MONITORING GOULAIS RIVER'S BAILEY BRIDGE FOR DEFORMATION

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1.0 INTRODUCTION

The Goulais River is a large tributary and the artery of the Algoma Highlands watershed (see Figure 1). The watershed contains over 100 lakes and 670 kilometers of rivers, all eventually passing through the Goulais River and out to Lake Superior (Goulais River Watershed, 2001). The meandering oxbow river attracts concern from the locals in the early spring when the snow melts and the ice thaw begins. As shown by the Ontario Base Map (20 meter contours) in Figure 2, all of the snow runoff from the surrounding hills is channeled through the Goulais River,

Figure 1. Algoma Highlands Watershed

posing a chance of severe flooding each spring. Complicating matters is the problem of ice buildup throughout sections of this oxbow river. One common spot of ice buildup and flooding is at the Bailey bridge, located in the town of Goulais River. This puts a considerable amount of strain on the structure, making it susceptible to deformations. Since 1986 the Ministry of Transportation (MTO) has been monitoring the Bailey bridge for such deformation.

This paper examines a portion of the

Figure 2. Ontario Base Map of Goulais River

deformation survey data that the MTO has assembled since 1986. It is the author's suspicion that deformations of the Bailey bridge have occurred due to spring flooding, ice buildup, and the soil conditions surrounding the structure. This paper presents a methodology for evaluating deformation survey measurements in the context of the data available for the Goulais River survey. Conclusions and recommendations are also presented pertaining to both the Goulais River survey and deformation surveys in general.

2.0 DEFORMATION SURVEYS

The simple definition of a deformation survey is determining whether or not an object has moved over a given period of time. This implies that at least two sets of data, from two different epochs of time, are required to perform a deformation survey, and that each dataset must use the same datum. Deformation surveys are often perceived as a challenge due to the rigorous statistical methods required to determine if movement has occurred; therefore, one of the objectives of this paper is to provide a straightforward analysis of the four steps involved in a deformation survey:

1. Perform a minimally constrained least squares adjustment for each epoch of data while allowing all control points to move freely.
2. Determine if there are any observations that are outliers (i.e. observational blunders).
3. Determine if the two epochs are congruent.
4. Compare the individual control points in each epoch to determine if they have moved over the course of time.

It is important to recognize that this deformation survey methodology can be applied for conventional surveying, photogrammetric, and GPS observations, but only conventional surveying observations were used in this case study.

2.1 Least Squares Adjustment

The first step in a deformation survey, which is similar to a control network survey, is to adjust the collected observations and solve for the optimal position of each control point. Typically this is done through a least squares adjustment. A diagram illustrating the necessary steps for a least squares adjustment in a deformation survey is shown in Figure 3.

The first difference between a control network survey and a deformation survey is the management of the primary control points. Typically in a control network survey primary control points are occupied and distance and angle observations are measured to establish secondary control points. The primary control points are usually considered errorless and, therefore, are fixed (i.e. do not move). In a deformation survey, one has to assume that the primary control points could be susceptible to movement and, as such, the primary control points should not be fixed but allowed to move freely.

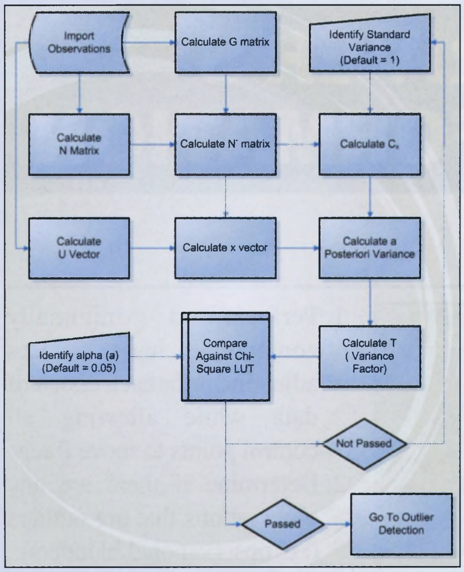

Figure 3. Least Squares Adjustment for Deformation Surveys

The second difference between a control network survey and a deformation survey is the definition of the datum. In a control network survey, the datum of the survey is generally defined by the datum that the primary control points are within. If this were the case in deformation surveys, small errors in the pre-established datum could skew the perceived movement. To overcome this problem, a matrix is added into the adjustment that represents a 3D similarity transformation, and is customarily called the G-matrix or S-matrix (Granshaw, 1980; Fraser and Gruendig, 1983):

$$G = \begin{pmatrix} 1 & 0 & 0 & 0 & Z & -Y & X \\ 0 & 1 & 0 & -Z & 0 & X & Y \\ 0 & 0 & 1 & Y & -X & 0 & Z \end{pmatrix} \quad (1)$$

