GNSS MONITORING GEOLO-ŠKO ZAHTEVNIH OBMOČIJ

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Ključne besede

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Izvleček

Spremljanje pomikov s pomočjo tridimenzionalnih globalnih navigacijskih satelitskih metod (GNSS), ki so del geodetskih metod, postajajo ključne preiskave pri ugotavljanju modelov vzrokov in posledic med zunanjimi naravnimi vplivi na eni in kriteriji, ki opisujejo nivo funkcionalnosti in varnosti naravnega ali zgrajenega objekta na drugi strani v primerih pomikov v prostoru in času.

Glavni cilj deformacijske analize je potrditi stabilnost referenčnih točk geodetske mreže. Uporablja se za določitev pomikov kontrolnih točk, ki so stabilizirane na opazovanem objektu. Domneva o stabilnosti določenih referenčnih točk mora temeljiti na trdnih dokazih skozi meritve in biti potrjena skozi numerične metode. To je en del deformacijske analize; takrat ko določamo vrednosti pomikov in deformacij. Za to je potrebna transformacija, pri kateri se izvede primerjava med koordinatami istih točk v dveh različnih časovnih epohah. Na osnovi ocenjenih transformacijskih parametrov se lahko sklepa o možnih pomikih znotraj referenčnih točk še posebej ali so se spremenili datumski parametri. Po potrditvi stabilnosti geodetske mreže se lahko določijo koordinatne razlike identičnih točk merjenih v različnih časovnih okvirjih, ki se lahko nato opredelijo kot pomiki in/ali deformacije opazovanega objekta. V članku je podana ocena viadukta glede na geologijo in tektonske aktivnosti pa tudi glede na izveden obremenilni preizkus. Viadukt je lociran na precej aktivnem območju, obremenilni preizkus pa je pokazal, da se objekt na zunanjo obtežbo obnaša v skladu s pričakovanji.

GNSS MONITORING OF GEOLOGICALLY DEMANDING AREAS

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Abstract

Displacement research using the three-dimensional global navigation satellite system (GNSS) as part of geodetic monitoring is becoming the key investigation for establishing a cause-and-effect relationships model between external natural factors, on the one hand, and the criteria that describes the level of functionality and safety of the observed natural or artificial object, on the other, in cases of motion of an object in space and time. The main objective of the deformation analysis is to confirm the stabilities of the reference points of a geodetic network, which are used to determine the movements of the control points that are stabilized on the observed objects. The assumption about the stabilities of certain reference points must be based on reasonable grounds, underpinned by measurements and proven by numerical methods. This is one part of the results of the deformation analysis when determining the extent of the movements and deformations. To do this a transformation is used in which a comparison is made between the coordinates of the points for two separate epochs. On the basis of the estimated transformation parameters, possible movements can be concluded within the reference points, i.e., on whether the datum parameters have changed. After confirming the stability of the geodetic network the coordinate differences of identical points measured within the different time windows can be determined as displacements and/or deformations of an object. In this paper one viaduct was assessed through geology and tectonic activities and also a load test of the viaduct was performed. The viaduct is in a quite active region, but the load test showed that the bridge response to the load is as expected.

1 INTRODUCTION

Facilities that are usually the main issue within the context of deformation monitoring are often only an indirect indicator of the dynamic processes associated with the earth's surface and subsurface. Artificial structures are now being built from materials and in ways that tend to reduce the effects of the deformation of nature rather than to create the stress. Therefore, the primary task of deformation monitoring is to determine the stabilities of the areas of land before the construction.

The stability of a surface is related to the degree of slip and the landslide of rocks under the surface as well as the tectonic shifts deeper into the ground. Therefore, the necessary work prior to the commencement of constructing geotechnical structures, geological and tectonic investigations must be carried out, which frequently replaces the deformation monitoring and which focuses exclusively on the surface changes, and so are not launched

before, but possibly after the start, and most often at the completion, of the construction. The reasons for such an inconsistent sequence of events are usually economic. Landslides usually show themselves at an inclined position or orientation of the object, which may be:

– newly created changes that have not shown any signs of unexpected tilting in the past,
– changes due to a currently active landslide,
– the result of a proximity to areas with existing geodynamic events.

