The Application of GPS To Dam Surface Monitoring

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Abstract

Dam monitoring relies on the long-term measurement of small structural motions at regular intervals. Traditional surveying techniques and geotechnical instrumentation can effectively monitor one- or two- dimensional modes of motion. However, spatial distribution of geotechnical instrumentation is usually limited to the locations that the instruments can be installed during dam construction, whilst surface monitoring by traditional surveying techniques is a relatively slow process which restricts the number of points that can be regularly monitored. As a supplement to existing geotechnical instrumentation, the Global Positioning System (GPS) offers a reliable and efficient method for three-dimensional monitoring. To date, GPS technology has been successfully applied to a variety of deformation monitoring applications. This paper reviews current GPS technology in the context of its application to dam deformation monitoring. The advantages and disadvantages of using GPS for this type of activity are discussed through three case studies of dam monitoring.

1 Introduction

All large engineering structures are susceptible to movements which may or may not be within design specifications. As the consequences of failure are severe, monitoring of dams commences in the early stages of construction, when it is important to validate assumptions made at the design stage, particularly regarding foundation seepage control. At the completion of the structure, monitoring is applied to control dam stability and behaviour, and continues at the stage of the dam's first impounding so that the safe establishment of the structure can be closely observed. Thereon, long-term monitoring of operational behaviour and regular measurement of stress states is maintained, to ensure that each component of the structure is functioning as intended.

The structural and geotechnical information needed to assess dam stability is primarily obtained with instrumentation systems that may vary for different monitoring purposes. The desirable characteristics of these systems include proven durability and robustness, simplicity of maintainance and use, provision of regular and reliable data sets, and minimal personnel requirements for the collection of data.

Although many different types of dam exist, the majority of instrumentation systems installed on dam structures are aimed at monitoring the following key precursors to failure: ground water pressure; chemical properties of the soil; pressure and stresses within the ground or structure itself; surface displacements on the dam structure or the surrounding bedrock. With respect to deformation properties, no two dams are identical and thus performance conclusions of one dam cannot be extrapolated to that of another. For this reason, each dam must be monitored regularly with a number of instruments (Wilson 1973). A typical dam will contain piezometers of various types, total stress cells, settlement devices, triaxial deformation tubes, inclinometers and extensiometers, all installed below the surface at the time of construction. Full details regarding geotechnical instrumentation and their arrangements can be found, for example, in Dunnicliff (1993), Fialovszky (1991), Bolt and Hudson (1975). Each of these instruments will be read regularly at intervals typically from one week to three months depending upon their relative importance and the era in the dam's life (Martin et al 1990). More recent systems can deliver continuous data in near real time, which may be logged to a local computer or transmitted directly back to the office.

Surface displacements are an important indicator of structural stability and surface monuments are often included in the overall monitoring regime. In the long-term, dams can be subject to alternating cycles of fast filling and rapid drawdown. Therefore, instrumentation that can provide measures of horizontal and vertical movement is desirable (Hanna 1973). For this reason, a large number of devices to measure longitudinal strains parallel to the axis along the crest of the dam are usually installed during construction to observe post-construction settlement of the crest for many years following completion of a dam (Seed 1973). Whilst geotechnical sensors such as inclinometers and extensiometers can measure one dimensional settlement measurements, it is difficult to extract true three-dimensional motions in the horizontal and vertical planes with this type of equipment (eg Knight 1990; Bozozuk 1984). The one-dimensional nature of these sensors means they may also be unable to detect certain modes of motion (Ding et al 1995). Alternatively, conventional surveying techniques, in which arrays of targets are situated on the monitoring surface and measured by electronic distance measurement devices (EDM), theodolites and optical levels, are used to monitor surface survey stations.

In the last decade, technological advances in instrumentation have revolutionised the surveying industry. In terms of surface measurements, the trend is towards measurement of more points more accurately and quickly than ‘traditional’ surveying techniques associated with Electronic Distance Measuring devices (EDM) and theodolite. The introduction of these new technologies will ultimately influence not only the amount and reliability of information available to the geotechnical engineer in the dam monitoring environment, but could also radically change the geotechnical analysis techniques currently employed.

In this paper, following a summary of conventional surveying methods for surface monitoring, we discuss the application of space-based positioning technology, namely the Global Positioning System (GPS) to dam surface monitoring. To date, GPS is a relatively mature technology which is currently being used in a wide number of applications. However, whilst GPS has several potential benefits to the field of dam monitoring, the dam environment is not ideal for GPS operations. The status of current GPS technology is reviewed and a number of case studies in which GPS techniques are adapted to the dam monitoring environment are presented.