The dimensions of the G-matrix (see Equation 1) are three times the number of control points by seven. The resemblance between the G-matrix and the well known 3D similarity transformation can be seen. The first three columns of the G-matrix represent the differential x, y, and z translations, respectively; columns four through six represent the rotations about the x, y, and z axis, respectively; and the seventh column represents the scale. Recalling that the purpose of the G-matrix is to define a unique datum, one can recognize that the control points used in all epochs must be the same. If all of the epochs contain the same control points, then the G-matrix for each epoch will be identical, which means the datums of each epoch will also be identical. The use of identical datums will allow the individual control points of the epoch to be compared against each other to determine if any movement has occurred.

To summarize the steps in Figure 3, the distance and angle observations should be measured, and from those measurements a typical least squares N matrix and a U vector can be formed (for more information on the nature of the N matrix and U vector see Mikhail and Gracie, 1981). A modified N matrix, called N^-, can be computed by adding the G-matrix to the N-matrix:

$$N^- = (N + GG^T)^{-1} \quad (2)$$

The U vector and the N^- matrix are used to calculate the x vector, which is the corrections to the approximate values of the three dimensional positions of the control points. This process is repeated until all of the corrections to the control point coordinates are smaller than one millimeter (a typical tolerance in deformation surveys).

Once the adjustment process has converged, the a posteriori variance can be computed, which illustrates how accurately the standard deviations represent the observations:

$$\hat{\sigma}_0^2 = \frac{r^T Cl^{-1} r}{n-u} \quad (3)$$

where r is the misclosure vector, Cl^{-1} is the weight matrix (inverse of the variance-covariance matrix), n is the number of observations, and u is the number of unknowns.

If the a posteriori variance is greater than one, the standard deviations associated with the observations were set too low, meaning that there was too much confidence in the observations. If the a posteriori variance is less than one, then the standard deviations were set too high and there is sufficient reason to have more confidence in the observations. Therefore, one of the objectives of the adjustment is to try and get the a posteriori variance equal to one, or within a reasonable range of one. A Chi-Square test can be used to identify if the a posteriori variance is within a reasonable range. The Single Variance Factor (T_SVF) can be calculated and compared against the Chi-Square distribution:

$$T\_SVF = \frac{(n-u)\hat{\sigma}_0^2}{\sigma_0^2} \quad (4)$$

To compare against the Chi-Squared distribution, a significance level (α) must be selected, which is typically 0.05. This means that if T_SVF is within the specified Chi-Square distribution region, there is a 95% probability that the a posteriori variance is indeed within a reasonable range of one, and a 5% chance that the a posteriori variance is outside the reasonable range, i.e.:

$$\chi^2_{1-\alpha/2,n-u} < T\_SVF < \chi^2_{\alpha/2;n-u} \quad (5)$$

If T_SVF does not fall within the Chi-Square distribution region, a new Standard Variance should be selected and the adjustment recomputed. This process continues until the T_SVF is accepted and at that time the detection of outliers can begin.

2.2 Outlier Detection

To ensure that the positions of the control points are calculated with the utmost accuracy, each observation in each epoch must be scrutinized to see if it is a blunder. The Student-t test can be used to carry out this task as shown in Figure 4. For each observation a T_outlier value can be calculated:

$$T\_outlier = \frac{Cl^{-1} \cdot r}{\hat{\sigma}_0 \sqrt{Cl^{-1} C_r Cl^{-1}}} \quad (6)$$

Similar to the Chi-Square test, a significance level (α) must be chosen for the Student-t test. Typically the significance level is set at 0.05. The observation is deemed to be error free if T_outlier is less than T_critical, i.e.,

$$|T\_outlier| < \eta_{\tau-\alpha,n,n-u-1} \quad (7)$$

If T_outlier is greater than T_critical, then the observation is a blunder and should be removed from the adjustment. Once a blunder is detected, it is removed from the dataset and the adjustment is recomputed. This process continues until all of the blunders have been detected and removed.

