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A DEFORMATION MONITORING WITH SIMULTANEOUS HETEROGENEOUS OBSERVATION SYSTEM

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ABSTRACT

Adequate measuring networks for objects' deformation monitoring have to meet high demands regarding selected known (starting) points and deformation network design. Selected known points have to assure stabile frame of deformation network and their position must be determined with adequate accuracy.
Deformation network design also have to assure correct geometric transfer of coordinate differences regarding variance-covariance propagation law.
The stated requests are assured even harder in mining and geotechnology because monitored objects are ussualy above underground excavations or underground building sites. The objects monitoring in this article is presented with quantities that are independent (invariant) from datum of known points. This quantities are slope distances between objects' characteristic points. In presented example observations between objects' characteristic points were not possible.
From the initial epoch results it is concluded that on the base of precision estimations of slope distances between object's characteristic points is expected that it will be possible to monitor slope distance changes larger than 10mm in any direction in space (at $\tau = 2$, the probability is 95.45%). If the most favorable conditions are considered, it will be possible to monitor slope distance changes larger than 3mm (at $\tau = 2$, the probability is 95.45%).

Key words: deformation monitoring, heterogeneous observation system, 3D adjustment, monitoring of mutual spatial relations, characteristic points, confidence pedaloid (surface).

INTRODUCTION

In deformation monitoring of objects or unstable areas between epochs the most important is to provide suitable monitoring network. Deformation networks must provide adequate stability and accuracy of starting (known) points and proper network design to assure correct geometric transfer of coordinate's differences regarding variance-covariance propagation law.

The pretentiousness of network design above all depends from largeness of unstable area which is monitored, design (geometry) and quality of the existing network, topography of monitored area, complexity of the monitored object or monitored area (the number of the characteristic points) and suitable and available survey methods.
Due the mining usually include large areas so the eventual impact of the mining is also manifested on the large areas what it makes especially difficult to assure appropriate deformation network for monitoring the details (objects) of the larger unstable area. For deformation monitoring the stabile (fixed) frame of the deformation network is needed which can be provided outside of the unstable (mining) area. The designing and monitoring of such deformation networks is usually technological and expertise very pretentious what leads us to the questions about economical justification of such networks.
When we are interested in mutual relations of some parts of the objects or mutual relations among more objects, than we can monitor relations changes between epochs with quantities that are independent (invariant) from selected datum. This invariant quantities can be slope distances between characteristic points of the object or objects that are monitored in individual epochs. The changes of mutual geometric relations of the objects are monitored with slope distance changes between characteristic points of the objects between epochs. In this article is presented monitoring of the four support columns with slope distances between characteristic points of the columns (one per column).

HETEROGENEOUS LOCAL NETWORK

Heterogeneous observation system is combined from different types of observation systems. Heterogeneous observation system contains observed points, observations, network adjustment and results interpretation. Regardless the observations types and observation systems, respectively, which are containing heterogeneous observation system all observations, are simultaneously adjusted.
The purpose of the heterogeneous local network (figure 1) will be monitoring of mutual spatial positions of four supporting columns (characteristic points), with a possibility of constraining local network into the existing network. Observations between object’s characteristic points could not be applied.
The design of the existing network on surveyed area and topography of surveyed area has narrowed the selection of appropriate points of existing network. The selected points of the existing network (*XI/A1* in *X/5*) are to distant regarding to available surveying instruments and surveying methods. For listed reasons above beside four object’s characteristic points (*STk1*, *STk2*, *STk3* in *STk4*) also two auxiliary points (*Pom1* and *Pom2*) in proximity of the supporting columns have been reconnaissanced and materialized.
Simultaneous observations of heterogeneous local network contain three observation systems:

- baselines of static DGPS observations (Differential Global Positioning System),
- height differences of differential leveling
- microtriangulation and microtrilateration:
    - horizontal directions,
    - zenith distances,
    - slope distances.

From existing network points the auxiliary points are observed with baselines of DGPS observation and height differences of differential leveling and from auxiliary points characteristic points are observed with combined resections (horizontal directions, zenith distances and slope distances).

