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Proposal for the Technology of Surveying Works Related to the Study of Deformation and Displacement Fresh Steam Pipeline to a Boiler**

1. Introduction

Studying stability of engineering and industrial structures is one of the key and geodetic tasks in which considerable responsibility is also involved. The results of geodetic measurements of the specific structural components of a facility should be provided with due care, and observing all valid accuracy standards. The deformation characteristics vary among the existing industrial structures. However, regardless of the structure type, each surveyor, prior to the measurements, must obtain essential accuracy requirements from the client, and, based on that, decide on the appropriate equipment and apply proper measuring techniques. All geodetic measurements should also meet the criteria set out in technical guidelines, elaborated by appropriate bodies, e.g. [1]. Also ambient conditions are an important factor affecting the measuring accuracy. High temperature, vibrations (unstable surface), vertical refraction etc. considerably determine the ultimate results.

Deformation measurements in engineering and industrial structures are, naturally, carried out cyclically in specified intervals. Therefore, it is significant for such studies to choose the height system properly [2]. It should be solid, stable and protected from damage. It is relatively easy to select or set up a height system in the open space. It is more challenging to set it out in enclosed space, e.g. production halls. In such places, particular attention should be drawn to the type of the height system, which is then of local character. For surveying a structure localised on one height level only, the surveyor applies conventional methods for setting up and marking the benchmarks. Yet, when the measured structure spans over several levels of a factory hall, the test points should be so arranged that their

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location ensure proper orientation of axes of the system of coordinates on all measured levels. To ensure accuracy of the designed height system in all levels (stores), the existing structural components of the hall may be used for the set up, which are located in one vertical axis in all measuring levels. In order to define the local system of coordinates, axes of edges of support columns of the hall are used. One must, of course, reassure as to their precise location to guarantee the vertical axis to be maintained in all stores, and the right angle in relation to other support columns used to determine the system of local X and Y axes.

Having ultimately defined local system of coordinates and the height system set out based on it, direct measurement of test points can begin in the structure being studied. The test points should be selected in the structure in such a manner that the exact representation and changes occurring in a specific time span are ensured.

The measurement results are subjected to detailed calculation and approximation procedure, resulting in the descriptive and graphic documentation in a form of the survey statement.

2. Surveying and Processing the Results for Fresh Steam Pipeline of a Steam Boiler

A fresh steam pipeline for a steam boiler in a heat and power plant was studied for deformations in an industrial structure. The structure extends over several stores, which makes it quite difficult to properly decide on the height system. During the investigation, 27 test points were selected and stabilised on the pipeline, in locations providing the best representation of the pipeline profile (Fig. 1). The test points were located at the beginning and end of each straight section, marking at the same time the extremes of the curve connecting two straight sections (R1 to R27 points). In figure 1, also the crossing points of the pipeline axis are presented (from 1 to 11), the coordinates of which are given in table 3. Also, documentation of selected structural components of a factory hall was analysed in detail, and decision was made as to the selection of the height system and local system of coordinates. The measuring system was set up in possibly stable locations, not exposed to damage, and linked to the adopted local system of coordinates. The defined system of coordinates is presented in the diagram in figure 2. Having the technical documentation of structural parts of the hall, and by taking measurements of those parts, a series of linking points for the height system adopted was selected. The edges of load-bearing columns of the hall were chosen as the linking points.

