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Application of GPS in structural deformation monitoring: A case study on Koyna dam

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Abstract: Construction of large engineering structures is essential for the development of a nation. Though essential, under excessive loading, they are subjected to deformation, thereby affecting the safety of the structure. Hence, the safety of these large engineering works demands their periodic monitoring, involving in-depth analysis of their structural behaviour and response of the structure to parameters contributing to deformation. The paper gives an overview of the application of Geodetic GPS technique in structural deformation monitoring of a large engineering structure, the Koyna dam as a case study. For monitoring deformation of this dam, a GPS network had been established by Indian Institute of Technology Bombay and observed periodically from year 2000 – 2006. Extensive fieldwork, detailed data processing and data analysis were done, to estimate the deformation of the dam during the period of study. An attempt was made to study the dynamical behaviour of the dam with respect to the change in the water load behind the dam. Analysis of the results indicated a significant correlation between the pattern of the deformation of the dam with the change in the water level in the reservoir. The results were also validated with coordimeter deflection data to justify the reliability of the GPS-obtained deformations.

Keywords: Koyna dam, GPS, Global and Local deformations, Water level

1. Introduction

Large engineering structures such as dams, bridges, high-rise buildings etc., are the king-plan for the socio-economic development of a nation. Though essential for development, they need a careful safety control along their life span, since under excessive loading they might undergo failure, causing loss to lives and property. Thus, the security of these large engineering works demands periodic monitoring of their deformations, which is the most relevant parameter to be monitored and which is essential to ensure their safety. Deformation or deflection of a structure is the only single parameter affected by all the loads on the structural system and is an important critical parameter that would throw light in a significant measure on the structural behaviour of the body (Narayana, 1982; Duff and Hyzat, 1997).

The main aim of the paper is mostly to emphasize only on dam deformation monitoring, a very important research area in India. During the last few decades, over fifty dam failures have been reported in the world, out of which twenty have been in India. For several years, extensive studies have been going on to study the deformations in a dam structure and understand the factors that make the structure vulnerable to foundation instability and occasionally a threat to thousands of people. These engineering structures are subject to external loads that cause deformation and permanent damage to the structure itself as well as the foundation, and thus the effects of these loads have to be monitored. However, there are some critical parameters mostly overlooked in structural analysis and that can cause deformation, namely crustal movements and structural factors such as reservoir water level and dam body temperature. Among these many structural factors, reservoir water level is a very important factor contributing to the deformation. The analysis of their effect on structural deformation should also find its importance in Structural health monitoring.

There are several ways of measuring them that can be broadly classified into Physical, Geodetic and Photogrammetric methods. More recently, the revolutionary space geodetic technique, the Global Positioning System (GPS) has found its advantage in measuring 3D deformations (Kulkarni, 1986a; Stewart and Tsakiri, 2001). Physical instrumentation and traditional surveying techniques can effectively monitor one- or two-dimensional modes of motion only. However, relative displacements, which are the key to access drift and stress conditions of a structure, are very difficult to measure directly with the above mentioned instruments. Further, these instruments involve high cost of equipment installation and maintenance (Celebi et al., 2001; Tsakeri et al., 2001). Owing to their expensive cost-installation and immense fieldwork, the studies have now shifted to the use of space geodetic technique, GPS. It has the advantage of directly providing displacement information in absolute as well as in real-time, making it a competitive alternative to the conventional surveying methods. It can provide 3D positions, simultaneously at all sites, with automated data collection and no line-of-sight requirement. It can provide continuous updating of positions of GPS receivers within few-mm accuracy with respect to stable points up to several km away. The major benefit of GPS is that the collected information on the response of the structure during strong-motion events can be used to analyse the performance of the structure and also assess long-term displacements of critical locations of structural systems. Some examples of use of GPS in deformation monitoring include KOMTAR building in Penang, Malaysia, Humber bridge in UK and the Hong Kong's Tsang Ma Bridge (cable-supported bridges) and Pacoima dam, located in the San Gabriel Mountains, California (Aziz et al., 2001; Behr et al., 1999; Cheng et al., 2002; Wong et al., 2001). In India, dam deformation studies have been carried out in the seismically active region, Koyna in Western Maharashtra.