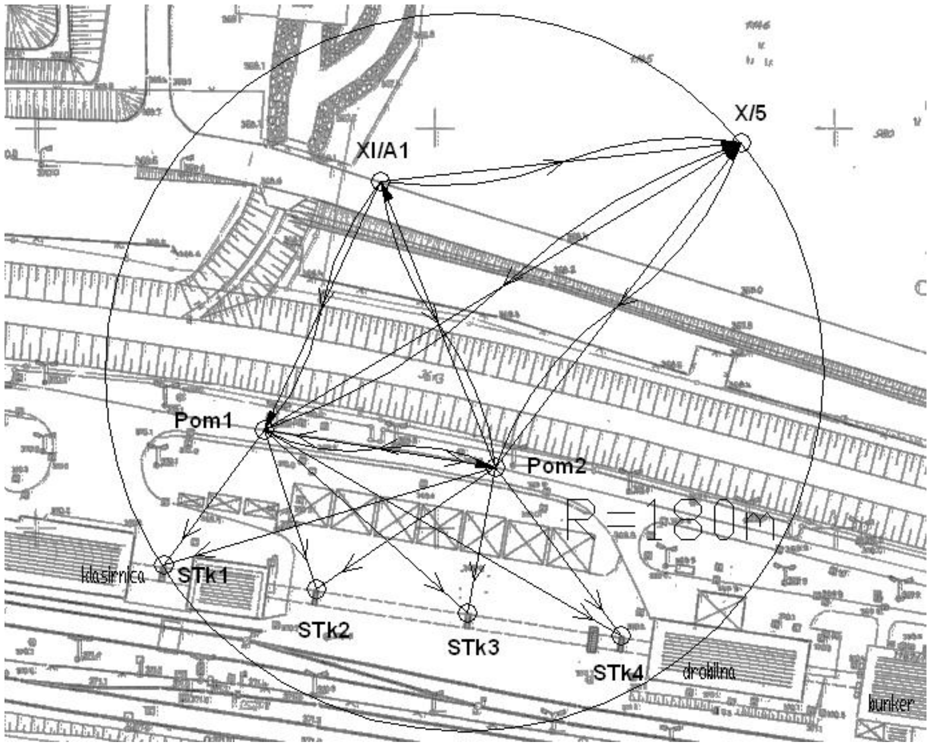

Figure 1.: Heterogeneous local network.

ADJUSTMENT OF HETEROGENEOUS LOCAL NETWORK

Local network, which is observed with terrestrial and GPS observations, is adjusted as spatial (3D) network in programme package *Leica Geo Office 5.0*.

Adjustment strategy of local network

The simultaneous adjustment procedure of terrestrial and GPS observations is realized in three steps:

- observation testing with adjustment of inner constrained or minimally constrained networks upon individual observation types or observation systems,
- quality known points control of the existing network which is illustrated with combined adjustment comparison (GPS network and leveling network) in minimally constrained network and fully constrained network in which the known points are datum,
- combined adjustment of terrestrial and GPS observations.

Individual observation types or observation systems are adjusted separately in inner constrained networks or minimally constrained networks. With this adjustment procedure the known points influences are eliminated and observations can be tested regarding to blunders (gross errors).
The known points (existing network) acquired data unfortunately did not include *a posteriori* precision estimation of known points. Because of that the known points influences on *a posteriori* precision estimation of auxiliary points are examined with combined network (DGPS baselines and height differential leveling differences) adjustments comparison in minimally constrained network and fully constrained network in which the known points are datum.

COMBINED ADJUSTMENT OF TERRESTRIAL AND GPS OBSERVATIONS

Objects will be monitored with slope distances changes between characteristic points. For that matter the slope distances precision is important. For precise slope distances determining the quality of auxiliary points mutual position is important.
From known points quality control is concluded, that the known points are determined with centimeter’s precision at best. Observation testing show that the characteristic points can be determine with millimeter’s precision by combined resections from auxiliary points.
From known points quality control and observation testing is obvious that carrying errors from known points to local network are not reasonable. Because of the stated findings the simultaneous adjustment of terrestrial and GPS observations is executed in two steps.
In first step the datums in adjustment are existing network points (figure 2). With first step the auxiliary points mutual position is determined.
In second step the datums in adjustment are auxiliary points adjusted coordinates determined in first step. With second step the adjusted (figure 3) characteristic points coordinates and variance-covariance matrix of unknowns $\mathbf{\Sigma}_{\hat{x}\hat{x}}$ is determined.