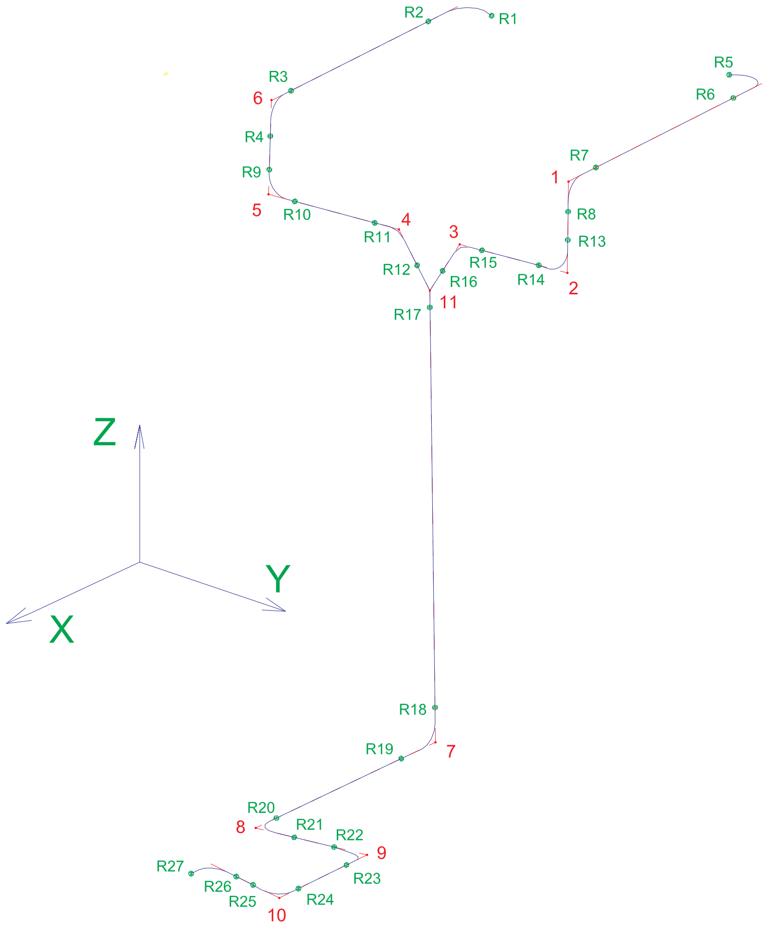
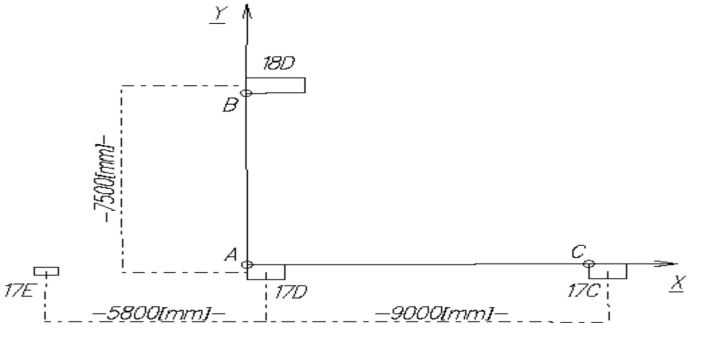


Fig. 1. Diagram of test points on the fresh steam pipeline of a steam boiler



17D_A – 17C_C: THE SET OF CO-ORDINATES X
17D_A – 18D_B: THE SET OF CO-ORDINATES Y

Fig. 2. Orientation diagram of the local system of coordinates adopted

The height system points were determined with the linear and angular indention method. Due to the high number of readings on site, the observation was equalised with the least square method, and coordinates of the height system points were obtained together with their location errors.

The following algorithm was used for calculations:

1. Calculating approximated coordinates of X_0 Y_0 points with the angular, linear and angular and linear indentation method.
2. List of error (corrections) equations for the L_i observation:

$$V = AX + L \tag{1}$$

where:

V – correction equation matrix,

A – matrix of coefficients for the unknowns being the fractional derivatives of the function in relation to individual unknowns,

X – matrix of unknowns the values of which will be determined from a system of regular equations,

L – matrix of free terms calculated as the differences of the approximated and measured observation values.

3. Compilation of regular equations with the function minimisation condition $V^T PV$ = min:

$$(A^T PA)X + A^T PL = 0 \tag{2}$$

where:

A_T – transposition matrix,

P – matrix of weights for observations determined as the reverse of the average error squares of those observations.

4. Solution to the system of normal equations:

$$X = -(A^T PA)^{-1} A^T PL \tag{3}$$

5. In order to determine the matrices of unknowns (3), the reverse symmetrical matrix must be calculated first.
6. This can be achieved with various methods, using known matrix connections, which will finally result in determining the components of reverse matrix, presented as: This can be achieved with various methods, using known matrix connections, which will finally result in determining the components of reverse matrix, presented as:

$$Q = (A^T PA)^{-1} \tag{4}$$

where Q – reverse matrix, the diagonal components of which are used for the evaluation of accuracy, for establishing the values of coordinate errors.

7. Another step is to determine the unit error m_0:

$$M_0 = \pm\sqrt{\frac{V^T PV}{n-u}} \tag{5}$$

where:

n – number of all observations,
u – number of unknowns.

The unit error of a single observation m_0 is one of the key parts of the accuracy evaluation, and its value allows to draw conclusions regarding the selection of linking points and adopted observation errors. An optimum value of the m_0 error is close to 1. Different values may indicate linking point coordinate errors, either decreasing the observation accuracy (for $m_0 >> 1$) or increasing the adopted average observation errors (for $m_0 << 1$).

