Accurate Measurement of the Riverbed Model for Deformation Analysis using Laser Scanning Technology

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Abstract. This paper presents an interesting application of the riverbed model shape and deformations monitoring using laser scanning technology and accurate local micro-network. The most interesting fact about this application is very high accuracy demand on deformation determination (maximum permissible error is only 2 mm) within quite large object (the size of the riverbed model is about 100 meters). Up to now, mechanical calipers in the selected profiles were used to detect the changes. This manual approach is very laborious and time-consuming and the gathered data resolution and accuracy is often not sufficient. The suggested solution contains two main parts. The first part deals with construction of highly accurate local micro-network for laser scanning needs (maximum required standard deviation in any coordinate is lower than 0.4 mm) and the second part deals with actual laser scanning and data processing. Design, measurement and processing of the experiment was conducted for the needs of the research project "Improvement of navigation conditions on the Elbe between Ústí nad Labem - state border CR / FRG - Navigation Step Děčín". The main goal of this project is design and realization of the river regulation to improve the navigation conditions. The key benefit of using river model is the possibility to easily simulate various catastrophic scenarios (various degrees of the floods) and their impacts on riverbed changes.

Keywords: engineering surveying; laser scanning.

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1. Introduction

Engineering geodesy deals with measuring of all possible subjects for needs of construction, industry and related sectors. Coordinates or specific geometric parameters are usually main outputs of these measuring. Frequent and important task can be also determination of changes of the outputs. A common denominator of all these works is a mandatory requirement for accuracy of the collected data and evaluated results. Shifts and deformations are determined not only by various geodetic methods, but also by geotechnical and other methods.

Frequently used geodetic methods for deformation measurements are trigonometric method as a part of geodetic network [18], geometric levelling [2], 3D scanning [11, 16] and an interesting application described in [12] and in [15], photogrammetry [13, 7], GNSS [17], and by combination of these methods and processing it altogether by adjustment.

Besides the shifts and deformations of the buildings and constructions displacements of natural formations like hillsides (landslides) [1, 19] are also measured. There are often used methods based on terrestrial 3D scanning [10, 8, 5], airborne 3D scanning [14], combination of both [21], or in combination with other instrument's measurement as ground penetrating radar [3].

Measurement of deformations of the construction models can be classified as a very specific task. The size of the measured area is significantly smaller, on the other hand demanded precision is significantly higher. The hydraulic models of the riverbed for simulation purposes of the various flows (including various degrees of the floods), assessing navigability and also for the purposes of the design of construction work are the main objectives of the research project. Description of the process including the numerical and physic modelling is available in [6]. This paper describes the geodetic part of measurement of the deformations of the riverbed model due to the simulated flows. The deformations themselves were determined by the 3D laser scanning with the use of spherical ground control points on the concrete banks of the river model as a frame. The first task of the presented measurement was to determine coordinates of the spherical control points for subsequent 3D scanning with standard deviation in each coordinate better than 0.4 mm. The ground control point coordinates had to be determined with such a high accuracy, because the maximum permitted error of the changes evaluation by the 3D scanning was 2 mm, it was the second and main task.

2. Characterisation of the hydraulic model

A model for the water of the Elbe River with a total length of 7 km at a scale of 1:70 in outdoor areas of the Water Research Institute T.G.M. Prague (Czech Republic) was built for purposes of the research project "Improvement of navigation conditions on the Elbe River between Ústí nad Labem - state border CR / FRG - Navigation Step Děčín" in 2015. The main goal of the project is design and realization of the river regulation to improve the navigation conditions. The impact of adaptations will be tested on the specified physical model first.

The model is made of concrete; the riverbed itself is modeled from sand with grain size corresponding to the real bottom cover (in scale 1:70). Model length is 100 m.

The whole model is covered by the wooden roof from above and by a dense mesh fence from the sides to avoid a damage of the riverbed by the weather or small animals. The watercourse is considerably winding and measurement situation is therefore similar to measurements in a narrow tunnel (width of about 2 m). A situation is on Fig. 1, a photograph of the riverbed model in reality is on Fig. 2.

