The Impact of Deformation on the Final Alignment of the Fermilab Main Injector

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1. Abstract

The determination of deformation of the reference points is very important for the final alignment process and the future performance of the FMI machine. In case of Main Injector Tunnel practically all points of the network were subject to deformation. The method of minimizing the first norm of the displacement vector of the reference points was chosen as the method to analyze the deformation experienced within the project.
Basic principles of deformation determination and analysis, evaluations movement of the network relative of the beam position will be exhibited in this poster.

1. Introduction

In an ideal world deformation would be monitored by comparing a number of points within and outside of the area of deformation. This absolute network would result in the comparison of both the stable and unstable points. At Fermilab the FMI vertical control was established as an absolute network with the tunnel control being established from the outside monuments through ten site pipe locations. Once the control was established inside the tunnel it became necessary to view the network as a relative system as the site pipes were filled, for shielding purposes, eliminating any additional ties to the outside vertical control.
Procedures for vertical and horizontal deformation analysis of the FMI tunnel network used a part of the ***UNB Generalized Method*** (Chrzanowski et al. 1982 and 1986, Chen, 1983, Secord 1985) developed in University of New Brunswick Fredericton, N.B. Canada. This paper will discuss the basic principles of the method and a practical approach of deformation analysis for alignment of the machine.

2. Network adjustments from the 1996, 1997, 1998 campaigns.

The Alignment and Metrology Group of the Fermi National Laboratory completed two full underground tunnel networks, one in August of 1996 and one in July of 1998. The vertical network was measured in 1996, 1997, and 1998. The method and results of the first 1996 laser tracker network measurement and adjustment were discussed in paper presented on International Workshop on Accelerator Alignment in 1997. Observations of the second Laser tracker campaign were completed in 1998. Significantly different environmental conditions existed between the two campaigns. The effect of environmental factors was determined through additional double measurements in more stable sections of the tunnel and applied to observations. After this "modification", the new measurements were evaluated and adjusted like the first.

Vertical campaigns were adjusted independently, constrained on the more stable points and reinforced with laser tracker vertical measurements.
The two campaigns in the Fermi Main Injector Tunnel (286 floor monuments and 207 wall mounted tierods vertical) allow us to perform an analysis of horizontal and vertical deformation.

3. Strategy for analysis and monitoring deformation of the network

The deformation trend in the new construction of the Fermi Main Injector can be predicted by an examination of the physical location of the tunnel on the site. On **Figure1** Indian Creek is shown with regard to the tunnel and the accompanying wet lands. The areas of creek intersections are considered to be more susceptible to deformation. Empirical data from the Main Ring tunnel has shown greater deformation with the vertical as compared to the horizontal components of the deformation. Recognizing this consideration, a strategy was developed to monitor the deformation at the FMI with two separate studies: a vertical study of one dimension and a horizontal study of two dimensions. This strategy allowed the monitoring effort to not only isolate on areas of greater concern; but also to schedule the frequency of the horizontal and vertical aspects at different frequencies as time and manpower dictated.