The objective of deformation monitoring is to determine facts about the stability of the observed object or the earth's surface in terms of the sizes of movements at certain points. In addition to stability, the importance of determining movements is in the evaluations of potential risks of built and natural objects to the environment and in particular to human life and its property. Therefore, determining the movements or deformations of natural and man-made structures is one of the more engaging and more demanding tasks of geodesy.

Deformation monitoring covers several temporal segments in terms of defining movements [1]:

– at the time before the appearance of natural forces that cause favourable conditions for the emergence of movements,

– during the operation of natural forces or the construction operation that realize movements of natural or man-made structures,
– completion of the construction operation, which also establish their long-term trends of movement for objects within a given area,
– when the natural forces end, i.e., during the straight influence of natural forces on the construction work, causing a relative annihilation of shifts or changes in the occurrences of the stagnations of these movements.

Deformation monitoring also covers several spatial segments in terms of determining movements:

– at the sites of the very origins of the phenomena of natural forces,
– at the place of the effective influence of natural forces or in the immediate vicinity of the facility itself,
– at all perceptual areas of influence of the natural forces,
– in places that are relatively stable
– indirectly also in areas that are absolutely stable.

Because of the fact that there are no absolutely stable points, especially on the earth's surface, the determination of displacements and deformations is virtually present in all scientific disciplines that in one way or another are related to the physical environment. The position
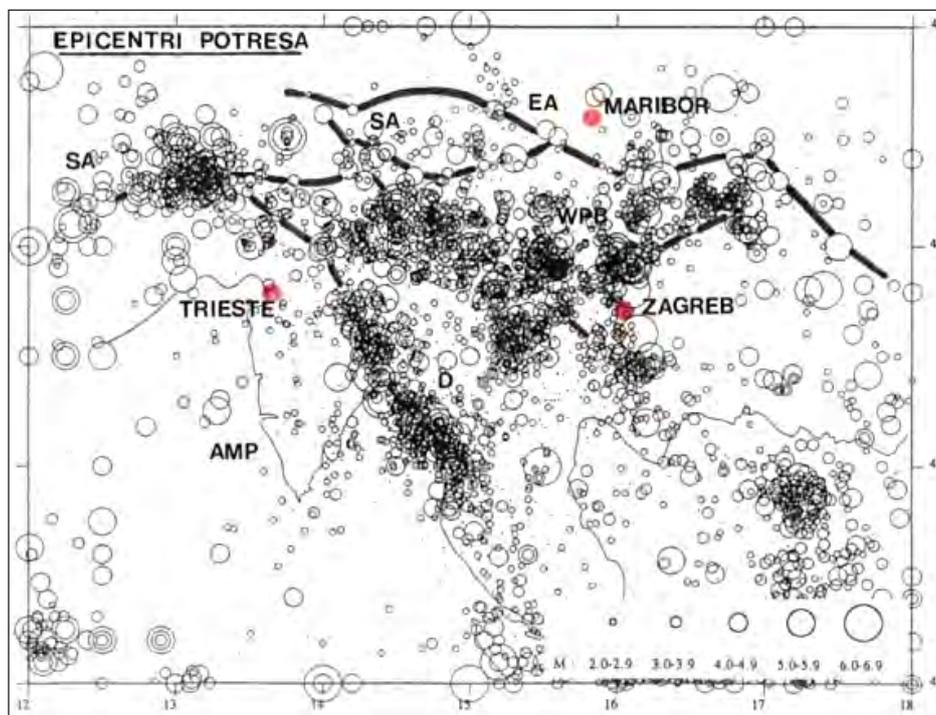

Figure 1. Earthquakes epicentres.

for determining movements when detecting landslides is determined by geomechanics in cooperation with surveyors to assess the suitability of the position due to the satellite's signal strength for deformation monitoring when using GNSS methods.

In order to collect the necessary data about the location of a viaduct, a detailed structural-geological mapping was needed. Thus, the most important structural data on the dynamics of a recent structural assembly was obtained and a series of outcrops of faults was discovered. The required measurements of the structural elements, which indicate the particular type, origin and location of faults in the structural part, were conducted, and the side faults of the movement and the related stress and deformation structures were found. Strict regulations of the position and the mutual relations of faults led to a study of additional satellite images. The collected data emphasize the determination of compression stress, its orientation and the angle of action. At each point of the measurement the orientation of the local compression stress is determined. Such a stress causes the deformation of parts of the structures. The orientation of the maximum compression stress is determined from several data. The maximum compression stress directly reveals the basic structural relationships, in fact the positions and movements of the complex of rock walls of different densities that forms the structural set.