2 Conventional surveying techniques for dam surface monitoring

The main disadvantage of most dam geotechnical measuring systems is that observations are restricted to the pre-designed locations where the instrumentation has been installed. The same locations must be measured separately in the horizontal and vertical components. Geotechnical monitoring techniques can be especially effective in areas on a slope where the mode of deformation motion has been previously identified. However, for general stability monitoring, where potential regions of failure on steep slopes or structures may not be evident, geotechnical methods are limited (eg Green and Mikkelsen 1986). It is infeasible to install a large number of geotechnical sensors over all parts of a potentially unstable dam structure.

In dam monitoring regimes, commonly used surveying techniques are: levelling for determination of changes in elevation of monitoring points, lateral displacement determination by offset measurement from a line of sight (theodolite), and measurement of range changes between known observation pillars or targets (EDM). Optical levelling usually requires second or third order accuracy in dam monitoring. As a rule of thumb, errors for these levelling orders are $4\sqrt{km}$ and $12\sqrt{km}$ mm respectively, where km is the length of the traverse in kilometres. First order levelling may be required where a high degree of accuracy is needed, for example the measurement of settlement of a dam. Digital levelling is capable of achieving such accuracies with instrumentation having resolution between 0.4-3mm for 1km double run. The measurement of lateral movement from offsets between points is usually performed by locating permanent targets at the two ends of a line of sight. Theodolites with a resolution of 1 second of arc are in common use for offset measurements. The sensitivity of the instrument is highly dependent on the type of target being used and sighting distances involved. EDM devices can measure to targets at distances up to several hundred metres. Providing the complete range of atmospheric and instrumental corrections are applied, resolution is in the order of 1-2mm ± 1ppm (Rueger 1996). Fully automated robotic total stations can be installed on dams to monitor the position of a number of reflectors with varying elevations at resolution between 0.5 to 7 seconds of arc and 1-2mm in range. Recent advances in this technology include motorised reflectorless total stations and theodolites with accuracies between 1.5-5 seconds of arc (eg Katowski 1993).

All conventional survey activities rely on optical techniques to make measurements to known points. In dam monitoring, as in any type of monitoring activity, a number of reference (control) points or benchmarks located well away from the zone of the ground movements are required. Otherwise, the control points themselves may also be affected by surface motion. The degree of sophistication of reference point or benchmark construction depends heavily on the accuracy required and the permanency of installation. For these reasons, the most usual practice is to locate any reference points in sound bedrock.

The requirement for 'line-of-sight' observations from stable reference points to the monitoring points cannot always be satisfied in all monitoring environments and can be a problem for the surveyor (as can vandalism and wear and tear of targets and survey marks). In addition, extreme conditions, such as temperature changes, atmospheric refraction and fluctuations, and the presence of dust, can alter the optical properties of the environment, thus inhibiting the operation of the equipment. This issue is particularly pertinent in monitoring regimes where different observation conditions between surveys may cause systematic errors which manifest themselves as apparent motion. Monitoring regimes with a low observation frequency (for example, quarterly or annually) are more susceptible to this type of problem as seasonal observing conditions may vary greatly and systematic measurement outliers are more difficult to detect with a poorly sampled time series.

Surface monitoring has the advantage that, in principle, many points can be accurately monitored throughout the lifetime of the dam structure. The spatial density of monitoring points can be increased relatively easily if any critical areas on the structure are identified. However, in practice, time limitations and pressures of finance restrict the total number of points that can be monitored on a structure. In spite of modern developments in instrumentation, such as robotic total stations, a conventional dam monitoring survey can be a time consuming process. For example, the Water Corporation of Western Australia is responsible for monitoring over fifty concrete and earth bank dam structures. A conventional survey of around 40 points takes between three and five days to complete. With requirements of monitoring every 6 months (3 months on newer dams), it is clear that the expense of increasing the density of monitoring points is prohibitive.

3 Dam Monitoring with GPS

Since its inception in the early 1970s, GPS has become a widely used surveying tool. Today, accuracies at the centimeter level or better are routinely achieved using a variety of relative positioning techniques. These techniques range from near-instantaneous positioning over relatively short reference receiver to unknown receiver distances, to solutions requiring many hours of data and advanced modelling for distances between receivers of up to several thousand kilometers. Removal of the line-of-sight dependency for survey observation has radically altered the practices of the survey community, allowing larger areas and more points to be measured.

Relative GPS also lends itself naturally to deformation monitoring and GPS has been widely used for a number of monitoring applications. Nowadays, regional GPS surveys are used for measurement of plate tectonic motions and to characterise the kinematics and geodynamics of active lithospheric areas for earthquake and volcano hazards (eg McClusky et al 2000). In small-scale deformation monitoring applications, GPS is now used to observe structures which, in the past, may have been monitored using traditional surveying techniques or using inclinometers or extensiometers. Examples of successful small scale monitoring using GPS can be found for bridges (eg Watson and Coleman 1998), buildings (eg Celebiet et al 1999a, 199b), volcanoes (eg Dvorak 1992), local and regional ground movements due to seismic events (eg Murray et al 1999), and ground subsidence (eg Mossop and Segall 1997).

