SURVEYING THE DEFLECTION OF AN ARCH BRIDGE TO SUB-MILLIMETRE PRECISION

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Abstract

This paper describes a survey of an engineering structure that required high precision results. It is intended as a case study, primarily for surveying students, though the application of the techniques may provide insight to a wider audience. The purpose of the survey was to monitor movements of a new arch bridge to better than ±1 mm. The coordinates of targets placed on the arch structure were not required, only deflections between subsequent epochs of measurements were required. Our survey procedures provided arch deflections in the vertical direction to better than ± 0.4 mm and in the in-plane direction to ± 0.8 mm.

Description of the arch

The CSR Humes CLASSIC™ arch structures are designed as bridges for civil engineering projects such as freeways. The arch can span 15 m to 21 m with up to 7 m vertical clearance. Many panel sections can be butted up to each other to form almost any width bridge. The arch we surveyed spans a small creek under the F4 Western Freeway near Pendle Hill in Sydney's western suburbs. This arch spanned 18m and contained 21 arch sections each 1.8m wide, to form a bridge 38 m wide. Each arch section is made of two precast panels. The panels were installed on prelaid 5 m deep footings (onto bedrock) in less than three days.

After the panels were installed the arch was monitored to determine the behaviour of the structure due to soil loading as back filling occurred, and the effect of a very heavy vehicle driven over the bridge after the majority of fill was complete. During the vehicle loading test, the vehicle stopped at several positions across the bridge and complete deformation surveys were made at each position. Three separate methods were used to monitor one typical cross section of the arch bridge. Strain gauges were placed to assess the induced bending moments and stresses in the arch panel. Soil pressure cells located on the outside of the arch were used to determine normal and radial forces acting on the arch. Survey measurements, the content of this paper, were designed to measure deflections of the arch panel. All three methods were used simultaneously.

Survey method

Survey measurements of the deflection of the arch structure were carried out by placing ten targets evenly around the inside of the arch. The target positions were determined in a three-dimensional coordinate system using spatial intersection techniques (Allan, 1988). The precision requirement for the deflection measurements was set at ±0.5 mm for both the vertical (height) and in-plane (east) components of movement.

Initial computer simulation studies were done to investigate suitable observing procedures and their necessary precision requirements. This work was based on the assumption that pillars were available for instrument observing stations. However, due to the nature of the on-site construction procedures, the use of pillars or permanent ground marks was not possible and alternate survey procedures had to be devised. It should be noted that centring over a ground mark would not be accurate enough for this sub-millimetre survey. Also, due to the changing nature of the site during construction, the theodolites were set up in different places for every day's observing. No ground mark was placed under the instrument. The location of the instrument was selected separately each day to optimise observing geometry and to avoid obstacles such as trucks and graders parked on line.

For each survey measurement epoch the observing sequence can be briefly summarised as follows:

(i) horizontal direction and zenith angle observations in Face Left (FL) and Face Right (FR) from two theodolite observing stations to an outer control network of up to 10 permanent control targets,

(ii) horizontal direction and zenith angle observations (FL & FR) from these two theodolite observing stations to 10 spherical targets attached to the arch structure,

(iii) horizontal direction and zenith angle observations (FL & FR) from these two theodolite observing stations to two targets on a precise scaling bar,

(iv) zenith angle observations (FL & FR) from these two theodolite observing stations to four graduations on an invar staff located on a nearby stable benchmark,

(v) horizontal direction and zenith angle observations (FL & FR) from each theodolite to the other theodolite's internal target (inside the telescope).

Simplistically, the coordinates of the theodolite stations are obtained by the resections in procedure (i). The scale of the survey is controlled by procedure (iii) and the height control of the survey is maintained by procedure (iv). The method used for precisely determining the height of instrument is described by Rüeger and Brunner (1982). The three-dimensional coordinates of the targets are thus obtained by spatial intersection techniques. However, none of the outer control marks were held fixed and all observations were included in one least squares adjustment that solved for instrument, arch target, and control mark coordinates in three dimensions.