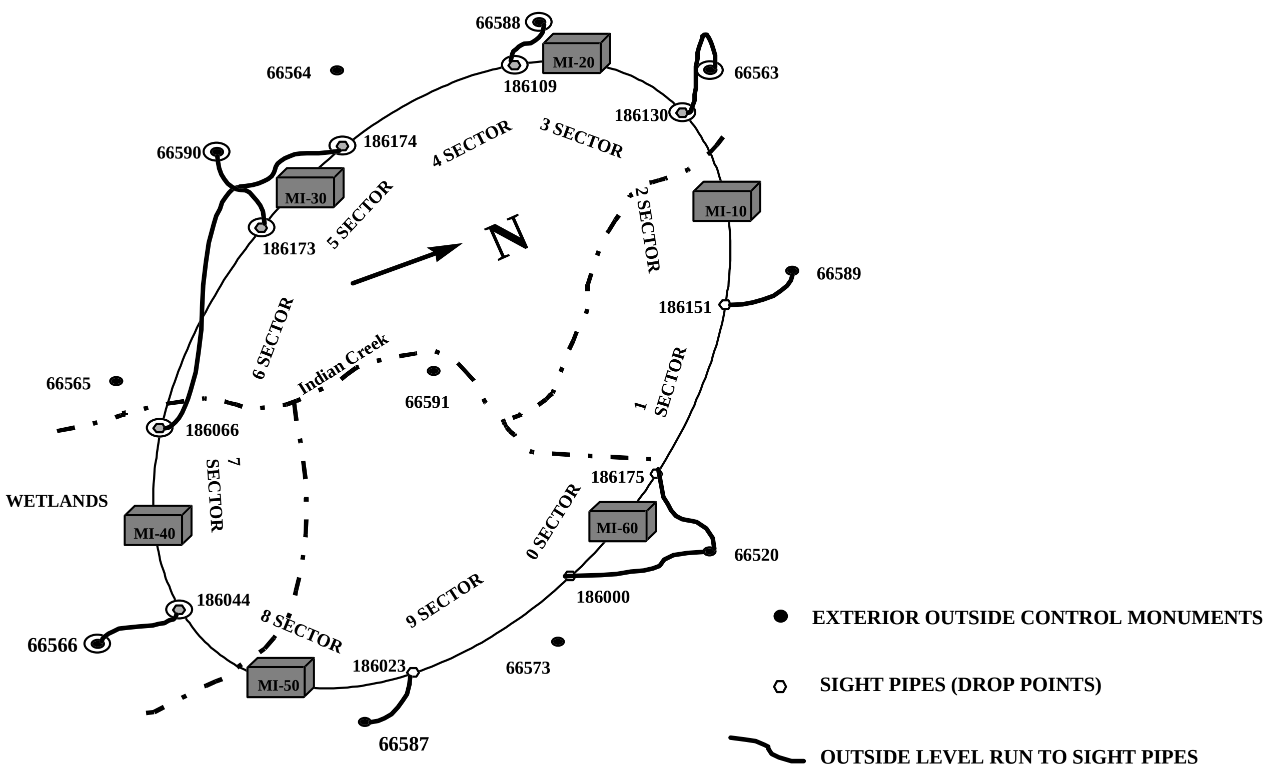

Figure1

4. Vertical adjustment strategies, the identification stabile points with network and an approach to estimate displacements.

The vertical observations from a minimum of two campaigns are adjusted using a minimally constrained least square adjustment by fixing on only one point. A comparison of the two campaigns leads to the computation of the vector of displacements for the surveyed points cofactor matrix.

$$\mathbf{d = x_2 - x_1} \qquad \mathbf{Q_d = Q_{x1} + Q_{x2}} \tag{1}$$

Where $\mathbf{x_2}$ and $\mathbf{x_1}$ are adjusted elevations from two campaigns
The poled variance factor $\partial \mathbf{d}^2$

$$\partial \mathbf{d}^2 = (\mathbf{df_1}\, \partial_{01} + \mathbf{df_2}\, \partial_{02})/(\mathbf{df_1} + \mathbf{df_2}) \tag{2}$$

Where

$\mathbf{df_1}$ is the degree of freedom of first adjustment
$\mathbf{df_2}$ is the degree of freedom of second adjustment
∂_{01} is the variance factor of the first adjustment
∂_{02} is the variance factor of the second adjustment

Because variance factor of $\partial \mathbf{d}$ is a priori not available a posterior, variances ∂_{01} and ∂_{02} are use to check of compatibility of the weighting of the observations between the two adjustments by the statistical test of the null hypothesis $\mathbf{H}$: $\partial_{01} = \partial_{02}$ a with significance level α

$$[F\alpha/2;\, df_2,\, df_1]^{-1} < \partial_{01}{}^2/\partial_{01}{}^2 < F\,(\alpha/2\,;\, df_1,\, df_2) \tag{3}$$

With the determination of proper weighting, the minimizing of the first normal of the deformation vector and the one-dimensional network the condition can be written as follows:

$$\min_{t_z} \left(\sum_i |\, w_i - t_z| \right) \tag{4}$$

Where $\mathbf{w_i}$ is the displacement of the point $\mathbf{P_i}$ and $\mathbf{t_z}$ is translation quantity in the vertical direction. The advantage is this method will find points minimally distorted by vertical deformation, which in turn will used to fix the adjustment of the new observations. The vertical displacement of a more recent survey is the difference between the old results (listed in the database) and newly adjusted points. Once a new elevation is established it may be used for all required deformation analysis as well as a vertical constraint for the horizontal networking.