With GPS having the capability to provide three-dimensional position information over time, it has much to offer as a tool for the direct measurement of deformation fields. However, as in any deformation monitoring application, the design of the optimal GPS monitoring system requires an understanding of the expected deformation signal. Depending on the application and accuracy requirements, monitoring strategies can vary from continuous collection of data recorded by permanently installed GPS receivers to sporadic (known an *episodic*) occupation of monitoring points. Permanent GPS networks offer the highest accuracies and temporal resolution (eg Hatanaka et al 1995). In addition, setup errors are minimised, as the requirement for the GPS antenna to be manually centred over the point of interest at the beginning of each occupation is eliminated. The disadvantage of continuous monitoring is the limited spatial resolution of the network of deforming point primarily due to the high cost of establishing such networks (a geodetic quality GPS receiver, antenna and communication link is required in perpetuity at each point).

Recent hardware and software developments have led to the development of *fast* or *rapid* techniques, which use a combination of lightweight GPS receivers and shorter observation spans. With occupation times of thirty minutes or less (depending on the number of visible satellites and their respective geometry), *fast-static* is now the most widely used GPS surveying technique for high precision positioning. This technique is ideally suited to episodic monitoring and fast-static GPS surveys can be significantly quicker to complete than their traditional surveying counterparts, which are of limited range and rely on line-of-sight. For example, episodic fast-static GPS monitoring surveys can be performed over between-survey timescales of one week upwards, and, due to lower cost, on a larger number of monitoring points than in permanent networks. Repeat monitoring with rapid static GPS has several disadvantages. First, monitoring points must be physically revisited in an environment where access to dangerous steep slope walls may be restricted. Secondly, repeat antenna setup over a monitoring point can cause centring errors of a similar order of magnitude to any deformation motion to be detected. Resolution of fast-static surveys in the dam monitoring environment is invariably worse than 'traditional' surveying techniques.

As stated above, routinely achievable accuracies with GPS are in the order of 1cm (although GPS is slightly worse in the height component). There are however two main causes for the degradation of GPS solutions to centimeter level accuracies from raw observations of millimetre level precision: satellite geometry and unmodelled error. Although individual phase observations from different satellites may be very precise, the geometrical distribution (and number) of satellites in the sky may limit the precision of the final computed position. This so-called 'dilution of precision' (DOP) effect is magnified when parts of the sky are obstructed by man-made structures. Whilst phase observations are very *precise*, they are contaminated by errors which cause them not to be particularly *accurate*. All error sources must be modelled or removed before millimetre (or lower) accuracies can be achieved with GPS. The main sources of unmodelled error pertain to unwanted reflected or diffracted signals travelling different paths to the direct path from the satellite to the antenna (the so-called multipath effect). Such multipathing effects are accentuated close to man-made structures. Unfortunately, both satellite geometry and unmodelled noise are a problem in dam monitoring, where monitoring points tend to be adjacent to dam walls, restricting satellite visibility and magnifying multipath (eg Eissfeller and Winkel 1996).

In relation to rapid-static GPS, GPS kinematic methods offer the prospect of positioning monitoring points with very short (theoretically instantaneous) occupation times with little degradation in coordinate accuracy relative to rapid-static GPS. A basic GPS kinematic solution computes the position of the GPS antenna from measured ranges to satellites using a single epoch of data. In the case of carrier phase observations, the carrier phase integer ambiguity must first be resolved to convert carrier phase measurements to range observations. Whilst kinematic methods offer the prospect of pseudo-real time positioning at frequencies of 1Hz or faster, they are considerably more vulnerable to multipath and poor satellite visibility. The aforementioned issues render the latest generation of rapid GPS positioning techniques (Real Time Kinematic – RTK) unreliable for dam monitoring at resolutions of 1cm or less.

The use of different types of GPS surveying techniques is illustrated in this paper with three case studies, designed to highlight the issues and possibilities for the application of this technology to dam surface monitoring.

3.1 Case Study 1 - Continuous monitoring system at Pacoima Dam, California

Background

Given the risk of earthquakes, monitoring the integrity of engineering structures receives high priority in the state of California. A number of dams in the region are currently being monitored by both conventional means and continuously operating GPS arrays. These include the Eastside Dam (Whitaker et al 1998) and the Pacoima Dam (Hudnut and Behr 1998), both of which are located in Southern California. The Pacoima Dam will be used to illustrate an example of a continuous GPS system in operation. The details and results given below are taken exclusively from Hudnut and Behr (1998) and Behr et al (1998) and the reader is referred to these papers for a complete treatment of the use of GPS at Pacoima Dam.