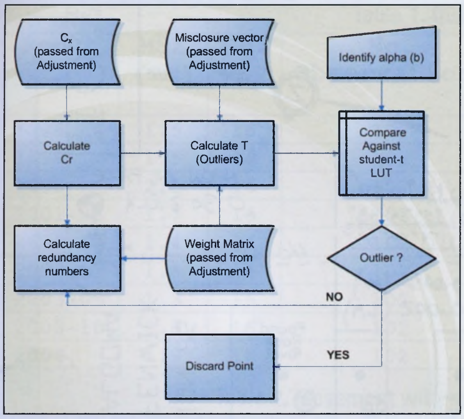

Figure 4. Outlier Detection Process

Another observation indicator that must be monitored is redundancy numbers. Each observation has a redundancy number which illustrates how much that observation contributes to the adjustment. Redundancy numbers range from zero to one. A redundancy number of zero (or very close to zero) means that the adjustment heavily relies upon that observation. Conversely, a redundancy number of one means that the observation does not contribute at all to the adjustment, and that the results of the adjustment would not change if that observation were to be removed. Redundancy numbers are calculated as follows (MacKenzie, 1985):

$$r_i = (Cl^{-1}C_r)_{ii} \qquad (8)$$

The diagonal terms of the resultant matrix of Equation 8 correspond to the redundancy numbers of the observations. Recalling that one of the premises of deformation surveys is that all of the control points must be allowed to move freely, redundancy numbers can be used to check if the control points are indeed allowed to move freely, or if they contribute to the adjustment. Stated another way, the weights corresponding to the initial approximates of the control point coordinates (which are observations) should yield redundancy values of one. If they are any value less than one, the weights of the control point coordinates must be decreased and the adjustment recomputed.

When all of the outliers have been detected and removed, and when all of the redundancy numbers corresponding to the weights of the control point positions equal one, the adjustment process for the individual epochs is finished, and the comparison between epochs can commence.

2.3 Epoch Comparison

Before any individual control point comparisons can be made between the two epochs, the two separate adjustments must pass a couple of statistical tests. The first test, as shown in Figure 5, is to determine if the adjustments are compatible with each other (as expected). Since both adjustments occupy the same primary control points, and both adjustments are based on measurements that are observed to determine the position of the secondary control points, it is expected that the two adjustments should have very similar a posteriori variances. This can be tested by computing the Variance Ratio (T_VR), and comparing it with the Fisher Distribution:

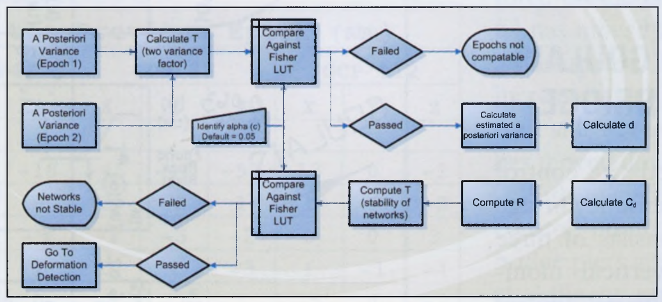

Figure 5. Epoch Comparison

$$T\_VR = \frac{\hat{\sigma}^2_{0i}}{\hat{\sigma}^2_{0j}} \qquad (9)$$

If T_VR is less than the critical Fisher value, than the two adjustments (*i* and *j*) are compatible, i.e.

$$T\_VR < F_{1-\alpha;ni-ui;nj-uj} \qquad (10)$$

If T_VR is greater than the critical Fisher value, then the two adjustments are not compatible, and an error resides in one of the a posteriori variances. Again, a significance level (α) must be pre-determined, which is most often 0.05.

The second test that is performed determines whether or not the control network is stable. When the deformation survey is initially established, the objective is to select secondary control points that will only move if the object in question moves, but there is always a possibility that control points could move on their own. In this case the deformation results would indicate that there was movement over the course of the two epochs, which would be incorrect. To prevent this erroneous result, the control networks stability is tested via the Fisher distribution:

$$T\_stability = \frac{d^T C_d d}{r \cdot \hat{\sigma}_0^2} \qquad (11)$$

where:

- $d = x_j - x_i$ (12) (coordinate difference vector)
- $C_d = C_{xi} + C_{xj}$ (13) (C_{xij} covariances)
- $r = rank(C_d)$ (14)

If T_stability is less than the critical Fisher value then the network is deemed to be stable, i.e.

$$T\_stability < F_{1-\alpha;r;ni+nj-ui-uj} \qquad (15)$$

If T_stablility is greater than the critical Fisher value then the control network is unstable and a comparison of individual control points will yield inaccurate results. If the two adjustments pass both the compatibility and the stability tests, then the final step in the deformation survey process is to compare the positions of the individual control points to detect movement.