Appendix A. **Example of vertical deformation analysis**, shows strategy of the identification of stable points. See Graphs: Figure 2 & 3

5. Estimation of the horizontal displacement of the deformed points.

The trend of deformation in X and Y directions were monitored using the minimally constrained adjustments of observations from the 1996 and 1998 laser tracker campaigns. From all appearances, the displacement vector as well the statistical calculations result in a one-dimensional network. The strategy of minimizing the first norm of the displacement vector of the surveyed points provides a datum, which readily identifies the unstable points and gives a less distorted resolution of the displacement. A transformation vector displacement to another datum is performed as follows:

$$\mathbf{d_{k+1}=S\ d_k} \qquad (5)$$

with

$$\mathbf{S = I - H(H^TWH)^{-1}H^TW} \qquad (6)$$

where $\mathbf{d_k}$, $\mathbf{d_{k+1}}$ are old and new displacement vectors and **H** datum defect matrix. The number of datum defects in the two dimensional network are four (two translation δ_x, δ_y, one rotation $\mathbf{H_z}$ and scale factor **k**)

$$\mathbf{H} = \begin{array}{cc} \begin{array}{cccc} \delta_x & \delta_y & H_z & k \end{array} & \\ \begin{pmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ 1 & 0 & -y_i^0 & x_i^0 \\ 0 & 1 & x_i^0 & y_i^0 \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{pmatrix} & \begin{array}{c} \\ \\ x \\ y \\ \\ \\ \end{array} \end{array} \qquad (7)$$

where $\mathbf{x_i^0}$, $\mathbf{y_i^0}$ are the coordinates of points $\mathbf{P_i}$ with respect to the centroid of the network and is calculated as follows:

$$\mathbf{x_0 = x_i - (\sum_1^m x_j) / m,\ y_i^0 = y_i - (\sum_1^m y_j) / m} \qquad (8)$$

In equation (6), **W** is the weight matrix and **I** identity matrix. The two-dimensional network minimizing vector for displacement is calculated using the method of iterative weight transformation with **W = I** for the initial iteration as follows:

$$\mathbf{W = diag(1/|d_i(k)|)} \qquad (9)$$

where $\mathbf{d_i(k)}$ is the $\mathbf{i^{th}}$ component of the vector $\mathbf{d_k}$ after $\mathbf{k^{th}}$ iteration. The iteration procedures will continue until the absolute differences between the transformed displacement components $\mathbf{(d_{k+1}-d_k)}$ are smaller than a priori given tolerance δ.

The last iteration cofactor matrix is calculated as:

$$\mathbf{Q_{k+1} = S_k\, Q_d\, S_k^{\,T}} \qquad \mathbf{(10)}$$

Using this method the deformation of 286 floor monuments was successfully calculated. An additional analysis of the deformation can now be performed.

6. Analysis of the deformation impact on the aligned components.

All components in Main Injector were aligned using precision optical tooling techniques or with a laser tracker. The alignment procedures began in 1997, using control established with a laser tracker network in 1996. During the alignment the vertical datum was updated as the vertical network was re-measured. Each campaign revealed changes in the vertical datum requiring additional deformation analysis. These additional studies defined which components were stable and which components would require realignment due to deformation. A rather interesting method was used during this process. If the vector of displacement implied changes in the position of any of the components, than a best fit to line was computed. Differences in elevations were computed between consecutive tierods throughout the ring for what had been the existing datum and the results from the new campaign. The differences between the two data sets were used to generate a best-fit line, which actually simulated a beam tuning. The residuals of this fit are extremely useful in determining if a re-alignment strategy should be considered. During the main injector project, the authors fitted both a line **(i, j, k**) beam coordinate system and a plane **(X,Y,Z)** tunnel coordinates system, see **Figure 6**. For deformation analysis connected directly to the beam position, calculations were performed as follows:

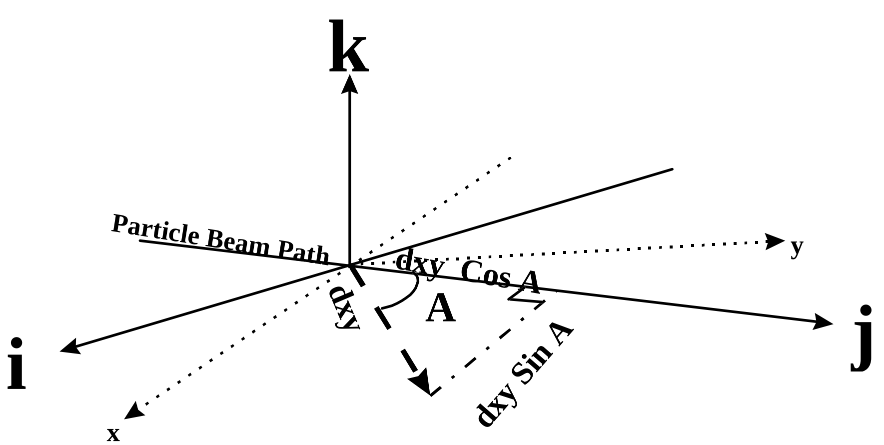

Figure 6

$$dxy = (dx^2 + dy^2)^{½} \qquad (11)$$

where **dx** and **dy** are elements of point displacement in X and Y directions after minimization.