The objective of this paper is to emphasize on the use of GPS technology in dam deformation monitoring. A case study on Koyna dam was chosen to highlight the advantage of advanced surveying technique of GPS over conventional techniques. This large engineering structure is located in one of the seismic-prone zones of Maharashtra and is therefore, an ideal site for deformation monitoring studies. The structure 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. The necessity for deformation measurement and analysis of the Koyna dam came into being with the need to study the effect of these external factors on the dam and most importantly, to determine the correlation between deformation and the parameters of deformation. This aim led to deformation studies of the dam using Geodetic GPS for the first time, by Indian Institute of Technology Bombay (IITB).

2. Koyna dam: Study area

The Koyna dam and its reservoir, Shivaji Sagar lake is located in the watershed of the Krishna river in the state of Maharashtra. The Koyna dam and the reservoir formed by it went under construction in 1956 and were completed in 1961. They are part of the Deccan plateau of Western India, which is located in the Peninsular Shield region. This dam is among the 23,000 large dams in the world. The details of the dam are given in Table 1 and Figure 1. This data was collected from the Koyna dam authorities.

Table 1: Details of Koyna dam and its reservoir, Western Maharashtra, India

Height of the dam above foundation level	103 m
Height of the dam above river level	85 m
Dam length at the crest	800 m
Beginning of reservoir filling with water	1962
Maximum capacity	2797.4 million cu. m
Catchment area	≈ 892 sq. km

The dam and its region has been a region of immense research for many years. Prior to the year 1962, the Indian Peninsular plate, one of the oldest continental blocks on the Earth's surface was traditionally referred to as a stable rock by geologists, which remained immune and free from any significant seismic disturbance. But the December 11, 1967 earthquake that occurred at approximately 4:21 am local time (IST), at Koyna of magnitude (M) 6.3 on Richter scale shook the theory about the seismic stability of the Peninsular plate. It contradicted all the assumptions and evoked interest on the part of geologists, geodesists, dam experts and engineers (Bhattacharya, 1982). However, the dam in the region withstood this significant seismic activity without any major damage. This occurrence in the Central Indian shield led to serious introspection among geo-scientists and led to various studies dealing with the stability of the dam structure and the areas in the vicinity of the dam (Manake and Kulkarni, 2002).