Figure 1: Situation plan of river model

3. Creation of local micro-network

The first part of the project was to design, create and determine a very accurate local area network (standard deviation in each coordinate is lower than 0.4 mm), which will include three pairs of spherical targets (at the beginning, middle and end model) as a ground control points for the 3D scanning measurement.

As a method of the geodetic measurement was selected a trigonometric micro-network with measured slope distances, horizontal directions and zenith angles between standpoints, and

Figure 2: River model in reality (sand riverbed and concrete banks

horizontal angles and zenith angles on the spherical targets. The spherical targets are used as a ground control points for the 3D scanner, and reference point is always a center of the sphere, calculated from the scanned points by fitting of the sphere with known diameter.

The spherical targets cannot be targeted to the center, and hence the horizontal direction and zenith angle to the center of the sphere was always calculated from the values measured to the upper, lower, left and right visible edge.

The best total station at the disposal of the department of the Special geodesy of the Faculty of Civil engineering of the Czech Technical University in Prague, the Trimble S8 (Fig. 3), with a nominal precision of the horizontal direction and zenith angle measurement 0.3 mgon and distance 0.8 mm + 1 ppm was used due to required high accuracy.

Standpoints of the network were not permanently marked (due to the required precision), they were established only temporary in the central point of the prisms (Leica GMP 101 Professional, Fig. 4) and total station. Only spherical ground control points and four witness points (see section 3.3) were permanently physically marked. Each temporary point was established by a tribrach on a tripod, where we placed either a prism or a total station with the same pivot point.

As can be seen on the Fig. 1, the watercourse is considerably winding and measurement situation is therefore similar to the measurements in a narrow tunnel (width of about 2 m). The micro-trigonometric network was designed as two parallel polygonal traverses, where the measurement was done from each standpoint to the five directly neighboring points. Design of the measurement is further discussed in the next section, as it was a product of the accuracy planning process.

Figure 3: Trimble S8

Figure 4: Leica GMP 101 Professional prism

3.1. A priori precision planning

The network was designed according to a local survey. To achieve the required precision, it was necessary to model the measurements and its precisions and prove that the required precision output will be met. Software PrecisPlanner 3D ([20]) was used for this purpose, with use of the approximate configuration of the determined points and standpoints. The procedure of the precision planning is described in detail in [9]. The configuration was designed at a guess and the optimization was made manually only by adding the measurement repetitions. The chosen points and planned measurements, generating a standard "braced quadrilateral" design, are shown on Fig. 5, where each line is a sightline described by a number of each type of the measurement performed (sd – slope distance, ze – zenith angle, di – direction).

Distance between points was approx. 3 m in the transversal direction, 15 m in the longitudinal direction. The expected precision of the aiming was lower than nominal and therefore 1.0 mgon was used (due to the short distances) as a standard deviation of the horizontal direction and zenith angle measurement. Standard deviation of the distance measurement 0.5 mm was used. This value was calculated from differences in oppositely measured distances and from a posteriori analysis of similar micro-networks.

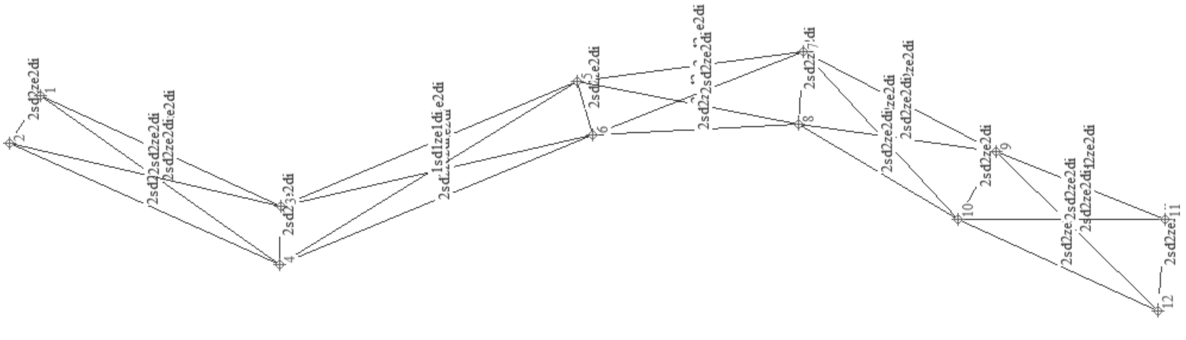

Figure 5: Configuration for precision planning with use of the PrecisPlanner 3D software

The result of the modelling showed that in order to achieve the required precision it is necessary to execute the measurement in two sets. All the requirements were met, the worst standard deviation of the standpoint coordinate was 0.1 mm in the lateral direction, 0.3 mm in the longitudinal direction and 0.08 mm in the height direction.