An important consideration for alignment is any movement of floor monuments relative to the beam (transverse and a long of beam directions) required calculations projection of **dxy** on **i** and **j** axis of beam coordinates system. Calculations were preformed as follows:

$$di = dxy \sin A \quad \text{and} \quad dj = dxy \cos A \qquad (12)$$

where **di, dj** elements transverse and a long of beam directions and Az angle between direction of vector **dxy** and beam path direction. Result of this type of analysis showed in :
Appendix B. Example of horizontal deformation analysis. Showed strategy to calculation deformations value directly impacted alignment of components. See Graphs: Figure 4 & 5

7. Conclusion and Recommendations

The determination of deformation of control points by this proposed method is very useful and can be applied for the economical planing of alignment surveys of the machine and monitoring deformation trends in sites like the Fermi Main Injector Tunnel. The method obtains the "best" displacement value, which can be obtained from field observations allowing for the combination and analysis of data from different methods of measurement.

To implement this procedure a software package has been developed and successively used to analyze the deformation from adjusted data resulting from the combined measurements with the Chesapeake Laser Tracker, the Kern Me5000 Mekometer, the Kern E2 Electronic theodolite and Leica NA3000 Electronic Level.

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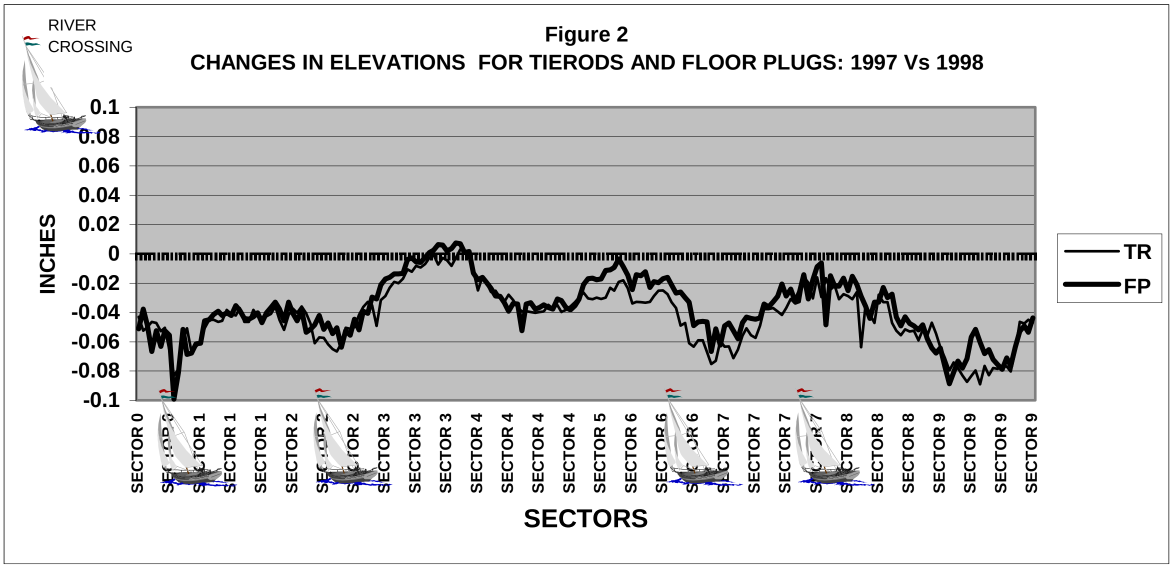
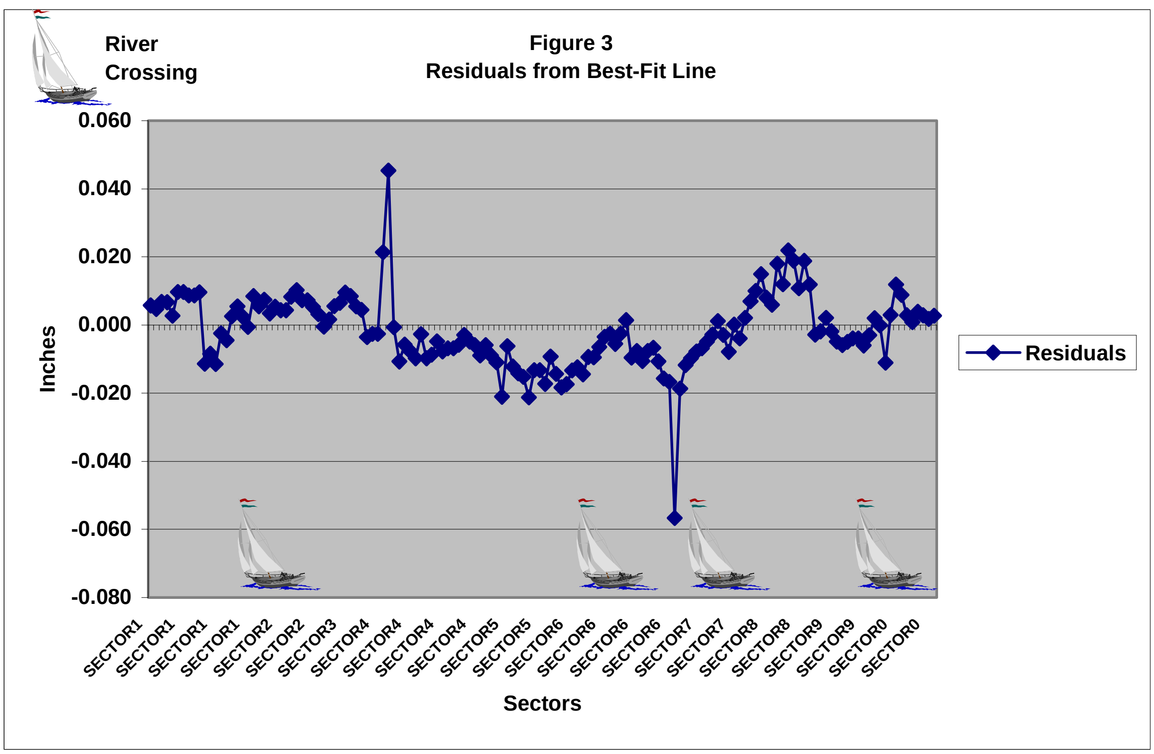