The Pacoima Dam is a 113m high concrete structure located in the San Gabriel mountains, about 5km northeast of Sylmar, California (figure 1). Completed in 1926, the dam has had to withstand major earthquakes in 1971 and 1994. A system of three continuously operating GPS receivers was installed by the US Geological Survey and the County of Los Angeles in September 1995.

Figure 1 Pacoima Dam, California (from Hudnut and Behr 1998).

Figure 2 GPS installation on Pacoima at location DAM 2 (from Hudnut and Behr 1998)

GPS Survey Procedure and Data Reduction

As can be seen in Figure 1, because of the necessity of installing GPS antennae on surface monitoring points, concrete dams are not well suited for GPS-based monitoring operations. For these types of dams, conventional surveying techniques, and other techniques such as photogrammetry and laser scanning (eg Lichti et al 2000), will continue to be used for the collection of information on surface movements. At Pacoima, two continuous geodetic GPS receivers, named DAM1 and DAM2, were installed on the top of the structure at the locations indicated in Figure 1. As can be seen in Figure 2, the GPS antennae were mounted on a steel pylon beneath a conical cover. The GPS receiver and communications equipment were locating in a nearby electrical box mounted on the nearby chain link fence. The reference receiver was installed on stable bedrock outside the steep-walled canyon containing the dam, about 2.5km from the dam site. Data from a further three continuous monitoring GPS stations operating at distances of up to thirty kilometres from the dam site were also included in the processing. These stations form part of the Southern California Integrated GPS Network (SCIGN). Raw GPS observations were logged to the internal memory of each receiver and downloaded using high speed modems daily. Quarter-daily solutions (derived from 6 hours of satellite observation to each receiver) were derived using GAMIT geodetic GPS processing software (King and Bock 1998). Figure 3 shows results in all components from approximately two years of observation.