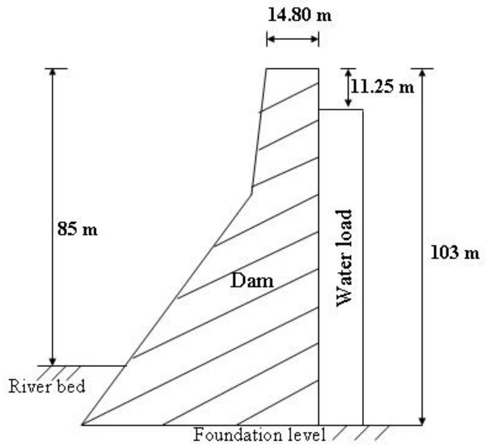

Figure 1: Sectional view of Koyna dam

Seismicity associated with Koyna reservoir is unique in many ways. It is the only known location in the world where seismicity that began after the start of impoundment of a reservoir, has persisted for more than 40 years and is believed to be a site of reservoir triggered seismicity. It is suggested that the enormous pressure of the water behind the dam causes shift in the underlying earth, eventually leading to increased seismicity (Gupta and Kumpel, 2000; Gupta, 2001). The region houses 2 major seismic zones (Figure 2), namely the NNE-SSW trending earthquake clusters referred as the Koyna seismic zone (KSZ) and clusters trending in the SSE-NNW direction, referred as the Warna seismic zone (WSZ) (Gahalaut et al., 2004). The KSZ include the 40 – 50 km long N10-15°E – S10-15°W trending Koyna River fault zone (KRFZ) and Patan fault. Evidence for the existence of the KRFZ comes from aerial photographs and LANDSAT images. The WSZ zones lies 20 km south of the Koyna dam and includes two different sets of NW-SE trending blocks. This is shown as L_1 and L_2 in Figure 2. The locations of these fault planes have been confirmed by LANDSAT, INSAT images and by field testing. It is believed that these faults are stressed to threshold that a change in water level in the reservoir triggers earthquakes (Langston, 1981; Talwani, 1997b; Sunmonu and Dimri, 2000; Talwani, 2000; Gupta, 2002; Pandey and Chadha, 2003).

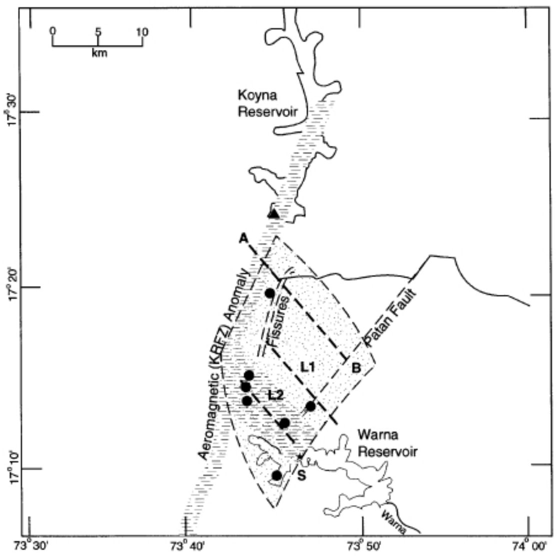

Figure 2: Tectonic features along Koyna-Warna region (Talwani, 1997b)

3. Deformation studies at Koyna

In order to study some of the factors that might be affecting the dam, the Koyna dam has been well instrumented for observations of its structural behaviour, right from the design stage. The instrumentation include physical instruments embedded in the dam structure or installed around the dam body like uplift pressure cells, thermometers, piezometers, stress and strain meters and coordimeters and these have been providing data since 1969 and the data is been archived and analysed by Central Water and Power Research Station (CWPRS) Pune (Bendre, 2003).

Geodetic and Research Branch of Survey of India (SOI), Dehradun had also been involved in deformation studies along the Koyna region and the dam even before the occurrence of the main earthquake of 1967. The first deformation studies using Levelling was originally done during 1946 – 48 to 1950 – 51 along the region. Field observations for geodetic triangulation, high precision levelling, geomagnetic, astro-deflection and gravity values were carried out in the region before the earthquake and were repeated after the earthquake. Dam targets and deformation stations along dam gallery, inside galleries, around the reservoir, near dam axis and along the vicinity of the dam were set up to study the stability of the dam and the surrounding areas for maximum and minimum water load using geodetic triangulation. Geodetic observations were taken from 1965 – 1966, 1967 – 69, 1971 – 72, 1975 – 76, 1978 – 79 and 1984 – 85 (Joshi and Kulkarni, 1986; Kulkarni, 1986b; Gahalaut and Kalpana, 2001). At present, no studies are being done using geodetic triangulation and levelling. With the advancement in technology, research has now been shifted to the use of space geodetic technique, GPS in monitoring the deformation of the dam.

In the recent years, GPS has been used extensively in deformation monitoring of dams, cable-stayed bridges and high-rise buildings worldwide. The advances in this technology evoked IITB to use Geodetic GPS for the first time in deformation studies in Koyna. IITB in collaboration with DST had been working in the field of deformation monitoring of the Koyna dam and its surrounding areas from December 2000 - May 2006. The main objective of work involved studying the behaviour of the Koyna dam body, using geodetic GPS technique. It included taking repeated observations over the network established, detailed GPS data processing using scientific software, estimating deformation of the dam, estimating parameters responsible for deformation and analysing the behaviour of the dam. The study also aimed at emphasizing on the reliability of the GPS-obtained results in deformation monitoring applications by proper validation.