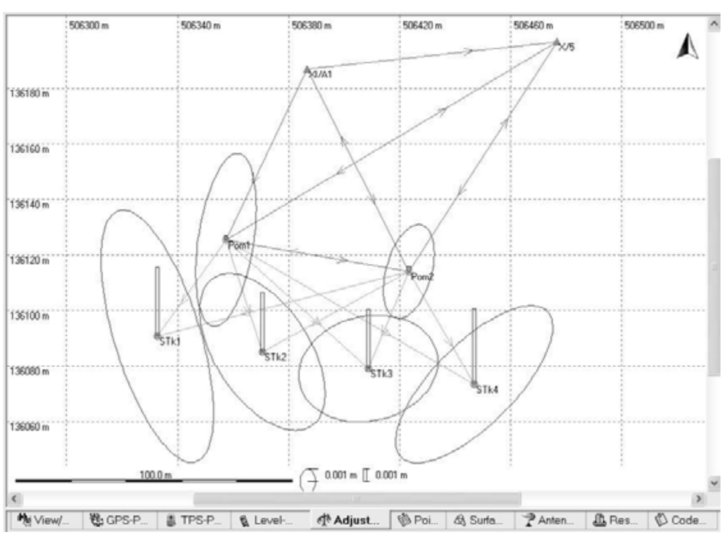

Figure 2.: First step of terrestrial and GPS observations simultaneous adjustment.

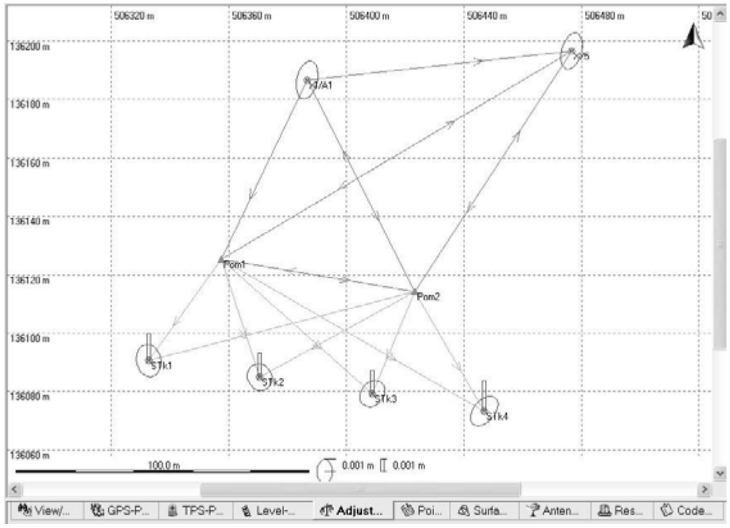

Figure 3. Second step of terrestrial and GPS observations simultaneous adjustment.

DETERMINATION AND PRECISION ESTIMATION OF SLOPE DISTANCES BETWEEN CHARACTERISTIC POINTS

Adjusted characteristic points spatial coordinates are determined with 3D adjustment model in ellipsoidal coordinates (φ, λ, h), which are then projected on a plane (Gauss-Krüger projection). Heights are defined with orthometric heights.

Characteristic points plane coordinates (Y, X) and orthometric heights (H) are adopted in further calculations as spatial coordinates (Y, X, H) because of the small local network dimensions (pictures 2 and 3).

From adjusted characteristic points coordinates are determined slope distances $d_{slope_{ij}}$ between characteristic points with expression:

$$d_{slope_{ij}} = \sqrt{\left(Y_j - Y_i\right)^2 + \left(X_j - X_i\right)^2 + \left(H_j - H_i\right)^2} \tag{1}$$

Index *i* is for slope distance starting point and index *j* is for slope distance finishing point.

A posteriori precision estimation of slope distances between characteristic points is acquired from variance-covariance matrix of unknowns $\mathbf{\Sigma}_{\hat{x}\hat{x}}$ (figure 8) which is adjustment product (simultaneous adjustment of all observations).