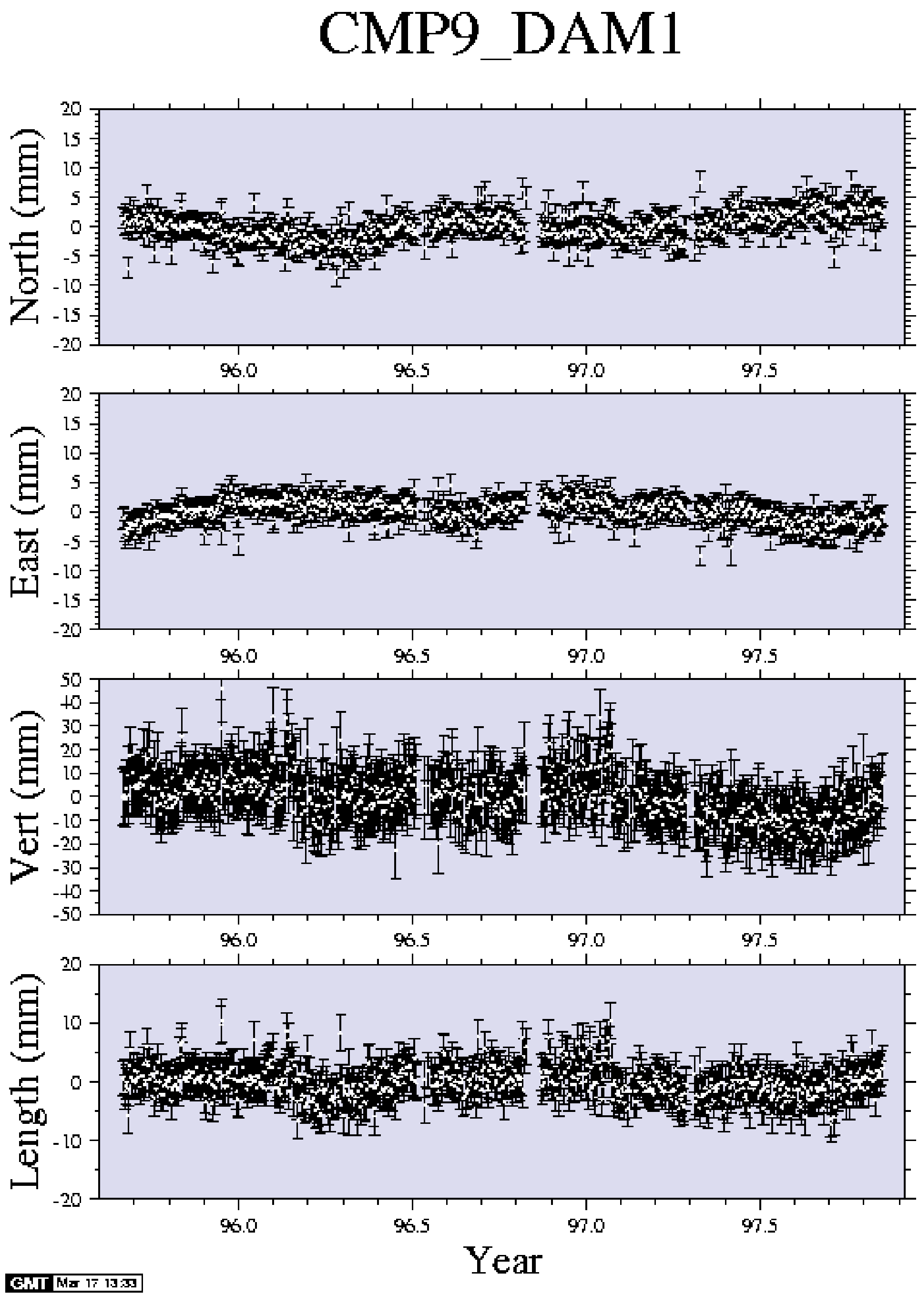

Figure 3 GPS results from two year data set at Pacoima Dam (from Hudnut and Behr 1998)

Discussion

The observation and GPS processing techniques used at the Pacoima Dam represent the pinnacle of what is achievable with GPS deformation monitoring. Similar techniques are routinely used to measure regional tectonic displacement and the results shown in Figure 3 illustrate the power of this type of monitoring regime. Millimetre-level displacements with frequencies of several months have been detected in three dimensions. It is interesting to note that the height component of the solutions at Pacoima Dam is considerably noisier than the horizontal components. This is a function of the geometry and error sources associated with the GPS satellites which tend to propagate more error into the height component than the horizontal components. In the case of the Pacoima Dam, this effect will be accentuated by the steep valley walls above the dam which obscure some lower elevation satellites from the receivers. Notwithstanding this fact, Figure 3 provides an excellent indication of the resolution achievable for structural monitoring using GPS.

The obstruction of visible satellites is a common theme in all dam monitoring studies, be it due to high valley walls, or if the monitoring points are located on the dam, as in the subsequent examples, the dam wall itself. Despite the quality of the results from the Pacoima Dam GPS monitoring system, this system has some limitations for general dam monitoring. The cost of the equipment required to install the type of continuously operating GPS receivers used at Pacoima Dam is prohibitive to many organisations. Conservatively speaking, installation of a geodetic GPS receiver, high quality GPS antenna, stable monumentation, a continuous power supply and a reliable communication link will cost upwards of $20 000 (US) per point. Although this type of system has relatively low running costs once installed, in general, dam surface monitoring requires a denser spatial distribution of monitoring points. Therefore, continuous GPS monitoring may be seen only as a useful supplement to conventional monitoring techniques. Note also that with concrete dams, it is only feasible to monitor points on the top of the dam with GPS.

3.2 Case Study 2 - Episodic monitoring regime at North Dandalup Dam, Western Australia

Background

Water supplies for the Perth region in Western Australia are drawn from two types of water resources: surface water and groundwater. Surface water, which is 60 percent of the current supply, is obtained from dams on rivers in the nearby Darling Range. In total, 24 dams are scattered around the state of Western Australia, 10 of which serve the metropolitan area. In Western Australia, the Water Corporation monitoring specifications for concrete dams require an absolute positioning accuracy of ±2mm at 95% confidence level. For earth dams, specifications are less stringent, with an absolute accuracy of ±5mm required at 95% confidence level.

The traditional dam surface monitoring strategy in Western Australia involves initial monitoring surveys conducted every three months to establish base data and show initial trends in settlement (standard geotechnical instrumentation is also installed in each dam structure). If these movements are within the values expected by design engineers, the frequency of monitoring may be reduced by the engineer responsible for surveillance. The frequency of observation of a given dam then depends on the risk/hazard associated with that structure, as defined by the Australian National Committee On Large Dams (ANCOLD 1994). All 24 West Australian dams are monitored regularly by survey companies under contract to the Water Corporation using terrestrial surveying techniques (total station and electronic level) at time intervals ranging from 1 to 6 months. This instrumentation allows Water Corporation specifications be met routinely. However each dam survey takes approximately one week to complete using the aforementioned surveying techniques.