4. GPS monitoring of Koyna dam

4.1 GPS Network and field observations

In order to carry out structural and crustal deformation studies, an extensive GPS network comprising of 31 stations had been established in and around the vicinity of the Koyna dam, at the beginning of the DST project, in December 2000 – January 2001, as shown in Figure 3.

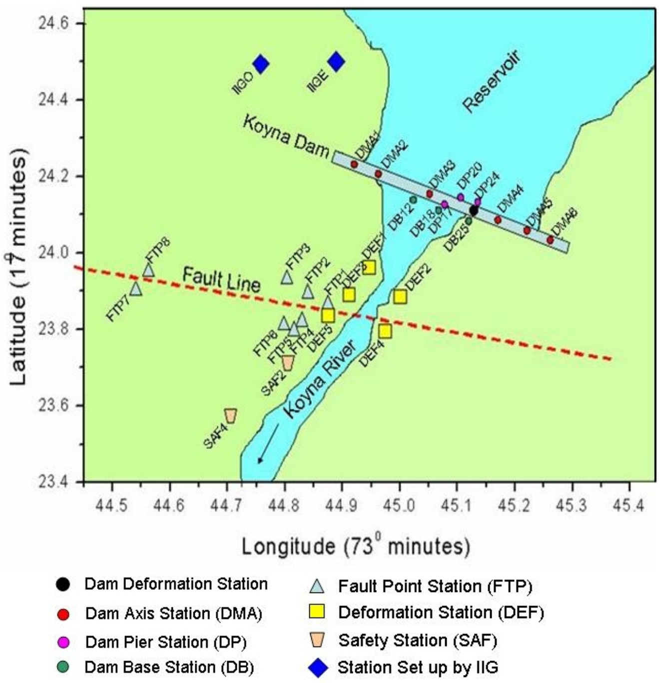

Figure 3: GPS network established on the Koyna dam and surrounding areas

Repeated observations over the entire network were periodically taken 2 – 3 times every year using dual frequency 4000SSi with Choke Ring antenna and 5700 with Zephyr Geodetic antenna of Trimble Navigation Ltd. Data was collected during the pre-monsoon or drawdown phase (minimum water load) and the post-monsoon or refill phase (maximum water load). A total of fourteen sets of repeat observations were taken, each field work period spanning approximately one – two weeks. GPS data was collected at the selected station points for a period of 6-8 hours with a sampling rate of 15 seconds and satellite elevation mask of 15°. The dam deformation station (DDS) set up on top of the dam was however monitored continuously (24 hours a day) throughout the period of observations during each of the field campaigns. In this paper, only the analysis of the DDS is emphasized on. The reason being that for validating the deformations estimated for the DDS, the coordimeter deflection data was available. However, no additional data was available for the other deformation stations.

4.2 Deformation analysis

The GPS data collected for all selected points for all 14 campaigns were processed using Bernese v4.2 software (Hugentobler et al., 2001) to yield single coordinates in both Cartesian Rectangular and Geodetic coordinate systems in WGS84 reference system. These coordinates were used for analysing deformation of dam. In order to determine the deformation of the dam, the change in coordinates between successive campaigns were estimated. For the present study, the deformation of the DDS was only considered. The deformations of the DDS for successive campaigns were estimated and this is given in Table 2 and Figure 4. Submillmetre RMS values of 0.2 mm was obtained on analysis which clearly indicated the accuracy of the results.

