct. 04	10.0	0.3	18.0	0.4	20.6	NE
Oct. 04-Feb.0 5	13.0	0.2	14.0	0.2	19.1	NE
Feb. 05-May 05	8.0	0.2	–3.0	0.2	8.5	NNW
May 05-Jan. 06	42.0	0.3	45.0	0.3	61.6	NE
Jan. 06-May 06	1.0	0.2	4.0	0.3	4.1	NE

Note: NE: North-East; NNW: North-North-West; and RMS: Root mean square.

Figure 4: Deformation of Reference Station Set Up at Surat



Discussion

From each of the above studies, it is observed that the horizontal movement during the period of study from February/March 2005-May/June 2005 fails to comply with the other campaigns of study for each of the stations at Koyna, Surat, IITB and IISc. The stations at Koyna, Surat and IITB were observed to shift in the NNW direction, i.e., direction different from the other campaigns, while IISc was observed to show a lesser plate motion in the NEE direction compared to the actual plate motion of 51-55 mm/yr.

The period of study for each of the above station points includes the occurrence of the major Sumatra-Andaman earthquake of Mw 9.0-9.3 on December 26, 2004. The aftereffects of this earthquake were felt over large distances of the world, including India, which may have altered the motion of the Indian plate. Therefore, the above anomalies may be ascribed to this phenomenon. The lesser velocity of movement of IISc and the NEE movement during March 2005-June 2005 campaigns may be accounted to the post-seismic adjustment of the Earth's surface to the effect of the Sumatra-Andaman earthquake. Similarly, the NNW direction (irrespective of the NE movement) of the western coast of the Indian peninsula, i.e., Koyna, Surat and IITB stations, may also be ascribed to the post-seismic adjustment of the Earth's surface due to the effect of this large earthquake.

Conclusion

An attempt was made to study the post-seismic effect of the devastating Sumatra-Andaman earthquake on the Indian plate using the advanced satellite-based technology, the GPS. Stations set up along central India (IISc) and the western coast of the Indian peninsular were considered, and the GPS data collected for these respective stations were analyzed thoroughly. From the results, an anomalous behavior of the Indian plate was observed as a result of the adjustment of the Earth's surface to the effect of the large earthquake of December 26, 2004. This is probably the first case where the post-seismic effect of the Sumatra-Andaman earthquake on the Indian plate, especially along the western coast of the Indian peninsular, has been studied and documented. This was made possible using GPS, thereby highlighting its advantage over other conventional instruments. Thus, GPS makes it possible to identify the factors that may be responsible for the deformation of a tectonic plate with better accuracy and precision.

In the present study, periodic observations were taken and analyzed. However, it is highly recommended that continuously operating GPS deformation monitoring systems should be considered for monitoring deformations associated with earthquakes, in real time or post-processing mode, so as to avert any major damage in the future.

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