Equipment

The following list gives the range of surveying equipment used during the arch survey. The majority of the equipment was owned by the School of Surveying, University of New South Wales.

Two Leica T3000 Electronic theodolites and GRE data recorders (GRE3 and GRE4). The T3000s have specially designed stable telescopes and graticules, internal targets, dual axis compensation, software correction for instrument errors, and a manufacturer's claim of ± 0.5" measurement precision.

A Leica TC1600 Electronic Total Station was used to measure distances from some observing stations to the outer control marks, with a precision of about ± 2mm.

A Zeiss Ni2 Precise Level and parallel plate micrometer was used to measure relative heights of the outer control marks and the benchmark, with a precision of better than ±1mm.

A Leica GWL182 Invar Level Staff was used for height transfers from instrument stations to the benchmark.

A Leica GIL1 Scaling Bar, about 1.3m long with the distance between the bar's two targets precise (according to the manufacturer) to about ± 0.002 mm.

Two halogen driving lights to illuminate the targets from the direction of each theodolite and other minor equipment.

Observing schedule and conditions.

The first measurement epoch was on 18 April, 1991. Measurements then occurred about every 5 days, yielding 14 epochs by 23 June, 1991. On 26 June, 1991 twelve separate epochs were measured between about 9am and 4pm. A final epoch (epoch 27) was measured on 14 May, 1992 just before the road was opened for use.

There were usually three people in the field, one on each theodolite plus one holding the torch or level staff.

During the all-day monitoring period (Epochs 15-26), three theodolite observing stations were used (two T3000s and one TC1600) to observe directions and zenith angles to the outer control and arch targets. This allowed for an increase in redundancy and precision for the arch target positioning.

Figure 1: Surveying in Progress. (different photos in actual paper)

The upper photograph in figure 1 shows observations in progress at Epoch 5. The view of the arch is looking towards the south-west, with the GIL1 scaling bar seen close to the eastern side of the arch. The lower photograph is at Epoch 4 observations, looking from the arch towards the north-east. Note the halogen lights on stands aimed at the arch targets. Also evident are the problems caused by the 'parking' of construction equipment.

Figure 2 : Surveying during the All-Day Monitoring session. (different photos in actual paper)

Figure 2 shows the observers 'at work' during the all-day period and the scraper (on the top of the arch) that was used to load the arch structure. The three theodolite observing stations are seen in the photograph which is looking directly southwards. The scaling bar position for this epoch was on the western side of the arch.

Except for the 'all-day' observations, all survey work was required to be finished before construction work started at 7 am. We travelled to the site and set up the equipment in the dark, observations generally commenced at about 6 am (sometimes earlier). At this time of year (May - June) it meant most observations were taken before sunrise. In particular, it was very dark under the arch and the contrast between the targets and the background concrete arch was poor. This meant the targets had to be artificially illuminated. However, the observing time ensured that the majority of the deflection measurements for the arch were made during similar atmospheric conditions.

Visibility of the arch targets was helped by pointing halogen driving lights, placed beside each theodolite, to the targets (see figure 1). The outer control network stations needed illumination by torchlight for most sightings. This process meant that the speed of observations was restricted to a relatively uniform measurement period. The steepest line of site had a zenith angle of 79°. Photographs of the typical observing geometry and site conditions at the time of measurement are given in Figures 1 and 2.

At each epoch of measurement, a different position for the two theodolite observing stations was chosen, depending on the construction sites conditions. Despite our requests, it was fairly normal to find construction equipment (graders, etc) obstructing the line of sight to some of the outer control targets. Once the theodolites had been carefully levelled, the measurement sequence comprised one arc of observations from each instrument observing station and if time permitted, an additional arc was observed.

A typical arc of observations consisted of 23 FL pointings (horizontal directions and zenith angles simultaneously) to the other theodolite and targets on the outer control network, arch, and scaling bar, and then FR pointings to the same targets in the reverse sequence. Then FL and FR zenith angles were made to four graduation marks on the invar staff.