8. Based on the average m_0 error and diagonal components of the matrix of weight coefficients Q, partial errors were calculated (m_X, m_Y) for the height system coordinates together with their average location error m_P:

$$m_X = m_0 \sqrt{Q_{X_iX_i}} \tag{6}$$

$$m_Y = m_0 \sqrt{Q_{Y_iY_i}} \tag{7}$$

$$m_{P_i} = \sqrt{m_{X_i}^2 + m_{Y_i}^2} \tag{8}$$

where: $Q_{X_iX_i}$, $Q_{Y_iY_i}$ – weight coefficients of the reverse matrix diagonal Q.

9. The last stage is to evaluate the observation accuracy after the equalisation. The values of observation corrections v, correction errors m_v and the relation of the correction value to the errors, which should not exceed 3 ($v/m_v < 3$), are analysed. The m_v parameter is the error of calculated correction determined with the formula:

$$m_v = m_0 m_{obs} \sqrt{\frac{r}{n}} \tag{9}$$

where:

m_{obs} – average observation error prior to equalisation,
r – number of extra observations,
n – number of all observations.

The equalisation of the coordinates of the height system was performed with the Winkalk application, and the coordinates and their respective errors are given in table 1.

Table 1. Accuracy parameters of the test point setting

No.	Test location	*X* [m]	*Y* [m]	m_0 [mm]	m_P [m]
1	PS1	1015.142	998.419	1.59	0.005
2	PS3	1017.341	999.042	3.33	0.007
3	PS4	1012.079	998.485	0.64	0.002
4	PS5	1056.861	1012.631	0.97	0.006
5	PS6	1033.222	1026.191	0.42	0.001

The measurement on each test point leading to the determination of its coordinates contained a significant number of extra observations. However, due to the severe conditions present on site, most of them had to be rejected based on the analysis of error values: m_0, m_P, v, m_v.

The difficulties involved in taking the measurements were of the following nature:

- weather conditions, high temperature, surface and air vibrations and uneven gradient of such changes;
- the pipeline extending over several levels;
- varied width of columns in individual stores, which was in fact taken into consideration while selecting and determining the coordinates of linking points, but, since the differences of column width were measured with a measuring tape and due to the difficult access to some structural parts, the accuracy was varied.

In order to determine the displacement of the pipeline, two measurements were made in the test point in so called "cold" and "hot" condition, using the same height system points and linking points. Each test location was linearly and angularly linked to numerous linking points, established based on the local system of coordinates. The measurement of the "cold" state was taken in July, and the "hot" state – two months later, in September. Measurements were taken with TOPCON 3005 LN electronic tachometer (angular measurement accuracy 15^{cc}, linear measurement accuracy +/– 2 mm + 2 ppm) [4].

X, *Y*, *Z* coordinates for the test points of the pipeline in hot and cold state, were obtained after processing the measurement results. In order to truly represent the pipeline shape, the above coordinates were reduced to achieve the configuration as per table 2.

Table 2. List of coordinates of the axis of the fresh steam pipeline of a steam boiler

No.	X [m]	Y [m]	Z [m]
R1	981.942	1014.445	140.130
R2	984.563	1012.038	140.071
R3	997.595	1012.060	139.979
R4	999.516	1012.032	137.892
R5	981.603	1030.245	139.993
R6	984.355	1032.487	139.957
R7	997.258	1032.405	139.788
R8	999.903	1032.414	138.002
R9	999.524	1011.967	135.914
R10	999.564	1013.718	134.441
R11	999.656	1019.180	134.393
R12	999.707	1022.079	132.545
R13	999.924	1032.406	136.345
R14	999.885	1030.416	134.412
R15	999.774	1026.501	134.410
R16	999.748	1023.829	132.615
R17	999.739	1022.963	131.266
R18	999.486	1023.131	106.747
R19	1002.557	1023.042	104.667
R20	1014.231	1022.934	104.707
R21	1016.144	1025.501	104.715
R22	1016.135	1028.187	104.729
R23	1018.093	1030.416	104.755
R24	1022.635	1030.427	104.763
R25	1024.449	1028.644	105.138
R26	1024.445	1027.508	105.381
R27	1026.346	1025.813	105.763

Also the coordinates of highest points of the pipeline were compiled (axis crossing) (Tab. 3). As there was no access possible to the stabilised additional benchmarks (test points), and consequently no possibility to measure them, after discussion with the client, 3 top points were not determined for the pipeline in question (axis crossing): between the R1–R2, R5–R6 and R26–R27 measuring points.