3.2. Measurement

Measurement was done according to the planning. The only detected problem was higher dispersion of the angle measurement at the transverse neighboring point (short distance, approx. 3 m). That's why standard deviation of angle measurement for these points in the adjustment was raised to 2.5 mgon.

3.3. Processing and results

The measurement was evaluated in the software EasyNet ver. 3.4.3 ([4]), including the field-book calculation, calculation of the approximate coordinates and reduction of the measured values for calculation of the coordinates. Adjustment was calculated completely in 3D, using also a robust estimation and other techniques for the outliers' detection. Detected as outliers and removed were only 5 measurements from 348 totally.

Achieved precision of spherical targets coordinates was sufficient, standard deviations after adjustment of each point coordinates (standard deviations in X, Y, Z coordinates σX, σY, σZ) are presented in Tab. 1. Error ellipses of the point positions can be seen at Fig. 6. Standpoints are numbered 4001 to 4010, spherical targets K1 to K6 and stabilized orientation points P1 to P4.

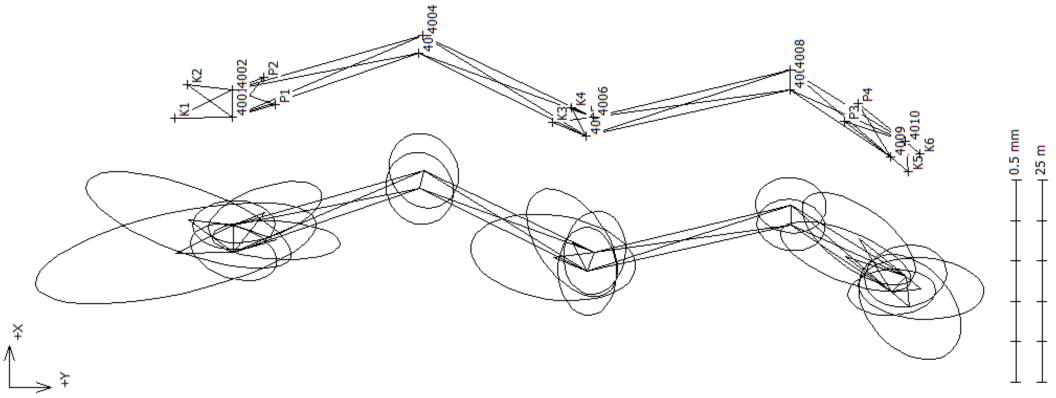

Figure 6: Configuration and error ellipses of the real measurement

4. Laser scanning

After determination of six spherical control points within the local micro-network the second part of the project, 3D laser scanning of the riverbed model was conducted successively in three separate stages, the first modelling the original model, the second and the third after the experiments simulating the influence of the water flow of a certain size (century flooding e.g.).

Table 1: A posteriori standard deviations in coordinates of the determined points

P.no.	σ_X [mm]	σ_Y [mm]	σ_Z [mm]
K1	0.12	0.35	0.10
K2	0.12	0.25	0.10
K3	0.11	0.20	0.07
K4	0.13	0.11	0.07
K5	0.13	0.13	0.09
K6	0.08	0.15	0.09
P1	0.05	0.16	0.08
P2	0.08	0.14	0.08
P3	0.09	0.16	0.08
P4	0.11	0.14	0.08
4001	0.07	0.11	0.07
4002	0.06	0.1	0.07
4003	0.09	0.08	0.06
4004	0.09	0.09	0.06
4005	0.11	0.07	0.05
4006	0.10	0.08	0.05
4007	0.06	0.08	0.06
4008	0.07	0.09	0.06
4009	0.06	0.11	0.07
4010	0.08	0.10	0.07

4.1. Measurement

The Surphaser 25HSX scanning system in the second most accurate configuration IR_X was used for the measurement due to very high demands on outputs accuracy. The manufacturer states accuracy for this configuration lower than 0.5 mm for 5 m, noise/precision 0.1 mm for 3 m. Other important parameters of these systems are: Scanning speed up to 1.2 million points per second, panoramic field of view, recommended measurement range 0.4-30 m.