Observations were recorded on the GRE recorders with a sequential number automatically generated by the instrument. However, we used a prepared booking sheet that included headings, point numbers and descriptions, and spaces for insertion of observation number (in case the target was observed out of the normal sequence), equipment, met values, comments, time, soil backfill height, and other details. The manual booking was invaluable to sort out data sequence problems. Directions and zenith angles were not booked by hand nor was a code entered to the data recorder, mainly because of time constraints.

Control Network

Ten outer control targets were selected in the vicinity of the arch to provide enough redundant control for the survey measurements. Figure 3 shows a sketch of the outer control network points and their relationship to the arch structure and approximate positions of the instrument stations.

Additional measurements were made at the first measurement epoch and at a later epoch to strengthen the coordinates of the outer network. The additional measurements included slope distances from theodolite stations to outer control marks and precise height differences (by levelling) between outer control marks. These data provided checks against movements of the outer control marks and checks for systematic and gross errors.

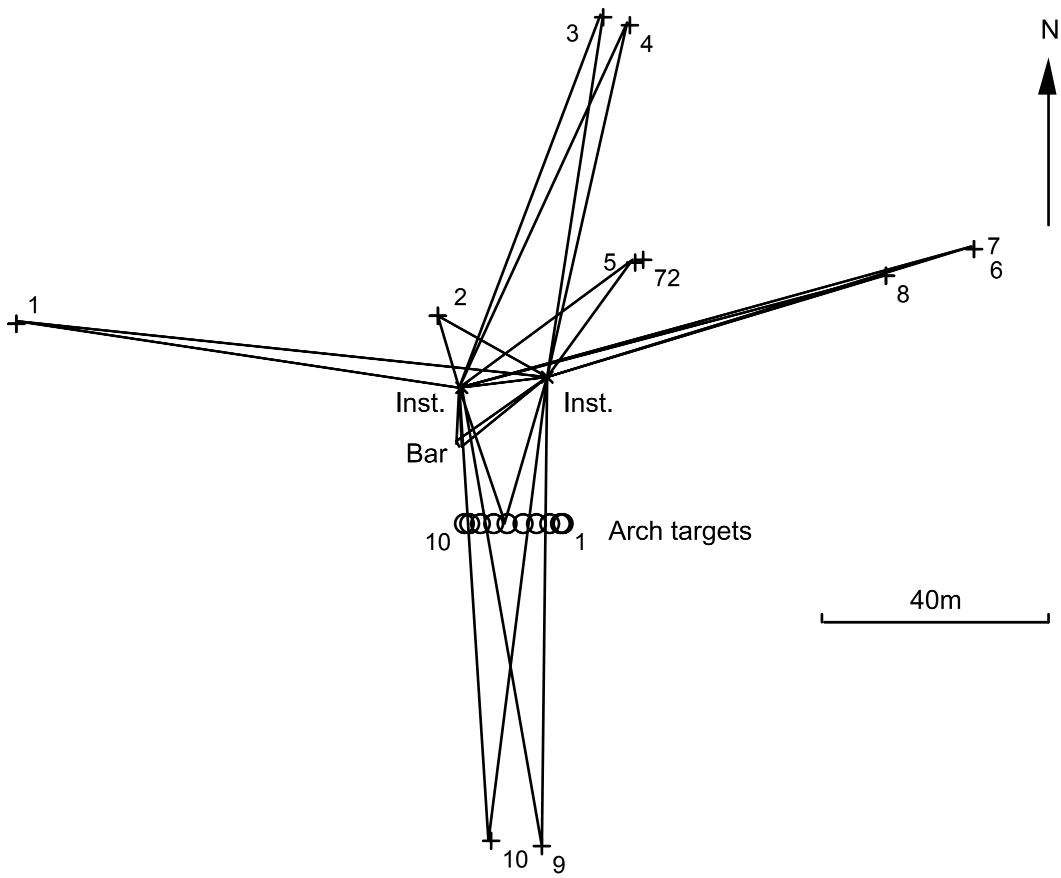

Figure 3: Control Network plan for a typical epoch.