2.4 Deformation Detection

The test for detecting movement between the two epochs once again uses the Fisher distribution:

$$T\_movement = \frac{d_i^T C_d^{-1} d_i}{m \cdot \hat{\sigma}_0^2} \qquad (16)$$

where *m* is the dimension of the control network. If T_movement is less than the critical Fisher value, no movement has occurred, i.e.

$$T\_movement < F_{1-\alpha;m;ni+nj-ui-uj} \qquad (17)$$

Conversely, if T_movement is greater than the critical Fisher value, then the control point and the object has moved over the course of time with the magnitude of

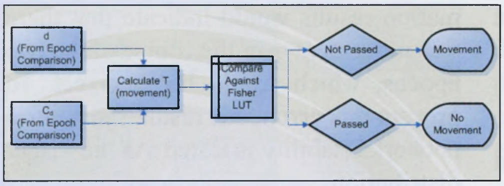

Figure 6. Deformation Detection

the movement equaling the value of *d* (Biacs, 1989). This test is applied for all of the primary and secondary control points that are common to both epochs. A flow diagram illustrating this process is shown in Figure 6.

3.0 MONITORING GOULAIS RIVER'S BAILEY BRIDGE

The MTO established a control network on and around the Bailey bridge in 1986. The network consists of three horizontal and twelve vertical monitoring points. The primary control consists of three round iron bars (RIB) set on a baseline that parallels the structure, but are set back from the bridge so that they are (deemed) not susceptible to the deformation of the structure. Two vertical Benchmarks (BM) are also on site. Both BM are utilized when monitoring the structure to ensure that the BM themselves are not sinking or rising. Sample field notes of the control network are shown in Figure 8, while Figure 7 illustrates the current state of the network baseline.

