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Geodetic Terrestrial Observations for the Determination of the Stability in the Krško Nuclear Power Plant Region

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1. Introduction

The first research of the stability in the Krško plain was carried out in the period 1964–1969, when the area was chosen as the potential location for a nuclear power plant. The foundation stone for the Krško Nuclear Power Plant (NEK) was laid on December 1, 1974. In January 1984 NEK acquired the full operation permit. NEK has been in commercial operation for more than 20 years. Regarding the standards of nuclear safety and stability, NEK is today in the top 25% of operational nuclear power plants in the world. The Krško Nuclear Power Plant is of strategic importance for the Republic of Slovenia, producing electricity for users in Slovenia and Croatia. High level of security is of high importance; therefore, a comprehensive supervision of structures is carried out. A special attention is paid to the security systems, including the measurements of vertical displacements of benchmarks and measurements of horizontal displacements of the dam on the Sava River. Periodic geodetic observations are carried out on important technological structures comprising the nuclear island, the Sava River dam and the nuclear waste storage.

Since local stability of the Krško nuclear power plant is very important, several research works were conducted to test the stability of the Krško region. Based on the Project of permanent observations of tectonic movements in the surroundings of the Nuclear Power Plant Krško and geological researches of crustral movements along the Orlica fault in Krško region the micro network Libna was established. The intention of the network was to determine the horizontal crustal movements along the Orlica fault. The points of the net were stabilized in 1998, when also the zero measurement was realised.

Several epochs of measurements in both micro networks Krško and Libna were made. After a careful analysis and quality estimation of single epochs, the displacements were estimated and the accuracy of estimating the two-epoch displacements was calculated. We proposed original method, where simulations of an actual probability distribution function are determined, providing the basis for calculating the right critical value at a chosen significance level. In this way, statistically significant point displacements can be determined far more accurately. When assessing point displacements, the information on the actual risk of making an error when rejecting the true null hypothesis is very useful and the calculation of this value is advisable. Based on the assumption that the distribution function is established in detail, the suggested test statistic is simple and fits for day-to-day use as well as refers to the first estimation of the geodetic network.

2. Determination of point displacements in the geodetic network

2.1 Single epoch processing

For the identification of point displacement by geodetic observations, the reference points need to be chosen. Characteristic points on the object are tested for displacements. According to the required accuracy of point displacement determination, the observations must be carried out carefully with proper tools while following standard observational rules. The observations in the geodetic network are adjusted and the network quality estimated.

Importantly, in networks for displacement identification network quality estimation is carried out prior to the measurements examining the accuracy, reliability and sensitivity of setting up a network. More details about network quality estimation can be found in Caspary (2000). For the identification of displacements, network reliability and sensitivity are of primary importance. Thus, great effort must be made in detecting the presence of undisclosed gross errors. In the planning and optimization phase, the sensitivity of observations needs to be enabled, thereby increasing the probability of detecting outliers.

2.1.1 Free network adjustment

In deformation analysis single epochs are usually adjusted as free networks. In this way the best linear unbiased estimation of the unknowns and independence of test statistic regarding the chosen network datum is enabled.

Observations of each epoch measurement individually have to be adjusted as free network with minimum trace of the matrix of coordinate point correction factors, as it is valid for other procedures of deformation analysis. This means that not only the sum of the squares of the weighted residuals $\mathbf{v}_i^{\mathrm{T}}\mathbf{P}_i\mathbf{v}_i = \min$. has to be minimal, but also the sum of the squares of unknowns $\hat{\mathbf{x}}_i^{\mathrm{T}}\hat{\mathbf{x}}_i = \min$.. Index i defines the epoch measurement. Previous epoch measurement is carried out in time t_1, and the current in time t_2. Of course, the orientation unknowns have to be removed by reducing the unknowns in the observation equations. Also any possible unknown due to the factor of network scale has to be reduced (Van Mierlo, 1978). If the number of network points in epoch measurement t_1 differs from those in epoch measurement t_2, the coordinate unknowns of non-identical points are eliminated by the S-transformation (Van Mierlo, 1978).

2.1.2 Detection and elimination of outliers

A well projected network for displacement detection should enable a high degree of detection and elimination of gross errors in observations as well as minimize the effect of potentially undetected outliers influencing the unknowns. Testing the relation between the a posteriori variance $\hat{\sigma}_0^2$ and the a priori reference variance σ_0^2 is called the *global model hypothesis testing*. At the same time, the presence of gross error observations in the network is tested, which is in turn possible only by having a reliable knowledge of the a priori reference variance. In case of incongruence between the observations and the model in the course of the global testing, the Baarda's Data Snooping method for examination, detection and elimination of outliers in observations is introduced. The Pope's Data Screening approach or the Danish approach is used when the a priori reference variance is not reliably known.

2.1.3 S-transformation

In the deformation analysis based on geodetic measurements conducted in different epoch moments the occurring point displacements and deformations of the physical surface of the earth are detected and defined using methods of statistical analysis. Of course, the point displacements can only be detected and defined at identical points. If not all points in the epoch measurements are identical, the non-identical points shall be eliminated. This can be done by the S-transformation of an individual epoch measurement into the datum of identical points. The S-transformation can also be used if the transformation of the results of adjustment from one datum to another is required.

In order to transform the vector of unknowns and the cofactor matrix from datum A to a newly selected datum B, the vector of unknowns and the cofactor matrix are calculated using the following equations (without derivation; for derivation see Caspary, 2000, Mierlo, 1978):

$$\hat{\mathbf{x}}_{\mathrm{B}} = \mathbf{S}_{\mathrm{B}}\hat{\mathbf{x}}_{\mathrm{A}} \tag{1}$$

$$\mathbf{Q}_{\hat{\mathbf{x}}\hat{\mathbf{x}}_{\mathrm{B}}} = \mathbf{S}_{\mathrm{B}}\mathbf{Q}_{\hat{\mathbf{x}}\hat{\mathbf{x}}_{\mathrm{A}}}\mathbf{S}_{\mathrm{B}}^{\mathrm{T}}\,, \tag{2}$$

where:

$\hat{\mathbf{x}}_{\mathrm{A}}$, $\mathbf{Q}_{\hat{\mathbf{x}}\hat{\mathbf{x}}_{\mathrm{A}}}$ are the vector of unknowns and the cofactor matrix in datum A,