In this figure, the outer control network targets are depicted by an '+', the sphere targets by an 'o' and an approximate location for the two theodolite observing stations by an 'x'. The target numbers are also indicated.

The outer control network targets were numbered from 1 to 10 for all epochs of measurement for which they were considered stable. Target 72, the sewer manhole benchmark, also had the same number for each epoch.

We aimed to have a pair of marks in each of the cardinal directions from the instrument sites, plus additional marks if possible. The reason for pairs of marks was in case of vandalism or obstruction of the mark by vehicles or construction materials. The cardinal directions were chosen to provide a strong resection for the determination of instrument position.

We were fortunate to have several very stable marks on the concrete culverts (3, 4, 9, 10) and the sewer manhole (5, 72). The manhole was large and consisted of vertical pipes cemented together to a depth of about 5 m. It was also close enough for instrument axis height determination. However, we would have preferred not to use marks on a fence post (1) or tree (8) and to have an additional mark in the direction of target 1. However the site conditions and the nature of the construction work did not allow a better network. The control marks were generally Hilti or Ramset nails, but small Leica precision targets were used high on the telegraph pole (target 7) and on the scaling bar. They could be pointed to more confidently than to the nail heads, however we did not believe they would remain if permanently placed within reach of vandals. The nails were surrounded by fluorescent paint and were placed on the sides of objects so that the circular head of the nail could be seen directly from the theodolite. Tripods and targets were not set up over the control marks thus avoiding centring errors.

To check for systematic errors, such as refraction effects on zenith angles, we placed a stable mark (number 2) on a shed. The shed was on the opposite side of the instruments to the arch but at about the same distance and elevation as some of the sphere targets. The coordinates of mark 2 should not change from epoch to epoch. When adjusting all the observations separate values of the coordinates of mark 2 could be determined for each measurement epoch. The magnitude of any variation represents errors in the survey. Mark number 5 was slightly further from the instruments but also proved a good check on stability of the survey method.

Height control for the survey was maintained with reference to the concrete sewer manhole (Target 72). This point was assumed fixed for the duration of the survey and was confirmed by height difference and zenith angle measurements to the outer control marks.

Scale control was carried out by direction and zenith angle observations from the theodolites to a Leica GIL1 scaling bar, the length of the bar being known to order ±0.002 mm. The targets at the ends of the scaling bar were assigned numbers 15 and 16. The bar was placed in a different position for each epoch.

Arch Network

To determine the deflections of the arch structure, ten targets were initially placed on the inside of the arch. The arch targets, theodolite instrument stations and the invar scaling bar targets were allocated a four digit number to provide a unique number for each epoch of measurement. The first two digits in the target number referred to the epoch number and the last two digits defined the target number. For example, target number 415 refers to measurements made at epoch 4 to control network point 15 (target 15 is the left hand end of the scale bar). This numbering convention was used for all booking sheets and analysis.

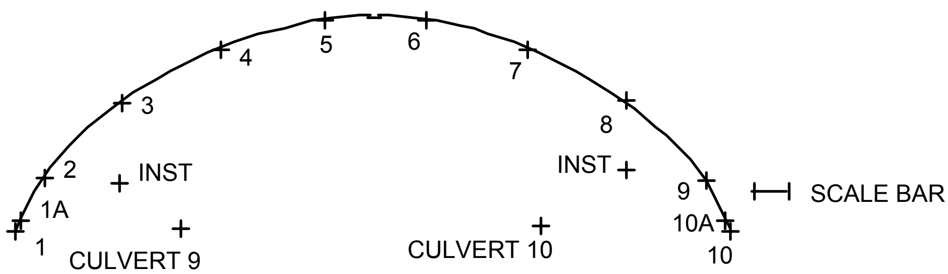

Figure 4: Cross section of the arch, looking south from the instruments. Also shown are the positions of instruments, two culvert marks and the scale bar.