Fig. 1 shows significant concentrations of epicentres in the peripheral parts of the Alps and the Dinarides and in the western part of the Pannonian Basin. The strongest earthquakes occur in the western part of the Southern Alps, in the northern part of the Dinarides and in the border region of the western and southern parts of the Pannonian Basin. Detailed locations of the epicentres sorted by magnitudes are shown in Fig. 2.

2 MONITORING WITH THE GNSS METHOD

In engineering practice, for monitoring the deformation of large structures (bridges, viaducts, hydro power plants, etc.), the technology of GNSS is generally used [2-6]. The method is also widely used for monitoring landslides [7-19]. Recently, the state geodynamic network is also more or less observed using this technology. Although GNSS allows positioning with an accuracy that is comparable to conventional methods, its use was restricted due to the need for observations of excessive length. With the development of instruments and, in particular, software, the observation time for the GNSS method was substantially reduced so that millimetre positioning can be obtained after less than 1 hour of observation. However, due to the elimination of the global movement of ground water and land masses
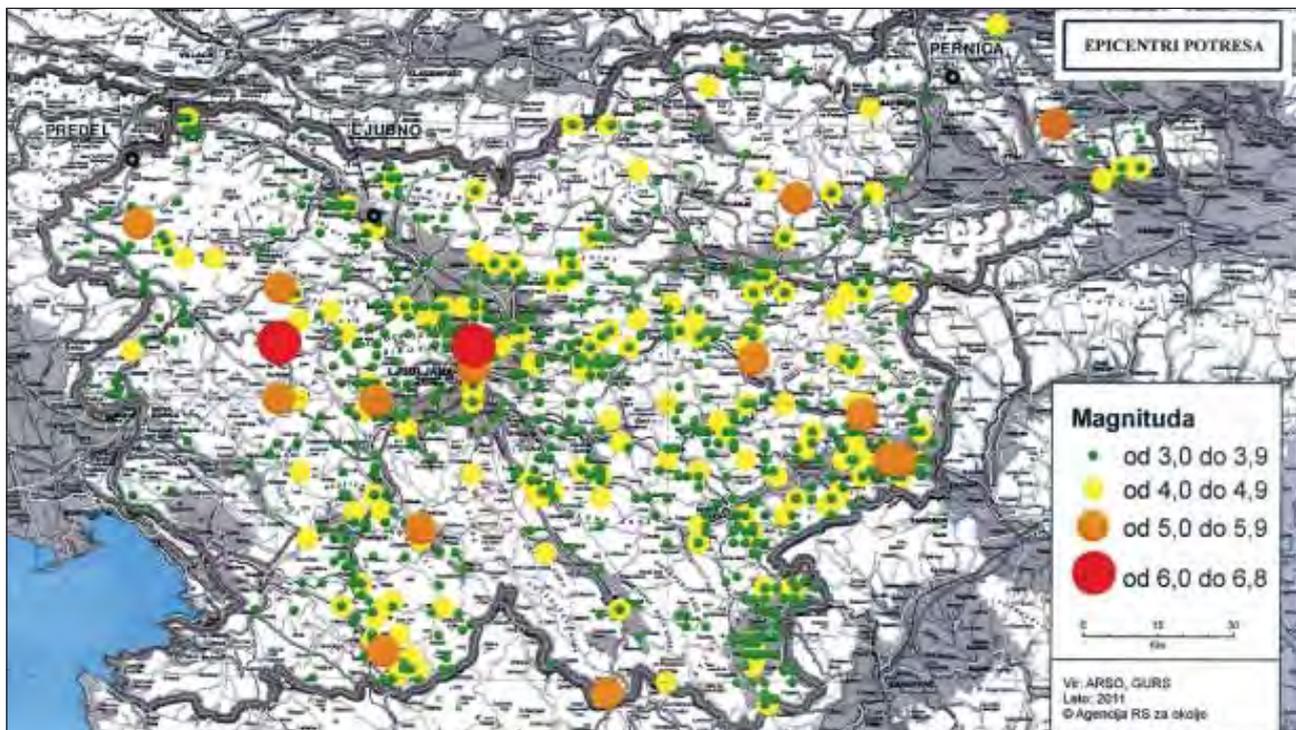