Table 3. List of coordinates of the highest points of the fresh steam pipeline of a steam boiler

No.	*X* [m]	*Y* [m]	*Z* [m]
1	999.882	1032.406	139.753
2	999.945	1032.396	134.413
3	999.769	1024.980	134.409
4	999.682	1020.810	134.379
5	999.531	1011.920	134.457
6	999.508	1012.079	139.965
7	999.464	1023.108	104.657
8	1016.152	1022.916	104.707
9	1016.127	1030.411	104.747
10	1024.454	1030.432	104.762
11	999.739	1022.963	131.807

After calculating the test points in both states (cold and hot), they were compiled in a table (Tab. 4), representing the displacement values of the test points for both pipeline states.

Table 4. List of coordinates of the test points and displacement values: hot state – cold state

No.	Cold state 05.07			Hot state 28.09			Displacement value		
	X [m]	*Y* [m]	*Z* [m]	*X* [m]	*Y* [m]	*Z* [m]	Δ*X* [mm]	Δ*Y* [mm]	Δ*Z* [mm]
R1	981.942	1014.445	140.523	981.925	1014.385	140.512	–17	–60	–11
R2	984.563	1012.038	140.464	984.546	1011.935	140.476	–17	–103	12

Table 4 cont.

R3	997.595	1012.060	140.372	997.652	1011.992	140.516	57	–68	144
R4	999.130	1012.032	137.892	999.212	1011.996	138.024	82	–35	132
R5	981.603	1030.245	140.386	981.579	1030.297	140.372	–24	52	–14
R6	984.355	1032.487	140.350	984.338	1032.560	140.336	–16	74	–14
R7	997.258	1032.405	140.181	997.320	1032.502	140.360	62	98	179
R8	999.517	1032.414	138.002	999.620	1032.519	138.197	103	105	195
R9	999.140	1011.967	135.914	999.234	1011.946	136.026	94	–21	112
R10	999.177	1013.718	134.441	999.272	1013.683	134.579	95	–35	138
R11	999.269	1019.180	134.393	999.353	1019.195	134.586	84	15	193
R12	999.321	1022.079	132.545	999.394	1022.120	132.729	73	42	184
R13	999.538	1032.406	136.345	999.650	1032.502	136.510	112	96	165
R14	999.499	1030.416	134.412	999.602	1030.495	134.580	103	79	168
R15	999.391	1026.501	134.410	999.499	1026.552	134.614	109	51	204
R16	999.362	1023.829	132.615	999.447	1023.860	132.807	84	31	192
R17	999.315	1022.963	131.266	999.379	1023.006	131.404	64	42	138
R18	999.486	1022.705	106.747	999.285	1022.668	106.709	–201	–37	–38
R19	1002.557	1023.042	105.093	1002.378	1023.021	105.057	–180	–21	–36
R20	1014.231	1023.360	104.707	1014.148	1023.349	104.710	–83	–11	3
R21	1015.718	1025.501	104.715	1015.642	1025.506	104.721	–76	5	6
R22	1015.709	1028.187	104.729	1015.621	1028.214	104.741	–87	27	12
R23	1018.093	1030.842	104.755	1018.002	1030.927	104.760	–91	85	5
R24	1022.635	1030.427	104.337	1022.584	1030.474	104.325	–52	47	–12
R25	1024.449	1028.644	104.712	1024.388	1028.667	104.701	–61	23	–11
R26	1024.445	1027.508	104.955	1024.379	1027.520	104.947	–66	12	–8
R27	1026.346	1025.813	105.337	1026.324	1025.810	105.331	–22	–4	–6

3. Summary

To sum up, there are several key issues of attention the surveyor may face while performing such geodetic works. The client and measurement contractor should closely cooperate as early as in the test point (benchmarks) design stage. It is important to locate the test points on the pipeline so that they are available for measurement both in hot and cold state. With such cooperation, situations can be avoided in which part of the stabilised test points is not available for measurement when hot.

Furthermore, during the design stage of the height system for measurements on several stores, it is important to select a reference system bearing in mind its stability and possibility to move the axes onto the following levels.

While setting out the measuring points, it is reasonable to perform quite a number of extra readings. This is because, due to harsh physical conditions, some of the observations may appear to be useless as they distort the equalisation results.

References

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