The target design was carefully chosen so that optimum pointing precision could be achieved accounting for the typical sighting distances from the theodolite observing stations to the targets and for the fact that the shape of the target should be invariant to the orientation of the line of sight to the target.

The theodolite's graticule contains concentric circles which made high quality pointing possible because a graticule circle could be placed around the spherical target more accurately than estimating the centre of the target (see figure 5).

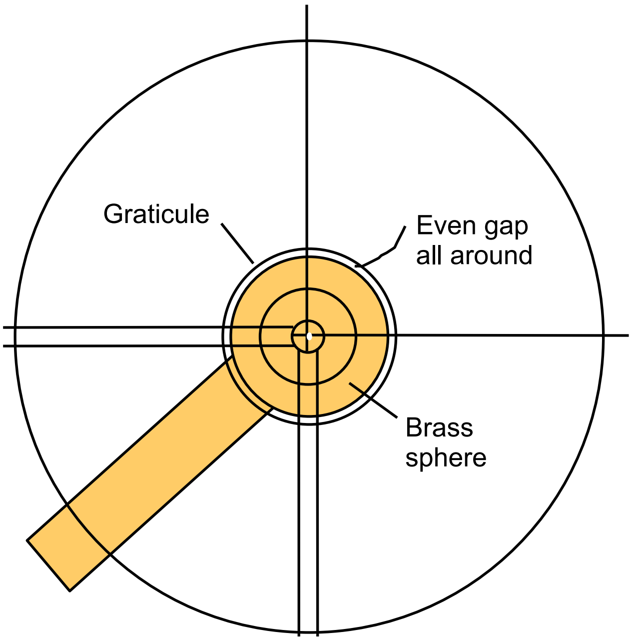

Figure 5: Placing the circular graticule over a spherical target.

The chosen target design consisted of a brass spherical ball (about 13 mm diameter) fixed to a 5 mm brass rod. The dimensions of the sphere were chosen to fit to the theodolite graticule at typical observing distances. These targets were placed by drilling holes into one of the arch panels prior to construction and gluing the target rods into the drill holes.

During the survey a number of the sphere targets on the arch were disturbed or destroyed resulting in a loss of deflection measurements for these targets for at least one measurement epoch. Only sphere targets 3 to 8 remained on the arch wall for the entire survey.

Data transfer

All theodolite observations to targets were directly recorded in the GRE data recorder units. The raw data files from the GRE's were subsequently transferred electronically to a desktop computer and then to a VAX mainframe computer. Initial screening of the observations was done by combining the FL and FR readings and also comparing each arc of observations, if there was more than one arc. A quality check of the observations yielded a priori estimates of the standard deviations of the horizontal direction and zenith angle readings (typically ± 2" in the pre-dawn observing conditions).

Coordinate system

A local, three-dimensional coordinate system was used for the survey. The horizontal coordinates of one arch target at one epoch were set at an arbitrary value of Easting (E) and Northing (N) and the azimuth from that target to another arch target fixed at 90°, i.e. east-west. The height of the benchmark, target 72, was held fixed. All other target coordinates were computed in relation to this minimally-constrained, coordinate system. No corrections for curvature of the earth were applied since it makes an insignificant difference to the computed arch deflections. This was determined after making all rigorous corrections and independently adjusting the network in a true XYZ reference system, using another adjustment package developed at the University of Sydney (Ding, 1992). At the 0.5mm level appropriate corrections for curvature of the earth are required to determine coordinates but not deflections (coordinate differences) since curvature corrections virtually cancel out (Ding, 1992).

Data Analysis

The data were analysed after each epoch of measurement, using the FIXIT network package (Harvey, 1991). As each epoch of observations was included in the adjustment, the precision of the outer control and arch targets improved due to the additional redundant observations. The final adjustment included all observations from epochs 1 to 27. This amounted to 50 distances, 1680 directions (mean of FL & FR), 85 height differences, and 1680 zenith angles. There were 346 x 3 coordinates and 90 orientation unknowns. So there were more than 3400 observations and more than 1100 parameters in the final least squares solution.

