THE EXTENSIVE GEODETIC SYSTEM USED FOR THE MONITORING OF A 185 METRE HIGH ARCH DAM IN SOUTHERN AFRICA

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Abstract

The 185 metre high Katse Dam in Lesotho completed in 1997 is the highest dam in Southern Africa. A geodetic monitoring system forms part of the dam safety surveillance system designed for the dam. The primary geodetic network beacons were constructed in 1991 before construction of the dam commenced in order to establish their long-term stability. Reduced geodetic measurements of the arch started in 1995 during construction of the dam but full-scale measurements could only commence in February 1998 after completion. The practical aspects of the geodetic measuring system, combined with pendulums are described in detail. The incorporation of this technique in the dam safety surveillance system is illustrated.

1. Introduction

The construction of Katse dam is a major binational project by the Governments of Lesotho and South Africa and involved impounding the surplus water from the rivers in the Highlands of Lesotho. Water is transferred through the Maluti mountains across the border of South Africa to supplement the overtaxed water resources of the Vaal River basin that serve the mining and industrial center of the Pretoria, Witwatersrand and Vereeniging area of South Africa, 400 km from Lesotho (Figure 1).

Figure 1 Lesotho Map

Figure 2 Katse Dam

The double curvature concrete arch dam (Figure 2), situated in a 230m deep gorge ±2 km downstream of the confluence of the Bokong and Malibamatso rivers at a elevation of 2060 masl, is 185 m high above foundation, crest length of 710m, crest thickness 9 meters, base 60 meters and a volume of concrete of 2,3 million m^3 and a catchment area of 1867 km^2.

The design of the deformation monitoring scheme was done for the Lesotho Highlands Development Authority under agreement with the Department of Water Affairs and Forestry of the Republic of South Africa.

A large Geodetic network scheme was introduced to complement the Swiss developed precise traverse scheme which was introduced in three galleries in the arch dam and two access galleries in the rock abutments. A Swiss developed HELMERT 91 software suite is used for adjustments and analysis of the measured data. Final results are three dimensional displacements of monitoring points, which reflect the behaviour of the dam under varying temperature and water load conditions.

2. Geotechnical Aspects

The geology of the damsite consists of a succession of sub-horizontal basalt lava flows of Jurassic age (*160 million years old*). The flows range in thickness from less than one meter to over 10m and are occasionally separated by thin deposits and pockets of volcanic ash and tuff (Lahmeyer, Macdonald 1986). The excavation for the foundations of the dam in the valley bottom revealed that there were high horizontal compressive stresses acting across the site *"locked in"* to the more competent basalt layers.

A geological fault, which is a weak planar surface in the crust of the earth opened up at the Ha Mapeleng village ± 5 km upstream of the dam site since the dam started filling in October 1995 when 350 million m3 of water was impounded which represented a weight of 350 million tons. The width of the openings varied from very small up to 70 mm.

Three seismograph stations are located around the Katse Reservoir to record continuously seismic activity after initial settlement of the crust. A precise levelling route was introduced in 1996 to Kolberg airstrip 8 km downstream of the dam wall on the Thaba-Tseka gravel road and a GPS geodetic control network was installed in 1999 for monitoring the stability of the area surrounding the reservoir and the primary beacons of the deformation monitoring scheme. The design of the Katse Dam was planned in such a manner that the structure could withstand an earthquake measuring 6.5 on the Richter scale.

3. Basic Layout

The primary geodetic network, as designed in 1991, was extended in 1997 with additional secondary pillars, balcony pillars on the arch dam, precise traverses in galleries and precise level routes on both flanks and downstream of the dam.

3.1 Triangulation Network

The triangulation network consists of 5 primary, 8 secondary beacons, 8 arch dam balcony pillars, 4 gallery exit brackets, 19 parapet targets, 6 optical alignment monitoring points, 24 crest benchmarks and 2 altrimetric wire anchors. Two Primary benchmarks are located on the left flank, two on the right flank and three downstream of dam (Figure 3).

Network pillars were constructed with a inner concrete reinforced Asbestos Cement CID pipe anchored in solid rock or concrete, protected by an outer Asbestos CID pipe filled with polystyrene and sealed. Centering is obtained by Kern forced centering or 5/8" bronze pillar plates.