$\hat{\mathbf{x}}_{\mathrm{B}}$, $\mathbf{Q}_{\hat{\mathbf{x}}\hat{\mathbf{x}}_{\mathrm{B}}}$ are the vector of unknowns and the cofactor matrix in datum B,

$\mathbf{S}_{\mathrm{B}} = (\mathbf{N} + \mathbf{G}_{\mathrm{B}}^{\mathrm{T}}\mathbf{G}_{\mathrm{B}})^{-1}\mathbf{N}$ is the S-transformation matrix, with the weakness that the inverse matrix $(\mathbf{N} + \mathbf{G}_{\mathrm{B}}^{\mathrm{T}}\mathbf{G}_{\mathrm{B}})^{-1}$ of the order $u \times u$ has to be calculated, which is why it is more appropriate to use the form $\mathbf{S}_{\mathrm{B}} = \mathbf{E} - \mathbf{B}^{\mathrm{T}}(\mathbf{G}_{\mathrm{B}}\mathbf{B}^{\mathrm{T}})^{-1}\mathbf{G}_{\mathrm{B}}$, where only the inverse matrix of the order $d \times d$ has to be calculated, which is a significant advantage,

$\mathbf{N} = \mathbf{N}\mathbf{Q}_{\hat{\mathbf{x}}\hat{\mathbf{x}}_{\mathrm{B}}}\mathbf{N}$ is the matrix of normal equations,

$$\mathbf{G}_{\mathrm{B}} = \mathbf{B}\mathbf{E}_{\mathrm{B}}\,, \tag{3}$$

$$\mathbf{B}_{(2D)} = \begin{array}{c} \begin{matrix} \hat{x}_1 & \hat{y}_1 & \hat{x}_2 & \hat{y}_2 & \dots & \hat{x}_m & \hat{y}_m \end{matrix} \\ \begin{bmatrix} 1/\sqrt{m} & 0 & 1/\sqrt{m} & 0 & \dots & 1/\sqrt{m} & 0 \\ 0 & 1/\sqrt{m} & 0 & 1/\sqrt{m} & \dots & 0 & 1/\sqrt{m} \\ -\eta_1 & \xi_1 & -\eta_2 & \xi_2 & \dots & -\eta_m & \xi_m \\ \xi_1 & \eta_1 & \xi_2 & \eta_2 & \dots & \xi_m & \eta_m \end{bmatrix} \end{array} \tag{4}$$

$$x_{\mathrm{s}} = \frac{1}{m}\sum_{k=1}^{m} x_k \text{ and } y_{\mathrm{s}} = \frac{1}{m}\sum_{k=1}^{m} y_k \tag{5}$$

$$\overline{x}_k = x_k - x_{\mathrm{s}} \text{ and } \overline{y}_k = y_k - y_{\mathrm{s}}\,,\ k = 1,\dots,m \tag{6}$$

$$c^2 = \frac{1}{\sum\limits_{k=1}^{m}(\overline{x}_k^2 + \overline{y}_k^2)} \tag{7}$$

$$\xi_k = c\bar{x}_k \text{ and } \eta_k = c\bar{y}_k\,,\; k = 1,\ldots,m\,, \tag{8}$$

where:
m is the number of all points,
$\mathbf{E}_\mathrm{B}$ is the datum matrix of datum B.

In order to transform the results of the free network adjustment to a network defined with the newly selected points, these networks have to be entered into the datum matrix at the places where the unknowns of the selected points, ones ($\mathbf{E}_\mathrm{B} = \begin{bmatrix} \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{I}_k & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} \end{bmatrix}$), are located. The transformation yields the solution (vector of unknowns), which minimizes the partial norm $\|\hat{\mathbf{x}}_k\|_2$ of k unknowns of the newly selected points. The sum of adequate k variances also reaches the minimum, i.e. the partial trace of the cofactor matrix of coordinate difference of the newly selected points $\mathbf{Q}_{\hat{\mathbf{x}}\hat{\mathbf{x}}_k}$ is minimal.

2.2 Testing statistical significance of displacements

The basis for displacement determination of a man-made object or any given object on the surface of the earth is to identify the displacements of characteristic points of an object. The points comprise networks, which are monitored in time intervals called *epochs*, set out in advance. The point displacements between two epochs can be inferred only from *identical points*, measured in two epochs. However the points are often damaged or they have to be included into the network due to changes of circumstances. Non-identical points are eliminated in the adjustment procedure or with S-transformation. More details about the procedure can be found in Mierlo (1978). After the two-epoch adjustment the point displacements and their standard deviations are estimated.

2.3 Displacement estimation and displacement accuracy estimation

In geodetic networks it is essential that both displacement and its standard deviation are determined. If the estimated displacements are several times the size of the displacement standard deviations, the most probable displacements can be inferred from the differences in point positions. In addition to determining the magnitude and direction of the displacements, the hypothesis testing for the displacement is also necessary. Consequently, these corresponding calculations must be performed.

Point displacements are determined on the basis of comparing point coordinates in two epochs. Let us assume the point coordinates $T(y,x)$ in a plane and time t and $t+\Delta t$. We assume that the coordinates in time t are not correlated with the coordinates in time $t+\Delta t$.

In order to calculate the estimation accuracy of point displacements, the covariance matrix of point coordinates for respective epochs must be known. $T_t(y_t, x_t)$ represents the position of point T in time t, $\mathbf{\Sigma}_t$ is the corresponding covariance matrix, and $T_{t+\Delta t}(y_{t+\Delta t}, x_{t+\Delta t})$ represents the coordinates of point T in time $t+\Delta t$ with the corresponding covariance matrix $\mathbf{\Sigma}_{t+\Delta t}$. This can be expressed as

$$\mathbf{\Sigma}_{T_t} = \begin{bmatrix} \sigma_{y_t}^2 & \sigma_{y_t x_t} \\ \sigma_{y_t x_t} & \sigma_{x_t}^2 \end{bmatrix} \quad \mathbf{\Sigma}_{T_{t+\Delta t}} = \begin{bmatrix} \sigma_{y_{t+\Delta t}}^2 & \sigma_{y_{t+\Delta t} x_{t+\Delta t}} \\ \sigma_{y_{t+\Delta t} x_{t+\Delta t}} & \sigma_{x_{t+\Delta t}}^2 \end{bmatrix}. \tag{9}$$