The deformations of the dam are dependent on several factors with the change in water load in the reservoir being the most important factor and dam body temperature, material property being the secondary factors. Here, for the analysis, to understand the pattern of deformation of the dam, the GPS-obtained deformations were analysed with respect to the different phases of water loading/unloading. To understand the deformation of the dam with respect to change in water level, an annual cycle of water table, i.e., from the period of start of refilling of the reservoir to the end of the drawdown phase was considered. During the period of filling of the reservoir, from Apr./May – Sep., a gradual rise in water table and therefore, a gradual increase in the surface water load behind the dam are normally observed. During this period, the stress due to the dead weight of water plays an important role in bringing about deformation. This can induce a bending moment on the dam that causes it to bend or tilt towards the downstream side. In addition to this, the peak in the water load is obtained by September which can again induce a heavy water load behind the dam. Thus, the deformation due to the water load behind the dam dominates the process. Therefore, for a rise in water table by 24 m during phases May 03 – Sep 03 and Apr. 04 - Sept. 04, the combined effect of all the forces resulted in a deformation of 8.3 mm towards the downstream side of the dam.

The peak in the water level obtained by September remains close to maximum till December with a very slight decrease in the water level by 7 – 8 m. Thus, the period from Sep. – Dec. represents the period of maximum retention of water in the reservoir and represents the time span where there is very slight change in water load behind the dam. Therefore, in the absence of any additional change in load during this period, other than the load due to maximum water load observed during September of the refill phase Apr./May. – Sep., the dam tends to rebound back to its original position. A rebound of the dam was seen during this period with a deformation of 5.1 mm in the upstream direction.

Dec. – Apr./May marks the period of drawdown of water table by 16 - 17 m behind the dam. This effect of release of the water load behind the dam can result in an elastic movement of the dam. This factor resulted in the deformation of 3.6 mm of the Koyna dam in the upstream direction (Talwani, 1997a).

Table 2: Local deformations of Dam Deformation Station (DDS)

Campaign	Resultant deformation (mm)	Change in Water level (m)	Direction of movement from North
Dec00-Oct01	5.9	5.0	SE
Oct01-Sep02	1.8	3.0	SW
Sep02-Dec02	-5.1	-8.0	NW
Dec02-May03	-4.6	-17.0	NW
May03-Sep03	8.3	24.0	SE
Sep03-Dec03	-5.1	-7.0	NW
Dec03-Apr04	-3.6	-16.0	NW
Apr04-Sep04	8.3	24.0	SE
Sep04-Mar05	-7.7	-16.0	NW
Mar05-Jan06	6.4	6.0	SW
Jan06-May06	-4.1	-15.0	NW

(Change in water level: '-' indicates drop in water level and '+' indicates rise in water level)
(NW: North-West; SE: South-East; SW: South-West)
('-' : upstream movement of dam and '+' : downstream movement of dam with respect to orientation of dam)

4.3 Validation of GPS results

One among the many methods is use of physical methods in deformation monitoring. Physical methods have been found to be useful for estimating structural deformation of dams from olden times, by periodic observations of instruments embedded in the body of the structure. A typical dam can contain piezometers, coordimeters, total stress cells, settlement devices, triaxial deformation tubes, inclinometers and extensometers, all installed below the surface at the time of construction that can provide horizontal or vertical deformations. However, the main disadvantage of this method is that observations are restricted to the pre-designed locations where the instrumentation has been installed. In addition, these instruments, deeply embedded in the body of a structure, are mostly inaccessible for maintenance and repair (Kulkarni, 1986b; Ding and Quinn, 2000).