Rapid-static GPS surveys have been under trial at North Dandalup Dam at three monthly intervals since 1996. At the time of writing, some 16 surveys have been completed. North Dandalup dam, situated about 70 km southwest from Perth city Figure 4), was completed in mid-1994 and is licensed to extract 22.2 GL per year. The dam is constructed from earthfill and rockfill and rises some 55 metres above the original level of the North Dandalup river. It comprises three saddles; the main dam with length of approximately 500m, the major saddle dam to the north with 350m length, and the minor saddle dam being only 100m long.

GPS survey procedure and data reduction

A schematic diagram of the monitoring points on the main dam is given in Figure 5. In total, some 40 points are monitored. Because the capabilities of rapid-static GPS are outside the Water

Corporation specifications, it has been specified that GPS is not to be used for reduced level determination. Therefore, all points are also measured using precise levelling techniques. The levelling data also provide a useful independent check of the vertical component of the GPS solutions.

Figure 4 Aerial view of North Dandalup Dam, Western Australia

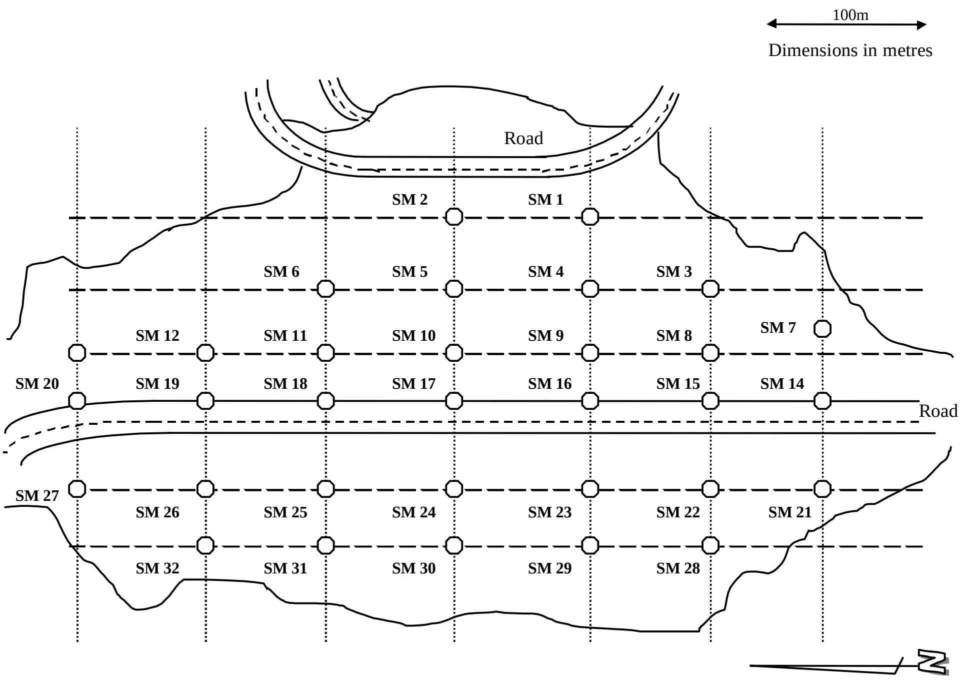

Figure 5 Monitoring points on the main saddle of North Dandalup Dam

During each site survey, geodetic quality receivers are situated on two GPS bedrock control points whilst a third 'roving' receiver visits each point. Unlike continuous GPS, the antenna must be carefully centered over the reference mark each time a point is visited (Figure 6). Baseline lengths are generally less than 1km. In rapid static surveys, the time spent at each point can range from 15 minutes to around 30 minutes, depending of satellite geometry and signal quality. Raw GPS observation data are logged onto the hard disks of the GPS receivers and the complete survey takes around 3 days for a team of two surveyors to complete. On return to the office, the data are downloaded and post-processed in a commercial GPS processing software package.

Figure 7 presents precise levelling solutions and GPS solutions for two sample monitoring points SM2 (situated at the bottom of the main saddle) and SM16 (situated on the top of the main saddle). GPS results from all 40 monitoring points exhibit similar charactersitics. It can be seen from the figure that results from the GPS surveys are considerably noisier than those from the precise levelling. Note that the GPS solutions will be somewhat better in the horizontal. In this case, however, no external control exists in the horizontal component. Therefore, only the vertical component is presented here.