The measurement was carried out from twelve standpoints placed on both sides of riverbed model and 22 control points were permanently mounted and used in total. The average distance between standpoints was about 10 meters due to partially winding shape of the model see Fig. 7. Control points were stabilized by polystyrene spherical targets with a diameter of 150 mm.

Scanning density was set 6 mm in orthogonal directions at the distance 10 m which leads to approximately 6 minutes measurement time on a standpoint and about 2 hours for the whole measurement of one stage.

4.2. Processing

Scanned data was exported in batch using console program ProcessC3d which is a part of used laser scanning system software SurphExpress Standard at first. It was necessary to use a format which keep ordered/structured format of the measured data to enable accurate and

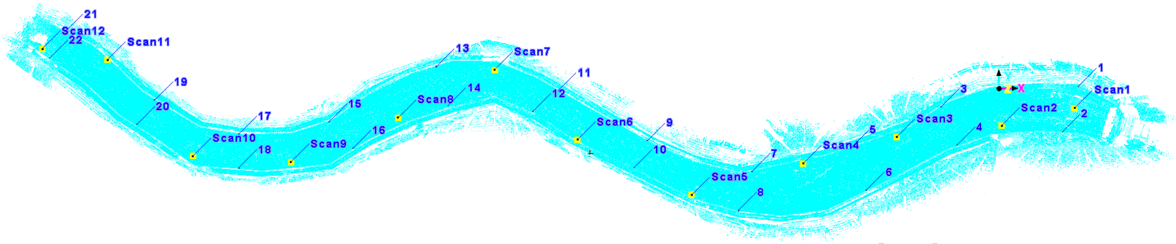

Figure 7: Standpoints (Scan1-Scan12) and control points (1-22) configuration for 3D laser scanning. Control points 1, 2, 11, 12, 21, 22 are identical to K1 – K6

fast normal computation in the following steps. The most suitable format is "btx" which is a binary format for ordered points.

The second used software was Geomagic Studio. It also supports batch processing and in addition to it macro scripting. It was used for point normal computation (exploiting structured format of points), for sampling with minimal spatial distance 5 mm and saving in text format.

The third step - registration took place in the Leica Cyclone software module Register. The control points were created by fitting spheres with the given diameter 150 mm. There were measured up to 8 control points on each standpoint from all together 22 control points. The actual registration was carried out twice. Only scanned data were registered in first step to verify absence of gross error and check inner data consistency. In the second step scanned data was registered together with control points determined within the local micro-network, which were placed in separated leveled "ScanWorld" (Leica Cyclone name for standpoint). This ScanWorld was set up as a "Home ScanWorld" (target coordinate system). Used control points were 1 (K1), 2 (K2), 12 (K4), 21 (K5) a 22 (K6) see Fig. 7 and 6. Control point 11 (K3) was damaged and couldn't be used.

This second registration was necessary to level scanned data (used scanning system is not equipped with inclinometer) and to check and compensate systematic influences caused by line character of measured object and by use of laser scanning system with relatively (to object size) low range. Systematic errors present in the measurement would sum and result in significant overall length difference between the scanned data and geodetic measurement.

The resulting "Mean Absolute Errors" of registration (accuracy property used in Cyclone software for registration) were for laser scanning data only 1.4 mm, 1.2 mm and 1.2 mm for three realized stages and 1.4 mm, 1.3 mm and 1.2 mm for second registration with control points from local micro-network after elimination of systematic influences (see section 4.3 below). The visualization of registered point cloud part is on Fig. 8.

The last processing step was transformation from local coordinate system to the national coordinate reference system (S-JTSK) and national vertical reference system (Balt po vyrovnání / Baltic Vertical Datum - After Adjustment). The client requested a transformation to place the measured deformations to the real world in the scale 1:1.