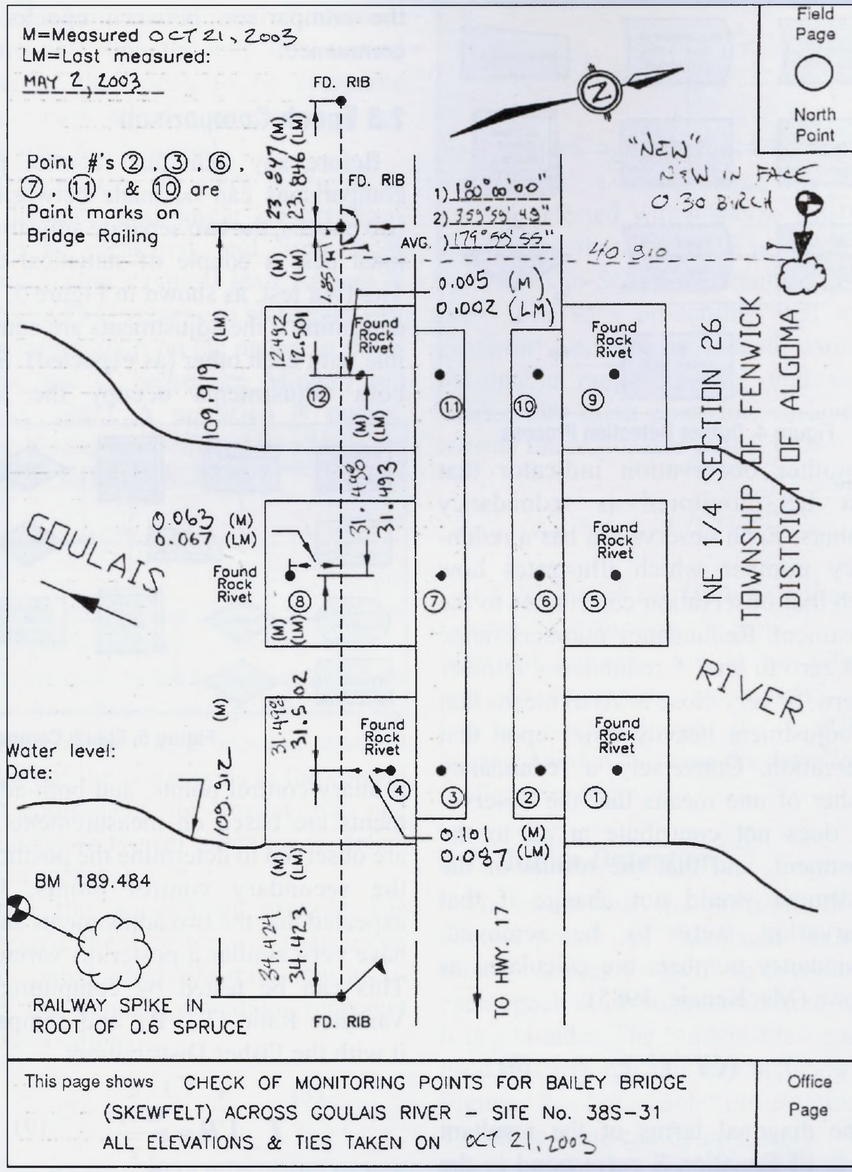

Figure 8. Sample MTO Field Notes

Figure 7. Network Baseline

The MTO provided field notes for the deformation surveys conducted in 1986, 1999, 2000, May 2001, November 2001, 2002, May 2003, October 2003, and May 2004. The field observations for the secondary control consisted of horizontal distances along the established baseline, as well as offset distances from the baseline to the control points (see Figure 8). Horizontal angles and distances were also measured between the primary ground control points (GCPs). With respect to the vertical control network, two BM's were used to measure the elevations on all twelve vertical control points. The standard deviations of the horizontal and height differences were assumed to be 0.0015m, and the standard deviations of the horizontal angles were assumed to be 2". From these observations, the positions of the control points for each epoch could be solved. Quality indicators of those adjustments are shown in Table 1. It should also be noted that the a posteriori variances of all epochs were close to 1.00, with a high and low of 1.09 and 0.89, respectively.

From Table 1 it can be implied (and was verified) that all of the epochs contained the same primary and secondary control points, and that the adjustment for each epoch yielded a mean standard error that was, on average, less than two millimeters.

When analyzing deformation surveys, it is useful to determine the amount of deformation of each epoch with respect to the previous epoch. Also, one should determine the amount of deformation with respect to the initial epoch. Tables 2 and 3 indicate both results of the Goulais

Table 1. Quality Indicators

Epoch	MSE (mm)	No. GCP	No. Observations	No. Unknowns	Degrees of Freedom	Outliers
1986	1.5	16	102	30	72	0
1999	1.5	16	102	30	72	0
2000	2.1	16	102	30	72	0
2001-05	1.7	16	102	30	72	0
2001-11	1.4	16	102	30	72	0
2002	1.8	16	102	30	72	0
2003-05	1.3	16	102	30	72	0
2003-10	2.6	16	102	30	72	0
2004	1.9	16	102	30	72	0

Table 2. Movement with respect to the Previous Epoch

Movement with respect to the Previous Epoch (mm)										
Epoch #1	Epoch #2	GCP #4			GCP #8			GCP #12		
		X	Y	Z	X	Y	Z	X	Y	Z
1986	1999	-6	61	-18	-45	-46	-57	13	0	-1
1999	2000	2	3	0	3	-2	1	-10	4	-3
2000	2001-05	2	9	-4	-1	-3	-2	0	0	3
2001-05	2001-11	0	3	1	0	1	-3	1	-1	-4
2001-11	2002	5	7	0	-4	-7	1	-5	4	-3
2002	2003-05	-5	2	-8	-4	2	-7	6	-2	4
2003-05	2003-10	0	12	2	2	-7	0	-2	4	-9
2003-10	2004	0	-2	-7	-4	4	-1	3	-1	2