Figure 2. Earthquakes epicentres in Slovenia with the magnitudes (ARSO, GURS, 2011).

for the most accurate deformation analysis, longer times, which should last at least 24 hours, are recommended. [20]

Depending on the types of observed quantities and the means of the data processing, several methods for determining positions using the GNSS method can be as follows: absolute, code differentiated and the relative phase-shift method. In addition to the classical kinematic and RTK (real time kinematics) methods there are also the VRS (Virtual Reference Station) and PPP (Precise Point Positioning) methods. The latter is the most accurate method for determining absolute position, which can be considered as static or kinematic. For the purposes of geodetic monitoring only the static mode is used, which gives us mm accuracy. [21]

Research over recent years has demonstrated the usefulness of GNSS for a precise determination of three-dimensional positions for controlling dangerous natural phenomena. A detailed analysis of the dynamics of avalanches, especially for the purpose of installing a security system (functioning in real time), requires a combination of accurate positioning in three dimensions (a few mm) and a good time resolution (less than 1 hour). Monitoring landslides with the GNSS technique is usually used in several epochs, as a complement to conventional methods. For quality monitoring of the implementation of GNSS method it is necessary to determine the period of the time observations. Only in this way can a precision of one to two millimetres be obtained.

However, all the GNSS methods are based on the same geometric principle, i.e., that the position of a point in space is determined by the intersections of at least four
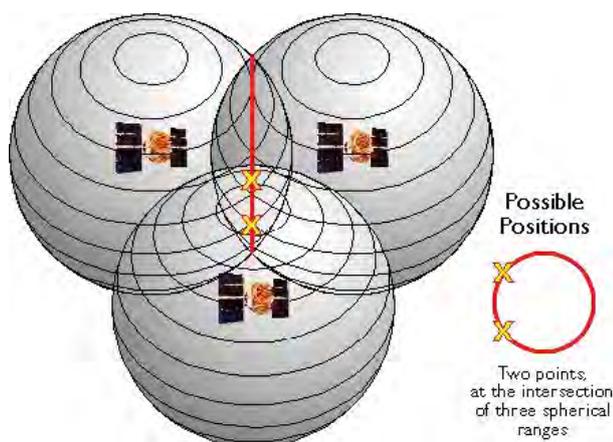

Figure 3. Two possible positions from observations from three satellites (https://www.e-education.psu.edu/natureofgeo-info/book/export/html/1796).

spheres, whose radii represent the measured distance to the point of interest from these four points. These four points are satellites around the Earth (Fig. 3). The principle is similar to terestic trilateration: by the laws of plane geometry the position of new points can be obtained from the circle intersections, where the values of the radii are derived from distance measurements and the centres of the circles represent the positions of the instrument standing points, from which the distances are measured. In principle three measured distances (receiver–satellite) should be enough, but it is necessary to obtain a reference to at least 4 different satellites due to satellite and Earth movements and thus difficulties in determining the exact clock situation at the time of the transmission and reception of signals. Indeed, determining the timing of a received signal requires an extremely accurate clock in the receiver. These requirements may be minimized by using a time signal from the fourth satellite because only then can the difference between the times of the receptions signals from the individual satellites be measured.

3   MEASUREMENT ACCURACIES

The GNSS method is a fairly new method that brings a lot of advantages over conventional methods. The positioning accuracy or determining the relative coordinates of a point with this method depends largely on the deployment of the satellites during the measurement and the quality of the performances of the observations. The accuracy could be easily described through evaluating the effects that cause errors in the measurement.

The main sources of error that contaminate the data obtained by GNSS technology can be divided into three groups:

– Error of signal propagation, tropospheric and iono-spheric refraction, multipath (Fig. 4).
– Errors of the receiver: error during determination of the phase centre of the antenna, receiver system noise, neglected multipath effects, inaccurate coordinates of instrument standing point (known points),
– Errors in connection with the satellites: errors when determining the trajectories and positions of satellites.