RIVER
CROSSING
Figure 2
CHANGES IN ELEVATIONS FOR TIERODS AND FLOOR PLUGS: 1997 Vs 1998
INCHES
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
SECTORS
TR
FP


River
Crossing
Figure 3
Residuals from Best-Fit Line
Inches
0.060
0.040
0.020
0.000
-0.020
-0.040
-0.060
-0.080
Sectors
Residuals

EXAMPLE OF VERTICAL DEFORMATION ANALISYS APPENDIX A

MORE STABLE POINTS   CAMPAIGN 2 ADJUSTMENT MAY BE CONSTRAINED ON **

NAME	DEFORM(m)	PROCESS		DEFORM(m)	DEFORM(mils)		SECTOR
	d=x2-x1	ABS SUM		dmin-d			
186172	-0.00147	0.50970	186172	-0.00119	-0.047		SECTOR1
207610	-0.00103	0.32696	207610	-0.00075	-0.030		SECTOR1
207614	-0.00031	0.10212	207614	-0.00003	-0.001	**	SECTOR1
207617	-0.00032	0.10251	207617	-0.00004	-0.001	**	SECTOR1
207627	0.00006	0.16139	207627	0.00034	0.013		SECTOR1
207633	0.00010	0.17401	207633	0.00038	0.015		SECTOR1
207634	0.00024	0.22349	207634	0.00052	0.020		SECTOR2
207107	-0.00015	0.11096	207107	0.00013	0.003	**	SECTOR2
207108	-0.00036	0.10571	207108	-0.00008	-0.002	**	SECTOR2
207109	-0.00055	0.11096	207109	-0.00027	-0.011		SECTOR2
207116	-0.00037	0.10571	207116	-0.00009	-0.002	**	SECTOR2
186130	-0.00013	0.14586	186130	0.00015	0.006		SECTOR2
207117	-0.00050	0.10698	207117	-0.00022	-0.009		SECTOR3
207118	-0.00036	0.11406	207118	-0.00008	-0.002	**	SECTOR3
207127	**-0.00028**	**0.10153**	**207127**	**0.00000**	**0.000**	**	**SECTOR3**
207206	-0.00026	0.10571	207206	0.00002	0.001	**	SECTOR3
207207	**-0.00028**	**0.10153**	**207207**	**0.00000**	**0.000**	**	**SECTOR3**
186109	0.00000	0.10169	186109	0.00028	0.011		SECTOR3
207208	-0.00020	0.10517	207208	0.00008	0.002	**	SECTOR4
207220	-0.00026	0.14411	207220	0.00002	0.001	**	SECTOR4
207221	-0.00036	0.10517	207221	-0.00008	-0.002	**	SECTOR4
207231	-0.00050	0.10169	207231	-0.00022	-0.009		SECTOR4
207232	-0.00050	0.10571	207232	-0.00022	-0.009		SECTOR4
186174	-0.00022	0.13233	186174	0.00006	0.002	**	SECTOR4
207301	-0.00045	0.13233	207301	-0.00017	-0.007		SECTOR5
207302	-0.00036	0.10351	207302	-0.00008	-0.002	**	SECTOR5
207300	-0.00018	0.12072	207300	0.00010	0.003	**	SECTOR5
207306	**-0.00028**	**0.10153**	**207306**	**0.00000**	0.000	**	**SECTOR5**