The covariance matrix of coordinates of identical points y_t, x_t, $y_{t+\Delta t}, x_{t+\Delta t}$ can be written as

$$\boldsymbol{\Sigma}_{T_t T_{t+\Delta t}} = \begin{bmatrix} \sigma_{y_t}^2 & \sigma_{y_t x_t} & 0 & 0 \\ \sigma_{y_t x_t} & \sigma_{x_t}^2 & 0 & 0 \\ 0 & 0 & \sigma_{y_{t+\Delta t}}^2 & \sigma_{y_{t+\Delta t} x_{t+\Delta t}} \\ 0 & 0 & \sigma_{y_{t+\Delta t} x_{t+\Delta t}} & \sigma_{x_{t+\Delta t}}^2 \end{bmatrix}. \tag{10}$$

The displacement of point T may be evaluated as

$$d = \sqrt{\Delta y^2 + \Delta x^2} = \sqrt{(y_{t+\Delta t} - y_t)^2 + (x_{t+\Delta t} - x_t)^2}\ . \tag{11}$$

Further on, the displacement variance is determined by

$$\sigma_d^2 = \mathbf{J}_d \boldsymbol{\Sigma}_{T_t T_{t+\Delta t}} \mathbf{J}_d^T, \tag{12}$$

where the Jacobi matrix $\mathbf{J}_d$ equals:

$$\mathbf{J}_d = \begin{bmatrix} \dfrac{\partial d}{\partial y_t} & \dfrac{\partial d}{\partial x_t} & \dfrac{\partial d}{\partial y_{t+\Delta t}} & \dfrac{\partial d}{\partial x_{t+\Delta t}} \end{bmatrix} = \begin{bmatrix} -\dfrac{\Delta y}{d} & -\dfrac{\Delta x}{d} & \dfrac{\Delta y}{d} & \dfrac{\Delta x}{d} \end{bmatrix}. \tag{13}$$

By inserting Equations (10) and (13) into Equation (12) we get the representation for displacement variance of point T

$$\sigma_d^2 = \left(\frac{\Delta y}{d}\right)^2 \left(\sigma_{y_t}^2 + \sigma_{y_{t+\Delta t}}^2\right) + 2\frac{\Delta y}{d}\frac{\Delta x}{d}\left(\sigma_{y_t x_t} + \sigma_{y_{t+\Delta t} x_{t+\Delta t}}\right) + \ + \left(\frac{\Delta x}{d}\right)^2 \left(\sigma_{x_t}^2 + \sigma_{x_{t+\Delta t}}^2\right), \tag{14}$$

that is used for testing displacements by a test statistics given in Equation (15) and described in the next section.

2.4 Distribution function of test statistic by simulations

After adjusting at least two epochs it is possible to determine the displacement of point d according to Equation (11) and standard deviation of displacement σ_d according to Equation (14). Since these two parameters can be calculated prior to a detailed deformation analysis, they are rightly used in the statistical testing.

When estimating displacements, the test statistic is often calculated as:

$$T = \frac{d}{\sigma_d} \tag{15}$$

and compared to the critical value according to the chosen significance level α. Point displacements are established with an appropriate probability only when the displacements are significantly larger than the estimation accuracy of displacements.

Assuming that the errors of observations are distributed normally $\varepsilon \sim N(0, \sigma^2)$, then the parameters being the linear functions of the observations $\hat{\mathbf{x}} \sim N(\mu_{\hat{\mathbf{x}}}, \sigma_{\hat{\mathbf{x}}}^2)$ are distributed normally as well. The point displacement is calculated with Equation (11). Since Δy and Δx are calculated as the difference of two normally distributed random unknowns, Δy and Δx

are distributed normally, too. This, however, is not the case for the point displacement d, which is a nonlinear function of Δy and Δx. Consequently, it is difficult to analytically determine the form and the type of the distribution of the test statistic (15). The distribution function for the discussed test statistic is therefore determined by simulations, see Rubinstein (1981).
The coordinate differences Δy and Δx are normally distributed random variables with variance-covariance matrix as follows:

$$\mathbf{\Sigma} = \begin{bmatrix} \sigma_{\Delta y}^2 & \sigma_{\Delta y \Delta x} \\ \sigma_{\Delta y \Delta x} & \sigma_{\Delta x}^2 \end{bmatrix} . \tag{16}$$

The standard deviations of coordinate differences in two epochs are calculated as

$$\sigma_{\Delta y} = \sqrt{\sigma_{y_t}^2 + \sigma_{y_{t+\Delta t}}^2}, \quad \sigma_{\Delta x} = \sqrt{\sigma_{x_t}^2 + \sigma_{x_{t+\Delta t}}^2} , \tag{17}$$

where $\sigma_{y_t}^2, \sigma_{y_{t+\Delta t}}^2, \sigma_{x_t}^2, \sigma_{x_{t+\Delta t}}^2$ are coordinate variances of $y_t, y_{t+\Delta t}, x_t, x_{t+\Delta t}$. The covariance is calculated as:

$$\sigma_{\Delta y \Delta x} = \sigma_{y_t x_t} + \sigma_{y_{t+\Delta t} x_{t+\Delta t}} , \tag{18}$$

where $\sigma_{y_t x_t}$ and $\sigma_{y_{t+\Delta t} x_{t+\Delta t}}$ are covariances of the coordinates in both epochs.
To generate the sample of the normally distributed random variables, the Box and Müller approach was applied (Box & Müller, 1985; Press et al., 1992). The basic idea of generating a sample of dependent normally distributed random variables is to generate a sample of *independent* normally distributed random variables and then use a linear transformation to obtain a sample of *dependent* random variables. Let us assume that u_{1i} and u_{2i}, $i = 1,\ldots,n$ are samples of two independent and uniformly distributed random variables U_1 and U_2, and n is the number of simulations. The sample of two independent normally distributed random variables Z_1 and Z_2 is calculated as follows:

$$\mathbf{z}_i = \begin{bmatrix} z_{1i} \\ z_{2i} \end{bmatrix} = \begin{bmatrix} \sqrt{-2\ln u_{1i}}\,\sin(2\pi\, u_{2i}) \\ \sqrt{-2\ln u_{1i}}\,\cos(2\pi\, u_{2i}) \end{bmatrix}, \; i = 1,\ldots,n . \tag{19}$$