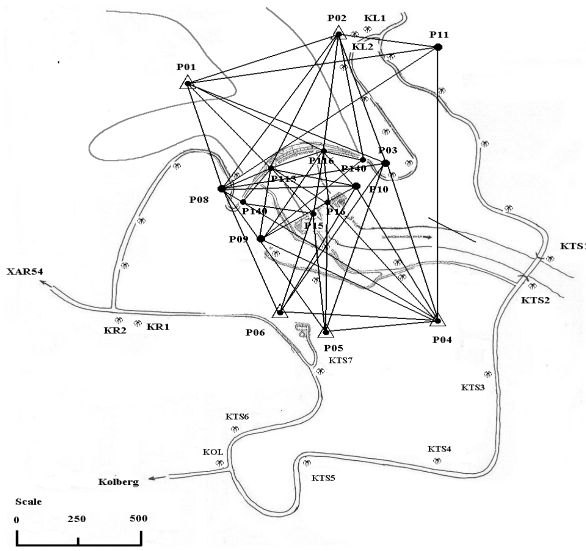

Figure 3 Triangulation Net

3.2 Precise Traverses

By request from the Lesotho Highlands Consultants (LHC) consortium monitoring points had to be installed in the center of every second block of the concrete arch dam at elevations 2060, 2005, 1945 and 1900 and in the drainage galleries and access galleries on both flanks.

The traverses in the arch dam consists of 6 optical alignment brackets at elevation 2050, 103 fixed brackets and 13 pillars in the drainage galleries on both flanks at elevations 2005, 1945 and 1900 (Figure 4) with 15 pillars and 16 brackets mounted in the rock wall between pillars in the access galleries at elevations 1990 and 2005 (Figure 5).

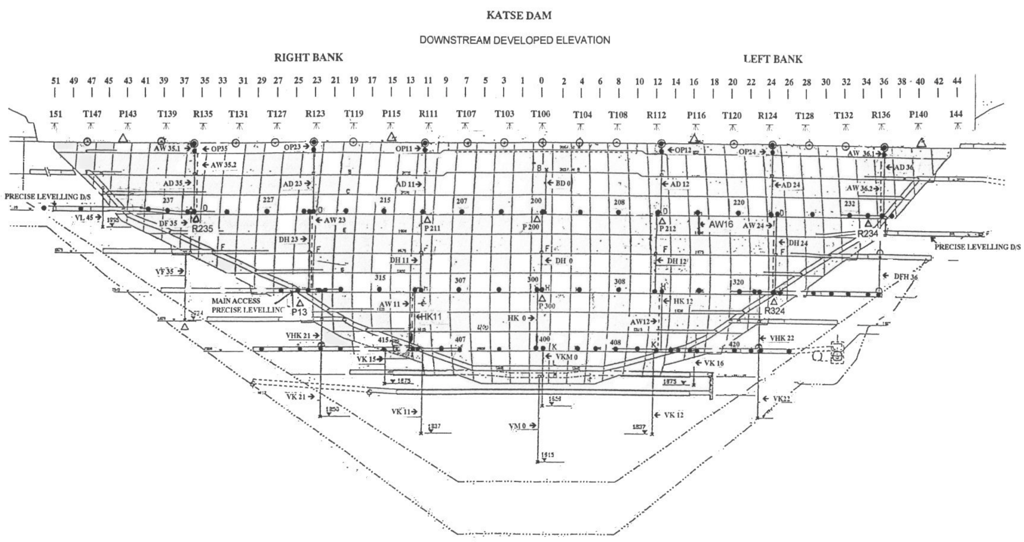

Figure 4 Downstream Developed Elevation

To fit stations in the center of every second block different lengths of invar distances 5, 15, 30 and 31m are used to align the traverses to entrances to pendulum chambers and gallery exits. Non-uniformed distances are measured by means of EDM from the main traverse brackets in the gallery to brackets inside the pendulum chambers used for observation of pendulum and balcony pillars/brackets at the exits of the galleries.