Table 3. Movement with respect to the Initial Epoch

Movement with respect to the Initial Epoch (mm)										
Epoch #1	Epoch #2	GCP #4			GCP #8			GCP #12		
		X	Y	Z	X	Y	Z	X	Y	Z
1986	1999	-6	61	-18	-45	-46	-57	13	0	-1
1986	2000	-4	64	-18	-42	-48	-56	4	4	-4
1986	2001-05	-3	73	-22	-43	-51	-58	4	4	-1
1986	2001-11	-2	76	-21	-43	-50	-61	5	3	-5
1986	2002	3	83	-21	-46	-56	-60	0	6	-8
1986	2003-05	-2	85	-28	-51	-55	-66	6	5	-3
1986	2003-10	-2	97	-26	-48	-62	-66	3	9	-12
1986	2004	-2	96	-33	-52	-58	-67	6	7	-10

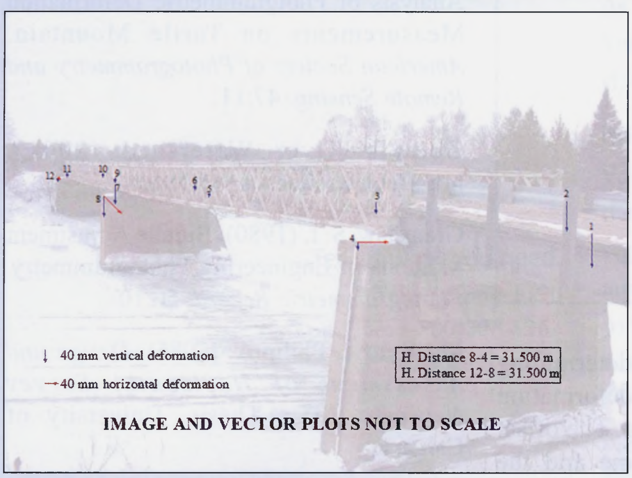

Figure 9. Bailey Bridge Deformation Vector Plot (1986 - 2004)

River survey, while Figure 9 graphically depicts the deformation in the Bailey bridge.

4.0 CONCLUSIONS AND RECOMMENDATIONS

Some conclusions can be derived from the results in Table 3 with respect to the movement of the GCP in all three directions. One can notice that both GCP #4 and GCP #12 have very small movements in the x-axis, which is the same axis that established the baseline. This can probably be attributed to the fact that GCP #4 and GCP #12 are situated on the east and west piers that butt up against the riverbank. This most likely means that the bank is stable enough to withstand the tensile force from the bridge and piers. Upon review of the x-component of GCP #8, there is considerable movement (52 mm), which can be attributed to the fact that GCP #8 is located on the middle pier, and does not abut the river bank.

Although it appears the bank can withstand the tensile force of the piers, the same cannot be said about the shearing force on the east side of the river. GCP #4 has moved upstream (y-axis) close to a decimeter. There has been a slight increase in GCP #12, which is on the west side of the river, and the middle pier has moved downstream six centimeters.

With respect to the elevations of the control points, one can see that the bridge piers are sinking into the riverbed at different rates. The west pier (GCP #12) has a slow sinking rate of 10mm/18 years, while the east and middle pier has subsided a considerable amount: 33 mm/18 years and 67 mm/18 years, respectively.

At the outset of this paper possible deformation causes were identified, including flooding, ice-buildup, and soil conditions. This investigation tends to support two of the three causes. The Goulais River has experienced flooding and ice-buildup on numerous occasions. Most recently, the river flooded in the spring of 2002, and had a combination of flooding and ice-buildup in 1998. However, the 1998 survey data was not used in this project. Therefore, no conclusions can be drawn about the impact of ice-buildup. Table 2, however, does indicate that flooding precipitates horizontal deformation in the Bailey bridge. Between November 2001 and September 2002, the Bridge had a (combined) horizontal deformation of 31 mm. This is the greatest amount of horizontal deformation amongst the eight epochs.

The soil conditions most likely accelerated the vertical deformation. The soil in the Goulais River basin is sandy, which allows the meandering river to cut back the banks of the River. Figure 10 depicts the sandy soil conditions at the bridge.