To generate a sample of dependent normally distributed random variables, a linear transformation is needed. The variance-covariance matrix $\mathbf{\Sigma}$ is decomposed by Cholesky decomposition

$$\mathbf{\Sigma} = \mathbf{U}^T \mathbf{U} . \tag{20}$$

In our case $\mathbf{U}$ takes the following form

$$\mathbf{U} = \begin{bmatrix} \sigma_{\Delta y} & \dfrac{\sigma_{\Delta y \Delta x}}{\sigma_{\Delta y}} \\ 0 & \sigma_{\Delta x}\sqrt{1 - \left(\dfrac{\sigma_{\Delta y \Delta x}}{\sigma_{\Delta y}\sigma_{\Delta x}} \right)^2} \end{bmatrix} . \tag{21}$$

For the transformation of a sample of independent normally distributed random variables to a sample of dependent random variables the linear transformation

$$\mathbf{y}_i = \mathbf{U}^T \mathbf{z}_i \ , \quad i = 1,\dots,n \tag{22}$$

is used.
In our case the coordinate differences are generated by the following equations

$$\begin{aligned} \Delta y_i &= z_{1i}\sigma_{\Delta y} \ , \\ \Delta x_i &= z_{1i}\frac{\sigma_{\Delta y \Delta x}}{\sigma_{\Delta y}} + z_{2i}\sigma_{\Delta x}\sqrt{1-\left(\frac{\sigma_{\Delta y \Delta x}}{\sigma_{\Delta y}\sigma_{\Delta x}}\right)^2} \ , \end{aligned} \tag{23}$$

where it is assumed that the means of Δy and Δx are zero ($\mu_{\Delta y} = \mu_{\Delta x} = 0$) and $i = 1,\dots,n$. The standard deviations of point coordinates in respective epochs vary from point to point. Therefore, the distribution function of the test statistic (15) takes on a different form for each point in each of the two epochs. By using the simulated normally distributed random variables (23), d is calculated using equation (11) and σ_d using equation (14). Consequently, in n simulations this procedure allows us to determine the empirical cumulative probability distribution function of the test statistic (15) for individual points.

2.4.1 Critical value T_{crit} and actual risk α_T

Critical value T_{crit} and actual risk α_T are determined from the obtained empirical cumulative distribution function by the following procedure (Savšek-Safić et al., 2006):

1. *generate coordinate differences* Δy_i, Δx_i; $i = 1,\dots,n$; Equation (23)
2. *calculate displacement* d_i; Equation (11), its standard deviation σ_{d_i}; Equation (14) and test statistic T_i; $i = 1,\dots,n$; Equation (15)
3. *form empirical cumulative probability distribution function* F_T^* by sorting T_i; $F_T^*(T_i) = \dfrac{i}{n}$; $T_i \le T_{i+1}$
4. *determine critical value* T_{crit} from F_T^*: $T_{crit} = T_{i=[(1-\alpha)\,n]}$ or
5. *determine actual risk* α_T from F_T^*: $\alpha_T = 1 - \dfrac{i}{n}$ for such *i* that $\min T_i > T$.

The test statistic is then tested according to the given null hypothesis and its alternative hypothesis:
H_0 : $d = 0$; the point is stable between two epochs, and
H_a : $d \neq 0$; the point has changed its position.
The test statistic (15) is compared to the critical value acquired from empirical cumulative distribution function. If the test statistic value is smaller than the critical value at a chosen significance level α , then the risk of rejecting the true null hypothesis is too high. Accordingly, it is established that the displacement is not statistically significant. If the test statistic value exceeds the critical value, the risk of rejecting the true null hypothesis is lower than the chosen significance level α . Therefore, the null hypothesis is rightly rejected and the statistical significance of the displacement is thereby confirmed.

This decision is supported by calculating the actual risk α_T of rejecting the true null hypothesis (the probability of committing *Type I Error*). Two possibilities are examined:

- $T > T_{crit}$ i.e. $\alpha_T < \alpha$: the null hypothesis is rejected; the point displacement is statistically significant and
- $T < T_{crit}$ i.e. $\alpha_T > \alpha$: the null hypothesis is not rejected; the point displacement is statistically insignificant.

Regarding the actual risk and the consequences of making a wrong decision, it is up to the user to decide upon the risk level of acceptability. As a consequence, a point is considered as stable or displaced.

3. Significant displacement testing in a test network

3.1 The network shape

3.1.1 The Krško network

The Sava River dam was built to ensure the minimum Sava River water level and thus enable the water pumping for cooling. The dam has six 15 m wide spillways. To ensure earthquake stability the dam is split into two large concrete frame structures. The structure height is 15.5 m and is therefore considered as large dam according to international standards, and needs to be technically monitored. 7 control points have been stabilised on the dam to determine horizontal displacements. Along the outlet, there were 5 reference observation points stabilised with concrete pillars (Figure 4).

3.1.2 The Libna network

The Libna network is classical terrestrial trigonometric net applied for the determination of local horizontal stability along the Orlica fault. The network's shape is that of an irregular pentangle with five circumferential points, where point 6 is a linking point amplifying the network reliability (Figure 6). The points represent the geometrical basis for determining the positions of four ground points defined on the basis of geologic situation. Basically, the ground points are ex-centre points of four points of the net.

The network size is described by indicating the area of the circumferential points of a polygon, amounting to approx. 4.27 ha. The longest length in the network is 385 m, the shortest length is less than 40 m. The network of the town of Libna in the vicinity of Krško was set up to determine point stability at the Orlica fault.

3.2 Stabilization of the ground points

3.2.1 The Krško network

The reference points of the base network for the performance of measurements are stabilised with concrete pillars, representing the conventional stabilisation of geodetic points for deformation measurements. The chosen stabilisation enables forced centring of the instrument and the reflector – *Leica Wild* system.

The stabilisation of control points on the dam also enables forced centring of the reflector – *Leica Wild* system. The control points were screwed into the concrete base, where the footplate can be fitted with the prism mount, which, in turn, enables horizontal alignment. Figure 1 shows the stabilisation and signalisation of the reference and control points.