From the resulting set of coordinates, the deflections of the arch targets can be readily computed. The distance and ΔE, ΔN, ΔH components that a target had moved were calculated from the differences of the adjusted coordinates at two separate epochs. For example, to determine the deflection of arch target 5 between epochs 8 and 9, we used the adjusted coordinates of points 805 and 905. The standard deviations of the deflections (distance and deflection components) were calculated using the full covariance matrix of the adjusted coordinates and propagation of variances equations (Harvey, 1991).

Results

The precisions and our estimates of systematic errors (based on analysis of subsets of the data) indicate that, in general, the east shift is resolved at the ±0.5 mm level and the height shift is slightly better resolved at the ±0.3 mm level.

On those days when more than one arc was observed, and especially on the day when 12 epochs were measured from the same sites without changing the orientation of the horizontal circle, a drift was noticed in the horizontal circle readings. This drift of a few seconds of arc or less per hour could be due to tripod twist (wooden tripods and umbrellas were used) or circle drift in the instruments. However the observing strategy that we used (clockwise FL then anticlockwise FR) should remove almost all error due to this source when the mean of FL and FR observations is taken.

Three outer control targets (1, 2 and 8) were assigned new target identification numbers after Epoch 10 due to their suspected movement, following major flooding of the area between epochs 10 and 11. Our analysis confirmed the movements were 1 cm or less. This movement was determined by analysis of all data and has no detrimental effect on the arch deflection calculations, provided these points are given different numbers before and after the flood (so that separate coordinates are determined).

The precision of the outer control network was of the order of ±2-3 mm in horizontal position (relative to the arch) and ±0.2 mm in height.

Figures 6 and 7 present some of the results from the survey measurements in graphical form. Figure 6 shows the time series of height shifts of a sphere near the top of the arch.