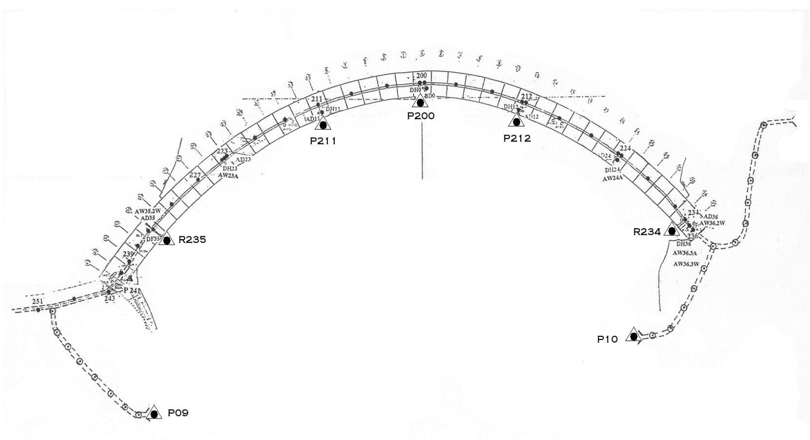

Figure 5 Traverse Layout at Elevation 2005 and 1990

Stainless steel plates (CERN type) are fixed to the brackets to fit adapters fixed to the theodolite's, illuminated targets, distometer and 60 cm bar coded levelling scales (Figure 16, 17 ,18).

To connect the traverses to the net, optical alignment monitoring points (Figure 6) were installed at elevation 2060, optical alignment brackets (Figure 7) at elevation 2050, exit balcony pillars/brackets at elevation's 2005 and 1945 and pillars at the exits of the access galleries.

Figure 6 Crest Optical alignment monitoring point with tripod.

Figure 7 Optical alignment bracket-hanging pendulum anchor.

3.3 Pendulums

The inverted and hanging pendulums form an essential part of the deformation monitoring system as they are connected to the traverse scheme at elevations 2050, 2005, 1945 and 1900m. The seven vertical lines (one every sixth block) are equipped with up to four stacked pendulums (Figure 8) with reading tables, sixty metres maximum height each, the lowest being the inverse type (Figure 9) in the foundation at elevation 1862.

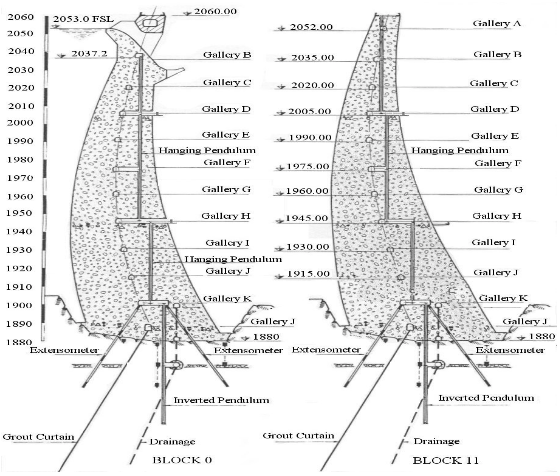

Figure 8 Cross section of pendulums in blocks 0 and 11.

Figure 9 Inverse pendulum chamber with traverse bracket and TC2002

3.4 Levelling

The primary benchmarks are located ±1.0, 1.2 and 1.7 km on the left, right flank and downstream of the dam wall (El 2070, 2145 and 1898.5 and levelling routes on the arch dam are at crest level 2060, gallery traverses levels 2005, 1945 and 1900.