If we succeed in minimizing the impacts or completely eliminate them during post processing then we can expect an accuracy of ± 2 mm in the horizontal direction and ± 3 mm in the vertical direction, of course for 24-hour observations.
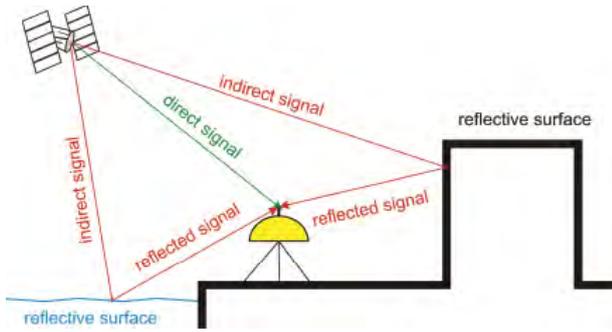
Figure 4. Signal multipath.

4 DETERMINING THE POSITION WITH GNSS OBSERVATIONS

On the basis of code or phase observations the absolute and relative positions of the GNSS receiver can be determined. The absolute position is determined only on the basis of the given positions of GNSS satellites in the selected coordinate system at the time of observation and with the observed distance between the satellite and the receiver. The relative position is determined relative to the known position of one or more points placed within the default coordinate system at the known satellite positions and the observed distance between the satellite and the receiver. Therefore, in both cases the basis for determining the position is the geometric distance between the satellite and the receiver. For this purpose, it is necessary to perform the linearization of the distance between the satellite and the receiver.

2.1 Linearization

Geometric distance $\rho_i^j(t)$ between the satellite j and the receiver i is:

$$\rho_i^j(t) = \sqrt{\left((X^j(t) - x_i)^2 + (Y^j(t) - y_i)^2 + (Z^j(t) - z_i)^2\right)}$$
$$\equiv f(x_i, y_i, z_i) \tag{1}$$

The connection (1) between the geometric distance $\rho_i^j(t)$, the GNSS satellite position in the chosen coordinate system

$$r^j(t) = \left[(X^j(t), Y^j(t), Z^j(t)\right]^T \tag{2}$$

and the position of the GNSS receiver

$$r_i = \left[x_i, y_i, z_i\right]^T \tag{3}$$

is non-linear.

For the use of the geometric distance $\rho_i^j(t)$ in the linear mathematical model, the expression for geometric distance should be linearized. Knowing the approximate receiver position

$$r_{i0} = \left[(X_{i0}, Y_{i0}, Z_{i0}\right]^T \tag{4}$$

an approximate value for the geometric distance $\rho_{i0}^j(t)$ can be obtained using

$$\rho_{i0}^j(t) = \sqrt{\left((X^j(t) - x_{i0})^2 + (Y^j(t) - y_{i0})^2 + (Z^j(t) - z_{i0})^2\right)}$$
$$\equiv f(x_{i0}, y_{i0}, z_{i0}) \tag{5}$$

The receiver position $r_i = \left[(X_i, Y_i, Z_i\right]^T$ when the known approximate position $r_{i0} = \left[(X_{i0}, Y_{i0}, Z_{i0}\right]^T$ can be calculated using

$$r_i = r_{i0} + \Delta r_i \quad \text{or}$$
$$x_i = x_{i0} + \Delta x_i, \, y_i = y_{i0} + \Delta y_i, \, z_i = z_{i0} + \Delta z_i \tag{6}$$

Therefore, the receiver position r_i is obtained by adding the vector of the known approximate position r_{i0} and the vector of unknown correction of approximate position

$$\Delta r_i = \left[(\Delta x_i, \Delta y_i, \Delta z_i\right]^T \tag{7}$$

The function:

$$f(r_i) = f(x_i, y_i, z_i) \tag{8}$$

is replaced with the function

$$f(r_i + \Delta r_i) = f(x_i + \Delta x_i, y_i + \Delta y_i, z_i + \Delta z_i) \tag{9}$$

Function (9) can be developed in a Taylor series at the point of the approximate receiver position:

$$f(x_i, y_i, z_i) \equiv f(x_{i0} + \Delta x_i, y_{i0} + \Delta y_i, z_{i0} + \Delta z_i)$$
$$= f(x_{i0}, y_{i0}, z_{i0}) + \frac{\delta f(x_{i0}, y_{i0}, z_{i0})}{\delta x_{i0}} \Delta x_i + \frac{\delta f(x_{i0}, y_{i0}, z_{i0})}{\delta y_{i0}} \Delta y_i$$
$$+ \frac{\delta f(x_{i0}, y_{i0}, z_{i0})}{\delta z_{i0}} \Delta z_i \tag{10}$$

In the Taylor series we keep only those parts where the component of correction Δr_i for the approximate vector is present in the first potency, otherwise the previous equation would be non-linear again for the vector of correction Δr_i for the approximate position.