Variance-covariance matrix $\mathbf{\Sigma}_{\hat{x}\hat{x}}$ is containing information about *a posteriori* precision estimation of all points' spatial coordinates (variances) which are taking part in adjustment and interdependences between all points' spatial coordinates (covariances).

From variance-covariance matrix $\mathbf{\Sigma}_{\hat{x}\hat{x}}$ submatrixes (3 x 3) the covariance matrixes $\mathbf{\Sigma}_{ij}$ for each slope distance are composed, for which the precision estimation is wanted. The belonging slope distance covariance matrix $\mathbf{\Sigma}_{\Delta ij}$ is then determine with taking into consideration the variance-covariance propagation law for random variables linear functions [*Vulić*]:

$$\mathbf{\Sigma}_{\Delta ij} = \mathbf{J}_{ij} \cdot \mathbf{\Sigma}_{ij} \cdot \mathbf{J}_{ij}^{T}$$

$$\mathbf{\Sigma}_{\Delta ij} = \begin{vmatrix} -\mathbf{I}_{3\times3} & \mathbf{I}_{3\times3} \end{vmatrix} \cdot \begin{vmatrix} \mathbf{\Sigma}_{\hat{x}_i\hat{x}_i} & \mathbf{\Sigma}_{\hat{x}_i\hat{x}_j} \\ \mathbf{\Sigma}_{\hat{x}_j\hat{x}_i} & \mathbf{\Sigma}_{\hat{x}_j\hat{x}_j} \end{vmatrix} \cdot \begin{vmatrix} -\mathbf{I}_{3\times3} \\ \mathbf{I}_{3\times3} \end{vmatrix} \tag{2}$$

$$\mathbf{\Sigma}_{\Delta ij} = \begin{vmatrix} \Sigma_{\Delta ij_{xx}} & \Sigma_{\Delta ij_{xy}} & \Sigma_{\Delta ij_{xz}} \\ \Sigma_{\Delta ij_{xy}} & \Sigma_{\Delta ij_{yy}} & \Sigma_{\Delta ij_{yz}} \\ \Sigma_{\Delta ij_{xz}} & \Sigma_{\Delta ij_{yz}} & \Sigma_{\Delta ij_{zz}} \end{vmatrix}$$

$\mathbf{J}_{ij}$ - the Jacobian matrix for slope distance's $d_{slope_{ij}}$ components functions

$\mathbf{\Sigma}_{\hat{x}_i\hat{x}_i}, \mathbf{\Sigma}_{\hat{x}_j\hat{x}_j}, \mathbf{\Sigma}_{\hat{x}_i\hat{x}_j}, \mathbf{\Sigma}_{\hat{x}_j\hat{x}_i}$ - submatrixes (3 x 3) of covariance matrix $\mathbf{\Sigma}_{\hat{x}\hat{x}}$

$\mathbf{\Sigma}_{\Delta ij}$ - covariance matrix $\mathbf{\Sigma}_{\Delta ij}$ of slope distance between characteristic points i and j

After all slope distances covariance matrixes determination $\mathbf{\Sigma}_{\Delta ij}$ it is proceeted to confidence surface's defining elements calculation (confidence pedaloid defining elements).

Main (characteristic) standard deviations of slope distances are determined with slope distance's covariance matrix $\mathbf{\Sigma}_{\Delta ij}$ eigenvalues λ_i:

$$\hat{\sigma}_{\xi\xi} = \sqrt{\lambda_{\xi\xi}}$$
$$\hat{\sigma}_{\eta\eta} = \sqrt{\lambda_{\eta\eta}} \tag{3}$$
$$\hat{\sigma}_{\zeta\zeta} = \sqrt{\lambda_{\zeta\zeta}}$$