Figure 6 Antenna setup for episodic monitoring surveys

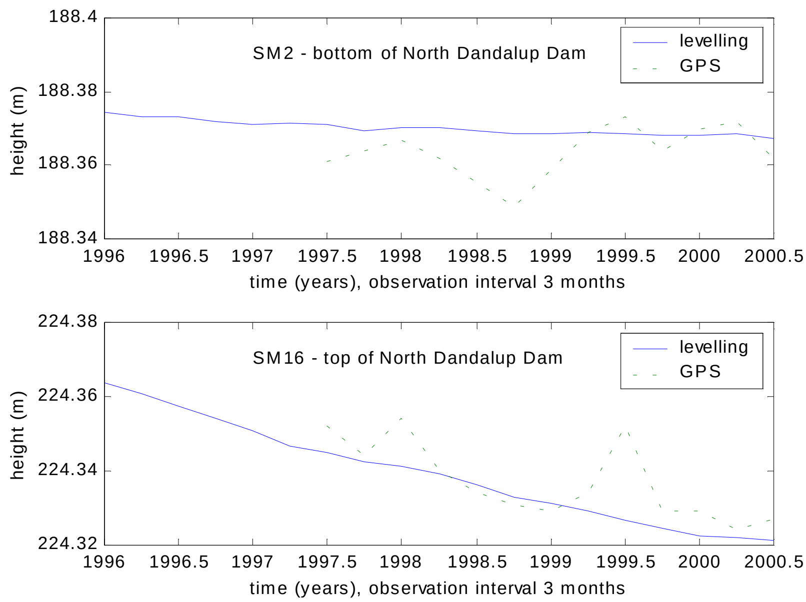

Figure 7 Comparison of height differences at SM2 and SM16 from precise levelling and GPS

Discussion

In relation to case study 1 (Figure 3), the drawbacks of episodic monitoring can be clearly seen in Figure 7. Individual coordinate estimates are at the 1-2cm level of accuracy. Not only does the resetting of the antenna during each survey provide an additional source of error, but shorter observation epochs (ie an average of 20 minutes data compared with 6 hours at Pacoima Dam) lead to less reliable results. Results from points on the dam slope are also contaminated by multipath effects and bad satellite geometry. Commercial GPS processing software has yet to come to terms with these types of systematic errors. Detecting structural motion using the weak temporal distribution of episodic monitoring results (ie 3 monthly) is clearly more problematic than in continuous monitoring case.

Episodic GPS monitoring, as applied at North Dandalup Dam, is a cost-effective solution when a large number of points must be monitored. At North Dandalup, only three geodetic receivers are required for three days per quarter. The trade-off is that fast-static GPS has proven to be inferior in accuracy to conventional surveying techniques. From these inferior accuracies we can conclude that this type of technique is inadequate for meeting most dam monitoring specifications.

3.3 Case Study 3 - Multi-antenna array at Harvey Dam, Western Australia

Background

Harvey Dam is currently under construction in the Darling Range of Western Australia. Situated about 120km from the Perth metropolitan region, water from Harvey Dam will supplement supplies from other dams, such as North Dandalup, in the area. Harvey Dam is to be an earth bank dam, some 50m in height. Standard geotechnical instruments such as electronic piezometers, internal vertical movement gauges and hydrostatic settlement gauges are to be installed within the fabric of the dam. A network of monumented surface monitoring points is to be installed on the dam wall (Figure 8). The dam is schedule for completion in late 2002.

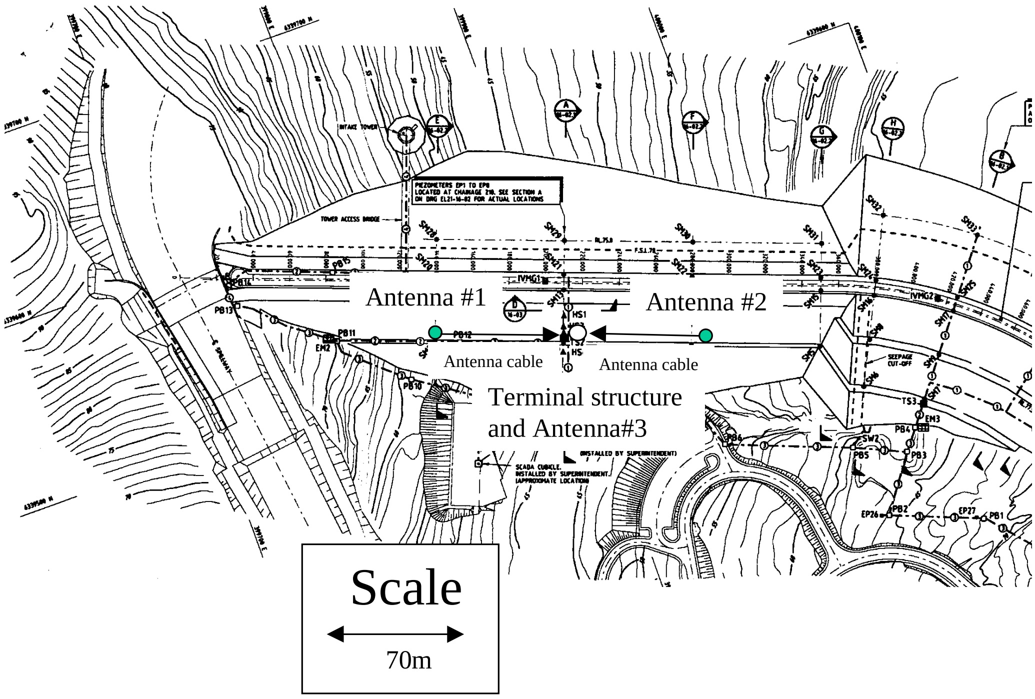

Figure 8 Schematic plan of Harvey Dam, Western Australia illustrating location of proposed multi-antenna GPS system