Fig. 1. Stabilisation and signalisation of the reference and control points

3.2.2 The Libna network

The measuring points were determined by a set of two physically stabilised points. The measuring points, onto which the reflector was forced-centred, presented the points monitored for displacements. In all measurement epochs we used the same reflectors - Kern ME 5000. All the measurements were carried out on the points that were – according to the reference measuring points – set up ex-centrally. The term ex-central stand was introduced. The distance from the ex-centre to the centre point was 10 – 20 m (Figure 2).
The reference points were stabilised by combining the methods described above (Figure 3). However, the implementation was simplified and the costs were lower. A mass-produced concrete tube with Φ = 0.25 m in diameter and 1 m length was used. A hole of the same diameter was drilled into the pillar, and a concrete tube was put into the hole. The tube was filled in with concrete and a device for forced-centring was built in. The cylinder top was covered with a mass-produced cover for full protection.

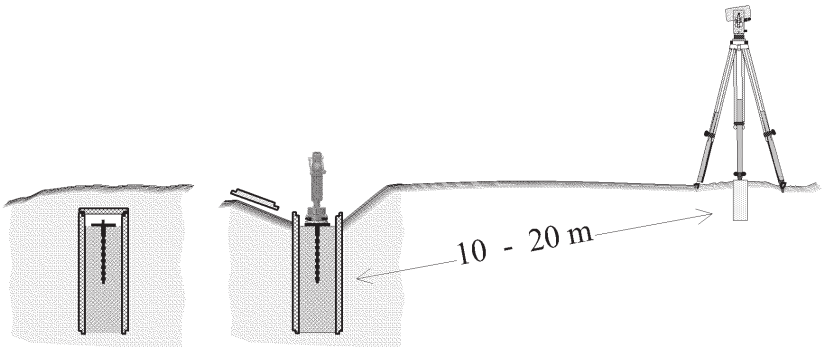


Fig. 2. Ground stabilisation of the centre and the ex-central stand

Fig. 3. Signalisation of the centre and the ex-central stand

The instrument stand was stabilised with the usual ground stabilisation by means of a concrete square stone with a built-in plug. Above the instrument stand, a tripod was set-up, centred and levelled. The centring accuracy did not influence the end results, since the co-ordinates of the measuring point onto which the reflector was forced-centred were of crucial importance, not the co-ordinates of the instrument stand. However, the tripod's stability during the measurements was essential.

The procedure of ensuring the appropriate network geometry and required precision for the determination of the horizontal coordinates of points in this way is theoretically and practically described in the article (Kogoj, 2004).

3.3 History of measurements and measuring accuracy

3.3.1 The Krško network

Due to the changed measuring instrument, in 2004 also the method of measurements based on simulation of observations was changed in the combined Krško micro network. We chose a combination of triangulation and trilateration, which provides a larger number of redundant observations. Since periodic measurements of the dam are foreseen twice a year (in spring and in autumn), so far 14 independent measurements have been conducted.

In the Krško micro trigonometric network the classic terrestrial surveying was chosen. The measurements were performed with the precision of electronic total station *Leica Geosystems TC2003* intended for precise angle and distance measurements in precision terrestrial geodetic networks (Savšek-Safić et al., 2007). Measuring accuracy for angle measurements is $\sigma_{DIN18723\text{-}Theo\ (Hz\text{-}V)}$ = 0.5" and for distance measurements σ_S : 1 mm; 1 ppm. Forced centring of the instrument, signalisation of measuring points and measurement of meteorological parameters were performed by tested and calibrated supplementary equipment (reflectors, footplate with reflector mounts, psychrometer, barometer). The first measurement in 2009 was due to changed instrument performed by precise electronic tachymeter *Leica Geosystems TCRP 1201.* Measuring accuracy for angle measurements is $\sigma_{DIN18723\text{-}Theo\ (Hz\text{-}V)}$ = 1.0" and for distance measurements σ_S : 2 mm; 2 ppm. In the same year we bought the most advanced electronic tachymeter by the manufacturer *Leica Geosystems TS30*, with which we performed

the last three measurements. The measuring accuracy for angle measurements is $\sigma_{DIN18723\text{-}Theo\ (Hz\text{-}V)} = 0.5''$ and for distance measurements σ_S : 0,6 mm; 1 ppm.
The measuring accuracy was determined on the basis of *Ebner' s* method of the a–posteriori weight determination (Vodopivec & Kogoj, 1997). The results included position accuracy and are given in Table 1.

Epoch	σ_a ["]	σ_s [mm]
August 2004	1.51	0.33
December 2004	1.89	0.23
August 2005	1.35	0.32
November 2005	2.96	0.37
July 2006	2.34	0.40
November 2006	1.23	0.15
May 2007	1.71	0.23
October 2007	2.05	0.32
April 2008	1.88	0.43
September 2008	1.60	0.37
May 2009	0.53	0.21
September 2009	0.80	0.27
May 2010	0.48	0.27
October 2010	0.53	0.10

Table 1. Measuring accuracy achieved in the Krško network

3.3.2 The Libna network

The Libna network was stabilised in 1998. So far, we have realised seven measurement epochs.
To determine horizontal coordinates of the net points, we used the combination of angle and distance measurements. The measuring method was a combination of triangulation and trilateration. In each epoch we realised measurements on all eccetrical stands.
We used the best instrumentation available. For the first six measuring epochs Electronic theodolite *Kern E2* was used for angle measurements. The instrument is one of the first most precise electronic theodolites of the first generation. Its construction and accuracy stability is excellent. The measuring accuracy defined on DIN standard procedure is $\sigma_{DIN18723\text{-}Theo\ (Hz\text{-}V)} = 0.5''$ For distance measurements we used precise distancemeter *Kern Mekometer ME 5000*. This instrument was constructed in the 1980's but it has been so far considered as the most precise geodetic electrooptical distance meter in series production. Measuring accuracy is σ_S : 0.2 mm; 0.2 ppm.
In last two measuring epochs electronic total station *Leica Geosystems TC2003* was used. This instrument is designed for the most precise angle and distance measurements. With the selected additional accessories the highest accuracy can be achieved. The measuring accuracy for angle measurements is $\sigma_{DIN18723\text{-}Theo\ (Hz\text{-}V)} = 0.5''$ and for distance measurements σ_S : 1 mm; 1 ppm.
For temperature and humidity measurements we used 2 *precise psyhrometers*, and for air pressure measurements we used *digital barometer Paroscientific*, model 760-16B.