Main standard deviations components of slope distances are determined with slope distance's covariance matrix $\mathbf{\Sigma}_{\Delta ij}$ eigenvectors $\mathbf{s}_i$:

$$\hat{\sigma}_{\xi\xi} \cdot \mathbf{s}_{\xi\xi}^{T} = \begin{vmatrix} s_{\xi x} & s_{\xi y} & s_{\xi z} \end{vmatrix}$$
$$\hat{\sigma}_{\eta\eta} \cdot \mathbf{s}_{\eta\eta}^{T} = \begin{vmatrix} s_{\eta x} & s_{\eta y} & s_{\eta z} \end{vmatrix} \tag{4}$$
$$\hat{\sigma}_{\zeta\zeta} \cdot \mathbf{s}_{\zeta\zeta}^{T} = \begin{vmatrix} s_{\zeta x} & s_{\zeta y} & s_{\zeta z} \end{vmatrix}$$

The precision estimation results of slope distances between characteristic points are in table 1.

In three-dimensional (3D) perpendicular coordinate system the confidence pedaloid (confidence surface) is determined with main standard deviations (the half-axis confidence pedaloid values) and with main standard deviations components (the half-axis confidence pedaloid directions).

Confidence pedaloid [*Vehovec*] is surface which is presenting (figure 4) estimated quantity errors values in optional direction in space. That is important in detailed analysis at construction monitoring. The approximation of confidence pedaloid is confidence ellipsoid.

The slope distance's precision estimations between characteristic points are presented with slope distances confidence ellipsoids (figures 5-8).

Table 1.: Defining elements of slope distances confidence pedaloids (surface) between characteristic points at $\tau = 2$ (the probability is 95.45%).

From	To	a [m]	a_X, a_Y, a_H [m]	b [m]	b_X, b_Y, b_H [m]	c [m]	c_X, c_Y, c_H [m]
STk1	**STk2**	0,006	0,0016	0,003	0,0028	0,002	-0,0007
			0,0006		-0,0010		-0,0023
			0,0058		-0,0007		0,0005
STk1	**STk3**	0,006	0,0017	0,003	-0,0030	0,003	0,0002
			0,0007		-0,0001		-0,0026
			0,0058		0,0009		0,0003
STk1	**STk4**	0,007	0,0011	0,004	-0,0036	0,004	0,0007
			0,0006		-0,0010		-0,0026
			0,0066		0,0007		0,0001
STk2	**STk3**	0,006	0,0014	0,003	-0,0025	0,003	0,0009
			0,0002		-0,0009		-0,0024
			0,0054		0,0007		-0,0001
STk2	**STk4**	0,006	0,0008	0,003	-0,0031	0,003	0,0009
			0,0001		-0,0012		-0,0025
			0,0063		0,0005		-0,0001
STk3	**STk4**	0,006	0,0007	0,003	-0,0028	0,002	0,0012
			0,0001		-0,0017		-0,0020
			0,0062		0,0003		-0,0001

a - main standard deviation value (major)
b - main standard deviation value (semi)
c - main standard deviation value (minor)
a_X, b_X, c_X, - main standard deviations components in direction X
a_Y, b_Y, c_Y, - main standard deviations components in direction Y
a_H, b_H, c_H, - main standard deviations components in direction H

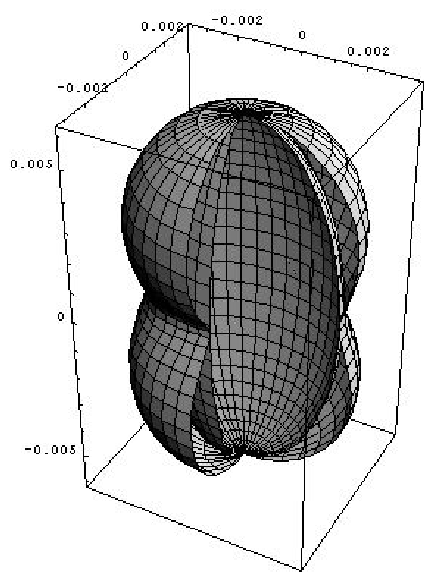

Figure 4.: Confidence pedaloid and confidence ellipsoid cross-section (at $\tau = 2$, the probability is 95.45%) of slope distance STk1-STk2.