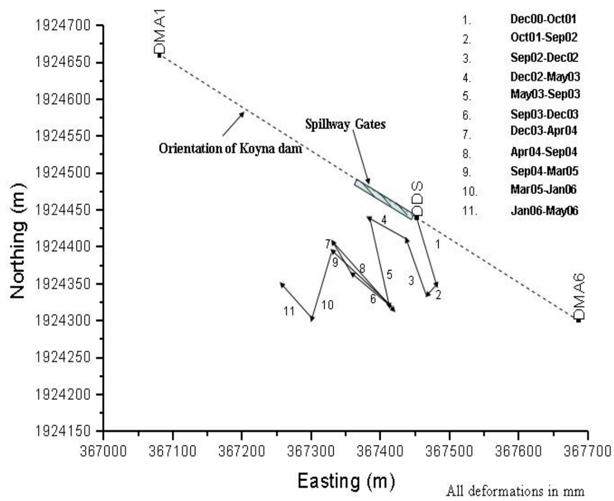

Figure 4: Movement of Koyna dam from 2000 – 2006 (Scale of deformation vector: 4 mm)

In this study, an attempt has been made to validate the GPS-obtained deformations for DDS with the deflections obtained from coordimeter set up inside the body of the dam and very near to the location of the DDS. Physical instruments like coordimeters, stress and strain meters etc., have been installed in the body of the dam during the construction of the dam, to continuously monitor the structural behaviour of the dam and have been providing data since 1969. In 1990, the coordimeter went under repair and was reinstalled again and its initial reading reset. From that period onwards, the instrument has been giving incorrect deflection readings. Due to this unreliable data, analysis pertaining to deflection of the dam by coordimeter was stopped. The coordimeter data collected from the Koyna authorities, thus, did not contain the data for the years from 2000 – 2006, i.e., the period of GPS data collection. However, Koyna authorities had a record of the corrected dam deflection for the year 2003 that the Central Water and Power Research Station (CWPRS) Pune, experts had corrected by statistical analysis. Therefore, owing to the unavailability of data files from 2000 – 2002 and 2004 – 2006, the data file for year 2003 was only considered for the study. The data consists of weekly deflection (averaged daily data) of top of the dam in mm.

The deformations estimated from GPS for the year 2003 were compared with those deflections obtained from the coordimeter. The deformations obtained between the following respective campaigns Dec. 02 – May 03, May 03 – Sep. 03, Sep. 03 – Dec. 03 were compared with what was observed with the coordimeter during the above campaigns. Figure 5 shows the movement of the dam estimated from GPS processed data. The number in circle represents the deformation in mm obtained from GPS processed data and the number in Italics represents the deflection in mm obtained from physical instrument during Dec 02, May 03, Sep 03 and Dec 03 respectively.

It is observed from Figure 5 that from Dec. 02 – May 03, the coordimeter show a decrease in the deflection reading, which is equal to 4.7 mm and is similar to what was obtained from GPS results. Dec. 02 is the end point of the North-West movement of Sep. 02 – Dec. 02 campaign (Table 2). Therefore, a North-West movement of the dam to May. 03 should result in a decrease in the deflection value during Dec. 02 – May 03. This is what is observed from the Figure 5 and also from the deflections obtained from the coordimeter. The South-East movement of the dam obtained from GPS for May 03 to Sep. 03 would result in an increase in the deflection value and this is what was obtained from coordimeter data. A decrease in the coordimeter deflection of approximately 5.4 mm towards the North-West direction was obtained for Sep. 03 – Dec. 03 campaigns. These above analysis show that GPS results are reliable and comparable with physical instrumentation results. Any change in the deformation results may be the error in coordimeter obtained data.

To further validate the GPS-obtained results, the local deformations obtained for the year 2003 were compared with the coordimeter deflection data recorded before the the instrument went under repair. Year 1982 showing the same variation in water load as in 2003 was considered for the analysis and this is shown in Figure 6. It is observed that from Dec. 1981 – May. 1982, a deflection of 4.4 mm was recorded by the coordimeter, which is similar to the year 2003 GPS results. For May 82 – Sep. 82, the physical instrument recorded a deflection of about 9 mm, which is almost similar to GPS-obtained result of 8.3 mm. Similarly, a deflection of 5.6 mm during Sep. 82 – Dec. 82 from coordimeter was recorded. This again clearly indicates the reliability of the GPS results.