Similar as in the Krško network, the measuring accuracy was determined on the basis of *Ebner's* method of the a–posteriori weight determination (Vodopivec & Kogoj, 1997). The results included position accuracy and are given in Table 2.

Epoch	σ_a ["]	σ_s [mm]
November 1998	1.03	0.45
December 1999	0.53	0.23
December 2000	0.62	0.52
November 2001	1.81	0.60
March 2003	0.94	0.72
April 2005	1.09	0.31
February 2008	3.30	0.62

Table 2. Measuring accuracy achieved in the Libna network

3.4 Determination of point displacements
3.4.1 The Krško network

3.4.1.1 The adjustment

The geodetic datum of the horizontal network was determined by two given assumingly stable points – reference points O1 and O5. To preserve the identical network geometry, as well as measurement and observation methods, the reference points were first tested for stability. The comparison of changes in coordinates between the last campaigns indicated that pillars O1 and O5 were statistically stable. In this way, the determination of the datum in the network enabled us to determine the statistically significant displacements of control points with a higher probability (Savšek-Safić et al., 2007).
The horizontal coordinates were calculated into the existing local co-ordinate system of the network to the level of the lowest point (reference point O4). The observations were tested for the potential presence of gross error, following the Danish method. The input data for the horizontal adjustment were the reduced averages of three sets of angles and the slope distances reduced to the chosen level. The reduction of distances took into account the instrumental, meteorological, geometric and projection corrections (Kogoj, 2005). The zenith angles were observed to establish the height stability of the reference and control points. The observations in the horizontal network were adjusted following the method of indirect observations. First, the adjustment of the free network was performed, which gave us an unbiased estimate of observations (Figure 4). Then the S-transformation was used, where the geodetic datum was determined by two statistically stable reference points O1 and O5. The results of the horizontal adjustment are the most probable values of horizontal coordinates of measuring points in the local system with the corresponding accuracy estimates.

3.4.1.2 The displacements

In the area of NEK the horizontal stability of the Sava River dam was investigated based on fourteen consecutive epochs. In December 2003, the transition to a new way of measurements (measurement method, instrument, network geometry) and the determination of a new geodetic datum in the micro network of Krško enabled a higher reliability of the determination of statistically significant displacements. Based on an expert geological opinion we decided that the geodetic datum in the Krško network would be represented by two assumingly most stable reference points O1 and O5.

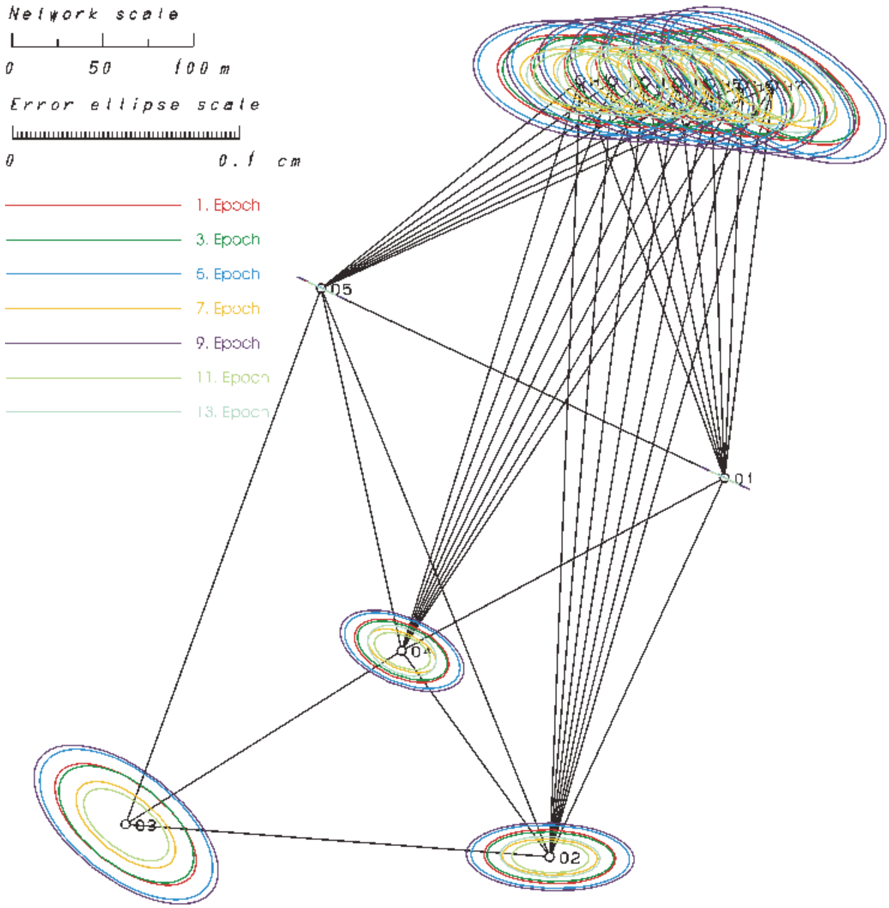
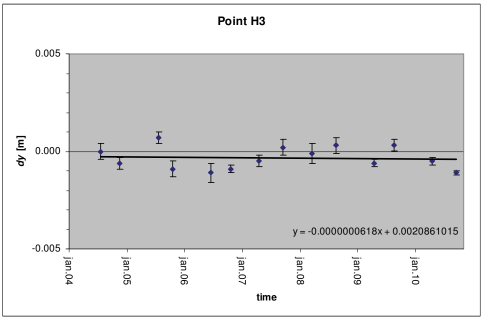


Fig. 4. Position accuracy for single epochs – Helmerts error ellipses - free net adjustment of the Krško network

After the adjustment of at least two epochs, it was possible to determine the displacement of point d and displacement variance σ_d^2. The probability function for the test statistic (15) was determined empirically with simulations, and then compared to the critical value considering the chosen significance level α. Displacements could be identified as statistically significant according to the distribution of test statistic and chosen significance level α. If the test statistic was smaller than the critical value at the chosen significance level α, we assumed that the displacement was statistically insignificant. If the test statistic is higher than the critical value, the hypothesis was justifiably rejected and we could confirm the statistical significance of the displacement. In Figure 5 the regression coefficient defines the displacement velocity in meters per day with transformation S on points O1 and O5.