Partial derivatives for Equation (10) can be calculated using (5):

$$\frac{\delta f(x_{i0}, y_{i0}, z_{i0})}{\delta x_{i0}} = -\frac{X^j(t) - x_{i0}}{\rho_{i0}^j(t)}; \frac{\delta f(x_{i0}, y_{i0}, z_{i0})}{\delta y_{i0}} =$$
$$= -\frac{Y^j(t) - y_{i0}}{\rho_{i0}^j(t)}; \frac{\delta f(x_{i0}, y_{i0}, z_{i0})}{\delta z_{i0}} = -\frac{Z^j(t) - z_{i0}}{\rho_{i0}^j(t)} \tag{11}$$

The partial derivatives in Eq. (11) represent the components of a single vector, directed from the satellite to the approximate receiver position. Inserting Eq. (11) in Eq. (10) we obtain:

$$\rho_i^j(t) = \rho_{i0}^j(t) - \frac{X^j(t) - x_{i0}}{\rho_{i0}^j(t)}\Delta x_i - \frac{Y^j(t) - y_{i0}}{\rho_{i0}^j(t)}\Delta y_i$$
$$- \frac{Z^j(t) - z_{i0}}{\rho_{i0}^j(t)}\Delta z_i \qquad (12)$$

Eq. (12) presents a linear connection between the geometric distance between the satellite and receiver $\rho_i^j(t)$ and corrections of the approximate positions $\Delta x_i, \Delta y_i, \Delta z_i$. This connection represents the starting equation for obtaining the GNSS position of the receiver, using the observations of pseudo distances between the GNSS satellite and the GNSS receiver [22].

5 GNSS MEASUREMENTS FOR THE DEMANDING AREA OF THE RAZDRTO REGION

The modern technology of GNSS measurements allows us to carry out observations without taking into account some important factors that have guided the work of surveyors for decades. These are primarily the weather conditions and the mutual visibility of geodetic points within a network. Planning a survey today is slightly different and depends on the intended method of GNSS surveying, and it is necessary to provide: the purpose, aim and accuracy of the measurement, the number of new and reference points, the time planning of satellite positions, the number and types of receivers, the duration of the observation, and the post processing methods in order to present the results properly.

The slope hills of Nanos near Razdrto are geologically very demanding, because there are a few landslides affecting the highway and the viaducts. When making a GNSS network it is necessary to take into account the general requirements for the implementation of GNSS observations. In particular, unimpeded GNSS signal reception, which means that within the vicinities of the points there should not be any physical obstacles. Sometimes this is hard to provide. However, since the GNSS method does not require mutual visibility of the points, the standings for the GNSS receiver can be placed in more accessible areas. The point needed to be observed but there is no signal that can be replaced with classical geodetic measurements. We can use different types of antennas and receivers (Fig. 5 a, b, c, d), but it is necessary to use the same equipment at the same point during different time epochs.

Figure 5. a-d: Different types of antennas and receivers.

Before observations on the route of a highway 50 points for the GNSS measurements were permanently stabilized on structures (retaining walls, viaducts, or pile walls) and in their proximity within a triangular design (Fig 6). For stabilization, concrete pillars, castes and metal plates were installed on the objects for the observation. Figure 4 shows the disposition of the measurement points on the object and its surroundings. The red points are GNSS standing points for 24-hour static observations and the blue points are classical points for total station observations.
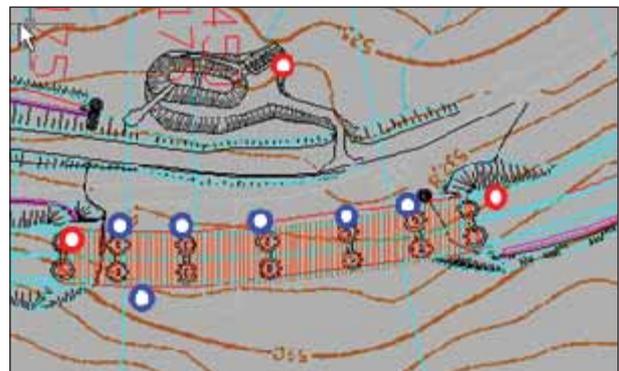

Figure 6. Example of different observation points on a viaduct.