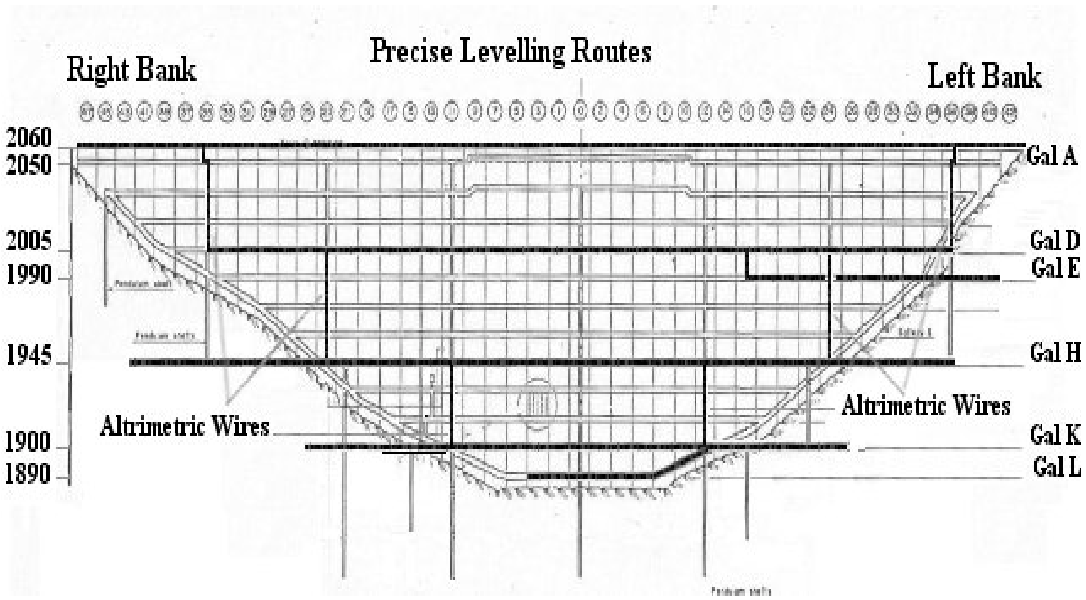

Figure 10 Altrimetric wires and levelling routes in the arch dam

Connections of the traverses in the arch dam are by means of altrimetric wires (Figure 10), hanging from elevation 2060 to 2050, 1945 and 1900. Access gallery at elevation 1990 is connected to the main traverse by means of an altrimetric wire from elevation 2005 (block 16), benchmarks in the gallery E to the station bracket at the exit and over bracket/pillar stations to the exits of the access gallery on the left flank.

Levelling routes from galleries H (El 1945) and K (El 1900) are connect to 8 anchor points of the TRIVEC system in galleries L, N and downstream of the dam. Each anchor point comprises a series of stainless steel anchor points firmly grouted in place at intervals in boreholes

4. Equipment Used

Network : Leica TC2002 electronic total station (Figure 11), Kern forced centring target/Leica & Kern precision prisms (Figure 15).

Traverse : Kern E2 precision theodolite (Figure 12 & 16), Distometer Iseth (Figure 13 & 17), Illuminated targets (Figure 18), 10m Steel tape.

Figure 11 TC2002

Figure 12 Kern E2

Figure 13 Distometer

Figure 14 NA3003

Figure 15 Leica prism with Kern target

Figure 16 Bracket & Kern E2 Adapter

Figure 17 Bracket & Distometer end piece

Figure 18 Traverse illuminated target

Levelling	:	Leica NA 3003 Digital Precise level (Figure 14), bar coded staves 3m, 1.8m and 60 cm scales;
Altrimetric wires	:	Invar wire 1.65mm dia.(5, 16, 42, 45 and 58 m), 8 kg weights;
Optical Alignment	:	Kern Roof /Ground plummet and du, dv mm scale adapter
Data capturing	:	Psion WorkAbout (TC2002) and Psion XL, XP (Kern E2)

5. Survey Methodology

5.1 Triangulation Net

The co-ordinate system of the geodetic scheme is based on the U - V setting out co-ordinates of the arch dam with the origin in the center of the dam wall.

Observations between pillars consists of two sets (circle left and right) of horizontal, vertical observations and EDM distances. Crest parapet targets and tripods set-up over optical alignment monitoring points are intersected by means of two polars (horizontal observations and EDM distances) from the crest balcony pillars.

To complete the triangulation net observations in the shortest period of time it was decided to observe the secondary or crest and gallery exit pillars by making use of 2 Leica TC2002 Electronic Total Stations simultaneously (horizontal, vertical observation and distances).

The observation sequence with the two instruments were chosen so that the targets and prisms are directed to the observation pillars located at different levels in the same block with the prisms tilted between the station points. To determine the scale factors of the two different distance meters, common distances are observed.

5.2 Traverses

Observations are obtained by two sets (circle left & right) of horizontal observations between stations and to pendulums in a forward and reverse run to eliminate centering eccentricity. Invar distance are measured with 2 different lengths of the 5, 15, 30 and 31 wires with the calibration of the Distometer before and after measurements of each length of wire. Calibration of the actual length of the invar wire is obtained by observing selected invar distances with EDM.

Two teams are used to record the horizontal observations and a third team observes the invar distances in all the galleries. Non-uniformed EDM distances between traverse brackets/pillars in the arch dam, drainage galleries and access galleries including tape distances to pendulum wires are measured by the observer of the gallery exit pillars.

5.3 Precise Levelling

Two teams are used to precise level the routes in the arch dam and outside. Observations are obtained in a forward and reverse direction between each bracket. Height differences are measured in the access galleries partly by precise levelling and 2 sets of vertical observations between the points on the slopes.