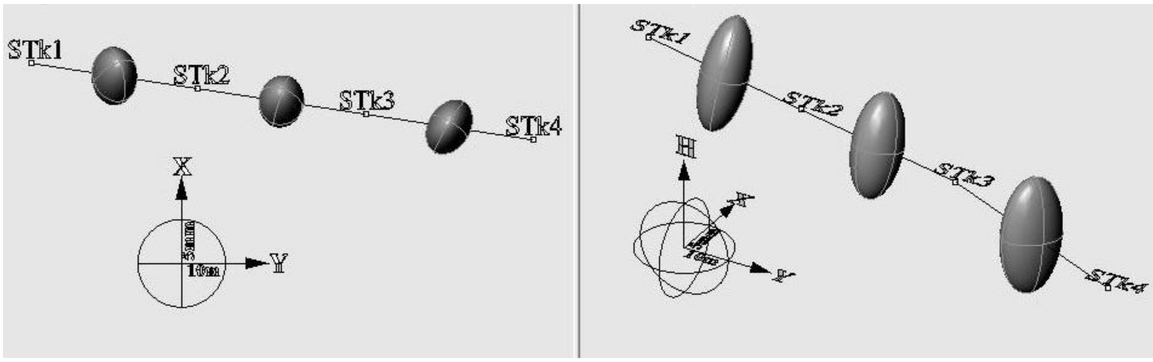

Figure 5. Confidence ellipsoids of slope distances STk1-STk2, STk2-STk3 and STk3-STk4 (at $\tau = 2$, the probability is 95.45%) in orthogonal projection on YX plane (left) and in aksonometric projection (right).

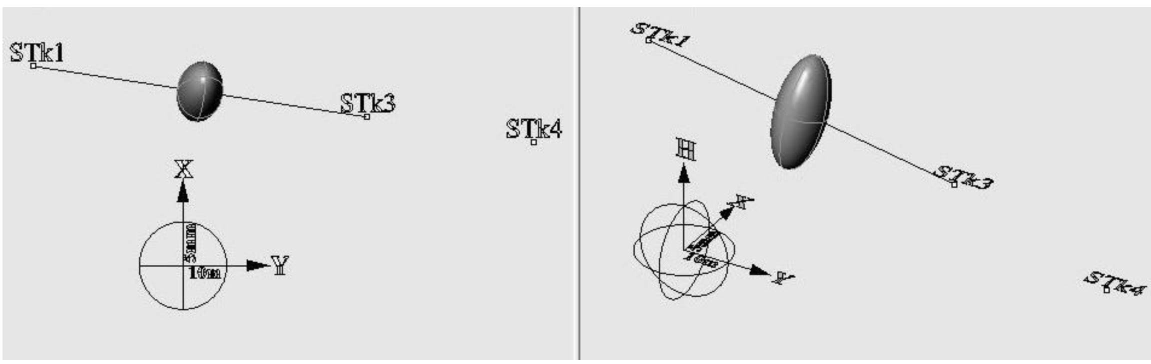

Figure 6.: Confidence ellipsoid of slope distance STk1-STk3 (at $\tau = 2$, the probability is 95.45%) in orthogonal projection on YX plane (left) and in aksonometric projection (right).

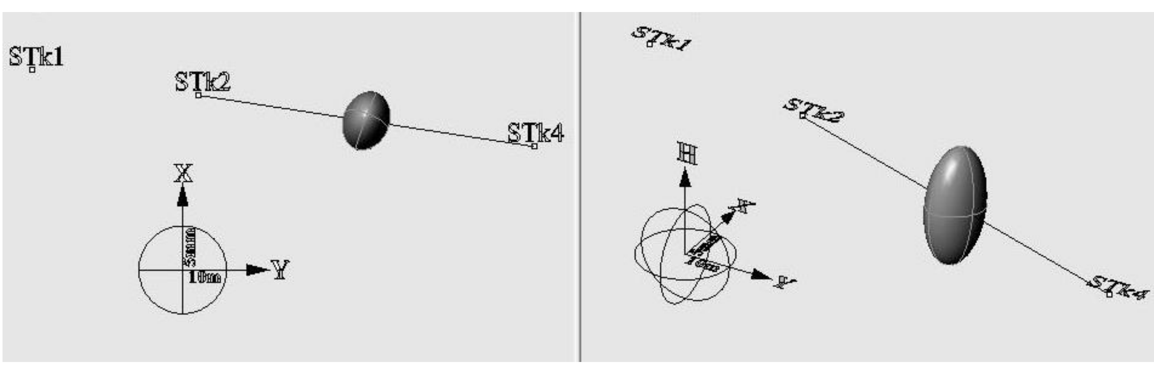

Figure 7.: Confidence ellipsoid of slope distance STk2-STk4 (at $\tau = 2$, the probability is 95.45%) in orthogonal projection on YX plane (left) and in aksonometric projection (right).