This part was quite difficult because only few suitable common known points in both coordinate systems exist on the barrage (a dam placed in a watercourse to increase the depth of water or to divert it into a channel for navigation or irrigation) at the beginning of the

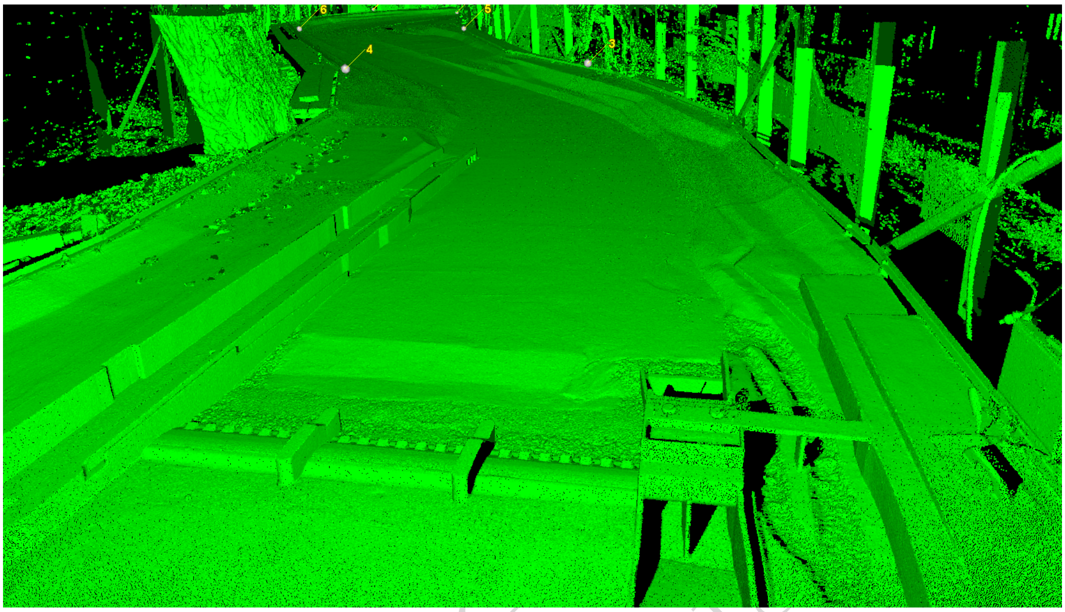

Figure 8: Screenshot of registered point cloud

riverbed model. The barrage itself exists only in measured Elbe river model (local coordinate system of measurement) and CAD design project (national coordinate reference system), but not in reality. The barrage fills only small part of the riverbed model (maximum barrage size is about 8 meters and model size 100 meters) and that's why it was not possible to use it for bearing determination (orientation/rotation) of scanned data and only one common known point on barrage was used. The rotations from local coordinate system to the national coordinate reference system (S-JTSK) was calculated as a difference between bearings in both systems from selected point on the barrage to the point in the middle of riverbed at the opposite side of the river model in exact distance (on point cloud in local coordinate system in distance 85.714 m and in CAD design project in the national coordinate reference system S-JTSK in distance 6 km). On the base of calculated (orientation, shift) or known (scale) values the parameters of similarity spatial transformation were computed and simple console program for large (about 9 million) point cloud transformation was created. The type of final transformation is "point and rotation" in horizontal space in addition with shift in vertical component and a priori known scale of the model.

4.3. Accuracy checks and improvements

The first accuracy check were the resulting "Mean Absolute Errors" of registration in Leica Cyclone for laser scanning data only. On the base of scanning system specification and lots of previous experience we had expected Mean Absolute Error about one millimeter, but the first result was nearly 3 millimeters which point to some unexpected error.

The second check, mostly for systematic errors, was comparison of shape and size between the laser scanning and "geodetic" outputs. The comparison was conducted using identity (rigid body) and similarity spatial transformation on five "identical" points in both coordinate systems. The result of the first application of identity transformation showed very high spatial position standard deviation 20 mm, which indicated important systematic influence. Moreover the significantly highest deviations were in longitudinal direction of riverbed model (and vertical deviations were order of magnitude lower). By the analysis of these results it was found out that the laser of 3D scanning system rangefinder penetrates the surface of used polystyrene spheres. Subsequently made experiments showed that the average value of this penetration is very close to 3 millimeters. The experiment was based on the same principle as determination of a prism – total station system constant (distance measured from middle and outside of a line).