GPS survey procedure and data reduction

A trial multi-antenna GPS system is to be installed during the construction process. The system will comprise three permanent GPS antennae co-located with conventional survey marks at SM2, SM3 and SM4. Subsurface cables will run from the antennae to a terminal structure housing a GPS receiver, power and communication equipment. The distances from the monitoring points to the terminal structure are approximately 90m for SM2 and SM4, whilst SM3 will be adjacent to the terminal structure. The GPS receiver will be connected to a switching system which will be used to sequentially collect data from each antenna. Each antenna will log for time periods of between ten minutes and two hours. Two continuously operating reference stations are to be located on nearby bedrock. Data will be transmitted automatically back to a processing centre in Perth.

Discussion

The concept of multi-antenna GPS arrays has been suggested by several authors (eg Petrovski et al 1999; Ding et al 2000). It attempts to take the best of continuous and episodic GPS monitoring techniques to produce a financially viable monitoring system. By sharing antennae between one receiver, the requirement for multiple receivers, each with its own communication system, is eliminated. Installation of permanent antennae removes the antenna setup error associated with episodic monitoring. The system is automatic, with similar maintenance benefits as continuous monitoring, and although less GPS data will be available than in a fully continuous system, it may be argued if baseline lengths remain short, much data collected by continuous systems is redundant.

The main weakness of this type of system is that a network of cables must be run between the terminal structure and individual antenna. GPS antenna cables are not generally longer than about 30m and longer cables require line amplification. The cost of cables is also an additional expense, although at current prices of around $2000 US per km, this cost seems insignificant in relation to $15 000 – 30 000 US for a geodetic GPS receiver. These cables are vulnerable to severance and will be buried in the dam wall in the construction phase of the dam.

4 Dedicated GPS techniques for deformation monitoring

It remains to be seen if multiple antenna GPS monitoring systems can provide results similar to those achieved at Pacoima Dam at a similar cost to the episodic surveys undertaken at North Dandalup Dam. What is clear is that whilst GPS appears to have great potential for dam surface monitoring, to date the techniques applied have not achieved the optimal solution, in terms of cost, spatial data acquisition and temporal data acquisition. Part of the problem has been that continuous and episodic monitoring data reduction techniques are not specifically designed for measuring small scale slow structural motions. Processing softwares tend to be designed for general use, rather than specific environments. Advanced data processing techniques are available at the research software level that can be applied specifically to the dam monitoring regime. These include noise reduction, systematic error propagation and ambiguity resolution (eg Jia et al 1999; Wang et al 1998). However, it may be several years before these research results make their way into mainstream commercial GPS software.

GPS hardware technology is advancing at a rapid rate, both in terms of receivers and the satellite hardware. The removal of selective availability by the US Department of Defense, essentially improving the accuracy of hand held receivers from 100m to 10m overnight, is an extreme example of the rapid progress in this field. Undoubtedly, hardware will continue to improve, becoming cheaper and more reliable. It may become affordable to put cheap continuously operating GPS receivers with built-in communication systems at every point. However, similar challenges remain, namely that of sky visibility and signal resolution in high multipath environments. Another issue to be addressed on many dams is security of equipment from theft or vandalism by the general public.

5 Conclusions

GPS has the potential to provide accurate, economically viable dam surface monitoring systems. GPS surveys are quicker and more efficient than conventional surveys and automated systems remove the requirement, and hence cost, for a surveyor. However, for this type of application, the technology is still in its infancy and ‘off the shelf’ systems cannot achieve the accuracies for most dam monitoring requirements, although GPS observations can supplement conventional surveying and geotechnical measurements with three-dimensional data. The dam monitoring environment is harsh for GPS and until hardware and software developments are dedicated to multipath reduction and poor satellite visibility, results will continue to be worse than for other GPS applications for all but the economically unviable continuous monitoring networks. It must be stressed, however, the success of any GPS monitoring regime depends strongly on the observing environment and this varies greatly from site to site. GPS offers the geotechnical engineer another useful option for dam monitoring and GPS should be seen as a potentially useful tool for many dam environments.

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