207307	-0.00046	0.10715	207307	-0.00018	-0.007		SECTOR5
207308	-0.00058	0.15501	207308	-0.00030	-0.012		SECTOR5
186173	-0.00045	0.12281	186173	-0.00017	-0.007		SECTOR6
207315	-0.00035	0.15501	207315	-0.00007	-0.002	**	SECTOR6
207316	-0.00039	0.12072	207316	-0.00011	-0.003	**	SECTOR6
207328	-0.00046	0.10466	207328	-0.00018	-0.007		SECTOR6
186330	**-0.00028**	**0.10153**	**186330**	**0.00000**	**0.000**	**	**SECTOR6**

EXAMPLE OF VERTICAL DEFORMATION ANALISYS APPENDIX A

MORE STABLE POINTS CAMPAIGN 2 ADJUSTMENT MAY BE CONSTRAINED ON **

NAME	DEFORM(m)	PROCESS		DEFORM(m)	DEFORM(mils)		SECTOR
	d=x2-x1	ABS SUM		dmin-d			
186330	**-0.00028**	**0.10153**	**186330**	**0.00000**	**0.000**	**	**SECTOR6**
207331	-0.00052	0.12281	207331	-0.00024	-0.009		SECTOR6
186066	-0.00036	0.10571	186066	-0.00008	-0.002	**	SECTOR6
207333	-0.00068	0.13749	207333	-0.00040	-0.016		SECTOR7
207340	-0.00078	0.10571	207340	-0.00050	-0.020		SECTOR7
186056	**-0.00028**	**0.10153**	**186056**	**0.00000**	**0.000**	**	**SECTOR7**
207408	-0.00043	0.22675	207408	-0.00015	-0.004	**	SECTOR7
207412	-0.00062	0.16833	207412	-0.00034	-0.013		SECTOR7
207416	-0.00048	0.11676	207416	-0.00020	-0.008		SECTOR7
186044	-0.00012	0.16833	186044	0.00016	0.006		SECTOR8
207502	-0.00047	0.12745	207502	-0.00019	-0.007		SECTOR8
186028	**-0.00028**	**0.10153**	**186028**	**0.00000**	**0.000**	**	**SECTOR8**
207504	-0.00041	0.12508	207504	-0.00013	-0.003	**	SECTOR8
186026	-0.00023	0.10280	186026	0.00005	0.001	**	SECTOR8
186023	-0.00018	0.11316	186023	0.00010	0.003	**	SECTOR8
207508	-0.00041	0.10280	207508	-0.00013	-0.003	**	SECTOR9
207509	-0.00040	0.10715	207509	-0.00012	-0.003	**	SECTOR9
207515	-0.00053	0.11316	207515	-0.00025	-0.010		SECTOR9
186018	**-0.00028**	**0.10153**	**186018**	**0.00000**	**0.000**	**	**SECTOR9**
207519	-0.00054	0.14022	207519	-0.00026	-0.010		SECTOR9
186001	-0.00160	0.10153	186001	-0.00132	-0.052		SECTOR9
207602	-0.00054	0.14297	207602	-0.00026	-0.010		SECTOR0
207604	-0.00031	0.56433	207604	-0.00003	-0.001	**	SECTOR0
207605	-0.00060	0.14297	207605	-0.00032	-0.013		SECTOR0
207606	-0.00050	0.10212	207606	-0.00022	-0.009		SECTOR0
186248	-0.00074	0.16155	186248	-0.00046	-0.018		SECTOR0