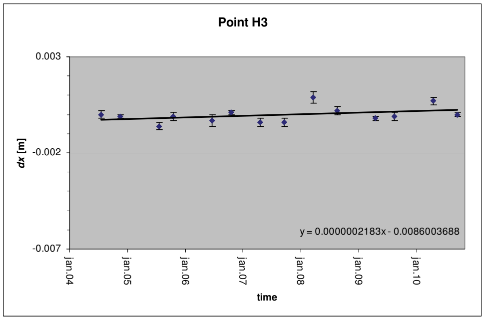


Fig. 5. The displacements of control point H3 in the directions of coordinate axes with the belonging standard deviations in time.

The time line of horizontal displacements of points on the Sava River dam was represented with the displacements of control points and the corresponding relative displacement ellipsoids referring to the two-epoch displacements. The relative displacement ellipsoids are calculated from the point determination accuracy in a single epoch.

3.4.2 The Libna network

3.4.2.1 The adjustment

For the adjustment we need mean values of six sets measured in horizontal directions. In each epoch a priori statistical analyses was made for the elimination of gross errors and for the computation of measuring accuracy.
The horizontal coordinates of net points are determined on the local level. We considered meteorological, geometrical and projectional reductions of measured distances (Kogoj, 2005). On the basis of measuring differences in both directions we also estimated the accuracy of the distances.
In zero epoch measurement the local datum of the net was determined. The orientation of the coordinate axes is nearly parallel with the Slovenian national Gauß-Krüger coordinate system.
The adjusted coordinates of ground points A, B C and D of zero epoch in 1998 are approximate coordinates for all other epochs. The definitive coordinates of points A, B, C and D for each epoch were determined on the basis of the adjustment process. We supposed that the accuracy of horizontal directions was the same for each instrumental standing point. The distances in the net were short. Based on this, we should determine the weights of the distances on the basis of only the constant part of the error. We always used the software GEM4 for simultaneous angle and distances network adjustment. The final results were the horizontal coordinates of the net points and the accuracy estimation (elements of error ellipses).
First we adjusted the net as a free network for all epochs. Based on the results we analysed the measuring accuracy and the position accuracy of the net points. The reason for this is that free network adjustment gives the most objective results of measuring accuracy because there is no influence of the datum parameter.
The following Figure 6 shows the size of the semi-major axis of the error ellipses (worst case), obtained in each epoch. Comparison of the absolute values of the ellipses is due to

high precision level questionable. The increase in value from 0.2 mm to 0.3 mm means a loss of numerical precision of about 50%. From geodetic point of view we know that between these values there are practically no differences!

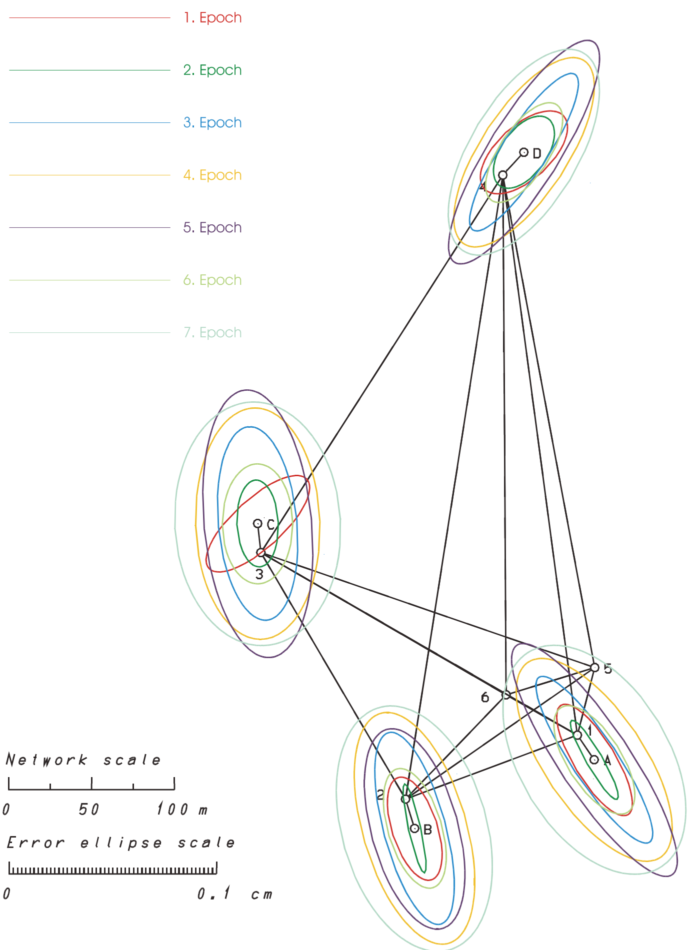


Fig. 6. Position accuracy for single epochs – Helmerts error ellipses - free net adjustment of the Libna network

3.4.2.2 The displacements

The main problem in the displacement determination process is the choice of stable points. The defect of the geodetic datum was 3, so we needed at least one and a half given points. On the basis of geological situation there were two logical possibilities. We could choose points A and B or C and D.
The differences of the coordinate values of points A and B between single epochs were minimal. We once again adjusted each epoch on four different datums of the net. The main conclusions, based on the results, are:

- the size of proven displacements on points C and D are practical invariants on the datum of the net based on points A and B,
- from the aspect of minimal influence of the accuracy of given points on the final parameters of displacement vectors the best choice is the determination of the datum based on the S-transformation.

We used our own software Premik. The elements of the displacement vectors for all epochs combinations were calculated.
In further analyses we computed the displacement velocity. The displacement velocities of points C and D in y and x directions with standard deviations determined on the basis of the S-transformation on points A and B are computed on the basis of linear regression analyses. We used the same procedure also for the determination of the datum on the basis of points C and D. In Figure 7 the regression coefficient defines the displacement velocity in meters per day with the S-transformation on points C and D.