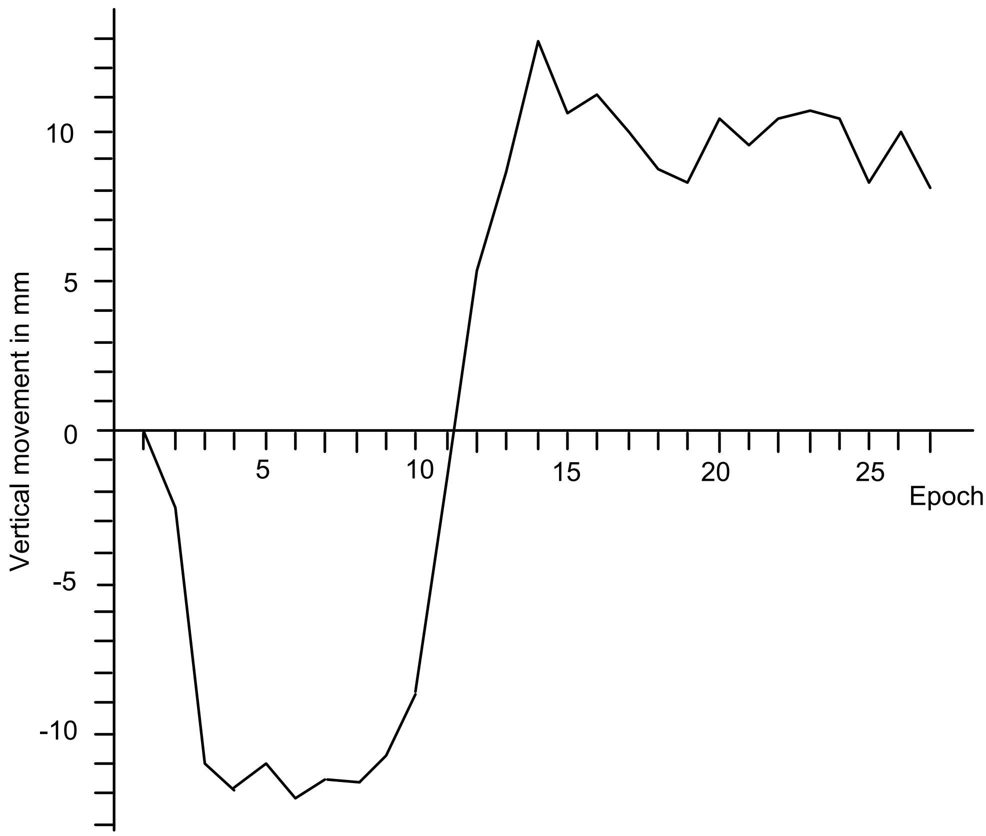

Figure 6. Height component of deflection of arch target 5.

Figure 7 is an exaggerated plot of the deflections of the arch targets between epochs 9 and 10. The arch is plotted as viewed from the theodolite observing stations looking southwards. The height of the backfill at epoch 9 was just above the height of targets 1 and 10. At epoch 10 the height of the backfill was just above the height of targets 2 and 9. At both epochs there was slightly more fill on the eastern side (left hand side in figure 7) than the western side. Note that targets move in the direction expected due to backfill loads and that each target's deflection is consistent with its neighbours.

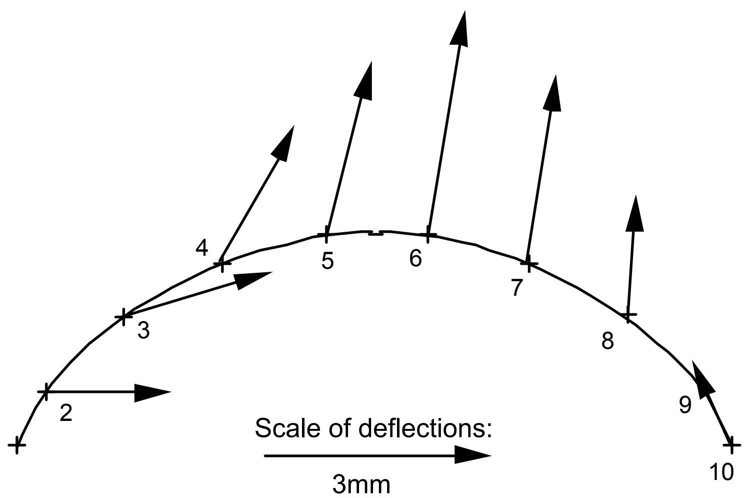

Figure 7. Deflections of arch targets between epochs 9 and 10. Target 1 was not visible and target 9 had been disturbed by about 18mm.

Figures 6 and 7 are typical of the overall results for all targets and all epochs. It is clear that the arch deflections have a direct relationship to the backfill sequences. When the backfill height reached 2m above the foundations, the arch was pushed inwards and upwards. Once the arch structure was completely covered, the incremental deflections were predominantly downwards. Overall, the arch shape was distorted to the west and pushed upwards from its original position. This was caused by the fact that fill on the eastern side of the arch generally progressed faster than on the western side.

Similar plots and analysis were done on the behaviour of the arch during the all-day period of load testing on the arch. The load was moved across the bridge from one position to another and an epoch of survey measurements was carried out at each position. The arch moved by a few millimetres as the load was moved across the bridge (confirmed by our visual estimates of target movement). After the final unloaded position, the arch structure showed evidence of distortion at the 0.5 mm level except for two of the eastern targets. This indicates the non-linear behaviour of the soil under loading.

Almost a year later, with additional backfilling and pavement construction completed, the final epoch of measurements indicated that the upper targets on the arch (5 and 6) had sunk by 2 to 3mm.

Conclusions

High precision, sub millimetre results were achieved. It was not a matter of merely showing more decimal places in our results! In this survey there were three key elements that made the results possible: high quality equipment, application of appropriate existing survey techniques, and rigorous analysis with least squares on computers.

Acknowledgments

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