dMIN **-0.00028**

1st page

Next page

EXAMPLE OF HORIZONTAL DEFORMATION ANALYSIS APPENDIX B

DEFORMATION VECTOR **d** BEFORE AND AFTER TRANSFORMATION

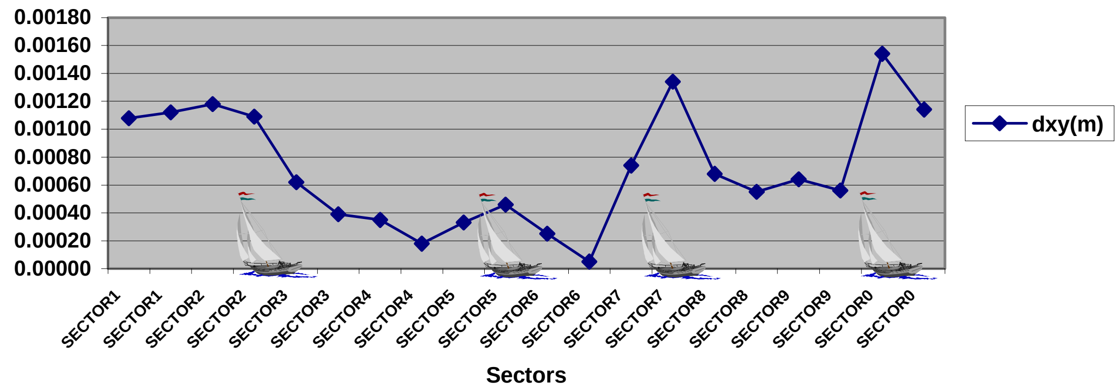
DP NAME	DX(m)	DY(m)	dx(m)	dy(m)
186175	0.00015	0.00110	-0.00026	0.00105
186172	-0.00014	0.00104	-0.00055	0.00098
186151	-0.00116	0.00049	-0.00116	0.00019
186150	-0.00099	0.00079	-0.00097	0.00049
186130	-0.00054	0.00082	-0.00004	0.00062
186129	-0.00023	0.00045	0.00029	0.00026
186109	-0.00107	-0.00026	-0.00034	-0.00006
186108	-0.00092	-0.00021	-0.00018	0.00001
186174	-0.00034	-0.00044	0.00024	0.00023
186324	-0.00023	-0.00038	0.00035	0.00030
186173	-0.00037	-0.00058	0.00010	0.00023
186086	-0.00046	-0.00077	0.00001	0.00005
186066	-0.00014	-0.00180	-0.00005	-0.00074
186065	-0.00018	-0.00239	-0.00012	-0.00133
186044	-0.00023	-0.00111	-0.00067	-0.00014
186043	-0.00005	-0.00074	-0.00051	0.00021
186023	0.00124	-0.00085	0.00057	-0.00028
186022	0.00119	-0.00079	0.00051	-0.00024
186000	0.00138	0.00119	-0.00086	0.00128
186247	-0.00005	0.00105	-0.00048	0.00103

VECTORS **dxy** DEFORMATION OF SINGLE POINT OF THE NETWOR

DP NAME	dx(m)	dy(m)	dxy(m)	SECTOR
186175	-0.00026	0.00105	0.00108	SECTOR1
186172	-0.00055	0.00098	0.00112	SECTOR1
186151	-0.00116	0.00019	0.00118	SECTOR2
186150	-0.00097	0.00049	0.00109	SECTOR2
186130	-0.00004	0.00062	0.00062	SECTOR3
186129	0.00029	0.00026	0.00039	SECTOR3
186109	-0.00034	-0.00006	0.00035	SECTOR4
186108	-0.00018	0.00001	0.00018	SECTOR4
186174	0.00024	0.00023	0.00033	SECTOR5
186324	0.00035	0.00030	0.00046	SECTOR5
186173	0.00010	0.00023	0.00025	SECTOR6
186086	0.00001	0.00005	0.00005	SECTOR6
186066	-0.00005	-0.00074	0.00074	SECTOR7
186065	-0.00012	-0.00133	0.00134	SECTOR7
186044	-0.00067	-0.00014	0.00068	SECTOR8
186043	-0.00051	0.00021	0.00055	SECTOR8
186023	0.00057	-0.00028	0.00064	SECTOR9
186022	0.00051	-0.00024	0.00056	SECTOR9
186000	0.00086	0.00128	0.00154	SECTOR0
186247	-0.00048	0.00103	0.00114	SECTOR0