Before the measurements, it was necessary to define the geodetic datum, which was provided with a set of given IGS points (International GNSS Service) that had known coordinates and speed vectors in the coordinate assembly ITRF2005 (International Terrestrial Reference Frame 2005) with high precision and accuracy. Further, four points of the Slovenian network of permanent stations of the SIGNAL (Slovenia Geodesy Navigation Area) were also taken in account during post processing, which is regarded as new point (with unknown coordinates). Points of the SIGNAL system have certain coordinates with lower accuracies so they could not be treated as given. SIGNAL points were selected so that they are the closest to the observed area, but none on the landslide area.

The post-processing of observations is carried out for each of the Julian day. Thus, it is necessary for each epoch to obtain two positions – two sets of coordinates for each point. On the basis of the differences in coordinates for each day the qualities of the observations and the post processing can be concluded.

The results of post-processing are the estimated coordinates of the points for each day with the corresponding accuracies. The accuracy assessment is based on these two variables since it represents a more realistic assessment of the accuracy. For each point obtained after post-processing in each epoch one set of coordinates in ITRF2005 coordinate system. Our goal is to present the coordinates of the points measured in each of the (new) state projections, i.e., the Transverse Mercator projection with corresponding accuracies. The transformation from ITRF2005 in the Slovenian state projection is carried out through the transformation to the ETRF89 coordinate assembly in which the positions are (depending on ITRF2005) reduced for movements of Eurasian tectonic plates. The positions in the ETRF89 points are then the basis for the conversion into the national cartographic projection.

It is assumed that the accuracies of the coordinates of points in the map projections and the precisions of geodetic coordinates in ITRF2005 are the same. Therefore, it is also assumed that with the transition to a state map projection (via ETRF89) the accuracies of the coordinates are not substantially altered. Table 1 shows some of the coordinates of the points on the Razdrto highway region in the Transverse Mercator projection with corresponding accuracies. The heights are "above sea level", which is obtained by ellipsoidal heights estimated via GNSS observations, reduced by the geoid height from the current geoid model of Slovenia. In Fig. 7, all the points are visible for that region.

Figure 7. 50 GNSS points on the Razdrto region.

Table 1. Measured coordinates and accuracies.

Point	Y [m]	Y [m]	H [m]	σ_Y [mm]	σ_X [mm]	σ_H [mm]
BAZ1	426090.0469	68720.5530	627.0367	1.85	0.87	1.93
BAZ2	418920.5057	77178.8702	112.9227	1.29	0.67	5.33
BO11	425303.9651	69705.3899	552.8670	1.74	3.06	4.38
BO13	425182.0177	69805.6379	545.7189	0.40	1.29	1.72
CER1	422999.0351	71962.3986	371.7237	0.98	1.11	1.20
CER2	423047.1678	71996.6312	385.2510	0.94	3.97	10.41
NPO2	422218.9394	72703.2487	333.3368	1.47	0.79	0.94
OZ41	420625.1227	74371.2769	250.1885	0.23	0.68	7.19
SUM1	424023.0656	70903.7784	455.9258	3.43	1.94	14.57
SUM2	423960.9856	70922.8898	429.2213	1.56	0.21	2.70
SUM3	423911.8404	71021.9010	439.5185	1.00	1.50	5.00
Z101	422617.1739	72155.0979	346.2361	1.46	1.32	2.15

From the table we can see that the data were captured with an accuracy of between 1 to 2 mm. At the points CER2 and SUM1 the determined positions were slightly less accurate because of the lower signal strength. This disadvantage was compensated for with conventional terestic measurements.

For any assessment of the possible movements of geodetic points it is necessary to determine the coordinates of points within several epochs. Based on a set of coordinates obtained in that way, it is necessary to assess the trends of potential changes in the coordinates of the points. The trends of coordinate changes can be well established only in the cases of quality coordinates or through high-quality time series of the coordinates of points. The graph below shows the changes in the coordinates of points in time for a one-year period for a point in Koper in the form of deviations from the mean of the individual coordinates for each point within the network. The coordinates in each epoch represent the deviations from this mean value with the specified standard deviation. The results are presented in graphical form (Fig. 8), where the positive axis ΔE represents the movements in an easterly direction, positive ΔN in the north and Δh in the vertical direction. Each vertical line represents the window within a certain epoch. If the mean value in every epoch is inter-connected, a line of movements can be obtained.