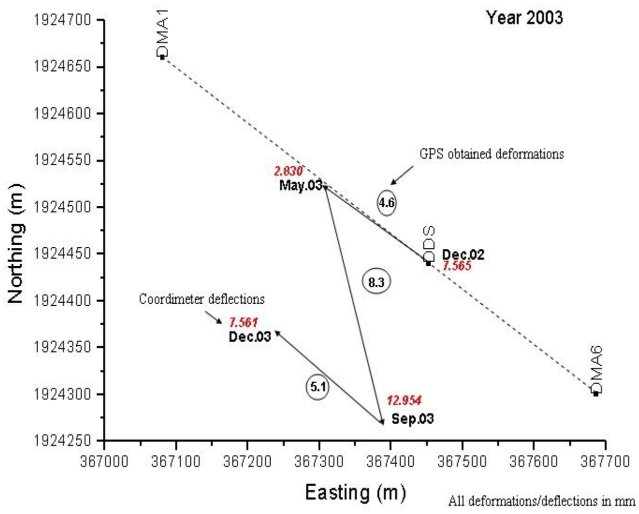

Figure 5: Comparison of GPS results with coordimeter deflections for year 2003
(Scale of GPS-obtained deformation vector: 10 mm)

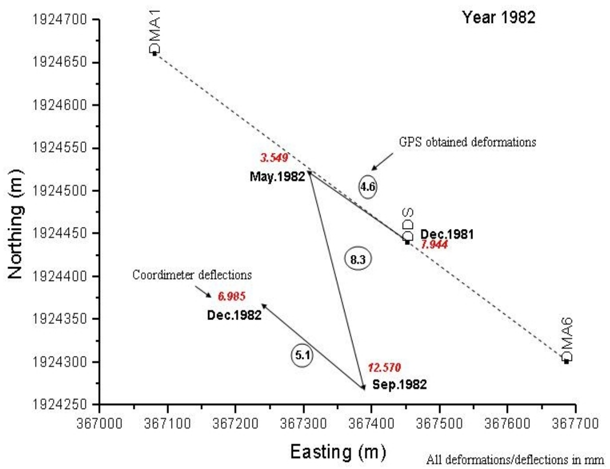

Figure 6: Comparison of GPS results of year 2003 with coordimeter deflections of year 1982
(Scale of GPS-obtained deformation vector: 10 mm)

5. Conclusions

An attempt was made to highlight the use and advantage of advanced space based technique, the GPS, in structural deformation monitoring by analysing the data collected for a large engineering structure, Koyna dam being subjected to external forces. An extensive network was established in and around the dam structure for this purpose and the data was collected periodically in campaign mode, 14 times, during year 2000 - 2006. For this study, the data collected for the station set up at the centre and top most portion of the dam was thoroughly processed and analysed. The deformations of the dam deformation station in the horizontal plane were thereby estimated and the effect of reservoir water level on the dam was studied. From the analysis of the local deformation obtained for the GPS station, it was seen that it is possible to define that the deflection of the dam is dependent on the self-weight of the water load behind the dam and is purely elastic.

It was found that during the refill phase (May – September), the increasing self-weight of water and the dominant water load during September causes the dam to tilt in the South-East direction (downstream). During the period of maximum retention of water table (September – December), a small decrease in water load causes the dam to move in the North-West direction (upstream), thereby showing a small rebound movement of the dam. The drawdown phase (December – May) showed that the release of the water load behind the dam causes the structure to deform in the North-West direction (upstream). The analysis showed that during the period of study, the dam deflected maximum during the refill phase and minimum during the drawdown phase. The deformations observed are not alarming during the period of observation and that the water load should be the main responsible parameter responsible for deformation of the dam.

The GPS-obtained local deformations were validated against the deflections of the dam obtained from physical instruments installed in the dam. Both the techniques showed similar pattern of movement of the dam, indicating the compatibility of the GPS-obtained results.

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