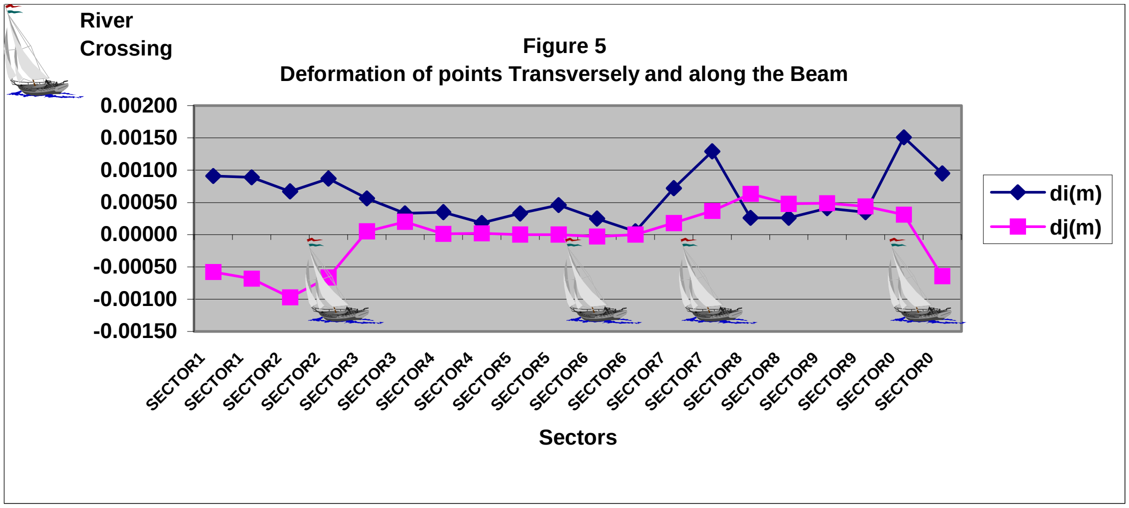
River
Crossing

Figure 4
Horizontal Deformation dxy Vector in meters



DEFORMATION OF POINTS **di, dj** TRANSVERSE AND A LONG THE BEAM

DP NAME	dxy(m)	di(m)	dj(m)	SECTOR
186175	0.00108	0.00091	-0.00058	SECTOR1
186172	0.00112	0.00089	-0.00068	SECTOR1
186151	0.00118	0.00067	-0.00097	SECTOR2
186150	0.00109	0.00087	-0.00066	SECTOR2
186130	0.00056	0.00056	0.00005	SECTOR3
186129	0.00039	0.00033	0.00020	SECTOR3
186109	0.00035	0.00035	0.00001	SECTOR4
186108	0.00018	0.00018	0.00002	SECTOR4
186174	0.00033	0.00033	0.00000	SECTOR5
186324	0.00046	0.00046	0.00000	SECTOR5
186173	0.00025	0.00025	-0.00003	SECTOR6
186086	0.00005	0.00005	0.00000	SECTOR6
186066	0.00074	0.00072	0.00018	SECTOR7
186065	0.00134	0.00129	0.00037	SECTOR7
186044	0.00068	0.00026	0.00063	SECTOR8
186043	0.00055	0.00026	0.00048	SECTOR8
186023	0.00064	0.00041	0.00049	SECTOR9
186022	0.00056	0.00035	0.00044	SECTOR9
186000	0.00154	0.00151	0.00031	SECTOR0
186247	0.00114	0.00095	-0.00064	SECTOR0


River
Crossing
Figure 5
Deformation of points Transversely and along the Beam
0.00200
0.00150
0.00100
0.00050
0.00000
-0.00050
-0.00100
-0.00150
SECTOR1
SECTOR1
SECTOR2
SECTOR2
SECTOR3
SECTOR3
SECTOR4
SECTOR4
SECTOR5
SECTOR5
SECTOR6
SECTOR6
SECTOR7
SECTOR7
SECTOR8
SECTOR8
SECTOR9
SECTOR9
SECTOR0
SECTOR0
Sectors
di(m)
dj(m)