The changes of the coordinates of points can also be displayed in a plane map projection. Fig. 9 shows the estimated coordinates of the points for each epoch. However, according to the calculated standard deviations of the estimated coordinate points and methods used in the measurement points it is difficult to talk about the movements of points.
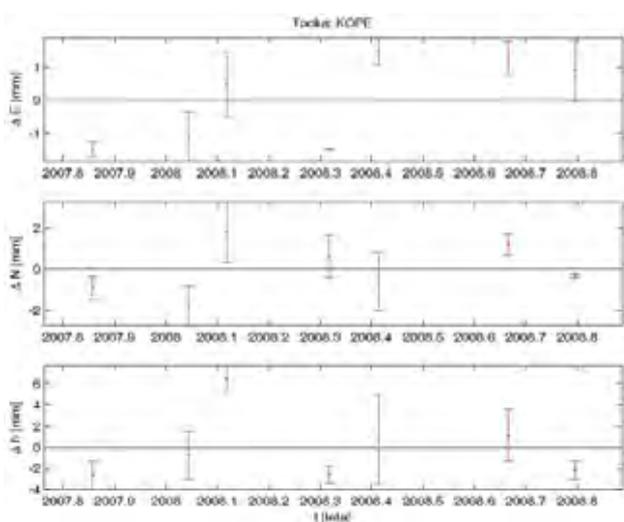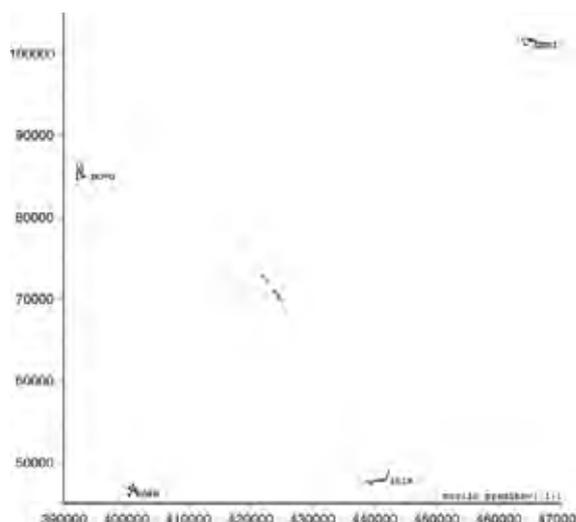

Figure 8. Coordinate differences over time.

Figure 9. Movements of points for the SIGNAL points.

6   CONCLUSION

Measurements of ground movements using the GNSS method are used very often today. With better and better instrumentation, increased numbers of satellites and better software for data processing this method can obtain highly accurate results. There are not many areas that could have implemented long-term monitoring in Slovenia. So far, classical geodetic measurements have been performed more or less, but the method shows some weaknesses, like shifts of station points and connecting points, weather conditions, invisibility between points, and large mutual distances.

The GNSS method is ideal because it does not need stable positioning points and mutual visibility. Major emphasis is given to the deformation analysis of measurements. In general, a deformation analysis is a set of methods described for the detection and evaluation of the movements and the deformations of natural or man-made structures. The focus is primarily on the concept of data processing so that the deformation analysis frequently indicates, more or less, a procedure for determining movements using appropriate and relevant analytical approaches. It denotes the procedure of processing the measurement results. Geodetic deformation monitoring is thus a wider concept, covering all stages from planning and establishing a system of continuous operation, data processing, analysis and the presentation of results, while under the deformation analysis we understand the processing of measured data and analysing them. The analysis of GNSS data for the purpose of monitoring the movement of soil should also use the knowledge of statistics, geomechanics, civil engineering and geology as well

as additional knowledge of geophysics, geodynamics, and geodesy. The results showed that the GNSS method can cover wider areas in which we need to provide a "clean" signal and all-day surveillance. Based on the results so far we can suggest that the method is very suitable for the long-term monitoring of soil movements for already built objects and for the observation of mutual positions.

In this paper one viaduct was assessed through geology and tectonic activities and also a load test of the viaduct was performed. The viaduct is in a quite active region but the load test showed that the bridge's response to the load is as expected.

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