After the application of corrected sphere diameters spatial position standard deviation of checking identity (rigid body) spatial transformation decreased from 20 to 3 millimeters and average registration Mean Absolute Error decreased near the expected one millimeter value.

The last check was spatial comparison of final point clouds of any two stages. Determined deformations should be lower than required 2 mm besides deformations on some parts of riverbed model bottom made from sand. There should be especially no deformation on concrete elevated sides of the model. Comparison was made using tool “3D Compare” in the software Geomagic Studio. Required accuracy was met on the vast majority of model surface see Fig. 9, where is one of the comparisons presented.

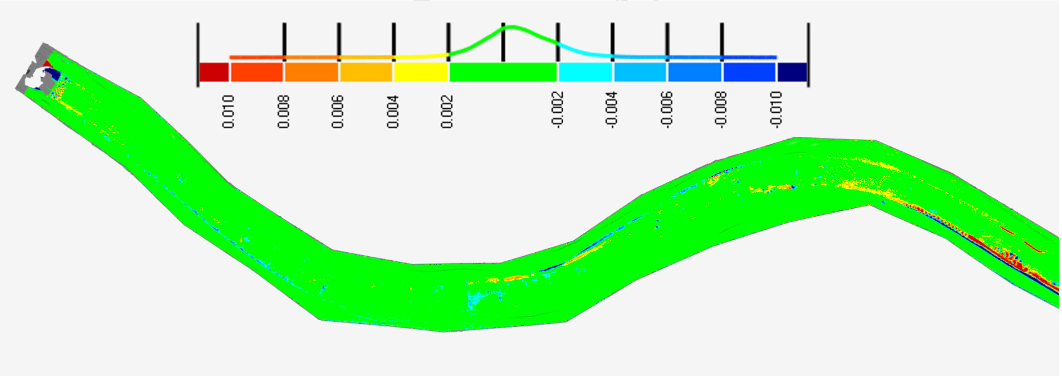

Figure 9: Hypsometric visualization of two stages distances (changes) [meters]

5. Conclusion

Experience with realization of riverbed model measuring for changes determination is presented in the paper. Due high demands on accuracy and precision and also on measurement resolution two different technologies must be combined. In the first step ground control points have to be determined. The technology of micro-network measured with total station was used for this task. These ground control points were used for referencing of individual standpoints for the second technology - 3D laser scanning. Laser scanning can achieve very high resolution of measurement but in the case of the most accurate devices it can be usually used only for short distances. A common denominator of both technologies was requirement on the highest possible quality of its outputs.

The high accuracy of geodetic micro-network points was made possible by using the most accurate total station, high quality tools and also a priori accuracy planning. Very important is choice of devices and tools with small eccentricities and also high quality tripods and tribrach, where repeated clamping of different devices (total stations, carriers with prism) causes very small movements. The eccentricities may encounter up to a 0.3 mm with the use of the conventional tools, but on the project were used tribrach with a maximum standard deviation of repeated clamping 0.05 mm. Furthermore, it is very important to carefully aim or, in the case of automatic aiming, accurately turn prisms toward total station.

Due to the short distances in this case, automatic aiming cannot be recommended. The advantage is motorized/robotized total station which greatly speeds up measurements, and which is not such demanding on the stamina and the concentration of the operator.

In the case of laser scanning part, the required accuracy was achieved using accurate scanning system (the most accurate 3D laser scanning system on the market at the time of release), suitable chosen scanning configuration and processing and especially using high accuracy local micro-network. This network was necessary to level scanned data and to check and compensate of systematic influences. Because of this accuracy checks the significant systematic error caused by rangefinder laser penetration through the surface of used spheres was discovered. After determination and correction of this error, the expected check results were finally achieved. The final result was a detailed 3D model of the deformations caused by the test water flow with demanded precision.

Researchers from T. G. Masaryk Water Research Institute were greatly satisfied with delivered outputs and recommend implementation of this technology for all similar research projects in their institution.

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