Figure 10 also illustrates the open area surrounding the Bailey bridge. This area

Figure 10. Goulais River's Bailey Bridge

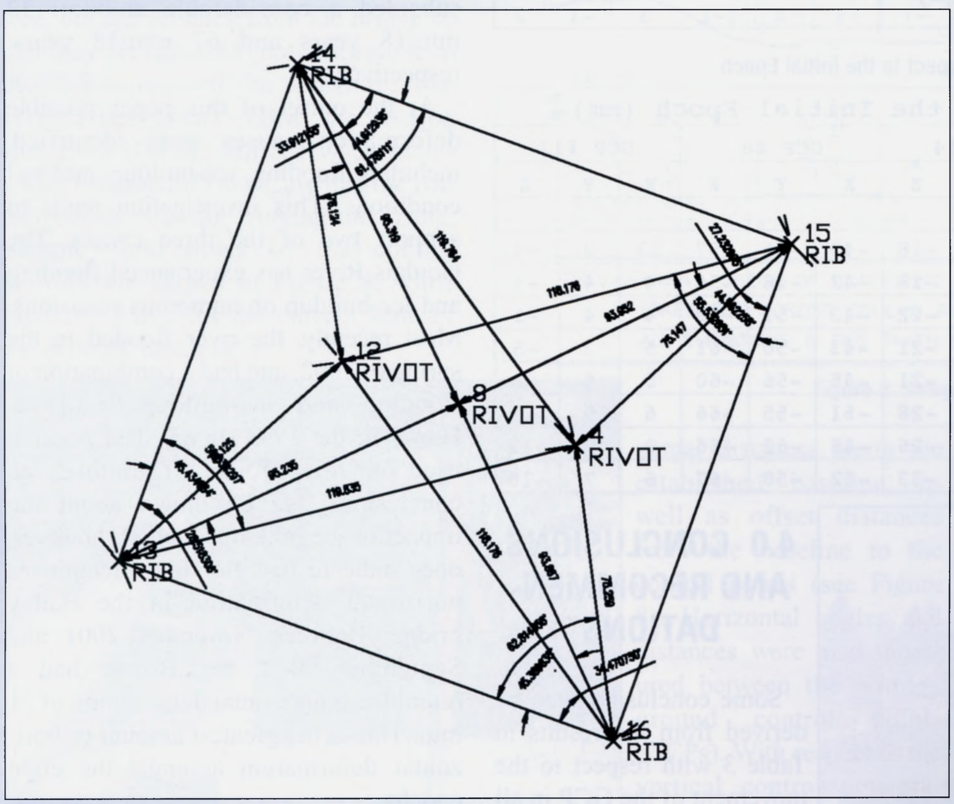

Figure 11. Proposed Control Network Design

can be used to optimize the design of the control network. Figure 8 shows the current design of the network. The horizontal network consists of a baseline along the south side of the bridge, where three primary control points are used to monitor three secondary control points; one on each of the bridge piers. This design lends itself well to determining the amount of horizontal deformation with minimal data processing. The offset distance between the baseline and the secondary control point indicates the amount of deformation. This design, however, lacks good geometry. If precise results are required, the current network may not be adequate, and a new design may be necessary. Therefore, the sole recommendation of this paper was to improve the geometry of the horizontal network. The network shown in Figure 11 would generate precise results as indicated by a pre-analysis adjustment.

This network could be employed at the Bailey bridge site by placing control monuments approximately 40 meters upstream and downstream, on either side of the river. This would create a robust geometric design, which would increase the reliability of the deformation results.

5.0 ACKNOWLEDGEMENTS AND COMMENTS

Mark Tulloch is currently completing his Masters of Applied Science degree in the Department of Civil Engineering at Ryerson University under the supervision of Dr. Michael Chapman. Both authors would like to acknowledge the Ministry of Transportation for generously supplying deformation survey field notes. Comments pertaining to this article are welcome, and can be directed to: mtulloch@ryerson.ca

6.0 REFERENCES

Biacs, Zoltan F. (1989). Estimation and Hypothesis Testing for Deformation Analysis in Special Purpose Networks. MSc. University of Calgary.

Fraser, C. S., and L. Gruendig. (1983). The Analysis of Photgrammetric Deformation Measurements on Turtle Mountain. *American Society of Photogrammetry and Remote Sensing.* 47:11.

Goulais River Watershed (2001). http://www.soonet.ca/wildland/

Granshaw, S. I. (1980). Bundle Adjustment Methods in Engineering Photogrammetry. *Photogrammetric Record.* 56:10

MacKenzie, Philip A. (1985). *Design and Assessment of Horizontal Survey Networks.* MSc. Thesis. University of Calgary.

Mikhail, Edward M. and Gordon Gracie (1981). Analysis and Adjustment of Survey Measurements. Scarborough: Van Nostrand Reinhold Company.