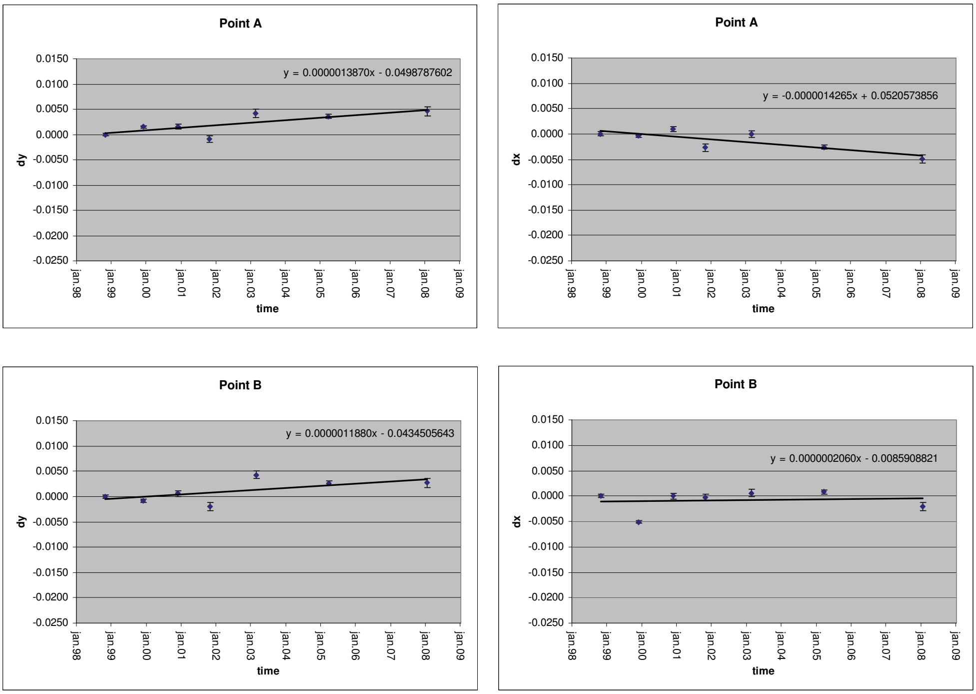


Fig. 7. The displacements of points A and B in the directions of coordinate axes with the belonging standard deviations in time.

4. Conclusion

A contractor of geodetic works is expected to present not only data on point displacements, but also to provide assurance in terms of the quality of displacement estimation. In addition to the assumed null hypothesis $H_0 : d = 0$ and the chosen significance level α, the actual risk of rejecting the true null hypothesis is crucial. The participation of the commissioning party in the process of evaluating the estimated displacements is highly recommended. The decision upon risk acceptability is then in the hands of the commissioner.

The Sava River dam has a specific place among the NEK buildings, since it is subjected to the great force of the Sava River flow and to the differences in filling and emptying of the reservoir, i.e. the difference between high flow and low flow. Periodically larger displacements of the entire dam are to be expected.

The Libna network was stabilised in such way that two points are located on one and two points on the other side of the fault. The purpose of several years of continuous measurements was to determine tectonic activities of the fault in question.

Due to expected small displacements in both networks we were mainly focused on:

- precise ground stabilisation (example Libna) or concrete observation pillars (example Krško), which allows forced centering of the instrument or reflector;
- use of precise measuring instruments and additional measuring equipment;
- meeting the condition of as large number of redundant observations as possible to assure quality measurements and results;
- consideration of all influences on the measured quantities;
- analysis of the precision of measurements and detection of any major errors (outliers) in the measurements;
- transformation of adjusted coordinate points into geodetic datum of assumingly stable points, where the displacement of other points can be measured.

As shown, test statistic (15) along with the empirical cumulative distribution function is appropriate tools for testing the significance of point displacements in a geodetic network. Since the displacement and its respective accuracy are acquired by a simple method, the suggested procedure is appropriate and provides good results that furnish a good first estimate of the situation in the discussed network. The test example illustrates that the estimation of displacement significance is directly dependent upon the critical value at a chosen significance level α . Accurate displacement estimation is achieved only if the critical value is determined according to the actual distribution function of the test statistic. Having in mind the difficulty level of the assignment and its consequences, the decision must be made whether there is the need for a detailed deformation analysis to be carried out using one of the known approaches.

5. Acknowledgment

We gratefully acknowledge the help of the company IBE d.o.o., specifically Mr. Božo Kogovšek, the expert responsible for the NEK technical monitoring.

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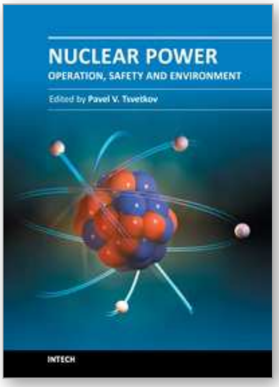

Nuclear Power - Operation, Safety and Environment
Edited by Dr. Pavel Tsvetkov

ISBN 978-953-307-507-5
Hard cover, 368 pages
Publisher InTech
Published online 06, September, 2011
Published in print edition September, 2011

Todayâ€™s nuclear reactors are safe and highly efficient energy systems that offer electricity and a multitude of co-generation energy products ranging from potable water to heat for industrial applications. At the same time, catastrophic earthquake and tsunami events in Japan resulted in the nuclear accident that forced us to rethink our approach to nuclear safety, design requirements and facilitated growing interests in advanced nuclear energy systems, next generation nuclear reactors, which are inherently capable to withstand natural disasters and avoid catastrophic consequences without any environmental impact. This book is one in a series of books on nuclear power published by InTech. Under the single-volume cover, we put together such topics as operation, safety, environment and radiation effects. The book is not offering a comprehensive coverage of the material in each area. Instead, selected themes are highlighted by authors of individual chapters representing contemporary interests worldwide. With all diversity of topics in 16 chapters, the integrated system analysis approach of nuclear power operation, safety and environment is the common thread. The goal of the book is to bring nuclear power to our readers as one of the promising energy sources that has a unique potential to meet energy demands with minimized environmental impact, near-zero carbon footprint, and competitive economics via robust potential applications. The book targets everyone as its potential readership groups - students, researchers and practitioners - who are interested to learn about nuclear power.

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In order to correctly reference this scholarly work, feel free to copy and paste the following:

S. Savšek, T. Ambrožič and D. Kogoj (2011). Geodetic Terrestrial Observations for the Determination of the Stability in the Krško Nuclear Power Plant Region, Nuclear Power - Operation, Safety and Environment, Dr. Pavel Tsvetkov (Ed.), ISBN: 978-953-307-507-5, InTech, Available from: http://www.intechopen.com/books/nuclear-power-operation-safety-and-environment/geodetic-terrestrial-observations-for-the-determination-of-the-stability-in-the-krs-ko-nuclear-power

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