The primary benchmarks on the left and right flanks of the crest of the dam wall is connected the downstream primary benchmarks by means of secondary benchmarks along the access roads around the dam (Figure 3).

Absolute vertical (dz) displacements which refer to the primary benchmarks of the triangulation net is obtained and compared to the cumulative relative displacements of the TRIVEC system assuming the foundation at level 1862.6 is fixed.

6. Data Processing

All electronically observed data is recorded by in-house developed software on dataloggers to evaluate the horizontal and vertical observations immediately after 2 sets are observed to ensure observations comply to set standards. If necessary re-observations are done before the observer leaves the station. Distances are also recorded electronically from the EDM.

All data is downloaded after each day to check on site by means of another developed software on a PC to eliminate gross errors by comparing observations with the reference measurement. Final accepted mean data is recorded in an input file for further processing.

7. Evaluation

The objectives of the evaluation are horizontal and vertical displacements of monitoring points around, on and in the dam. Although the requested results are displacements, each measurement is separately calculated and the requested displacements are the co-ordinate differences between the actual and the reference measurement. The reference measurement is usually the first complete measurement.

It is advisable to basically keep to the evaluation procedure chosen in the reference measurement. Considerable changes in the number of observations or the definition of constant and unknown parameters, as well as greater modifications of the stochastic model, may have unwanted consequences or call for re-computations.

The deformations of a dam like Katse are:

- seasonal due to changing water loads and temperatures (elastic deformations); and
- long term (plastic deformations)

It is particularly because of these small plastic deformations, some of which develop very slowly in the course of time, that measurements should always be compared to the reference measurement.

The geodetic scheme of Katse dam is very large. It consists of approx. 1150 observations/ 200 unknowns in the network and approx. 900 observations/400 unknowns in the traverses. For practical reasons network and traverses are evaluated separately.

The traverses are connected to the network by optical alignment monitoring points on the crest and downstream gallery exit pillars and interconnected by mechanical and optical pendulums.

8. Adjustments

The Helmert/91 program system is a true three-dimensional adjustment software for the computation of general geodetic nets and is based on the theory of least squares. The observations, direction, azimuths, vertical angles, slope and horizontal distances, levelled height differences, co-ordinates and co-ordinate differences, GPS observations, latitude and longitude (etc) depend on given or unknown point - and auxiliary parameters (co-ordinates in a given projection system, ellipsoidal heights, deviation of the vertical, instrumental and physical parameters).

The definition of the adjustment consists of the selection of constant and unknown parameters (co-ordinates etc.), definition of the generalised Helmert – transformation and the definition of an adequate stochastic model.

The stochastic model is based on empirical values or actual observation errors and the following mean errors a priori are introduced into the adjustment of network and traverses:

	Network	Traverses
UV	± 0.3 - 0.5 mm	± 0.03 - 0.5 mm
Z	± 0.1 - 0.2 mm	± 0.1 mm
Directions (mean)	± 0.7 ″ or ± 0.5 mgon	± 0.7 ″ or ± 0.5 mgon
Vertical angles (mean)	± 1.6 ″ or ± 0.5 mgon	± 1.0 ″ or ± 0.3 mgon
Electro-optical distances	± 0.2 mm + 1.5 ppm	± 0.2 mm + 1.5 ppm
Levelled height differences	± 0.1 mm per set-up	± 0.05 mm per set-up
Invar wire distances		± 0.05 mm
Tape-distances		± 0.7 mm + 100 ppm
Co-ordinate differences		± 0.1 - 0.2 mm

The ratio mean error a posteriori/a priori proves the values correct. Based on these definitions the program system selects the observations and forms the condition - equations, which in the case of a Helmert - transformation are added to the normal equations.

9. Analysis of Results

The adjustment calculation provides not only adjusted, final co-ordinates and displacements but also mean errors of the point parameters (co-ordinates UVZ). These mean errors or mean error ellipses depend on the accuracy of observations, geometry of the geodetic network and selection of fix points/Helmert control points and are a simple and practical tool for the analysis of the results of an adjustment.

To get the mean error ellipse of a displacement the mean error ellipses of the reference and the actual measurement have to be correctly added, which is in most cases a multiplication by $\sqrt{2}$. The theory of probability applies and the usual level of confidence of 99% calls for a further multiplication of the mean error ellipse by 3.