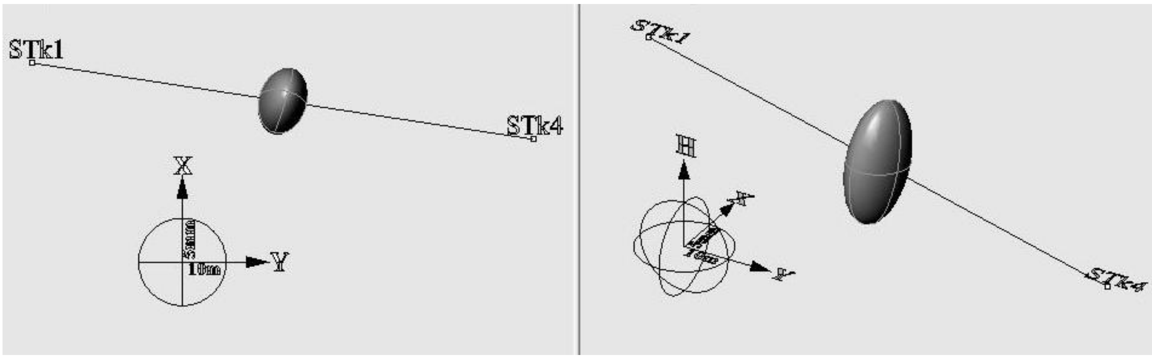

Figure 8.: Confidence ellipsoid of slope distance STk1-STk4 (at $\tau = 2$, the probability is 95.45%) in orthogonal projection on YX plane (left) and in aksonometric projection (right).

CONCLUSIONS

Defined and estimated slope distances as described in this article, between object characteristic points at the initial epoch will be together with the following epochs, used for analyze at construction monitoring.

On base of slope distance precision estimations in two epochs and with consideration of variance propagation law for mutual independent random variables, there can be an estimation of precision made for slope distance changes between two epochs. The standard deviation (equation 5) values of slope distance changes between two epochs are at the same time the values of minimal changes that can be monitored.

$$\hat{\sigma}^2_{\Delta ij_{\max}} = \hat{\sigma}^2_{i_{\max}} + \hat{\sigma}^2_{j_{\max}} \tag{5}$$

$\hat{\sigma}_{\Delta ij_{\max}}$ - the maximal standard deviation of slope distance change between two epochs

$\hat{\sigma}_{i_{\max}}$ - the maximal main standard deviation of slope distances in epoch i

$\hat{\sigma}_{j_{\max}}$ - the maximal main standard deviation of slope distances in epoch j

From the initial epoch results (table 1) and if the initial epoch results are adopted for following epoch there can be determined (equation 6) expected minimal slope distance change that can be monitored between two epochs:

$$\begin{aligned} \hat{\sigma}^2_{\Delta ij_{\max}} &= 2 \cdot \hat{\sigma}^2_{\max} \\ \hat{\sigma}_{\Delta ij_{\max}} &= \sqrt{2} \cdot \hat{\sigma}_{\max} = \sqrt{2} \cdot 0{,}007m = 0{,}0099m = 10mm \end{aligned} \tag{6}$$

From maximal value of slope distances main standard deviation of initial epoch (7mm at $\tau = 2$, the probability is 95.45% , table 1) can be concluded that without any local network survey method improvement it will be possible to monitor slope distance changes between object's characteristic points between two epochs larger than 10mm in any direction. If there are most favorable conditions considered (minimal main slope distance standard deviation is 2mm at $\tau = 2$, the probability is 95.45% , table 1) it will be possible to monitor slope distance changes down to 3mm.

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