This triple mean error ellipse of a displacement at confidence level of 99 % is useful for the analysis or interpretation of displacements of monitoring points such as points on the crest of the dam as well as fix points or Helmert control points.

At Katse most displacements greater than ± 2 mm may be considered as real. Typical results are shown in graphs in Figure 19, 20, 21 and 22.

10. Reduced Measurements

The geodetic deformation monitoring scheme of Katse dam is large and consumes considerable time for its observations. In the planning the observation schedule of the measurement, the observation at pillars are so planned that the measurement progresses from a mini, reduced to a full measurement.

Reduced and mini measurements are distinguished from complete measurements by smaller amounts of information they yield, lower reliability, less accuracy and will consist of one type of observation (triangulation, traversing or levelling), therefore there must be a distinction between the instruments and methods of evaluation used.

Time and man-days needed to take these measurements are far less than for a complete measurement.

11. Typical Results

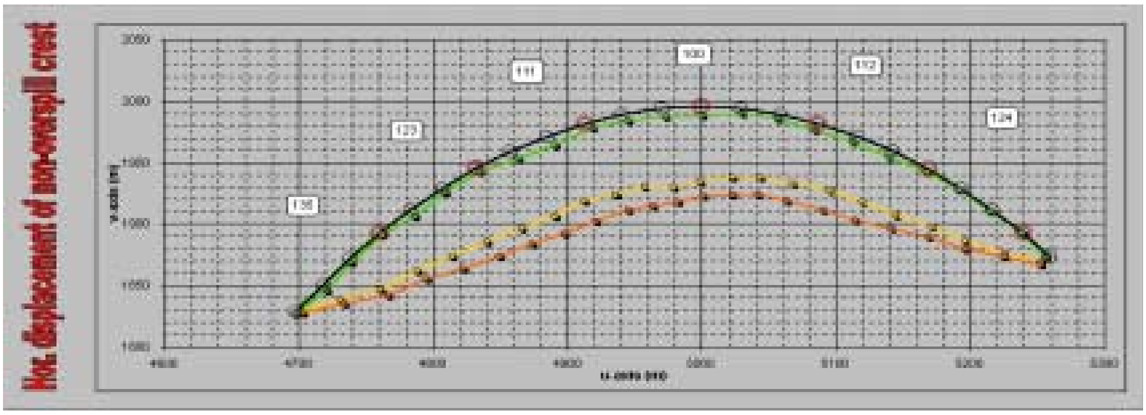

Figure 19 Horizontal Displacements Elevation 2060 Displacement Scale 1 : 4000

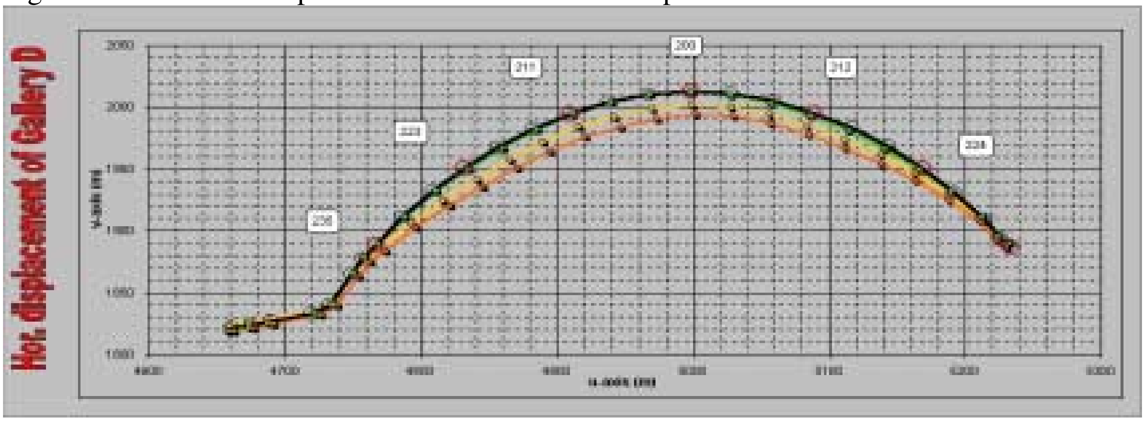

Figure 20 Horizontal Displacements Elevation 2005 Displacement Scale 1 : 4000

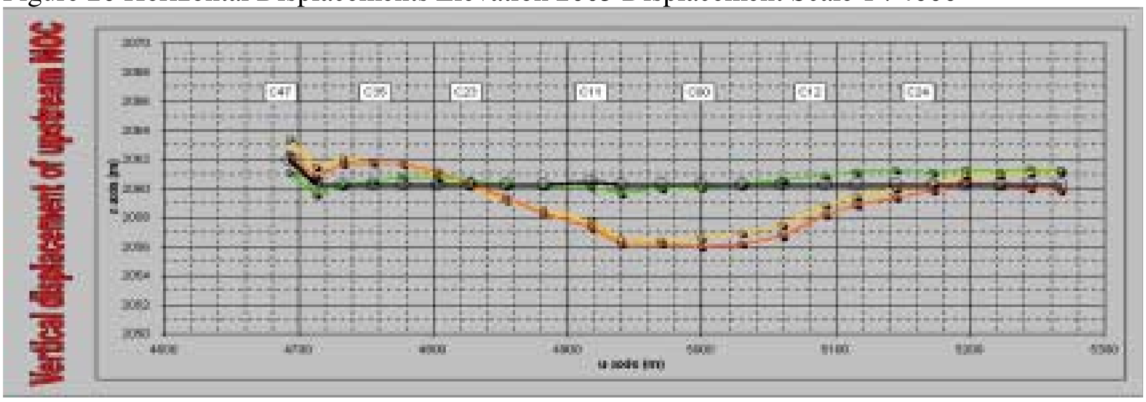

Figure 21 Vertical Displacement Elevation 2060 Scale 1 :1000

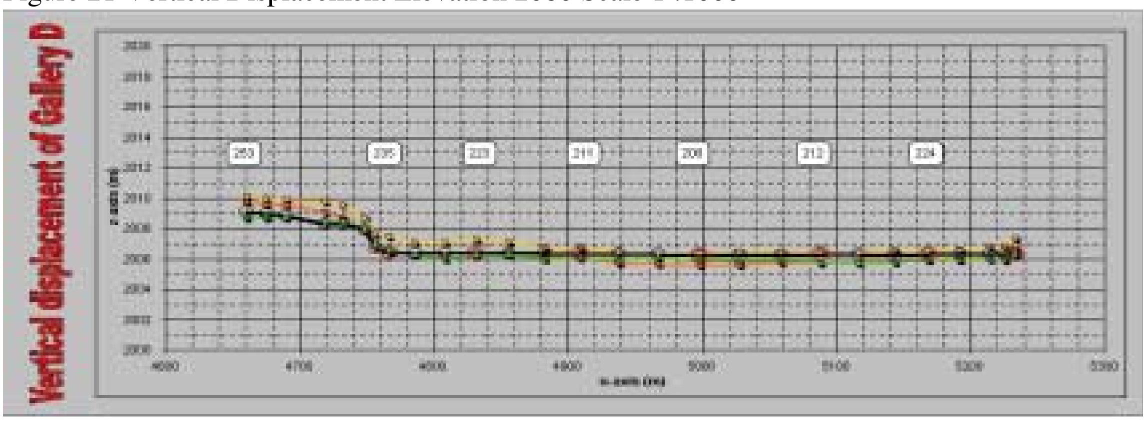

Figure 22Vertical Displacement Elevation 2005 Scale 1: 1000

12. Problems experienced

The theft of equipment is of great concern to the Precise Engineering Survey section as information is lost and replacement of the equipment is done at a great cost. Highjack of vehicles also take place in the mountains of Lesotho which means the surveys teams must travel in convoys with snow and ice on the roads in the mountains during the winter making access to the dam difficult.

All geodetic measurements (Deformation and Crustal) has to be done with the permission of the Lesotho Highlands Development Authority which at times causes delays or postponements of measurements.

13. Conclusions

The Deformation Geodetic Scheme of Katse dam - triangulation, traverses and levels – is of a high standard and gives a high degree of information on the behaviour of the dam. The monitoring scheme is not only based on the triangulation network and traverse disposition but also on the inclusion of the total pendulum system. The network and traverse scheme offers a variety of reduced measurements. The traverses are easily accessible and ensure high efficiency.

The Deformation monitoring system presented here is designed to provide adequate geodetic information of the structure and surrounding area over a long period of time for reporting to the Lesotho Highlands Development Authority. However, a continual assessment is done to identify any shortcomings to the scheme and to improve the reliability, accuracy and survey methods used.

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